Estimating bioturbation from replicated small-sample radiocarbon ages.

Andrew Mark Dolman1,1, Jeroen Groeneveld2,2, Gesine Mollenhauer3,3, Sze Ling Ho4,4, and Thomas Laepple5,5

1Alfred-Wegener Institute for Polar and Marine Research
2University of Bremen
3Alfred-Wegener-Institute
4National Taiwan University
5Alfred Wegener Institute for Polar and Marine Research

November 30, 2022

Abstract

Marine sedimentary records are a key archive when reconstructing past climate; however, mixing at the seabed (bioturbation) can strongly influence climate records, especially when sedimentation rates are low. By commingling the climate signal from different time periods, bioturbation both smooths climate records, by damping fast climate variations, and creates noise when measurements are made on samples containing small numbers of individual proxy carriers, such as foraminifera. Bioturbation also influences radiocarbon-based age-depth models, as sample ages may not represent the true ages of the sediment layers from which they were picked. While these effects were first described several decades ago, the advent of ultra-small-sample 14C dating now allows samples containing very small numbers of foraminifera to be measured, thus enabling us to directly measure the age-heterogeneity of sediment for the first time. Here, we use radiocarbon dates measured on replicated samples of 3-30 foraminifera to estimate age-heterogeneity for five marine sediment cores with sedimentation rates ranging from 2-30 cm / kyr. From their age-heterogeneities and sedimentation rates we infer mixing depths of 10-20 cm for our core sites. Our results show that when accounting for age-heterogeneity, the true error of radiocarbon dating can be several times larger than the reported measurement. We present estimates of this uncertainty as a function of sedimentation rate and the number of individuals per radiocarbon date. A better understanding of this uncertainty will help us to optimise radiocarbon measurements, construct age models with appropriate uncertainties and better interpret marine paleo records.
Estimating bioturbation from replicated small-sample radiocarbon ages

Andrew M. Dolman\textsuperscript{1}, Jeroen Groeneveld\textsuperscript{1,2}, Gesine Mollenhauer\textsuperscript{3,4,5}, Sze Ling Ho\textsuperscript{6}, Thomas Laepple\textsuperscript{1,4,5}

\textsuperscript{1}Alfred-Wegener-Institut Helmholtz-Zentrum für Polar-und Meeresforschung, 14473 Potsdam, Germany
\textsuperscript{2}Institute of Geology, Hamburg University, 20146 Hamburg, Germany
\textsuperscript{3}Alfred-Wegener-Institut Helmholtz-Zentrum für Polar-und Meeresforschung, 25570 Bremerhaven, Germany
\textsuperscript{4}Department of Geosciences, University of Bremen, 28359 Bremen, Germany
\textsuperscript{5}University of Bremen, MARUM – Center for Marine Environmental Sciences and Faculty of Geosciences, 28334 Bremen, Germany
\textsuperscript{6}Institute of Oceanography, National Taiwan University, 10617 Taipei, Taiwan

Key Points:

\begin{itemize}
\item Age-heterogeneity within sediment layers adds hidden uncertainty to radiocarbon-based age estimates.
\item The amount of age-heterogeneity depends on the sedimentation rate and bioturbation mixing depth.
\item We present a method to estimate \textsuperscript{14}C age-heterogeneity and lookup figure to estimate age uncertainty.
\end{itemize}

Corresponding author: Andrew M. Dolman, andrew.dolman@awi.de
Abstract

Marine sedimentary records are a key archive when reconstructing past climate; however, mixing at the seabed (bioturbation) can strongly influence climate records, especially when sedimentation rates are low. By commingling the climate signal from different time periods, bioturbation both smooths climate records, by damping fast climate variations, and creates noise when measurements are made on samples containing small numbers of individual proxy carriers, such as foraminifera. Bioturbation also influences radiocarbon-based age-depth models, as sample ages may not represent the true ages of the sediment layers from which they were picked. While these effects were first described several decades ago, the advent of ultra-small-sample $^{14}$C dating now allows samples containing very small numbers of foraminifera to be measured, thus enabling us to directly measure the age-heterogeneity of sediment for the first time. Here, we use radiocarbon dates measured on replicated samples of 3-30 foraminifera to estimate age-heterogeneity for five marine sediment cores with sedimentation rates ranging from 2-30 cm kyr$^{-1}$. From their age-heterogeneities and sedimentation rates we infer mixing depths of 10-20 cm for our core sites. Our results show that when accounting for age-heterogeneity, the true error of radiocarbon dating can be several times larger than the reported measurement. We present estimates of this uncertainty as a function of sedimentation rate and the number of individuals per radiocarbon date. A better understanding of this uncertainty will help us to optimise radiocarbon measurements, construct age models with appropriate uncertainties and better interpret marine paleo records.

1 Introduction

Proxy records recovered from sediments are an important source of information about the history of the Earth’s climate prior to the instrumental era. For example, the ratio of magnesium to calcium (Mg/Ca) in the shells of marine organisms such as foraminifera contains information about the temperature of the environment in which calcification took place (Nürnberg et al., 1996; Lea, 2014; Rosenthal et al., 2000). These shells settle to the sediment surface and are buried as further sediment accumulates. Over time this produces an archive of recorded (proxy) temperatures that can be read in sequence by taking a sediment core and measuring the Mg/Ca ratio of shells found at progressively deeper, and therefore older, positions in the core.

