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Plateaus and jumps in the atmospheric radiocarbon record – Potential origin and value as global age markers for glacial-to-deglacial paleoceanography, a synthesis

Michael Sarnthein[1)], Kevin Küssner[2)], Pieter M. Grootes[3)], Blanca Ausin[4)], Timothy Eglinton[4)], Juan Muglia[5)], Raimund Muscheler[6)], Gordon Schlolaut[7)]

1) Institute of Geosciences, University of Kiel, Olshausenstr. 40, 24098 Kiel, Germany, michael.sarnthein@ifg.uni-kiel.de, (corresponding author)
2) Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Department for Marine Geology, 27570 Bremerhaven, Germany, kevin.kuessner@awi.de
3) Institute of Ecosystem Research, University of Kiel, Olshausenstr. 40, 24098 Kiel, Germany, pgrootes@ecology.uni-kiel.de
4) Geological Institute, ETH Zürich, Sonneggstr. 5, 8092 Zuerich, Switzerland, blanca.ausin@erdw.ethz.ch
5) College of Earth, Ocean and Atmospheric Sciences, Oregon State University, 104 CEOAS Administration Building, 101 SW 26th St, Corvallis, OR 97331, USA, juanmuglia@gmail.com
6) Quaternary Sciences, Department of Geology Lund University, Sölvegatan 12, S-223 62 Lund, Sweden, raimund.muscheler@geol.lu.se
7) Climate Dynamics and Landscape Evolution, GFZ German Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany, SchlolautG@gmail.com

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Preprint. Discussion started: 25 October 2019

Climate of the Past Discussions

ABSTRACT

Changes in the geometry of ocean Meridional Overturning Circulation (MOC) are crucial in controlling changes of climate and the carbon inventory of the atmosphere. However, the precise timing and global correlation of short-term glacial-to-deglacial changes of MOC in different ocean basins still present a major challenge. A possible solution is offered by the fine structure of jumps and plateaus in the record of radiocarbon (^{14}C) concentration of the atmosphere and surface ocean that reflects changes in atmospheric ^{14}C production as well as in the ^{14}C exchange between air and sea and within the ocean. Boundaries of atmospheric ^{14}C plateaus in the ^{14}C record of Lake Suigetsu, now tied to Hulu U/Th model-ages instead of optical varve counts, provide a stratigraphic 'rung ladder' of ~30 age tie points from 29 to 10 ka for correlation with and dating of planktic oceanic ^{14}C records. The age difference between contemporary planktic and atmospheric ^{14}C plateaus gives an estimate of the global distribution of ^{14}C reservoir ages for surface waters of the Last Glacial Maximum (LGM) and deglacial Heinrich Stadial 1 (HS-1), as shown by 19 planktic ^{14}C records. Clearly elevated and variable reservoir ages mark both high-latitude sites covered by sea ice and/or meltwater and upwelling regions. ^{14}C ventilation ages of LGM deep waters reveal opposed geometries of Atlantic and Pacific MOC. Similar to today, Atlantic deep-water formation went along with an estuarine inflow of old abyssal waters from the Southern Ocean up to the northern North Pacific and an outflow of upper deep waters. Vice versa, ^{14}C ventilation ages suggest a reversed MOC during early HS-1 and a ~1500 year long flushing of the deep North Pacific up to the South China Sea, when estuarine circulation geometry marked the North Atlantic, gradually starting near 19 ka. Elevated ^{14}C ventilation ages of LGM deep waters reflect a major drawdown of carbon from the atmosphere. Inversely, the subsequent massive age drop and change in MOC induced two major events of carbon release to the atmosphere as recorded in Antarctic ice cores, shifts that highlight the significance of ocean MOC for atmospheric CO_2 and its ^{14}C inventory. These new features of MOC and the carbon cycle offer a challenge to model simulations that, in part because of insufficient spatial model resolution and reference data for testing the model results, still poorly reproduce them.

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Climate of the Past
Discussions

LIST of CONTENTS

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Climate of the Past Discussions

1. INTRODUCTION

1.1 A variety of terms linked to the notion '^{14}C age'

The ^{14}C concentration in the troposphere is mainly determined by ^{14}C production, atmospheric mixing, moreover, air-sea gas exchange, and ocean circulation that vary over time (e.g., Alves et al., 2018; Alveson et al., 2018). The ^{14}C content of living terrestrial plants is in equilibrium with the atmosphere via processes of photosynthesis, respiration, and accordingly, the ^{14}C of terrestrial plant remains in a sediment section directly reflects the amount of radioactive decay, thus the time passed since the plant's death, and the ^{14}C composition of the atmosphere during the time of plant growth.

Contrariwise, ^{14}C values of marine waters are cut off from cosmogenic ^{14}C production in the atmosphere, hence depend on the carbon transfer at the air-sea interface and transport and mixing of carbon in the ocean. For surface waters, the air-sea transfer is relatively fast and effective involving a time span of ten years and less (e.g., Nydal et al., 1998). Yet, vertical and horizontal water mixing results in surface ocean ^{14}C concentrations differing from those in the contemporaneous atmosphere, expressed as differential ^{14}C 'reservoir ages' (or 'reservoir effects' *sensu* Alves et al., 2018). These 'ages' reflect the local oceanography and are highly variable through time. Differences may range from near zero up to values of more than 700 yr, in some regions up to 2500 yr, induced, for example, by old waters upwelled from below (e.g., Stuiver and Braziunas, 1993; Grootes and Sarnthein, 2006; Sarnthein et al., 2015). Apart from U/Th dated corals (many papers on their reservoir age since Adkins and Boyle, 1997) the ^{14}C age of planktic foraminifers is the most common tracer of surface water ages in marine sediments, a rough estimate of the time passed since sediment deposition. Initially, marine geologists were most interested in this 'simple' age value. Soon, however, they were confronted with

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

age inconsistencies that implied a series of unknowns, in particular the ^{14}C 'reservoir age' that finally turned out to be a most valuable tracer of oceanography.

In turn, ^{14}C records of benthic carbonate particles in deep-sea sediments sum the time of radioactive decay since their deposition with the apparent 'ventilation age' of the deep waters in which they lived. Ventilation age is primarily the time span from the moment when carbon dissolved in the (later) deep waters lost contact with the ^{14}C level of the atmosphere and the somewhat reduced level of surface waters until the precipitation of benthic carbonate. Details on the derivation of ventilation ages are given in Cook and Keigwin (2015) and Balmer and Sarnthein (2018). In addition, however, ventilation ages depict hardly quantifiable lateral admixtures of older and/or younger water masses, moreover, ^{14}C-enriched organic carbon supplied by the biological pump, thus are called 'apparent'. Today, the apparent transit times of carbon dissolved in the deep ocean range from a few hundred up to ~1800 ^{14}C yr found in upper deep waters of the northeastern North Pacific (Matsumoto, 2007).

Over the last decades, it turned out that both the reservoir ages of surface waters and the ventilation ages of deep waters present robust and high-resolution tracers essential for drawing quantitative conclusions on past ocean circulation geometries, marine climate change, and the processes that drive both past ocean dynamics and carbon budgets, given the ages rely on a number of robust age tie points. Obtaining such tie points presents a problem, since any attempt to date a deep-sea sediment record by means of ^{14}C encounters a number of intricacies of how to disentangle (i) the effects of atmospheric ^{14}C variations due to past changes in cosmogenic ^{14}C production and carbon cycle, still hampered by the need for a generally accepted atmospheric reference record for the

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

period 14–50 ka, from (ii) depositional effects such as sediment hiatuses and winnowing, differential bioturbational mixing depth, sediment transport by deep burrows, (iii) the effects of ocean mixing resulting in reservoir and ventilation ages that change through time and space (e.g., Alves et al. 2018; Grootes and Sarnthein, 2006), and (iv) from the final target, quantitatively 'pure' ^{14}C ages due to radioactive decay.

By now, ^{14}C-based chronologies of deep-sea sediment records, used to constrain and correlate the age of glacial-to-deglacial changes in ocean dynamics and climate on a global scale, are often of unsatisfactory quality when they are based on (i) age tie points spaced far too wide-spaced (e.g., on DO-events 1, 2, and 3 only for the time span 30–14 cal ka), (ii) disregarding atmospheric ^{14}C plateaus, (iii) the risky assumption of ±constant planktic ^{14}C reservoir ages and other speculative stratigraphic correlations/compilations, and (iv) on ignoring small-scale major differences in low-latitude reservoir age. Likewise, clear conclusions are precluded by an uncertainty range of 3-4 kyr sometimes accepted for tie points during the glacial-to-deglacial period (Lisiecki and Stern, 2016), where significant global climate oscillations occurred on decadal-to-centennial time scales as widely shown on the basis of speleothem and ice core-based records (Steffensen et al., 2008; Svensson et al., 2008; Wang et al., 2001).

Thus marine paleoclimate and paleoceanographic studies today focus on the continuing quest for a high-resolution and global, hence necessarily atmospheric ^{14}C reference record that is marked by abundant, narrow-standing tie points on the calibrated (cal.) age scale. Such pertinent tie points are provided by a suite of reproducible 'plateaus' and 'jumps' that mark the atmospheric ^{14}C record (Figs. 1 and S1; Sarnthein et al., 2007 and 2015; Bronk

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Ramsey et al., 2012 and 2019; Schlolaut et al., 2018; Umling and Thunnell, 2017), hence form the basis of this synthesis.

1.2 Review of tie points used to fix calibrated and reservoir ages in marine ^{14}C records

The tree ring-based calibration of ^{14}C ages provides a master record of decadal changes in atmospheric ^{14}C concentrations back to ~14 cal. ka (Reimer et al., 2013 and 2019) with floating sections beyond (from ~12.5–14.5 cal. ka and around 29–31.5 and 43 cal. ka; Turney et al., 2010, 2017). The evolution of Holocene and late deglacial ^{14}C ages with time is not linear but reveals variations with numerous distinct jump (= rapid change) and (short) plateau-shaped (slow or no change or even inversion) structures indicative of fluctuations in atmospheric ^{14}C concentration. Prior to 8500 cal. yr BP, various plateaus extend over 400–600 cal. yr and beyond (Fig. 2). Given the quality of the tree ring calibration data, these fluctuations can be considered real, suitable for global correlation (Sarnthein et al., 2007, 2015; Sarnthein and Werner, 2018). Air-sea gas exchange transfers the atmospheric ^{14}C fluctuations into the surface ocean where they can provide high-resolution tie points to calibrate the marine ^{14}C record and marine reservoir ages back to ~14 ka (via the so-called ^{14}C wiggle match approach). In the near future, however, it is unlikely that a continuous tree ring-based record will become available to trace such atmospheric ^{14}C variations further back, over the period 14–29 cal. ka crucial for the understanding of last-glacial-to-interglacial changes in climate. Hence various other, less perfect ^{14}C archives have been employed for this period to tie past changes in atmospheric ^{14}C concentration/age to an 'absolute' or 'calibrated' (e.g., incremental) age scale and to constrain the widely unknown evolution of ^{14}C reservoir ages of surface waters for various regions of the ocean.

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Suites of ^{14}C ages of paired marine and terrestrial plant-borne samples, e.g. paired planktic foraminifers and wood chunks, provide most effective but rarely realizable absolute-age markers and reservoir ages of local ocean surface waters (Zhao and Keigwin, 2018; Rafter et al., 2018; Schroeder et al., 2016; Broecker et al., 2004). Likewise successful can be the alignment of ^{14}C-dated variations in downcore sea-surface temperatures (SST) with changes in hydroclimate as recorded in age-calibrated sedimentary leaf-wax hydrogen isotope (δD) records from ancient lakes (Muschitiello et al., 2019), assumed to be synchronous. Further tie points are derived from volcanic ash layers (Waelbroeck et al., 2001; Siani et al, 2013; Davies et al., 2014), paired U/Th- and ^{14}C-based coral ages (e.g., Adkins and Boyle, 1997; Chen et al., 2015), and the (fairly fragmentary) alignment of major tipping points in ^{14}C dated records of marine SST and planktic $\delta^{18}O$ to the incremental age scale of climate events dated in Greenland and Antarctic ice core records (Waelbroeck et al., 2011). Such well-defined climate-age tie points, however, are wide-spaced in peak glacial-to-early deglacial ice core records. Finally, various data compilations tentatively rely on the use of multiple age correlations amongst likewise poorly dated marine sediment records, an effort necessarily problematic.

In the absence of robust age tie points an increasing number of authors resort to ^{14}C reservoir age simulations for various sea regions by ocean GCMs (e.g. Butzin et al., 2017; Muglia et al., 2018) to quantify the potential difference between marine and atmospheric ^{14}C dates during glacial-to-interglacial times. Considering the complexity of the ocean MOC and the global carbon cycle it is not surprising that the results of a comparison of a

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

selection of robust empiric vs. simulated ^{14}C reservoir ages are not that encouraging yet (as discussed further below).

