Radiocarbon, 2018, p. 1–12 DOI:10.1017/RDC.2018.53
Selected Papers from the 2nd Radiocarbon in the Environment Conference, Debrecen, Hungary, 3–7 July 2017

MORE RAPID ^{14}C EXCURSIONS IN THE TREE-RING RECORD: A RECORD OF DIFFERENT KIND OF SOLAR ACTIVITY AT ABOUT 800 BC?

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ABSTRACT. Two radiocarbon (^{14}C) excursions are caused by an increase of incoming cosmic rays on a short time scale found in the Late Holocene (AD 774–775 and AD 993–994), which are widely explained as due to extreme solar proton events (SPE). In addition, a larger event has also been reported at 5480 BC (Miyake et al. 2017a), which is attributed to a special mode of a grand solar minimum, as well as another at 660 BC (Park et al. 2017). Clearly, other events must exist, but could have different causes. In order to detect more such possible events, we have identified periods when the ^{14}C increase rate is rapid and large in the international radiocarbon calibration (IntCal) data (Reimer et al. 2013). In this paper, we follow on from previous studies and identify a possible excursion starting at 814–813 BC, which may be connected to the beginning of a grand solar minimum associated with the beginning of the Hallstatt period, which is characterized by relatively constant ^{14}C ages in the period from 800–400 BC. We compare results of annual ^{14}C measurements from tree rings of sequoia (California) and cedar (Japan), and compare these results to other identified excursions, as well as geomagnetic data. We note that the structure of the increase from 813 BC is similar to the increase at 5480 BC, suggesting a related origin. We also assess whether there are different kinds of events that may be observed and may be consistent with different types of solar phenomena, or other explanations.

KEYWORDS: ^{14}C excursions, cosmic rays, dendrochronology, radiocarbon dating.

INTRODUCTION

Cosmic rays interact with the Earth's atmosphere to produce secondary particles and also various products. These products are called cosmogenic nuclides. Carbon-14 is produced in the atmosphere by the action of secondary galactic cosmic-ray neutrons on nitrogen in the atmosphere according to the reaction $^{14}N(n,p)^{14}C$ (Burr 2007; van der Plicht 2007). The mean production rate has been the subject of much discussion in the past, but the current consensus values are 1.6–2.0 atoms/cm^2/s (Masarik and Reedy 1995; Kovaltsov et al. 2012).

The atmosphere today is estimated to contain 829 Gt of carbon (Schuur et al. 2016), equivalent to ca. 4.8×10^{28} ^{14}C atoms at a $^{14}C/^{12}C$ value of 1.21×10^{-12} (Fraction modern = 1.02). The amount of carbon in the atmosphere is increasing due to anthropogenic industrial emissions, and indeed has increased from 750 Gt by 10% in the last 20 years (see Schimel et al. 1996; Schuur et al. 2016). Before the industrial era, the concentration of CO_2 was closer to 600 GtC, and one can calculate that the atmosphere contained ca. 3.5×10^{28} ^{14}C atoms (ca. 814 kg ^{14}C). This value was relatively constant since the end of the Pleistocene. With an annual average production rate of ca. 1.8 ± 0.2 ^{14}C/cm^2/s (Kovaltsov et al. 2012), this would produce ca. 3×10^{26} ^{14}C atoms/yr (6.7 kg/yr).

A number of observations of rapid excursions of ^{14}C in the tree ring records with annual time resolution have been found. The idea that solar flares can increase the production of ^{14}C has been discussed at least since the paper of Lingenfelter and Ramaty (1970). We know from recent

