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VARIATIONS IN THE RADIOCARBON CALIBRATION CURVES AROUND KNOWN AND SUSPECTED Δ^{14}C EXCURSIONS

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Abstract
The rapid increase in tree-ring radiocarbon concentration of 12‰ between 774–775 CE marked the first confirmed cosmic-origin event identified through annual tree-ring records. Subsequent studies have independently verified this signal in dendrochronologically dated material from multiple regions, confirming its global nature. Since then, several comparable events have been identified across different periods. These radiocarbon spikes are of particular importance because they provide precise annual tie-points that can significantly improve chronological resolution in fields such as archaeology and geology. In this paper, we present a simple method for detecting such events in high-resolution radiocarbon datasets.

Keywords
radiocarbon dating, tree rings, calibration curves, Miyake event, SEP

1. Introduction

Radiocarbon (^{14}C) is a cosmogenic nuclide produced when thermal neutrons collide with nitrogen nuclei through the nuclear reaction $^{14}N(n,p)^{14}C$. Its average production rate – estimated at 1.64 atoms·cm^{-2}·s^{-1} in modern times and 1.88 atoms·cm^{-2}·s^{-1} in the preindustrial era (Kovaltsov *et al.*, 2012) – varies with fluctuations in cosmic-ray flux. Several mechanisms have been proposed to explain these fluctuations, including solar energetic particles events (SEPs), supernova explosions (SNe), gamma-ray bursts (GRBs), and the modulation of cosmic-ray intensity by solar, interplanetary, and terrestrial magnetic fields.

Once formed in the atmosphere, ^{14}C is eventually oxidized to $^{14}CO_2$ and incorporated into plants via photosynthesis (Jöckel *et al.*, 1999). Its concentration in plant tissues reflects atmospheric ^{14}C levels during the growing season, with variations arising from plant species differences and geographic location. Dendrochronologically dated tree rings are a key archive for reconstructing past changes in ^{14}C over the last 12,500 years, revealing both production rate variations and carbon cycle changes (Reimer *et al.*, 2020; Hogg *et al.*, 2020). Advances in accelerator mass spectrometry (AMS) have greatly improved measurement precision and resolution while reducing the sample size required (Synal *et al.*, 2007; Molnar *et al.*, 2016), enabling the construction of radiocarbon calibration curves at annual resolution (Reimer *et al.*, 2020; Hogg *et al.*, 2020).

In a landmark discovery, Miyake *et al.* (2012) identified an abrupt ~12‰ increase in Δ^{14}C between 774–775 CE in Japanese cedar tree rings. This so called "M12 event" was the first confirmed, globally synchronous ^{14}C anomaly of likely cosmic origin, later independently verified in tree-ring records from multiple continents (Jull *et al.*, 2014; Güttler *et al.*, 2015a, 2015b; Rakowski *et al.*, 2015; Büntgen *et al.*, 2018). Such events provide valuable insights into processes affecting ^{14}C production rates and have significant implications for radiocarbon dating

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accuracy. If not accounted for during the conversion to calendar years using calibration curves, these sharp increases may lead to substantial dating errors, particularly for short-lived materials such as seeds, leaves, or annually formed tree rings, assuming they were affected by such events.

The incorporation of these short termed, rapid ^{14}C excursions into calibration datasets opens the door to ultra-precise dating – sometimes to within a single calendar year – using techniques such as wiggle-matching in longer ^{14}C sequences covering such events. Wacker *et al.* (2014) demonstrated this by precisely dating timber from the Holy Cross Chapel of St. John the Baptist Convent in Val Müstair, Switzerland. Similarly, Krąpiec *et al.* (2020) used the 993–994 CE excursion to anchor a floating pine chronology spanning 859–1085 CE. Other studies have used such events to pinpoint the timing of volcanic eruptions (Oppenheimer *et al.*, 2017; Hakozaki *et al.*, 2018), the onset of long-distance Norse trade (Philipsen *et al.*, 2022), and the Viking settlement at L'Anse aux Meadows, Newfoundland (Kuitems *et al.*, 2022).

2. Material and methods

This study introduces a deliberately simple mathematical approach for detecting short periods of rapid increases in radiocarbon (^{14}C) concentration. Detection was performed using the IntCal20 calibration dataset (Reimer *et al.*, 2020). The underlying raw measurements that contributed to the construction of this curve were consulted only for a few specific examples, not as part of the primary search for ^{14}C increases. IntCal20 file as well as "raw" datasets were downloaded directly from http://calib.org IntCal20 database server.