Accepting a generally close link between ^{14}C concentrations in the troposphere and in the surface ocean, the fine structure of planktic ^{14}C records with centennial-scale-resolution provides far superior (though costly) evidence, similar to that of tree rings, to furnish a series of age tie points with semi-millennial-scale time resolution for a global correlation of glacial-to-deglacial marine sediment sections. These suites of tie structures can link the marine sediment records to a reference suite of narrow-standing jumps and boundaries of the apparent plateaus found in the atmospheric ^{14}C record of Lake Suigetsu (Bronk Ramsey et al., 2012, 2019) provided that common ^{14}C variations are robustly identified in both atmospheric and marine records. Prior to 14 cal. ka, the absolute age of these atmospheric ^{14}C structures can be calibrated either by (microscopy-based) varve ages or by a series of paired U/Th- and ^{14}C-based model ages correlated from the Hulu Cave speleothem record (Bronk Ramsey, 2012 and 2019; Southon et al., 2012; Cheng et al., 2018). The difference between these calibrations (Fig. 3) is discussed below. It is, however, little important for both the correlation and the derivation of the time-varying offsets in ^{14}C concentration of planktic sediments from coeval concentrations in the atmospheric record, an offset derived from the average ^{14}C age difference between two 'coeval' planktic and Suigetsu ^{14}C plateaus correlated.

A basic philosophical controversy exists whether the apparent jump and plateau structures in the Suigetsu and planktic ^{14}C records reflect real ^{14}C fluctuations or statistical noise. In the 'null hypothesis' the ^{14}C values shaping plateaus of the calibration curve are regarded as result of mere statistical scatter. Thus, the record of atmospheric ^{14}C ages against time would form a simple continuous rise resulting from radioactive decay and the advance of time, such as suggested by a fairly straight progression of the highly resolved deglacial Hulu Cave ^{14}C record plotted vs. U/Th ages (Southon et al., 2012; Cheng et al., 2018).

This null hypothesis is contradicted by the 'master record' of tree ring data (Fig. 2; Reimer et al., 2013 /2020). Unequivocally it shows fluctuations in atmospheric ^{14}C concentration on the order of 2–3 % over the last 10 kyr (Stuiver and Braziunas, 1993) and even larger back to ~14 ka (Reimer et al., 2013, 2020). Though not resolved in speleothem data these plateau/jump structures are real and widely reproducible in marine sediment records. Under glacial and deglacial low-CO_2 conditions beyond 14 ka, when climate and ocean dynamics were less constant than during the Holocene, atmospheric ^{14}C fluctuations were, most likely, even stronger than those reported by Stuiver and Braziunas and ^{14}C plateaus and jumps accordingly larger.

Thus, the age-defined plateaus and jumps in the Suigetsu atmospheric ^{14}C calibration curve may most likely be regarded as a suite of 'real' structures, extending the tree ring record for Holocene and B/A-to-Early Holocene times (Fig. 2) into early deglacial and LGM times. In part the plateau/jump structures may be linked to changes in cosmogenic ^{14}C production, as possibly shown in the ^{10}Be record (Fig. 4; based on data of Adolphi et al., 2018), and – presumably more dominant – to short-term changes in ocean mixing and the carbon exchange between ocean and atmosphere, the latter crucial, since the carbon reservoir of the ocean contains up to 60 (preindustrial) atmospheric carbon units (Berger and Keir, 1984). The apparent contradiction with the smooth Hulu Cave ^{14}C record (Southon et al., 2012; Cheng et al., 2018) may possibly be explained by (i) the Hulu Cave speleothem precipitation system acting as a low-pass filter for fluctuating atmospheric ^{14}C

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

concentrations (statistical tests of Bronk Ramsey et al., pers. comm. 2018), (ii) to a very limited degree by the obvious scatter in the Suigetsu data that, however, appears insufficient to feign plateaus in view of the evidence based on tree ring based plateaus (Fig. 2). The filter for Hulu data possibly led to a sweeping loss especially of short-lived structures in the preserved atmospheric ^{14}C record, though some remainders indeed were preserved in the ^{14}C records of Hulu Cave (Fig. 1). So we rather trust in the amplitude of Suigetsu 14C structures, but trust in the timing of Hulu Cave data as discussed below.

Like a 'rung ladder' the age-calibrated suite of ^{14}C plateau boundaries and jumps is suited for tracing the calibrated age of numerous plateau boundaries in glacial-to-deglacial marine ^{14}C records likewise densely sampled. Moreover, one may record the offset of planktic ^{14}C ages from paired atmospheric ^{14}C ages that is the planktic reservoir age, for each single ^{14}C plateau (Sarnthein et al., 2007, 2015). For the first time, this suite of tie points may facilitate a precise temporal correlation of all sorts of changes in surface and deep-water composition on a global scale, crucial for a better understanding of past changes in ocean and climate dynamics.

Over the time span 14–40 ka, the Suigetsu record of optical varve counts (Schlolaut et al., 2018) presents a rare means of age calibration of terrestrial and marine sediment records being based on an incremental age scale similar to that of ice cores (e.g. Svensson et al., 2008). In the crucial sediment sections of the Last Glacial Maximum (LGM) and deglacial Heinrich Stadial 1 (HS-1), however, the degree of varve quality/perceptibility in the Suigetsu profile is highly variable (Fig. 5), a problem met by Schlolaut (2018) who developed a special computer program to derive Suigetsu calendar ages from varve counts. Nonetheless the interpolated varve counts have limited accuracy and precision. To

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Climate of the Past
Discussions
Open Access

further improve the chronology the varve data were combined with Hulu Cave-based U/Th-based model ages employed in this paper (Bronk Ramsey et al., 2012). The different age models, however, do not affect our conclusions on planktic reservoir ages.

1.3 Items to be addressed in this synthesis

(1) The purely varve-based chronology of ^{14}C plateau boundaries previously employed for the Suigetsu record (Sarnthein et al., 2015) may be incomplete in view of broad poorly laminated sediment sections interpolated in Suigetsu sediment cores, recently recorded by Schlolaut et al. (2018). As compared to a U/Th-based age model (Bronk Ramsey et al. 2012; Cheng et al., 2018) many hundred years appear to have been missed. Thus, the value of different age calibrations needs to be re-evaluated.

(2) In view of most recent findings on the quality of varve counts (Fig. 5; Schlolaut et al., 2018) our suite of tie points is now extended from 23 to 27/29 cal. ka. The calibrated-age uncertainties of ^{14}C plateau boundaries and jumps in the redefined Suigetsu record (Bronk-Ramsey et al., 2012, 2019; Sarnthein et al., 2015) and their correlatives in ocean sediment cores, values crucial for any accurate correlation of these tie points to possibly underlying ocean events over the period 10–27/29 cal. ka, are now discussed in Supplement Text no. 1.

(3) Our set of records of marine ^{14}C reservoir ages (Sarnthein et al. 2015) has now been amended by several records from the Southern Hemisphere (Balmer et al., 2016 and 2018; Küssner et al., 2017, and in prep.) and northeast Atlantic (Ausin et al., 2019 and in prep.). In total, 18 (LGM) / 19 (HS-1) empiric records plus 3 wood chunk-based records

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

(e.g. Broecker et al., 2004; Zhao et al., 2018) now depict the spatial and temporal variation of past ^{14}C reservoir ages of surface waters for different ocean regions.

(4) In the discussion we will compare our local reservoir ages with independent LGM estimates of surface water ^{14}C reservoir ages simulated by the GCM of Muglia et al. (2018). Differences between the results may help to constrain potential caveats in the boundary conditions and fine structure of model simulations.

(5) We discuss some habitat- and season-specific ^{14}C reservoir ages characteristic of different planktic foraminifera species, ages that monitor for past changes in the local geometry of surface ocean dynamics (Sarnthein and Werner, 2018).

(6) Finally, we refer to ^{14}C reservoir and ventilation ages of surface and deep waters that form a robust tracer of circulation geometries and the dissolved inorganic carbon (DIC) in different basins of the ocean (Sarnthein et al., 2013). The estimates provide crucial insights into the origin of past changes in the global carbon cycle from glacial to interglacial times, an important correlative to model simulations.

2. AGE TIE POINTS BASED ON ^{14}C PLATEAU BOUNDARIES

2.1 A slight revision of absolute age control of the Suigetsu ^{14}C record

Originally, we based the chronology of ^{14}C plateau boundaries in the Suigetsu record (Sarnthein et al., 2015) on a scheme of varve counts by means of light microscopy of thin sections (Bronk Ramsey et al., 2012; Schlolaut et al., 2018). In parallel, varve-based age estimates have been derived from counting various elemental peaks in µXRF data,

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

interpreted as seasonal signals (Marshall et al., 2012). In general, the results obtained from these two independent counting methods and their interpolations widely support each other. The microscopy-based counts ultimately formed the backbone of a high-resolution chronology obtained by tying the Suigetsu ^{14}C record to the U/Th based time scale of the Hulu cave ^{14}C record (Bronk Ramsey et al., 2012). Recently the scheme of varve counts was revisited by Schlolaut et al. (2018) who showed that Suigetsu varve preservation is fairly high both over late glacial Termination I and prior to ~32 ky BP. However, it is fairly poor over large parts of the LGM and HS-1, from ~15 - ~32 cal ka (17.3-28.5 m c.d. in Fig. 5), where less than 20-40 % of the annual layers expected from interpolation between clearly varved sections are distinguished by microscopy per 20 cm sediment section. The varve count using µXRF data (Marshall et al., 2012) can distinguish subtle changes in seasonal element variations, which are not distinguishable in thin section microscopy, hence results in higher varve numbers, for example, during early deglacial-to deglacial times (Fig. 3). Yet, some subtle variations are difficult to distinguish from noise, thus also introduce a degree of uncertainty to the µXRF-based counts. Thus the results deduced from either counting method are subject to uncertainties, as shown by error estimates that rise with increased varve age in Fig. 5.

In addition, Bronk Ramsey et al. (2012) established a time scale based on ^{14}C wiggle matching to U/Th dated ^{14}C records of the Hulu Cave and Bahama speleothems. In part, this calibrated (cal.) age scale was based on Suigetsu varve counts, in part on the prerequisite of the best-possible fit of a pattern of low-frequency ^{14}C concentration changes obtained from Suigetsu und Hulu Cave within the uncertainty envelope of the Hulu 'Old / Dead Carbon Fraction' (OCF/DCF) of ^{14}C concentration. The uncertainty of this model is debatable while the character of the Hulu DCF and thus, its uncertainty back in

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

time is still incompletely understood. We surmise that the U/Th-based age model of Suigetsu may suffer from the wiggle matching of atmospheric ^{14}C ages of Lake Suigetsu with ^{14}C ages of the Hulu Cave (Southon et al., 2012) in case of major short-term changes in the memory effect of soil organic carbon in carbonate-free regions of the cave. These carbonate-based ages may have been influenced far more strongly by short-term changes in the local DCF than assumed, as suggested by major variations in a paired $\delta^{13}C$ record, that reach up to 5 ‰, mostly subsequent to short-term changes in past monsoon climate (Kong et al., 2005). Thus Hulu ^{14}C ages cannot directly be set equal to atmospheric ^{14}C ages under the assumption of a constant OCF/DCF (Southon et al. 2012; Cheng et al., 2018), a caveat that hampers the age model correlation between Hulu and Suigetsu records. It turns out, U/Th-based model ages of ^{14}C plateau boundaries are much higher than the microscopy-based varve ages over HS-1 and LGM we used thus far, a difference accumulating from ~200 yr near 15.3 cal. ka to ~600 near 17 ka and 2000 yr near ~29 ka (Fig. 3) and finally accepted by means of independent evidence shown below.

To calibrate the age of thirty ^{14}C plateau boundaries with the 'best possible' cal. time scale we compared the results of the two timescales independently deduced from varve counts with those of the U/Th-based model age scale using as test case the base of ^{14}C Plateau 2b. In contrast to 16.4 cal. ka suggested by optical varve counts, the XRF-based varve counts suggest an age of ~16.9 cal. ka (Marshall et al., 2012; Schlolaut et al., 2018). Most important, this estimate matches closely that of 16.93 ka on the U/Th-based time scale, a robust argument supporting the latter age scale (Fig. 1). Moreover, different from the microscopy-based varve age scale the U/Th model time scale is further corroborated by a decent match with the ages of Mono Lake at 34

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

ka and Laschamp at 41 ka independently dated by other methods. We therefore chose the U/Th model age scale to calibrate the age of ^{14}C boundaries.

The U/Th-based cal. ages result in reasonable stratigraphic correlations of millennial-scale events in paleoceanography. Fig. 6 displays potentially correlative events of peak glacial and deglacial change independently dated by means of annual-layer counts and/or U/Th ages in ice cores and stalagmites (Table 2). As outlined below, atmospheric ^{14}C plateaus may largely result from changes in air-sea gas exchange, and in turn, from changes in ocean ventilation. A suite of deglacial ^{14}C plateaus indeed displays a temporal match with major deglacial events in ocean degassing of CO_2 (Marcott et al., 2014) (Table 2 and Fig. 6). Also, short-term North Atlantic warmings matched three ^{14}C plateaus each during the peak glacial and earliest deglacial times, similar to that at the end of HS-1.

In view of the recent revision of time scales (Schlolaut et al., 2018; Bronk Ramsey et al, 2019) we extended our plateau tuning and now also defined the boundaries and age ranges of ^{14}C plateaus and jumps for the interval ~23–27/29 cal. ka, which results in a total of ~30 atmospheric age tie points for the time span 10.5–29 cal. ka (Fig. 1; summary in Table 1; following the rules of Sarnthein et al., 2007 and 2015). Prior to 25 cal. ka, the definition of ^{14}C plateaus somewhat suffered from an enhanced scatter of raw ^{14}C values of Suigetsu. -- In addition to visual inspection, the ^{14}C jumps and plateaus were also defined with higher statistical objectivity by means of the first-derivative of all trends in the ^{14}C age-to-calendar age relationship (or –core depth relationship, respectively) by using a running kernel window (Sarnthein et al., 2015).