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studies that ^{14}C in tree rings can record apparently large excursions. These events have been demonstrated for AD 774–775, AD 994–995, 660 BC, and 3372–3371 BC (e.g. Miyake et al. 2012, 2013, 2017a; Usoskin et al. 2013; Jull et al. 2014; Güttler et al. 2015; Fogtmann-Schulz et al. 2017; Park et al. 2017; Wang et al. 2017). These four events appear to have similar structures, with a rapid rise and slow decay, although different amplitudes. The 660 BC event also rises over a longer time (~4–11 yr) compared to the other records. At 5480 BC, a different behavior is observed (Miyake et al. 2017a), but also with a rise time of approximately 10 years. Other different kinds of events at 2460 BC have already been proposed by Larsson and Larsson (2017). In the case of the most well-documented event at AD 774–775, Mekhaldi et al. (2015) and Miyake et al. (2015) have confirmed the nature of the event from studies of other radionuclides, by measuring ^{10}Be and ^{36}Cl in ice cores. Other smaller events at AD 993–994 have also been observed, initially by Miyake et al. (2013) and recently confirmed by Fogtmann-Schulz et al. (2017). In addition, other events at 5480 BC (Miyake et al. 2017a) and 660 BC (Park et al. 2017) have been reported. There is also one report of excursions in corals growing in near-surface ocean (Liu et al. 2014), although this is not independently reproduced. Because the amount of ^{14}C in the atmosphere is clearly much higher than the annual average production rate, a tremendous upsurge in production rate is needed to explain the dramatic increase in the AD 774–776 sequence (Pavlov et al. 2013; Usoskin et al. 2013). It is important to understand that even a twofold increase in production rate in one year (and presumably, cosmic-ray flux) would only increase the ^{14}C in the atmosphere by less than 1%. The excursion at AD 774–775 was estimate to require a change in annual flux by a factor of 4 (Miyake 2014).

We know that the global magnetic field directs much of the cosmic-ray flux to latitudes >45ºN and past efforts have also stressed the importance of geomagnetic field changes to long-term measurements of ^{14}C. It is not yet known if very rapid geomagnetic field changes, perhaps due to a coronal mass ejection (CME, e.g. the Carrington Event) can also cause ^{14}C excursions since at least the AD 1859 geomagnetic event (Desnains and Cherault 1859; Shea and Smart 2006) has not been shown to produce enough ^{14}C to be recorded in the annual layers of tree rings (Jull et al. 2014).

Carbon-14 concentrations in tree rings are used to study regular and irregular variations of the ^{14}C production rate in the atmosphere. Almost all studies of ^{14}C spikes measured in tree rings propose that there is a rapid change to the production rate of ^{14}C, which must be several times the normal production rate of galactic cosmic ray (GCR). But what is the nature and origin of these excursions? Much has already been written about the specific AD 774–775 event, with estimates of the cause of this excursion, the size of potential radiation doses and the potential for these events to have effects on biological systems (e.g. Hambaryan and Neuhäuser 2013; Thomas et al. 2013; Usoskin et al. 2013; Cliver et al. 2014; Eastwood et al. 2017). However, it is impossible to understand the nature and scope of these important excursions in the ^{14}C record without a precise chronology of these events, how often they occur and long enough to overlap with other observations and also historical accounts. It is also necessary to identify as many of these events as possible to build up a record of the periodicity and character of these events. Therefore, we need to separate external events from events that could be attributed to changes in the carbon cycle. In this paper we present (1) a new record of annually resolved ^{14}C measurements from tree rings of sequoia (36° 35′ 5′′N, 118° 44′ 59′′W, 2100 m asl) and cedar (39°13′7′′N, 140°1′7′′E, 360 m asl) grown at similar latitudes locations near 36°N but 8600 km apart (5350 mi), and (2) identification of a new ^{14}C excursion around 813 BC.

SAMPLES AND METHODS

We studied ^{14}C in a series of tree rings of sequoia (*Sequoiadendron giganteum*) from the Laboratory of Tree-Ring Research Collection and Archives, the University of Arizona. The sampled tree specimen (#CMC-3f, Figure S1) was collected from the Circle Meadow trail in the Sequoia National Park, California. We also studied a series of tree rings from a Japanese cedar (*Cryptomeria japonica*) from Mt. Choukai, Japan, measured at the Nagoya University. In both cases, the wood specimens were cross-dated against the master tree-ring chronologies, annual growth layers were separated through cutting with a razor blade, and were grounded to 20-μm mesh. In the case of the cedar, biannual samples were combined. Each powdered sample was converted to holocellulose using standard procedures (Molnar et al. 2013). Sequoia cellulose samples were combusted to CO_2 and converted to graphite and ^{14}C dating was performed using the 200kV MICADAS at the Institute of Nuclear Research in Debrecen, Hungary (Molnar et al. 2013). Sample calculation and data reduction were done using the standard BATS software (Wacker et al. 2010). The Japanese cedar measurements were independently measured on the 3MV HVEE AMS machine at the Nagoya University, Japan.

