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Were last glacial climate events simultaneous between Greenland and western Europe?

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Abstract

During the last glacial period, several large abrupt climate fluctuations took place on the Greenland ice cap and elsewhere. Often these Dansgaard/Oeschger events are assumed to have been synchronous, and then used as tie-points to link chronologies between the proxy archives. However, if temporally separate events are lumped into one illusionary event, climatic interpretations of the tuned events will obviously be flawed. Here, we compare Dansgaard/Oeschger-type events in a well-dated record from south-eastern France with those in Greenland ice cores. Instead of assuming simultaneous climate events between both archives, we keep their age models independent. Even these well-dated archives possess large chronological uncertainties, that prevent us from inferring synchronous climate events at decadal to multi-centennial time scales. If possible, tuning of proxy archives should be avoided.

1 Introduction

Some of the most intriguing climatic features of the last glacial period are the large abrupt temperature fluctuations that recurred at millennial time-scales. These Dansgaard/Oeschger (D/O) events, originally seen in δ^{18}O variations in Greenland ice cores (Dansgaard et al., 1993), have subsequently been reported from proxy archives around the North Atlantic (Bond et al., 1997; Allen et al., 1999; Sánchez-Goni et al., 2002; Voelker and Workshop Participants, 2002; Tzedakis et al., 2004; Roucoux et al., 2005; Andersen et al., 2006; Vautravers and Shackleton, 2006; Wohlfarth et al., 2008) and beyond (Wang et al., 2001; Voelker and Workshop Participants, 2002; Burns et al., 2003; Rohling et al., 2003; Hughen et al., 2004; Turney et al., 2004). D/O events have been hypothesized to result from major shifts in North Atlantic meridional overturning circulation (Knutti et al., 2004; EPICA Community Members, 2006). A rapid atmospheric transmission of the signal could have led to more or less synchronous D/O style events within the Northern Hemisphere. Indeed, abrupt climatic events recognized in marine and terrestrial proxy time series are frequently reported to have been synchronous with Greenland D/O events (Bond et al., 1997; Allen et al., 1999; Wang et al., 2001; Sánchez-Goni et al., 2002; Burns et al., 2003; Hughen et al., 2004; Roucoux et al., 2005; Vautravers and Shackleton, 2006).

2 Synchronicity of D/O events?

The inference of synchroneity between regions is constrained by numerous factors, including the response of the analysed marine or terrestrial proxies to local, regional and global climate signals, the temporal resolution of the studied sequence, and the chosen age model. The lack of an internationally accepted radiocarbon (^{14}C) calibration curve beyond 26 thousand calibrated years before present (Reimer et al., 2004; van der Plicht et al., 2004) (cal ka BP), uncertain and time-dependent radiocarbon reservoir age offsets for glacial marine records (Muscheler et al., 2008) and chronological uncertainties of up to 2600 years (2 standard deviations) in the Greenland ice cores (Andersen et al., 2006) further add to this complexity. In order to overcome these difficulties, time scales and events in marine and terrestrial records are often tuned (artificially synchronized) to ice core chronologies (e.g. Bond et al., 1997; Rohling et al., 2003; Tzedakis et al., 2004). However, the assumptions of synchronicity between regions eliminates any potential for objective evaluation of relative timing in different time scales (Wunsch, 2006; Blaauw et al., 2007).

Here, we employ a different approach to compare D/O signals in Greenland ice cores (Andersen et al., 2006) with abrupt events recorded in the high resolution dated sediment sequence from the site Les Echets in south-eastern France (Wohlfarth et al., 2008). This multi-proxy lake record is dated with numerous radiocarbon and infrared stimulated luminescence (IRSL) measurements, and covers the time period ca. 45–15 cal ka BP. The record displays pronounced environmental changes which show striking similarities to D/O events in the Greenland ice cores. Instead of implying synchroneity through tuning of the proxy events, we apply Bayesian techniques (Blaauw et al., 2007) to systematically compare the timing of the events recognized in the Les Echets sequence with those in the NGRIP ice core.