Note, any readjustment of the calendar age of a ^{14}C plateau boundary does not entail any

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

change in ^{14}C reservoir ages afore deduced for surface waters by means of the plateau technique (Sarnthein et al., 2007, 2015), since each reservoir age presents the simple difference in average ^{14}C age for one and the same ^{14}C plateau likewise defined in both the Suigetsu atmospheric and planktic ^{14}C records of marine surface waters, independent of the precise position of this plateau on the calendar age scale.

2.2 Uncertainties of age control (Chapter to be presented as Suppl. Text #1)

Rough estimates of uncertainty and aspects of analytical quality were published by Sarnthein et al. (2007, 2015). We now focus on uncertainties tied to the calendar age definition for each ^{14}C plateau boundary both in the Suigetsu atmospheric and the various marine sediment records (Table 1). To recap, an age/sediment section is formally defined as containing a '^{14}C plateau', when ^{14}C ages show almost constant values with an overall gradient of <0.3 to <0.5 ^{14}C yr per cal. yr (based on visual description and/or statistical estimates by means of the 1st derivative of all downcore changes in the ^{14}C age – calendar age relationship; Sarnthein et al., 2015) and a variance of less than ±100 to ±300 ^{14}C yr, and up to 500 ^{14}C yr prior to 25 cal. ka. Here ^{14}C ages form a plateau-shaped scatter band with up to 10% outliers, that extends over more than 300 cal. yr in the Suigetsu record and/or equivalent sections of marine sediment depth (following rules defined by Sarnthein et al., 2007).

On visual inspection a plateau boundary is assigned to the break point between the low to zero or reversed slope of a ^{14}C plateau and the normally high regression slope of the ^{14}C concentration jump that separates two consecutive plateaus (Figs. 1 and S1). More precisely, a boundary marks the point, where the ^{14}C curve exceeds the scatter band of

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Climate of the Past Discussions

the plateau either crossing the upper or lower envelope line. Thus the boundary is chosen about halfway between the last ^{14}C age within a plateau band and the next following age outside the scatter band (Figs. 1 and 2). Both on the previously varve-based and the now U/Th-based model age scale (Bronk Ramsey et al., 2012) most ^{14}C dates of the Lake Suigetsu section are spaced at intervals of <10–60 yr from 10 to 15 cal. ka and ones of 20–140 yr between 15 and 29 cal. ka (Fig. 1). Thus the uncertainty of a plateau boundary age assigned halfway between two ^{14}C ages nearby inside and outside a plateau's scatter band would, on average, amount to ±10–±70 cal. yr.

In principle, the calendar age uncertainties of marine ^{14}C plateau boundaries are treated likewise: After being tuned to those in the Suigetsu ^{14}C record, the uncertainties are deduced for the position of all plateaus of a suite within the uncertainty envelope of the U/Th model-based age calibration. Hence the estimates of total age uncertainty present the square root of the squared uncertainty of the calibrated age of each plateau boundary at Suigetsu plus that of the marine record, where variable depth spacing of ^{14}C ages is converted into average time spans.

3. DISCUSSION

3.1 Origin of short-term structures in the atmospheric ^{14}C record: Changes in cosmogenic ^{14}C production versus changes in ocean dynamics

Besides possible climate influences, variations in ^{10}Be deposition in ice cores reflect past changes in ^{10}Be production as a result of changes in solar activity and the strength of the Earth's magnetic field (Adolphi et al., 2018). Correspondingly, the changes in ^{10}Be also reflect past changes in the cosmogenic production of ^{14}C. If we accept to omit assumptions on the modulation of past ^{14}C concentrations by changes in the global carbon cycle over last glacial-to-deglacial times we can calculate the atmospheric ^{14}C changes with a carbon cycle model and convert it into ^{14}C ages (Fig. 4), although being aware that carbon cycle changes are prominent and necessarily modify the ^{10}Be-based ^{14}C record if included correctly into the modeling. Between 10 and 13.5 cal. ka, the modeled ^{14}C record displays a number of plateau structures that show a decent match with Suigetsu-based atmospheric ^{14}C plateaus. Between 15 and 29 cal. ka, however, ^{10}Be-based ^{14}C plateaus are far more rare and/or less pronounced, except for a distinct equivalent of Plateau 6a, that is, most plateaus are far shorter than those displayed in the suite of atmospheric ^{14}C plateaus of Lake Suigetsu (e.g., plateaus near to the top 2a, 2b, and top 5a of Suigetsu plateaus). On the whole, the structures show little coherence, thus indicating that any direct relationship between variations in cosmogenic ^{14}C production and the Suigetsu plateau record is obscured by the carbon cycle, uncorrected climate effects on the ^{10}Be deposition and/or noise in the ^{14}C data.

On the other hand, three long ^{14}C plateaus (no. 2a, 1, and Top YD) that dominate the ^{14}C record during deglacial times (Table 2 and Fig. 6) may be ascribed to coeval brief periods being marked by a short-term major rise in global ocean degassing (Marcott et al. 2014). We thus assume that these events which induced a rapid rise in ^{14}C depleted atmospheric CO_2 may be linked to a variety of fast changes such as that of sea ice cover in the Southern Ocean and/or changes in the salinity and buoyancy of surface waters in high latitudes. These factors control upwelling and meridional overturning of deep waters, in particular, as found in the Southern Ocean (Chen et al., 2015) and/or North Pacific (Rae et al. 2014, Gebhardt et al., 2008). Such events of changes in MOC geometry and intensity may be responsible for ocean degassing and the ^{14}C plateaus as outlined below.

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

In an extreme case, ventilation ages in the Southern Ocean near New Zealand (SO213-76 in Fig. S4; Küssner et al., 2019, in prep.) drop from 4000 years (~60 % of the contemporaneous level of past atmosphere 1.4 'Fraction of Modern Carbon' [FMC] at that time leading to 1.4 x 0.6 = 0.84 FMC) to 1000 years (equal to 88 % of past atmosphere FMC) around 18 cal. ka with an otherwise constant atmospheric ^{14}C of 1.4 FMC. This implies an increase to 1.4 x 0.88 = 1.232 FMC of local deep ocean ^{14}C at this site. The concentration difference of ~0.4 FMC means a major ^{14}C shift in DIC at that very MOC key region of the deep Southern Ocean (Rae and Broecker, 2018) over 200 yr. This enhanced mixing of the Southern Ocean and a similar mixing event in the North Pacific (MD02-2489; Fig. S4) may have triggered – with phase lag – two trends in parallel, (1) a rise in atmospheric CO_2, in part abrupt (*sensu* Chen et al., 2015; Menviel et al., 2018), and (2) a gradual enrichment in ^{14}C depleted atmospheric carbon, reflected as ^{14}C plateau.

By contrast, there is little information for the origin of peak glacial ^{14}C plateaus no. 4 to 11. Some of them may possibly be tied to major short-term warmings / MOC modifications in the North Atlantic such as that during plateau 'YD', during plateaus no. 3 (at the onset of Antarctic warming; e.g., Kawamura et al., 2007) and no. 8 (on the U/Th-based age scale; Table 2). These warmings were probably linked to enhanced overturning and short-term degassing of ^{14}C depleted deep waters in the North Atlantic. However, the causal links of various further peak glacial plateaus to events in ocean MOC still remain to be uncovered.

3.2 ^{14}C plateau boundaries – A suite of narrow-spaced age tie points to rate short-term changes in marine sediment budgets, chemical inventories, and climate 29–10 cal. ka

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

In continuation of previous efforts (Sarnthein et al., 2007 and 2015) the tuning of high-resolution ^{14}C records of ocean sediment cores to the new age-calibrated atmospheric ^{14}C plateau boundaries now makes it possible to establish a 'rung ladder' of ~30 age tie points covering the time span 29 – 10.5 cal. ka. On a global scale these tie points show a time resolution of several hundred to thousand years, now used to constrain the chronology and potential leads and lags of any kind of event that occurred during peak glacial and deglacial times (Fig. 1). The locations of the 18(20) cores are shown in Fig. S2. The time histories of the benthic and planktic reservoir ages are summarized in Figs. S3 and S4 and the information these provide is discussed below.

In particular, five examples show the power and value of additional information obtained by means of the ^{14}C plateau-tuning method. (i) Signals of the onset of northern hemisphere deglaciation can now be distinguished in detail from the subsequent beginning of deglaciation in the southern hemisphere (Kawamura et al., 2007; Küssner et al., 2019 in prep.). (ii) A multicentennial-scale phase lag has been specified for the end of the Antarctic Cold Reversal (ACR) vs. the onset of the Younger Dryas cold spell (Küssner et al., 2019 in prep.), a finding important to further constrain the details of 'bipolar see-saw' (Stocker and Johnsen, 2003). (iii) Signals of deep-water formation in the subpolar North Pacific can now be separated from signals originating in the North Atlantic (Rae et al. 2014; Sarnthein et al., 2013). In this way we now can specify and tie major short-lasting reversals in Atlantic and Pacific MOC on a global scale. (iv) Signals of deglacial meltwater advection can now be distinguished from short-term interstadial warmings in the northern subtropical Atlantic, which helps to locate meltwater outbreaks far beyond the well-known Heinrich belt of ice-rafted debris (Balmer and Sarnthein, 2018). (v) As outlined above, the timing of marine ^{14}C plateaus can now be compared in detail with that of deglacial events of the atmospheric

CO_2 rise independently dated by means of ice core-based stratigraphy (Table 2; Fig. 6). These linkages enable a better understanding of deglacial changes in deep-ocean MOC once the suite of ^{14}C plateaus has been properly tuned at any particular ocean site.

Furthermore, the refined scale of age tie points reveals unexpected details for changes in the sea ice cover of high latitudes as reflected by anomalously high ^{14}C reservoir ages (e.g. north of Iceland and near to the Azores Islands) and for the evolution of Asian summer monsoon in the northern and southern hemisphere as reflected by periods of reduced sea surface salinity (e.g., Sarnthein et al., 2015; Balmer et al., 2018). Finally, the plateau-based high-resolution chronology has led to a detection of numerous millennial-scale hiatuses (e.g., Sarnthein et al., 2015; Balmer et al., 2016; Küssner et al., 2019 in prep.) previously undetected by conventional, e.g., *AnalySerie*-based methods (Paillard et al. 1996) of stratigraphic correlation (Fig. S4). In turn, the hiatuses give intriguing new insights into past changes of bottom current dynamics linked to different millennial-scale geometries of overturning circulation and climate change such as in the South China Sea (Sarnthein et al., 2013 and 2015), in the South Atlantic (Balmer et al. 2016) and southern South Pacific (Ronge et al., 2019).

Clearly, the new 'rung ladder' of closely-spaced chronostratigraphic tie points has evolved to a tool indispensable to uncover functional chains in paleoceanography, that actually have controlled events of climate change over glacial-to-deglacial times.

3.3 Definition and origin of Zoophycos burrows: A key foe of high-resolution stratigraphy in Pleistocene sediment records turned into an ally?

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

The *Zoophycos* producer displaces planktonic foraminifera tests, each marked by the ^{14}C age of its shell formation, down to deep sediment levels, hence may severely bias the faunal and isotopic composition and in particular, the ^{14}C age of the ambient host sediment if (parts of) a Zoophycos burrow is picked in a sample. The well-defined 'rung ladder' of ^{14}C plateaus defined in the host sediment now provides a clear yardstick both for the relative chronostratigraphic displacement of the 'outlier' foraminiferal specimens downcore in the host sediment and in particular, for the precise age of the source level of these tests, that is the real time when a burrow was produced.

In continuation of previous studies (Löwemark and Grootes, 2004) Küssner et al. (2018) demonstrated that *Zoophycos*-based vertical grain transport may reach down to sediment depths of 150 cm. In particular, they showed that *Zoophycos* burrows formed during brief episodes of enhanced burrowing activity that coincided with a marked drop in sedimentation rate, that is, with events of reduced benthic nutrient supply. Thus the "foe" Zoophycos may help corroborate reconstructed changes in climate and MOC.

3.4 Empiric vs. model-based ^{14}C reservoir ages acting as tracer of past changes in surface ocean dynamics and as incentive for further model refinements

The tuning of ^{14}C plateau boundaries presents a technique unique to establish a suite of highly resolved and robust age tie points on short and long time scales in ^{14}C-dated marine sediment sections wherever retrieved in the global ocean (Fig. S2a). In addition, and likewise intriguing, ^{14}C plateau tuning results in a suite of changing ^{14}C reservoir ages over time, prime tracers of past oceanography of local surface waters and a data set crucial to deduce past apparent deep-water ventilation ages (e.g.,

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Muglia et al., 2018; Cook and Keigwin, 2015; Balmer and Sarnthein, 2018). Two aspects help to sort out short-term climate-driven intra- and inter-plateau changes in ^{14}C reservoir age, (i) the evaluation of individual reservoir ages is solely based on judging a complete suite of plateaus, (ii) our experience shows that different climate regimes in control of changes in surface ocean dynamics generally occurred on (multi-) millennial time scales (e.g., YD, B/A, HS-1), whereas atmospheric ^{14}C plateaus hardly lasted longer than a few hundred up to ~1000 yr. Thus intra-plateau changes in ^{14}C reservoir age are less likely, but indeed may amputate and/or deform a plateau to be checked in detail for each suite of ^{14}C plateaus (Sarnthein et al., 2007, 2015).