To obtain a down-core proxy record, samples of foraminiferal shells (hereafter foraminifera) are picked from a series of sediment slices or down-core samples. Assuming, for example, that these slices are 1 cm thick and come from a core location with a constant sedimentation rate of 5 cm kyr$^{-1}$, foraminifera from a single slice would have a uniform distribution of ages with a width of 200 years, with a corresponding standard deviation (SD) of 58 years. However, wherever oxygenated, the surface layer of marine and freshwater sediments is mixed or bioturbated by the burrowing and feeding actions of benthic organisms, thus increasing the age-heterogeneity of material at a given depth (Guinasso & Schink, 1975; Boudreau, 1998). For simple models of sediment mixing, the standard deviation of ages at a given depth is simply the ratio of the mixed depth $L$ and the sediment accumulation rate $s$ (Guinasso & Schink, 1975). For a core with a 5 cm kyr$^{-1}$ sedimentation rate and 10 cm bioturbation depth, $L/s = 2000$ years, and therefore bioturbation greatly increases the expected age-heterogeneity of a sediment slice from 58 to approximately 2000 years.

The additional age-heterogeneity created by bioturbation has important implications for sedimentary proxy records. Proxies measured on samples containing multiple individual signal carriers (e.g. foraminifera) will represent means over the time periods that have been mixed together. This has a smoothing or filtering effect on any signal, so that the observed amplitude of climate variations is reduced (Anderson, 2001). In addition to this smoothing effect, if proxies are measured on samples containing only a small
number of individual signal carriers, the resulting values will be noisy means of the cli-
climate state over the time interval that has been mixed together (Schiffelbein & Hills, 1984; Kunz et al., 2020; Dolman et al., 2020). It would therefore be very useful to have an es-
timate of the degree of age-heterogeneity when interpreting proxy climate records.

Radiocarbon dating is the principle method used to estimate the age of sediment material younger than about 50 ka BP. The age inferred from the measured radiocar-
bon content is an estimate of the mean age of the particles in a given sample, and simi-
larly, the reported machine error represents uncertainty in the mean age of the specific sample. However, the particles in a given sample are themselves only a sub-sample of the material from a given depth, and there is therefore additional, hidden uncertainty about how representative the sample is of the age of the rest of the material from the same depth. Traditionally, radiocarbon dating required large samples of material that would necessarily include 100s of individual foraminifera (typically the equivalent of 1-
5 mg C). Therefore, although it would give no indication of the heterogeneity in the age of the material, a single radiocarbon date would be a good estimate of the mean age of material at a given depth. However, the advent of ultra-small sample radiocarbon dat-
ing (Wacker et al., 2010) means that samples consisting of very small numbers of foraminifera can now be dated. With fewer individuals per sample, radiocarbon measurements be-
come noisier estimates of the mean age of material at a given depth. However, by radio-
carbon dating replicated samples of just a few individual foraminifera we can use this "noise" to estimate the age-heterogeneity of the sediment and to aid our interpretation of proxy climate records.

As described above, assuming a simple sediment mixing model, age-heterogeneity can be estimated from the ratio of the mixing depth and sedimentation rate, L/s. How-
ever, while the sedimentation rate for a given core can be readily determined using a se-
ries of down-core radiocarbon dates, the mixing depth is harder to estimate. Direct mea-
surements using particle tracers show that L is highly variable in space (8.37 ± 6.19 cm, Teal et al., 2010) and mixing intensity may be particle size dependent (Wheatcroft, 1992; Thomson et al., 1995). Short life-span tracers, such as $^{210}$Pb (half-life 26 years) may sim-
ply miss sporadic mixing events that compound over time to produce the long-term mix-
ing behaviour. Additionally, these direct estimates of mixing depth are rarely available at proxy record core sites and in any-case give an estimate of the current mixing depth and cannot inform us about mixing depths in the past when the sediment archive was formed. Mixing depth can also be inferred from the "kink" in a series of down-core $^{14}$C measurements (e.g., Trauth et al., 1997), but this requires a large number of measure-
ments in the first 0-20 cm of the sediment core, and for gravity and piston cores the up-
per few centimetres are often lost during recovery. Although they integrate mixing over a longer time period than tracer experiments, kink based estimates also cannot tell us about mixing depths in the past.

Here we propose and test a method to directly estimate the age-heterogeneity of sediment by radiocarbon dating replicated samples of small numbers (3-30) of foraminifera and using the age-variation between these samples to estimate inter-individual age-heterogeneity. From this we can further infer bioturbation depths in these cores at the time the dated material was deposited. The wider use of this method would allow for a more rigorous interpretation of proxy climate records by providing direct estimates of age-heterogeneity and its smoothing effect on a per-core basis. The hidden uncertainty in radiocarbon based age-control points can also be estimated, resulting in better age-depth models. With this knowledge we can also further optimise future drilling campaigns sampling strategies. We examine the necessary conditions to use this method and estimate correction factors for the bias due to the exponential relationship between radiocarbon activity and age.
2 Materials and Methods

2.1 Physical Sampling and Radiocarbon Dating

We used foraminifera picked from five sediment cores recovered that span a range of sediment accumulation rates (approximately 2-30 cm kyr\(^{-1}\)). The sites were sampled as part of the SO184, SO213/2 and OR1-1218 cruises (Table 1, Figure 1) (Hebbeln & cruise participants, 2006; Tiedemann et al., 2014).

