Quaternary Science Reviews xxx (2010) 1–12

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Out of tune: the dangers of aligning proxy archives

Maarten Blaauw

School of Geography, Archaeology and Palaeoecology, Queen's University Belfast, BT7 1NN Belfast, UK

A R T I C L E I N F O

Article history:
Received 5 February 2010
Received in revised form
7 October 2010
Accepted 8 November 2010
Available online xxx

A B S T R A C T

Tuning is a widespread technique to combine, date and interpret multiple fossil proxy archives through aligning supposedly synchronous events between the archives. The approach will be reviewed by discussing a number of literature examples, ranging from peat and tephra layers to orbital tuning and $\delta^{18}O$ series from marine and ice deposits. Potential problems will be highlighted such as the dangers of circular reasoning and unrecognised chronological uncertainties, and some solutions suggested. Fossil proxy research could become enhanced if tuning were approached in a more quantitative, reliable and objective way, and especially if individual proxy archives were non-tuned and kept on independent time-scales.

> Doubt is not a pleasant condition, but certainty is absurd. - *Voltaire*

1. Introduction

The principles of superposition and lateral continuity can be used to deduce that distinct sediment layers were deposited simultaneously and originally extended horizontally in all directions, even if now separated by for example a valley. Through aligning fossil proxy archives at wide spatial scales, supra-regional, hemispheric or even global pictures of past environmental changes can be reconstructed. The reasoning applied is that sediment boundaries or proxy events must have been produced by major climate or environmental events of such intensity and scale that they were registered in multiple regions and types of deposits in a (nearly) simultaneous manner. These same events can then be used as *isochrons* to date individual archives by aligning their proxy events to those in other, distant archives. Here I review this process of "tuning" or "wiggle-matching". After presenting case studies of tuning from a range of published fossil proxy archives, potential problems are examined and alternative approaches suggested.

All palaeoecological and palaeoclimatological proxy data come with a degree of uncertainty, in both the measurements of the proxies themselves and in their age estimates (Fig. 1). Therefore, whereas recent time series of perfectly measurable data can be represented by single "true" curves (Fig. 1a), historical environmental time series possess uncertainties in the proxy measurements (Fig. 1b), and palaeo data series have errors in both the proxies and the age-model (Fig. 1c). Even if these uncertainties are not generally depicted in fossil proxy diagrams (single curves as in Fig. 1a; Maher, 1972; Blaauw et al., 2007), it is well-known that the data are uncertain and can thus be "moved around" in order to fit to certain hypotheses. For example, a major climate or environmental event might have caused environmental changes across a region, registered as fossil proxy events in a range of sites (e.g., Gale, 2009), or the depth of a decline in *Ulmus* pollen in a single core can be assigned the age of the Elm decline as inferred from regional ^{14}C dated pollen archives. Measurement errors and internal variability will cause imperfect proxy expressions (e.g., slightly asynchronous) of these synchronous events. Therefore individual time series have some flexibility to be adapted, e.g., by aligning supposedly synchronous proxy events between archives, even if the raw data indicate asynchroneity (Figs. 2 and 3). The reverse can also happen, where time-transgressive events in diverse regions appear to have happened simultaneously owing to dating errors (Baillie, 1991; Fig. 3).

As will become clear from the literature review below, there are several approaches to tuning. Firstly, one could apply no absolute dating information at all and assume synchroneity of proxy events with other archives (e.g., aligning pollen zones, tephra markers or $\delta^{18}O$ series). Secondly, one could date a proxy archive using a mix of absolute and relative tuning-based dating points (e.g., Cacho et al., 1999). Yet another approach is to date archives absolutely and independently to obtain an initial time-scale, after which the time-scale is adapted (preferably within its errors) to make proxy events align to those in other archives (e.g., Bond et al., 2001; Hoek and Bohncke, 2001; Neff et al., 2001; Burns et al., 2003; Charman et al., 2006). As discussed above, any difference in timing of dated events between proxy archives is then attributed to errors in

---

E-mail address: maarten.blaauw@qub.ac.uk.

0277-3791/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.quascirev.2010.11.012

Please cite this article in press as: Blaauw, M., Out of tune: the dangers of aligning proxy archives, Quaternary Science Reviews (2010), doi:10.1016/j.quascirev.2010.11.012

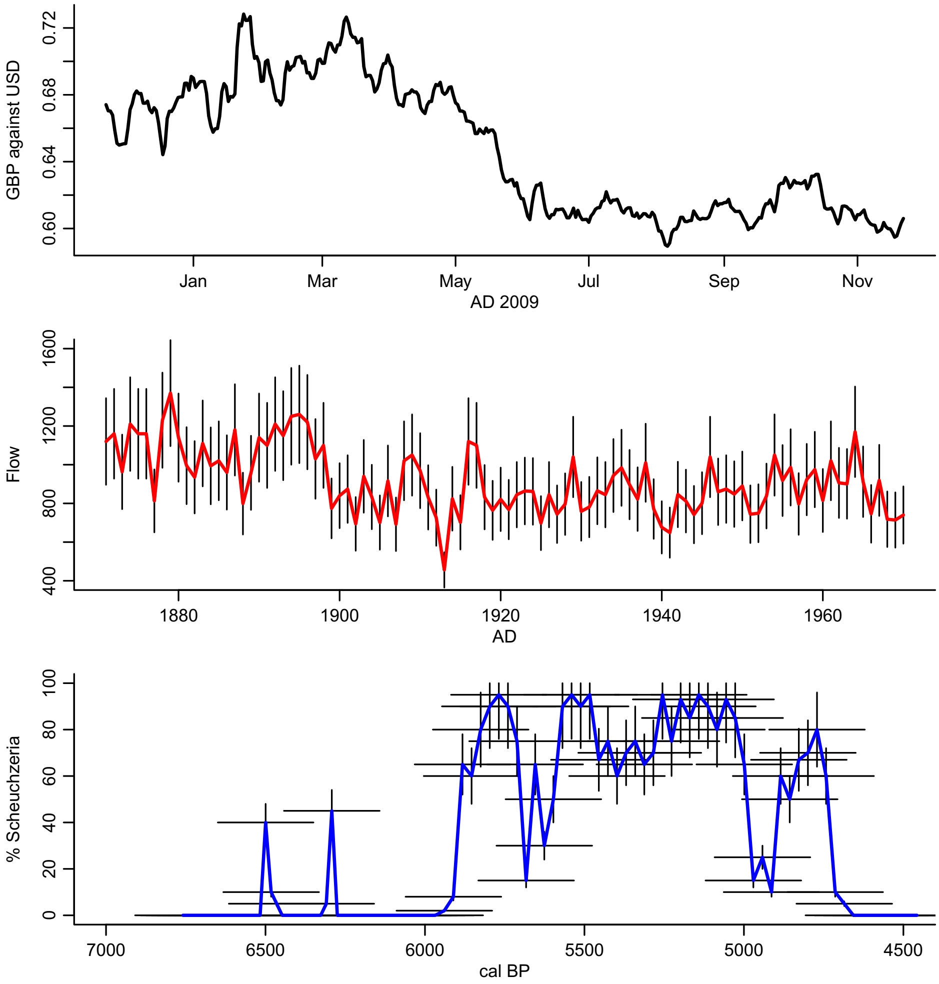

Fig. 1. Three independently obtained time series. The upper panel (black curve) shows the value of the British Pound against the American Doller over the year AD 2009 (data obtained from http://www.xe.com). The mid panel (red curve) shows the outflow of the river Nile over the last century, estimated from regular spot measurements (data available within R software, http://www.r-project.org, latest version 2.11.1). Data uncertainties were estimated to be 20% (black error bars; Di Baldassarre and Montanari, 2009). The bottom panel shows the relative amount of *Scheuchzeria palustris* remains in the Dutch raised bog peat core MSB-2K (Blaauw et al., 2004), indicative of wet conditions. For illustration purposes, the proxy data were here assumed to have an uncertainty of 20%, whereas chronological uncertainties are estimated at 150 calendar years. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

individual age-depth models. The last approach is that of avoiding tuning by keeping all time-scales absolute and independent, and obtain quantitative estimates of the timing of events between archives (e.g., Bennett and Fuller, 2002; Blaauw et al., 2007,2010b; Parnell et al., 2008; Charman et al., 2009).

1.1. Peat

One of the earliest examples of dating climatic events was based on reconstructing the ages of peat layers in Scandinavian bogs. The layers contained a range of fossilized vegetation types, each reflecting distinct cool, warm, dry and/or moist climatic periods during the Holocene. The peat layers were dated by Rutger Sernander in 1894 through correlations with archaeology, sea level changes and the Swedish varve chronology (Birks, 2008). Later, common features in peat layers or pollen curves were used to align sites within and between regions (von Post, 1946) or even between continents (Dachnowski, 1922). This type of dating is relative, depending on the chronologies of other archives, but the development of radiocarbon method as a dating tool (Arnold and Libby, 1949; Libby et al., 1949) meant that absolute ages could be obtained from fossil organic matter such as peat. Although initial comparisons between relative and absolute chronologies appeared to confirm the validity of relative dating (Godwin, 1960), Smith and Pilcher (1973) showed that the idea of synchronous pollen zones was invalid even within a relatively small region such as the British Isles. Indeed, well-known pollen events such as the mid-Holocene elm decline probably took place over centuries (Parker et al., 2002).

