Testing the timing of radiocarbon-dated events between proxy archives

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Received 8 June 2006; revised manuscript accepted 20 September 2006

Abstract: For interpreting past changes on a regional or global scale, the timings of proxy-inferred events are usually aligned with data from other locations. However, too often chronological uncertainties are ignored in proxy diagrams and multisite comparisons, making it possible for researchers to fall into the trap of sucking separate events into one illusionary event (or vice versa). Here we largely solve this ‘suck in and smear syndrome’ for radiocarbon (14C) dated sequences. In a Bayesian framework, millions of plausible age-models are constructed to quantify the chronological uncertainties within and between proxy archives. We test the technique on replicated high-resolution 14C-dated peat cores deposited during the ‘Little Ice Age’ (c. AD 1400–1900), a period characterized by abrupt climate changes and severe 14C calibration problems. Owing to internal variability in proxy data and uncertainties in age-models, these (and possibly many more) archives are not consistent in recording decadal climate change. Through explicit statistical tests of palaeoenvironmental hypotheses, we can move forward to systematic interpretations of proxy data. However, chronological uncertainties of non-annually resolved palaeoclimate records are too large for answering decadal timescale questions.

Key words: Bayesian age-modelling, radiocarbon, chronological uncertainty, meta-analysis, synchronicity of events, ‘Little Ice Age’.

Introduction

Past environmental change (eg, climate change) is usually inferred from changes in pollen, isotopes and other fossil proxies found in deposits from, for example, lakes, peat bogs, ice sheets or oceans. However, climate change can have a complex spatial pattern, proxy changes can be forced by other factors (eg, human impact, internal processes, measurement errors) and many proxy archives have non-negligible chronological uncertainties. Therefore, even replicate reconstructions within regions often differ considerably in details. This becomes especially problematic when proxy-inferred abrupt climate events such as the last glacial–interglacial transition, ‘8.2 kyr event’ or ‘Little Ice Age’ are linked between regions

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Bennett and Fuller, 2002; Telford et al., 2004a; Blaauw and Christen, 2005; Heegaard et al., 2005), (ii) $^{14}$C dates have associated measurement uncertainties, (iii) $^{14}$C dates could be offset, inaccurate or outlying (Blaauw et al., 2005), and (iv) after calibration, $^{14}$C dates often obtain a multimodal calibrated distribution without an obvious best point estimate for its calendar age (Telford et al., 2004b). Even with many data and sophisticated models, accumulation histories (changes in accumulation rate, hiatuses) of non-annually layered deposits will thus never be known exactly. This is especially true for periods such as during the past four centuries where the $^{14}$C calibration curve shows major wiggles, resulting in exceptionally problematic age-models. Many proxy archives apparently register climate change during such periods (van Geel et al., 1998; Mauquoy et al., 2002a,b; Soon and Balintas, 2003; Mayewski et al., 2004; Rohling and Pälike, 2005), further enlarging the danger of ‘suck-in and smear’ (Baillie, 1991).

Although statistical methods exist to estimate uncertainties of $^{14}$C age-models (Bennett, 1994; Bennett and Fuller, 2002; Blaauw and Christen, 2005; Heegaard et al., 2005), there has hitherto been no method that can translate these uncertainties to display graphically the chronological uncertainty of the proxy values (van Geel et al., 1998; Bond et al., 2001; Mauquoy et al., 2002a,b; Hu et al., 2003; Blaauw et al., 2004; Rohling and Pälike, 2005; VanderGoes et al., 2005; Wang et al., 2005). This is because generally a single age – depth curve is used to translate core depths into point estimates of calendar ages, resulting in line-graphs which falsely suggest that the timing of changes is known exactly (even where it is known that this is not the case).

Raised bog deposits are regularly used for reconstructing Holocene climate changes in temperate regions (Mauquoy et al., 2002a,b; Blaauw et al., 2004; Charman et al., 2004). Raised bog surfaces consist of dry hummocks, intermediate lawns and wet hollows or pools, each having their characteristic moisture-sensitive vegetation. As raised bogs depend entirely on precipitation for their water and nutrients, climate change should affect their vegetation composition. Increased precipitation or lower temperatures would lead to a higher water-table and thus to the extension of wet and moist microforms (wet-shift) (Mauquoy et al., 2002b; Blaauw et al., 2004; Charman et al., 2004). As inception dates for dry-shifts are more difficult to pinpoint, we will limit our focus to clearly registered wet-shifts and will thus reconstruct events of climatic cooling/moistening only.