If we know the age of the tree-ring, we can define $\Delta^{14}C$ as:

$$\Delta^{14}C = 1000(Fe^{\lambda_T t} - 1)$$

where λ_T is the true decay constant of ^{14}C based on the half-life of 5730 yr, and t is the known age of the material. The fraction of modern carbon, F is defined as the $^{14}C/^{12}C$ ratio relative to 1950 AD (Stuiver and Polach 1977; Donahue et al. 1990).

RESULTS AND DISCUSSION

New ^{14}C Excursion Beginning at 814–813 BC

Decadal fluctuations of measured ^{14}C age in IntCal13 show occasionally abrupt and large changes over relatively short intervals that currently are not well understood nor explained. We selected the period beginning at 835 BC because this section of the radiocarbon (^{14}C) curve shows a large decline in the apparent age from 2750 to 2450 yr BP over the period of 100

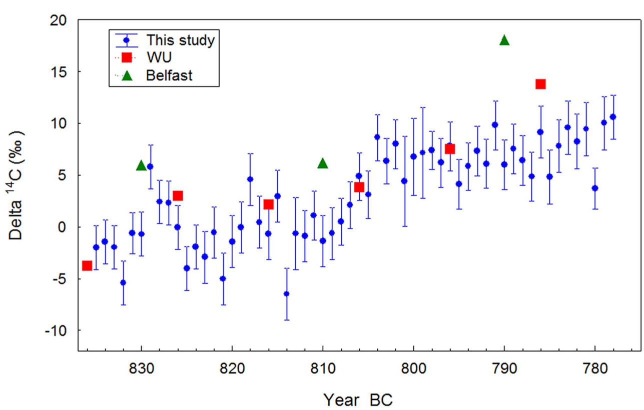

Figure 1 Details of the $\Delta^{14}C$ measured in sequoia from 835 to 778 BC in this study. The red squares are raw data from the University of Washington (WU) and Queen's University of Belfast (green triangles). Data from Washington and Belfast were obtained from the IntCal database (http://intcal.qub.ac.uk/intcal13/). (See online version for color figures.)

calibrated years from 850 to 750 BC (Stuiver and Becker 1993). The Belfast data in the IntCal database (Reimer et al. 2013; http://intcal.qub.ac.uk/intcal13/) show a change of 114 ^{14}C years in the 21 years from 810 to 789 BC. Our new measurement results for the period BC 823–778 are also shown in the supplement Table S1 for the giant sequoia and its Δ^{14}C plotted in Figure 1. We note that there is an increase from about BC 814 where Δ^{14}C is –6.5‰ to BC 804–802 (2753–2751 BP), at which point the value of Δ^{14}C reaches +8‰, with a slow increase back to +10.6‰ at BC 778. In order to confirm our results, we have also compared the results obtained on sequoia with a comparable record from Japanese cedar, independently measured in the Nagoya laboratory. Supplemental Table S2 shows the measurements on Japanese cedar. Both results plotted together in Figure 2 clearly demonstrate that the sequoia and cedar records have a similar increase over the period, although with some differences in the fine structure.

Some interesting features are apparent if we compare the two records. Both records show what appear to be periodicities on the timescale of 10–15 years of the order of a few per mil. There is good agreement between the two datasets apart from the sequoia value at 814 BC (2763 BP). In general, the data do not show any systematic offset between the two datasets, as might be expected if there was a regional effect (Kromer et al. 2001; Miyahara et al. 2007). Previous work (Miyake et al. 2017a) also ruled out any systematic differences between the laboratories. The only exception is that cedar data also shows a minimum at around 794–789 BC not clearly observed in the sequoia data. We postulate this could be related to solar cycles, which impact Japanese trees to a different extent that Californian ones (Miyahara et al. 2007).

