Composition and consequences of the IntCal20 radiocarbon calibration curve

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Abstract

Radiocarbon calibration is necessary to correct for variations in atmospheric radiocarbon over time. The IntCal working group has developed an updated and extended radiocarbon calibration curve, IntCal20, for Northern Hemisphere terrestrial samples from 0 to 55,000 cal yr BP. This paper summarizes the new datasets, changes to existing datasets, and the statistical method used for constructing the new curve. Examples of the effect of the new calibration curve compared to IntCal13 for hypothetical radiocarbon ages are given. For the recent Holocene the effect is minimal, but for older radiocarbon ages the shift in calibrated ages can be up to several hundred years with the potential for multiple calibrated age ranges in periods with higher-resolution data. In addition, the IntCal20 curve is used to recalibrate the radiocarbon ages for the glaciation of the Puget Lowland and to recalculate the advance rate. The ice may have reached its maximum position a few hundred years earlier using the new calibration curve; the calculated advance rate is virtually unchanged from the prior estimate.

Keywords: Radiocarbon; calibration; IntCal20

INTRODUCTION

Radiocarbon ages require a correction to account for changes in atmospheric concentration of ^{14}C over time. Without this correction, or calibration, radiocarbon ages cannot be directly compared to historical dates or ages measured by other methods nor can rates of change be calculated. Radiocarbon calibrations have been done through the use of a curve based on compilations of ^{14}C measurements of known-age material, such as dendrochronologically dated tree rings, since the 1960s (e.g., Stuiver and Suess, 1966; Clark, 1975). To prevent confusion from the use of the various calibration curves available, an international working group was established to provide a consensus curve (Klein et al., 1982). Since that time, updated calibration curves have been ratified by the radiocarbon community. Separate curves for the Northern and Southern Hemisphere terrestrial samples and for marine samples are now available. Numerous researchers have contributed to the calibration effort by providing high-precision ^{14}C measurements from tree rings and other archives.

From 2004, the IntCal Working Group has updated, extended, and refined radiocarbon calibrations semi-regularly. As more independently dated archives have been radiocarbon dated and our understanding of the Earth's systems has increased, calibration curves have been extended and refined. The most recent calibration curves for the Northern and Southern Hemispheres and the ocean surface have recently been published (Heaton et al., 2020a; Hogg et al., 2020; Reimer et al., 2020) for 0 to 55,000 cal yr BP. The methods and datasets used for the IntCal20 curve are summarized in this paper. Calibrations of some hypothetical radiocarbon ages with both IntCal13 (Reimer et al., 2013a) and IntCal20 are used to highlight some of the similarities and differences between the two curves. An example of the effect of the new calibration curve on previously published radiocarbon ages for the timing and rate of advance of the Cordilleran ice sheet in the Pacific Northwest, USA (Porter and Swanson, 1998), is given.

NEW STATISTICAL TOOLS

The construction of the IntCal20 calibration curve was underpinned by a new statistical model. Heaton et al. (2020b) adapted Bayesian splines to provide a flexible method for curve construction suited to the complexities of the different types of data and error structures. The Bayesian method also allowed for prior knowledge to inform the construction. For

instance, reported laboratory errors do not usually include all sources of uncertainty, as evidenced by the Sixth International Radiocarbon Intercomparison exercise (SIRI; Scott et al., 2017). For tree rings, growing season and, potentially, species differences may contribute additional uncertainty (e.g., Kromer et al., 2001; Dee et al., 2010). The Bayesian model used prior information for additional radiocarbon uncertainty based on tree ring data from the SIRI exercise, although the resulting curve uncertainty was dominated by the high-quality IntCal data. In addition, wiggle-matching of floating tree ring series (i.e., not dendrochronologically linked to an absolutely dated chronology) was done internal to the model within estimated uncertainty. The Bayesian spline also allows for rapid changes in ^{14}C to be captured in the curve. Complete details of the Bayesian spline implementation are given in Heaton and colleagues (2020b).