### Methods

Bayesian statistics combines new data with prior observations in order to infer the probability that a hypothesis may be true. When Bayesian statistics is applied to age-modelling, chronological uncertainties of high-resolution $^{14}$C-dated sequences can be much reduced, because the calibrated ages of individual $^{14}$C dates become constrained by prior assumptions and by all other $^{14}$C dates in a sequence. Here we fit the sequences of uncalibrated $^{14}$C dates from raised bog peat cores from Denmark (Lille Vildmose, core LYM; Mauquoy et al., 2002a,b) and England (Walton Moss, replicate cores WLM19, WLM20 and WLM21; Mauquoy et al., 2002a,b) to the IntCal04 calibration curve (Reimer et al., 2004) assuming piece-wise linear accumulation of the peat deposits (wiggle-match dating; Blaauw and Christen, 2005). Our assumptions are: (i) all cores are divided into three sections, with each section having accumulated linearly (the same number of sections was used for the WLM cores by Mauquoy et al. 2002a,b. Using three sections, section breaks often coincided with vegetation composition changes, and the fit $F$ was satisfactory; Blaauw and Christen, 2005; (ii) fresh bogs accumulate at $10 \pm 5$ cm/yr (AlphaMean 10, AlphaStd 5, see figure 3a in Blaauw and Christen, 2005), (iii) hiatus lengths are very short (HiatusA: 0.0005, HiatusB: 0.005. These parameters shape the prior distribution, see figure 3b in Blaauw and Christen, 2005); (iv) prior outlier probabilities of $^{14}$C dates are 5%; (v) a weak dependency of accumulation rates exists between sections; (vi) as historically anchored pollen evidence shows that the upper $^{14}$C-dated levels in the four cores should be older than AD 1850 (Mauquoy et al., 2002a), the upper allowed ages are restricted to 100 cal. BP (where BP = before AD 1950).

Under the above assumptions the posterior distributions of many parameters are estimated through several hundreds of millions of Markov Chain Monte Carlo (MCMC) iterations (Blaauw and Christen, 2005), where every iteration may be regarded as a simulation of the corresponding (posterior) probability distribution of all parameters. Chronological uncertainties become especially large in core WLM20 where a hiatus was inferred. Inferred levels of accumulation rate change often coincide with notable changes from long-lasting dry to consistently wetter and more variable conditions (confirming accumulation rate changes). We develop grey-scale proxy graphs based on millions of Bayesian ‘wiggle-match’ age-models (Blaauw and Christen, 2005; Figures 1 and 2), which convey the important message that even high-precision dated proxy archives possess inherent chronological uncertainties. Here instead of plotting depth against calendar age, we plot the proxy values obtained at the depths against calendar age. Wide light-grey areas warn us of high chronological uncertainty, while narrow dark areas indicate more secure sections in chronologies.

The MCMC calendar age estimates obtained for the depths in a sequence, can be used to calculate the probabilities of wet-shifts over time. First we define the probability of a wet-shift event in a single core during a certain period of time as $p(W_{\max}, y_{\min})$, where $W$ is the wet-shift event, and $y_{\max}$ and $y_{\min}$ form the boundaries (in cal. BP years) of the period of interest. Those depths in the core where clear wet-shifts have been found using the macrofossil proxy data are called $d_w$. For every set of parameters $M$, in a MCMC iteration, these depths $d_w$ will be translated into point estimates of their calendar ages, $y_{\min}$, $y_{\max}$. If in iteration $i$ the estimated calendar age $y_{\min}$, for any of the depths $d_w$ falls within our period of interest ($y_{\max} - y_{\min}$), this iteration is counted as ‘successful’ and we assign a 1 to the variable $I_i$; otherwise $I_i$ becomes 0. We calculate the above for all MCMC iterations and find the proportion of ‘successful’ iterations. This then forms our estimate of the probability of a wet-shift having taken place in a core during a period of time, $p(W_{\max}, y_{\min})$. $p(W_{\max}, y_{\min})$ can be calculated for specific periods of interest, or repeatedly for an entire core using an appropriate resolution. High values of $p(W_{\max}, y_{\min})$ indicate that a wet-shift likely occurred during the period of interest; low values either indicate the absence of a wet-shift, or lack of information (eg, hiatus). To combine the $p(W_{\max}, y_{\min})$ of multiple cores, we calculate the average of all $p(W_{\max}, y_{\min})$. The methodology for analysing synchronous events in chronologies is not restricted to the particular age-modelling assumptions (here piece-wise linear accumulation), and other age models and accumulation assumptions may be used.
Results and discussion

Many raised bog studies report synchronicity of wet-shifts within sites and regions (Barber et al., 1998; Langdon and Barber, 2005). However, these studies were based on low resolution of analysis and dating, and synchronicity was assessed subjectively (proxy diagrams based on single age-depth curves were aligned by eye). The cores used in this study were analysed and dated at much higher resolution (centimetre-scale macrofossil analysis and $>20^{14}$C dates per core); here the cores are tested systematically for synchronicity of wet-shifts within a given time window. Vegetation composition shows obvious shifts from dry/moist to wetter conditions at 75.5–71.5 and 64.5 cm depth in core LVM, at 74.5–73.5, 54.5 and 45.5 cm in WLM19, at 70.5, 41.5 and 38.5 cm in WLM20, and at 46.5, 44.5 and 42.5–41.5 cm in WLM21 (Mauquoy et al., 2002a). A visual comparison of the four wet-shift chronologies suggests that around c. 700, 450 and 350 cal. BP wet-shifts were synchronous between cores (Figures 2 and 3). However, instead of the usual approach of letting our eyes judge the (a)synchrony of events, we calculate the actual probabilities of specific hypotheses.