Besides pollen markers, also major peat layers are often assumed to reflect climate changes that were synchronous over regions or even continents (Dachnowski, 1922; Barber et al., 2000). Any non-agreement in responses between bogs is then regularly explained by non-climatic factors (Langdon and Barber, 2005):

> *Although there are clear phases of coherence between the records, it is notable that there are also phases when the records do not agree, suggesting that some of the bogs were not sensitive during these phases and did not respond to any change in climate and/or that autogenic changes such as pool infilling obscured the climate signal.*

Tephra-dating showed that the “Schwarztorf-Weißtorf-Kontakt” or “Grenzhorizont” - an ubiquitous boundary between peat layers in north-west European bogs - was asynchronous even within small regions (van den Bogaard et al., 2002). Despite such

Please cite this article in press as: Blaauw, M., Out of tune: the dangers of aligning proxy archives, Quaternary Science Reviews (2010), doi:10.1016/j.quascirev.2010.11.012

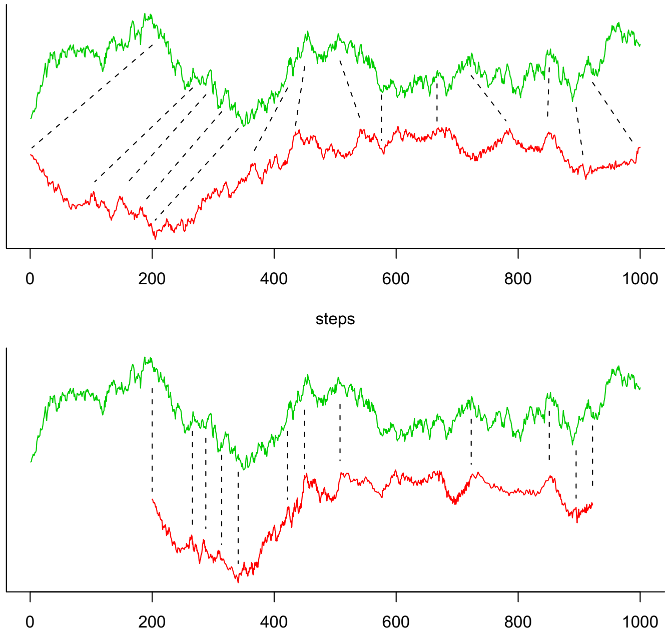

Fig. 2. Schematic representation of tuning process. Similar features within two time series are identified (tie-points indicated by dashed lines in upper panel), after which the tie-points within one series (red) are aligned with those of the other series (green; lower panel). Both time series were independently obtained by a Gaussian random walk process (see Blaauw et al., 2010a), where the value at step *i* is sampled from a normal distribution with the mean taken from its value at the previous step *i-1*, and standard deviation set at 0.1. As both time series are independent random walks, any similarities between the series are fortuitous. Both series however have similar standard deviations and thus possess similar degrees of autocorrelation. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

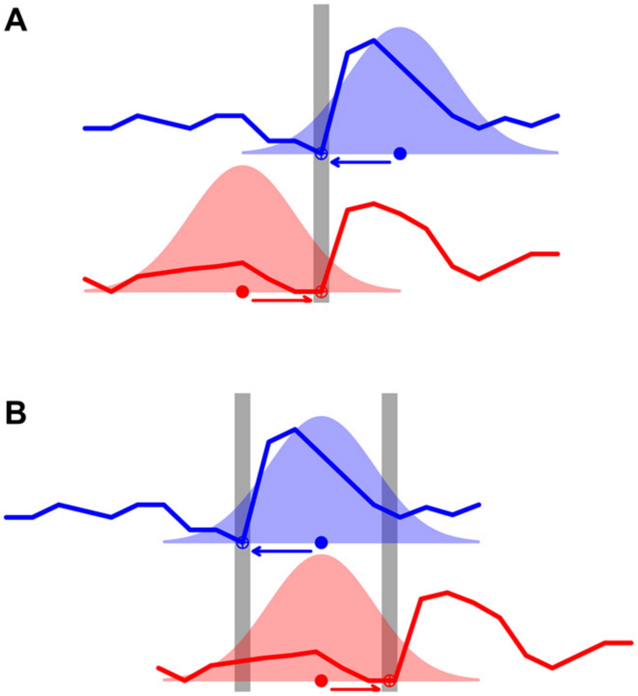

Fig. 3. Schematic of "sucking in" (A) and "smearing" (B) of proxy events (open circles with crosses on grey bars) owing to chronological uncertainties (bell-shaped distributions). In panel A, the proxy events in two time series are separate in time (filled dots). However, chronological uncertainties allow for some flexibility in the assigned timing of the events (arrows), in this case sucking the separate events into an illusionary single synchronous event (grey bar). In panel B, the two proxy series in reality reacted synchronously to a single event (filled dots), but chronological errors caused imperfect dating of the proxy changes, smearing out the single event into two separate events (grey bars). Time on arbitrary horizontal axis.

evidence, the idea that peat layers extend synchronously over large distances remains alive. For example, Charman et al. (2006), Blundell et al. (2008) and Swindles et al. (2010) produced regional syntheses of past climate change through synchronising, or "stacking", ^{14}C dated peat layers within regions.

1.2. *Tephra*

As fall-out products of volcanic eruptions, tephras can form highly precise and reliable isochrons to align proxy archives across regions (Lowe, in press). Some volcanic eruptions deposit their ashes over very large areas, such as the tephra from the AD 1259 El Chico eruption in Mexico which has been reported in Arctic and Antarctic ice (Palais et al., 1992). Moreover, their rapid atmospheric transport and subsequent deposition ensures that tephras can be used as essentially simultaneous events between different proxy archives. But even tephra-based correlations can be misleading. The Hekla 3 tephra was first dated at c. 3140-2885 cal BP (95% intervals calibrated from Icelandic ^{14}C dates by Dugmore et al., 1995). This period overlapped with a severe narrow-ring event in Northern Irish trees, several archaeological/historical events in Ireland and China, and a major acid spike in Greenland ice, leaving (Baillie and Munro, 1988; Baillie, 1989, 1991) with "little doubt that this event is the Hekla 3 eruption". However, this link was subsequently refuted through high-precision ^{14}C dating, which placed Hekla 3 a century after said events (Plunkett, 1999; van den Bogaard et al., 2002). For comparable accounts see Denton and Pearce (2008), Lowe and Higham (1998) or Lowe (in press) who warn against uncritical attribution of specific tephras to acid peaks.

Until now only few geochemical fingerprints have been published of tephra in ice (e.g., Davies et al., 2008), whereas most identifications are based on stratigraphic reasoning that acid peaks pertain to known volcanic eruptions (e.g., Vinther et al., 2006; Baillie, 2008). Moreover, as reviewed by Lowe (in press), some eruptions have multiple fingerprints, ice-rafting and other processes can (re)deposit tephra long after eruptions (Austin et al., 2004), several tephras of similar composition stem from multiple volcanic eruptions separated in time by centuries (e.g., Borrobol or NAAZ-II, see Davies et al., 2004 resp Wastegård et al., 2006), and some tephras are spread out over large depth intervals in sediment cores (Wastegård et al., 2006). Thus, at their best tephras can be used to align sites with remarkable precision and reliability, but only as long as the tephra grains in those sites occur at distinct depths and can be geochemically linked to specific volcanic eruptions.

1.3. *Orbital tuning*

Chronologies for long fossil proxy archives are frequently obtained through tuning. Half a century ago, Emiliani (1955) compiled δ^{18}O time series from foraminifera in deep ocean cores and tuned them to "Milankovitch" orbital cycles. The idea was that fossil foraminifer δ^{18}O reflects past temperatures and/or extents of ice sheets. Initial age-depth profiles for the cores were based on accumulation rate estimates from a few radiocarbon dates, and extrapolating these accumulation rates to much older times. Imbrie et al. further developed these tuned time-scales by applying additional radiometric markers and the 730 ka BP Brunhes-Matuyama magnetic reversal as initial time-scales for five marine cores, followed by tuning the δ^{18}O curves to orbital frequencies (Bassinot,

Please cite this article in press as: Blaauw, M., Out of tune: the dangers of aligning proxy archives, Quaternary Science Reviews (2010), doi:10.1016/j.quascirev.2010.11.012

2007; see also Shackleton and Opdyke, 1973). This then led to a 300 ka long SPECMAP time-scale (Pisias et al., 1984; Martinson et al., 1987; partly reproduced in Fig. 4). SPECMAP has been updated by Shackleton et al. (1990) and Lisiecki and Raymo (2005).

Examples of tuning-based sediment chronologies include Hooghiemstra et al. (1993), Tzedakis et al. (1997, 2001), Cayre et al. (1999), Prokopenko et al. (2006) and Hayashi et al. (2009). For terrestrial sites this can be seen as "double tuning"; dating pollen curves by aligning them to supposedly synchronous features in marine $\delta^{18}O$ curves, which themselves were dated through tuning to orbital insolation curves. Antarctic ice cores have been aligned to orbital insolation and to cores from Greenland (Bender et al., 1994; Blunier and Brook, 2001; Suwa and Bender, 2008). The Antarctic ice proxies used to tune against orbital insolation differ between studies, e.g., Ruddiman and Raymo (2003) applied the methane record, Petit et al. (1999) and Shackleton (2000) used $\delta^{18}O$, while Suwa and Bender (2008) used ice-entrapped atmospheric O_2/N_2 ratios. Resulting age-models differ by up to several millennia between the studies (e.g., Ruddiman and Raymo, 2003; Suwa and Bender, 2008).

Over the years, doubts have been expressed on the reliability of SPECMAP. Shackleton (2000) as well as Ruddiman (2003) questioned the original phasing of the orbital forcing-SPECMAP relationship, which might cause additional tuning errors. Bailey (2009) places doubts on the statistical reliability of orbitally tuned stratigraphical sequences. Muller and MacDonald (1997) warned a decade ago that

> *to turn a record of $\delta^{18}O$ versus depth into a record versus time, the sedimentation rate must be estimated. This is often done with a process called tuning, in which the instantaneous sedimentation rate is deduced by matching cycles in $\delta^{18}O$ to calculated perturbations in Earth's orbit. Parameterized sedimentation rates are adjusted to bring the observed proxy variations into consonance with the predictions of the model. This approach is potentially circular if the results are used to validate the climate model used to tune the record. […] Given enough parameters, tuning procedures can successfully match data to an incorrect model, resulting in an inaccurate time scale as well as in a false validation of the model.*

1.4. *Oxygen isotope stratigraphy*

Although independent radiometric dating of sea level changes has largely confirmed SPECMAP's timing (Thompson and Goldstein, 2006), its chronological uncertainties are on the order of several