3 Methods

Core EC1 was drilled in the deepest part of the former lake at Les Echets (LE, 45°54′ N, 4°56′ E, 275 m above sea level) and analysed at high temporal resolution for multiple environmental proxies (Wohlfarth et al., 2008). The alternating organic and inorganic sediments between 30.06 and 5 m depth were dated using 46 accelerator mass spectrometry (AMS) radiocarbon dates on plant remains, pollen grains, and the insoluble sediment organic fraction (SI Table 1: http://www.clim-past-discuss.net/4/1203/2008/cpd-4-1203-2008-supplement.pdf), as well as 21 IRSL dates (SI Table 2). The major source of uncertainty for the ^{14}C dates lies in the calibration to calendar ages, whereas for the IRSL dates uncertainty resides in the variability of the water content of the sediments. Differential compaction of the organic and inorganic sediments indicates that their water content changed during and after deposition. Therefore present day moisture measurements were corrected using an estimated average water content of 80±10% over time.

Most of the LE radiocarbon ages are older than the limit of the IntCal04 calibration curve at 26 cal ka BP (Reimer et al., 2004). Although several curves for estimating calendar ages beyond that range are potentially available (van der Plicht et al., 2004; Fairbanks et al., 2005; Hughen et al., 2006; Danzeglocke et al., 2008) (see Supplementary Information at http://www.clim-past-discuss.net/4/1203/2008/cpd-4-1203-2008-supplement.pdf), we chose here the curves of Hughen et al. (2006), hereafter called Hughen06, and Fairbanks et al. (2005), hereafter called Fairbanks05, because of their long time-spans, high-dating resolution and reasonable between-curve agreements. While the calendar ages of Hughen06 are based on tuning Cariaco Basin sediment paleoclimate records to the high-resolution U/Th dated Hulu cave δ^{18}O record (Wang et al., 2001), those of Fairbanks05 were constructed from independently obtained U/Th dates on corals. Both curves have uncertainties in their calendar age models (errors 300–500 yr for Hughen06, 50–100 yr for Fairbanks05), and imprecisely known and possibly varying local marine reservoir effects (Muscheler et al., 2008) create additional uncertainties in the radiocarbon ages of both curves.

Age-depth models for EC 1 were constructed through >1.7 billion iterations with the Bayesian modelling software Bpeat (Blaauw and Christen, 2005), using linear interpolation between dated levels and including prior information on accumulation rates, hiatus lengths and outlier probabilities (generally assigned values of 5–50%, see Supplementary Information) (Fig. 1). Most dates fit within 1 standard deviation (sd) of the comparison curves (radiocarbon) or the 1:1 curve (IRSL), with the exceptions of i) the lower part of the sequence where IRSL dates suggest much older ages than the radiocarbon dates, ii) the upper part where IRSL dates suggest somewhat older ages than the radiocarbon dates, and iii) some outlying radiocarbon dates between ca. 37–26 ka BP. Histograms of the calendar age distribution can be obtained for every depth through calculating the assigned calendar age for each of the iterations, and graphed as greyscales where more likely calendar ages (appearing more frequently in the sampling process) are darker (Fig. 1c–d). The intervals with conflicting IRSL and radiocarbon dates obtained much larger chronological uncertainties (wide grey areas). We therefore focus on the high-resolution dated middle part of the sequence, between 40 and 26 ka BP, where average 1 sd uncertainties are ca. 400 years.

