than any other ecosystem, globally comprising some 550 Gt C. As such, they comprise a vital component of the global carbon budget, and by providing time-series of site-specific carbon accumulation they can also play an important role in understanding many of the controls and feedbacks in global carbon dynamics. David Beilman and colleagues discuss the role of northern peatlands as carbon sinks during the Holocene, and reveal new insights into the contribution of these vast peatlands to the global carbon cycle emerging from analysis of large-scale patterns of peat accumulation and spread over time. Tropical peatlands are not as well known as northern and boreal peatlands, but are receiving increasing attention in view of their very high carbon density and potential for human- and climate-driven conversion from atmospheric sinks to sources. Sue Page and colleagues discuss the extensive peatlands of Southeast Asia in this context and demonstrate the severity of impacts on the global atmosphere when such carbon-rich ecosystems are disturbed. Many tropical peatlands remain undiscovered or imperfectly known. Outi Lähteenoja and Katherine Roucoux describe recently discovered ombrotrophic (precipitation-fed) peatlands in the Upper Amazon basin, and discuss their importance for carbon cycling and their scientific potential as paleo-archives.

The interactions among climate, carbon and peatlands are complex, and there are substantial risks of unexpected feedbacks and rapid transformations. Understanding these interactions will require increasing engagement between the peatland paleoscience community and scientists studying processes of gas exchange and energetics in modern peatlands and related ecosystems. The final paper by Torben Christensen and colleagues highlights improved understanding of methane dynamics in peatlands in permafrost regions and argues for greater integration of process studies with peatland paleoscience to better understand methane flux in high-latitude settings. This argument is broadly applicable to peatlands throughout the world; linking process and paleo-studies in peatlands will help advance our understanding of peatland dynamics, climate variability and the risks of unwelcome carbon-cycle feedbacks in the centuries ahead.

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Peatland archives of late-Holocene climate change in northern Europe

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Peatland archives in northern Europe now provide multi-proxy decadal records of past environmental change for the mid and late Holocene.

Peatlands in northern Europe have long been recognized as a climate archive, yielding the first climatostratigraphic division of the Holocene—the Blytt–Sernander scheme (Blytt, 1876; Sernander, 1908); however, their detailed exploitation awaited refutation of long-standing misconceptions about bog growth (cf., Backéus, 1990). Barber (1981) proposed instead that ombrotrophic (precipitation-fed) bogs provide a continuous record of past hydrological change, because they are "directly coupled" to the atmosphere. Though omitted as a climate archive from Bradley's (1999) compendium of paleoclimatology, studies on peat bogs have since gained greater prominence (Chambers and Charman, 2004); a wide array of climate proxies has been developed, involving an increasing number of specialists from a range of disciplines (de Jong et al., in press).

European peat–climate research has concentrated on blanket bogs (e.g., western Ireland; UK uplands; western Norway) and raised bogs (e.g., central Ireland; Britain; Denmark; northern Germany; southern Sweden; Estonia; southern Finland; Poland; Czech Republic). High rainfall, typically >1250 mm a^{-1}, sustains the blanket bogs, but raised bogs exist in areas of much lower precipitation. The latter owe their origin to low relief and impeded drainage, but their domed growing surfaces are (like blanket bogs) hydrologically isolated from groundwater. Some 90% of the mass of an actively growing bog is water, held mainly in the anoxic catotelm (bottom layer of peat permanently below the water table) where decay processes are markedly reduced compared with the thin upper layer of the bog, the acrotelm, which experiences a seasonally fluctuating water table, and in dry conditions can experience much higher decay rates.

ACCROTELM project

To examine the synchronicity, direction, magnitude, rate and causes of past climate changes in northern Europe, a recent, European Commission-funded project "Abrupt Climate Changes Recorded Over The European Land Mass" (ACCROTELM; Chambers et al., 2007a) included an East–West transect of ombrotrophic bogs, from Estonia and Finland to Ireland, for which proxy-climate data were generated for up to the past 4.5 ka. The E–W transect extended across the Atlantic to Newfoundland (Hughes et al., 2006), while a bog in northern Spain was included at the southern ombrotrophic limit. Lake sites also featured, allowing comparison with data on changing lake levels in west-central Europe (Magny, 2006).