Holocene events of sharply increasing atmospheric $^{14}$C levels ($\Delta^{14}$C; Reimer et al., 2004) are caused by declines

![Figure 1](http://hol.sagepub.com)
in solar activity and linked with wet-shifts in northwest European raised bog deposits (van Geel et al., 1998; Mauquoy et al., 2002a,b; Blaauw et al., 2004) and with climate change in several other regions (van Geel et al., 1998; Bond et al., 2001; Magny, 2004; Wang et al., 2005). To the eye, most wet-shifts in our cores appear simultaneous with Δ¹⁴C peaks (Figure 3). However, this apparent synchronicity does not hold when tested in our Bayesian framework (Table 1, Figure 3). Only the Maunder Minimum and the long-lasting Spörer Minimum are accompanied by moderate to high probabilities for wet-shifts (although not for core WLM20). The age-ranges of some wet-shifts appear to overlap with major volcanic eruptions that might have had considerable influence on ‘Little Ice Age’ climate (Zielinski, 2000). However, when focusing on these short-lived events, probabilities of wet-shifts having occurred within 5 years after major volcanic eruptions (Zielinski, 2000) become even lower (Table 1, Figure 3). Besides assessing synchronicity of short-lived, decadal events, we test whether evidence is found in the cores for regional climate cooling/moistening during any part of the ‘Little Ice Age’ (c. 550 to 50 cal. BP). The probabilities of wet-shifts having occurred during these century-long periods, are 100% for all cores (Table 1).

Our analysis shows that synchronicity of events between proxy archives (van Geel et al., 1998; Mayewski et al., 2004; Rohling and Pälike, 2005; VanderGoes et al., 2005) depends heavily on the assumed length of the event, as should be expected. Moreover, chronological uncertainties of even high-precision ¹⁴C age-models (in the best of cases c. 30 to 140 calendar years at 95% confidence intervals) prevent the assessment of short timescale events such as volcanic eruptions, and thus force us to limit our resolution to multidecadal or longer lasting events. On centennial timescales probabilities of synchronous reactions become much higher, but in such cases we might well be sucking separate events into one (Bailie, 1991; Soon and Baliunas, 2003). As an alternative to our approach, one could consider events from multiple archives to be synchronous if their age estimates have overlapping confidence intervals. However, in that case comparisons of less precise chronologies would inevitably result in more events being labelled synchronous (with the obvious danger of ‘sucking in’ separate events). Using our approach, if events are dated at higher precision, truly synchronous events will indeed receive higher probabilities of being identified as such.

The Bayesian methods developed here form an important step towards more systematic assessments of links, leads and lags between different palaeoclimate archives (Bailie, 1991). Although we tested our methods on high-resolution macrofossil archives from ‘Little Ice Age’ raised-bogs, they are fully applicable to other types of geological archives (dated with ¹⁴C or otherwise). Inherent chronological uncertainties need no longer be neglected in proxy-graphs nor in interpretations. Moreover, using proxy information from single cores, or subjectively aligning multiple cores, presents dangers also in many other types of proxy archives. As the palaeoclimate community is increasingly zooming in towards decadal-scale events (van Geel et al., 1998; Bond et al., 2001; Mayewski et al., 2004; Rohling and Pälike, 2005; VanderGoes et al., 2005; Wang et al., 2005), efforts should be increased to acknowledge,

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**Figure 2** Chronologies of macrofossil-inferred local wetness from core LVM (a,e,i) and replicate cores WLM19 (b,f,j), WLM20 (c,g,k) and WLM21 (d,h,l) (Mauquoy et al., 2002a,b). a–d, combined abundances of pool/hollow species (Sphagnum cuspidatum, S. Sect. Cuspidata and S. tenellum), indicating wet conditions; e–h, combined abundances of lawn species (S. magellanicum and S. papillosum), indicating intermediate moisture; i–l, combined abundances of hummock species (S. imbricatum and S. capillifolium), indicating dry conditions.
Acknowledgements

MB is supported by SEMARNAT-CONACYT (SEMARNAT-2004-C01–7). We thank Jon Pilcher and an anonymous reviewer for their positive and helpful comments.

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