The structure of this excursion was compared to the 5480 BC anomaly of Miyake et al. (2017a). We have plotted them on a comparable scale, which clearly shows considerable similarity to the 5480 BC event as shown in Figure 3. This tends to suggest a similarity in the origin of these two excursions. Figure 4 shows comparison of our results with ^{14}C raw data of the Seattle and Belfast labs for the interval 500–900 BC included into the calibration curve. It shows the relationship between the modeling ages within the studied interval from 835 BC (2784 BP) to 778 BC (2727 BP) on a slope of the rapid decline in apparent ^{14}C age from about 800 to 700 BC. We also compare the 660 BC event of Park et al. (2017), which interrupts the flat feature of constant ^{14}C age for the period 700–500 BC. In order to understand the relationship to Δ^{14}C, we show the same period in Figure 5 and add the 660 BC event studied by Park et al. (2017) on the same scale. There is a marked peak in Δ^{14}C in the IntCal data at 751 BC (2700 BP) followed by

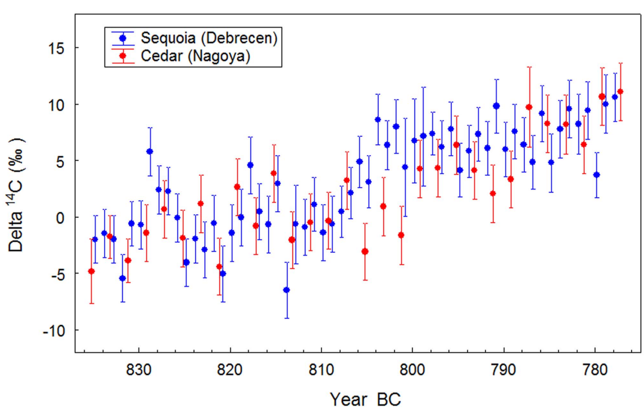

Figure 2 Comparison of the Δ^{14}C results from sequoia and Japanese cedar.

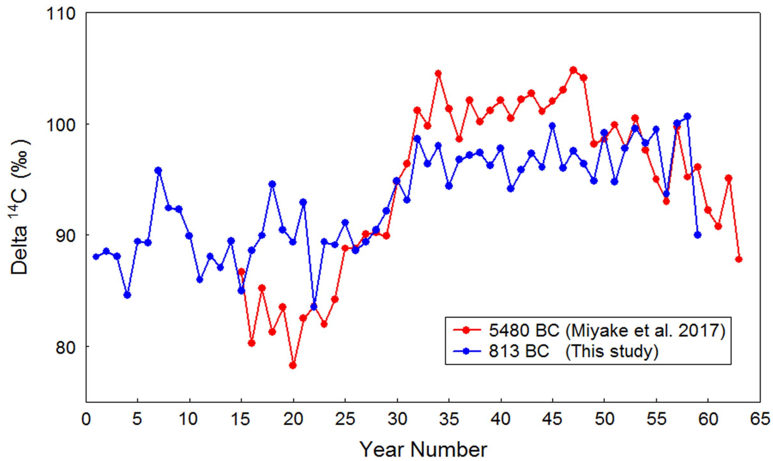

Figure 3 Comparison of the increase in Δ^{14}C for the sequoia samples and the 5480 BC event (Miyake et al. 2017a). The Δ^{14}C results from sequoia beginning at 835 BC are plotted with an offset of +90‰ to compared the two plots.