CALIBRATION DATASETS

Dendrochronologically dated tree ring archives are still preferred for radiocarbon calibration for terrestrial samples because they are direct recorders of atmospheric ^{14}C and there is little or no uncertainty in the calendar age. The number of calibration-quality radiocarbon measurements on known-age tree rings, many of them single year, has proliferated especially since the discovery of rapid increases in atmospheric ^{14}C at AD 774–775 and AD 993 (Miyake et al., 2012, 2013). Other time periods have been targeted for single-ring measurements to search for additional ^{14}C events (e.g., Miyake et al., 2017a, 2017b; Jull et al., 2018) and to improve calibration around a radiocarbon plateau ca. 2700–2400 cal yr BP (Park et al., 2017; Fahrni et al., 2020), as well as to attempt to pinpoint the timing of the Minoan eruption of Santorini (Thera) (Pearson et al., 2018, 2020; Friedrich et al., 2020; Kuitems et al., 2020). The oldest dendrochronologically dated tree ring chronology in the Northern Hemisphere is the central European Preboreal Pine Chronology (PPC; Friedrich et al., 2004), which has been extended to 12,235 cal yr BP (Reinig et al., 2020). Older tree rings used in calibration remain floating. Multi-laboratory ^{14}C measurements of the late glacial New Zealand kauri floating chronology (Hogg et al., 2016) pointed to an error in the link between the absolutely dated Central European PPC and the floating Swiss Late Glacial Master Chronology (Kaiser et al., 2012) used in IntCal13. Investigating the previous tree ring links resulted in an improved match with the Swiss floating chronology shifting it 35 ± 8 years older. This was supported by the overlap with new ^{14}C measurements from a floating chronology from the southern French Alps (Capano et al., 2018, 2020). A major discovery at a construction site in Zurich of hundreds of pine trees buried in situ has provided ample material for chronological replication and increased resolution ca. 13,160–11,950 cal yr BP (Reinig et al., 2020; Sookdeo et al., 2020).

Three floating tree ring series from northern Italy, which had previously been fitted to Greenland ice core ^{10}Be to ca. 14,700 to 14,000 cal yr BP (Adolphi et al., 2017), were incorporated by ^{14}C matching to the other IntCal data. These measurements add structure to the otherwise rather smooth calibration curve in this time period. A 2000-year-long floating tree ring series from New Zealand (Turney et al., 2016) was also incorporated using an interhemispheric offset of 43 ± 23 ^{14}C yr (Hogg et al., 2013). This series adds structure to the curve during Heinrich Stadial 3. Another glacial New Zealand series with 1300 rings (Turney et al., 2010) was also ^{14}C matched into the curve.

The most influential dataset in the IntCal20 curve older than ca. 14,000 cal yr BP is undoubtedly the U-Th dated Hulu cave ^{14}C record from China (Cheng et al., 2018) which extends to 53,900 cal yr BP. The correction for old carbon (dead carbon fraction) in the ^{14}C ages, estimated from the overlap with tree ring data, can be assumed to be relatively constant within uncertainty because the speleothem formed in a portion of the cave where the limestone had largely been replaced by iron oxides. In addition, a short residence time for the soil carbon above the cave is presumed due to the observation of seasonal δ^{18}O values and lack of high ^{14}C levels from nuclear weapons testing observed in the dripwaters (Cheng et al., 2018). The δ^{18}O fluctuations recorded in the speleothem (Wang et al., 2001; Cheng et al., 2016) also serve as tie-points for marine foraminifera records from the Iberian margin, Pakistan margin, and Cariaco basin (Bard et al., 2013; Heaton et al., 2013; Hughen and Heaton, 2020). In addition, the Lake Suigetsu varved sediment record, which contains terrestrial macrofossils, has been revised and extended (Schlolaut et al., 2018), and the calendar age has been modelled with the Hulu cave timescale (Bronk Ramsey et al., 2020). Also included in IntCal20 were two speleothem records from an underwater cave on Grand Bahamas (Beck et al., 2001; Hoffmann et al., 2010). The Bahamas speleothem records, despite having large uncertainty on the dead carbon fractions, serve as a check on the Hulu cave data. By incorporating a range of datasets we can assess which features are likely to represent atmospheric signals and which are local features or noise.

