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Temperature variability at Dürres Maar, Germany during the migration period and at high medieval times, inferred from stable carbon isotopes of *Sphagnum* cellulose

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Abstract

This paper presents a high resolution reconstruction of local growing season temperature (GST) anomalies at Dürres Maar, Germany, spanning the last two millennia. The GST anomalies were derived from a stable carbon isotope time series of cellulose chemically extracted from *Sphagnum* leaves ($\delta^{13}\text{C}_{\text{cellulose}}$) separated from a kettle-hole peat deposit of several metres thickness. The temperature reconstruction is based on the *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ /temperature dependency observed in calibration studies. Reconstructed GST anomalies show considerable centennial and decadal scale variability. A cold and presumably also wet phase with below-average temperature is reconstructed between the 4th and 7th century AD which is in accordance with the so called European Migration Period marking the transition from the Late Roman Period to the Early Middle Ages. At High Medieval Times above-average temperatures are obvious followed by a temperature decrease. On the contrary, a pronounced Late Roman Climate Optimum, often described as similar warm or even warmer as medieval times, could not be detected. The temperature signal of the Little Ice Age (LIA) is not preserved in Dürres Maar due to considerable peat cutting that takes place in the first half of the 19th century. The local GST anomalies show a remarkable agreement to northern hemispheric temperature reconstructions based on tree-ring data sets and are also in accordance with climate reconstructions on the basis of lake sediments, glacier advances and retreats, and historical data sets. Most notably, e.g. during the Early Middle Ages and at High Medieval Times, temperatures were not low or high in general. Rather high frequency temperature variability with multiple narrow intervals of below- and above-average temperatures at maximum lasting a few decades are reconstructed. Especially the agreements between our estimated GST anomalies and the NH temperature reconstructions derived from tree-ring chronologies indicate the great potential of *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ time series from peat deposits for palaeoclimate research. This is particularly the case, given that a quantitative $\delta^{13}\text{C}_{\text{cellulose}}$ /temperature relationship has been found for several *Sphagnum* species. Although the time resolution

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of *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ data sets certainly wouldn't reach the annual resolution of tree-ring data, reconstructions of past temperature variability on the basis of this proxy hold one particular advantage: due to often relatively high peat accumulation rates, especially in kettle-hole bogs accumulated on temperate latitudes over periods of up to several millennia, they allow extending temperature reconstructions based on tree-ring series into the past to enhance our knowledge of natural climate variability during the Holocene.

1 Introduction

There is current specific interest in climate change during our historical past and in human impact on past and future climate and ecosystem dynamics (e.g. Esper et al., 2005; Wanner et al., 2008). In this context, the reconstruction of decadal to centennial scale natural climate variability is of importance to estimate to what extent human activities contribute to the recent warming trend observable at regional and global scale. Terrestrial archives are of particular interest for such reconstructions since they can offer proxy time series of high temporal resolution developed within human habitat. Tree-ring based proxies have been frequently used for such reconstructions and the response of these proxies to climatic factors has been shown (e.g. Grudd et al., 2002; Hantemirov and Shiyativ, 2002; Naurzbaev et al., 2002). Long-time temperature sensitive tree-ring time series, however, are almost exclusively from high latitudes ($> 65^\circ \text{N}$) and alpine timber lines where temperature is the most important growth limiting factor. Other terrestrial archives like lake sediments and speleothems also provide data for estimates of past temperature variability, but the quantification of proxy/climate relationships is complicated by missing direct linkages between climate parameter and proxies.

Peat bogs and fens form additional important terrestrial archives of past environmental and climate variability. They are widely distributed and cover a large part of the earth's land surface often within human habitat (Charman, 2002). Due to partially

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high accumulation rates they allow developing high resolution proxy records spanning several millennia (e.g. Mauquoy et al., 2008; Charman et al., 2009). Multiple botanical proxies (e.g. pollen and plant remains) are established and a range of methods has been developed to make inferences about Holocene environmental and climate dynamics (Warner and Charman, 1994; Birks, 2003; Charman et al., 2009). Isotope-geochemical methods applied on peat deposits have also great potential to provide proxies for climate variability, because empirical relationships between the stable isotope composition of plant cellulose from typical bog species and different climatic parameters, including temperature and relative humidity, have been found (Proctor et al., 1992; Ménot and Burns, 2001; Zanazzi and Mora, 2005; Skrzypek et al., 2007). Thus, contrary to tree-ring time series, peat bogs and fens offer the possibility to perform climate reconstructions based on several biotic and abiotic proxies (Kühl et al., 2010).

Sphagnum is the most abundant peat forming genus in ombrotrophic bogs in northern and western Europe and is present in many late Holocene peat accumulations (Clymo, 1970). *Sphagnum* plant remains are therefore the ideal material to use in isotope-geochemical studies on peat deposits. Plant cellulose is usually used for stable isotope studies since isolation of a single chemical component reduces problems associated with changes in the relative proportion of chemical compounds over time (Rinne et al., 2005). Calibration studies have systematically investigated the relationship between climate parameters and the stable carbon isotope composition of cellulose ($\delta^{13}\text{C}_{\text{cellulose}}$) from modern *Sphagnum* plants. Ménot and Burns (2001) found that in addition to atmospheric CO_2 partial pressure, temperature and water availability play significant roles for their $\delta^{13}\text{C}_{\text{cellulose}}$ values. Regarding potential relationships between the $\delta^{13}\text{C}_{\text{cellulose}}$ of *Sphagnum* plant material and micro-climatological parameters, Skrzypek et al. (2007) report strong correlations between the $\delta^{13}\text{C}_{\text{cellulose}}$ values of *Sphagnum* and air temperature during the growing season. The major problem in the application of the *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ to peat records in order to derive climatic signals arises from the finding that a significant offset exists between the stable carbon isotope composition of cellulose from different *Sphagnum* plant components (Loader

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et al., 2007; Moschen et al., 2009). Thus, physical separation of individual plant parts prior to isotope analyses is a necessity to avoid misinterpretations of stable isotope time series.

The aim of this study was to perform a high resolution climate reconstruction based on the stable carbon isotope composition of cellulose chemically extracted from selected well identifiable *Sphagnum* plant components. This study is a test if the empirical relationship between the stable carbon isotope composition of *Sphagnum* and temperature found in calibration studies can be transferred to the palaeo-record. At Dürres Maar, a kettle-hole peat accumulated in a small maar crater, more than five meters of *Sphagnum* peat developed during the last 2000 yr. Dürres Maar therefore forms an outstanding archive to establish a high resolution stable carbon isotope time series spanning the last two millennia. The peat is situated in a region where human settlement and agriculture was highly variable during the last 2000 yr. We assess the resilience of this proxy to potential human impact on the peat ecosystem by linking the isotope data with the results of palynological investigations and compare our reconstruction with suchlike based on other proxies, especially tree-ring chronologies.

