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Assessing the differences between the IntCal and Greenland ice-core time scales for the last 14,000 years via the common cosmogenic radionuclide variations

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ABSTRACT

Variations in galactic cosmic rays reaching the Earth's atmosphere produce globally synchronous variations in the production rates of cosmogenic radionuclides. In consequence, they leave their imprint in tree-ring ^{14}C and ice-core ^{10}Be records. By identifying this signal and correcting for the known geochemical influences on the radionuclides, it is possible to compare and synchronize the tree-ring chronology and the Greenland ice-core time scale. Here, we compare the IntCal13 and the GICC05 time scales for the last 14,000 years via identification and synchronization of the common short-term variations in the ice-core ^{10}Be and tree-ring ^{14}C records most likely induced by variations in the solar modulation of galactic cosmic rays. We conclude that systematic time-scale differences have to be accounted for if ice-core and ^{14}C-dated records are compared on decadal time scales. These are mostly within the uncertainties of the time scales and the method proposed here. However, for large parts of the mid to late Holocene (i.e. after 7000 yrs BP) the best agreement between ice-core ^{10}Be and tree-ring ^{14}C records is obtained for time shifts outside the stated errors of the respective time scales. A transfer function is proposed that can be applied to synchronize the GICC05 ice-core time scale to the radiocarbon time scale.

1. Introduction

Paleoclimate archives open up the possibility to study natural climate changes under different forcing conditions and in the absence of human influences. Therefore, they provide a variety of test cases for our understanding of the climate system. Especially the timing of climate change at different locations might provide valuable information about the processes underlying climate change. However, very precise and accurate absolute time scales are required to study the leads and lags in climate change inferred from different natural archives. Alternatively, climate-independent synchronization methods are needed to achieve robust relative time control between different climate reconstructions. This can be achieved by measuring globally synchronous variations in the concentration of atmospheric trace gases in ice cores (e.g. Blunier et al., 1998). This method, however, is limited to ice cores and it requires knowledge of the difference between the gas age relative to the age of the ice. Another method to synchronize the time scales of natural archives can be achieved via identification and geochemical characterisation of the emissions of volcanic eruptions (e.g. Abbott and Davies, 2012; Blockley et al., 2012). This method, however, is restricted by the fallout patterns and the possibility to find and unequivocally identify the traces of volcanic eruptions. By contrast, globally synchronous variations in the incoming cosmic ray flux leave their signature in almost every natural archive via the production and subsequent deposition of cosmogenic radionuclides. These particles are produced in a cascade of nuclear reactions in the Earth's atmosphere induced by high-energy cosmic rays (Lal and Peters, 1967). The challenges in using radionuclides as a synchronization tool lie in the time-consuming and expensive measurements of cosmogenic radionuclides, the unequivocal attribution of the common cosmogenic radionuclide variations in different natural archives, and the possible additional geochemical influences on the deposition of cosmogenic radionuclides in natural archives that might mask or distort the production signal.

A method to synchronise and date archives with the radionuclide method is the ^{14}C "curve fitting" or "wiggle match dating" approach (Pearson, 1986). The idea is to achieve a more precise time

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control via matching of variations in the ^{14}C calibration curve and the variations in a series of ^{14}C dates (e.g. Van Geel and Mook, 1989; Mellström et al., 2013). Similarly, ^{10}Be variations have been used to match Greenland and Antarctic ice cores in an effort to study the precise timing of climate change in Greenland and Antarctica (Raisbeck et al., 2007). Likewise, a very precise synchronization between sediment, tree-ring and/or ice-core records can be achieved by comparing relative changes in ^{10}Be and/or ^{14}C concentrations from the individual archives and taking into consideration the known differences in the geochemical behaviour of ^{10}Be and ^{14}C (e.g. Muscheler et al., 2008; Nilsson et al., 2011; Martin-Puertas et al., 2012). ^{10}Be variations in ice cores and changes in the tree-ring based ^{14}C records have been investigated previously to study the time scales of these archives (e.g. Finkel and Nishiizumi, 1997; Muscheler et al., 2000; Southon, 2002; Knudsen et al., 2009). However, this has not yet been done with the combined Greenland ice-core ^{10}Be record on the latest ice-core time scale. Furthermore, a time scale transfer function between ^{14}C and ice-core time scales with an error estimate is missing so far.

In the following, we will present a new method to assess the timing of cosmogenic radionuclide variations observed in high-resolution ice-core ^{10}Be and tree-ring ^{14}C records. We confine this analysis to the last approximately 14,000 years, where the presently available IntCal13 ^{14}C calibration record is well-dated and of high-resolution and quality (Reimer et al., 2013). The known carbon-cycle influences on the atmospheric ^{14}C concentration are corrected for via reconstructing a ^{14}C production-rate record from the atmospheric ^{14}C data (Stuiver and Quay, 1980; Muscheler et al., 2005). The possible climate influences on the ^{10}Be deposition are hard to assess and we assume that the ^{10}Be fluxes directly reflect the ^{10}Be production signal delayed by the average atmospheric residence time of about 1 year (Raisbeck et al., 1981). Since it is easy to misalign small radionuclide variations, we will present a method that objectively compares the radionuclide records in order to provide a transfer function between the IntCal13 and GICC05 ice-core time scale.