4 Synchronicity of Les Echets and Greenland ice core events?

Intervals of higher lake organic productivity (LE events A-G in Fig. 2) with warmer and more humid climatic conditions are indicated by rising values for loss-on-ignition (LOI) and planktonic diatom concentrations, among many other analysed proxies in LE sediments (Wohlfarth et al., 2008). In contrast, low lake organic productivity together with a colder and drier climate is suggested by low values of LOI and planktonic diatom concentrations. Peaks A–D clearly denote events of increased lake organic productivity (high event probabilities), whereas events E-G appear more subtle. Wohlfarth et al. (2008) hypothesized that the shifts between higher and low lake organic productivity phases resemble D/O and Greenland Interstadial (GI) events in the Greenland ice cores. Although it would be tempting to tune these intervals by eye to GI events 8–3 (Fig. 2), instead we calculate the statistical probability that both independently dated archives reacted simultaneously within certain time windows, taking into account their chronological uncertainties (Blaauw et al., 2007).

The probability that an event took place in a proxy archive during a certain period depends on i) the archive's chronological uncertainty (Fig. 1), ii) the strength of the proxy evidence for an event (i.e. signal strength) (Fig. 2), and iii) the duration of the period or window width (indicated by colours in Fig. 3). Here for the first time we assess all of these uncertainty sources together by calculating the event probability within a time window for the individual archives. The LOI and planktonic diatom proxies of LE were normalized to 100 and re-sampled assuming normal errors (1% for LOI, 2% for diatoms), after which a running median was calculated (smoothing 25 for LOI, 11 for lower resolution diatom data). All depths d where the running median increased beyond the error threshold were flagged. This process was repeated 1000 times, after which for all depths of the individual proxies, the ratios of flagged iterations were plotted (Fig. 2a–b). The means of the ratios of both proxies estimate the probabilities of enhanced lake productivity (Fig. 2c). Depths with probabilities <5% were neglected. For all age-model iterations of LE or NGRIP, we find those depths d, with event probabilities $p(e_d)$, that fall within a time-window with boundaries $y_{\max}$ and $y_{\min}$. The probability that an event took place in an archive during this time-window is equal to $1-\Pi(1-p(e_d))$.

Significant LE event probabilities (95%) are only reached by employing time windows of 400 years or wider. The choice of ^{14}C comparison curve has a considerable effect on the timing of events A-D in particular, owing to disagreements between Hughen06 and Fairbanks05 around 37–34 cal ka BP (SI Fig. 1: http://www.clim-past-discuss.net/4/1203/2008/cpd-4-1203-2008-supplement.pdf). This disagreement is partly caused by Fairbanks05 having fewer evenly spaced data points for this time interval, and thus more kinks than Hughen06. Overlapping, closely spaced GI events (Fig. 3c) can hardly be distinguished from each other on an absolute time scale. Although the relative timing between GI events is well known (see below), NGRIP chronological uncertainties (Andersen et al., 2006) prevent us from assigning an individual GI event to any particular decade or even century (>95% event probabilities using time windows of 1550 yr or wider).

To test for synchronous events between LE and NGRIP within a time-window, we can simply calculate the product of the event probabilities from the individual archives (Fig. 3d, e). High probabilities indicate that an event of increased lake organic productivity in Les Echets likely occurred simultaneously with a GI event, whereas low probabilities indicate the absence of a simultaneous reaction and/or a lack of information (e.g. hiatus, large chronological uncertainties). Probabilities of synchronous events between LE and NGRIP never reach 100% at centennial resolutions. For example, only within >1000 year time windows does it seem likely (95%) that event LE-G co-occurred with one of the closely spaced GI events 4 or 3 in NGRIP. The other events show significant synchroneity using time windows of 1250 years or wider. In all cases, synchronous reactions at decadal to multi-centennial year resolution are very unlikely, since probabilities never exceed 10% (red shades in Fig. 3d, e).