ACCROTELM researchers developed and applied revised protocols of three proxy-climate measures in "multi-proxy" studies of the bogs: (1) the degree of peat humification—largely a measure of the decay rate of peat before becoming incorporated in the permanently saturated catotelm (cf., Aaby and Tauber, 1975; Aaby, 1976; Blackford and Chambers, 1993; Borgmark, 2005); (2) quantitative leaf count macrofossil analysis (QLCMA) of vegetation remains in the peat—reflecting the former surface plant community (Barber et al., 1994; McClymont et al., 2008, 2009); and (3) the species assemblage of testate amoebae—used to estimate water-table depth, calibrated using a transfer function from modern "training sets" (Charman et al., 2007). Each proxy is (to a greater or lesser degree) dependent on the prevailing environmental conditions at the time of peat formation, and reflects (with some caveats) past climate. These three principal measures provided a continuous record of past climate change, with dating provided by AMS ^{14}C (Yeloff et al., 2006), ^{210}Pb and spheroidal carbonaceous particles.

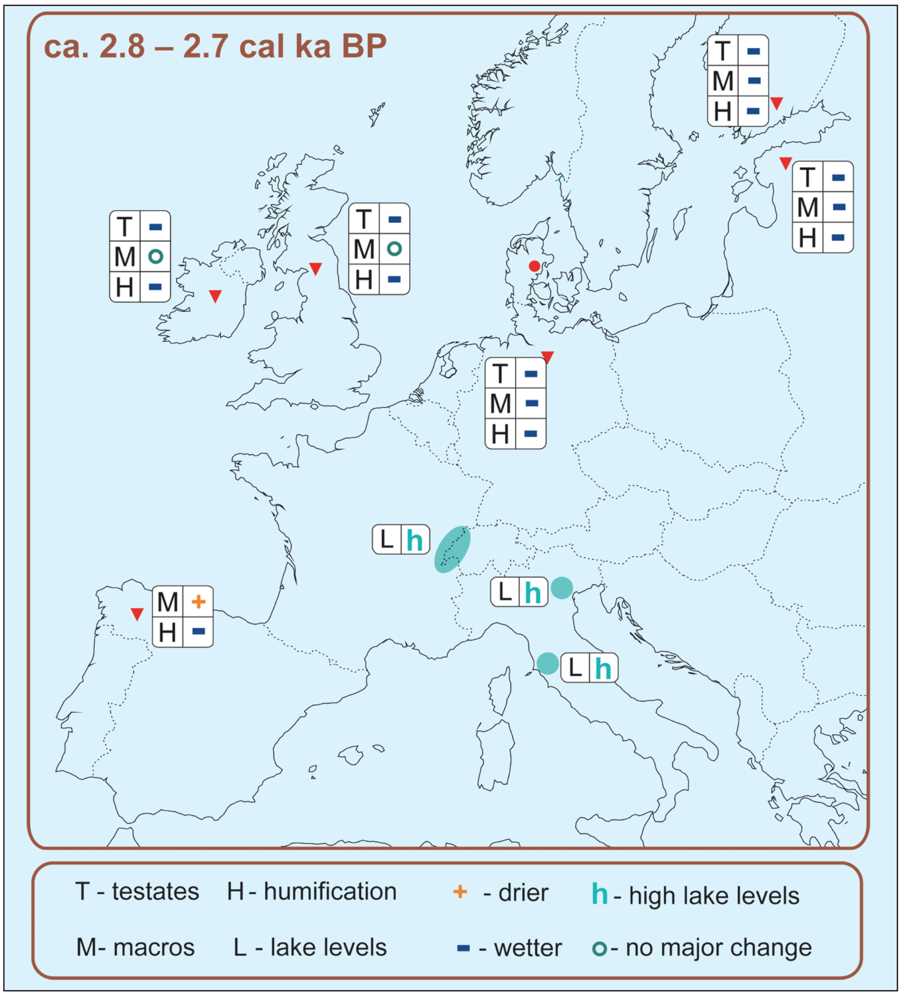

*Figure 1: Schematic ACCROTELM project map, showing direction of change in the century following the "2.8 cal ka BP event", as indicated by up to three proxy-climate records at each of six bog sites (**red triangles**; **red circle** shows location of younger Danish bog site highlighted in Fig. 2) and coincident high lake-level records of lake sites. Note: plant macrofossil evidence from the bog site in Finland (see Väliranta et al., 2007) actually shows pronounced dryness commencing ca. 2.82 cal ka BP, so this schematic map is potentially misleading. (View ACCROTELM film at http://noorderlicht.vpro.nl/artikelen/31866284/)*

Abrupt climate shifts

Additional analyses (e.g., pollen, biomarkers) were concentrated in three "Focus Intervals" of abrupt climate changes, centered on ca. 4.2 cal ka BP, 2.8 cal ka BP, and the period AD 800–1800 covering the Medieval Warm Period and Little Ice Age. Pollen analytical data were used to investigate the effects of climate changes on human populations (e.g., Yeloff et al., 2007a; Sillasoo et al., 2009); analyses of biomarkers were conducted to trace *Sphagnum* species (Bingham et al., 2009); non-pollen microfossils were also recorded (van Geel, 2006; Yeloff et al., 2007b).