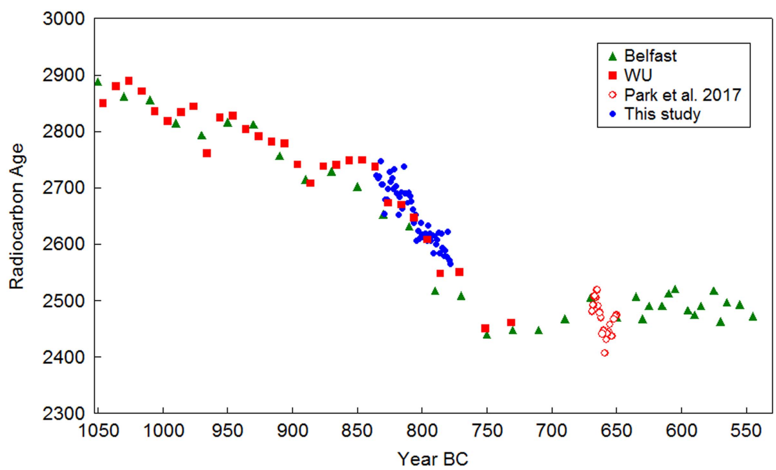

Figure 4 Plot of ^{14}C age vs. calibrated age for the period 1000–500 BC. The points shown are from University of Washington (red squares), Queen's University of Belfast (green triangles), Park et al. (2017) (open red circles), and our new results (sequoia: solid blue circles). Data from Washington and Belfast were obtained from the IntCal database (http://intcal.qub.ac.uk/intcal13/).

a relatively constant decline in Δ^{14}C across this time (see also figure 3 of Miyake et al. 2017b). Park et al. (2017) already noted this phenomenon, showing the decline of Δ^{14}C from +20 to −10‰ over the 200-year span from 750 to 550 BC (which can be seen in Figure 4), although this is punctuated by an increase in Δ^{14}C at about 660 BC. We note that the decline of 30‰ in ^{14}C effectively cancels the increase in ^{14}C over 200 years with a decrease in ^{14}C age equivalent to 240 years in the younger (550 BC) sample. This effect causes a relatively flat period in apparent ^{14}C age, as has been noted by earlier studies and referred to as the Hallstatt period (Friedrich and Henning 1996; Grabner et al. 2007; Jacobssen et al. 2017).

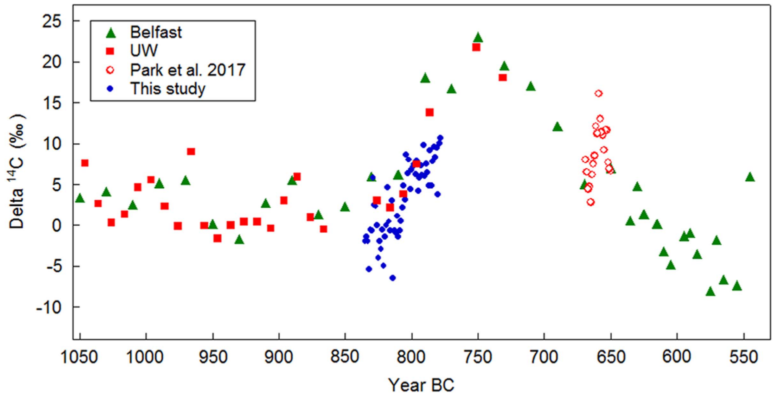

Figure 5 Plot of $\Delta^{14}C$ vs. calibrated age for the period 1000–500 BC. The points shown are from University of Washington (solid red squares), Queen's University of Belfast (solid green triangles), Park et al. (2017) (open red circles), and our new results (solid blue circles). Data from Washington and Belfast were obtained from the IntCal database (http://intcal.qub.ac.uk/intcal13/).

To continue our comparison with the 660 BC event (Park et al. 2017), we note the rise time of that event is about 11–12 years between BC 667.5 to 659.5, similar to the increase observed in 814–804 BC and the 5480 BC event (Miyake et al. 2017a). The 660 BC event of Park et al. (2017) is an increase followed by a rapid decline, in contrast to the 5480 BC event and our new event presented here. However, as noted by Park et al. (2017), that event is on a trend of declining $\Delta^{14}C$. Our excursion of 814–802 BC occurs during a period of increasing $\Delta^{14}C$ from −4.05‰ to 22‰, between 846 and 751 BC (2795 and 2700 BP). This period then declines very gradually in the IntCal record back to about 0‰ at 2540 cal BP (see Figure 5). This gradual decrease is the reason for the apparently shift to younger ^{14}C ages about 750–850 BC. The increase over the period of 814–799 BC is almost 14‰, which then declines over the next 11 years, reaching a peak of 9.8‰ at 791 BC and similarly ~9.5‰ at same peak again at 780–782 BC, exhibiting a periodicity similar to a solar cycle of 10–12 yr.