Radiocarbon dating was performed on samples of single species of foraminifera picked from discrete 1 cm thick sediment slices. With the exception of one sample from GeoB 10066-7, a single species was used from each core, either *Globigerina bulloides* (SO213-84-2, 250-400 µm size fraction) or *Trilobatus sacculifer* without sac-like final chamber (GeoB 10054-4, GeoB 10058-1, GeoB 10066-7, 250-400 µm size fraction; and OR1-1218-C2-BC, 300-355 µm or 315-355 µm) (Table 2).

To estimate sediment age-heterogeneity, replicated ”small-n” radiocarbon dates were measured on samples consisting of between three and thirty individual foraminifera, \(n_f\), with multiple replicate samples taken from each sediment slice, \(n_{rep}\). We use the term ”small-n” to refer specifically to samples consisting of a small number of discrete particles, or individuals, rather than samples with a small mass of carbon, but which may contain parts from a great many individuals. Additional radiocarbon dating was performed on non-replicated ”bulk” samples consisting of larger numbers of foraminifera, to provide down-core age control points for estimating sediment accumulation rates. With the exception of the bulk samples from core SO213-84-2, all Accelerated Mass Spectrometry (AMS) \(^{14}\)C dates were generated using a Mini Carbon Dating System (MICADAS) at the Alfred Wegener Institute, Bremerhaven, Germany (Wacker et al., 2010). MICADAS’ capability of analysing a gas target was used for small-n samples (Ruff et al., 2010), larger samples were measured using a graphite target. Radiocarbon dating of the bulk samples from core SO213-84-2 was carried out at NOSAMS, Woods Hole Oceanographic Institution and Keck Carbon Cycle AMS Laboratory, University of California, Irvine.

Radiocarbon dates were converted to calendar ages using the Marine13 calibration (Reimer et al., 2013) and the R package Bchron (Haslett & Parnell, 2008). The Marine13 calibration includes a time-varying global marine reservoir effect. We did not adjust for local marine reservoir effects as this should not influence the variance in ages found in a given sediment slice. For each sample, the probability density function (PDF) for calendar age was summarised by its mean and standard deviation, as none of the PDFs were bi- or multi-modal.

Sediment accumulation rates were estimated by linear regression of calibrated calendar age on depth. Bulk and small-n dates from the depth range 15-100 cm (10-37 cm for OR1-1218-C2-BC) were used so as to exclude the mixed layer and to estimate the sediment accumulation rate over the range of depths for which replicated \(^{14}\)C measurements were made. For replicated small-n dates, a mean date was first calculated for each depth. The multicore GeoB 10058-1 and gravity core GeoB 10054-4 were intended to be taken at the same site, but due to technical difficulties were in fact taken on subsequent days at locations 3 km apart (Hebbeln & cruise participants, 2006). However, their down-core radiocarbon data indicate very similar sedimentation rates (approximately 16 cm kyr\(^{-1}\)) and we combined these to create a single more robust sedimentation rate estimate.

2.2 Estimation of Age-Heterogeneity

For each sediment slice, we calculated the variance between replicated calendar age estimates, \(\sigma^2_{rep}\). From this we subtracted the mean measurement error reported by the MICADAS lab for samples from that slice, \(\sigma^2_{meas}\). As the ages of the individuals are in-
Table 1. Sediment cores used in this study with their locations and the research cruise during which the core was taken.

| Core           | Cruise   | Latitude    | Longitude    | Water depth [m] |
|----------------|----------|-------------|--------------|-----------------|
| GeoB 10054-4   | SO184    | 8°40'54"S  | 112°40'6"E  | 1076            |
| GeoB 10066-7   | SO184    | 9°23'33.6"S| 118°34'31.8"E| 1635            |
| OR1-1218-C2-BC | OR1-1218 | 10°54'1.8"N| 115°18'27.6"E| 2208            |
| GeoB 10058-1   | SO184    | 8°40'S     | 112°38'E    | 1103            |
| SO213-84-2     | SO213/2  | 45°7'28.2"S| 174°35'11.4"E| 992             |

Table 2. Summary of radiocarbon dating per core and depth. Sub-core or tube is indicated in parentheses when appropriate. $n_f$ is the number of individual foraminifera per radiocarbon dated sample, $n_{rep}$ is the number of replicated radiocarbon dated samples.