2 Background – the *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ temperature dependency

The photosynthetic uptake of CO_2 by terrestrial plants leads to a fractionation of the carbon isotopes. During *Sphagnum* moss photosynthesis, which follows the C_3 photosynthetic pathway, a constant fractionation factor via the Rubisco carboxylation enzyme occurs, since the later preferentially uses $^{12}\text{CO}_2$ (Farquhar et al., 1982). In addition to this consistent fractionation, a number of environmental factors, including temperature, bog surface wetness, relative humidity and CO_2 partial pressure, affect the stable carbon isotope composition of *Sphagnum* plant material (Williams and Flanagan, 1996). Due to the closed coupling of several environmental factors to air temperature, a (presumably indirect) dependency of the stable carbon isotope composition of *Sphagnum* cellulose on local air temperature has been assumed. To date there is no

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laboratory study on this relationship however the *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ /temperature dependency has been proven in field studies (Ménot and Burns, 2001; Skrzypek et al., 2007). Alongside an altitudinal transect in the European Alps, in addition to the effect of decreasing atmospheric CO_2 partial pressure with increasing altitude, both, temperature and water availability, have been found to play significant roles for the $\delta^{13}\text{C}_{\text{cellulose}}$ values of modern *Sphagnum* plants. As a result of this study statistically significant $\Delta\delta^{13}\text{C}_{\text{cellulose}}/\Delta T_{\text{air}}$ coefficients for *Sphagnum magellanicum* and *Sphagnum capillifolium* of $-0.41\text{‰}^\circ\text{C}$ and $-0.20\text{‰}^\circ\text{C}$ have been calculated. The different coefficients were attributed to differences in the leaf anatomy of the two species potentially leading to variations in the CO_2 diffusion resistance (Ménot and Burns, 2001). *Sphagnum magellanicum* (*Sphagnum* type) possesses oval photosynthetic cells which are fully enclosed by the water-filled hyaline cells. *Sphagnum capillifolium* (*Acutifolia* type) possesses triangle-shaped photosynthetic cells which are exposed at the leaf surface (Laine et al., 2009). It seems reasonable that the latter pattern leads to a lower diffusional resistance to CO_2 uptake because of a potentially smaller aqueous barrier created by the hyaline cells.

Other field studies regarding the $\delta^{13}\text{C}_{\text{cellulose}}$ /temperature relationship of modern *Sphagnum* plant material indicate that the stable carbon isotopic signatures recorded within different species are more related to the micro-topographic position of the *Sphagnum* plants within a bog or fen. Greater ranges of stable carbon isotope values in hollow species than in suchlike growing on relatively dry hummocks has been observed along surface moisture gradients on several European and sub arctic Canadian bogs (Loisel et al., 2009). Additionally, ^{13}C -depleted values of multiple *Sphagnum* species have been shown to be related to low water table depth, while ^{13}C -enriched values correspond to a water table close to the peat surface (Price et al., 1997). Thus, slightly different site specific hydrological conditions could therefore also explain the different temperature coefficients calculated for different *Sphagnum* species (Skrzypek et al., 2007). Whether the significantly different $\Delta\delta^{13}\text{C}_{\text{cellulose}}/\Delta T_{\text{air}}$ coefficients for *Sphagnum magellanicum* and *S. capillifolium* depend on species-specific anatomical characteristics or

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on the micro-topographic position of individual *Sphagnum* moss pads within a bog or fen micro-habitat can solely be clarified by substantial plant-physiological investigations not performed on *Sphagnum* so far.

To summarise, there is evidence that the stable carbon isotope composition of *Sphagnum* cellulose reflects environmental conditions during plant growth and cellulose biosynthesis. There are a number of environmental factors that vary in concert with air temperature and, thus, it is difficult to separate the effects of temperature from other controls on the $\delta^{13}\text{C}_{\text{cellulose}}$ of *Sphagnum* including relative humidity and rainfall amount or distribution and the resulting water table variation. Nevertheless, due to the closed coupling of most environmental factors to air temperature, the $\delta^{13}\text{C}_{\text{cellulose}}$ of *Sphagnum* is a potential recorder of air temperature (Ménot and Burns, 2001; Skrzypek et al., 2007, Kaislahti Tillman et al., 2010).

3 Study site

Dürres Maar is a kettle-hole typed peat deposit located in a small maar crater situated in the mountainous West Eifel Volcanic Field, Germany (50°52' N, 6°53' E). The current mesotrophic bog has a diameter of 140–175 m with a surface area of 0.029 km² and is 455 m a.s.l. The maximum elevation of the crater rim is 470 m a.s.l. (Fig. 1). The surface of the bog is wet, but walkable, and two vegetation zones can be distinguished, which are mainly due to hydrological conditions and nutrient supply. Closest to the edge and relatively wet is the lagg where *Carex lasiocarpa* and *C. rostrata* dominate and where fen species exist such as *Potentilla palustris*. A transitional zone follows towards the central relatively dry bog area where the vegetation consists of raised bog species. Dominating elements of the central bog are *Sphagnum magellanicum* and *S. capillifolium* var. *rubellum* in combination with *Vaccinium oxycoccos* and *Eriophorum angustifolium*. Several small birches (*Betula pubescens*) and scattered small pines (*Pinus sylvestris*) cover the current bog (Fig. 2). The average growing season lasts from mid-April to mid-October (Forst et al., 1997).

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4 Material and methods

4.1 Core collection and sampling

In 2007 we have recovered a 5.5 m long core (core DM-01) in the relatively dry centre of Dürres Maar (Fig. 2). The core has been taken using two different coring devices: the upper 3 m of peat were cored with a lopsided open peat corer (Eijkelkamp “Gouge auger”) providing sections of 1 m length and 6.0 cm diameter. At greater depths the peat contains some small sections of very watery peat requiring a different coring device in order to avoid core loss. The use of a Russian corer (Eijkelkamp “Peat sampler”) at depths greater than 3 m avoided core loss due to the closure of the coring device. The Russian corer allows to core half-round sections of 50 cm length with a diameter of 5.5 cm. After removing a section, the corer was cleaned with deionised water. Core sections were stored in a freezer at -24°C .

Each frozen core section was cut into 2 cm increments in the lab under room temperature using a stainless steel saw in combination with a mitre lay. The width of the blade is 1 mm, which causes loss of approximately 5% of each slice during cutting. Immediately after cutting, the outermost ~ 2 mm of each deep frozen slice was removed and the samples were additionally washed carefully with deionised water to remove possible contaminations with plant fragments originating from lower depths or adheres to the core during field work (Givelet et al., 2004).

4.2 Dating

A total of twelve samples of core DM-01 were radiocarbon dated at the Poznań Radiocarbon Laboratory, Poland. Samples consist of pure *Sphagnum* plant fragments each representing a 2 cm depth interval. Pure *Sphagnum* is used for radiocarbon dating because *Sphagnum* plants grow in situ, do not have roots, and grow in an upward direction from the plant’s apex. Therefore, it is unlikely that they derive carbon from the underlying older peat or were transported from the vicinity to the central bog area where

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the core was taken. In one case (Sample Poz-23192 from a depth of 5.02–5.04 m) plant fragments from *Vaccinium spec.* were used for ^{14}C dating, because *Sphagnum* plant material was not available in an adequate amount. Details of the laboratory procedure are described by Czernik and Goslar (2001).

5 4.3 Separation of *Sphagnum* plant material from bulk peat sediments

To obtain reliable *Sphagnum*-specific stable isotope records from a peat deposit which reflect environmental and climate dynamics, it is necessary to separate single *Sphagnum* plant components from the mixture of plant remains (Loader et al., 2007; Moschen et al., 2009). The manual separation of *Sphagnum* branches or stem sections for cellulose extraction and subsequent stable isotope measurement is, however, very time consuming and restricts the time resolution of potential stable isotope time series. Therefore, we have tested if sieving of the bulk peat samples into different size fractions can serve to substitute the separation of morphological parts of *Sphagnum* plants (Daley et al., 2009). To separate *Sphagnum* remains from the bulk peat samples each sample was washed through a sieve stack with mesh sizes of 2000, 630, 355, and 200 μm . Before sieving of bulk peat samples, approximately 5 g of wet peat was placed in 800 ml beakers in deionised water on a heatable magnetic stirrer and was simmered for one hour at 85 °C. Subsequently, each sample was carefully wet sieved on the sieve stack with a minimum of 5 litre of deionised water. Due to simmering and sieving the peat samples were easily fragmented into single leaves, branch fragments and the less fragile stem sections. Each size fraction was examined for its composition under a stereoscopic binocular microscope (Nikon SMZ 2B). The size fraction of 355–630 μm has been identified to consist of almost pure *Sphagnum* leaves. Therefore, this size fraction was used for cellulose extraction and stable isotope measurement. Compared to the very time consuming manual separation of adequate amounts of single *Sphagnum* plant components for cellulose extraction, the use of this size fraction enables us to process an approximately five times higher amount of samples compared to hand picking of plant components.