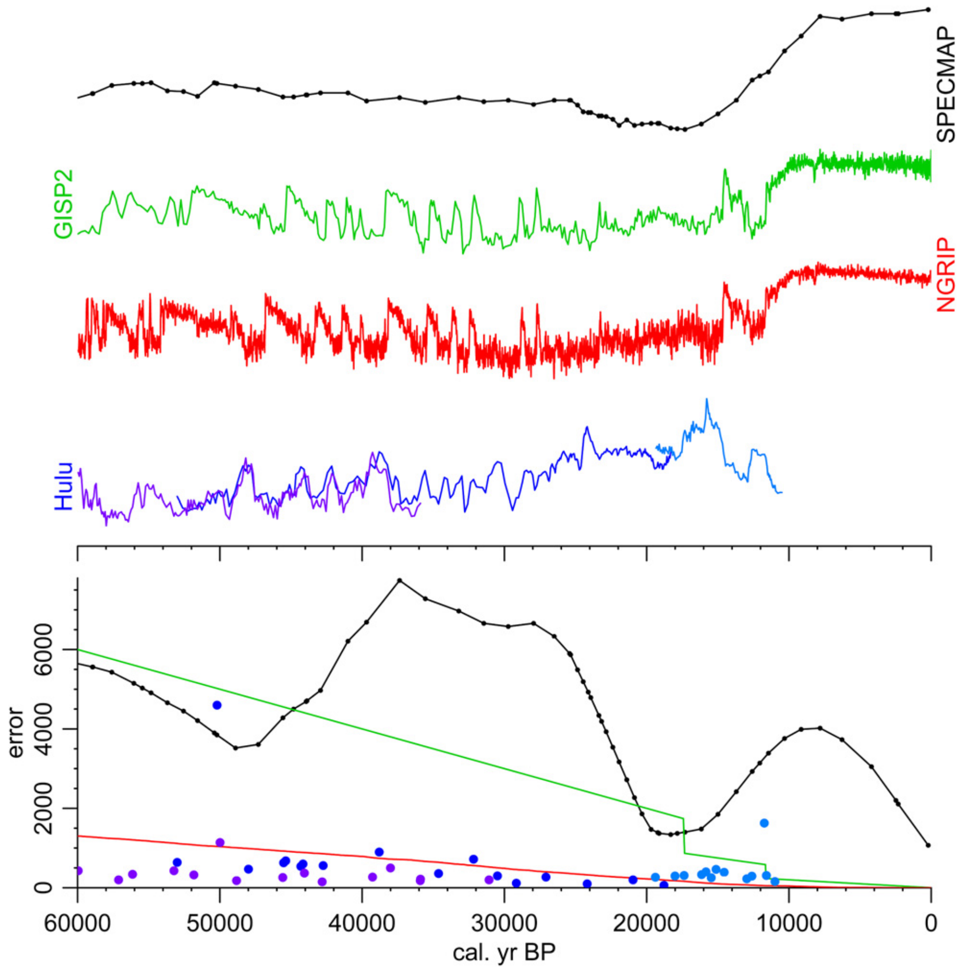

Fig. 4. Major $\delta^{18}O$ time series over the past 60,000 years (the limits of ^{14}C dating). Upper panel shows the $\delta^{18}O$ records, lower panel shows reported chronological uncertainties. SPECMAP data (black) from Martinson et al. (1987) and http://doi.pangaea.de/10.1594/PANGAEA.56039. GISP2 (green) taken from ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/gisp2/; errors based on http://nsidc.org/data/gisp_grip/document/gispinfo.html (2% < 11.64 kcal BP, 5% 11.64–17.38 kcal BP and 10% > 17.38 kcal BP). NGRIP (red) from Svensson et al. (2008) and http://icecores.dk. Hulu Cave (Wang et al., 2001) based on speleothems MSD (dark blue), MSL (pink) and PD (light blue), downloaded from ftp://ftp.ncdc.noaa.gov/pub/data/paleo/speleothem/china/hulu_2001.txt. Hulu uncertainties based on individual U/Th measurements. Isotope excursions in Greenland are generally asymmetric with abrupt rises and gradual decreases; Hulu Cave curves appear distinct. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

Please cite this article in press as: Blaauw, M., Out of tune: the dangers of aligning proxy archives, Quaternary Science Reviews (2010), doi:10.1016/j.quascirev.2010.11.012

thousand years (Martinson et al., 1987; Lisiecki and Raymo, 2005). Such error sizes are acceptable for studies at resolutions of c. 10^4–10^5 years, but arguably not for studies on centennial to millennial scales. This is perhaps why, more recently, marine cores have been tuned to higher resolution δ^{18}O times series such as from Greenland ice (Fig. 4) or from marine core MD95-2042 (Shackleton et al., 2000). In the first paper on this latter core, Cayre et al. (1999) constructed a chronology through tuning against SPECMAP (Martinson et al., 1987) and a nearby marine core. They mentioned that

> *the δ^{18}O record of stage 3 of core MD 95-2042 shows a rapid alternation of glacial and interglacial values. It could be tempting to try to relate those to the "Dansgaard-Oeschger" events […] detected in GRIP […], but synchroneity cannot be established because the resolution as well as the chronological databases are very different in the two records.*

After increasing the resolution of this core's δ^{18}O time series, Shackleton et al. (2000) became far less cautious:

> *It is apparent that our new, high-resolution δ^{18}O record can be readily correlated in detail with the Greenland record. A striking feature of the Greenland record is that the beginning of each interstadial is very abrupt […], implying that the polar front must have migrated northward very rapidly. It therefore seems reasonable to develop a higher-resolution GRIP-based time-scale for stage 3 by assuming that the rapid warming events recorded in core MD95-2042 are synchronous with those observed in Greenland.*

Thus the original chronology for the marine core was altered by up to several thousand years in order to match the δ^{18}O history of Greenland. Subsequent studies take Shackleton et al.'s (2000) chronology as given (e.g., Shackleton et al., 2004) and some use MD95-2042 as a tuning target, e.g., Itambi et al. (2009) assume that changes in benthic foraminifer δ^{18}O must be synchronous between MD95-2042 and their core from offshore Senegal, nearly 3000 km distant. They then report proxy events synchronous to those in the North Atlantic. This is hardly surprising given that their core was tuned to MD95-2402, and the latter to Greenland ice Pahnke et al. (2003) tuned their core off New Zealand to MD95-2042, 20,000 km away and in a different ocean.

It can be argued that the climate history constructed by aligning many δ^{18}O time series across and beyond the North Atlantic is convincing, owing to the frequent replication of registered climate events between archives, and also because it seems likely that major climate anomalies such as Dansgaard-Oeschger events must have been expressed on large spatial scales (e.g., Bond et al., 1993; Voelker et al., 2002; Rohling et al., 2003; Shackleton et al., 2004; Haesaerts et al., 2009; Harrison and Sanchez Goñi, 2010). However, it must be noted that these reconstructions were largely obtained through tuning, which is based on the very assumption that the events were synchronous. While compilations of absolutely (but rather low resolution) dated marine cores (Bond et al., 1993; Voelker et al., 2002; Rohling et al., 2003) seem to confirm the general patterns, the timing of registered events differs by up to thousands of years (see also Skinner, 2008). Independent U/Th age estimates of millennial scale climate events from speleothems in the eastern Mediterranean (Fleitmann et al., 2009) seem several millennia older than those in Greenland, and the same holds for Hulu Cave (Wang et al., 2001; Fig. 4). Climate modelling by Ganopolski and Roche (2009) suggests moreover that marine δ^{18}O signals carry a considerable local hydrological and temperature component, which indicates "that synchronization of records via δ^{18}O can lead to large absolute and relative dating errors". Also Lisiecki and Raymo (2009) warn that δ^{18}O signals can be asynchronous over large distances. Blaauw et al. (2010b) compared the timing of Dansgaard-Oeschger type climate events in Greenland with independently OSL and ^{14}C dated Lateglacial lake level changes in southern France (Wohlfarth et al., 2008). Even using these very precisely dated archives, chronological uncertainties precluded a secure assessment of (a) synchroneity between the sites (Figs. 5–7; Section 3).

1.5. Tuning to other key sites

Many late Quaternary studies use Greenland ice cores as reference when interpreting other proxy archives, even if the region is hardly typical of global climate (Wunsch, 2010). There are additional key sites at lower latitudes. Sediment from the Cariaco basin (Venezuela) has been ^{14}C dated at high-resolution (Hughen et al., 2006). Its deglacial to Holocene sections were dated by varve counting, and indicate climate changes that were synchronous to within dating error with Greenland ice. However, older sections of Cariaco were only partly laminated and could thus not be absolutely dated. Instead, grey-scale changes in the sediment were assumed to reflect Dansgaard-Oeschger type climate changes and were used to tune the proxy archive against other sites. The archive was tuned to c. 7300 km distant GISP2 originally (Fig. 4; Hughen et al., 2004), but the chronological uncertainties of GISP2 become very large beyond 40 kcal BP and the GISP2 chronology does not agree well with that of GRIP (Southon, 2004). Therefore later chronologies (Hughen et al., 2006) were obtained by tuning to absolutely U/Th dated stalagmites from Hulu Cave in China (Fig. 4; Wang et al., 2001), at about 15,000 km distance from the Cariaco Basin.

The Hulu δ^{18}O records were reported to show a close correspondence to those of the Greenland GISP2 core (Wang et al., 2001). However, Rohling et al. (2009) suggest tele-connections with both poles. Thus they tune Hulu to a temporally evolving blend of (tuned) Greenland and Antarctic ice core events, where at times either the northern or the southern hemisphere has a more dominant influence (e.g., 60% vs. 40%). Such alternative tuning tests are important since, as noted by Rohling et al. (2009),

> *Hulu Cave is being used to 'anchor' other chronologies (e.g., Shackleton et al., 2004; Skinner, 2008), and even to constrain radiocarbon calibration (Hughen et al., 2006; Weninger and Jöris, 2008). Any change in the correlation paradigm, even if only by a few centuries, may therefore affect our understanding of radiocarbon calibration through time.*

Indeed, the exercise of Rohling et al. (2009) indicates that even if two archives seem to be tele-connected, the underlying mechanisms might be more complex than generally thought. van Andel (2005) wrote:

> *The success of ice-core-based calibrations has fostered a belief that the D/O climatic events were near-global in extent, providing a handy and reliable palaeoclimatic short-cut for the late Pleistocene not only in Europe but also in much wider regions and later times. The proven extent of the D/O events, however, is limited to the glacial maritime climate of the North Atlantic region […], but a worldwide applicability is very uncertain. The farther east and south-east this climate regime is extrapolated, the more likely it is that other regional climate systems played the dominant role.*

Also the famous Kilimanjaro ice cap (Thompson et al., 2002; Gasse, 2002) has been dated through tuning. One of several depletions in Kilimanjaro's δ^{18}O record was argued to reflect the Wolf solar minimum and thus assigned an age of AD 1325. Another depletion near the base of the ice core was aligned to the δ^{18}O record of a U/Th dated speleothem about four thousand kilometres further north (Bar-Matthews et al., 1999). This led to an estimated age of 11.7 ka BP for the base of the Kilimanjaro ice cap, even though

Please cite this article in press as: Blaauw, M., Out of tune: the dangers of aligning proxy archives, Quaternary Science Reviews (2010), doi:10.1016/j.quascirev.2010.11.012