The most coherent signal of past abrupt climate change is shown in the ACCROTELM site record ca. 2.8–2.7 cal ka BP, when proxy-climate measures from the majority of bog sites showed evidence of increased climate wetness (Fig. 1). Indeed, ca. 2.8 cal ka BP is the most notable climate shift recorded in many European bogs, when increased wetness recorded in continental peat bogs, corresponding generally to the Blytt–Sernander Subboreal–Subatlantic transition, apparently coincides with a marked reduction in solar activity (van Geel and Renssen, 1998), as reflected in coincident increased concentration of cosmogenic isotopes in other archives (Beer and van Geel, 2008). "Wiggle-matching" of AMS radiocarbon dates on above-ground plant material (such as *Sphagnum* leaves) has permitted its precise and accurate dating (Speranza et al., 2000). The timing is, however, not corroborated in bogs in Northern Ireland, north of the ACCROTELM transect, where Swindles et al. (2007) suggested a delayed response to solar variability. Alternatively, the atmospheric circulation changes that gave rise to very wet conditions recorded in bogs in The Netherlands, northern Germany and the Czech Republic were occasioned by a sudden southward displacement of storm tracks, such that initially a drier than normal phase was produced in Northern Ireland (akin to the contemporaneous "dry" episode recorded by Chambers et al. (2007b) in a South American bog), which then reverted to higher moisture when solar activity recovered. This hypothesis remains to be tested. Others have linked abrupt climate changes recorded in bogs with past solar variability (van Geel et al., 1996; Chambers and Blackford, 2001; Speranza et al., 2002; Blaauw, 2003; Blaauw et al., 2004; Mauquoy et al., 2002, 2004; Plunkett and Swindles, 2008; van Geel and Mauquoy, this issue). Notable, however, is the record from ACCROTELM lakes, in which higher lake levels in west-central Europe, indicating cooler and wetter conditions (Magny, 2006; Magny et al., 2009), corresponded with the wetter climate inferred from most ACCROTELM bogs (Fig. 1).

ACCROTELM peatland data have decadal resolution (Väliranta et al., 2007), and in Focus Period III (AD 800–1800), reconstructions of water level changes from testate amoebae data (Fig. 2) imply a close relationship with putative solar-forcing, although the multi-proxy peatlands data are not unequivocal. The inferred magnitude of change reinforces evidence from other archives for the severity of the Little Ice Age in northern Europe.

