A multi-proxy high-resolution approach to reconstructing past environmental change from an Alpine peat archive

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High-resolution multiproxy studies on alpine peatlands reveal how environmental changes (including human impact) have influenced the developmental history of these unusual ecosystems. Here we summarize results of new paleoclimate reconstructions based on calibration and validation with the instrumental climate record.

Global warming is dramatically changing mountain ecosystems; glaciers are shrinking and current snow conditions differ considerably from those that existed 50 years ago (Laternser and Schneebeli, 2003; Wipf et al., 2009). Among various types of mountain ecosystems, peatlands stand out because of their ecologically and biogeographically unique flora and fauna, and their role as carbon pools and sinks. Peatlands are also highly sensitive to human impact and climatic change. Because peatlands accumulate records of their developmental history, including responses to climate changes, land-use and human impact, they represent a valuable source of information on past and ongoing global changes (Charman, 2002). However, paleoecological data on peatland development in alpine regions are scarce.

Most modern high-resolution multiproxy studies of mountainous regions have been based on lake sediments (e.g., Ammann, 1986; Ammann et al., 2000, van der Knaap et al., 2000). However, in the past decade, peatlands have been used to address specific questions that demand high spatial or temporal resolution. Small peatlands have been used to gain records of Holocene and Late-Glacial stand-scale dynamics (where "stand" is defined as an area of sufficient homogeneity to be regarded as a single unit; Dahlgren and Turner, 2010) (van der Knaap et al., 2003; Genries et al., 2009; Stahli et al., 2006). Such paleoenvironmental records may differ from more regional signals, such as those recorded in lacustrine sequences. For instance, Hofstetter et al. (2006) analyzed a small peatland (0.05 ha) in the Southern Alps and suggested that important tree species (e.g., *Abies alba*, *Castanea sativa*) were present locally millennia before they could be unambiguously recorded in the larger (5-20 ha) lake archives.

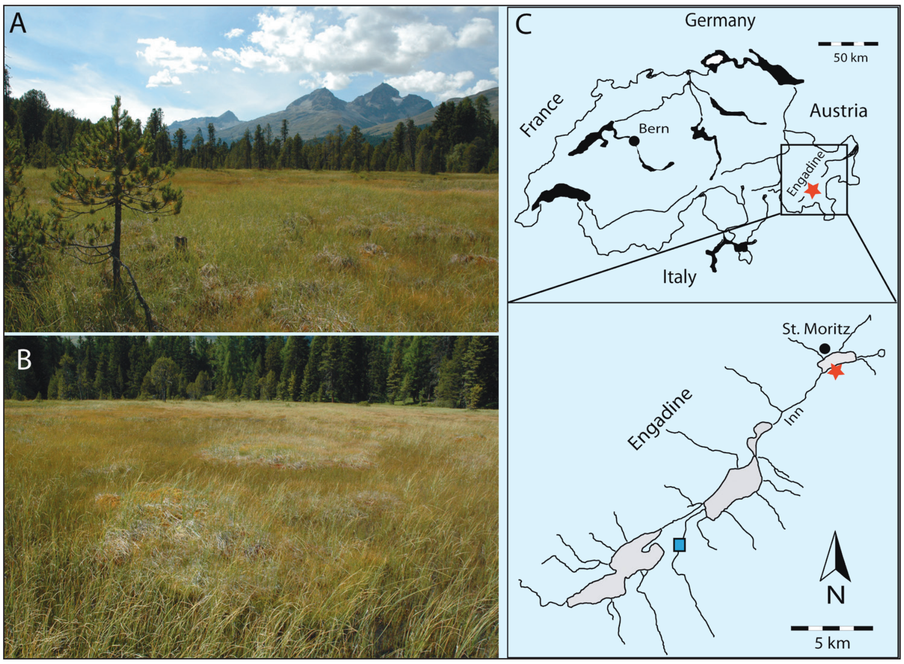

*Figure 1: **A**) The Alpine landscape where the peatland is situated; **B**) Typical vegetation with* Sphagnum fuscum *hummocks surrounded by brown mosses and vascular plants, **C**) Location of Mauntschas Mire (red star) in the Engadine region, Switzerland. The meteorological station Sils Maria is indicated by the blue square (Map modified from Lamentowicz et al., 2010).*

It is currently not clear which factors have the strongest influence on peatland development. For example, the hydrology of alpine peatlands is controlled not only by summer precipitation but also by the amount and duration of snow cover. Addressing these issues requires integrated studies of modern peatlands and their history.