4.4 Cellulose extraction and stable carbon isotope measurements

We have chemically extracted cellulose from a total of 257 samples using an improved extraction method based on sample bleaching with sodium chlorite and a following cellulose dissolution and re-precipitation with cuprammonium solution (CUAM). After conventional sodium chlorite bleaching following the method described by Ménot and Burns (2001), cellulose was dissolved in the CUAM solution ($[\text{Cu}(\text{NH}_3)_4](\text{OH})_2$) and re-precipitated using sulphuric acid (Wissel et al., 2008). Contrary to the Ménot and Burns method, no solvent extraction stage prior to the extraction of cellulose was carried out, since this step has been found to be unessential for the purification of cellulose, even from resinous woods (Rinne et al., 2005). Compared to conventional methods the CUAM approach achieves pristine cellulose not by removing any contaminants from the cellulose, but by dissolving the cellulose from bulk peat samples. That way, contaminations of *Sphagnum* cellulose with small amounts of minerogenic matter like silt and clay and/or biogenic opal as well as of residual non-cellulose organic compounds could be excluded. Additionally, the received cellulose is very homogenous ensuring isotopic homogeneity when using small sample amounts for isotope measurements. After freeze-drying of the extracted cellulose a cellulose yield (given in percentages by weight) was determined representing the amount of cellulose dissolved and re-precipitated from a freeze-dried sample of *Sphagnum* leaves.

Stable carbon isotope ratios of *Sphagnum* cellulose were measured by on-line combustion of 200–300 μg dry cellulose weighed into tin foil cups and combusted at 1080 °C using an EuroEA elemental analyser (Euro Vector Instruments, Italy) to generate CO_2 for an interfaced IsoPrime continuous flow isotope ratio mass spectrometer (GV Instruments, UK). Results are reported using the conventional δ -notation ($\delta = (R_S/R_{St} - 1) \times 1000$) with R_S and R_{St} as isotope ratios ($^{13}\text{C}/^{12}\text{C}$) of samples and standards. They are expressed as $\delta^{13}\text{C}_{\text{cellulose}}$ [‰] vs. V-PDB. USGS24 graphite and IAEA-C3 cellulose were used as certified reference materials. Two internal standards (Fluka cellulose and graphite 4) were used for drift corrections. The analytical precision

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measured by replicate cellulose standards was ± 0.06 (1σ). Every tenth sample was measured twice to check the reliability of the measurements. The overall precision of these replicate analyses was better than ± 0.1 (1σ).

Anthropogenic fossil fuel burning which increases the concentration of atmospheric CO_2 have resulted in a lowering of the $\delta^{13}\text{C}$ value of air by about 1.7 since industrialisation. Therefore, all $\delta^{13}\text{C}$ values of samples younger than AD 1850 were corrected for this effect by adding a $\delta^{13}\text{C}$ correction factor to the measured data (Leuenberger, 2007).

4.5 Ash content

Determination of the ash content follows a four step method described in detail by Kempster (1996). After an initial evaporation of moisture at room temperature, about 0.5 g of bulk peat were subsequently oven dried at 105°C and cooled down to room temperature in a desiccator. After determination of the dry weight using a micro balance with an accuracy-range of 0.001 mg (Mettler Toledo XP25) samples were immediately igniting oven combusted in a muffle furnace at 600°C for 6 h. Hereafter the weight of the residual was determined after cooling the samples to room temperature in a desiccator using the same micro balance and expressed in percentage of the dry weight.

5 Results and discussion

5.1 *Sphagnum* peat stratigraphy, age-depth model and peat accumulation

Most of the sediments of Dürres Maar consist of scarcely decomposed highly organic *Sphagnum* peat. From its basis at ~ 5.20 m to a depth of ~ 0.70 m the profile predominantly consists of *Sphagnum capillifolium* var. *rubellum* plant fragments (Moschen et al., 2009) and the minerogenic proportion of the peat is on average around 2%

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(Fig. 3a). At a depth of ~ 70 cm a pronounced alteration in the peat structure and composition is obvious and both, the plant macrofossil and geochemical composition considerably change. A section with higher decomposition appears consisting of a mixture of *Eriophorum* and *Sphagnum* plant fragments. The uppermost four centimetres of this section (60–64 cm) are dominated by *Eriophorum* leaf sheaths and *Sphagnum* is only present in a very small amount. This section shows by far highest ash content of the entire profile (Fig. 3a). Simultaneously the amount of *Sphagnum* cellulose yielded by the CUAM extraction was very low pointing to intensified degradation of the *Sphagnum* plant material (Fig. 3b). Above, again scarcely decomposed *Sphagnum* peat developed and in turn a very small minerogenic proportion (on average between 2 and 3%) can be observed. The moss composition of this section however differs from the underlying approximately 4.5 m of almost pure *Sphagnum capillifolium* var. *rubellum* peat. In the upper ~ 60 cm of the profile, the dominating moss species is *Sphagnum magellanicum* which is accompanied by small amounts of *S. palustre* and *S. capillifolium* var. *rubellum* (Moschen et al., 2009). Remains from *Cyperaceae*, *Vaccinium*, or *Erica* are very rare.

The occurrence of the *Eriophorum* dominated peat section and the high ash content above several meters of scarcely decomposed, highly organic *Sphagnum* peat indicate a major rearrangement of the mire ecosystem. We hypothesise that the *Eriophorum* peat section follows considerable peat cutting. Such peat cutting during the 19th century AD has been already assumed by Kempter (1996) and Forst et al. (1997), but was never examined in detail. The Dürres Maar peat deposit is situated in a small maar crater without any surficial outflow. Peat cutting, thus, would result in a shallow wet marsh, first re-colonised by *Eriophorum* spec. much more adapted to a wet habitat and inundation than *Sphagnum* mosses (Wieder and Vitt, 2006). Afterwards a rearrangement of the bog's ecosystem would take place and in turn a *Sphagnum*-dominated ecosystem developed whereby peat formation progressed until today. This succession would also explain the high ash content of the *Eriophorum* dominated peat section and the low *Sphagnum* cellulose yield indicating a reduction in the peat accumulation rate

and a simultaneously higher aerobic decomposition of the plant material. Summarised, above several meters of scarcely decomposed, highly organic *Sphagnum* peat, a considerable disturbance is obvious which is interpreted as a result of peat cutting. In consequence, the profile consists of a deeper *Sphagnum capillifolium* var. *rubellum* dominated section and an upper *S. magellanicum* dominated section.

The age-depth model for core DM-01 provides additional information for a division of the profile into two sections. Ten ^{14}C values (Table 1) and a palynological examination of selected samples of the profile (for details see Kühl et al., 2010) form the basis for establishing the model. From the bottom at ~ 5.20 m to a depth of ~ 0.70 m the model indicates two phases of considerably different peat accumulation rates (Fig. 4). After ~ 400 yr with a relatively low peat accumulation rate of ~ 1 mm yr $^{-1}$, an increase to ~ 5 mm yr $^{-1}$ is obvious. This increase corresponds well with a significant shift to lower pollen concentrations in the bulk peat samples supporting higher peat accumulation (Kühl et al., 2010). After another ~ 600 yr $^{-1}$ a slight decrease to about 3 mm yr $^{-1}$ at \sim AD 980 (~ 1.7 m) could be identified. At least until the middle 15th century, the age-depth model is consistent and confirmed by various radiocarbon data. During a time span of more than 1500 yr about 4.5 m of scarcely decomposed and highly organic peat has been accumulated.