2. Data and methods

The following calculations are based on a combined ^{10}Be record that includes the GRIP data back to about 9400 yrs BP (Muscheler et al., 2004; Vonmoos et al., 2006) extended with the GISP2 ^{10}Be data (Finkel and Nishiizumi, 1997) back to 14,000 yrs BP (Fig. 1c). In the following, we follow the convention that "yrs BP" means years before 1950 AD. The data are shown versus the GICC05 time scale (Rasmussen et al., 2006; Vinther et al., 2006). The GICC05 time scale is based on counting the annual layers in different ice cores and uncertain years are counted as half years with an uncertainty of $\pm 1/2$ yr (2σ) (Rasmussen et al., 2006). The GISP2 record is synchronized to the GICC05 time scale via common volcanic markers (Rasmussen et al., 2006, 2008). For the flux calculation, we estimated the snow accumulation rate according to the layer thickness inferred from the depth-age relationship. The layer thickness is subsequently corrected for the thinning due to the ice flow (Johnsen et al., 1995). It is important to note that the results do not depend on the method used to infer the ^{10}Be fluxes as there are differences in the estimates of the snow accumulation rates for central Greenland (e.g. Wagner et al., 2001). Time-scale uncertainties imply accumulation rate uncertainties but, again, the uncertainties are too small to affect our results. To reduce the scatter of the raw data, we applied the same moving-average filter as used in Vonmoos et al. (2006) which extracts variations on time scales longer than 25 years (Vonmoos et al., 2006).

The ^{10}Be data is compared to the ^{14}C production-rate record inferred from the IntCal13 ^{14}C calibration curve (Reimer et al., 2013)

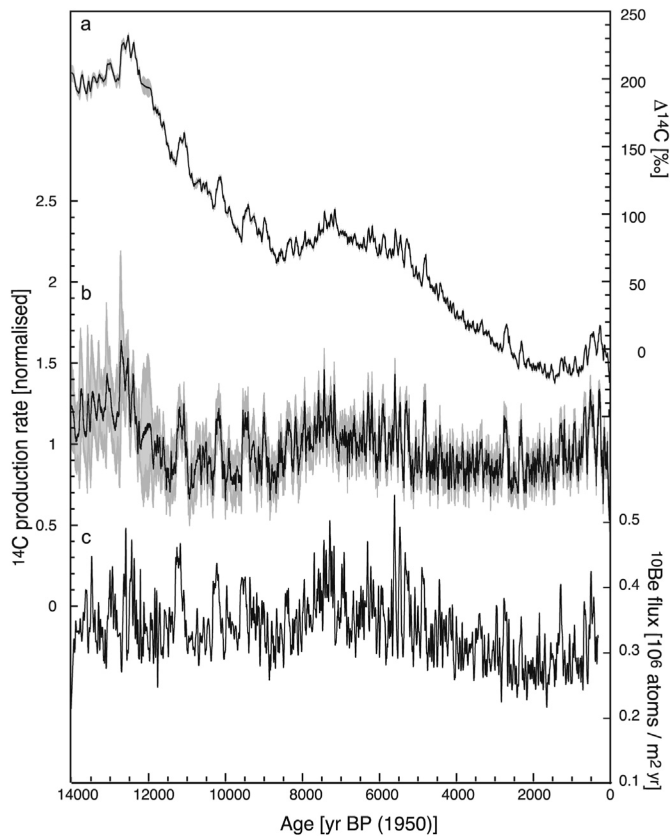

Fig. 1. The data that underlies the time-scale transfer between IntCal13 and the ice-core time scale GICC05. Panel a shows past atmospheric ^{14}C concentration (expressed as relative variations from the standard) based on the IntCal13 calibration curve (Reimer et al., 2013). Panel b shows the ^{14}C production rate inferred from the $\Delta^{14}C$ record. The black line shows the average of the results of 1000 Monte-Carlo simulations and the error band is indicated in grey. Panel c shows the spliced Summit ^{10}Be flux record with the GRIP data back to 9400 yrs BP (Muscheler et al., 2004; Vonmoos et al., 2006) and the GISP2 data before (Finkel and Nishiizumi, 1997). The errors of individual ^{10}Be measurements are on the order of 5–7%. The ice-core ^{10}Be data are smoothed with a 61-pt binomial filter applied to the ^{10}Be data interpolated to a resolution of 2 years (Vonmoos et al., 2006). The ^{10}Be data is plotted versus the GICC05 ice-core time scale (Rasmussen et al., 2006; Vinther et al., 2006).

(Fig. 1a, b). For the last ~14,000 years, this record is based on tree-ring ^{14}C measurements which allow reliable estimates of the atmospheric ^{14}C variations (expressed as $\Delta^{14}C$ which are the ^{14}C variations relative to a standard in ‰ after correction for decay and fractionation). These high-quality $\Delta^{14}C$ estimates are a prerequisite for the time-scale comparison as it requires that the "wiggles" in the ^{14}C calibration curve are reliably reconstructed to allow for the comparison to the variations observed in the ice-core ^{10}Be data. Back to 12,550 yrs BP these data are inferred from dendrochronologically-dated trees (Friedrich et al., 2004; Reimer et al., 2013) with assumed virtually perfect time scale. In spite of the presence of trees, a definitive dendrochronological match has not yet been achieved for the records from 12,550 to 14,000 yrs BP. Before 14,000 yr BP, the calibration curve is based on a mix of different more indirect ^{14}C records (Reimer et al., 2013) which hampers comparison to the ^{10}Be data.

The ^{14}C production rate is reconstructed using a Box-Diffusion carbon-cycle model (Oeschger et al., 1975; Siegenthaler, 1983). This procedure corrects for the delayed and dampened reaction of the atmospheric ^{14}C concentration to changes in the ^{14}C production rate (Siegenthaler et al., 1980). In general, the results hardly depend on the carbon-cycle model (e.g. Delaygue and Bard, 2010). To account for the errors in the $\Delta^{14}C$ data, we included 1000 Monte-