To recap, the atmospheric ^{14}C plateaus of Suigetsu provide a suite of up to 18 reference plateaus over the time span 10 – 29 cal. ka (Fig. 1). In marine sediment cores the ^{14}C reservoir age of past surface waters is inferred from the difference between the average ^{14}C age of an atmospheric ^{14}C plateau and that of a coeval ^{14}C plateau analyzed on monospecific planktic foraminifera (Sarnthein et al., 2007). In low-to-mid latitudes our ^{14}C records are based on *G. bulloides*, *G. ruber,* or *G. sacculifer* with habitat depths of 0–80/120 (Jonkers and Kucera, 2017). In high latitudes, most ^{14}C records are derived from *N. pachyderma* (s) living at 0–200 m depth (Simstich et al., 2003). Averaging of ^{14}C ages within a ^{14}C plateau helps to bypass the analytical noise in ^{14}C records such as short-term apparent ^{14}C age reversals and to deduce the regional evolution of planktic ^{14}C reservoir ages with semi-millennial-scale resolution. Nine plateaus are located in the LGM, 18–27 cal. ka (Fig. 1). Here, plankton-based reservoir ages show analytical uncertainties of >200 to >300 yr each. By comparison, short-term temporal variations in reservoir age reach 200–400 yr, occasionally up to 600 yr, in particular, close to the end of the LGM (Table 3).

To better decode the informative value of LGM empiric ^{14}C reservoir ages we compare them with estimates generated by a General Circulation Model (GCM) of ocean surface waters (model of Muglia et al., 2018; 0–50 m w.d.; Fig. 7 and Suppl. Fig. S3d), an approach similar to that of Toggweiler et al. (2019) applied to modern reservoir ages of the global ocean. Low LGM values (300–750 yr) supposedly document an intensive exchange of surface waters with atmospheric CO_2, most common in model- and foraminifera-based estimates of the low- and mid-latitude Atlantic. Low empiric values also mark LGM waters in mid to high latitudes off Norway and off middle Chile, that is, close to sites of potential deep and/or intermediate water formation. Off Norway and in the northeastern Atlantic, model-based reservoir ages of Muglia et al. (2018) largely match the empiric range. This is no proof yet for model quality, since the uncertainty envelopes (±560 yr for data shown in Fig. 7b; r = 0.59) generally far exceed the spatial differences calculated for the empiric data. Contrariwise, model-based reservoir ages reproduce only poorly the low plankton-based estimates off Central Chile and values in the Western Pacific and Southern Ocean.

In part, the differences may be linked to problems like insufficient spatial resolution along continental margins and/or the estimates of a correct location and extent of seasonal sea ice cover used as LGM boundary condition such as east off Greenland, in the subpolar N.W. Pacific, and off Southern Chile, where sea ice hindered the exchange of atmospheric carbon (per analogy to that of temperature exchange, as recorded by Sessford et al, 2019). In turn, model estimates are compared to ^{14}C signals of planktic foraminifera that mostly formed during summer only, when large parts of the Nordic Seas were found ice-free (Sarnthein et al., 2003). Hence, models may need to better constrain local and seasonal sealing effects of LGM sea ice cover.

In general, however, the foraminifera-based reservoir age estimates for our sites that represent various hydrographic key regions in the high-latitude ocean appear much higher than model-derived values. Deviations reach up to 1400 yr, in particular in the Southern Ocean. In part, the discrepancies may result from the fact that present models may not yet be suited to capture values with great small-scale variability. Here, model-based reservoir ages appear far too low in LGM regions influenced by regional upwelling such as the South China Sea then governed by an estuarine overturning system (Wang et al., 2005; Fig. 8), by coastal upwelling off N.W. Australia (Xu et al., 2010; Sarnthein et al., 2011), or by a melt water lid such as off eastern New Zealand (Bostock et al., 2013; Küssner et al., 2019, in prep.). Local oceanic features are likely to be missed in model simulation, for example, by comparison to details in modern current geometry displayed by Yashayaev et al. (2015) because of a model resolution still too coarse, a lack that suggests directions for future model refinement. More narrow-spaced empiric data will help to weight more correctly and develop the skill of models to capture past ^{14}C reservoir ages.

Various differences amongst plankton- and model-based reservoir ages may result from differential seasonal habitats of the different planktic species analyzed that, in turn, may trace different surface and subsurface water currents. Pertinent details are largely unknown for the modern scenario because of the ‘bomb effect’, likewise no pertinent data exist yet for the LGM. However, distinct interspecies differences were found in the northern Norwegian Sea for the time span of the Preboreal ^{14}C plateau, 9.6–10.2 cal. ka (Sarnthein and Werner, 2018). These differences amount up to 600 yr amongst paired ^{14}C records of Arctic *Turborotalita quinqueloba* dominantly formed close to the sea surface during peak summer, Arctic *Neogloboquadrina pachyderma* formed in subsurface waters, and the subpolar species *N. incompta* mainly advected from the south by Norwegian

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Current waters well mixed with the atmosphere during peak winter. This makes closer specification of model results as product of different seasonal extremes a further target.

3.5 Plankton-based ^{14}C reservoir ages – A prime database to estimate past changes in the ^{14}C ventilation age of deep waters, ocean MOC, and DIC for past states of the ocean

'Raw' apparent benthic ventilation ages (in ^{14}C yr; 'raw' *sensu* Balmer et al., 2018) express the difference between the (coeval) atmospheric and benthic ^{14}C levels measured at any site and time of foraminifer deposition. These ages are the sum of (1) the planktic reservoir age of the ^{14}C plateau that covers a group of paired benthic and planktic ^{14}C ages and (2) the (positive or negative) ^{14}C age difference between any benthic ^{14}C age and the average ^{14}C age of the paired planktic ^{14}C plateau. The benthic ventilation ages necessarily rely on the high quality of ^{14}C plateau-based chronology, since the atmospheric ^{14}C level has been subject to substantial short-term changes over glacial-to-deglacial times. Necessarily, the ventilation ages include a mixing of different water masses that might originate from different ocean regions and may contribute differential ^{14}C ventilation ages, an unknown justifying the modifier 'apparent'.

In a further step, the $\Delta\Delta^{14}C$ equivalent of our 'raw' benthic ventilation age may be adjusted to changes in atmospheric ^{14}C that occurred over the (short) time span between deep-water formation and benthic sediment deposition (e.g., Balmer and Sarnthein, 2018; Cook and Keigwin, 2015). In most cases, however, this second step is omitted since its application usually does not imply any major modification of the ventilation age estimates (Fig. S4a; Skinner et al., 2017; Sarnthein et al., 2013).

On the basis of ^{14}C plateau tuning we now can rely on 18 precisely dated records of apparent benthic ^{14}C ventilation ages (Fig. S4a-c) to reconstruct the global geometry of LGM and HS-1 deep and intermediate water circulation as summarized in ocean transects of Figs. 8 and 9. The individual matching of our 20 planktic ^{14}C plateau sequences with that of the Suigetsu atmospheric ^{14}C record is displayed in Sarnthein et al. (2015), Balmer et al., (2016), Küssner et al. (2019, in prep.), and Ausin et al. (2019, in prep.). In addition, robust estimates of past reservoir ages are obtained for 4 planktic and benthic ^{14}C records from paired atmospheric ^{14}C ages of wood chunks (Rafter et al., 2018; Zhao and Keigwin, 2018; Broecker et al., 2004).

3.5.1 — Major features of ocean meridional overturning circulation during LGM (Fig. 9)

Off Norway and near the Azores Islands very low benthic ^{14}C ventilation ages of <100–750 yr suggest ongoing deep-water formation in the LGM northern North Atlantic reaching down to more than 3000–3500 m water depth, with a flow strength possibly similar to today (and a coeval deep countercurrent of old waters from the Southern Ocean flowing along the East Atlantic continental margin off Portugal). This pattern clearly corroborates the assembled benthic $\delta^{13}C$ record showing plenty of elevated $\delta^{13}C$ values for the northwestern, eastern and central North Atlantic (Sarnthein et al., 1994; Millo et al., 2006; Keigwin and Swift, 2017). Irrespective of unspecified potential zonal variations in deep-water ventilation age at mid latitudes and different from a number of published models (e.g., Ferrari et al., 2014; Butzin et al., 2017) this 'anti-estuarine' pattern has been confirmed by MIROC model simulations (Gebbie, 2014; Sherriff-Tadano et al., 2017, Yamamoto et al., 2019) and, independently, by ε_{Nd} records (Howe et al., 2016; Lippold et al., 2016). The latter suggest an overturning of AMOC possibly even stronger than today,

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

in particular due to a 'thermal stronghold' overlooked in other model simulations. Muglia et al. (2018) tested in their model also a number of different AMOC flows with a strength of 6, 8, 9, and 13 Sv each, with estimates of 13 Sv appearing somewhat more consistent with our results.

In contrast to the northern North Atlantic, North Atlantic Deep Waters and old Circumpolar (CP) deep waters in the subpolar South Atlantic show an LGM ^{14}C ventilation age of ~3640 yr, finally rising up to 4100 yr (Fig. 9). These waters were upwelled and admixed from below to surface waters near to the sub-Antarctic Front during terminal LGM (Fig. S4b; Skinner et al., 2010; Balmer and Sarnthein, 2016; model of Butzin et al., 2012).

In the southwestern South Pacific abyssal, in part possibly Antarctic-sourced waters (Rae and Broecker, 2018) likewise show high apparent ^{14}C ventilation ages that rise from 3900 to 4800 yr over the LGM, in particular close to its end (Figs. 9 top and S4c) (^{14}C dates of Ronge et al., 2016, modified by planktic ^{14}C reservoir ages of Küssner et al., 2019). A vertical transect of benthic $\delta^{13}C$ (McCave et al., 2008) suggests that the abyssal waters were overlain by CP waters, separated by pronounced stratification near ~3500–4000 m water depth. In part, the CP waters stemmed from North Atlantic Deep Water. Probably, their apparent ventilation age came close to 3900–4500 yr, similar to the values found in the southern South Atlantic. East of New Zealand the CP waters entered the deep western Pacific and spread up to the subpolar North Pacific, where LGM ^{14}C ventilation ages reached 3700 yr.

Similar to today, the MOC of the LGM Pacific was shaped by estuarine geometry, probably more weakened than today (Du et al., 2018) and more distinct in the far northwest than in

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

the far northeast. This geometry resulted in an upwelling of old deep waters in the subarctic Northwest Pacific, here leading to a ^{14}C reservoir age of ~1700 yr for surface waters at terminal LGM. On top of the Lower Pacific Deep Waters we may surmise Upper Pacific Deep Waters that moved toward south (Fig. 9, top panel).

The Pacific deep waters were overlain by Antarctic / Pacific Intermediate Waters (IW) with LGM ^{14}C ventilation ages as low as 1400–1600 yr, except for a shelf ice-covered site at the southern tip of Chile with IW ages of 2460–3760 yr, possibly a result of local upwelling of CP waters. In general, however, the low values of Pacific IW are similar to those estimated for South Atlantic IW and likewise reflect a vivid exchange with atmospheric CO_2 in their source regions in the Southern Ocean (Skinner et al., 2015).

When entering and crossing the entrance sill to the marginal South China Sea the 'young' IW were mixed with 'old' CP waters entrained from below, here leading to ^{14}C ventilation ages of 2600–3450 yr (Figs. 8 and S4d). The LGM South China Sea was shaped by an estuarine-style overturning system marked by major upwelling near to its distal end in the far southwest (Wang L. et al., 1999). This upwelling led to planktic ^{14}C reservoir ages as high as 1200–1800 yr, values rarely found elsewhere in surface waters of low latitudes.

Our wide-spaced distribution pattern of 18 ^{14}C ventilation ages (plus 4 values based on paired wood chunks) in Fig. 9 agrees only in part with the circulation patterns suggested by the much larger datasets of ^{14}C ventilation ages compiled by Skinner et al. (2017) and Zhao et al. (2018). Several features in Fig. 9 directly deviate, e.g., the ages we derive for the North Atlantic and mid-depth Pacific. These deviations may be linked to both the different derivation of our ^{14}C ventilation age estimates and the details of our calendar-year

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

chronology now based on the narrow-standing suite of ^{14}C plateau-boundary ages. The quality of our ^{14}C reservoir ages of surface waters also controls the apparent ventilation age of deep-waters, as it results from direct subtraction of a short-term ^{14}C average of an atmospheric ^{14}C plateau from the paired benthic ^{14}C value, that is coeval with the planktic ^{14}C plateau during the time of benthic foraminifera growth.

3.5.2 — Major features of meridional overturning circulation during early HS-1 (Fig. 9)

Near the onset of deglacial Heinrich Stadial 1 (HS-1; ~18–14.7 cal. ka) major shifts in ^{14}C ventilation age suggest some short-lasting but fundamental changes in the circulation geometry of the deep ocean, a central theme of marine paleoclimate research (Fig. 7, lower panel of Fig. 9, and Figs. S2, S4a and b). Deep waters in the eastern Nordic Seas, west of the Azores Islands, and off northern Brazil show a rapid rise to high ^{14}C ventilation ages of ~2000–2500 yr and up to 4000 yr off Brazil, values that give first proof for a brief switch from ‘anti-estuarine’ to ‘estuarine’ circulation that governed the central North Atlantic and Norwegian Sea during early HS-1. This geometry continued – except for a brief but marked and widespread event of recurring NADW formation near 15.2 ka – until the very end of HS-1 near 14.5 ka (Fig. S4a; Muschitiello et al., 2019). The MOC switch from LGM to HS-1 is in line with changes depicted in paired benthic $\delta^{13}C$ data (Sarnthein et al., 1994), but not confirmed by the coeval ε_{Nd} record that suggests a constant source of ‘mid-depth waters’, with the $\delta^{13}C$ drop being simply linked to higher ages (Howe et al., 2018).