Park et al. (2017) already have discussed that the $\Delta^{14}C$ declined prior to the subsequent increase they observed over approximately 7–10 yr between 669 and 660 BC, a similar increase of ~12–13‰, although it is important to note this is part of the long-term $\Delta^{14}C$ decline from 2700 to 2450 BP. The difference with the peak of Park et al. (2017) and the event at 814 BC is that the former declines in a similar time-scale, whereas the $\Delta^{14}C$ after 814 BC declines at a similar rate, but against a backdrop of generally increasing $\Delta^{14}C$, masking the effect. Our new results are less dramatic than the 660 BC event. Although the changes in slope have a similar magnitude, the peak at 660 BC is more apparent, since it occurs on a flatter part of the calibration curve. However interpreted, both these sets of data show increases and decreases occurring on the order of one solar cycle, even though the solar cycle today (e.g. Stuiver et al. 1998) only has an effect of a few per mil on the value of $\Delta^{14}C$. Hence, we must conclude either that the solar cycles had higher amplitude at this time (800–660 BC) or that there were other changes going on with the solar modulation, perhaps associated with the extended decline of $\Delta^{14}C$ to 540 BC, which is coincident with the period of the Hallstatt ^{14}C period (Friedrich and Henning 1996; Grabner et al. 2007). As suggested by Park et al. (2017) and also noted in Miyake et al. (2017b), the association of "spikes" with the onset or decline of solar minima needs further study. We emphasize that these rapid excursions of up to 12–13‰ still require a rapid change in the cosmic-ray flux on an annual basis, so that short-term phenomena such as solar flares or CME are the most likely cause.

Implications of the New ^{14}C Excursion

There is no good explanation or clear understanding of the causes of ^{14}C excursions shown here documented with fine annually resolved ^{14}C measurements. Previously, solar effects were proposed for the AD 774–775 event (Miyake et al. 2012; Usoskin et al. 2013; Jull et al. 2014; Güttler et al. 2015). For our new data, the broad peak of increased ^{14}C with a slow decline is consistent with past variations of ^{14}C during Grand solar minima, as discussed by Miyake et al. (2017a). Another account for our observed effects may be rapid changes in the geomagnetic field (Mazaud et al. 1991; Stuiver and Becker 1993), but in our view the more rapid events must be of solar origin. Previously, Stuiver and Braziunas (1993a) had identified various periodicities in the $\Delta^{14}C$ and ascribed century-scale variability to solar effects, but they ascribed a longer ~512 yr cycle to instabilities in North Atlantic thermohaline circulation. At that time, indeed, they attributed the $\Delta^{14}C$ changes to such an effect.

Obviously, these results highlight the need for detailed study of annual $\Delta^{14}C$ measurements in tree rings from different parts of the world. Another effect noticeable in the record at this interval is the difference between the Seattle and Belfast data on tree rings included in the IntCal curve. A series of results presented at a recent IntCal workshop (Pearson and Jull 2017) highlighted several periods where annual data of Bristlecone pine (Pearson et al. 2017), juniper from Jordan (Manning et al. 2018), Japanese cedar (Nakamura et al. 2017), and European oak (Wacker et al. 2017) sometimes give results older than the consensus IntCal13 calibration curve. In general, these deviations appear to be in close agreement with the original Seattle data (Stuiver and Becker 1993). Recently, Manning et al. (2018) discuss some offsets in ^{14}C age from the calibration curve in the period AD 1640–1910 of about 20, but sometimes as much as 50 years. Pearson et al. (2017) discuss similar offsets during the period 1700–1500 BC. It is clear that these small offsets, which are now more easily distinguished with AMS measurements on annual rings, warrant further investigation.