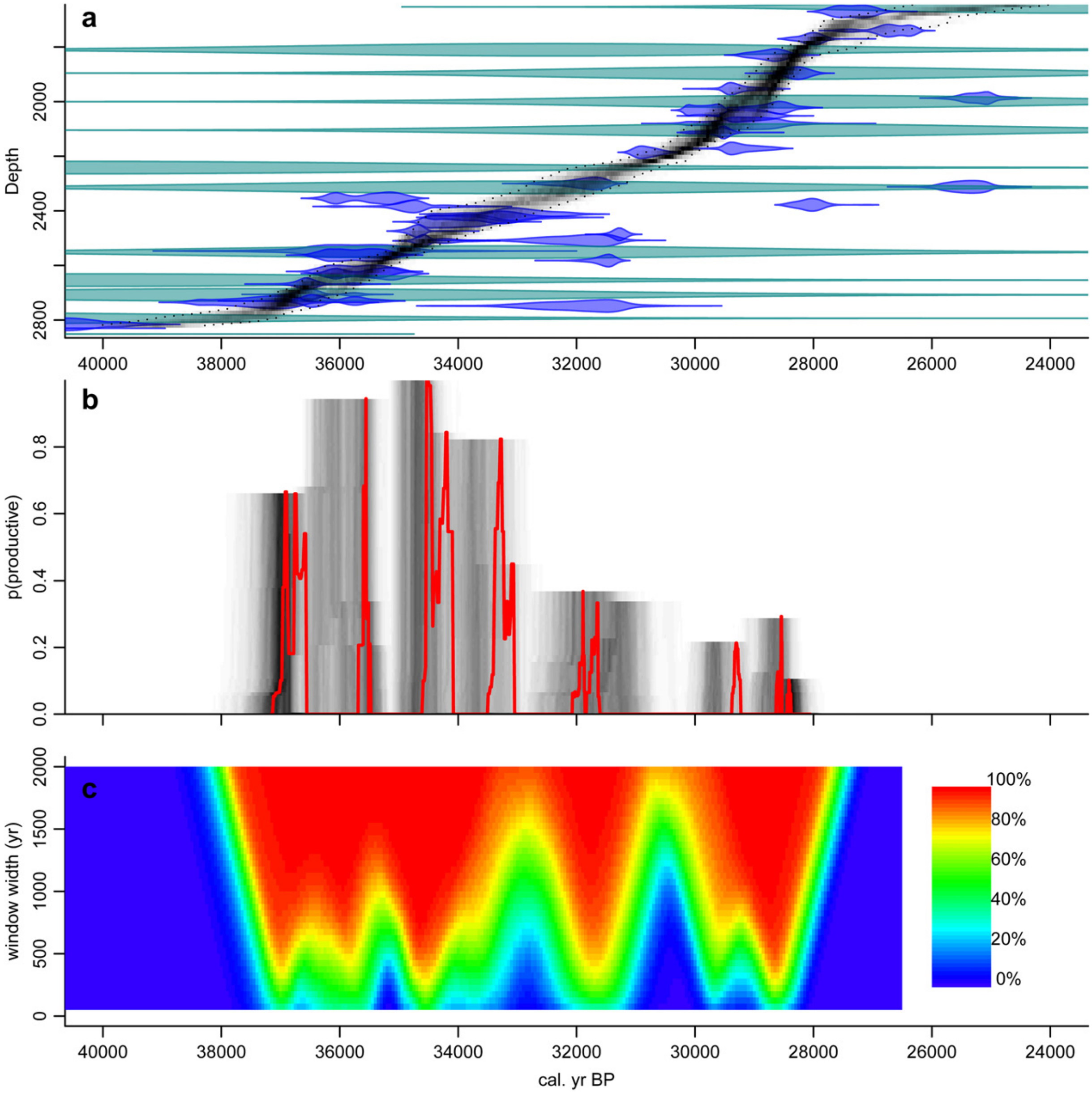

Fig. 5. Age-depth model for a high-density dated section of Les Échets, south-eastern France between 40 and 24 kcal BP (Wohlfarth et al., 2008; Blaauw et al., 2010b). The dark blue shapes in panel a show ^{14}C dates, while the light blue shapes show OSL dates (with much larger errors). Grey-scale shows flexible Bayesian age-depth model based on many short sections of piece-wise linear accumulation, and incorporating limits on accumulation rate and its variability (Blaauw and Christen, submitted for publication). Dark areas indicate sections with high chronological precision, while sections with lighter grey show sections with higher uncertainties. Panel b shows reconstructed lake productivity (Blaauw et al., 2010b). Red line shows reconstruction based on single "best" age-depth model; grey-scale shows the chronological uncertainty of the proxy graph (Blaauw et al., 2007). Panel c shows probabilities of events of increased lake productivity within moving time-windows of widths 50–2000 yr. Vertical axis shows width of time window. Colours indicate probabilities. Re-analysed and adapted from Blaauw et al. (2010b) (now using updated calibration curve IntCal09; Reimer et al., 2009). For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

radiocarbon dates suggested much younger ages (the dates were discarded owing to their small sample size). Kaser et al. (2010) provide an alternative explanation, suggesting that instead of having persisted for over 11 millennia, the Kilimanjaro ice cap might have come and gone repeatedly during the Holocene. If this proves true, then the tuning-derived paleoclimate interpretations of Thompson et al. (2002) will likely be wrong.

2. Problems of tuning

Many of the original papers that propose a tuning-based chronological framework are quite explicit and cautious about the uncertainties involved. However, subsequent papers often seem to neglect those warnings and take the tuning as "certain truth". As detailed above, even though Cayre et al. (1999) warned against tuning of key core MD95-2042, Shackleton et al. (2000) proposed to tune it anyway, and some subsequent papers do not even mention the dangers. Weninger and Jöris (2008) assert that "reliable synchronisms between marine records and high-resolution Greenland ice cores can be established by comparison of oxygen isotope signatures", and Haesaerts et al. (2009) assume the same for central Eurasian loess stratigraphies and Greenland δ^{18}O series. Itambi et al. (2009) extend the purported synchroneity of proxy archives within the North Atlantic to lower latitudes without any

Please cite this article in press as: Blaauw, M., Out of tune: the dangers of aligning proxy archives, Quaternary Science Reviews (2010), doi:10.1016/j.quascirev.2010.11.012

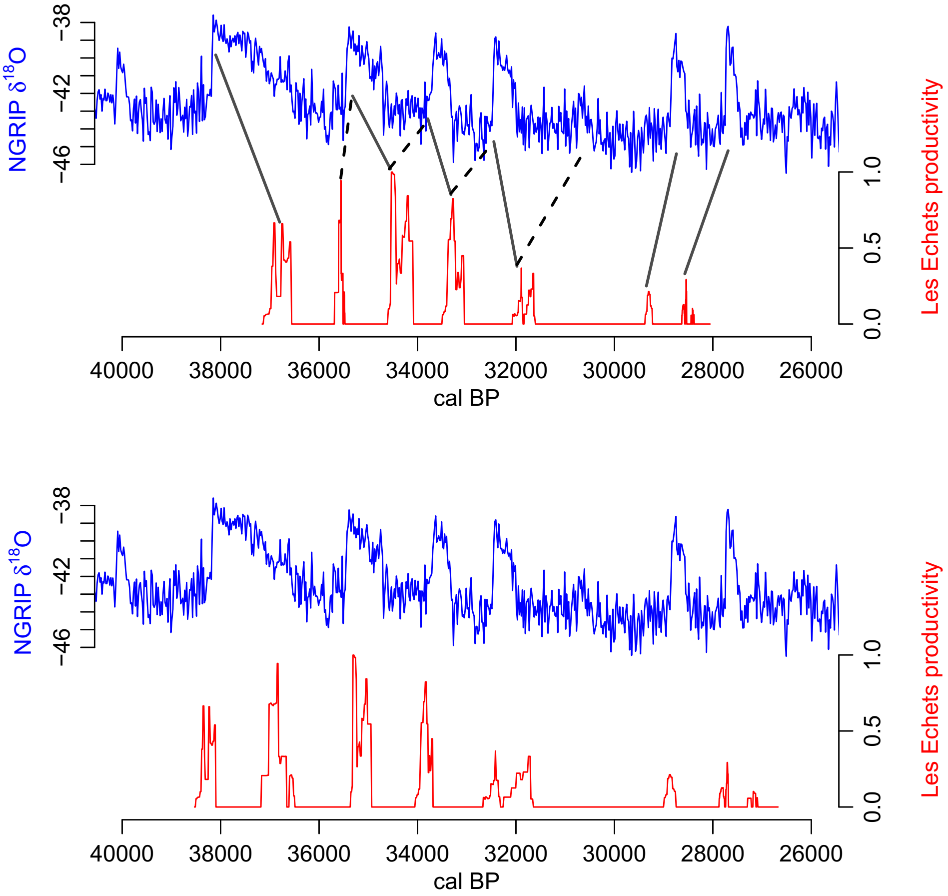

Fig. 6. Tuning of the productivity record of core Les Échets (red; Wohlfarth et al., 2008; Blaauw et al., 2010b) against the δ^{18}O record of NGRIP (blue; Svensson et al., 2008) between 40 and 26 kcal BP. Upper panel shows the two curves on their own, independent time-scales. Black continuous lines show proposed aligning of events between the cores. Dashed lines show alternative tuning. Lower panel shows how Les Échets would align with NGRIP using the continuous black lines of the upper panel. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

discussion as to whether this can or should actually be done. Similarly, Philips et al. (1994) proposed a tentative correlation between U/Th dated water level changes in a Californian lake and Greenland δ^{18}O but warned that their correlation was ambiguous. However, later work (Cacho et al., 1999) neglected these warnings and took the correlations as proof for synchronous climate events across large regions. Given the above examples, it becomes clear that some proposed alignments “will eventually move along the pathway from ’reasonable speculation’ to ’proven fact’” (Lowe and Higham, 1998).

The climatic history of synchronous Dansgaard-Oeschger events across the Atlantic seems very plausible. However, it must not be forgotten that most evidence was obtained through tuning marine, terrestrial and ice archives, based on the very assumption that these events were synchronous (Harrison and Sanchez Goñi, 2010; Blaauw et al., 2010b). By fitting loosely dated strands of apparently comparable time series together into a supposedly single event, one is in danger of creating a “coherent myth”, “reinforcement syndrome” (both Oldfield, 2001), or “suck-in effect” (Baillie, 1991) (Figs. 2 and 3). Already before radiocarbon dating was implemented, von Post (1946) warned that worldwide reconstructions of past climates should be

> *done without bias, and independently within each of the various areas of work. For following a stereotyped plan leads here, as always, into a blind alley, and it is not to be expected that the course of the climate curve has been the same in detail in all parts of the world, though in its main features it shows such a striking correspondence […]. If the facts appear to agree approximately then the theory becomes positively dangerous, for it may tempt us to wishful thinking which obscures our vision of the empirical realities. This has happened to a lamentable extent in dealing with the Quaternary climatic history.*

Oldfield (2001) reiterated this warning when commenting on a low resolution dated terrestrial δ^{18}O archive from China, which was correlated to δ^{14}C as a solar activity proxy:

> *Poorly substantiated correlations with target chronological templates, irrespective of their origin, can provide a stimulating basis for provocative discourse, but they do not provide acceptable chronological frameworks under any circumstances. Although adequately supported ’tuning’, used with caution, will sometimes, pending further advances in dating, be the best approach to chronology, such tuning is applicable only in the spatial domain within which coherence with the reference sequence can be unequivocally demonstrated.*

Related to the reinforcement syndrome mentioned above, circular reasoning is perhaps the most obvious danger of tuning. Courtillot et al. (2008) provide an example when arguing for tuning a δ^{18}O time series with records of solar variability:

> *The match can of course not be perfect because of the [measurement] uncertainties. If solar variability played only a minor role in*