Marine ^{14}C measurements of coral and foraminifera from marine sediments have been included with a correction for the marine reservoir age (MRA) of the ocean region where they grew. In the past the MRA was assumed to be constant in time, but there is an abundance of evidence to suggest this is not a valid assumption, especially for the last glacial period. For IntCal20 we used MRAs calculated with the Hamburg Large Scale Geostrophic Ocean General Circulation Model (LSG OGCM) with atmospheric input provided by a curve constructed with a Bayesian spline of the Hulu data (Butzin et al., 2020). The calculated MRAs were only used as prior information to correct the marine ^{14}C ages in the Bayesian spline, which was then adjusted to best fit the data within uncertainty. The LSG OGCM–modelled MRA for the Cariaco basin did not agree with the data, possibly due to the coarse resolution of the model compared to the size of the basin, so a slowly varying spline was used instead (Heaton et al., 2020b; Hughen and Heaton, 2020).
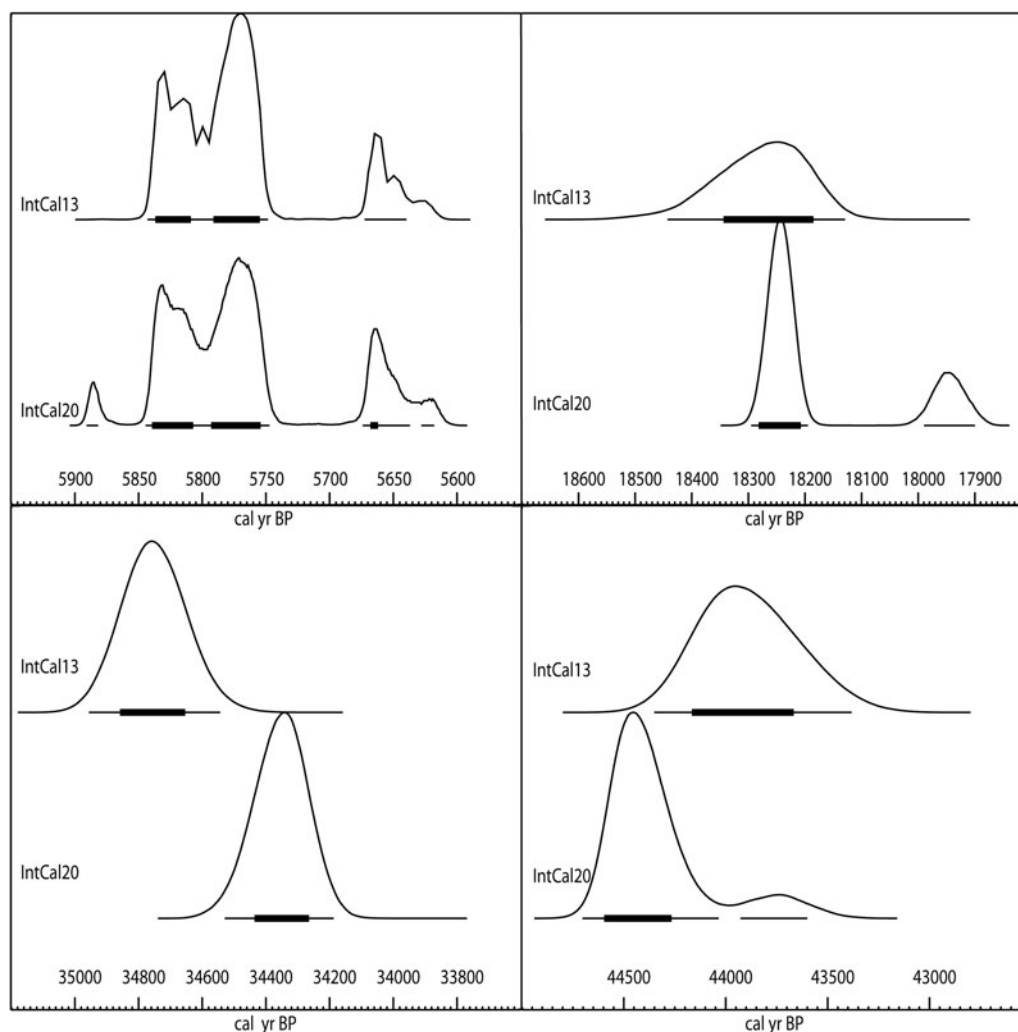
Figure 1. Calibrated probability distributions are shown for hypothetical radiocarbon ages of 5000 ± 20 ^{14}C yr BP, $15,000 \pm 30$ ^{14}C yr BP, $30,000 \pm 50$ ^{14}C yr BP, and $40,000 \pm 200$ ^{14}C yr BP. 1 sigma age ranges are shown as thick lines and 2 sigma as thin lines at the base of each distribution. Calibrations were done using IntCal13 and CALIB 7.04 and using IntCal20 with CALIB 8.1 (Stuiver and Reimer, 1993).