| Core           | Core depth [cm] | Species     | Size fraction [µm] | $n_f$ | $n_{rep}$ |
|----------------|-----------------|-------------|--------------------|-------|-----------|
| GeoB 10054-4   | 28-29           | T. sacculifer| 250-400            | 50    | 1         |
| GeoB 10054-4   | 48-49           | T. sacculifer| 250-400            | 50    | 1         |
| GeoB 10054-4   | 68-69           | T. sacculifer| 250-400            | 10    | 10        |
| GeoB 10054-4   | 88-89           | T. sacculifer| 250-400            | 50    | 1         |
| GeoB 10058-1   | 11-12           | T. sacculifer| 250-400            | 5-6   | 20        |
| GeoB 10058-1   | 17-18           | T. sacculifer| 250-400            | 110   | 1         |
| GeoB 10058-1   | 20-21           | T. sacculifer| 250-400            | 110   | 1         |
| GeoB 10058-1   | 23-24           | T. sacculifer| 250-400            | 110   | 1         |
| GeoB 10058-1   | 26-27           | T. sacculifer| 250-400            | 110   | 1         |
| GeoB 10058-1   | 29-30           | T. sacculifer| 250-400            | 5-6   | 20        |
| GeoB 10066-7   | 23-24           | T. sacculifer| 250-400            | 50    | 1         |
| GeoB 10066-7   | 48-49           | T. sacculifer| 250-400            | 49    | 1         |
| GeoB 10066-7   | 53-54           | G. bulloides | 250-400            | 10    | 10        |
| GeoB 10066-7   | 98-99           | T. sacculifer| 250-400            | 53    | 1         |
| OR1-1218-C2-BC (1) | 36-37       | T. sacculifer| 315-355            | 5     | 10        |
| OR1-1218-C2-BC (1) | 36-37       | T. sacculifer| 300-355            | 30    | 1         |
| OR1-1218-C2-BC (1) | 36-37       | T. sacculifer| 315-355            | 200   | 3         |
| OR1-1218-C2-BC (7,8,9) | 10-12      | T. sacculifer| 315-355            | 200   | 6         |
| SO213-84-2 (1) | 1-2            | G. bulloides | 250-400            | 5-6   | 10        |
| SO213-84-2 (1) | 18-19          | G. bulloides | 250-400            | >350  | 1         |
| SO213-84-2 (1) | 23-24          | G. bulloides | 250-400            | 5-6   | 10        |
| SO213-84-2 (1) | 23-24          | G. bulloides | 250-400            | >350  | 1         |
| SO213-84-2 (2) | 17-18          | G. bulloides | 250-400            | >350  | 1         |
| SO213-84-2 (2) | 20-21          | G. bulloides | 250-400            | >350  | 1         |
| SO213-84-2 (2) | 17-18          | G. bulloides | 250-400            | >350  | 1         |
| SO213-84-2 (3) | 21-22          | G. bulloides | 250-400            | 3     | 12        |
| SO213-84-2 (3) | 21-22          | G. bulloides | 250-400            | 5-6   | 10        |
| SO213-84-2 (3) | 21-22          | G. bulloides | 250-400            | 30    | 8         |
| SO213-84-2 (3) | 22-23          | G. bulloides | 250-400            | >350  | 1         |

$^a$G. bulloides were picked from a single slice from GeoB 10066-7
dependent, the variance between individuals, $\sigma^2_{\text{ind}}$, can be inferred as the variance between replicates of size $n_f$ multiplied by $n_f$.

$$\sigma^2_{\text{ind}} = n_f (\sigma^2_{\text{rep}} - \sigma^2_{\text{meas}}) \quad (1)$$

The inter-individual variance contains a component from the finite sediment width $\tau_{\text{slice}}$ (here 1 cm) and additional variation due to sediment mixing. We can estimate the variance due to the slice thickness using equation (2), where the $1/12$ comes from the formula for the variance of a uniform distribution. After subtracting the variance due to the slice thickness we attribute the remaining excess variance to bioturbation, assuming that the radiocarbon age during deposition was the same for all particles.

$$\sigma^2_{\text{slice}} = \frac{1}{12} \left( \frac{1000 \cdot \tau_{\text{slice}}}{s} \frac{[\text{cm}]}{[\text{cm kyr}^{-1}]} \right)^2 \quad (2)$$

$$\sigma^2_{\text{bioturbation}} = \sigma^2_{\text{ind}} - \sigma^2_{\text{slice}} \quad (3)$$

To interpret this value, we use the simple bioturbation model proposed by Berger and Heath (1968) to infer a mixing depth from $\sigma^2_{\text{bioturbation}}$. Assuming that the upper $L$ centimetres of sediment are fully and instantaneously mixed but below this level there is no further mixing, and in which the sedimentation rate and flux of foraminifera is assumed to be constant (Berger & Heath, 1968; Matisoff, 1982; Officer & Lynch, 1983), the bioturbation depth required to produce this excess age-variance is given by:

$$L = \frac{s}{1000} \sqrt{\sigma^2_{\text{bioturbation}}} \quad (4)$$
2.3 Bias Correction

Due to the exponential relationship between age and radiocarbon activity, estimates of both mean age, and age-variance between multiple samples, are biased because younger individual particles contribute exponentially more to the mean $^{14}C/^{12}C$ ratio. When the underlying age distribution is exponential, and there are infinitely many particles in the sample, there is an analytical formula for the bias in the mean radiocarbon age (Andree, 1987), however, we are not aware of a general solution for finite sample sizes. To address this we carried out a Monte-Carlo simulation study to investigate the properties of this bias and to obtain correction factors to adjust our measured age-heterogeneity estimates.