Our method was designed to be transparent, reproducible, and adaptable across different datasets, making it a practical screening tool for identifying candidate events quickly – without the need for extensive modelling infrastructure. In contrast, the approach of Brehm *et al.* (2021) relied on high-precision annual ^{14}C measurements from multiple absolutely dated tree-ring chronologies, combined with advanced carbon-cycle box modelling, Monte Carlo simulations, and geomagnetic field normalization. While such sophisticated frameworks provide detailed event characterization and cross-archive synchronization, our streamlined method plays a complementary role: enabling rapid initial detection of anomalies, which can then be subjected to more detailed analyses using advanced methods like those of Brehm *et al.* (2021).

The IntCal20 dataset integrates multiple sources. Its most recent 13,900-year segment is derived from tree-ring data with annual resolution back to 5000 years BP, followed by 5-year resolution extending to 15,000 years BP. Beyond this, the dataset incorporates both terrestrial and marine archives, including laminated lake sediments, U/Th-dated speleothems, and U/Th-dated corals. Temporal resolution between 13,900 and 25,000 BP is 10 years, and for >25,000 BP, the resolution is 20 years.

Documented ^{14}C excursions are typically short-lived, often spanning only a few years, and have amplitudes of several permille in Δ^{14}C. To identify such events in the IntCal20 tree-ring portion, we applied a moving average comparison method. Specifically, for each year of interest (n), we calculated the average Δ^{14}C value for the three preceding years (n+1, n+2, n+3) and compared it to the Δ^{14}C value in year n. The resulting difference is referred to as the temporal Δ^{14}C rise, defined as:

$$\text{Temporal } \Delta^{14}\text{C rise} = \Delta^{14}\text{C}_n - \frac{\Delta^{14}\text{C}_{n+3}+\Delta^{14}\text{C}_{n+2}+\Delta^{14}\text{C}_{n+1}}{3} \quad (1)$$

where n – is a year BP of the data-point in the IntCal20 data set.

We initially identified candidate excursions through an iterative heuristic process. Because excursion amplitudes can be as small as a few permille – and the IntCal20 curve is smoothed (Heaton *et al.*, 2020) – we systematically adjusted the detection threshold to ensure all known ^{14}C excursions (**Table 1**) were captured, while minimizing background noise. A 1‰ threshold for a temporal Δ^{14}C rise was found to be optimal. Although this may seem low, smoothing in IntCal20 necessitates a reduced detection limit. This threshold is illustrated by the red horizontal line in **Figs. 1** and **2**. Lowering it further may reveal additional potential Δ^{14}C increases.

3. Results and discussion

The results of the search for rapid ^{14}C excursions in radiocarbon concentration are presented in **Figs. 1** and **2** and in **Table 1**. **Table 1** lists all identified and possible periods of abrupt increases in radiocarbon concentration.

Besides the M12 event in 774–775 CE (Miyake *et al.*, 2012), several similar events have been confirmed at different periods. An increase of 11.3‰ was recorded between 993 and 994 CE (Miyake *et al.*, 2013, 2014) and later confirmed by Rakowski *et al.* (2018), Fogtman-Schulz *et al.* (2017), and Büntgen *et al.* (2018). An event around 660 BCE was confirmed by Park *et al.* (2017), Rakowski *et al.* (2019), O'Hare *et al.* (2019), and Sakurai *et al.* (2020). Measurements of radiocarbon concentrations in sub-annual tree rings for this period suggest a two-phase pattern, with a first event between 665–664 BCE followed by a second in late spring of 663 BCE (Rakowski *et al.*, 2024).

Other radiocarbon excursions have been observed between 814–815 BCE (Jull *et al.*, 2018), 1054–1055 CE (Tarrasi *et al.*, 2020), and as a series of events between 1261–1262, 1268–1269, and 1279–1280 CE (Miyahara *et al.*, 2022). The oldest observed rapid increases in radiocarbon concentration occurred during the mid-Holocene around 5480 BCE (Miyake *et al.*, 2017), 5410 BCE (Miyake *et al.*, 2021), 5259 BCE, and 7176 BCE, with magnitudes comparable to the strongest M12 event (Brehm *et al.*, 2022), though these are not included in this study.