Since the NGRIP time scale is based on annual layer counting, its dating error is cumulative and relative dating uncertainties will thus be much smaller than the absolute age uncertainties (Andersen et al., 2006). Therefore, the timings between GI events 8 to 3 are much more tightly constrained than those between the IRSL/^{14}C dated events LE-A to LE-G. Given the large absolute chronological uncertainties on the timing of individual events (Fig. 3), we investigate the patterns of timing between events (Fig. 4). With a common climate mechanism forcing both the NGRIP and LE events, a shared "fingerprint" of the timing between events should be expected (but see Wunsch, 2006). Whereas the timing between LE events F and G is comparable to that between GI events 4 and 3, the relative timing of the other events differs by many centuries. Moreover, there appear to be more LE than GI events in the studied period.

We could postulate several reasons for the offsets between the timing of events, e.g. large systematic changes in marine reservoir age for the Hughen06 and Fairbanks05 curves, unrecognised hiatuses, low resolution, erosion and/or reworking of older layers in the LE record, or hundreds of false years in the NGRIP time scale. However, the most parsimonious explanation is that the timings between events were asynchronous between both archives.

5 Conclusions

The abrupt temperature fluctuations reconstructed from Greenland ice cores (Dansgaard et al., 1993) must have been forced by major climatic events, arguably also with effects on larger spatial scales (Wunsch, 2006). However, most of the reported synchronous climate events outside Greenland were tuned to GI-events (Bond et al., 1997; Sánchez-Goni et al., 2002; Rohling et al., 2003; Roucoux et al., 2005) and thus cannot be used to infer synchroneity. Even with the best available age-models (67 radiocarbon and IRSL dates for Les Echets, multi-proxy annual layer counting for Greenland; Andersen et al., 2006), chronological uncertainties are currently too high to resolve whether last glacial D/O climate events were simultaneous between Greenland and western Europe. These problems are even more serious with proxy archives dated and analysed at lower resolution. Although one would wish to resolve the spatio-temporal nature of past glacial climate events at annual or, at most, decadal scales, currently we are limited to comparisons at multi-centennial to millennial resolution only. However, this problem could be reduced significantly if common time markers such as well-defined tephra layers were to be found.

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References

Allen, J. R. M., Brandt, U., Brauer, A., Hubberten, H.-W., Huntley, B., Keller, J., Kram, M., Mackensen, A., Mingram, J., Negendank, J. F. W., Nowaczyk, N. R., Oberhänsli, H., Watts, W. A., Wulf, S., and Zolitschka, B.: Rapid environmental changes in southern Europe during the last glacial period, Nature, 400, 740–743, 1999. 1204, 1205

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., and Clausen, H. B.: The Greenland ice core chronology 2005, 15–42 ka. Part 1: constructing the time scale, Quat. Sci. Rev., 25, 3246–3257, 2006. 1204, 1205, 1209, 1210, 1215, 1216, 1217

Blaauw, M. and Christen, J. A.: Radiocarbon peat chronologies and environmental change, Appl. Statist., 54, 805–816, 2005. 1207

Blaauw, M., Christen, J. A., Mauquoy, D., van der Plicht, J., and Bennett, K. D.: Testing the timing of radiocarbon-dated events between proxy archives, The Holocene, 17, 283–288, 2007. 1205, 1208, 1214, 1216

Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., and Bonani, G.: Correlations between climate records from North Atlantic sediments and Greenland ice, Nature, 365, 143–147, 1997. 1204, 1205, 1210

Burns, S. J., Fleitmann, D., Matter, A., and Al-Subbary, A. A.: Indian Ocean climate and an absolute chronology over Dansgaard/Oeschger events 9 to 13, Science, 301, 1365–1367, 2003. 1204, 1205

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gundestrup, N. S., Hammer, C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjornsdottir, A. E., Jouzel, J., and Bond, G.: Evidence for general instability of past climate from a 250-kyr ice-core record, Nature, 364, 218–220, 1993. 1204, 1210

Danzeglocke, U., Jöris, O., and Weninger, B.: CalPal-2007$^{\text{online}}$, http://www.calpal-online.de/, last access 17 October 2008. 1206