We simulated the process of sampling foraminifera from discrete depths by sampling replicated sets of $n_f$ foraminifera from an exponential age distribution with a standard deviation corresponding to a given combination of $L$ and $s$. For the purpose of the simulation we ignored the difference between calendar and radiocarbon age and convert the age of each foraminifera to an $F^{14}C$ value with the expression $F^{14}C = e^{-age/8000}$. For each replicate of $n_f$ foraminifera we then calculated its mean age and mean $F^{14}C$ value. Mean $F^{14}C$ values were then back-transformed to (radiocarbon) ages, $age_{F^{14}C}$. The standard deviation between mean age and mean $age_{F^{14}C}$ values were then calculated for the replicated groups. We repeated this process for a range of underlying age variances and for groups with differing number of foraminifera per $F^{14}C$ "measurement". The difference between the standard deviation in age and standard deviation in $age_{F^{14}C}$ represents the expected bias in estimates of age-heterogeneity.

To adjust for this underestimation of age-heterogeneity we calculated correction factors by which to multiply biased estimates of age-heterogeneity (Figure 2). These correction factors likely represent an upper limit on the potential bias, as the bias depends on the shape of the underlying age distribution. If the true age-distribution differs from the assumed exponential, it is probably less skewed than an exponential and hence would produce a smaller bias. In the results we present both adjusted and un-adjusted age-heterogeneities and implied bioturbation depths. The simulation was written in R code and carried out with R version 3.6.2 (R Core Team, 2019). For more detail see Supporting Text S1 and Figure S1.

3 Results

3.1 Age-Heterogeneity in Core SO213-84-2

We first examine radiocarbon dates from the multicore SO213-84-2, for which we made measurements on groups of 3, 6 and 30 individual foraminifera, all picked from a single depth of multicore tube 3 (21-22 cm). For samples of 30 individuals, calendar ages range from 7.50 to 9.93 ka BP, with a standard deviation ($\sigma_{rep}$) of 726 years, a value far greater than the reported measurement error of about 150 years. Variation in age between samples is even greater for replicates of 6 foraminifera (range = 6.57 - 12.23 ka BP, $\sigma_{rep} = 1514$ years) and 3 foraminifera (range = 4.32 to 13.99 years BP, $\sigma_{rep} = 2895$ years). Clearly, the calibrated calendar ages of these replicated samples do not agree with each other within their reported uncertainties and this excess variation decreases strongly with the number of foraminifera per measurement (Figure 3). Additional measurements on replicated samples of 5-6 individuals taken from multicore tube 1 at depths of 1-2 and 23-24 cm have similarly large $\sigma_{rep}$ values of 1187 and 1575 years.

The relationship between $\sigma_{rep}$ and the number of individuals per measurement very closely follows an inverse relationship (Figure 4). This is a strong indication that inter-individual age variation ($\sigma_{ind}$) is the major component of the between sample variation and allows us to infer $\sigma_{ind}$ by scaling for the number of foraminifera per sample, after first subtracting the much smaller reported measurement error (Equation 1). Inferred age-heterogeneity between individuals, $\sigma_{ind}$, from core SO213-84-2 ranges from 2854 to
Figure 2. Bias correction factors to correct for the underestimation of age-heterogeneity due to the exponential relationship between radiocarbon activity and age.

4990 years (Table 3). Bias correction factors for SO213-84-2 estimated by simulation vary between 1.36 and 1.51, depending on the number of foraminifera per sample. Adjusting for the bias, the range of $\sigma_{\text{ind_adj}}^2$ increases to 3881 - 6847 years. Also shown in Table 3 is the much smaller age-heterogeneity of approximately 100 years expected due to the 1 cm thickness of the slice and the 2.9 cm kyr$^{-1}$ sedimentation rate. After subtracting this, and assuming a simple sediment mixing model (Berger & Heath, 1968), the excess age-heterogeneity implies a mixing depth of 11.2 - 19.8 cm (8.3 - 14.4 before bias adjustment) (Equations 1-4, Table 3). Age-heterogeneity is somewhat lower for the samples from 1-2 cm deep, which would be in the active mixing layer, than for the other deeper samples.

3.2 Age-Heterogeneity Across Multiple Cores

To test the generality of this result we performed similar replicated small-$n$ radiocarbon measurements at 4 additional sites with sediment accumulation rates of approximately 2, 16 (2 sites), and 29 cm kyr$^{-1}$. We again adjust the measured age-heterogeneity for bias assuming an exponential age distribution and present both adjusted and un-adjusted age-heterogeneities and bioturbation depths for comparison. To examine the relationship between age-heterogeneity and sedimentation rate across cores, we additionally present the inter-individual age-heterogeneity and implied bioturbation depth for core T86-10P from the North Atlantic using data published in Lougheed et al. (2018).