Conversely, benthic ^{14}C ventilation ages in the northeastern North Pacific (Site MD02-2489) show a coeval and distinct but brief minimum of 1050-1450 yr near 3640 m w.d.

during early HS-1 (~18.1–16.8 ka; Figs. 9, S2, and S4d). This minimum was produced by extremely small benthic-planktic age differences of 350–650 yr and provides robust evidence for a short-lasting event of deep-water formation, that has flushed the north-eastern North Pacific down to more than 3640 m w.d. (Gebhardt et al., 2008; Sarnthein et al., 2013; Rae et al., 2014). Similar circulation geometries were reported for the Pliocene (Burls et al., 2017). 'Young' Upper North Pacific Deep Waters (North Pacific Intermediate Waters *sensu* Gong et al., 2019) then penetrated as 'western boundary current' far south, up to the northern continental margin of the South China Sea (Fig. 8b and S4d). The short-lasting North Pacific regime of anti-estuarine overturning was similar to that we find in the modern and LGM Atlantic and, most interesting, simultaneous with its estuarine episode.

Recent data on benthic-planktic ^{14}C age differences (Du et al., 2018) precisely recover our results at ~680 m w.d. off southern Alaska. However, they do not depict the 'young' deep waters at their Site U1418 at ~3680 m w.d., as corroborated by a paired autigenic ε_{Nd} maximum suggesting a high local bottom water age nearby. We assume that the amazing difference in local deep-water ventilation ages is due to small-scale differences in the effect of Coriolis forcing at high latitudes between a site located directly at the Alaskan continental margin (U1418; Fig. 9b) and that on the distal Murray Sea Mount in the 'open' Pacific (MD02-2489; Fig. S4d), which has been washed by a plume of newly formed North Pacific deep waters probably stemming from the Bering and/or Ochotsk Seas. In contrast, the incursion of almost 3000 yr old deep waters from the Southern Ocean has continued along the continental margin all over HS-1. In summary we may conclude that the geometry of ocean MOC was briefly reversed in the 'open' North Pacific over almost 1500 years during HS-1, far deeper than suggested by previous authors (e.g., Okazaki et al.,

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

2012; Gong, S., et al. 2019), but similar to changes in geometry first proposed by Broecker et al. (1985) then, however, for an LGM ocean.

3.5.3 — Deep-Ocean DIC inventory

Apart from the changing geometries in ocean MOC, the global set of ^{14}C plateau-based, hence refined estimates of apparent ^{14}C ventilation ages (Fig. 9) has ultimately revealed new insights into glacial-to-deglacial changes in the ocean DIC inventories (Sarnthein et al., 2013). On the basis of GLODAP data (Key et al., 2004) any drop in ^{14}C concentration (i.e., any rise in average ^{14}C ventilation age) of modern deep waters is tied linearly to a rise of carbon (DIC) dissolved in deep ocean waters below ~2000 m, making for 1.22 micromole C / -1 ‰ ^{14}C. By and large, GCM and box model simulations of Chikamoto and Abé-Ouchi (2012) and Wallmann et al. (2016) suggest that this ratio may also apply to LGM deep-water circulation, when apparent ^{14}C ventilation ages in the Southern Ocean increased significantly (from 2400 up to ~5000 yr) and accordingly, thermohaline circulation was more sluggish and transit times of deep waters extended. Accordingly, a ‘back-of-the-envelope’ calculation of LGM ventilation age averages in the global deep ocean suggests an additional carbon absorption of 730–980 Gt (Sarnthein et al., 2013). This estimate can easily accommodate the glacial transfer of ~200 Gt C from the atmosphere and biosphere, moreover, may also explain 200–450 Gt C then most probably removed from glacial Atlantic and Pacific intermediate waters. These estimates offer an independent evaluation of ice core-based data, other proxies, and model-based data on past changes in the global carbon cycle (e.g., Menviel et al., 2018).

4. SOME CONCLUSIONS

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

– Regarding the upgraded Plateau-Tuning, despite some analytical scatter, ^{14}C ages for the top and base of Lake Suigetsu-based atmospheric ^{14}C plateaus and coeval planktic ^{14}C plateaus do not present statistical 'outliers' but real age estimates that are reproduced by tree ring-based ^{14}C ages over the interval 10–13 cal. ka and further back.

– Hulu U/Th model-based ages of ^{14}C plateau boundaries of the Suigetsu atmospheric ^{14}C record appear superior to those derived from microscopy-based varve counts only, since U/Th model-based ages match far more closely the age deduced from XRF-based varve counts for a crucial test case of lower plateau boundary 2b in the early deglacial, moreover, the age assigned to the Laschamp event.

– During deglacial times, several ^{14}C plateaus paralleled a rise in air-sea gas exchange, and, in turn, distinct changes in ocean MOC. By contrast, changes in cosmogenic ^{14}C production rarely offer a complete explanation for the plateaus identified in the Suigetsu ^{14}C data under discussion.

– In total, ^{14}C plateau boundaries in the range 29–10 cal. ka provide a suite of ~30 tie points to establish – like chronological ladder rungs – a robust global age control for deep-sea sediment sections and global stratigraphic correlations of last glacial to deglacial climate events, 29–10 cal. ka. U/Th model ages confine the cal. age uncertainty of Suigetsu plateau boundaries assigned halfway between two ^{14}C ages nearby inside and outside a plateau's scatter band to less than ±50–±70 yr.

– Regarding oceanographic implications, ^{14}C ages in a sediment section that form a separate population of ^{14}C outliers clearly distinct from the 'normal' ^{14}C plateau suite help to trace the reach and origin of Zoophycos burrows, a key 'foe' of high-resolution stratigraphy in marine sediment cores, and allow for inferences on their origin in a major reduction in sediment and nutrient supply.

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

– The difference in ^{14}C age between coeval atmospheric and planktic ^{14}C plateaus presents a robust tracer of planktic ^{14}C reservoir ages and their temporal and spatial variability, for the LGM and HS-1 now established for 18/20 sediment sites.

– Paired reservoir ages obtained from different planktic species document the local distribution patterns of different surface water masses and prevailing foraminiferal habitats at different seasons.

– A new, more reliable set of deep-water ^{14}C ventilation ages can be derived on the basis of our robust planktic ^{14}C reservoir ages. These ventilation ages reveal geometries of LGM overturning circulation, the main traits of which are similar to those of today. In contrast, ^{14}C ventilation ages of early HS-1 suggest an almost 1500 yr long event of widely reversed circulation patterns marked by deep-water formation and brief flushing of the northern North Pacific and estuarine circulation geometry in the northern North Atlantic.

– Increased glacial ^{14}C ventilation ages and carbon (DIC) inventories of ocean deep waters suggest an LGM drawdown of about 850 Gt C into the deep ocean and an early deglacial abrupt carbon release to the atmosphere during HS-1 (Sarnthein et al., 2013).

– Comparison of planktic and model-based reservoir age estimates reveals some major discrepancies, in particular at sites in middle to high latitudes, and pointe the way to further model refinements to make the models better reflect the real complex patterns of ocean circulation, including seasonality.

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https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Climate of the Past
Discussions

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Author contribution

All authors contributed data and valuable suggestions to write up this synthesis. MS and PG designed the outline of this manuscript. KK, BA, TE and MS provided new marine 14C records in addition to records previously published. GS displayed the details of Suigetsu varve counts. RM provided a ^{10}Be-based ^{14}C record and plots of raw ^{14}C data sets of Suigetsu und Hulu Cave. Discussions amongst PG, RM, GS and MS served to select U/Th-based model ages as best-possible time scale.

Data availability

Primary radiocarbon data of most sites are available at PANGAEA de, except for the ^{14}C data of 5 marine cores still under publication by Küssner et al. and Ausin et al. (in prep.; see caption of Fig. S4).

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Discussions
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https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Climate of the Past
Discussions
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TABLE CAPTIONS

~~V~~ **Table 1 a and b.** Summary of varve- and U/Th model-based age estimates (Schlolaut et al., 2018; Bronk Ramsey et al., 2012) for ~30 plateau (pl.) boundaries in the atmospheric ^{14}C record identified in Lake Suigetsu Core $SG06_{2012}$ by means of visual inspection over the interval 10.5–27 cal. ka (Sarnthein et al., 2015, suppl. and modified). At the right hand side, three columns give the average (Ø) and uncertainty range of ^{14}C ages for each ^{14}C plateau.

SUIGETSU SG06_2012 Plateau no.	Plateau Top **Varve-based** age (yr BP)	***U/Th-based*** *age (yr BP)*	Depth (cm c.d.)	Plateau Base **Varve-based** age (yr BP)	***U/Th-based*** *age (yr BP)*	Depth (cm c.d.)	Ø 14C Age of 14C Plateau (14C yr)	±Uncertainty (14C yr)	14C age BP min/max. (1.6 σ range)
'Preboreal'	10525	***10560***	1325	11100	***11108***	1383	**9525**	–170/+110	9356/9635
'Top YD'	11290	***11281***	1402	11760	***11755***	1453	**10060**	–100/+35	9963/10095
'YD'	11950	***11895***	1467	12490	***12475***	1525	**10380**	–170/ 124	10211 10504
1a	13580	***13656***	1626	13980	***14042***	1657	**12006**	100	11857 12050
1	14095	***14160***	1666	15095	***15100***	1740	**12471**	185	12315 12683
2a	15310	***15420***	1754	16140	***16520***	1802	**13406**	245	13174 13665
2b	16075	***16520***	1802	16400	***16930***	1820	**13850**	40	13808 13885
3	16835	***17500***	1847	17500	***18220***	1888	**14671**	105	14582 14792
4	17880	***18650***	1913	18830	***19590***	1971	**15851**	190	15661 16044
5a	18960	***19720***	1978	19305	***20240***	2003	**16670**	90	16570

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Climate of the Past
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Discussions
EGU

									16750
5b	19305	***20240***	2003	20000	***20900***	2032	**17007**	190	16830 17247
6a	20190	***21000***	2050	20920	***21890***	2105	**17667**	262	17435 17960
6b	20920	***21890***	2105	21275	***22300***	2132	**18075**	140	17960 18240
7	21375	***22400***	2140	21790	***22870***	2171	**18843**	117	18741 18975
8	21835	***22940***	2175	22730	***24250***	2257	**19715**	–290 325	19425 20041
9	22730	***24250***	2257	23395	***25150***	2312	**20465**	–227 263	20238 20728
10a	23935	***25880***	2358	25080	***27000***	2400	**22328**	–380 270	21946 22600
10b	25080	***27000***	2400	25800	***27600***	2426	**22708**	–475 440	22233 23147
11	26110	***27770***	2443	27265	***28730***	2525	**24088**	–360 505	23727 24595

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Table 2. Temporal match of ^{14}C plateaus and deglacial periods of major degassing of the ocean (AA = Antarctic).

DEGLACIAL EVENTS of pCO_2 RISE vs. age of pla. ^{14}C PLATEAUS (in cal. ka)

pCO_2 RISE (~12 ppm) AGE based on annual layers AA ice core (Marcott et al. 2014)	Plateau no.	Plateau boundaries AGE (cal. ka) based on varve counts (Schlolaut et al. 2018; Bronk Ramsey et al., 2012)	**U/Th model ages**
11.7 – 11.5	# 'Top YD'	11.76 – 11.32	**11.83 – 11.3**
14.8 – 14.53	# 1	15.1 – 14.1	**15.1 – 14.2**
16.4 – 16.15	# 2a	16.14 – 15.3	**16.52 – 15.5**
17.4 – ~17.1	# 3	17.5 – 16.83	**18.22 – 17.5**
FURTHER POTENTIAL CORRELATIVES:			
Progressive N. Atlantic warming during the YD at 12.39 – 12.03 ka *	# 'YD'	12.49 – 11.87	**12.46 – 11.98**
Onset of Antarctic ** warming at 18.3–17.6 ka (ice-based time scale)	#3	17.5 – 16.85	**18.22 – 17.5**
Onset of North Atlantic *** warming at 19.3–18.6 ka (U/Th-based time scale)	# 4	18.83 – 17.9	**19.6 – 18.65**
Top H2: GIS 2 N. Atlantic warming at 23.4 – 23.3 ka ****	#9 / #8	23.4 – 22.73	**24.25 – 22.95**

AGE CONTROL based on

* Naughton et al. (2019)

** Kawamura et al. (2007)

*** Balmer and Sarnthein (2018)

**** Grootes and Stuiver (1997)

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Climate of the Past
Discussions

~~V~~ **Table 3** a-c. ^{14}C reservoir / ventilation ages of surface (top 50-100 m) and bottom waters vs. U/Th-based model age at 19/22 core sites in the ocean – (a) Spatial and temporal changes over the LGM (22–20 and 20–18 cal. ka), (b) HS-1, and the B/A. LGM estimates are compared to model-based estimates of Muglia et al. (2018). (c) Data sources. For core locations see Fig. S2.