Data from aragonitic coral that grew close to the surface of the ocean were included in previous IntCal curves if the corals met previously established criteria (Reimer et al., 2013b). However, some of the coral ^{14}C data older than 25,000 cal yr BP is highly variable regardless of meeting the criteria. It is likely there has been some undetected diagenesis due to exposure to freshwater during the Last Glacial Maximum lowstand ($21,000 \pm 2000$ cal yr BP). Therefore, no corals older than 25,000 cal yr BP were used in IntCal20.

RESULTS AND DISCUSSION

The effect of the IntCal20 calibration curve compared to IntCal13 (Reimer et al., 2013a) is shown for hypothetical radiocarbon ages of 5000 ± 20 ^{14}C yr BP, $15,000 \pm 30$ ^{14}C yr BP, $30,000 \pm 50$ ^{14}C yr BP, and $40,000 \pm 200$ ^{14}C yr BP (Figure 1). For 5000 ^{14}C yr BP there is hardly any noticeable difference between the probability distributions calculated using IntCal13 and IntCal20. However, at 15,000 ^{14}C yr

BP the distribution for IntCal20 has an additional younger peak compared to that for IntCal13. For 30,000 ^{14}C yr BP the distribution calculated with IntCal20 is about 400 years younger than with IntCal13, whereas for 40,000 ^{14}C yr BP the IntCal20 distribution is bimodal but the main peak is about 500 years older than with IntCal13.

A good example of the consistency of the overall shape of radiocarbon calibration curves over the past three decades, is the case of the advance rate of the Puget Lobe of the Cordilleran ice sheet in Washington State during the last glaciation and the timing of the arrival of the ice in the Issaquah delta calibrated with IntCal93 (Stuiver and Reimer, 1993) and with the new IntCal20 curve. Porter and Swanson (1998) presented seven radiocarbon dates on outer wood and branches of pine taken from the top of a pro-glacial delta near Issaquah, Washington (Figure 2). The weighted mean of these radiocarbon dates was $14,546 \pm 55$ ^{14}C yr BP, and the mean intercept with the IntCal93 calibration curve was given as $17,420 \pm 90$ cal yr BP. Although it is no longer recommended to use the
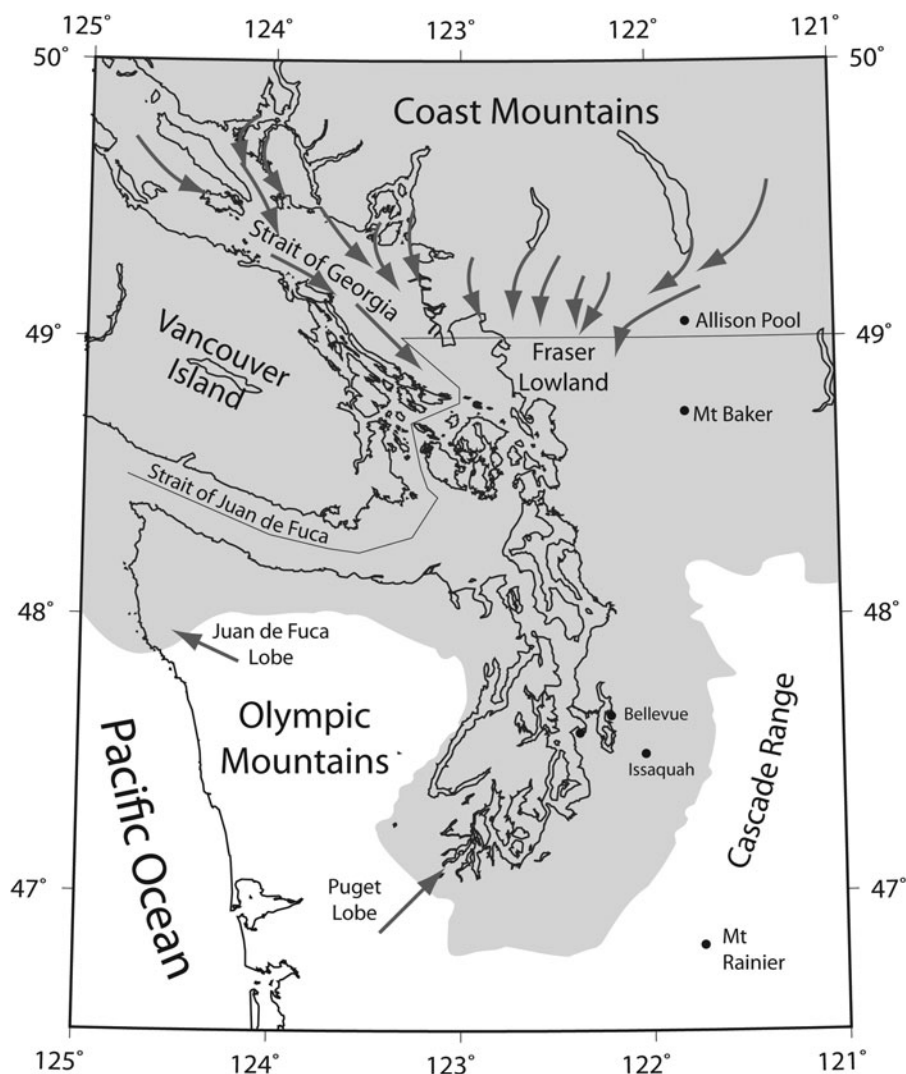
Figure 2. Map showing the extent of the Puget Lobe of the Cordilleran ice sheet in Washington State during the last glaciation (shaded region) adapted from Porter and Swanson ([1998](#)). Dark grey arrows indicate inferred flow direction.