Estimated age-heterogeneity is again much higher than the measurement error in most cases, with between replicate standard deviations of 287, 603 and 3208 years, compared to measurement errors of 153, 110, and 304 years (Table 3). The one exception is core GeoB 10066-7 for which $\sigma_{\text{rep}}$ is only 172 years (+- 40 SE) compared to a measurement error of 185 years. While this could imply no mixing at all ($L=0$ cm), because this core has a relatively high sedimentation rate of 29 cm kyr$^{-1}$, and because the value
Figure 3. Replicated radiocarbon dates converted to calendar ages from a single 1 cm thick sediment slice, taken at a depth of 21-22 cm, from core SO213-84-2. Each individual density plot shows the probability density function of calendar age obtained by calibrating a radiocarbon age measured on a sample consisting of 3, 5-6 or 30 individual foraminifera ($^{14}$C age ± 1 SD) with the Marine13 calibration curve (Reimer et al., 2013). No local adjustment was made to the global marine reservoir effect contained in Marine13.

Figure 4. Standard deviation in age between radiocarbon dated samples from core SO213-84-2 as a function of the number of foraminifera they contain. The dashed red lines show extrapolation back to samples of single individual foraminifera assuming the theoretical proportional relationship between standard deviation and the square root of sample size. The samples came from two different multicore tubes of the same deployment.
Table 3. Measured standard deviation between replicated $^{14}$C measurements on small-{$n_f$} samples of foraminifera, inferred age-heterogeneity between individual foraminifera and the implied bioturbation depth. $n_f$ is the number of individual foraminifera per radiocarbon measurement, $n_{rep}$ is the number of replicate radiocarbon measurements made on samples of $n_f$ individuals, $\sigma_{rep}$ is the standard deviation between replicated radiocarbon measurements made from samples from the same sediment slice, $SE_{\sigma_{rep}}$ is the standard error of the estimate of $\sigma_{rep}$, $\sigma_{meas}$ is the reported measurement error, $\sigma_{ind}$ is the inferred standard deviation in age between individuals. $Bias$ is the estimated proportional bias in $\sigma_{age}$ due to the exponential relationship between radiocarbon activity and age. Values with the subscript $adj$ have been corrected for this bias. $s$ and $L$ are the sediment accumulation rate [cm kyr$^{-1}$] and inferred bioturbation depth [cm], respectively. Several samples at 11-12 cm from core GeoB 10058-1 had negative radiocarbon dates indicating the presence of modern material and could not be calibrated.

| Core          | Depth [cm] | $n_f$ | $n_{rep}$ | $\sigma_{rep}$ | $SE_{\sigma_{rep}}$ | $\sigma_{meas}$ | $\sigma_{ind}$ | $Bias$ | $\sigma_{ind,adj}$ | $\sigma_{slice}$ | $s$ | $L$ | $L_{adj}$ |
|---------------|------------|------|-----------|----------------|--------------------|----------------|--------------|--------|-------------------|-----------------|----|-----|---------|
| GeoB 10054-4  | 68.0       | 10   | 10        | 287            | 58                 | 153            | 766          | 1.07   | 820               | 18              | 16.3| 12.5| 13.4    |
| GeoB 10058-1  | 11.5       | 5-6  | ..        | ..             | ..                | 98             | ..           | 1.10   | ..                | 18              | 16.3| ..  | ..      |
| GeoB 10058-1  | 29.5       | 5-6  | 20        | 603            | 97                 | 110            | 1327         | 1.10   | 1458              | 18              | 16.3| 21.7 | 23.8    |
| GeoB 10066-7  | 53.0       | 10   | 10        | 172            | 40                 | 185            | 526          | 1.05   | 553               | 10              | 28.9| 15.2| 16.0    |
| OR1-1218-C2-BC| 36.5       | 5    | 10        | 3208           | 763                | 304            | 7142         | 1.66   | 11855             | 169             | 1.7 | 12.2| 20.2    |
| SO213-84-2    | 1.5        | 5-6  | 10        | 1187           | 281                | 169            | 2854         | 1.36   | 3881              | 100             | 2.9 | 8.3 | 11.2    |
| SO213-84-2    | 23.5       | 5-6  | 10        | 1575           | 374                | 168            | 3836         | 1.36   | 5218              | 100             | 2.9 | 11.1| 15.1    |
| SO213-84-2    | 21.5       | 3    | 12        | 2895           | 621                | 283            | 4990         | 1.37   | 6847              | 100             | 2.9 | 14.4| 19.8    |
| SO213-84-2    | 21.5       | 5-6  | 10        | 1514           | 359                | 176            | 3668         | 1.36   | 4989              | 100             | 2.9 | 10.6| 14.4    |
| SO213-84-2    | 21.5       | 30   | 8         | 726            | 193                | 152            | 3888         | 1.51   | 5858              | 100             | 2.9 | 11.3| 17.0    |
Table 4. Sediment accumulation rate $s$ (cm kyr$^{-1}$) and estimated bioturbation depth $L$ (cm) at 4 sites measured in this study, plus one (T86-10P) previously published by Lougheed et al. (2018). $SE_s$ is the standard error of the estimate of $s$, $L_{adj}$ is the inferred bioturbation depth adjusted for the bias due to the exponential relationship between age and radiocarbon content.