Spatial variability of the climate signal

The controlling influence of water on peatland development led many peat scientists to assume that the paleoclimate records obtained from peat bogs largely reflect past changes in precipitation, rather than temperature. Comparisons between instrumental climate data and high-resolution water table reconstructions corroborate this, but show that the precipitation–evaporation balance largely determines water table changes (Charman et al., 2007; Charman, 2007; Booth et al., this issue). Summer temperature is a secondary influence, albeit a more significant one in continental settings (Charman, 2007; Charman et al., 2009). Generally, the ACCROTELM records showed considerable spatial variability of the European climate through time. This is unsurprising if the principal influence upon peatlands is precipitation, as it is to be expected that there would be less spatial coherence in a precipitation signal than in one of temperature.

Future prospects

Peat has played a major role in reconstructing the late Holocene of northern Europe, but ACCROTELM set an agenda indicating that a fuller picture of past European climate may be obtained when multi-proxy peat bog records are combined with data from complementary archives such as lakes (e.g., Magny et al., 2009), exemplified subsequently by de Jong et al. (2009) and Andersson et al. (in press). Peat can also reveal other climatic aspects, notably storminess, through examination of its in-

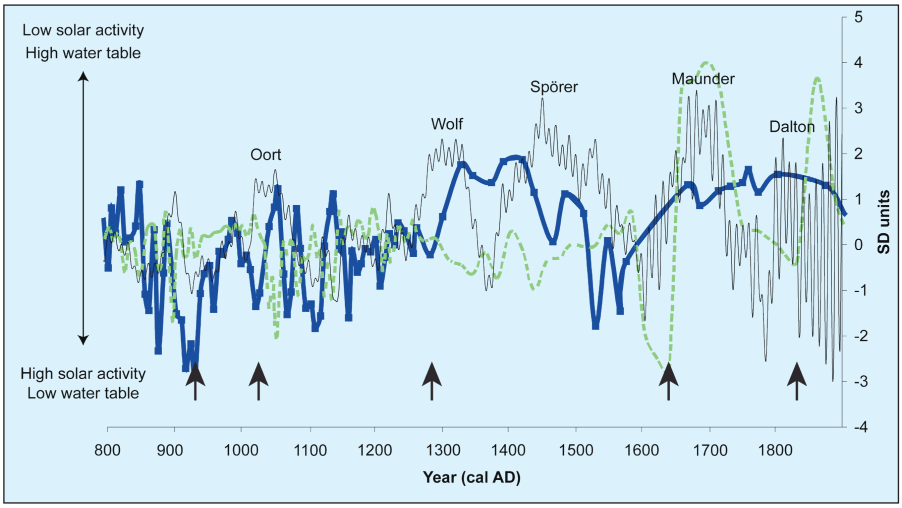

Figure 2: Focus Interval III (cal a AD 800–1800) of the ACCROTELM project, showing proxy-climate data from the Danish bog site: ***Blue line*** *= normalized testate amoebae water table reconstruction (inverted);* ***Green dashed line*** *= plant macrofossil Dupont wetness index;* ***Gray line*** *= normalized ^{14}C relative production rate (q). Arrows indicate start of significant rises in water table. Historical solar minima are indicated. Figure adapted from Mauquoy et al., 2008. For further discussion of solar-climate relationships in peat records, see van Geel and Mauquoy, this issue.*

organic and elemental content (de Jong et al., 2006; De Vleeschouwer et al., 2009), and research continues to extract a separate temperature signal from biomarkers.

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For full references please consult:

http://www.pages-igbp.org/products/newsletters/ref2010_1.html

Using peatland archives to test paleoclimate hypotheses

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A network of peatland surface-moisture reconstructions is providing a richly detailed, synoptic-scale perspective on past hydroclimate variability in many regions, well suited to investigate the spatial structure and dynamics of past hydroclimate changes.

