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# Composition and consequences of the IntCal20 radiocarbon calibration curve~~: composition and consequences~~

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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 ~~because the assumption that~~ atmospheric concentration of $^{14}C$ ~~has been constant~~ over time~~, which is essential in the age calculation, is not valid~~. 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-ring~~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-ring~~tree ringtree 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 systems have increased, calibration curves have been extended and refined. The most recent calibration curves for the Northern and Southern Hemisphere and the ocean surface have recently been published (Reimer et al. 2020; Hogg et al. 2020; Heaton et al. 2020a) ~~extending~~ 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 don't usually include all sources of uncertainty as evidenced by the Sixth International Radiocarbon Intercomparison exercise (SIRI, Scott et al. 2017). For ~~tree-ring~~tree ringtree 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~~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~~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 et al. (2020b).

**Calibration datasets**

Dendrochronologically-dated ~~tree-ring~~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-ring~~tree rings, many of them single year, has proliferated especially since the discovery of rapid increases in atmospheric $^{14}$C at AD 774-5 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,b; Jull et al., 2018) and to improve calibration around a radiocarbon plateau ca. ~~400-800~~2700-2400 cal yr ~~BC~~ BP (Park et al., 2017; Fahrni et al., 2020) as well as attempting to pinpoint the timing of the Minoan eruption of Santorini (Thera) (Friedrich et al., 2020; Kuitems et al., 2020; Pearson et al., 2018; 2020). The oldest dendrochronologically dated ~~tree-ring~~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,~~049~~ 235 cal yr BP (~~Sookdeo~~ Reinig et al. 2020~~a~~). Older ~~tree-ring~~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~~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~~b~~).

Three floating ~~tree-ring~~tree ring series from northern Italy, that 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~~tree ring series from New Zealand (Turney et al. 2016) was also incorporated using an interhemispheric offset of 43 ± 23 $^{14}$C yr~~s~~ (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 ~~ka~~ BP ~~(0 BP = AD 1950)~~. The correction for old carbon (dead carbon fraction) in the $^{14}$C ages, estimated from the overlap with ~~tree-ring~~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 $\delta^{18}$O values and lack of high $^{14}$C levels from nuclear weapons testing observed in the dripwaters (Cheng et al. 2018). The $\delta^{18}$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 modeled 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 not applied directly to the marine $^{14}$C ages but~~ were only used as prior information to correct the marine $^{14}$C ages in the Bayesian spline which 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).

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 ~~ka~~ BP is highly variable regardless of meeting the criteria. It's likely there has been some undetected diagenesis due to exposure to freshwater during the Last Glacial Maximum lowstand (21,000 ±2000 cal ~~k~~BP). Therefore, no corals older than 25,000 cal ~~ka~~ 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 ± 30 $^{14}$C yr BP, 30,000 ± $^{14}$C yr 50 BP, and 40,000± 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 ~~IntCal20~~IntCal13.

A good~~s an~~ example of the consistency of the overall shape of radiocarbon calibration curves over the past ~~20 years~~three decades, ~~I consider~~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 7 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 ± 55 $^{14}$C yr BP and the mean intercept with the IntCal93 calibration curve was given as 17,420 ± 90 cal yr BP. Although it is no longer recommended to use the 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 to 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 et al. 2009; 2017) gives 1939-1355 ~~$^{14}$C~~ 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 774-75 ~~AD~~ and AD 993 ~~AD~~. For older periods, calibrated age ranges may shift by several hundred years either direction compared to IntCal13 and there may be additional ~~intercepts~~ calibrated age ranges where the curve is comprised of 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 BPdoes 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 ~~ka~~ 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) for the calibration of marine samples (Heaton et al. 2020a).

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Figure captions:

Figure 1. Calibrated probability distributions are shown for hypothetical radiocarbon ages of 5000 ± 20 $^{14}C$ yr BP, 15,000 ± 30 $^{14}C$ yr BP, 30,000 ± 50 $^{14}C$ yr BP, and 40,000± 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).

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 Swanson1998. Dark grey arrows indicate inferred flow direction.