| Core/Site               | $s$  | $SE_s$ | $L$  | $L_{adj}$ |
|-------------------------|------|--------|------|-----------|
| GeoB 10054-4/58-1       | 16.3 | 1.8    | 16.3 | 17.7      |
| GeoB 10066-7            | 28.9 | 2.4    | 15.2 | 16.0      |
| OR1-1218-C2-BC          | 1.7  | 0.1    | 12.2 | 20.2      |
| SO213-84-2              | 2.9  | 0.7    | 11.1 | 15.5      |
| T86-10P                 | 2.2  | ..     | 10.8 | 10.8      |

of $\sigma_{\text{meas}}$ is itself an estimate with its own uncertainty, it is also consistent with mixing of several centimetres. For example, assuming a 15 cm bioturbation depth and given the 10 foraminifera per sample, the expected $\sigma_{\text{rep}}$ would be just 164 years. To provide an upper estimate on the inter-individual age-variance and bioturbation depth for this core, we subtract only the error due to the binomial counting statistics for $^{14}\text{C}/^{12}\text{C}$ (45 years), essentially assigning all additional error to age-heterogeneity. Additionally, several samples taken from GeoB 10058-1 at 11.5 cm deep could not be calibrated with Marine13 as they were younger than the minimum 448 radiocarbon years that can be calibrated with Marine13, including some with negative radiocarbon dates indicating the presence of modern material down to at least 11-12 cm.

Across all analysed cores we found a strong negative relationship between sedimentation rate $s$ and inter-individual age-heterogeneity, a clear indication that sediment mixing influences age-heterogeneity. Due to this negative relationship, the implied bioturbation depths for all sets of replicated samples fall within a relatively narrow range of 11.2 - 23.8 cm (Figure 5, Table 3). At the site level, after combining estimates for the same core taken from different depth layers, and combining GeoB 10054-4 and GeoB 10058-1 which come from two sites less than 3 km apart, implied bioturbation depths for the individual sites range from 15.5 - 20.2 cm (Table 4). For core T86-10P, Lougheed et al. (2018) report a mixing depth of 10.8 cm.

The relationship between $s$ and $\sigma_{\text{rad}}$ is only slightly altered by the bias adjustment, which is small compared to other sources of variation in age-heterogeneity. Adjustment is largest for core OR1-1218-C2-BC, for which the simulation study indicated a factor of 1.66, and which has the lowest sedimentation rate and highest estimates of individual age-heterogeneity. The adjustment shifts the implied bioturbation depth from 12.4 to 20.2 cm.

4 Discussion

We found variation in radiocarbon ages between replicated small-$n$ samples of foraminifera that far exceeded the reported machine uncertainty at three of the four sites we examined. Between-replicate age-variation was only within the machine uncertainty for core GeoB 10066-7, which has a comparatively high sedimentation rate of 29 cm kyr$^{-1}$. Age-heterogeneity also far exceeds measurement error for a fifth core examined by Lougheed et al. (2018). This excess age-variation can be interpreted as within-sediment-layer heterogeneity caused by bioturbation. Assuming the classical Berger and Heath (1968) mixing model, the implied mixing at the five sites is 11-20 cm. This is somewhat higher than the 10 cm often assumed as typical value in literature (Boudreau, 1998) and consider-
Figure 5. Inferred standard deviation in age between individuals $\sigma_{\text{ind,adj}}$ plotted against sediment accumulation rate $s$. Error bars indicate one standard error of the standard deviation and sedimentation rate estimates. The dashed isolines indicate bioturbation depths $L$ consistent with a given sedimentation rate and $\sigma_{\text{ind}}$. The grey arrows indicate $\sigma_{\text{ind}}$ prior to correcting for the bias due to the exponential relationship between age and radiocarbon content. The bias adjustment is much larger for cores with low sedimentation rates and high estimates of $\sigma_{\text{age}}$.

Age-heterogeneity of this magnitude has important implications for proxy records recovered from these cores. The climate signal is strongly smoothed by the mixing together of time periods, reducing the inferred amplitude of climate variations (e.g., Anderson, 2001), but, if the proxy measurements are made on small numbers of foraminifera, records can also become noisier as the signal from different climate states is mixed together. In extreme cases measurements can include both glacial and interglacial material. This noise is especially problematic when the variance itself is of interest, for example in individual foraminiferal analyses (Groeneveld et al., 2019; Wit et al., 2013; Koutavas & Joanides, 2012; Thirumalai et al., 2019, 2013). Estimates of age-heterogeneity from replicated small-$n$ radiocarbon dates can be used to parametrise proxy forward models to quantitatively assess this smoothing and noise generation (Lougheed, 2020; Dolman & Laepple, 2018).