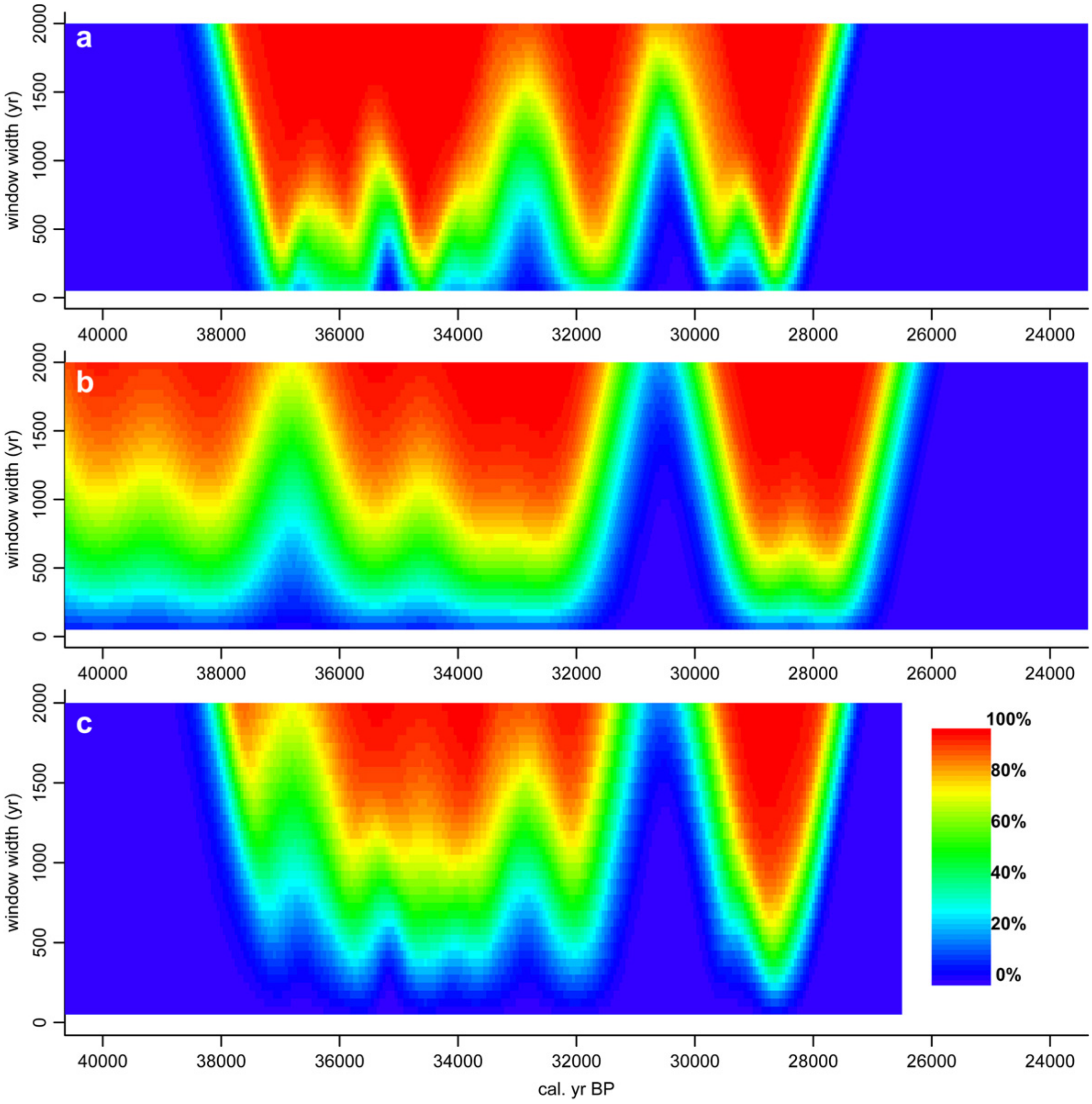

Fig. 7. Comparison of events within Les Échets (a, see Fig. 5c) and NGRIP (b, calculated is in a using data from Fig. 4). Note that Les Échets reaches higher probabilities at narrow time widths (“hot” colours reach further down) than NGRIP. Therefore, during this period chronological precision is higher for Les Échets than for NGRIP. Panel c shows the probability of events taking place in both archives within specific time-windows (the product of event probabilities for both archives for each time window). Note that high probabilities of synchronous events are only reached at time-windows of widths >1000 yr; synchroneity between both archives can only be inferred at low temporal resolution. For details of calculations, see Blaauw et al. (2010b).

> *the past two millennia, tuning could not improve the correlation. The correlation coefficient is only 0.6, and other forcing factors need to be taken into account. It is therefore not surprising that the tuned curve should reveal the link between solar activity and* $\delta^{18}O$.

Courtillot et al. (2008) seem unaware that tuning between any two time series will improve their correlation, no matter whether they are related or not (e.g., Fig. 2). Indeed, Bard and Delaygue (2008) warn that “to prove correlations and make inferences about solar forcing, only untuned records […] with their respective and independent time-scales, should be used.” Once chronologies are constructed through tuning climate events between archives, the resulting chronologies cannot be used to assess the timing between these same climatic events (e.g., synchroneity, leads or lags). This holds for the original papers where tuning is proposed as well as for subsequent papers that use these tuned chronologies.

Although tie-points might convey a zero-year uncertainty, in fact the chronological uncertainties of the events in the target archives can be surprisingly large. For example, both the SPECMAP and Greenland ice uncertainties reach millennial time-scales during the Lateglacial (Martinson et al., 1987; Lisiecki and Raymo, 2005; Andersen et al., 2006). Thus any tie-points to these archives will be at least as uncertain. Moreover, often a degree of subjectivity is involved in deciding which proxy events should be aligned with which proxy peak. Such decisions are usually based on aligning sequences of major and minor peaks as well as their shapes (e.g., “w-shaped”, “striking features”, rapid rises followed by slow decreases; Fig. 4). However, given the fact that often many peaks within a core are similarly shaped, and given the risk of the reinforcement syndrome, one cannot and should not have high confidence while tuning a proxy peak to a supposedly connected climatic event. Such tuned peaks are therefore less reliable than, for example, uniquely

Please cite this article in press as: Blaauw, M., Out of tune: the dangers of aligning proxy archives, Quaternary Science Reviews (2010), doi:10.1016/j.quascirev.2010.11.012

geochemically identified tephra layers, and should not be given the same chronological status. Some studies obtain chronologies by tuning one proxy, and then infer climate leads and lags using another proxy from the same core (e.g., Sanchez Goñi et al., 2002; Itambi et al., 2009). Although this might appear to provide independent evidence for leads and lags as the climate proxy was not tuned, in reality any synchroneity, leads or lags between the tuned archive and the target archive will still have been caused by assuming synchroneity (of the other proxy).

Alternative tuning solutions sometimes differ by up to millennia (Imbrie et al., 1984; Shackleton, 2000; Lisiecki and Raymo, 2005; Landais et al., 2006). Lisiecki and Raymo (2009) suggest asynchronous δ^{18}O records between Atlantic and Pacific oceans. Noise or low resolution of proxy analysis can cause problems in defining the exact start, mid or endpoint of a proxy event (see Parnell et al., 2008). Furthermore, cores are generally assumed to have accumulated linearly between the tuned tie-points (e.g., Fig. 2). Linear interpolation produces unrealistic age-models since it is highly unlikely that accumulation rates changed exactly at the tie-points and not in between (Bennett, 1994). Moreover, very few tuning studies report whether reconstructed accumulation rates and their variability are reasonable (for rare examples see Imbrie et al., 1984; Lisiecki and Raymo, 2009). Finally, only few studies try to quantify the chronological uncertainties of tuning (e.g., Hughen et al., 2006; see next section).

The intensity of past climate/environmental effects are often thought to imply that events must have been expressed on wide spatial scales. However, separate or interacting climate systems do not always behave as expected across regions. The risk exists of two independent environmental events happening nearly synchronously by chance (e.g., Yule, 1926). Further, separate climate systems might possess similar autocorrelations causing comparable event frequencies, even if unrelated and out of phase (Wunsch, 2006), resulting in fortuitous correlations if those events are tuned (see Fig. 2 and Blaauw et al., 2010a). Even more, each proxy archive will be subject to a unique combination of climatic thresholds, environmental settings, ecosystem configurations, and internal variability (e.g., Winkler and Matthews, 2010). For example, non-responses to inferred climate changes in bogs are sometimes thought to be due to the bog being in a “complacent” state (e.g., Langdon and Barber, 2005). Non-linear dynamics could cause proxy changes that are hard to attribute to single forcing factors (Blaauw et al., 2010a). Moreover, faulty measurements can cause false proxy peaks (e.g., Baldini et al., 2007). To speak with Wunsch (2010), the world is not as simple as we hope it to be. Events can thus be expressed quite uniquely in different locations. This is one of the reasons that Charman et al. (2006) tuned their peat archives only within relatively small regions such as Scotland.

Peat deposits contain specific organic components such as seeds and leaves that can be ^{14}C dated very precisely, and indeed in these types of deposits, detailed dating has proven wrong previous tuning-based hypotheses (e.g., Smith and Pilcher, 1973; van den Bogaard et al., 2002). Generally, marine cores are dated at much lower resolution and suffer from an imprecisely known marine reservoir effect. Perhaps this is one of the reasons why tuning has been, and remains, so popular in this type of deposits (as it was in the early days of Holocene pollen analysis). Given the wide error margins of absolute ^{14}C dates, absolute chronologies for marine archives can be shifted about to a large degree on the calendar scale, and tuning appears to provide more precise (additional) dating points than what can be obtained by absolute dates. With higher precision and higher resolution dating, chronologies will become more precise and thus less flexible regarding their possibilities to be tuned to other archives. Therefore, an increased absolute dating resolution might paradoxically lead to less clear-cut reconstructions. Bennett (2002) mentioned that we need

> *confidence in experimental and observational data, even where these appear to conflict with other results.[…] The key […] has to be confidence or otherwise in the age determinations. If we are confident with them, we can proceed. If we are not, they are useless, and we are placed in a situation where the cores are effectively undated. The events recorded in them might, in principle, correlate with the particular Greenland event of interest, or they might correlate with anything else: we don’t know. […] Without testable hypotheses, we end up with correlation by assertion, and it becomes difficult or impossible to disentangle what is based on data and what is based on the opinions of the author(s)”.*