Geomagnetic Field Effects

Fluctuations of geomagnetic field intensity modulate the behavior of ^{14}C activity. It is important to consider rapid ^{14}C changes of the studied interval in comparison to abnormal changes in the Earth's geomagnetic field occurring at the same time. The geomagnetic dipole moment is often expressed as the virtual axial dipole moment (VADM), which estimates the equivalent dipole required to produce the observed geomagnetic field (that varies with geomagnetic latitude) at a given location. The period 1000–500 BC is characterized by a high VADM with average values higher than today (see Figure 5 of Shaar et al. 2016), Various geomagnetic proxy records show rapid "spikes" in the geomagnetic signal at certain locations of the Northern Hemisphere. Schaar et al. (2016) discuss geomagnetic phenomena beginning about 1300 BC, which appears to be a precursor to other spikes observed in Chinese and other Far Eastern archeomagnetic samples from East Asia at around 1000 BC (Hong et al. 2013; Cai et al. 2017). Ben Yosef et al. (2009) and Schaar et al. (2011) also found geomagnetic "spikes" in ^{14}C carbon-dated slag mounds from southern Israel dated to ~980 and 890 BC. Indeed, Cai et al. (2017) have also reported on several apparent excursions as high as 165.8 $10^{21}Am^2$, compared to the average of about 100–110 $10^{21}Am^2$ for ~1000 BC (Cai et al. 2017), which were suggested earlier by Hong et al. (2015). Not only high VADM anomaly, Cai et al. (2017) also report a low in VADM about 2200 BC.

Sternberg and Damon (1992) indicate that the global production rate of ^{14}C correlates approximately with the square-root of the magnetic field intensity. Hence, a doubling of

VADM should result in a reduction of ^{14}C production by ~ 1.4 times. Depending on the length of time this occurred, the amount of ^{14}C in the atmosphere might only be reduced by ~ 6‰ per year. Such a reduction, followed by a return to more normal production rates might be misinterpreted as an increase. The ^{14}C curve during the period 1000–500 BC shows a gradual decline in apparent ^{14}C age (that is, an increase in the amount of ^{14}C) from 1000 to 800 BC with a rapid drop at 814 BC, which we have already discussed. The change from 1000 to 800 BC is ~ 140 years, and the drop at 814 BC alone is 114 years (a change of $\Delta^{14}C$ of ~ 14‰). It would be difficult to explain this following increase in ^{14}C production (resulting in a younger apparent age) at a time of high geomagnetic field, if it were due only to geomagnetic field variations, but a significant contribution to an explanation of ^{14}C offsets is possible. Hong et al. (2013) note several rapid decreases in VADM at approximately 800–700 BC and AD 700. The VADM maximum varies by location of measurement and is an estimate of the global dipole based on that location. The peak in geomagnetic VADM is about 500 BC (deGroot et al. 2015; Kissel et al. 2015; Cai et al. 2017) for sample centered on the Canary Islands, consistent with a reduced $\Delta^{14}C$ during this time.

Archaeological, Socio-Cultural, and Climatic Implications

The first millennium BC elapses one of the major technological shifts in the prehistoric world manifested through the transition from the Bronze Age to the Iron Age in Eurasia. High dynamism of socio-economic changes in the ancient communities by 800 BC culminated in the progression of new cultures (e.g. La Tène Celts in Central Europe, Scythians and Sarmatians in Eurasian Steppe, Saka in Central Asia, Yuezhi and Kushans in China) have been linked in many cases to landscape transformations, particularly, vegetation due to the climate change (Davis-Kimball et al. 1995; Koryakova and Epimakhov 2007). For example, cooling of the Eurasian steppe is often described as the key factor leading to the shift from the Late Bronze Age (LBA) agro-pastoralism to mobile nomadism and riparian agriculture expansion of Iron Age (Davis-Kimball et al. 1995; Macklin et al. 2015). Development and initial spread of carbon steel metallurgy (ironworking) marks the boundary between the LBA to the Early Iron Age (EIA) dated ca. 900–800 BC for most regions of Inner Asia, Near East and Europe, and ca. 500 BC for China and South Asia (LeHuray and Schutkowski 2005; Koryakova and Epimakhov 2007; Higham et al. 2011). The lack of reliable chronology for the multifaceted exchange of technology during the first millennium BC has resulted in multiple dates and many different models proposed for the LBA-EIA transition.

Although the ambiguous structure of the ^{14}C calibration curve for the transition and EIA complicates the archeological dating, using the 813 BC and 660 BC cosmogenic events as time markers may help to constrain the chronology of technological exchange and synchronization of these cultural changes. Moreover, measuring ^{14}C on tree rings around the cosmogenic event(s) provides the opportunity to date an archaeological occurrence to a single year (Wacker et al. 2014). We note also the importance of the Hallstatt period in ^{14}C dating (Friedrich and Henning 1997; van der Plicht 2004; Grabner et al. 2007; Jacobssen et al. 2017), due to its original association with LBA mine workings at Hallstatt in Austria. Therefore, if we can improve our understanding of the detailed structure of the ^{14}C record in this period, this also has implications for archaeological dating in this region, as well as for our understanding of solar effects on climate.