EPICA Community Members: One-to-one coupling of glacial climate variability in Greenland and Antarctica, Nature, 444, 195–198, 2006. 1204

Fairbanks, R. G., Mortlock, R. A., Chiu, T. C., Cao, T., Kaplan, A., Guilderson, T. P., Fairbanks, T. W., Bloom, A. L., Grootes, P. M., and Nadeau, M. J.: Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired ^{230}Th/^{234}U/^{238}U and ^{14}C dates on pristine corals, Quat. Sci. Rev., 24, 1781–1796, 2005. 1206

Hughen, K., Lehman, S., Southon, J., Overpeck, J., Marshal, O., Herring, C., and Turnbull, J.: ^{14}C activity and global carbon cycle changes over the past 50,000 years, Science, 303, 202–207, 2004. 1204, 1205

Hughen, K., Southon, J., Lehman, S., Betrand, C., and Turnbull, J.: Marine-derived 14C calibration and activity record for the past 50,000 years updated from the Cariaco Basin, Quat. Sci. Rev., 25, 3216–3227, 2006. 1206

Knutti, R., Flückiger, J., Stocker, T. F., and Timmermann, A.: Strong hemispheric coupling of glacial climate through freshwater discharge and ocean circulation, Nature, 430, 851–856, 2004. 1204

Muscheler, R., Kromer, B., Björck, S., Svensson, A., Friedrich, M., Kaiser, K. F., and Southon, J.: Tree rings and ice cores reveal 14C calibration uncertainties during the Younger Dryas, Nature Geosci., 1, 263–267, 2008. 1205, 1207

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J. H., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, G., Manning, S., Bronk Ramsey, C., Remmele, R. W. R. S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J., and Weyhenmeyer, C. E.: INTCAL04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP, Radiocarbon, 46, 1029–1058, 2004. 1205, 1206

Rohling, E. J., Mayewski, P. A., and Challenor, P.: On the timing and mechanism of millennial-scale climate variability during the last glacial cycle, Clim. Dynam., 20, 257–267, 2003. 1204, 1205, 1210

Roucoux, K. H., de Abreu, L., Shackleton, N. J., and Tzedakis, P. C.: The response of NW Iberian vegetation to North Atlantic climate oscillations during the last 65 kyr, Quat. Sci. Rev., 24, 1637–1653, 2005. 1204, 1205, 1210

Sánchez-Goni, M. F., Cacho, I., Turon, J. L., Guiot, J., Sierro, F. J., Peypougoet, J. P., Grimalt, J. O., and Shackleton, N. J.: Synchroneity between marine and terrestrial responses to millennial scale climatic variability during the last glacial period in the Mediterranean region, Clim. Dynam., 19, 95–105, 2002. 1204, 1205, 1210

Turney, C. S. M., Kershaw, A. P., Clemens, S. C., Branch, N., Moss, P. T., and Fifield, L. K.: Millennial and orbital variations of El Niño/Southern Oscillation and high-latitude climate in the last glacial period, Nature, 428, 306–310, 2004. 1204

Tzedakis, P. C., Frogley, M. R., Lawson, I. T., Preece, R. C., Cacho, R. C., and de Abreu, L.: Ecological thresholds and patterns of millennial-scale climate variability: The response of vegetation in Greece during the last glacial period, Geology, 32, 109–112, 2004. 1204, 1205

van der Plicht, J., Beck, J. W., Bard, E., Baillie, M. G. L., Blackwell, P. G., Buck, C. E., Friedrich, M., Guilderson, T. P., Hughen, K. A., Kromer, B., McCormac, G., Ramsey, C. B., Reimer, P. J., Reimer, R. W., Remmele, S., Richards, D. A., Southon, J. R., Stuiver, M., and Weyhenmeyer, C. E.: NotCal04 – comparison/calibration 14C records 26–50 cal kyr BP, Radiocarbon, 46, 1–14, 2004. 1205, 1206