3. Solutions to tuning problems

Currently, most tuning seems to be performed in a rather *ad hoc* way, assessing the timing, shapes and amplitudes of proxy events in a visual and subjective manner. Future tuning exercises should aim for more objective, numerical approaches to identifying tuning tie-points (e.g., Haam and Huybers, 2010). Statistical methods should be developed to quantify the shapes of proxy events (e.g., asymmetry, sizes of peaks, shoulders and tails) and assess their reliability, uncertainties and alternative alignments. First steps to such an approach were taken by Hughen et al. (2006), who aimed to quantify three sources of uncertainties involved in tuning the Cariaco basin to the Hulu archive: *i*) the errors of Hulu’s U/Th dates, *ii*) its resolution, and *iii*) the correlation between Cariaco-grey-scale and Hulu-δ^{18}O. If any sequence of tie-points has alternative matches, these should be shown, and multi-proxy tuning could prove more reliable than tuning-based on single proxies (e.g., Bokhorst and Vandenberghe, 2009). Any tuning should be limited to within regions that have independently been shown to pertain to the same climate regime. For future studies it would be worthwhile to apply realistic forward climate models in order to find mechanisms of climate change that are likely to have caused specific proxy reactions in a range of sites and archives (e.g., Wiersma et al., 2006). The INTIMATE group (Walker et al., 1999) suggested that for tuning, as first step one should

> *identify local events or sequences of events at key sites on the basis of independent evidence. The second stage is to correlate these site-specific records with the type sequence, i.e. the GRIP oxygen isotope profile, on the basis of what are considered to be comparable major events. The third step (which is perhaps the most difficult, but perhaps also the most important) is to use independent dating evidence to establish the degree of synchroneity between local and GRIP events.*

Probably the safest, though most pessimistic, “null-hypothesis” for any proxy event would be to assume that it is unrelated to events in other proxy archives, until proven otherwise by independently dated, replicated evidence (Parnell et al., 2008; Charman et al., 2009; Blaauw et al., 2010a, 2010b). Replicating proxy events through tuning would not be the solution, owing to the “reinforcement syndrome” (Oldfield, 2001; see also Fig. 2). One way to convey the chronological uncertainties of (multiple) reconstructions is to plot proxy grey-scale graphs and time-windows as in Figs. 5–7 (adapted from Blaauw et al., 2010b using the updated IntCal09 calibration curve from Reimer et al., 2009). Events of productivity increases in a site from south-eastern France (Wohlfarth et al., 2008) are compared to Dansgaard-Oeschger events in the δ^{18}O record of NGRIP (Svensson et al., 2008). Chronologies for the proxy-derived events are kept non-tuned, deriving their chronologies through

Please cite this article in press as: Blaauw, M., Out of tune: the dangers of aligning proxy archives, Quaternary Science Reviews (2010), doi:10.1016/j.quascirev.2010.11.012

independent dating (Figs. 5 and 7). Although tuning of the archives could result in apparently precise and simple chronologies, it is not clear which peaks in Les Échets should be compared with which peaks in NGRIP, and some peaks remain without counterparts in the other archive (Fig. 6). Probabilities of synchronous events between both archives can be calculated by comparing the independent chronologies (Fig. 7). Unfortunately, dating uncertainties are so high that synchroneity cannot be assessed at decadal to multi-centennial scale. Only at millennial resolution can synchroneity between both archives be inferred (with the possible exception of multiple events around c. 29-28 kcal BP).

Given the problems with tuning, absolute dating should be preferred when reconstructing past climate or environments from multiple proxy archives. However, absolute dates are expensive, not every depth in a proxy series can be dated (e.g., lack of datable material), they might need correction such as for a spatio-temporally varying reservoir effect in marine ^{14}C dates and calibration, and every measurement comes with its reported uncertainty. As can be seen in Figs. 5 and 7, these uncertainties become especially large during the Lateglacial, not in the least owing to errors introduced by ^{14}C calibration. Baillie (1991) warns that these chronological uncertainties tend to "smear" short-lived events over longer periods. However, this situation is improving as smaller samples can be ^{14}C dated, and at higher precision, than before AMS dating was available. Moreover, statistical approaches to age-modelling of high-resolution dated sequences can quantify and reduce age uncertainties (e.g., based on ^{14}C wiggle-match dating), and the timing of events between archives can be quantified (e.g., Blaauw et al., 2007, 2010b). The dating resolution of many terrestrial proxy studies is gradually increasing from a handful of dates to high-resolution, reliable absolute chronologies (e.g., Blaauw and Christen, 2005; Wohlfarth et al., 2008; Verschuren et al., 2009), although calibration issues remain an obstacle to high-precision age-models. Similar absolute dating efforts should be made for more marine archives. Although absolute dating is time-consuming and expensive, especially if done at high-resolution, the costs would amount to just a fraction of those of marine coring expeditions.

Research questions should be set at the resolution that can be obtained within the chronological uncertainties of the proxy data. For example, given that chronological uncertainties for many late-glacial archives are at millennial scales (e.g., SPECMAP, Greenland ice, ^{14}C dated cores; Martinson et al., 1987; Lisiecki and Raymo, 2005; Blaauw et al., 2010b; Figs. 4 and 7), one cannot answer research questions at higher precision (e.g., decadal or centennial). If tuning is attempted, time-scales should be adapted only to within quantified chronological uncertainties from absolute age-depth models (e.g., Neff et al., 2001; Charman et al., 2006). Age-depth curves resulting from tuning should be plotted in order to check for unlikely accumulation rate changes.

4. Conclusions

Seven-league boots are folkloric devices that can take extremely long strides, allowing for near-instant travel over huge distances. We have seen that late Quaternary literature abounds with "seven-league boot" alignments on regional, continental and even hemispheric scales.

I am not implying that all environmental histories obtained through tuning are wrong, although some original tuning studies have been refuted by absolute dating (e.g., Smith and Pilcher, 1973; Plunkett, 1999). Indeed, many syntheses seem highly plausible. However, the danger of falling into the trap of a "coherent myth" is very present in tuning-based reconstructions. Ideally, age-models should be constructed independent of any pre-conceived ideas about the timing of certain proxy changes. Temporal misalignments of inferred climate events between absolutely dated archives could be explained by errors in the proxies or in the dating process (e.g., changes in marine reservoir effect; Skinner, 2008). However, the alternative explanation that the dating is correct and the events asynchronous or even unrelated, should always be considered (Blaauw et al., 2010b). If one climate event, or some well-dated cores, appear to show synchroneity, this cannot and should not imply that all climate events were synchronous across entire regions, and certainly not that the events were caused by a shared process.

If tuning is applied, any warnings provided in the original tuning target papers should be heeded, and readers should be informed about the uncertainties inherent in the tuning process (e.g., Hughen et al., 2006). Readers should be made aware that nothing can be implied about any synchroneity, leads or lags between tuned events. Future global warming will likely not be globally synchronous in timing, nor globally identical in scope, nature and rate. Climate and environments are too complex to fit simple models. We need fossil proxy records to learn about the spatio-temporal variability of past climate change, and this information will be flawed if we assume that all climate events were synchronous.

Existing scientific paradigms should be questioned, even if these paradigms were developed by influential and pioneering scientists (e.g., Wunsch, 2010). Most of the early tuning examples were aimed at long temporal scales (tens of thousands of years; Emiliani, 1955; Martinson et al., 1987), but currently the same approaches are being used at much shorter time-scales. We should ask ourselves whether tuning remains an appropriate technique also at these resolutions, especially since absolute chronologies have become much more precise over the past decades.

Acknowledgements

Two unnamed referees are thanked for their valuable input which enhanced this paper. Thanks also to Keith Bennett, Paula Reimer, Mike Baillie, Barbara Wohlfarth, Graeme Swindles, David Lowe and other colleagues for sharing their thoughts about tuning. Barbara Wohlfarth is thanked for the Les Échets data.

References

Andersen, K.K., Svensson, A., Johnsen, S.J., Rasmussen, S.O., Bigler, M., Röhlisberger, R., Ruth, U., Siggaard-Andersen, M.L., Steffensen, J.P., Dahl-Jensen, D., Vinther, B.M., Clausen, H.B., 2006. The Greenland ice core chronology 2005, 15–42 ka. Part 1: constructing the time scale. Quaternary Science Reviews 25, 3246–3257.

Arnold, J.R., Libby, W.F., 1949. Age determinations by radiocarbon content: checks with samples of known age. Science 110, 678–680.

Austin, W.E.N., Wilson, L.J., Hunt, J.B., 2004. The age and chronostratigraphical significance of North Atlantic Ash Zone II. Journal of Quaternary Science 19, 137–146.

Bailey, R.J., 2009. Cyclostratigraphic reasoning and orbital time calibration. Terra Nova 21, 340–351.

Baillie, M.G.L., 1989. Hekla 3: how big was it? Endeavour 13, 78–81.

Baillie, M.G.L., 1991. Suck-in and smear – two related chronological problems for the 90s. Journal of Theoretical Archaeology 2, 12–16.

Baillie, M.G.L., 2008. Proposed re-dating of the European ice core chronology by seven years prior to the 7th century AD. Geophysical Research Letters 35, L15813.

Baillie, M.G.L., Munro, M.A., 1988. Irish tree rings, Santinori, and volcanic dust veils. Nature 332, 334.

Baldini, J.U.L., McDermott, F., Fairchild, I.J., 2007. Retraction of an interpretation. Science 317, 748.

Bar-Matthews, M., Ayalon, A., Kaufman, A., Wasserburg, G.J., 1999. The Eastern Mediterranean paleoclimate as a reflection of regional events: Soreq cave, Israel. Earth and Planetary Science Letters 166, 85–95.

Barber, K.E., Maddy, D., Rose, N., Stevenson, A.C., Stoneman, R., Thompson, R., 2000. Replicated proxy-climate signals over the last 2000 yr from two distant UK peat bogs: new evidence for regional palaeoclimate teleconnections. Quaternary Science Reviews 19, 481–487.

Bard, E., Delaygue, G., 2008. Comment on "Are there connections between the Earth's magnetic field and climate?". Earth and Planetary Science Letters 265, 302–307.

Please cite this article in press as: Blaauw, M., Out of tune: the dangers of aligning proxy archives, Quaternary Science Reviews (2010), doi:10.1016/j.quascirev.2010.11.012

Bassinot, F.C., 2007. Oxygen isotope stratigraphy of the oceans. In: Elias, S.A. (Ed.), Encyclopedia of Quaternary Science, pp. 1740–1748.

Bender, M., Sowers, T., Dickson, M.-L., Orchardo, J., Grootes, P., Mayewski, P.A., Meese, D.A., 1994. Climate correlations between Greenland and Antarctica during the past 100,000 years. Nature 372, 663–666.

Bennett, K.D., 1994. Confidence intervals for age estimates and deposition times in late-Quaternary sediment sequences. The Holocene 4, 337–348.

Bennett, K.D., 2002. Comment: the Greenland 8200 cal. yr BP event detected in loss-on-ignition profiles in Norwegian lacustrine sediment sequences. Journal of Quaternary Science 17, 97–99.

Bennett, K.D., Fuller, J.L., 2002. Determining the age of the mid-Holocene *Tsuga canadensis* (hemlock) decline, eastern North America. The Holocene 12, 421–429.