The model for the upper section of the profile is comparatively poor. Because solely one radiocarbon data is available, we have established the model for this upper section by the aid of the palynological investigation. The available AMS value of the sample from a depth of 20–22 cm is 130pMC and reflects the bomb peak of atmospheric ^{14}C in the middle of the 20th century. The amount of 130pMC occurred twice, between AD 1960 and AD 1961 and in AD 1979 (Goslar et al., 2005). Thus, two different peat accumulation rates are possible. If the sample from a depth of 20–22 cm matches to AD 1960–61 the mean peat accumulation rate is ~ 4.5 mm yr $^{-1}$, if this sample matches to AD 1979 the mean accumulation rate is ~ 8 mm yr $^{-1}$. Although a constant accumulation rate from the bog's surface to a depth of ~ 65 cm is not very likely, both accumulation rates seem reasonable. The palynological examination provides evidence that a

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mean accumulation rate of $\sim 4.5 \text{ mm yr}^{-1}$ is the best approximation. At a depth of 56–58 cm, core DM-01 displays the first appearance of a larger quantity of *Picea* pollen (9.5% of the total pollen sum) indicating the existence of *Picea* forests in the vicinity of Dürres Maar (Fig. 3c). The high *Picea* pollen sum is clearly attributable to the afforestation of the Eifel low mountain range with *Picea abies* under Prussian governance (Schwind, 1984). In the West Eifel Volcanic Field large-scale *Picea abies* afforestation started around AD 1850 (Wacker, 1991). According to the start of the Prussian afforestation and since *Picea abies* trees need a minimum of 30 yr before they produce larger amounts of pollen (Schmidt-Vogt et al., 1986), we estimate the mean age of the sample from a depth of 56–58 cm to a maximum of \sim AD 1880. This value supports the assumption that the mean peat accumulation rate of the upper section of the profile is $\sim 4.5 \text{ mm yr}^{-1}$. Although this approximation disregards any peat compaction which certainly takes place in particular at the transition from the fresh uncompacted acrotelm to the underlying catotelm peat, this is the best assumption on the basis of the three anchor points of the age-depth model of the younger section of our profile (Fig. 4). To summarise, a hiatus divides the profile into two independent sections and a former inbetween lying portion of peat of nearly $\sim 1 \text{ m}$ thickness accumulated during approximately 400 yr must have been cut. Whether such a large amount of peat was removed during one substantial intervention or smaller amounts of peat have been cut several times after another cannot be answered.

5.2 Estimating the past growing season temperature variability at Dürres Maar

Today *Sphagnum magellanicum* is the dominating moss species in the central relatively dry area of Dürres Maar and the scarcely decomposed peat accumulated during the last approximately 150 yr almost exclusively consists of *S. magellanicum* plant remains. In contrast, the underlying peat sequence developed from AD 1 to \sim AD 1450 almost exclusively consists of *S. capillifolium* var. *rubellum* plant remains (Moschen et al., 2009). Both taxa are typical raised bog species and common in late Holocene peat

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deposits in Western Europe (Frahm and Frey, 2004; Mauquoi and van Geel, 2007). For both species a dependency of their $\delta^{13}\text{C}_{\text{cellulose}}$ values on growing season temperature has been shown and statistically significant $\Delta\delta^{13}\text{C}/\Delta T$ coefficients of $-0.20\text{‰}/^\circ\text{C}$ for *S. capillifolium* and $-0.41\text{‰}/^\circ\text{C}$ for *S. magellanicum* were determined (Ménot and Burns, 2001). We have used both coefficients to estimate the past local growing season temperature variability at Dürres Maar. The $\Delta\delta^{13}\text{C}/\Delta T$ coefficient of $-0.20\text{‰}/^\circ\text{C}$ was applied on the *S. capillifolium* var. *rubellum* dominated peat section developed from AD 1 to ~AD 1450, the coefficient of $-0.41\text{‰}/^\circ\text{C}$ was applied on the *S. magellanicum* dominated section grown after the rearrangement of the bog ecosystem in the first half of the 19th century.

Figure 5b illustrates the resulting reconstructed local growing season temperature (GST) showing considerable centennial and decadal scale variability. After four centuries of moderate GST variations and slightly above average GST values, at ~AD 400, a transition to lower temperatures is indicated. It coincides with a remarkable increase in the peat accumulation rate pointing to more favourable growth conditions for *Sphagnum* and, thus, to a relatively high water table. Onset and duration of the reconstructed cold and presumably also relatively wet phase is in accordance with the so called European Migration Period from the 4th to the 7th century AD that marked the transition from the Late Roman Period to the Early Middle Ages and is described as time span with poor living conditions in central Europe (Fouracre, 2005). For this time span a marked decline in land use is documented for the West Eifel region (Litt et al., 2009)

In the following, a transition to higher temperatures is obvious which goes along with an increase in the high-frequency signal magnitude whereby multiple distinct colder and warmer episodes at maximum lasting a few decades are detectable. During High Medieval Times lasting from the 10th to 13th century, our reconstruction shows evidence for above-average temperatures. However, temperatures were not high in general rather distinct warmer episodes lasting a few decades are demonstrated. Afterwards the reconstructed GST gradually reduces to average- and slightly below-average temperatures during the 14th and 15th century. In contrast to the temperature

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anomalies during the European Migration Period and at High Medieval Times, the temperature signal of the Little Ice Age (LIA) is not preserved in our archive due to considerable peat cutting that most likely took place in the first half of the 19th century. Nevertheless, peat cutting during the 19th century, when the Eifel region was considerably deforested (Schwind, 1984), refers to poor living conditions presumably accompanied by low temperatures because peat was used as solid fuel and stable litter (Forst et al., 1997).

The centennial scale variations of palaeo-GST anomalies at Dürres Maar are in accordance with climate reconstructions on the basis of lake sediments and historical data sets from western and north-western Europe (e.g. Hammarlund et al., 2003; Brázdil et al., 2005). Results from the Swiss Alps indicate several glacial retreats during a period lasting from the 9th to 12th century AD (Holzhauser et al., 2005). In the Italian Alps, temperatures presumably have reached higher values than nowadays during the 11th and 12th century AD when soils developed on mountain slopes presently characterized by periglacial debris (Giraudi, 2009). At Medieval Times, two phases of distinct ice retreat are also described for Norwegian glaciers. The most pronounced retreat during the last two millennia has been dated to ~ 1000 yr cal. BP (Nesje et al., 2001). Although one has to take into account that the time resolution of the reconstructions on the basis of glacier advances and retreats is relatively poor compared to the *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ time series presented here, these proxies also show distinct periods during High Medieval Times where temperatures were probably as high as today or even higher.

Unlike the above-average temperatures at High Medieval Times and slightly before, we do not find evidence for any prior warm phase. Although our reconstruction shows slightly above-average temperatures during the second half of the 1st century AD, a Late Roman Climate Optimum often described as similar warm or even warmer as medieval times could not be detected. This is in accordance with other millennial-scale climate reconstructions based on multiple proxy data sets (e.g. Jones and Mann, 2004; Moberg et al., 2005). In contrast to these reconstructions in favour of the absence of

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a pronounced Roman Climate Optimum, there are other proxy records that point to relatively high temperatures during the first two centuries AD. Proxies of glacier retreat and low lake levels indicate warm and/or dry conditions in the Alps (Holzhauser et al., 2005; Joerin et al., 2006; Giraudi, 2009). On the contrary, a record of reconstructed temperatures derived from a well-dated stalagmite $\delta^{18}\text{O}_{\text{CaCO}_3}$ record from the Central Alps shows remarkably low winter temperatures during the first four centuries AD (Mangini et al., 2005). The results of Mangini et al. (2005) suggest that the climate of this period was continental and dry. Thus, the dryness of the climate rather than its warmth would explain the widely accepted glacier recession accompanied by low lake levels in the Alps during the Late Roman Period.