mean intercept (Telford et al., [2004](#)), the calibrated age range from IntCal20 is only slightly older than this at 17,455–18,005 cal yr BP (at 2σ, rounding out to 5 years). The glacier advance rate was calculated from two radiocarbon dates on spruce wood from Allison Pool, southern British Columbia (ca. 200 km from Issaquah) which had a mean radiocarbon age of 16,059 ± 71 ^{14}C yr BP (Clague et al., [1988](#)) with a reported IntCal93 calibrated age of 18,925 cal yr BP. The difference in mean calibrated ages between Allison Pool and Issaquah delta gave an advance rate of 135 m/yr. With IntCal20 the mean of the Allison Pool radiocarbon dates calibrates to 19,175–19,550 cal yr BP (at 2 σ, rounding out to 5 years). Calculating the difference in the calibrated probability distributions using OxCal (Bronk Ramsey, [2009](#); [2017](#)) gives 1939–1355 years at 95% probability resulting in an advance rate of 103–148 m/yr. The estimated advance rate from Porter and Swanson ([1998](#)) of 135 m/yr falls well within that range.

CONCLUSIONS

For much of the Holocene, the IntCal20 curve will not have a large effect on the calibration of radiocarbon ages from single samples with the exception of potentially intercepting younger radiocarbon ages with the sharp radiocarbon declines resulting from the ^{14}C events at AD 774–775 and AD 993. For older periods, calibrated age ranges may shift by several hundred years in either direction compared to IntCal13, and there may be additional calibrated age ranges where the curve comprises higher-resolution data. Despite increased detail in calibration curves over time, the overall shape of the IntCal20 curve back to a least 25,000 cal yr BP does not differ greatly from much older curves as seen by the relatively small change for the advance rate of the Cordilleran ice sheet into the Puget Lowland of Washington State as calibrated with IntCal93.

IntCal20 now extends to 55,000 cal yr BP so that it is now possible to calibrate radiocarbon ages including two standard deviations up to ca. 50,000 ^{14}C yr BP. The entire IntCal20

curve is available to download, and access to the database can be found at http://intcal.org. The calibration programs CALIB (http://calib.org) and OxCal (https://c14.arch.ox.ac.uk/) have been updated to use the IntCal20 curve. It should be noted that IntCal20 is intended for the calibration of Northern Hemisphere atmospheric samples. SHCal20 should be used for the calibration of Southern Hemisphere atmospheric samples (Hogg et al., 2020), and Marine20 (with application of a local reservoir adjustment) should be used for the calibration of marine samples (Heaton et al., 2020a).