Birks, H.J.B., 2008. Holocene climate research – progress, paradigms, and problems. In: Battarbee, R.W., Binney, H.A. (Eds.), Natural Climate Variability and Global Warming: A Holocene Perspective. Wiley-Blackwell, Chichester, pp. 7–57.

Blaauw, M., Christen, J.A., Flexible paleoclimate age-depth models using an autoregressive gamma process. Bayesian Analysis, submitted for publication

Blaauw, M., Christen, J.A., 2005. Radiocarbon peat chronologies and environmental change. Applied Statistics 54, 805–816.

Blaauw, M., Christen, J.A., Mauquoy, D., van der Plicht, J., Bennett, K.D., 2007. Testing the timing of radiocarbon-dated events between proxy archives. The Holocene 17, 283–288.

Blaauw, M., van Geel, B., van der Plicht, J., 2004. Solar forcing of climate change during the mid-Holocene: indications from raised bogs in the Netherlands. The Holocene 14, 35–44.

Blaauw, M., Bennett, K.D., Christen, J.A., 2010a. Random walk simulations of fossil proxy data. The Holocene 20, 645–649.

Blaauw, M., Wohlfarth, B., Christen, J.A., Ampel, L., Veres, D., Hughen, K.A., Preusser, F., Svensson, A., 2010b. Were last glacial climate events simultaneous between Greenland and France? A quantitative comparison using non-tuned chronologies. Journal of Quaternary Science 25, 387–394.

Blundell, A., Charman, D.J., Barber, K., 2008. Multiproxy late Holocene peat records from Ireland: towards a regional palaeoclimate curve. Journal of Quaternary Science 23, 59–71.

Blunier, T., Brook, E.J., 2001. Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. Science 291, 102–112.

Bokhorst, M.P., Vandenberghe, J., 2009. Validation of wiggle-matching using a multi-proxy approach and its palaeoclimatic significance. Journal of Quaternary Science 24, 937–947.

Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., Bonani, G., 1993. Correlations between climate records from North Atlantic sediments and Greenland ice. Nature 365, 143–147.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent solar influence on North Atlantic climate during the Holocene. Science 294, 2130–2136.

Burns, S.J., Fleitmann, D., Matter, A., Kramers, J., Al-Subbary, A.A., 2003. Indian Ocean climate and an absolute chronology over Dansgaard/Oeschger events 9 to 13. Science 301, 1365–1367.

Cacho, I., Grimalt, J.O., Pelejero, C., Canals, M., Sierro, F.J., Flores, J.A., Shackleton, N., 1999. Dansgaard-Oeschger and Heinrich event imprints in Alboran Sea paleotemperatures. Paleoceanography 14, 698–705.

Cayre, O., Lancelot, Y., Vincent, E., Hall, M.A., 1999. Paleoceanographic reconstructions from planktonic foraminifera off the Iberian Margin: temperature, salinity, and Heinrich events. Paleoceanography 14, 384–396.

Charman, D.J., Blundell, A., Chiverell, R.C., Hendon, D., Langdon, P.G., 2006. Compilation of non-annually resolved Holocene proxy climate records: stacked Holocene peatland palaeo-water table reconstructions from northern Britain. Quaternary Science Reviews 25, 336–350.

Charman, D., Barber, K., Blaauw, M., Langdon, P., Mauquoy, D., Daley, T., Hughes, P., Karofeld, E., 2009. Climate drivers for peatland palaeoclimate records. Quaternary Science Reviews 28, 1811–1819.

Courtillot, V., Gallet, Y., Le Mouël, J.L., Fluteau, F., Genevey, A., 2008. Response to comment on “Are there connections between Earth’s magnetic field and climate?”. Earth and Planetary Science Letters 265, 308–311.

Dachnowski, A.P., 1922. The correlation of time units and climatic changes in peat deposits of the United States and Europe. PNAS 8, 225–231.

Davies, S.M., Wohlfarth, B., Wastegård, S., Andersson, M., Blockley, S., Possnert, G., 2004. Were there two Borrobol Tephras during the early Lateglacial period: implications for tephrochronology? Quaternary Science Reviews 23, 581–589.

Davies, S.M., Wastegård, S., Rasmussen, T.L., Svensson, A., Johnsen, S.J., Steffensen, J.P., Andersen, K.K., 2008. Identification of the Fugloyarbanki tephra in the NGRIP ice core: a key tie-point for marine and ice-core sequences during the last glacial period. Journal of Quaternary Science 23, 409–414.

Denton, J.S., Pearce, N.J.G., 2008. Comment on “A synchronized dating of three Greenland ice cores throughout the Holocene” by B.M. Vinther et al.: no Minoan tephra in the 1642 B.C. layer of the GRIP ice core. Journal of Geophysical Research 113, D04303.

Di Baldassarre, G., Montanari, A., 2009. Uncertainty in river discharge observations: a quantitative analysis. Hydrology and Earth System Sciences 13, 913–921.

Dugmore, A.J., Cook, G.T., Shore, J.S., Newton, A.J., Edwards, K.J., Larsen, G., 1995. Radiocarbon dating tephra layers in Britain and Iceland. Radiocarbon 37, 379–388.

Emiliani, C., 1955. Pleistocene temperatures. Journal of Geology 63, 538–578.

Fleitmann, D., Cheng, H., Badertscher, S., Edwards, R.L., Mudelsee, M., Göktürk, O.M., Fankhauser, A., Pickering, R., Raible, C.C., Matter, A., Kramers, J., Tüysüz, O., 2009. Timing and climatic impact of Greenland interstadials recorded in stalagmites from northern Turkey. Journal of Geophysical Research 36, L19707.

Gale, S.J., 2009. Event chronostratigraphy: a high-resolution tool for dating the recent past. Quaternary Geochronology 4, 391–399.

Ganopolski, A., Roche, D.M., 2009. On the nature of lead–lag relationships during glacial–interglacial climate transitions. Quaternary Science Reviews 28, 3361–3378.

Gasse, F., 2002. Kilimanjaro’s secrets revealed. Science 298, 548–549.

Godwin, H., 1960. Radiocarbon dating and Quaternary history in Britain. Proceedings of the Royal Society of London B 163, 287–320.

Imbrie, J., Hays, J.D., Martinson, D.G., McIntyre, A., Mix, A.C., Morley, J.J., Pisias, N.G., Prell, W.L., Shackleton, N.J., 1984. The orbital theory of Pleistocene clmate: support from a revised chronology of the marine δ^{18}O record. In: Berger, A.L., Imbrie, J. (Eds.), Milankovitch and Climate, Part 1. D. Reidel, Dordrecht, pp. 269–305.

Haam, E., Huybers, P., 2010. A test for the presence of covariance between time-uncertain series of data with application to the Dongge Cave speleothem and atmospheric radiocarbon records. Paleoceanography 25, PA2209.

Haesaerts, P., Borziac, I., Chekha, V.P., Chirica, V., Damblon, F., Drozdov, N.I., Orlova, L.A., Pirson, S., van der Plicht, J., 2009. Climatic signature and radiocarbon chronology of middle and late pleniglacial loess from Eurasia: comparison with the marine and Greenland records. Radiocarbon 51, 301–318.

Harrison, S.P., Sanchez Goñi, M.F., 2010. Global patterns of vegetation response to millennial-scale variability and rapid climate change during the last glacial period. Quaternary Science Reviews 29, 2957–2980.

Hayashi, T., Tanimura, Y., Kuwahara, Y., Ohno, M., Mampuku, M., Fujii, R., Sakai, H., Yamanaka, T., Maki, T., Uchida, M., Yahagi, W., Sakai, H., 2009. Ecological variations in diatom assemblages in the Paleo-Kathmandu Lake linked with global and Indian monsoon climate changes for the last 600,000 years. Quaternary Research 72, 377–387.

Hoek, W.Z., Bohncke, S.J.P., 2001. Oxygen-isotope wiggle matching as a tool for synchronising ice-core and terrestrial records over Termination 1. Quaternary Science Reviews 20, 1251–1264.

Hooghiemstra, H.H., Melice, J.L., Berger, A., Shackleton, N.J., 1993. Frequency spectra and paleoclimatic variability of the high-resolution 30–1450 ka Funza I pollen record (Eastern Cordillera, Colombia). Quaternary Science Reviews 12, 141–156.

Hughen, K.A., Lehman, S.J., Southon, J., Overpeck, J.T., Marchal, O., Herring, C., Turnbull, J., 2004. ^{14}C activity and global carbon cycle changes over the past 50,000 years. Science 303, 202–207.

Hughen, K., Southon, J., Lehman, S., Bertrand, C., Turnbull, J., 2006. Marine-derived ^{14}C calibration and activity record for the past 50000 years updated from the Cariaco Basin. Quaternary Science Reviews 25, 3216–3227.

Itambi, A.C., von Dobeneck, T., Mulitza, S., Bickert, T., Heslop, D., 2009. Millennial-scale northwest African droughts related to Heinrich events and Dansgaard-Oeschger cycles: evidence in marine sediments from offshore Senegal. Paleoceanography 24, PA1205.

Kaser, G., Mölg, T., Cullen, N.J., Hardy, D.R., Winkler, M., 2010. Is the decline of ice on Kilimanjaro unprecedented in the Holocene? The Holocene 20, 1079–1091.

Landais, A., Waelbroeck, C., Masson-Delmotte, V., 2006. On the limits of Antarctic and marine climate records synchronization: lag estimates during marine isotopic stages 5d and 5c. Paleoceanography 21, PA1001.

Langdon, P.G., Barber, K.E., 2005. The climate of Scotland over the last 5000 years inferred from multiproxy peatland records: inter-site correlations and regional variability. Journal of Quaternary Science 20, 549–566.

Libby, W.F., Anderson, E.C., Arnold, J.R., 1949. Age determination by radiocarbon content: world-wide assay of natural radiocarbon. Science 109, 227–228.

Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene–Pleistocene stack of 57 globally distributed benthic δ^{18}O records. Paleoceanography 20, PA1003.

Lisiecki, L.E., Raymo, M.E., 2009. Diachronous benthic δ^{18}O responses during late Pleistocene terminations. Paleoceanography 24, PA3210.

Lowe, D.J., Higham, T.F.G., 1998. Hit-or-myth? Linking a 1259 AD acid spike with an Okataina eruption. Antiquity 72, 427–431.

Lowe, D.J., in press. Tephrochronology and its application: a review. Quaternary Geochronology. doi:10.1016/j.quageo.2010.08.003

Maher, L.J., 1972. Nomograms for computing 0.95 confidence limits of pollen data. Review of Palaeobotany and Palynology 13, 85–93.

Muller, R.A., MacDonald, G.J., 1997. Glacial cycles and astronomical forcing. Science 277, 215–218.

Neff, U., Burns, S.J., Mangini, A., Mudelsee, M., Fleitmann, D., Matter, A., 2001. Strong coherence between solar variability and the monsoon in Oman between 9 and 6 kyr ago. Nature 411, 290–293.