Due to their annual resolution, tree-ring data series offer the highest accuracy possible regarding the age control of terrestrial proxy time series (e.g. Briffa et al., 2004). Figure 6 shows the estimated GST temperature at Dürres Maar compared to the northern hemispheric temperature reconstruction of Esper et al. (2002). The tree-ring curve is based on multiple standardised tree-ring width series and is interpreted to reflect changes of mean annual air temperature over the past 1000 yr in the Northern Hemispheric extratropics. Although the age-depth control of our reconstructed GST anomalies is doubtless not as precise as those of the signals derivable from the tree-ring series, on centennial time scale, the agreement of both reconstructions is remarkable. The multicentennial low frequency Northern Hemispheric climate signal is thus preserved in our record. Where the two series disagree is on decadal time scale. Given that our estimated GST is a local signal whereas the Esper et al. (2002) record is a large-scale average of tree-ring data from all over the extratropic northern hemisphere ($30^\circ\text{--}70^\circ\text{N}$), it is not surprising that both records do not fit on decadal time scale. It is obvious that a temperature reconstruction on a local scale must exhibit notable differences compared to a northern hemispheric reconstruction (Bradley et al., 2003; Wanner et al., 2005). Even a comparison of multiple tree-ring records from different European sites reveals inconsistencies between the individual proxy records (Briffa, 2000; Crowley and Lowery, 2000).

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Although the two reconstructions differ in the timing of the intervals of most prominent medieval warmth they closely agree in the magnitude of reconstructed temperature variability. This agreement is particularly noteworthy since our proxy time series is not standardised or filtered. It remains uncertain whether the offset in timing is partially caused by the less precise age-depth control of our record compared to the annually resolved tree-ring series. Nevertheless, it is important to note that both reconstructions show the same multicentennial climate variability. This is superimposed by high frequency variability with multiple narrow intervals of highest warmth or relatively low temperatures. Thus, contrary to the impression that most multi-proxy and multi-site climate reconstructions might give, our results confirm regional inconsistency in natural climate variability (Hughes and Diaz, 1994; Crowley and Lowery, 2000). Such-like is known from modern meteorological observations indicating that decadal scale climate variability is no global or Northern Hemispheric phenomenon, rather temperature trends vary by region and season. E.g. while current warming and accompanied reduced sea ice cover is prevalent over most of the Arctic, some areas, such as Greenland, appear to be cooling.

5.3 Testing the reliability of the estimated GST anomaly – the calibration data set

In contrast to the results from the older section of the peat sequence, the chronological control of our *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ time series from the upper section has to be considered with caution (see chapter 5.1). Nevertheless, relatively long time series of instrumental data are available and allow examine the relationship between the *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ values and measured growing season temperatures (GST). The nearest long lasting daily temperature data set in the surrounding of Dürres Maar is from the meteorological station Trier ~35 km to the southwest which is operated by the German Meteorological Survey (DWD). The observations started at AD 1907 but lack the time period from 1935 to 1947. Assuming a more or less linear peat accumulation rate during the time span of meteorological observations, i.e. the last

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~100 yr, each single 2 cm peat increment has been theoretically accumulated during ~4.5 yr. Therefore the individual *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ values were compared to average growing season temperatures calculated for each ~4.5 yr time interval to maintain the same temporal resolution than the peat samples. Due to the *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ /temperature relationship shown in calibration studies (Ménot and Burns, 2001; Skrzypek et al., 2007) and since a significant correlation between the $\delta^{13}\text{C}_{\text{cellulose}}$ values of *Sphagnum* and summer temperature has recently been reported for *Sphagnum fuscum* from subarctic Canada (Kaislahti Tillman et al., 2010), a good agreement between our measured *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ values and the respective mean GST was expected. However, a relatively low correlation ($r = 0.43$) was found which is solely slightly higher than the dependency of the *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ values on the respective mean annual temperatures ($r = 0.39$) (Fig. 7).

The correlation between our estimated GST anomalies and instrumental temperature data is certainly hampered by two main reasons: First, the chronological control of the *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ calibration data set is not very reliable (see chapter 5.1). Due to solely three anchor points within ~65 cm of scarcely decomposed peat, a linear peat accumulation rate has to be assumed. Such a linear accumulation over a period of about 100 yr is not very likely and would additionally imply that no compaction of the peat took place over time. Second, one has to consider that a variety of environmental variables are integrated by the *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ value. Because of the close coupling of the carbon isotope signal to the diffusional limitation of CO_2 supply, which is controlled by the thickness of the water film surrounding the plant's chloroplasts, precipitation amount and distribution, relative humidity and, thus, the bog surface wetness most likely plays a major role. On the other hand, in the central relatively dry bog area of Dürres Maar, water table fluctuations are significantly related to local temperature whereas there is a lack of response to the amount or distribution of precipitation (Fig. 8). This is in accordance with the finding of Schoning et al. (2005) who demonstrate that water table fluctuations in two ombrotrophic mires in central Sweden are closely related to changing temperature conditions while there is no correlation

to fluctuations in precipitation amount and distribution. Consequently, despite overall relatively low correlation coefficients for the *Sphagnum* $\Delta\delta^{13}\text{C}/\Delta T$ relationship, we assume that at Dürres Maar local temperature is linked with the factors directly forcing the carbon isotope fractionation by *Sphagnum* mosses, i.e. the diffusional resistance to CO_2 uptake through the aqueous barrier surrounding the plants chloroplasts and the rate of photosynthesis.

Our reconstructed GST anomalies however considerably underestimate the interannual temperature variability. Compared to the amplitude of $\geq 3.0^\circ\text{C}$ in the instrumental annually mean temperature and the respective growing season temperature values, our reconstructed amplitude of $\sim 1.1^\circ\text{C}$ is rather small (Fig. 9). Even though an application of the temperature coefficient resulting from our calibration data set of $-0.44\text{‰}/^\circ\text{C}$, which is slightly higher than the published coefficient of $-0.41\text{‰}/^\circ\text{C}$ for *S. magellanicum* (Ménot and Burns, 2001), wouldn't enlarge the amplitude of reconstructed GST significantly. On the other hand side, each single sample of *Sphagnum* plant material used for the calibration data set has been accumulated during approximately 4.5 yr. Consequently each *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ value integrates the temperature information of up to five vegetation periods. If one compares the reconstructed GST anomalies with a five year running mean of instrumental vegetation period temperatures, the reconstructed amplitude of $\sim 1.1^\circ\text{C}$ stands opposite to amplitude of $\sim 1.6^\circ\text{C}$ as derived from the instrumental annually mean temperatures. Thus, the amplitude of our reconstructed GST anomalies is comparable to instrumental data. Nevertheless part of the underestimation of the temperature variability by our reconstruction must be originated from another reason. This phenomenon has been previously described for tree-ring based reconstructions of temperature variability and was attributed to the overwhelming problem that a proxy is not controlled by one single environmental variable (e.g. Büntgen et al., 2005; Corona et al., 2010). *Sphagnum* plants and trees however certainly react in very different ways on climate variables. For *Sphagnum* both, relative growth rate and biomass productivity are linked to temperature and the plants water content (Rice, 2000; Robroek et al., 2007). The maximum rate of CO_2 assimilation

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and thus the highest biomass productivity has been found at a water content of approximately 7 (weight of fresh vs. dry *Sphagnum* plants). Above and below this value CO₂ assimilation declined (Williams and Flanagan, 1996). In contrast the discrimination against ¹³CO₂ is a more or less linear function of water content. The higher the water content is the lower are the δ¹³C_{cellulose} values of the *Sphagnum* plant tissue (Williams and Flanagan, 1996). We hereof hypothesise that the underestimation of the instrumental temperature data by our reconstruction partially results from the overall high biomass productivity at mean water content. At higher and lower water content (associated with lower and higher temperatures; Fig. 8), cellulose synthesis is reduced and the proportion of cellulose with depleted or enriched δ¹³C values is relatively small leading to a dampening of the amplitude of the stable carbon isotope time series of *Sphagnum* cellulose.