Table 1. *Confirmed and proposed periods in IntCal20 (Reimer et al., 2020) showing rapid changes in radiocarbon concentration. The uncertainty was estimated as the duration of the period during which Δ^{14}C exceeded the selected criterion, relative to the running mean average, plus one year.*

Year BP	Calendar year	Possible event	Literature
4420 ± 12	2470 ± 12 BCE	–	this study
4152 ± 9	2202 ± 9 BCE	–	this study
3480 ± 5	1530 ± 5 BCE	–	this study
2756 ± 8	806 ± 8 BCE	814–815 BCE	Jull *et al.*, 2018
2614 ± 9	664 ± 9 BCE	665–664 BCE	Park *et al.*, 2017 O'Hare *et al.*, 2019 Rakowski *et al.*, 2019, 2024 Sakurai *et al.*, 2020
2344 ± 5	394 ± 5 BCE	–	this study
1533 ± 5	417 ± 5 CE	–	this study
1178 ± 10	772 ± 10 CE	774–775 CE	Miyake *et al.*, 2012 Jull *et al.*, 2014 Rakowski *et al.*, 2015 Güttler *et al.*, *2015a*, *2015b* Büntgen *et al.*, 2018
958 ± 9	992 ± 9 CE	993–994 CE	Miyake *et al.*, 2013, 2014 Fogtman-Schultz *et al.*, 2017 Rakowski *et al.*, 2018 Büntgen *et al.*, 2018
927 ± 5	1023 ± 5 CE	–	this study
Undetected at the 1‰ threshold	-	1054–1055 CE	Terrasi *et al.*, 2020 Brehm *et al.*, 2021
731 ± 8	1219 ± 7 CE	–	this study
Undetected at the 1‰ threshold	-	1261–1262 CE	Miyahara *et al.*, 2022
673 ± 9	1277 ± 9 CE	1268–1269 CE 1279–1280 CE	Brehm *et al.*, 2021 Miyahara *et al.*, 2022
557 ± 8	1393 ± 8 CE	–	this study
155 ± 10	1795 ± 10 CE	–	this study
140 ± 7	1810 ± 7 CE	–	this study

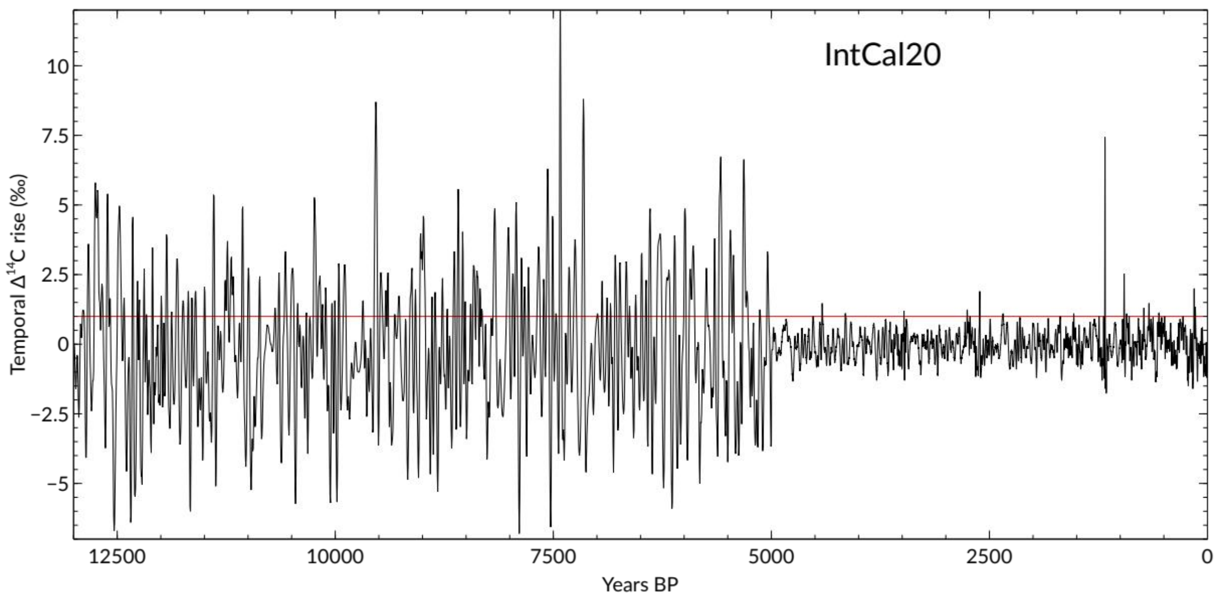

Fig. 1. *Results of extreme fluctuations events seach in tree rings-based part of IntCal20. Data-points above the red line suspected to be results of ^{14}C concentration excursions.*