Vautravers, M. J. and Shackleton, N. J.: Centennial-scale surface hydrology off Portugal during marine isotope stage 3: Insights from planktonic foraminiferal fauna variability, Paleoceanography, 21, PA3004, doi:10.1029/2000PA000517, 2006. 1204, 1205

Voelker, A. H. L., and Workshop Participants: Global distribution of centennial-scale records for Marine Isotope Stage (MIS) 3: a data base, Quat. Sci. Rev., 21, 1185–1212, 2002. 1204

Wang, Y., Cheng, H., Edwards, R. L., An, Z., Wu, J., Shen, C. C., and Dorale, J. A.: A high-resolution absolute-dated monsoon record from Hulu Cave, China, Science, 294, 2345–2348, 2001. 1204, 1205, 1206

Wohlfarth, B., Veres, D., Ampel, L., Lacourse, T., Blaauw, M., Preusser, F., Andrieu-Ponel, V., Kéravis, D., Lallier-Vergés, E., Björck, S., Davies, S. M., de Beaulieu, J.-L., Risberg, J., Hormes, A., Kasper, H. U., Possnert, G., Reille, M., Thouveny, N., and Zander, A.: Rapid ecosystem response to abrupt climate changes during the last glacial period in western Europe, 40–16 ka, Geology, 36, 407–410, 2008. 1204, 1205, 1206, 1207, 1208

Wunsch, C.: Abrupt climate change: An alternative view, Quat. Res., 65, 191–203, 2006. 1205, 1209, 1210