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REFERENCES

Adolphi, F., Muscheler, R., Friedrich, M., Güttler, D., Wacker, L., Talamo, S., Kromer, B., 2017. Radiocarbon calibration uncertainties during the last deglaciation: Insights from new floating tree-ring chronologies. *Quaternary Science Reviews* 170, 98–108.

Bard, E., Ménot, G., Rostek, F., Licari, L., Böning, P., Edwards, R.L., Cheng, H., Wang, Y., Heaton, T.J., 2013. Radiocarbon calibration/comparison records based on marine sediments from the Pakistan and Iberian margins. *Radiocarbon* 55, 1999–2019.

Beck, J.W., Richards, D.A., Edwards, R.L., Silverman, B.W., Smart, P.L., Donahue, D.J., Hererra-Osterheld, S., *et al.*, 2001. Extremely Large Variations of Atmospheric ^{14}C Concentration During the Last Glacial Period. *Science* 292, 2453–2458.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51, 337–360.

Bronk Ramsey, C., 2017. OxCal Program, Version 4.3, Oxford Radiocarbon Accelerator Unit: University of Oxford.

Bronk Ramsey, C., Heaton, T.J., Schlolaut, G., Staff, R.A., Bryant, C.L., Brauer, A., Lamb, H.F., Marshall, M.H., Nakagawa, T., 2020. Reanalysis of the atmospheric radiocarbon calibration record from Lake Suigetsu. *Radiocarbon* 62, in press.

Butzin M., Heaton, T.J., Köhler, P., Lohmann, G., 2020. A short note on marine reservoir age simulations used in IntCal20. *Radiocarbon* 62, in press.

Capano, M., Miramont, C., Guibal, F., Kromer, B., Tuna, T., Fagault, Y., Bard, E., 2018. Wood 14C Dating with AixMICADAS: Methods and Application to Tree ring Sequences from the Younger Dryas Event in the Southern French Alps. *Radiocarbon* 60, 51–74.

Capano, M., Miramont, C., Shindo, L., Guibal, F., Marschal, C., Kromer, B., Tuna, T., Bard, E., 2020. Onset of the Younger Dryas recorded with 14C at annual resolution in French subfossil trees. *Radiocarbon* 62, in press.

Cheng, H., Edwards, R.L., Sinha, A., Spötl, C., Yi, L., Chen, S., Kelly, M., Kathayat, G., Wang, X., Li, X., 2016. The Asian monsoon over the past 640,000 years and ice age terminations. *Nature* 534, 640.

Cheng, H., Edwards, R.L., Southon, J., Matsumoto, K., Feinberg, J.M., Sinha, A., Zhou, W., Li, H., Li, X., Xu, Y., 2018.

Atmospheric 14C/12C changes during the last glacial period from Hulu Cave. *Science* 362, 1293–1297.

Clague, J.J., Saunders, I.R., Roberts, M.C., 1988. Ice-free conditions in southwestern British Columbia at 16000 years BP. *Canadian Journal of Earth Sciences* 25, 938–941.

Clark, R.M., 1975. A calibration curve for radiocarbon dates. *Antiquity* 49, 251–266.

Dee, M.W., Brock, F., Harris, S.A., Ramsey, C.B., Shortland, A.J., Higham, T.F.G., Rowland, J.M., 2010, Investigating the likelihood of a reservoir offset in the radiocarbon record for ancient Egypt. *Journal of Archaeological Science* 37, 687–693.

Fahrni, S.M., Southon, J., Fuller, B.T., Park, J., Friedrich, M., Muscheler, R., Wacker, L., Taylor, R.E., 2020. Single-year German oak and Californian bristlecone pine 14C data at the beginning of the Hallstatt plateau from 856 BC to 626 BC. *Radiocarbon* 62, in press.

Friedrich, M., Remmele, S., Kromer, B., Hofmann, J., Spurk, M., Kaiser, K.F., Orcel, C., Küppers, M., 2004. The 12,460-year Hohenheim oak and pine tree ring chronology from central Europe—a unique annual record for radiocarbon calibration and paleoenvironment reconstructions: *Radiocarbon* 46, 1111–1122.

Friedrich, R., Kromer, B., Wacker, L., Olsen, J., Remmele, S., Lindauer, S., Land, A., Pearson, C., 2020. A new annual 14C dataset for calibrating the Thera eruption. *Radiocarbon* 62 in press.