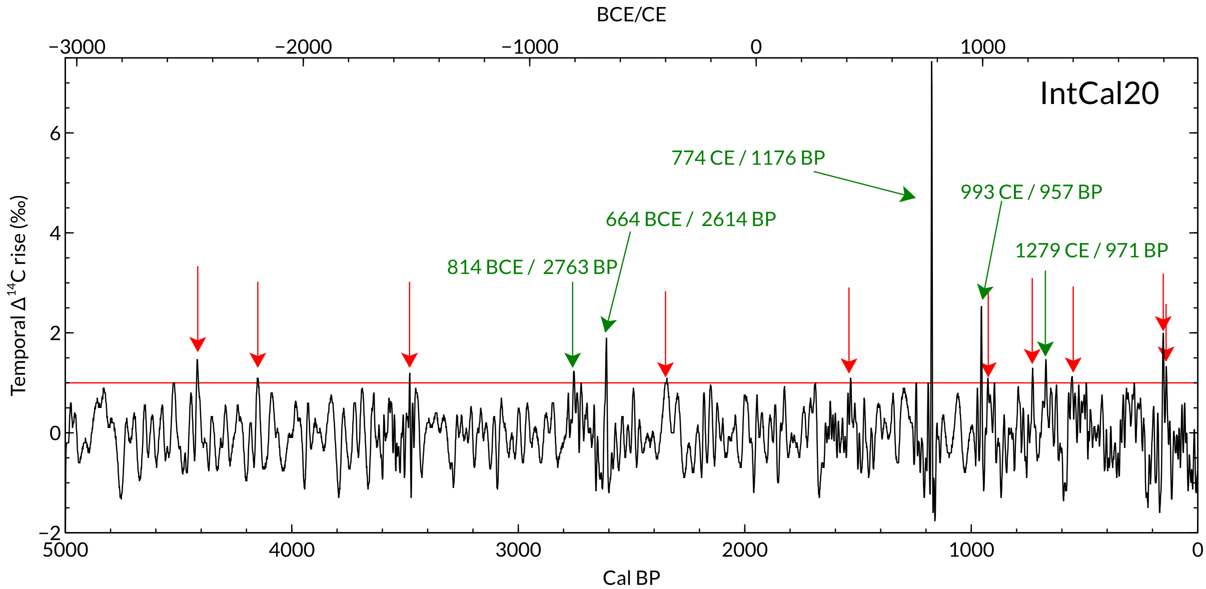

Fig. 2. *Results of extreme fluctuations events search for youngest 5k years tree rings based IntCal20. Data-points above horizontal red-line (1) are suspected to be results of ^{14}C concentration excursions. Already know excursions are being marked green, red arrows are the new finds.*

For most of these events, their origin has been linked to solar energetic particle (SEP) events, with corresponding increases in ^{10}Be and ^{36}Cl production rates confirming their solar origin (775 CE – Pavlov *et al.*, 2013; Mekhaldi *et al.*, 2015; 994 CE – Mekhaldi *et al.*, 2015; ~660 BCE – O'Hare *et al.*, 2019; 7176 BCE – Paleari *et al.*, 2022; 5480 BCE – Kanzawa *et al.*, 2021).

For events such as those between 814–815 BCE (Jull *et al.*, 2018), 1054–1055 CE (Terrasi *et al.*, 2020), and the series between 1261–126 2, 1268–1269, and 1279–1280 CE (Miyahara *et al.*, 2022), the origin remains unknown. Their magnitudes are significantly lower than that of the M12 event, and without data on changes in ^{10}Be and ^{36}Cl production rates, it is difficult to determine whether they are of solar origin. In the case of the 1054–1055 CE event, the Crab Nebula supernova (SN 1054; Mayall, 1939) has been discussed as a possible cause of increased radiocarbon production (Terrasi *et al.*, 2020).

Figs. 3 and **4** present a detailed inspection of the IntCal20 last-millennium and raw datasets covering our findings for the periods 1393 ± 8 CE, 1795 ± 10 CE, and 1810 ± 7 CE. The last-millennium dataset was selected for presentation in this paper as it may be of particular interest to the archaeology of Eastern Europe.