6 Conclusions

A high resolution reconstruction of local growing season temperature (GST) spanning the last two millennia was established on the basis of the stable carbon isotope composition of *Sphagnum* cellulose from a kettle-hole peat deposit. The reconstructed GST shows relevant centennial and decadal scale variability. From the 4th to the 7th century AD a cold and presumably also wet phase with below-average temperature is reconstructed which is in accordance with the so called European Migration Period marking the transition from the Roman Period to the Early Middle Ages. During High Medieval Times above-average temperatures are obvious. Most notably, temperatures were not low or high in general, rather high frequency temperature variability with multiple narrow intervals of below- and above-average temperatures lasting a few decades is demonstrated. In contrast, a pronounced Late Roman Climate Optimum often described as similar warm or even warmer as medieval times could not be detected. The reconstructed GST shows a remarkable agreement with temperature reconstructions based on tree-ring data sets and is also in accordance with climate

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reconstructions on the basis of lake sediments and glacier advances and retreats. The good agreement between our reconstructed GST and the Esper et al. (2002) temperature reconstruction on centennial time scale indicates the advantage of performing temperature reconstructions on the basis of *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ data sets. Due to often high peat accumulation rates in raised bogs and fens, *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ time series allow to develop high resolution proxy records spanning several millennia. In contrast, most of the environmental and temperature reconstructions which have been processed from local tree-ring chronologies, span the last ~ 300 to ~ 600 yr only. From such proxy records much evidence of a Little Ice Age cooling is reported for different regions around the North Atlantic. Few tree-ring data sets that extended back prior to $\sim \text{AD } 1000$ also assess the climatic variability during High Medieval Times (e.g. Hantemirov et al., 2002; Naurzbaev et al., 2002; Büntgen et al., 2006). Because of the scarcity of wood material from the first millennium AD, the European Migration Period and the Late Roman Period are not well documented (Nicolussi et al., 2009). This applies in particular for western and central Europe. Although the time resolution of *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ data sets would not reach an annual resolution tree-ring data sets provide, an extension of climate reconstructions until the middle Holocene or even longer is possible.

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Table 1. Results of radiocarbon dating: *Sphagnum* plant material is used for radiocarbon dating to avoid admixture of plant material relocated from the bog's vicinity. In one case (*) plant fragments from *Vaccinium spec.* were used for ^{14}C dating, because *Sphagnum* plant material was not available in an adequate amount. The standard deviation for the calendar ages is given as 2σ . The sample from a depth between 502 and 504 cm has been omitted from the model, since its ^{14}C age is obviously too young.

depth [cm]	Lab. no.	^{14}C age	age cal. BP	calendar age (2σ)
20–22	Poz-22240	130.27 ± 0.39 pMC		1960–1961 AD
84–86	Poz-24702	640 ± 30 BP	610–544	1368 ± 28 AD
132–134	Poz-23191	890 ± 30 BP	834–733	1167 ± 51 AD
172–174	Poz-22243	1075 ± 30 BP	1015–930	978 ± 43 AD
228–230	Poz-20797	1140 ± 30 BP	1142–968	895 ± 87 AD
292–294	Poz-22244	1270 ± 30 BP	1286–1167	724 ± 60 AD
356–358	Poz-20798	1490 ± 30 P	1416–1305	590 ± 56 AD
422–424	Poz-20799	1585 ± 30 BP	1538–1405	479 ± 67 AD
472–474	Poz-20773	1650 ± 30 BP	1622–1508	385 ± 57 AD
502–504	Poz-24706	1350 ± 30 BP	1314–1235	676 ± 40 AD
520–522*	Poz-23192	2125 ± 35 BP	2160–1997	129 ± 82 BC

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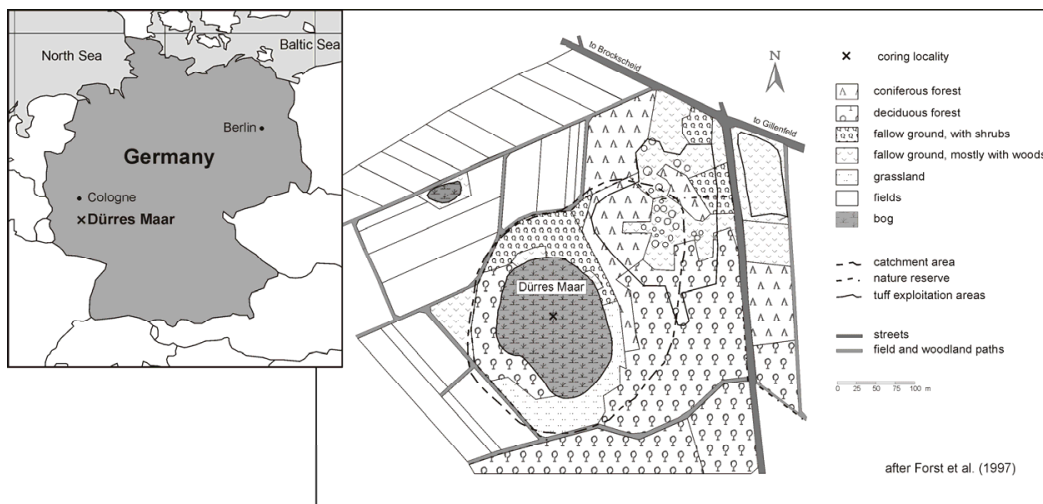


Fig. 1. Location of Dürres Maar and map of the hosted peat deposit and the surrounding vegetation cover (modified after Forst et al., 1997).

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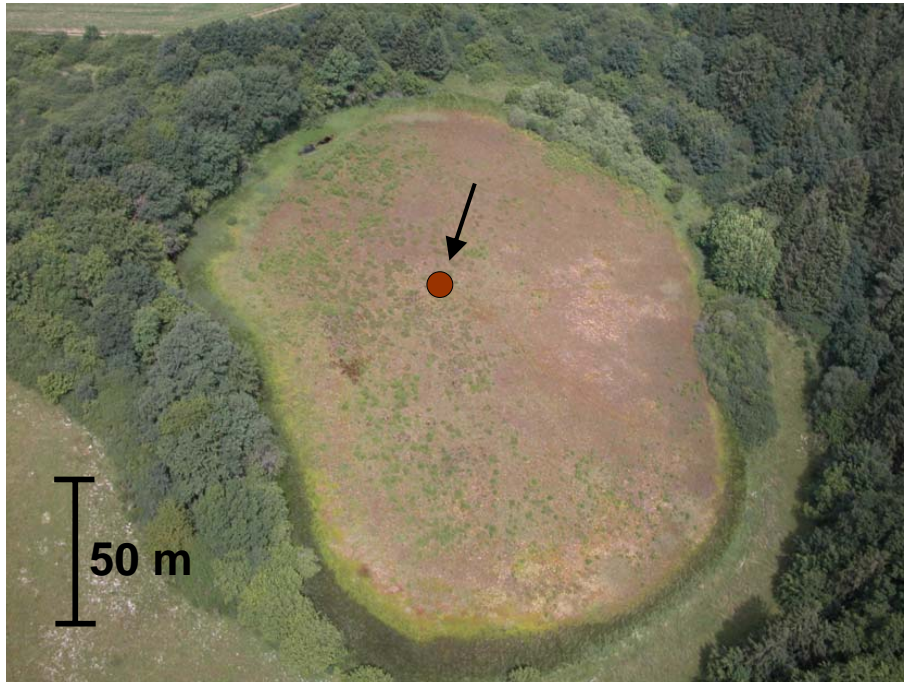


Fig. 2. Aerial photograph of Dürres Maar with borehole location.