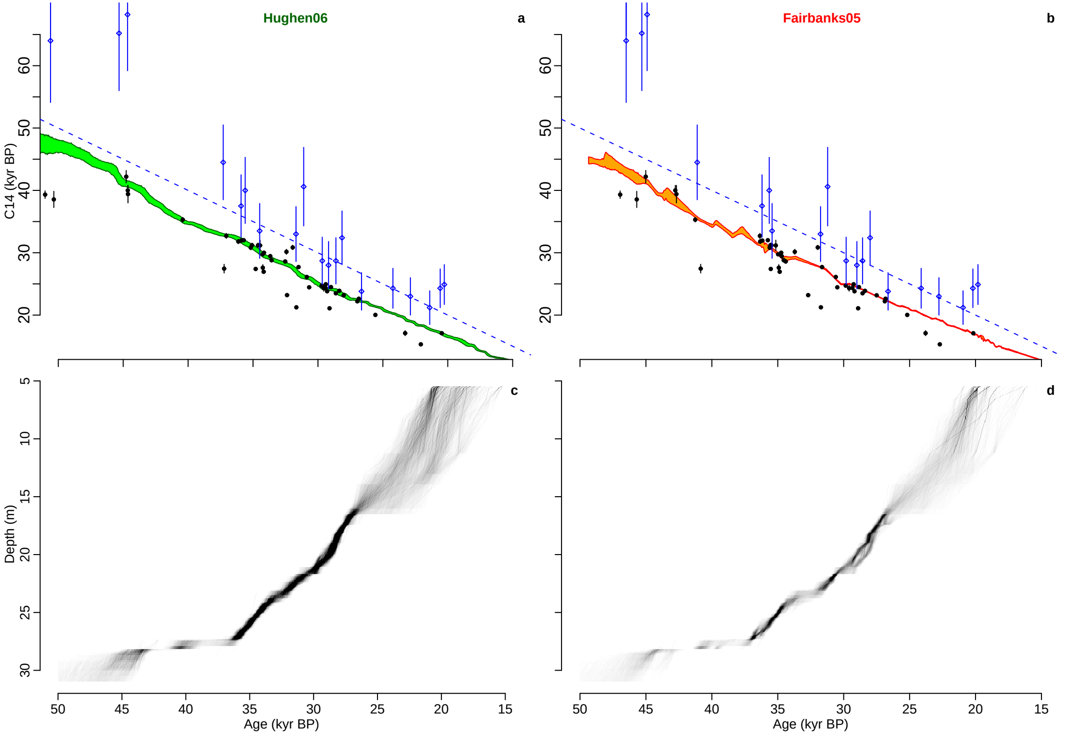

Fig. 1. Bayesian age-depth models using two alternative radiocarbon comparison curves. The radiocarbon (black circles) dates of Les Echets were matched against the Hughen06 (green, **a, c**) and Fairbanks05 (red, **b, d**) comparison curves. Blue dashed curve is 1:1 line to which the IRSL dates (blue open diamonds) were matched. The age distributions are graphed as grey-scales (Blaauw et al., 2007) (c–d). Dark areas indicate secure sections of the age-models, while lighter grey areas warn us of sections of a core where the chronological uncertainty is large.

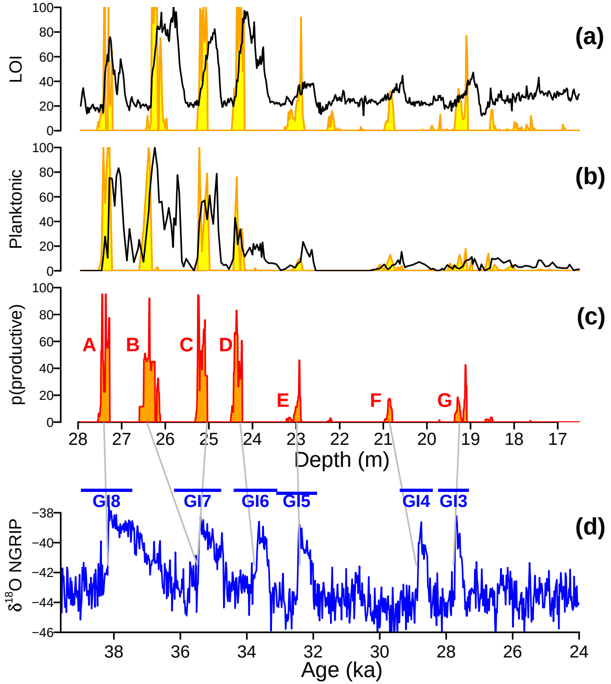

Fig. 2. Les Echets proxies plotted against depth (black lines) and compared with the NGRIP δ^{18}O record [2]. Probabilities of enhanced lake productivity in Les Echets were calculated, through finding those depths with major increases in LOI **(a)** or planktonic diatoms **(b)** (see text). Clear increases of the individual proxies are plotted as yellow histograms. The means of these proxy increases estimate the probabilities of enhanced lake productivity (orange histograms in c). The events A–G of enhanced lake productivity could be tuned (grey connecting lines show possible links) to abrupt δ^{18}O rises in NGRIP (Andersen et al., 2006), Greenland Isotope (GI) events 8 to 3 **(d)**. Blue horizontal lines indicate 1 sd dating confidence intervals of the GI events.