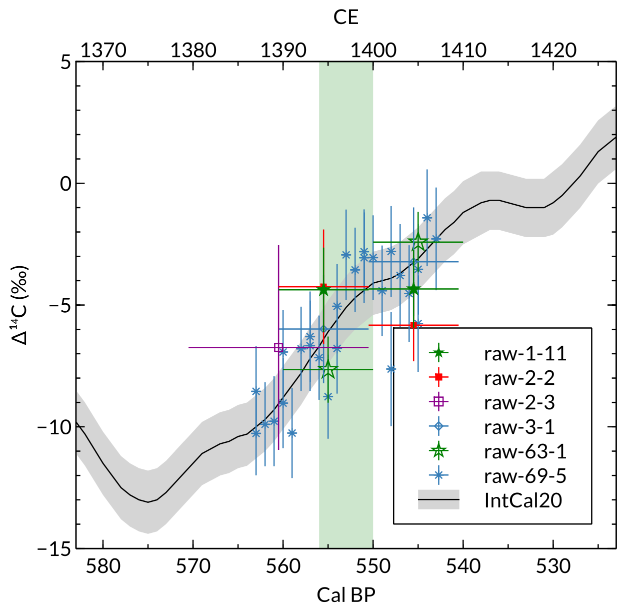

Fig. 3. *Insight into the suspected period of 553±7 BP (1397±7 CE) of IntCal20 and raw-data sets used to build the curve. raw-1-11 data from Stuiver and Braziunas (1993), raw-2-2 data from McCormac et al. (1998). raw 2-3 data from Pearson et al. (1986). raw-3-1 data from McCormac et al. (1998). raw-63-1 data from Manning and Kromer (2012). raw-69-5 data from Wacker et al. (in prep.). Green-shaded area represents the period suspected of ^{14}C excursion.*

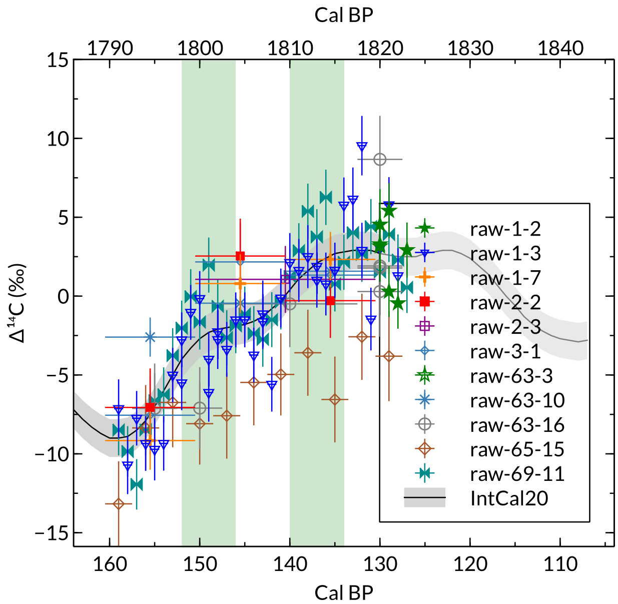

Fig. 4. *Insight into the suspected periods: 149±9 BP (1801±9 CE) and 137±6 BP (1813±6 CE) of IntCal20 and raw-data sets used to build the curve. raw-1-2, raw-1-3 and raw-1-7 data from Stuiver and Braziunas (1993), raw-2-2 data from McCormac et al. (1998). raw 2-3 data from Pearson et al. (1986). raw-3-1 data from McCormac et al. (1998). raw-63-3 and raw-63-10 data from Manning and Kromer (2012). raw-63-16 data from Manning et al. (2018). raw-65-15 data from Sakamoto et al. (2017). raw-69-11 data from Wacker et al. (in prep.). Green-shaded areas represent the periods suspected of ^{14}C excursions.*

4. Conclusions

This study presents a straightforward method for detecting periods of rapid radiocarbon excursions within the IntCal20 tree-ring dataset (Reimer *et al.*, 2020). The admittedly simple algorithm (i.e. temporal concentation difference to preceeding three year average ≥ 1‰) identified intervals where abrupt increases in radiocarbon concentration exceed the normal variability of IntCal20. Of the seven known rapid ^{14}C increases from the past 5,000 years, five were successfully detected. In addition, ten new potential candidate periods were identified, which require confirmation from independent atmospheric isotope datasets. Our results also show that, due to the need for single-year resolution, only the portion of the calibration curve covering the last 5,000 years is suitable for such analysis.

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