Oldfield, F., 2001. A question of timing: a comment on Hong, Jiang, Lui, Zhou, Beer, Li, Leng, Hong and Qin. The Holocene 11, 123–124.

Pahnke, K., Zahn, R., Elderfield, H., Schulz, M., 2003. 340,000-year centennial-scale marine record of southern hemisphere climatic oscillation. Science 301, 948–952.

Palais, J.M., Germani, M.S., Zielinski, G.A., 1992. Inter-hemispheric transport of volcanic ash from a 1259 AD volcanic eruption to the Greenland and Antarctic icesheets. Geophysical Research Letters 19, 801–804.

Parker, A.G., Goudie, A.S., Anderson, D.E., Robinson, M.A., Bonsall, C., 2002. A review of the mid-Holocene elm decline in the British Isles. Progress in Physical Geography 26, 1–45.

Parnell, A.C., Haslett, J., Allen, J.R.M., Buck, C.E., Huntley, B., 2008. A flexible approach to assessing synchroneity of past events using Bayesian reconstructions of sedimentation history. Quaternary Science Reviews 27, 1872–1885.

Please cite this article in press as: Blaauw, M., Out of tune: the dangers of aligning proxy archives, Quaternary Science Reviews (2010), doi:10.1016/j.quascirev.2010.11.012

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Lipenkov, V., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., Stievenard, M., 1999. Climate and atmospheric history of the last 420,000 years from the Vostok ice core, Antarctica. Nature 399, 429–436.

Philips, F.M., Campbell, A.R., Smith, G.I., Bischoff, J.L., 1994. Interstadial climatic cycles: a link between western North America and Greenland? Geology 22, 1115–1118.

Pisias, N.G., Martinson, D.G., Moore, T.C., Shackleton, N.J., Prell, W., Hays, J., Boden, G., 1984. High resolution stratigraphic correlation of benthic oxygen isotopic records spanning the last 300,000 years. Marine Geology 56, 119–136.

Plunkett, G.M., 1999. Environmental Change in the Late Bronze Age in Ireland (1200-600 cal. BC). Unpublished PhD thesis, Queen's University, Belfast.

Prokopenko, A.A., Hinnov, L.A., Williams, D.F., Kuzmin, M.I., 2006. Orbital forcing of continental climate during the Pleistocene: a complete astronomically tuned climatic record from Lake Baikal, SE Siberia. Quaternary Science Reviews 25, 2431–3457.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0-50,000 years cal BP. Radiocarbon 51, 1111–1150.

Rohling, E.J., Mayewski, P.A., Challenor, P., 2003. On the timing and mechanism of millennial-scale climate variability during the last glacial cycle. Climate Dynamics 20, 257–267.

Rohling, E.J., Liu, Q.S., Roberts, A.P., Stanford, J.D., Rasmussen, S.O., Langen, P.L., Siddall, M., 2009. Controls on the East Asian monsoon during the last glacial cycle, based on comparison between Hulu Cave and polar ice-core records. Quaternary Science Reviews 28, 3291–3302.

Ruddiman, W.F., 2003. Orbital insolation, ice volume, and greenhouse gases. Quaternary Science Reviews 22, 1597–1629.

Ruddiman, W.F., Raymo, M.E., 2003. A methane-based time scale for Vostok ice. Quaternary Science Reviews 22, 141–155.

Shackleton, N.J., 2000. The 100,000-year ice-age cycle identified and found to lag temperature, carbon dioxide, and orbital eccentricity. Science 289, 1897–1902.

Shackleton, N.J., Opdyke, N.D., 1973. Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year scale. Quaternary Research 3, 30–55.

Shackleton, N.J., Berger, A., Peltier, W.A., 1990. An alternative astronomical calibration of the lower Pleistocene time-scale based on ODP Site 677. Transactions of the Royal Society of Edinburgh: Earth Sciences 81, 251–261.

Shackleton, N.J., Hall, M.A., Vincent, E., 2000. Phase relationships between millennial-scale events 64,000-24,000 years ago. Paleoceanography 15, 565–569.

Shackleton, N.J., Fairbanks, R.G., Chiu, T.-C., Parrenin, F., 2004. Absolute calibration of the Greenland time scale: implications for Antarctic time scales and for Δ^{14}C. Quaternary Science Reviews 23, 1513–1522.

Skinner, L.C., 2008. Revisiting the absolute calibration of the Greenland ice-core age-scales. Climate of the Past 4, 295–302.

Smith, A.G., Pilcher, J.R., 1973. Radiocarbon dates and vegetational history of the British Isles. New Phytologist 72, 903–914.

Southon, J., 2004. A radiocarbon perspective on Greenland ice-core chronologies: Can we use ice cores for ^{14}C calibration? Radiocarbon 46, 1239–1259.

Suwa, M., Bender, M.L., 2008. Chronology of the Vostok ice core constrained by O_2/N_2 ratios of occluded air, and its implication for the Vostok climate records. Quaternary Science Reviews 27, 1093–1106.

Svensson, A., Andersen, K.K., Bigler, M., Clausen, H.B., Dahl-Jensen, D., Davies, S.M., Johnsen, S.J., Muscheler, R., Parrenin, F., Rasmussen, S.O., Rothlisberger, R., Seierstad, I., Steffensen, J.P., Vinther, B.M., 2008. A 60 000 year Greenland stratigraphic ice core chronology. Climate of the Past 4, 47–57.

Swindles, G.T., Blundell, A., Roe, H.M., Hall, V.A., 2010. A 4500-year proxy climate record from peatlands in the North of Ireland: the identification of widespread summer 'drought phases'? Quaternary Science Reviews 29, 1577-1589

Thompson, W.G., Goldstein, S.L., 2006. A radiometric calibration of the SPECMAP timescale. Quaternary Science Reviews 25, 3207–3215.

Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Henderson, K.A., Brecher, H.H., Zagorodnov, V.S., Mashiotta, T.A., Lin, P.-N., Mikhalenko, V.N., Hardy, D.R., Beer, J., 2002. Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa. Science 298, 589–593.

Tzedakis, P.C., Andrieu, V., de Beaulieu, J.-L., Crowhurst, S., Follieri, M., Hooghiemstra, H., Magri, D., Reille, M., Sadori, L., Shackleton, N.J., Wijmstra, T.A., 1997. Comparison of terrestrial and marine records of changing climate of the last 500,000 years. Earth and Planetary Science Letters 150, 171–176.

Tzedakis, P.C., Andrieu, V., de Beaulieu, J.-L., Birks, H.J.B., Crowhurst, S., Follieri, M., Hooghiemstra, H., Magrif, D., Reille, M., Sadori, L., Shackleton, N.J., Wijmstra, T.A., 2001. Establishing a terrestrial chronological framework as a basis for biostratigraphical comparisons. Quaternary Science Reviews 20, 1583–1592.

van Andel, T.H., 2005. The ownership of time: approved ^{1s}C calibration or freedom of choice? Antiquity 79, 944–948.

van den Bogaard, C., Dörfler, W., Glos, R., Nadeau, M.-J., Grootes, P.M., Erlenkeuser, H., 2002. Two tephra layers bracketing late Holocene paleoecological changes in northern Germany. Quaternary Research 57, 314–324.

Verschuren, D., Sinninghe Damsté, J.S., Moernout, J., Kristen, I., Blaauw, M., Fagot, M., Haug, G.H., CHALLACEA project members, 2009. Half-precessional dynamics of monsoon rainfall near the east African equator. Nature 462, 637–641.

Vinther, B.M., Clausen, H.B., Johnsen, S.J., Rasmussen, S.O., Andersen, K.K., Buchardt, S.L., Dahl-Jensen, D., Seierstad, I.K., Siggaard-Andersen, M.-L., Steffensen, J.P., Svensson, A., Olsen, J., Heinemeier, J., 2006. A synchronized dating of three Greenland ice cores throughout the Holocene. Journal of Geophysical Research 111, D13102.

von Post, L., 1946. The prospect for pollen analysis in the study of Earth's climatic history. New Phytologist 45, 193–217.

Voelker, A.H.L, and workshop participants, 2002. Global distribution of centennial-scale records for Marine Isotope Stage (MIS) 3: a data base. Quaternary Science Reviews 21, 1185–1212.

Walker, M.J.C., Björck, S., Lowe, J.J., Cwynar, L.C., Johnsen, S., Knudsen, K.-L., Wohlfarth, B., INTIMATE Group, 1999. Isotopic 'events' in the GRIP ice core: a stratotype for the late Pleistocene. Quaternary Science Reviews 18, 1143–1150.

Wang, Y.J., Cheng, H., Edwards, R.L., An, Z.S., Wu, J.Y., Shen, C.-C., Dorale, J.A., 2001. A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China. Science 294, 2345–2348.

Wastegård, S., Rasmussen, T.L., Kuijpers, A., Nielsen, T., van Weering, T.C.E., 2006. Composition and origin of ash zones from marine isotope stages 3 and 2 in the north Atlantic. Quaternary Science Reviews 25, 2409–2419.

Weninger, B., Jöris, O., 2008. A ^{14}C age calibration curve for the last 60 ka: the Greenland-Hulu U/Th timescale and its impact on understanding the Middle to Upper Paleolithic transition in Western Eurasia. Journal of Human Evolution 55, 772–781.

Wiersma, A.P., Renssen, H., Goosse, H., Fichefet, T., 2006. Evaluation of different freshwater forcing scenarios for the 8.2 ka BP event in a coupled climate model. Climate Dynamics 27, 831–849.

Winkler, S., Matthews, J.A. , 2010. Holocene glacier chronologies: are 'highresolution' global and inter-hemispheric comparisons possible? The Holocene 20, 1137–1147.

Wohlfarth, B., Veres, D., Ampel, L., Lacourse, T., Blaauw, M., Preusser, F., Andrieu-Ponel, V., Kéravis, D., Lallier-Vergès, E., Björck, S., Davies, S.M., de Beaulieu, J.-L., Risberg, J., Hormes, A., Kasper, H.U., Possnert, G., Reille, M., Thouveny, N., Zander, A., 2008. Rapid ecosystem response to abrupt climate changes during the last glacial period in western Europe, 40–16 ka. Geology 36, 407–410.

Wunsch, C., 2006. Abrupt climate change: an alternative view. Quaternary Research 65, 191–203.

Wunsch, C., 2010. Towards understanding the paleocean. Quaternary Science Reviews 29, 1960–1967.

Yule, G.U., 1926. Why do we sometimes get nonsense correlations between time series? A study in sampling and the nature of time series. Journal of the Royal Statistical Society 89, 1–64.

Please cite this article in press as: Blaauw, M., Out of tune: the dangers of aligning proxy archives, Quaternary Science Reviews (2010), doi:10.1016/j.quascirev.2010.11.012