The evidence of a short-lived but extreme change of cosmic ray flux at ~ 813 BC followed by the onset of Grand Solar Minimum could have a noteworthy impact on the climatic variability around this time. Climate response to orbital forcing and incoming solar radiation accounts for the significant part of the long-term scale of global climate variation. Cooling of the climatic system between 800 BC and 400 BC is a distinct long-term event across the Eurasian continent related to the two prolonged intervals of low solar activity (8th BC Minimum and 4th BC Minimum) that could be comparable to the Little Ice Age (Dergachev et al. 2004; Plunkett and Swindles 2008). Changes in the moisture variability driven by astronomical alterations of seasonal solar radiation and cyclone formation documented by geological archives suggest centennially scaled increase of precipitation over Inner Eurasia, Central Europe and other mid latitude regions of the Northern Hemisphere at that interval (Kutzbach and Gallimore 1988; Dergachev et al. 2004).

It is also interesting to note the possible effects of large cosmic-ray events. Most recently it has been demonstrated that increased cosmic ionization significantly amplifies the nucleation rate of small aerosols contributing to cloud formation (Svensmark et al. 2017). This revolutionizes our understanding of the linkages between the intensity of cosmic rays and ion-induced condensation on the short-term scale, and could have implications for anomalous behavior of thermohaline circulation (e.g. position of North Atlantic Jet and Polar Jet) and extreme precipitation during and shortly after large changes in cosmic ray intensity. Consequently, better documentation of the 813 BC event and other ^{14}C excursions may help to pinpoint the extreme paleo-weather events) in the mid-latitude regions where the irregularity in intensity of cyclonic activity occurs in the response to a large solar-geomagnetic disturbance (Kutzbach and Gallimore 1988; Svensmark and Friis-Christensen 1997; Sukhodolov et al. 2017).

CONCLUSIONS

It is clear that there are several types of rapid events in the $\Delta^{14}C$ record (Stuiver and Braziunas 1993a; Miyake et al. 2017a, 2017b; Park et al. 2017 and references cited therein). The new events reported here and by Miyake et al. (2017a) and Park et al. (2017) seem to associate rapid excursions of ^{14}C with longer-term variations caused by solar minimum-like periodicities. This is a different phenomenon from the apparently short-term and isolated $\Delta^{14}C$ events at AD 774–775 and AD 993–994. We also confirm that the behavior of the new record from 813–778 BC is similar in behavior but different amplitude compared to the 5480 BC event. However, we need to better understand the interplay of these various perhaps overlapping series of events. We also plan to extend our study in both directions to better quantify the variations in ^{14}C occurring in this 800–700 BC time period.

Although the rapid events so far observed indicate that a solar event, either solar flare or a CME, is the most easily understood cause for the results reported here and other similar events, the connection with solar minima is an added consideration. So far, many diverse explanations have been offered. It is likely that several different phenomena, including possible rapid changes in the carbon cycle, cannot be totally excluded, as was suggested by Stuiver and Braziunas (1993a, 1993b, 1998). It is important to try to understand the origins of these different periodicities and which ones can be correlated with external forcing due to solar effects, or whether there is the interplay of several other phenomena. The question arises whether solar flare and CME effects also directly cause other perturbations in the climate system, as some have proposed (Thomas et al. 2013; Sukhodolov et al. 2017), which could make the cause-effect relationship more complex.

ACKNOWLEDGMENTS

We are grateful to the staff of the AMS laboratories in Debrecen and Nagoya for assistance with these measurements. This study was supported by the European Union and the State of

Hungary, co-financed by the European Regional Development Fund in the project GINOP-2.3.2.-15-2016-00009 'ICER'. The work at the Nagoya University was funded by JSPS KAKENHI Grant Number JP26887019.

SUPPLEMENTARY MATERIALS

To view supplementary material for this article, please visit https://doi.org/10.1017/RDC.2018.53

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