(a)

Sediment Core U/Th-based model age Plateau (Pl.) no.	Latitude	Longitude	Water depth (m)	LGM pla. res age 24–21 ka Pl. 8 - 7 - 6	Error (yr)	21–18.7 ka Pl. 5 - 4/3 (yr)	Error (yr)	LGM model res. age strong AMOC (yr)	weak (yr)
ATLANTIC O.									
PS2644	67°52.02'N	21°45.92'W	777	2100	±390	1920–2200	±325 –±125	1136	1100
GIK 23074	66°66.67'N	4°90'E	1157	620–790	±145–±270	550–1175	±100–±200	1054	1059
MD08-3180	38°N	31°13.45'W	3064	–		320–605	±125–±405	827	887
SHAK06-5K	37°34'N	10°09'W	2646	700–930		330–650		872	855
(= MD99-2334)	(37°48'N	10°10'W	3146						
ODP 1002	10°42.37'N	65°10.18'W	893	700–210	±230–±310	25 – -205	±205–±215	751	738
GeoB 3910-1	4°15'S	36°21'W	2361	–		–		779	796
GeoB 1711-4	23°17'S	12°23'W	1976	1080	±290	730–840	±240–±190	711	721
KNR 159-5-36GG	27°31'S	46°48'W	1268	540	±140	870	±120	757	777
MD07-3076	44°4'S	4°12'W	3770	–		2300	±200	928	989
INDIAN O./TIMOR SEA									
MD01-2378	13°08.25'S	121°78.8'E	1783	–		2000–1700	±300–±320	885	890
PACIFIC O.									
MD02-2489	54°39.07'N	148°92.13'V	3640	–		1560–1110	±310–±335	972	965
MD01-2416	51°26.8'N	167°72.5'E	2317	–		1710	±440	1227	1202
ODP 893A	34°17.25'N	120°02.33'V	588	–		1065	±280	839	846
MD02-2503	34°16.6'N	120°01.6'W	580	–		–		839	846
GIK 17940	20°07.0'N	117°23.0'E	1727	1820–1260	±320–±230	hiatus		836	838
(= SO50-37)	18°55'N	115°55'E	2655	1820–1260				836	840
PS75/104-1	44°46'S	174°31'E,	835	1650–1280		1500		881	895
(= SO213-84)	45°7.5'S	174°34,9'E	972	1650–1280		1500		881	895
MD07-3088	46°S	75°W	1536	380		200-350		917	–
SO213-76-2	46°13'S	178°1.7´W	4339	–		1600–1560		915	842
PS97/137-1	52°39.5'S	75°33.9'E	1027	2290–2110		2400–1800		1505	1419

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

(b)

Sediment Core	HS-1 pla. res. age				B/A pla. res. age		LGM be. vent age		LGM b.w. model age	
U/Th-based model	18 –16.5 ka		16.5–15.5 ka		14.7 –13.6 ka		(yr)		strong AMOC	weak
Plateau (Pl.) no.	Pl. 3 - 2b (yr)	Error (yr)	Pl. 2a (yr)	Error (yr)	Pl. 1 - 1a	Error (yr)	early	late	(yr)	(yr)
ATLANTIC O.										
PS2644	1775–1660	±105–±160	1900	±355	–		345	2400	948	918
GIK 23074	1730–2000	±125–±160	670	±310	140–310	±250–±100	375	375	960	931
MD08-3180	1420–1610	±310–±160	1460	±390	630–360	±310	600	600	1031	1004
SHAK06-5K	350–420		550		800–1200		—		—	—
(= MD99-2334)							2200–2700	1900	—	—
ODP 1002	–100 – 20	±140	90	±345	355	±200	—		1247	1175
GeoB 3910-1	630–560	±160–±180	175	±475	210–230	±220–±110	2150	2150	—	—
GeoB 1711-4	660–690	±195–±45	420	±320	880	±255	1500	1500	1387	1714
KNR 159-5-36GGC	460–340	±380–±300	170	±700	180–230	±370–±310	1470	1470	1354	1563
MD07-3076	1650	±180	–		920	±230	3640	3640	1653	2060
INDIAN O./TIMOR SEA										
MD01-2378	740	±125	–		200–185	±345–±135	2720	—	1679	1881
PACIFIC O.										
MD02-2489	800–550	±155–±120	550	±305	440	±285		2625	2332	2595
MD01-2416	1480–1140	±135–±195	–		720–570	±285–±140		3700/510	2400	2683
ODP 893A	1065–1490	±280–±125	1400	±370	520	±185		1430	1677	1705
MD02-2503	965–1365	±160–±165	1215	±325	395–535	±240–±130	—	—	—	—
GIK 17940	1210–1370	±200–±470	1045	±320	870–970	325–±100	3300–1800		1807	1897
(= SO50-37)							3225	3225	2373	2667
PS75/104-1	1050		1100		800–250		—	—	—	—
(= SO213-84)							1500	2400	1101	1146
MD07-3088	800–1090		1010		730–940		1600	1600	1808	1701
SO213-76-2	200		–		–		4685	4685	1712	2001
PS97/137-1	1500–670		435		–		3300	2100	1631	1871

(c)

Sediment Core	DATA Source	
ATLANTIC O.		
PS2644	Samthein et al. 2015	Be.data suppl.
GIK 23074	Samthein et al. 2015	
MD08-3180	Balmer et al. 2018	
SHAK06-5K	Ausin et al., 2019	
(= MD99-2334)	Skinner et al. 2014	
ODP 1002	Samthein et al. 2015	
GeoB 3910-1	Balmer et al. 2016	
GeoB 1711-4	Balmer et al. 2016	
KNR 159-5-36GGC	Balmer et al. 2016	data suppl.
MD07-3076	Balmer et al. 2016	
INDIAN O./TIMOR SEA		
MD01-2378	Samthein et al. 2015	
PACIFIC O.		
MD02-2489	Samthein et al. 2015	
MD01-2416	Samthein et al. 2015	modified
ODP 893A	Samthein et al. 2015	data suppl.
MD02-2503	Samthein et al. 2015	
GIK 17940	Samthein et al. 2015	
(= SO50-37)	Samthein et al. 2015	
PS75/104-1	Küssner et al., 2018	
(= SO213-84)	Ronge et al., 2016	
MD07-3088	Küssner et al., 2019	
SO213-76-2	Küssner et al., 2019	
PS97/137-1	Küssner et al., 2019	

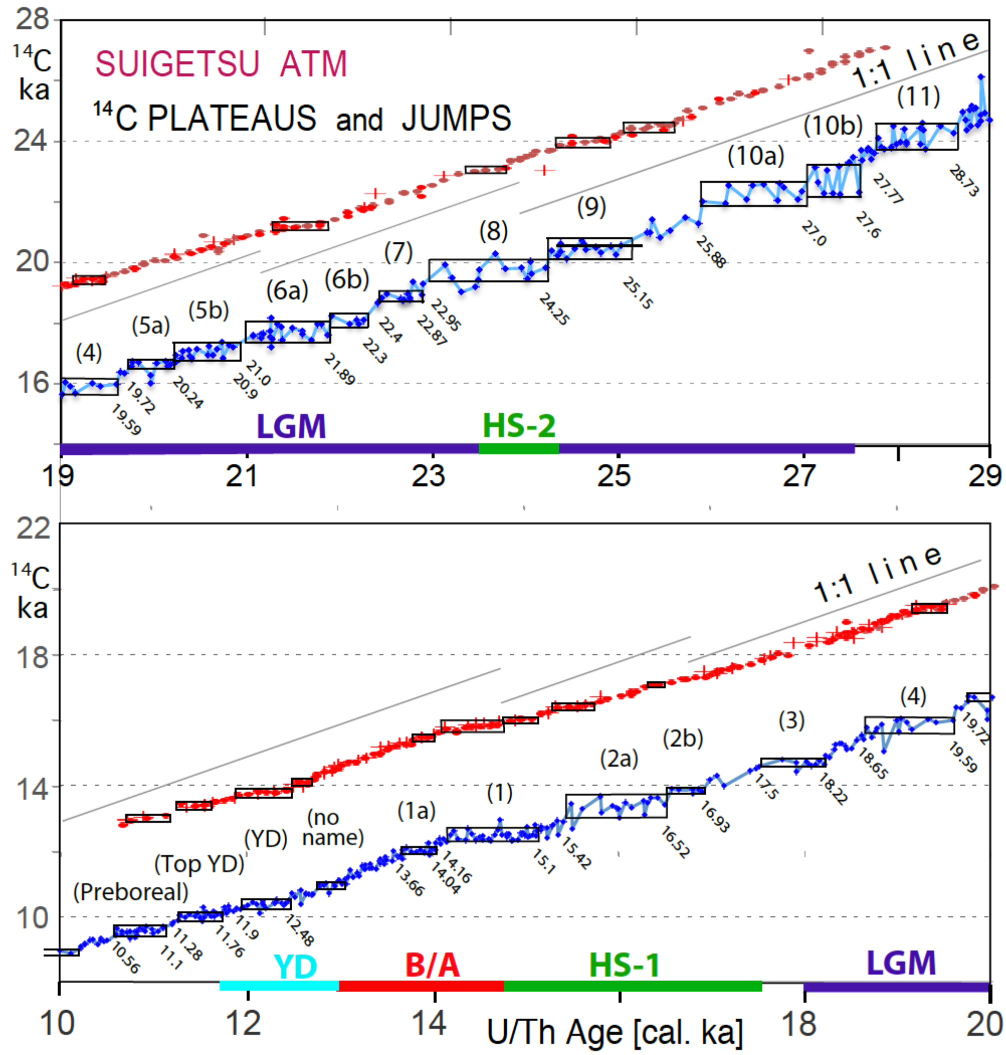
https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019

Climate of the Past
Discussions

FIGURE CAPTIONS

– Fig. 1. Atmospheric ^{14}C ages of Lake Suigetsu plant macrofossils 10–29 cal. ka vs. U/Th-based model age (blue dots; Bronk Ramsey et al., 2012). Double and triple ^{14}C measurements are averaged. (In part large) error bars of single ^{14}C ages are given in Suppl. Fig. S1. Suite of labeled horizontal boxes that envelop scatter bands of largely constant ^{14}C ages shows ^{14}C plateaus longer than 250 yr (plateau boundary ages listed in Table 1). Red and brown dots (core samples from trench and wall) and + signs (off-axis core samples) depict raw ^{14}C ages of Hulu stalagmite core H82 (Cheng et al., 2018; Southon et al., 2012; plot offset by +3000 ^{14}C yr). Suite of short ^{14}C plateaus (black boxes) tentatively assigned to Hulu-based record occupy age ranges slightly different from those deduced for Suigetsu-based plateaus. The difference possibly results from short-term changes in the Old / Dead Carbon Fraction (ocf / dcf) that in turn may reflect major short-term changes in LGM and deglacial monsoon climate (Wang et al., 2001; Kong et al., 2005).

https://doi.org/10.5194/cp-2019-127
Preprint. Discussion started: 25 October 2019



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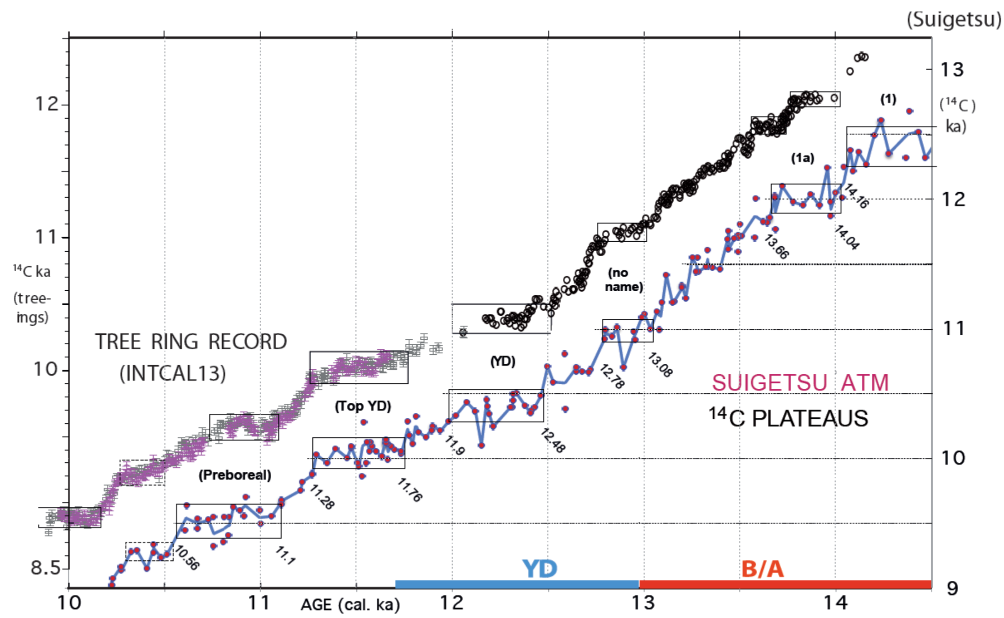
Preprint. Discussion started: 25 October 2019

~~V~~ Fig. 2. High-resolution record of atmospheric ^{14}C jumps and plateaus (= suite of labeled horizontal boxes that envelop scatter bands of largely constant ^{14}C ages extending over >300 cal. yr) in a sediment section of Lake Suigetsu vs. tree ring-based ^{14}C jumps and plateaus 10–14.5 cal. ka (Reimer et al., 2013). Blue line averages paired double and triple ^{14}C ages of Suigetsu plant macrofossils. Age control points (cal. ka) follow varve counts (Schlolaut et al., 2018) and U/Th model-based ages of Bronk Ramsey et al. (2012). YD = Younger Dryas, B/A = Bølling-Allerød.