Synoptic networks of proxy records of hydroclimate variation provide an important means for identifying long-term relationships between oceanic forcing and continental-scale patterns of decadal- to centennial-scale drought variability, and for assessing responses of the coupled ocean-atmosphere system to changes in external forcing. Tree-ring records provide the gold standard in this context, because of their demonstrated hydroclimatic sensitivity, temporal precision and accuracy, robustness of proxy inferences, and widespread distributions in space. However, tree-ring records are limited in temporal depth and spatial coverage, and inferences can be confounded by other factors, particularly in humid regions. Alternative archives are desirable to extend temporal depth, corroborate tree-ring inferences, and add complementary information and sensitivity at different time and spatial scales. Among the alternative archives are ombrotrophic peatlands, which are sensitive to hydroclimatic variation at decadal timescales, capable of sub-centennial chronological precision and accuracy, contain multiple paleohydrological and paleoclimatic proxies (Fig. 1a), and are widely distributed at mid- to high latitudes in the northern and southern hemispheres. Comparison of peatland proxies with instrumental records

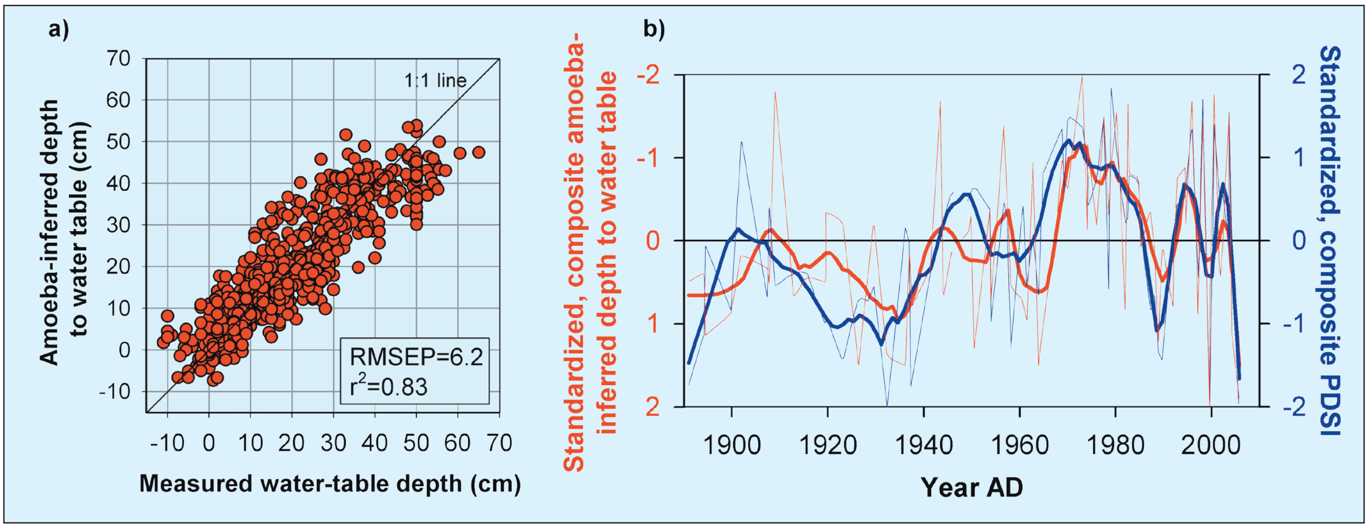

Figure 1: Validation of the hydrologic and climatic sensitivity of peatland surface-moisture reconstructions. ***a)*** *Cross-validation of testate amoeba transfer function for mean annual water-table depth, based on over 650 samples from North American peatlands (modified from Booth, 2008).* ***b)*** *Comparison of a composite testate amoebae-inferred paleohydrological reconstruction (depth to water table) derived from three ^{210}Pb-dated peatland records (red lines) and instrumental records of Palmer Drought Severity Index (PDSI; blue lines) (data from Booth, 2010). Thick, solid lines show approximately decadal-scale smoothing of the composite datasets (thin lines).*

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