Heaton, T.J., Bard, E., Hughen, K.A., 2013. Elastic tie-pointing—transferring chronologies between records via a Gaussian process. *Radiocarbon* 55, 1975–1997.

Heaton, T.J., Blaauw, M., Blackwell, P.G., Bronk Ramsey, C., Reimer, P., Scott, E.M., 2020b. The IntCal20 approach to radiocarbon calibration curve construction: A new methodology using Bayesian splines and errors-in-variables. *Radiocarbon* 62, in press.

Heaton, T.J., Köhler, P., Butzin, M., Bard, E., Reimer, R.W., Austin, W.E.N., Bronk Ramsey, C., *et al.*, 2020a. Marine20—the marine radiocarbon age calibration curve (0–55,000 cal BP). *Radiocarbon* 62, in press.

Hoffmann, D.L., Beck, J.W., Richards, D.A., Smart, P.L., Singarayer, J.S., Ketchmark, T., Hawkesworth, C.J., 2010. Towards radiocarbon calibration beyond 28 ka using speleothems from the Bahamas. *Earth and Planetary Science Letters* 289, 1–10.

Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton, T.J., *et al.*, 2013. SHCal13 Southern Hemisphere Calibration, 0–50,000 Years cal BP. *Radiocarbon* 55, 1889–1903.

Hogg, A., Heaton, T.J., Hua, Q., Bayliss, A., Blackwell, P.G., Boswijk, G., Ramsey, C.B., *et al.*, 2020. SHCAL20 Southern Hemisphere calibration, 0–50,000 years cal BP. *Radiocarbon* 62, in press.

Hogg, A., Southon, J., Turney, C., Palmer, J., Ramsey, C.B., Fenwick, P., Boswijk, G., Büntgen, U., Friedrich, M., Helle, G., 2016. Decadally resolved lateglacial radiocarbon evidence from New Zealand kauri. *Radiocarbon* 58, 709–733.

Hughen, K., Heaton, T.J., 2020. Updated Cariaco Basin 14C Calibration Dataset from 0–60k BP. *Radiocarbon* 62, in press.

Jull, A.T., Panyushkina, I., Miyake, F., Masuda, K., Nakamura, T., Mitsutani, T., Lange, T.E., Cruz, R.J., Baisan, C., Janovics, R., 2018. More Rapid ^{14}C Excursions in the Tree-Ring Record: A Record of Different Kind of Solar Activity at About 800 BC? *Radiocarbon* 60, 1237–1248.

Kaiser, K.F., Friedrich, M., Miramont, C., Kromer, B., Sgier, M., Schaub, M., Boeren, I., *et al.*, 2012. Challenging process to

make the Lateglacial tree-ring chronologies from Europe absolute—an inventory. *Quaternary Science Reviews* 36, 78–90.

Klein, J., Lerman, J.C., Damon, P.E., Ralph, E.K., 1982. Calibration of Radiocarbon Dates: Tables Based on the Consensus Data of the Workshop on Calibrating the Radiocarbon Time Scale: *Radiocarbon* 24, 103–150.

Kromer, B., Manning, S.W., Kuniholm, P.I., Newton, M.W., Spurk, M., Levin, I., 2001. Regional $^{14}CO_2$ Offsets in the Troposphere: Magnitude, Mechanisms, and Consequences. *Science* 294, 2529–2532.

Kuitems, M., Plicht, J.v.d., Jansma, E., 2020. Wood from the Netherlands around the time of the Santorini eruption dated by dendrochronology and Radiocarbon. *Radiocarbon* 62, in press.

Miyake, F., Jull, A.J.T., Panyushkina, I.P., Wacker, L., Salzer, M., Baisan, C.H., Lange, T., Cruz, R., Masuda, K., Nakamura, T., 2017a. Large 14C excursion in 5480 BC indicates an abnormal sun in the mid-Holocene. *Proceedings of the National Academy of Sciences* 114, 881–884.

Miyake, F., Masuda, K., Nakamura, T., 2013. Another rapid event in the carbon-14 content of tree rings. *Nature Communications* 4.

Miyake, F., Masuda, K., Nakamura, T., Kimura, K., Hakozaki, M., Jull, A.J.T., Lange, T.E., *et al*., 2017b. Search for Annual ^{14}C Excursions in the Past. *Radiocarbon* 59, 315–320.