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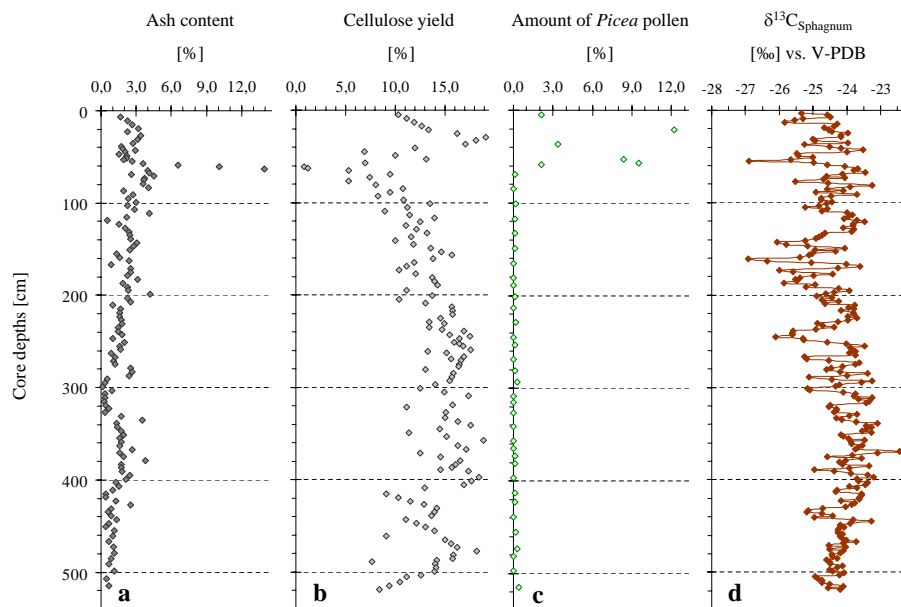


Fig. 3. The stable carbon isotope composition of *Sphagnum* cellulose (**d**) in combination with the ash content (**a**), the cellulose yield (**b**), and the *Picea* pollen concentration (**c**) of selected samples from core DM-01. No error bars are added to the individual symbols of figure (**d**) because the overall precision of replicate analyses is better than $\pm 0.1\%$ and the error bars thus would be smaller than the symbol size.

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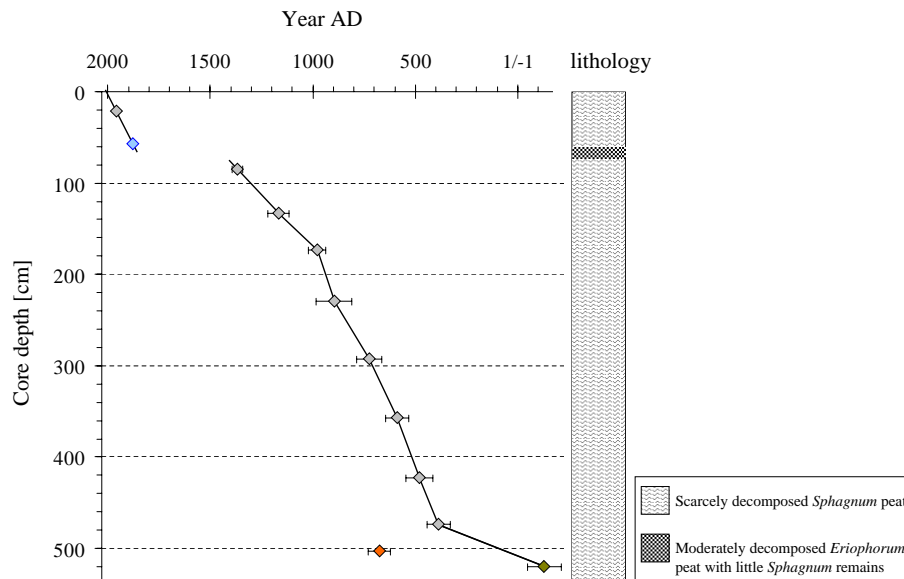


Fig. 4. Age-depth model and lithology of core DM-01 taken in the centre of the Dürres Maar peat deposit. The model is based on 10 ^{14}C results calibrated and transformed to calendar ages (years AD) using CALIB 5.0 (Reimer et al., 2004). The age at a depth of between 56 and 58 cm (blue diamond) is determined on the basis of the paleynological investigation performed on selected samples of the profile (for details see chapter 5.1). The sample from a depth between 502 and 504 cm was omitted from the model, since its ^{14}C age is obviously too young. In one case (dark green diamond) plant fragments from *Vaccinium* spec. were used for ^{14}C dating, because *Sphagnum* plant material was not available in an adequate amount.

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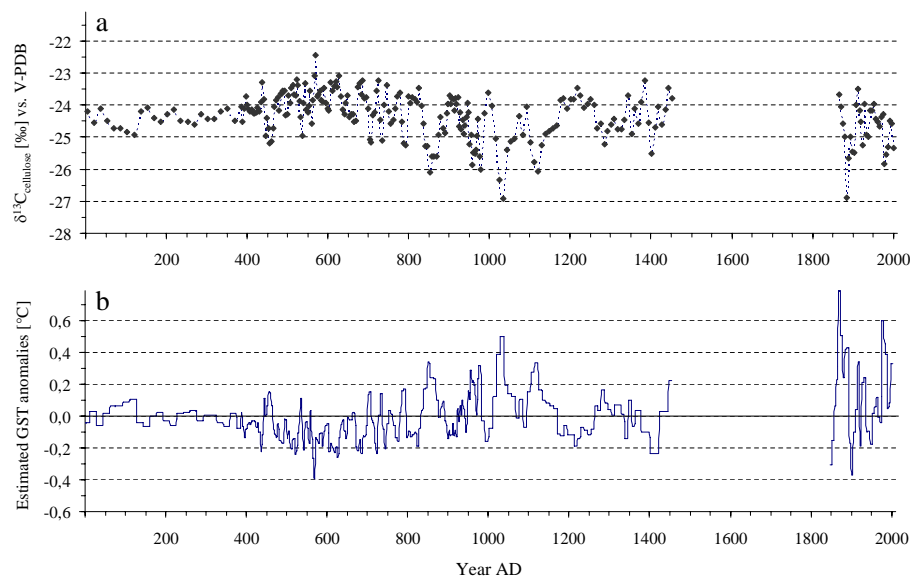


Fig. 5. The stable carbon isotope composition of *Sphagnum* cellulose (a) in combination with the estimated growing season temperature anomalies at Dürres Maar (b). On the basis of our age-depth model a top age and a bottom age for each sample was calculated narrowing the time span any 2 cm peat increment accumulated to a specific number of years. Calculating a top and bottom age for each individual sample thus enables generating estimated temperature values for each year of the time period under investigation. They are given in Fig. 5b.

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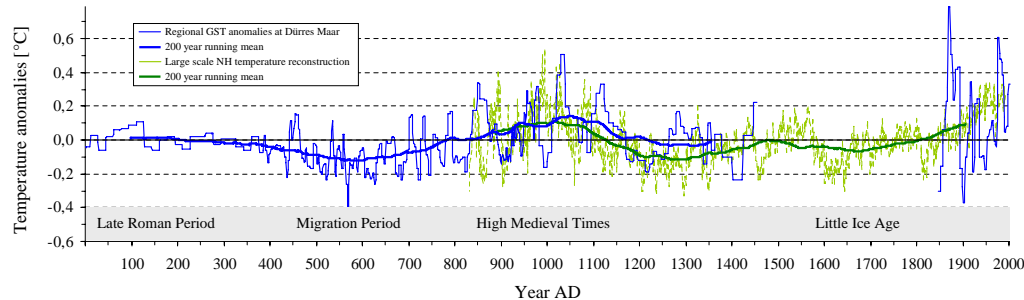


Fig. 6. The estimated growing season temperature (GST) anomalies at Dürres Maar compared to the northern hemispheric extratropical temperature reconstruction (NHT) of Esper et al. (2002) which is based on multiple standardised tree-ring width series. Our estimated GST anomalies are non-homogenised values, whilst the NHT record has been corrected for age-related tree growth trends using a regional standardisation technique (details in Esper et al., 2003). Both proxy data sets are not scaled to any observational record. The bolt lines show the 200 yr running means.