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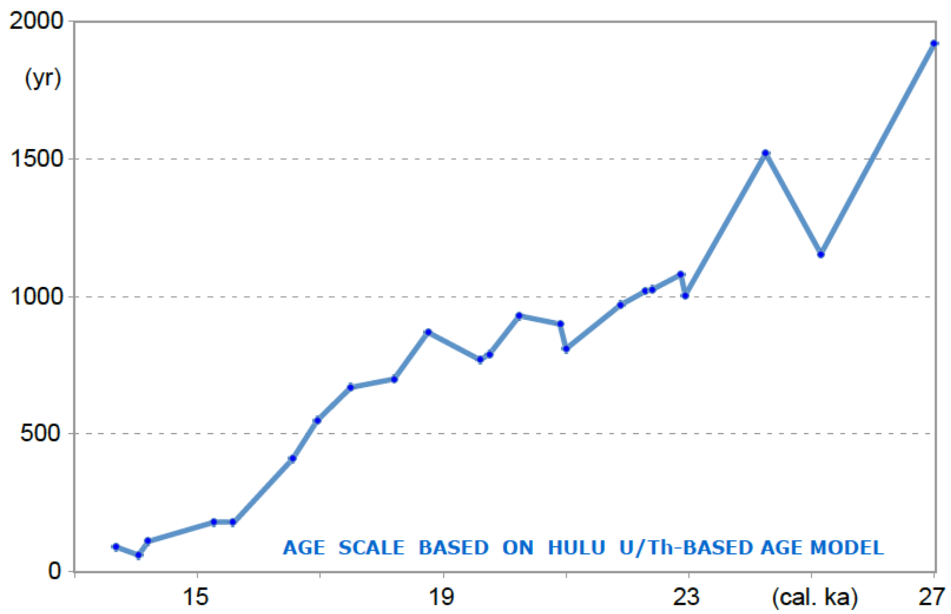
Preprint. Discussion started: 25 October 2019

Climate of the Past Discussions

~~V~~ Fig. 3. Difference between Hulu Cave U/Th-based model ages (Southon et al., 2012; Bronk Ramsey et al., 2012; Cheng et al., 2018) and varve count-based cal. ages for atmospheric ^{14}C plateau boundaries in Lake Suigetsu sediment record (Schlolaut et al., 2018) (Sarnthein et al., 2015, suppl. and revised), displayed on the U/Th-based time scale 13–27 cal. ka.



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Preprint. Discussion started: 25 October 2019

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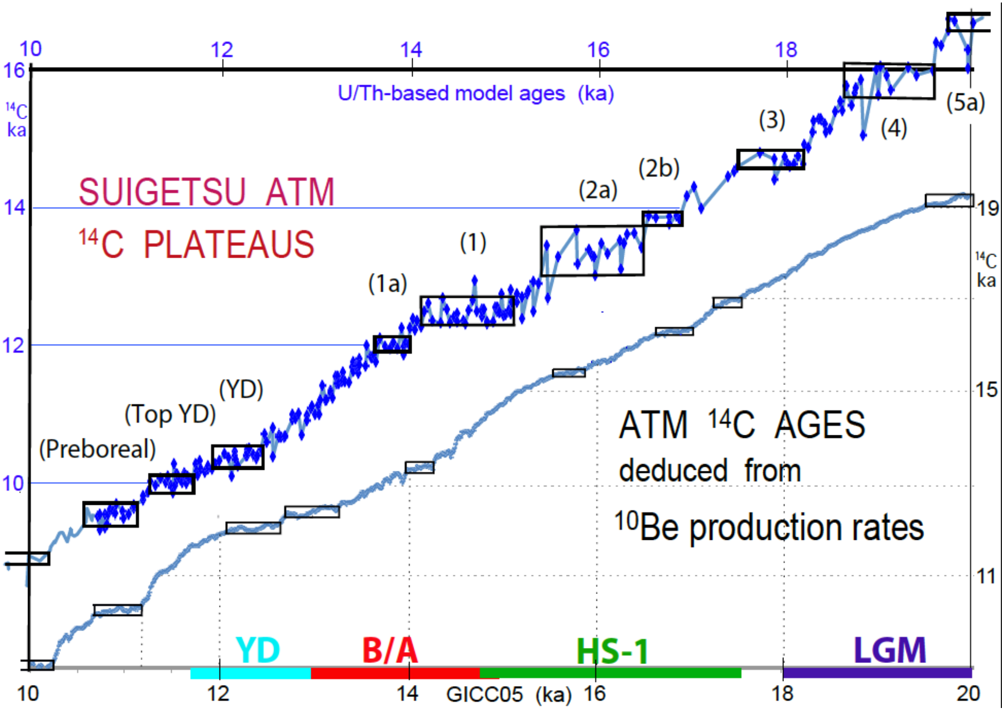
Fig. 4 a and b. Atmospheric ^{14}C ages and plateaus (horizontal boxes) deduced from ^{10}Be production rates vs. GICC05 age scale (Adolphi et al., 2018) compared to the Suigetsu record of atmospheric ^{14}C plateaus vs. Hulu U/Th-based model ages (Southon et al., 2012; Cheng et al., 2018).



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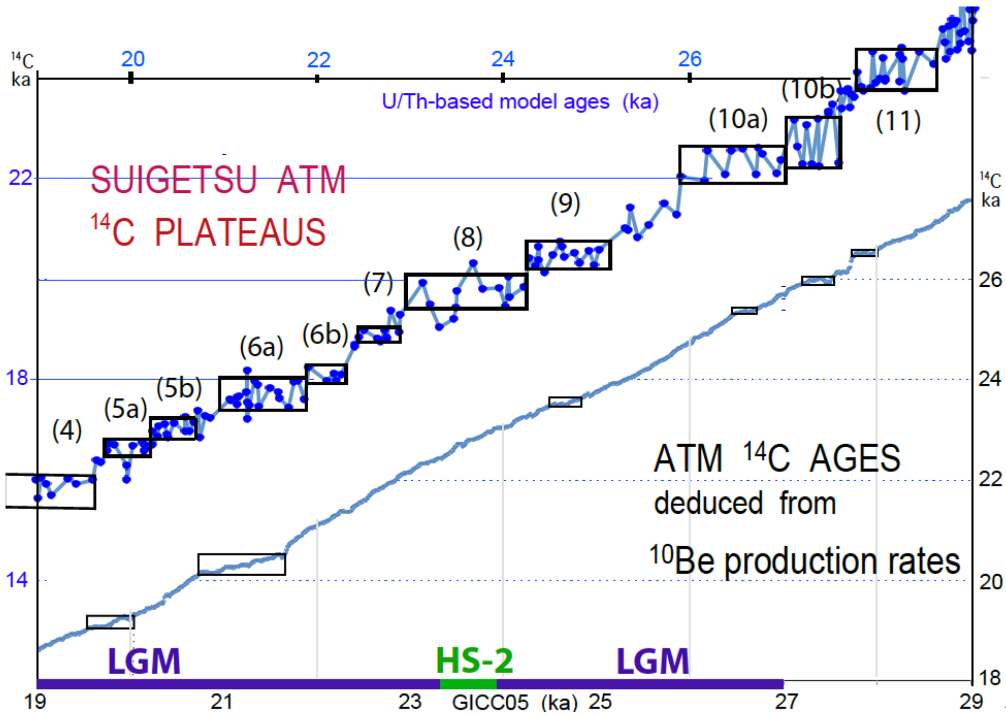
Preprint. Discussion started: 25 October 2019

Climate of the Past
Discussions



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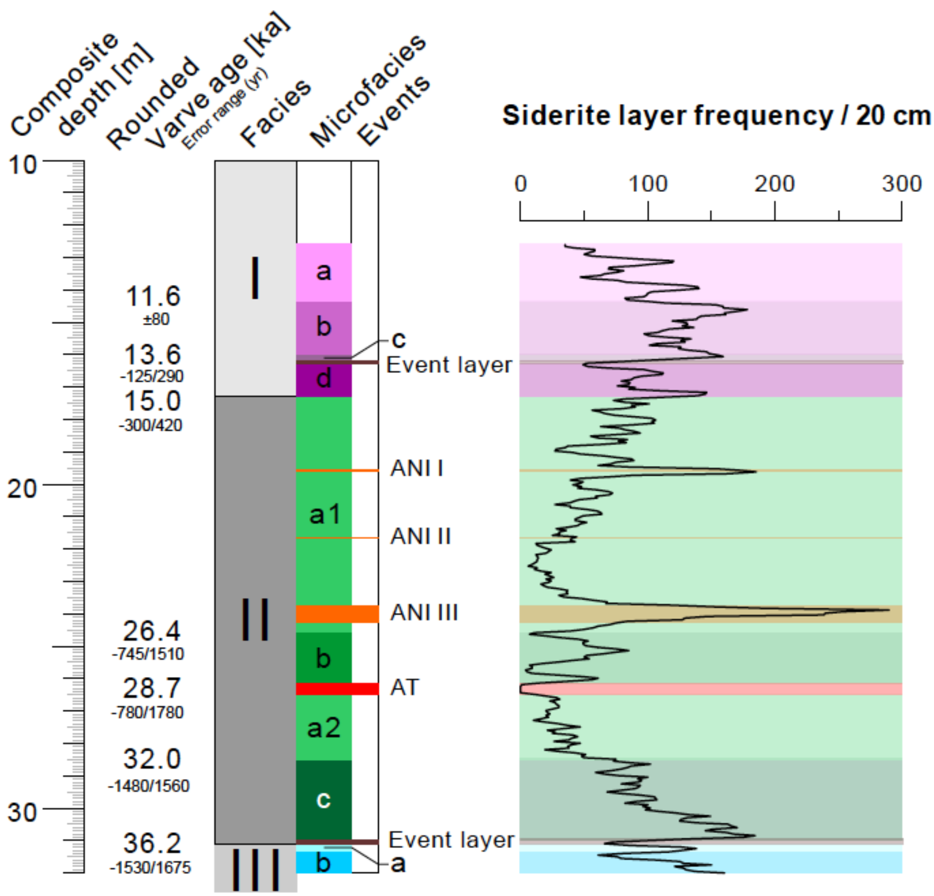
Preprint. Discussion started: 25 October 2019

~~V~~ Fig. 5. Sediment facies and microfacies zones in Lake Suigetsu Core SG06, ~13–32 m depth (simplified and suppl. from Schlolaut et al., 2018). Microscopy-based frequency of siderite layers with quality 1–3 in 20-cm sediment sections (= running average of layer counts for 5 cm thick sections each), a measure of seasonal lamination quality with gradual transitions between varved and poorly varved sediment sections. Rounded varve ages are microscopy based and constrain age of major facies and microfacies boundaries. ANI I to III mark core sections with ultrafine lamination due to sedimentation rate minima, AT marks tephra layer named AT, 'Event layers' label major thin mud slides probably earth quake-induced.



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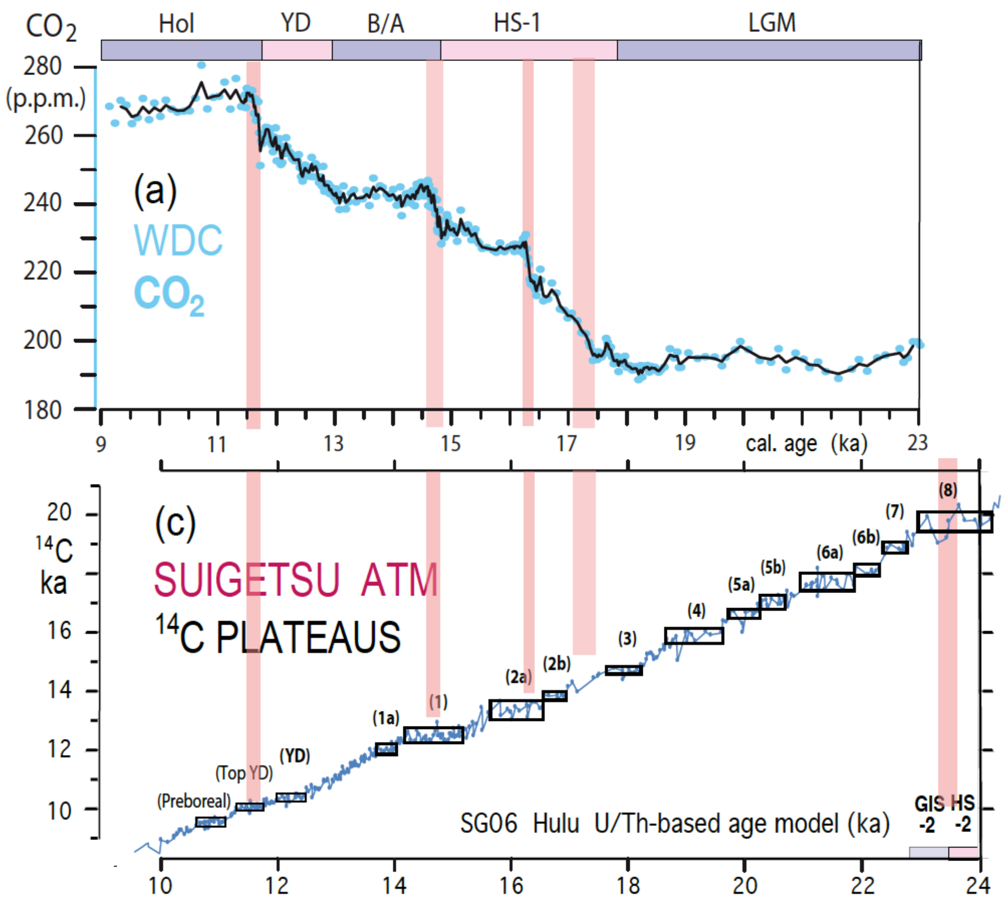
Preprint. Discussion started: 25 October 2019

~~V~~ Fig. 6 (a). Four sudden steps (pink bars) in the deglacial atmospheric CO_2 rise at West Antarctic Ice Sheet Divide ice core (WDC) reflect events of fast ocean degassing, that may have contributed to the origin of deglacial ^{14}C plateaus. Age control based on ice cores (Marcott et al., 2014). (b) The steps are compared to suite of atmospheric ^{14}C plateaus dated by Hulu U/Th-based model ages (Bronk Ramsey et al., 2012). Hol = Holocene; YD = Younger Dryas; B/A = Bølling-Allerød; HS = Heinrich stadial; LGM = Last Glacial Maximum.