Multiple proxies in peat deposits can be studied at near-annual resolution, at least for recent centuries, but such studies are still very rare. Although time-consuming, they provide a temporally precise continuous paleoecological record. Moreover, peat archives from the last 150 years offer an opportunity to correlate reconstructed time series with instrumental meteorological data and other historical information. We use a high-resolution time series to validate transfer function-based quantitative reconstructions against measured climate variables (temperature and precipitation).

Case study – Mauntschas Mire

Within the framework of the EU project MILLENNIUM (http://geography.swan.ac.uk/millennium), we obtained a high-resolution (near-annual) multi-proxy record from Mauntschas Mire, a subalpine peatland (1818 m asl) at the bottom of the Upper Engadin Valley in the southeastern Swiss Alps (Fig. 1). The site recorded local hydrological changes that can be related to local precipitation/temperature changes since AD 1000. The aim of this multi-proxy study was to reconstruct climate and other environmental changes of the last millennium using the highest possible sampling resolution, close to annual whenever possible. To achieve this aim, the core was divided into 2 mm slices with the Damocles device (Joosten and

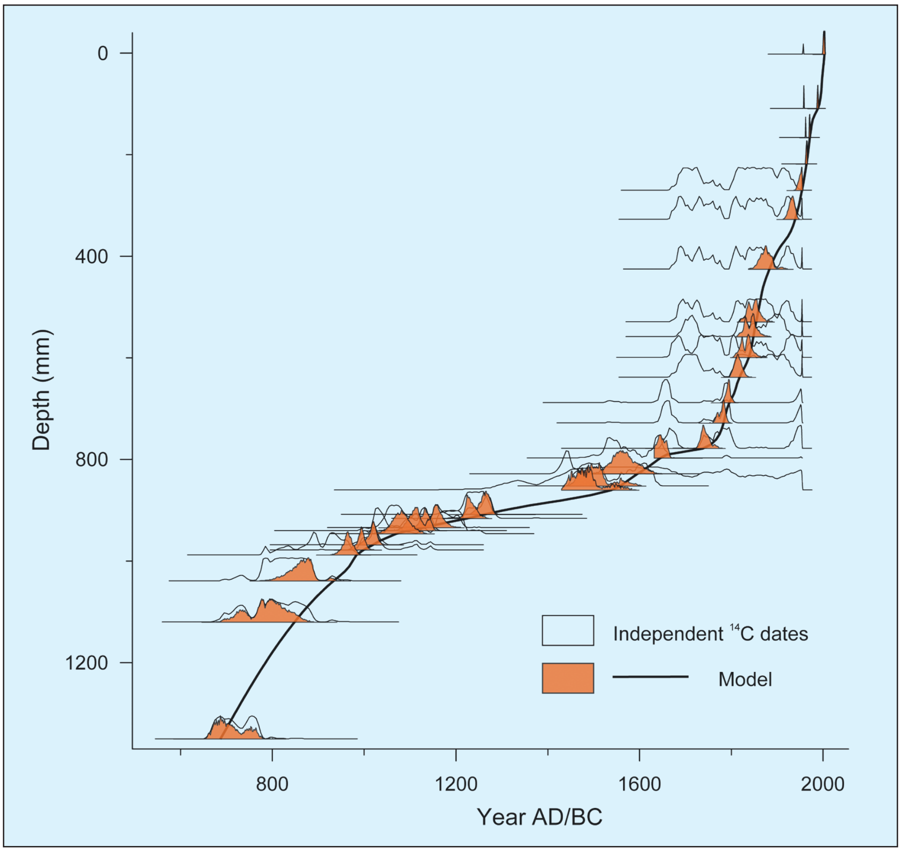

Figure 2: Age-depth model of the peat profile Mauntschas MA2, calculated with a free-shape modeling algorithm with information on relative changes of peat-accumulation rate. Open silhouettes show results of calibration of individual ^{14}C dates, treated as independent of one another. The best-fit age-depth model is shown with a solid line, while uncertainty of the model is illustrated with orange silhouettes (modified from Goslar et al., 2009).

De Klerk, 2007). High-resolution radiocarbon dating combined with advanced age-depth modeling (Goslar et al., 2009) and the study of plant macrofossils, pollen, stable isotopes and testate amoebae enabled precise paleoenvironmental reconstructions.

Chronology – age-depth modeling

An age–depth model, based on 29 radiocarbon dates spanning the last 1.3 ka, was constructed (Fig. 2) using the algorithm of free-shape modeling (Goslar et al., 2009). This algorithm searched for a reasonable compromise between fit of ^{14}C dates to the radiocarbon calibration curve, general smoothness of the age–depth line, and similarity of relative changes in the modeled sediment-accumulation rates to those suggested by independent data. The complicated shape of the age-depth curve was indicated by parallel fluctuations in concentrations of most pollen taxa, supported in the upper part of the profile by the record of anthropogenic spheroidal carbonaceous particles, and in some levels also by the ^{14}C dates themselves.