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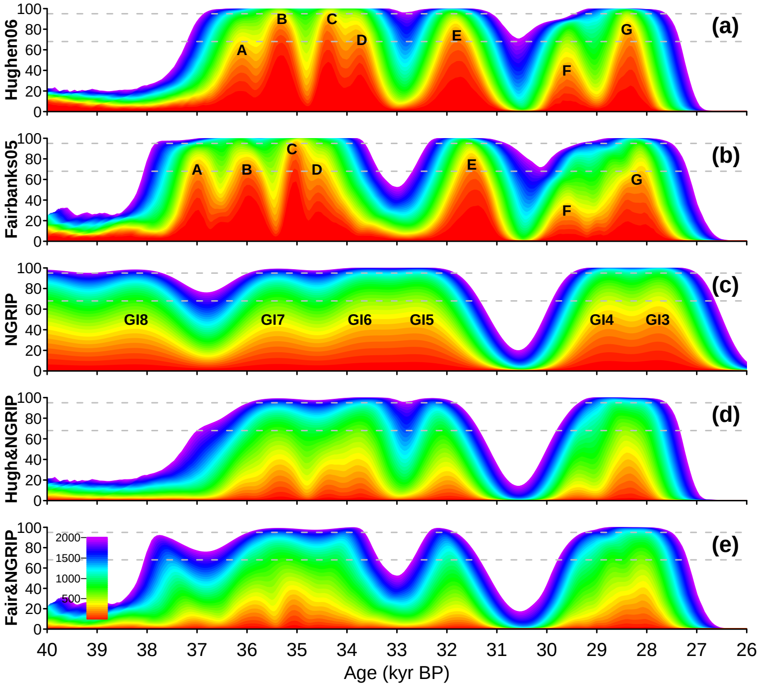

Fig. 3. Events of enhanced lake productivity in Les Echets from age-depth models using either Hughen06 **(a, d)** or Fairbanks05 **(b, e)**, compared with GI-events in NGRIP (c–e). Probabilities of events of enhanced lake productivity (Les Echets) or temperature rises in Greenland (GI events from Andersen et al., 2006) were calculated using a time-window approach modified from Blaauw et al. (2007) (see text). Time windows moved at 50 year jumps. Window sizes were 50 to 2000 years in steps of 50 years, shown as rainbow colours in the probability histograms. The probabilities of simultaneous events between Les Echets and NGRIP within time-windows are shown in (d, e).

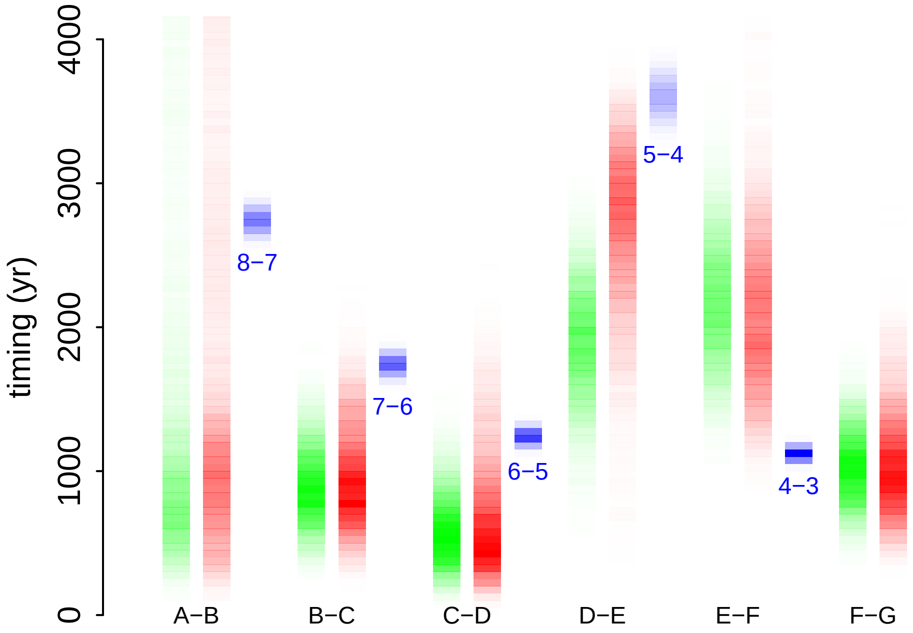

Fig. 4. Timing in calendar years between neighbouring events of the Les Echets and NGRIP records. Colour shading shows the timing between Les Echets A to G using Hughen05 (green) or Fairbanks05 (red), and NGRIP GI events 8 to 3 (blue). Darker colours indicate more likely timing. Uncertainties of NGRIP timing are based on the accumulated counting error between neighbouring events (Andersen et al., 2006).