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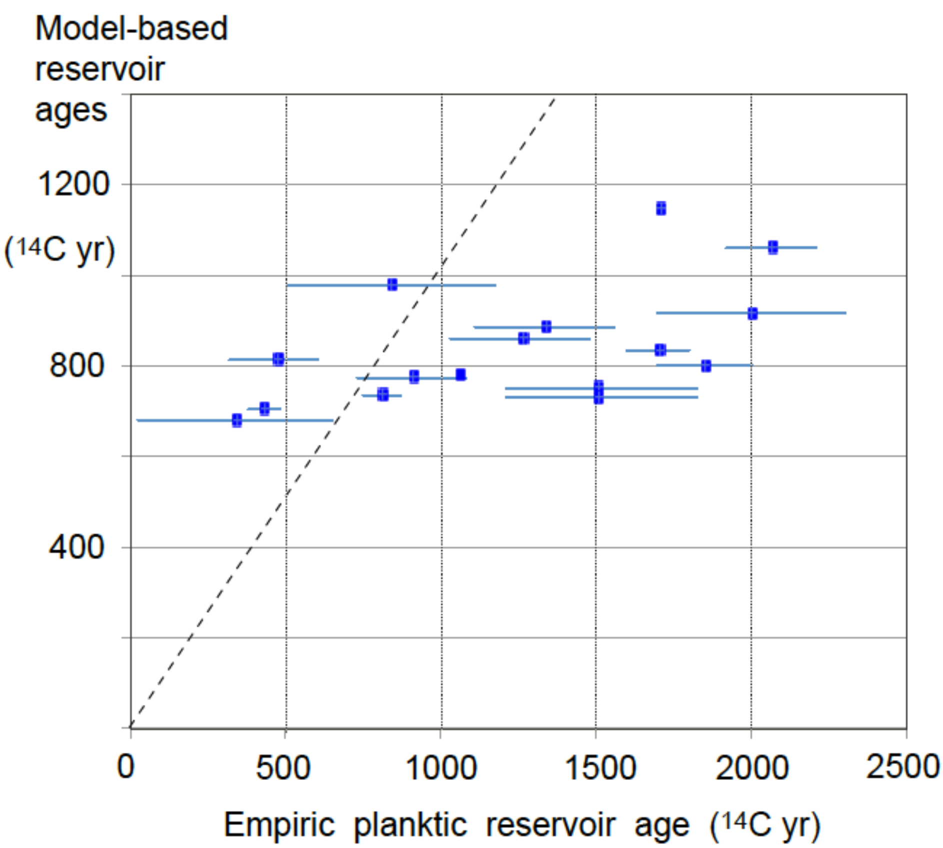
Preprint. Discussion started: 25 October 2019

~~V~~ Fig. 7. Global distribution of ^{14}C reservoir ages of Late LGM surface waters estimated by means of planktic ^{14}C plateau tuning and model-based estimates (general circulation model of Muglia et al., 2018), assuming an AMOC strength of 13 Sv). X-Y graph (a) and map (b) show (rounded) differences and intra-LGM trends with minor differences displayed in magenta, larger differences of >400 yr in red. Planktic habitat depths and model estimates are largely confined to 0–100 m water depth. Regional distribution patterns of LGM surface, intermediate, and deep-water ages are given in Table 3 and Suppl. Fig. S2.



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Discussions

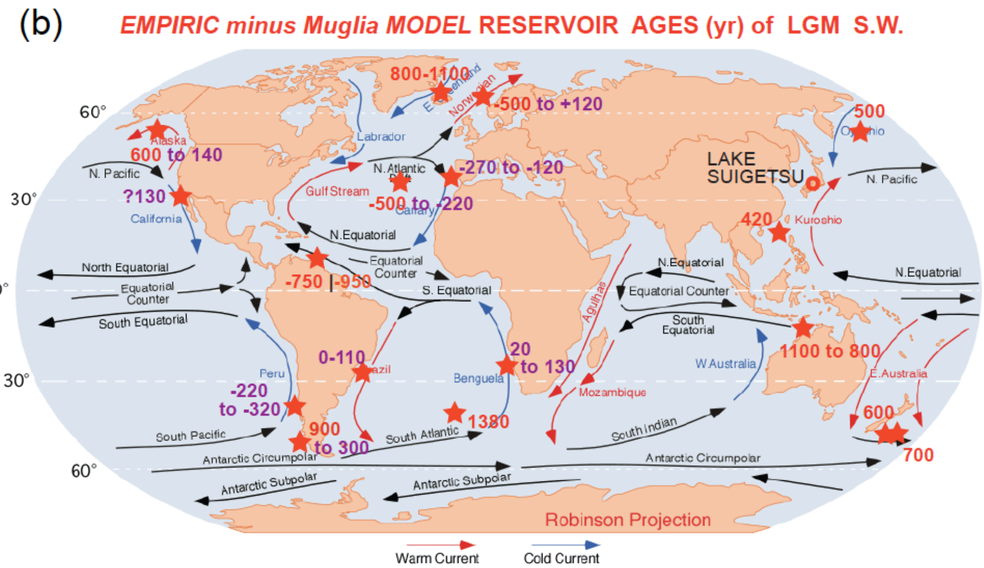

Fig. 8. SW–NE transect of ^{14}C reservoir and changes in ventilation ages across sites GIK17940 and SO50-37 in the South China Sea during late LGM (^{14}C Plateaus 5 an 4; upper panel) and HS-1 (lower panel). Insert map shows location of transect. Core locations are given in Fig. S2. An extreme epibenthic $\delta^{13}C$ minimum in far southwest (Core GIK17964; Sarnthein et al., 1999) reflects an LGM incursion of Lower/Upper Pacific Deep Waters (L./ U. PAC DW) with extremely high ^{14}C ventilation age and DIC enrichment in contrast to a low ventilation age of North Pacific Deep Water (N. PAC DW). Arrows reflect direction of potential deep and intermediate-water currents.

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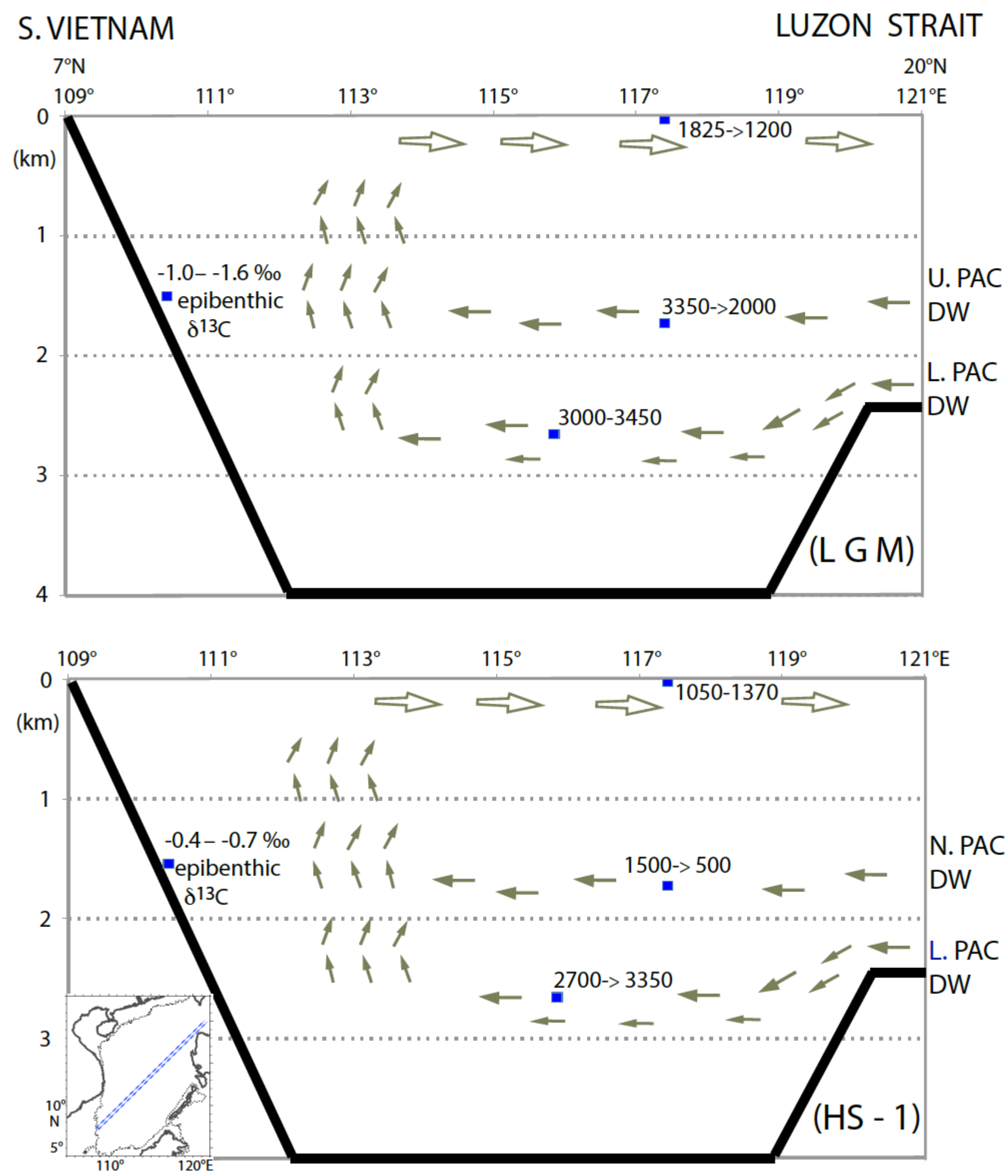
Preprint. Discussion started: 25 October 2019

Climate of the Past
Discussions



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Preprint. Discussion started: 25 October 2019

Climate of the Past
Discussions

~~V~~ Fig. 9. North Atlantic and North Pacific changes in benthic ^{14}C ventilation records reflect seesaw-style reversals in global MOC at the onset and end of early HS-1 (first proposed by Broecker et al., 1985, however, for LGM times). Arrows within numbers show temporal trends (a) Late LGM ocean transect reveals global MOC geometry largely similar to today. Blue and yellow arrows suggest average deep and intermediate-water currents that follow the gradient from low to high ventilation ages based on paired planktic ^{14}C reservoir ages derived by means of the ^{14}C plateau tuning technique (Sarnthein et al., 2013, Balmer et al., 2018, Küssner et al., 2019). Note major east-west gradient between LGM eastern and central Atlantic (off Portugal (PORT) vs. Mid-Atlantic Ridge W of Azores (MAR)). At some Pacific sites age control is based on paired ^{14}C ages of planktic foraminifera and wood chunks (marked by green 'w'; Sarnthein et al., 2015; Zhao and Keigwin, 2018, Rafter et al., 2018). Zigzag lines mark location of major frontal systems separating counter rotating ocean currents (e.g., W of Portugal and N of MD07-307: sensu Skinner et al., 2014). (b) HS-1 transect reveals a short-lasting Atlantic-style overturning in the subpolar North Pacific and a coeval Pacific-style stratification in the northern North Atlantic. Increased ventilation ages reflect an enhanced uptake of dissolved carbon in the LGM deep ocean (Sarnthein et al., 2013), sudden major drops suggest major degassing of CO_2 both from the deep Southern Ocean and North Pacific during early HS-1. SCS = South China Sea. – AABW = Antarctic Bottom Water; AAIW = Antarctic Intermediate Water. NADW = North Atlantic Deep Water. Blue arrows = high ventilation, yellow = poor ventilation, red arrows mark poleward warm surface water currents. Note many arrows are speculative using circumstantial evidence of benthic $\delta^{13}C$ records and likely local Coriolis forcing at high-latitude sites per analogy to modern scenarios. Location and names of sediment cores are given in Suppl. Fig. S2, short-term variations in planktic and benthic ^{14}C reservoir/ ventilation age in Suppl. Fig. S4 and Table 3.

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