Uncertainty in the obtained model was assessed using Monte Carlo simulations. This uncertainty is 1–2 years in the post-bomb period (AD 1950–2004), does not exceed ±30 years between AD 1550–1950 (ca. 660 mm in peat profile MA2), and is less than ±50 years between AD 1000–1550. Adding constraints derived from pollen concentration distinctly improved precision of the age–depth model, without any deterioration in the fit of ^{14}C dates.

Hydrological reconstruction

Subfossil testate amoebae, stable oxygen isotopes, and pollen were used to reconstruct the hydrological history of the last 1 ka. Using a testate-amoeba training set from peatlands in the same valley (Lamentowicz et al., 2010) we reconstructed depth to the water table in Mauntschas Mire. Comparison of reconstructions with instrumental records from AD 1864 showed that decreasing water tables were correlated with increasing temperatures (Lamentowicz et al., 2010). However, analyses also showed a significant positive correlation between winter precipitation and mire wetness. Despite the apparently complex causes for the water table fluctuations, in the wider time frame we observed a clear hydrological signal related to documented climate changes.

The stable oxygen isotope chronology ($\delta^{18}O$) from *Sphagnum* (moss) stems shares similarities with the water-table reconstruction both before and during the instrumental period, with an anti-correlated phase at the end of the 19th century. The $\delta^{18}O$ data from *Sphagnum* and *Polytrichum* are highly correlated and lead to the conclusion that $\delta^{18}O$ fractionation in both moss genera and in different parts of the plant occurs in a similar way. A multi-proxy analysis of $\delta^{18}O$ and testate amoebae might reveal underlying hydrological processes in Mauntschas Mire (Lamentowicz et al., in prep.).

Pollen based calibration-in-time

Quantitative pollen-based reconstructions are challenging in mountainous regions because of vertical pollen transport across vegetation boundaries. Thus, instead of applying the usual calibration-in-space approach, selected pollen taxa were calibrated in time (AD 1954 – 2002) on temperature measured at the nearby meteorological station Sils Maria. This approach was based on the rationale that local factors controlling vertical pollen transport (e.g., slope, dominant winds, exposure) were constant at a site that is used for calibration and reconstruction alike. Calibration in time resulted in a cross-validated (jackknifed) root mean square error of prediction of 0.23°C for mean April–November air temperature (Kamenik et al., 2009) (Fig. 3). Potential anthropogenic effects, such as de- or re-forestation, were removed prior to calibration. This "calibration-in-time", which was carefully tested against measured temperature, was possible only because two crucial pre-conditions were met: near-annual to quasi-annual sampling resolution and excellent dating (see above) provided by the ^{14}C bomb peak and spheroidal carbonaceous particles. Independent validation using the instrumental record revealed that pollen picked up decadal- to centennial-scale climate change during this period. Still, pollen-based reconstructions might be challenged by non-climatic factors, such as pre-industrial deforestation and fire.

Other studies from Alpine peatlands

Investigations of small peatlands can also help address important nature-conservation and forest-management issues. For instance, an ongoing interdisciplinary project is providing a scientific basis for natural and sustainable forest management in the Italian part of Switzerland (Valsecchi et al., 2010). In the northern Alps, a recent multi-proxy study investigating peatland development and its effect on landscape dynamics and tufa formation (Wehrli et al., 2010), showed that wetlands can reflect environmental changes at extra-local scales.