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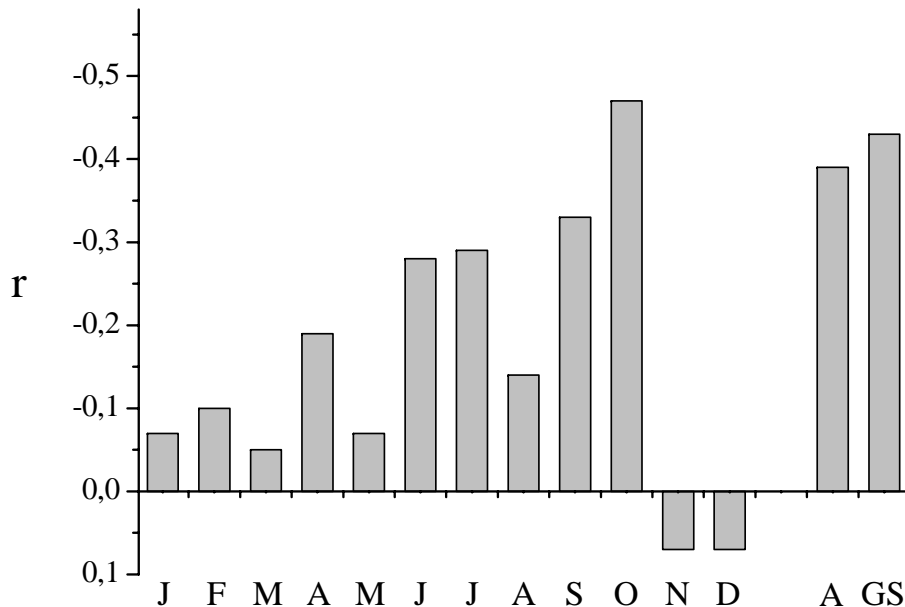


Fig. 7. Linear correlations between the *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ values and average temperatures based on daily temperature data (1907–2004) from the meteorological station Trier ~35 km to the Southwest of Dürres Maar ($n = 21$). Bars 1–12 represent the correlations between the $\delta^{13}\text{C}$ values and mean monthly temperatures (January–December); A represents the correlation between the *Sphagnum* $\delta^{13}\text{C}_{\text{cellulose}}$ values and the mean annual temperature; GS represents the correlation $\delta^{13}\text{C}$ values and the mean growing season temperature (15 April–15 October). Average monthly-, growing season-, and *Sphagnum* related growing season temperatures were calculated for each ~4.5 yr time interval to maintain the same temporal resolution than the peat samples (for details see Sect. 5.3).

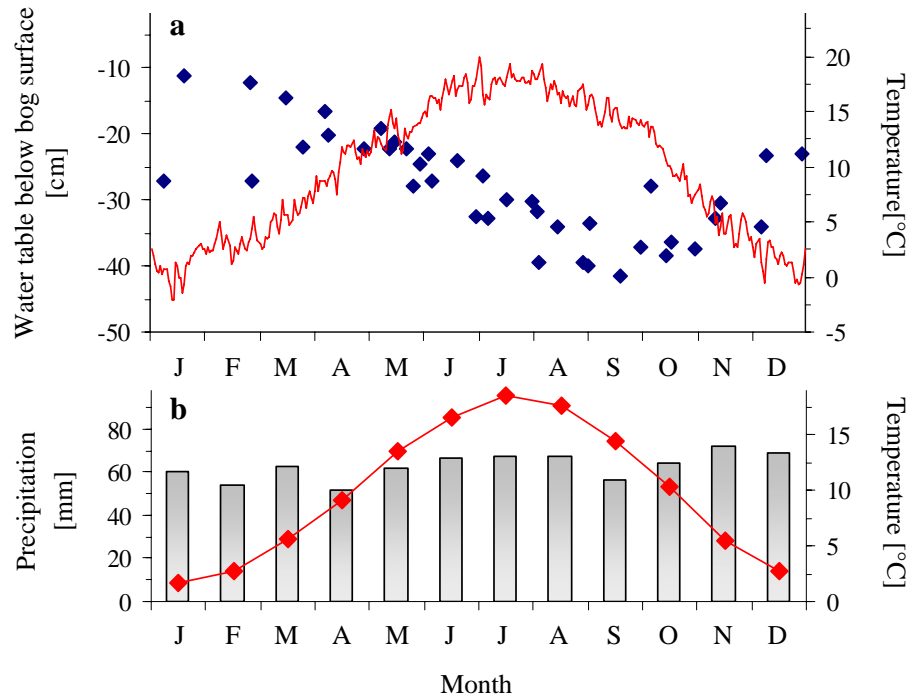


Fig. 8. Water table fluctuations in the centre of Dürres Maar (dark blue diamonds) in combination with average daily temperatures **(a)** and monthly sum of precipitation in combination with average monthly temperatures (1961–1990) **(b)**. Water table fluctuations were measured from April 1991 until December 1993 by Forst et al. (1996). The depicted average daily temperatures for the years 1991, 1992 and 1993 were recorded at the meteorological station Manderscheid approximately 6 km to the south of Dürres Maar operated by the German Meteorological Service. Also the monthly sum of precipitation and the average monthly temperatures of the time period from 1961 until 1990 were recorded at Manderscheid.

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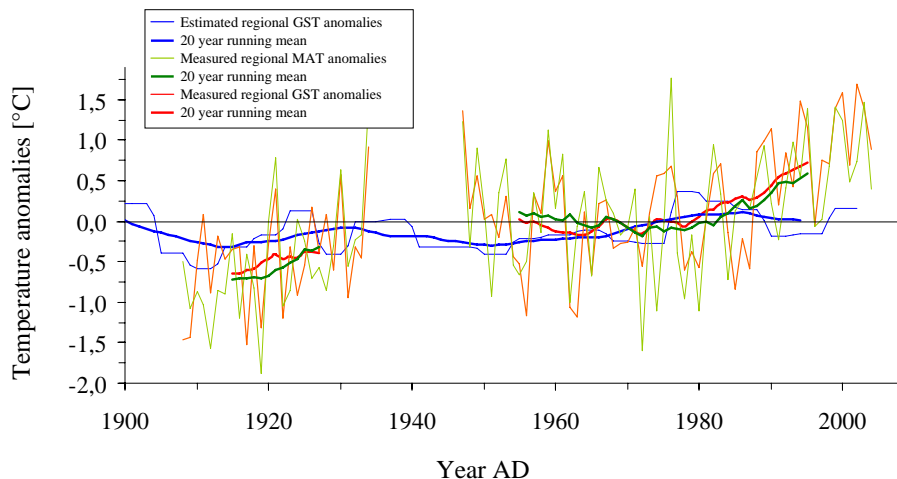


Fig. 9. Estimated growing season temperature anomalies (GST) at Dürres Maar in combination with calculated mean annual air temperature (MAT) anomalies and calculated growing season temperature anomalies (GST). Averaged temperatures are based on daily temperature data (1907–2004) from the meteorological station Trier ~35 km to the Southwest of Dürres Maar. For comparison of proxy and instrumental data the individual time series were scaled using 1961–1990 as the calibration period. The bolt lines show the 20 yr running means.

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