Miyake, F., Nagaya, K., Masuda, K., Nakamura, T., 2012. A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan. *Nature* 486, 240–242.

Park, J., Southon, J., Fahrni, S., Creasman, P.P., Mewaldt, R., 2017. Relationship between solar activity and $\Delta^{14}C$ peaks in AD 775, AD 994, and 660 BC. *Radiocarbon* 59, 1147–1156.

Pearson, C.L., Brewer, P.W., Brown, D., Heaton, T.J., Hodgins, G.W., Jull, A.T., Lange, T., Salzer, M.W., 2018. Annual radiocarbon record indicates 16th century BCE date for the Thera eruption. *Science Advances* 4, eaar8241.

Pearson, C.L., Wacker, L., Bayliss, A., Brown, D.M., Salzer, M., Brewer, P.W., Bollhalder, S., Boswijk, G., Hodgins, G.W.L., 2020. Annual variation in atmospheric ^{14}C between 1700 BC and 1480 BC. *Radiocarbon* 62, doi:10.1017/RDC.2020.14.

Porter, S.C., Swanson, T.W., 1998. Radiocarbon Age Constraints on Rates of Advance and Retreat of the Puget Lobe of the Cordilleran Ice Sheet during the Last Glaciation. *Quaternary Research* 50, 205–213.

Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Ramsey, C.B., Butzin, M., *et al*., 2020. The IntCal20 Northern Hemisphere radiocarbon calibration curve (0–55 cal ka BP). *Radiocarbon* 62, in press.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Brown, D.M., Buck, C.E., Edwards, R.L., Friedrich, M., 2013b. Selection and treatment of data for radiocarbon calibration: an update to the International Calibration (IntCal) criteria. *Radiocarbon* 55, 1923–1945.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., *et al*., 2013a. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55, 1869–1887.

Reinig, F., Sookdeo, A., Esper, J., Friedrich, M., Guidobaldi, G., Helle, G., Kromer, B., *et al*., 2020. Illuminating IntCal during the Younger Dryas. *Radiocarbon* 62, in press.

Schlolaut, G., Staff, R.A., Brauer, A., Lamb, H.F., Marshall, M.H., Ramsey, C.B., Nakagawa, T., 2018. An extended and revised Lake Suigetsu varve chronology from ∼50 to ∼10 ka BP based on detailed sediment micro-facies analyses. *Quaternary Science Reviews* 200, 351–366.

Scott, E.M., Naysmith, P., Cook, G.T., 2017. Why do we need 14C inter-comparisons?: The Glasgow-14C inter-comparison series, a reflection over 30 years. *Quaternary Geochronology* 43, 72–82.

Sookdeo, A., Kromer, B., Buentgen, U., Friedrich, M., Friedrich, R., Helle, G., Pauly, M., *et al*. 2020. Quality Dating: A well-defined protocol implemented at ETH for high-precision ^{14}C dates tested on Late Glacial wood. *Radiocarbon* 62, in press.

Stuiver, M., Reimer, P.J., 1993. Extended C-14 Data-Base and Revised Calib 3.0 C-14 Age Calibration Program. *Radiocarbon* 35, 215–230.

Stuiver, M., Suess, H.E., 1966. On the relationship between radiocarbon dates and true sample ages. *Radiocarbon* 8, 534–540.

Telford, R.J., Heegaard, E., Birks, H.J.B., 2004, The intercept is a poor estimate of a calibrated radiocarbon age. *The Holocene* 14, 296–298.

Turney, C.S.M., Fifield, L.K., Hogg, A.G., Palmer, J.G., Hughen, K., Baillie, M.G.L., Galbraith, R., *et al*., 2010. The potential of New Zealand kauri (*Agathis australis*) for testing the synchronicity of abrupt climate change during the Last Glacial Interval (60,000–11,700 years ago). *Quaternary Science Reviews* 29, 3677–3682.

Turney, C.S.M., Palmer, J., Ramsey, C.B., Adolphi, F., Muscheler, R., Hughen, K.A., Staff, R.A., Jones, R.T., Thomas, Z.A., Fogwill, C.J., 2016. High-precision dating and correlation of ice, marine and terrestrial sequences spanning Heinrich Event 3: Testing mechanisms of interhemispheric change using New Zealand ancient kauri (*Agathis australis*). *Quaternary Science Reviews* 137, 126–134.

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.