Alpine peatlands are underused as a source of paleoenvironmental informa-

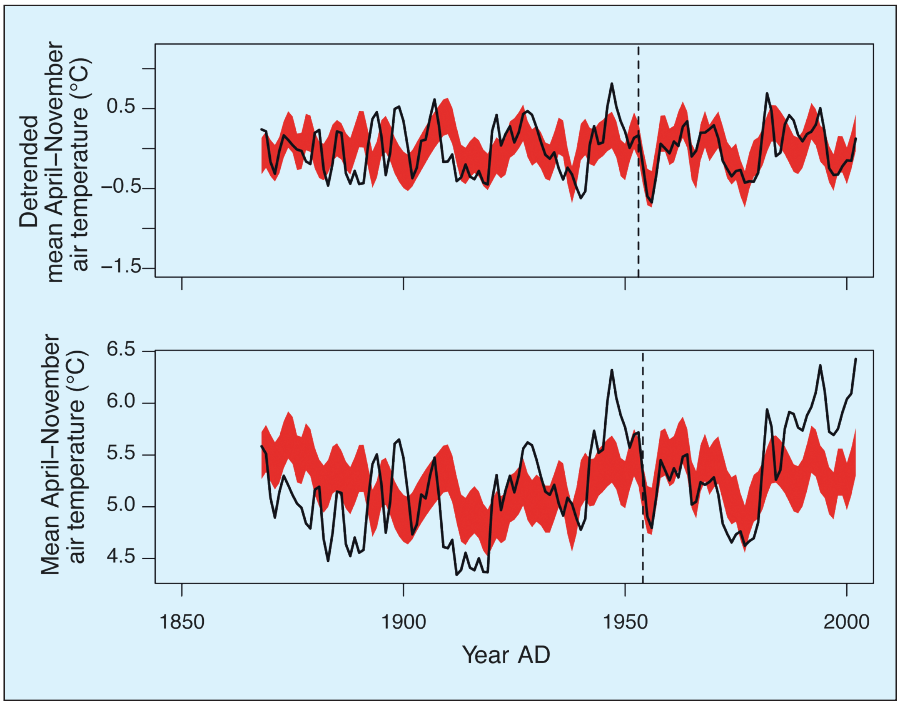

*Figure 3: Confidence bands (95%) of detrended (upper panel) and non-detrended (lower panel) pollen-based warm-season temperature reconstructions (**red**) versus measured temperature (**solid black line**) during the instrumental period. Pollen picked up long-term (at least decadal-scale) temperature changes (e.g., 1900-1950). Time series were detrended to reduce the effects of human impact. Calibration period (AD 1954 onwards) and verification period (pre-AD 1954) are delineated by a dashed vertical line (modified from Kamenik et al. 2009).*

tion. There is potential for scientists to use peatlands in mountain regions as archives of past climate change and landscape transformation. However, peatland ecology and the relationship between climate and peatland development needs to be better understood.

Perspectives

The comparison of testate amoeba-inferred water table depth, δ^{18}O data from *Sphagnum* stems, and instrumental climatic data revealed some interesting correlations. We now need 1) more high-resolution multi-proxy studies similar to that from Mauntschas to determine if these patterns can also be observed elsewhere, and 2) manipulative experiments to assess the relative influences of temperature, precipitation and water table depth on testate amoeba communities and the *Sphagnum* δ^{18}O isotopic signal. Such combined studies will help understand which factors most strongly control the development of alpine peatlands, how these peatlands can be fully exploited for inferring paleoclimatic and environmental signals, and how they may respond to ongoing and future climate changes.

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Stable isotopes and organic geochemistry in peat: Tools to investigate past hydrology, temperature and biogeochemistry

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Characterizing the stable isotope and biomarker geochemistry of peat cores enables reconstruction of key climatic and environmental variables in the past, including temperature, hydrology and the cycling of carbon.

Proxy targets and the value of geochemistry

Peatlands are valuable archives of terrestrial environmental change due to their sensitivity to the hydrological regime and the excellent preservation of organic matter. Peat geochemistry reflects the composition of the original peat-forming plant assemblage (which is itself dependent on air temperature and hydrology), and the subsequent transformation of that organic matter in the aerobic surface layer (the acrotelm) and the anaerobic catotelm (below the water table). Changes to air temperatures and water table depth are thus reflected in peat via changes to both organic matter input and its subsequent degradation (Fig. 1). Precipitation and evaporation cause isotopic fractionation of hydrogen (δD) and oxygen (δ^{18}O), so that the isotopic composition of the meteoric water used by peatland plants reflects a combination of precipitation source and peatland hydrology (Daley et al., in press). Stable carbon isotopes (δ^{13}C) give important information on carbon pathways, including fractionation during photosynthesis (White et al., 1994; Williams and Flanagan, 1996), and the recycling of organic matter and consumption of CO_2 and methane by microbial activity (Pancost et al., 2000). Humic acid formation during degradation of plant material (humification) is a proxy for peatland wetness (Yeloff and Mauquoy, 2006). Total carbon and nitrogen contents also indicate wetness (McClymont et al., 2008), since drier conditions cause the plant remains to spend a longer time in the acrotelm, where degradation preferentially releases nitrogen over carbon (Kuhry and Vitt, 1996). However, isolating whether changes to biomass and/or peatland hydrology drive the humification or bulk geochemistry signals recorded in peat cores makes environmental interpretations of such records difficult (Yeloff and Mauquoy, 2006). Here, we discuss the

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