A further implication is that radiocarbon dates used for age-depth modelling may require much larger uncertainties than the reported machine errors that are typically used. Although they may correctly quantify the uncertainty in the age of the sample, they ignore the uncertainty in how representative the sample may be of mean age of material at the depth from which it was recovered (Heegaard et al., 2005). The size of this effect will depend on the bioturbation depth, the sedimentation rate and the sample size. We can see this effect for the low sedimentation rate multicore SO213-84-2, for which a series of down-core radiocarbon dates were made in each of 3 sub-cores. These replicated age-depth series show very little overlap within their reported age-uncertainties (Figure 6a), despite having been measured on samples of approximately 350 foraminifera each.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5}
\caption{Inferred standard deviation in age between individuals $\sigma_{\text{ind,adj}}$ plotted against sediment accumulation rate $s$. Error bars indicate one standard error of the standard deviation and sedimentation rate estimates. The dashed isolines indicate bioturbation depths $L$ consistent with a given sedimentation rate and $\sigma_{\text{ind}}$. The grey arrows indicate $\sigma_{\text{ind}}$ prior to correcting for the bias due to the exponential relationship between age and radiocarbon content. The bias adjustment is much larger for cores with low sedimentation rates and high estimates of $\sigma_{\text{age}}$.}
\end{figure}
Figure 6. Replicated down-core radiocarbon age estimates for SO213-84-2. Each down-core record corresponds to a separate multicore tube or half tube from the same deployment. Age-uncertainties in subplot (a) are \( \pm 2 \) times the reported machine error, whereas those in (b) include the inferred \( \sigma_{age} \) between individuals, scaled for samples of 350 individuals.

However, adding the expected uncertainty due to age-heterogeneity brings the three down-core age-depth series into much closer agreement (Figure 6b). Radiocarbon dating small-\( n \) samples, either because the sediment material contains only few foraminifera or to save picking and processing time, risks further inflating this additional error. To guide the choice of sample size, we have created lookup figures, based on equation 5, for mixing depths of 5, 10, 15 and 20 cm (Figure 7, S2). These can be used to get a rapid idea of the number of individual foraminifera per sample required to reduce the additional age-uncertainty below a desired level, or inversely, given a radiocarbon date we can estimate the additional hidden uncertainty from age-heterogeneity from the sedimentation rate and an estimate of the number of individuals in the sample.

\[
n_f = \left( \frac{1000L}{s \cdot \sigma_{rep}} \right)^2
\]  

(5)
Figure 7. A reference chart to obtain estimates of the additional age-uncertainty $\sigma_{\text{age}}$ for a sample measured on a given number of foraminifera, from the sedimentation rate of the core $s$, and assuming a bioturbation depth $L$ of 10 cm. Or alternatively, an estimate of the number of foraminifera per sample needed to reduce $\sigma_{\text{age}}$ below a given level. E.g. for a core with $s = 5$ cm kyr$^{-1}$, to get the additional age-uncertainty below 200 years you need at least 100 foraminifera; if $s$ were 20 cm kyr$^{-1}$ you would need only 6-7 foraminifera. The $\sigma_{\text{age}}$ values of the isolines are proportional to $L$, so if a larger, 20 cm, bioturbation depth is suspected, double the isoline values. Note however, altering the mass of material processed and measured may also influence the reported instrument error - and the characteristic sizes of different foraminiferal taxa will impose their own constraints on the number of specimens required.
4.1 The Physical Mixing Process and Outliers

The concept of a bioturbation depth is an obvious simplification; however, as the age-heterogeneity is related to the sedimentation rate regardless of the precise mixing process (Matisoff, 1982), the specific mixing model assumed is not particularly important for the main conclusions here. We can still however question the extent to which our measured radiocarbon dates are consistent with the Berger and Heath (1968) mixing model. In contrast to Lougheed et al. (2018), who estimated that around 10% of their foraminifera had ages inconsistent with a simple mixing model, we found very few extreme outlying dates which might be evidence of unusually deep mixing events like Zoophycos burrows (Küssner et al., 2018). However, as we dated samples containing multiple foraminifera, individuals with aberrant ages may be hidden, as every distribution will converge towards a Gaussian distribution as the number of individuals increases (Figure S3). Therefore it is unclear the extent to which additional disturbance by Zoophycos, or other deep mixing mechanisms, contribute to the age-heterogeneity we measure.

The single clear outlier we did obtain was measured on just three individuals, and was too young by about 5000 years in a core with sedimentation rate of 2.9 cm kyr$^{-1}$ (core SO213-84-2). This implies a relative displacement of approximately 43.5 cm for one of the three foraminifera, which would be consistent with the known size of Zoophycos burrows (Wetzel & Werner, 1980). Additional displaced individuals hidden inside multi-individual measurements would mean that we have overestimated the depth of the well mixed layer.

The specific form of mixing and its resulting probability distribution of ages does have implications for the bias generated by the exponential relationship between age and the $^{14}$C/$^{12}$C ratio. We calculated biases for the highly skewed exponential distribution resulting from the Berger and Heath (1968) mixing model; less skewed distributions, resulting for example from incomplete mixing or a smooth transition between the mixed layer and the unmixed sediment, will generate a smaller bias. Therefore our bias correction which assumes an exponential distribution may be too strong and probably represents an upper limit. This bias could potentially be eliminated by dating individual larger foraminifera (e.g., Lougheed et al., 2018), which would also remove the issue of hidden outliers.

In principle, $\Delta^{14}$C variations across the water column also cause some apparent age-heterogeneity due to differences in the calcification depth of the individual foraminifera. However, even assuming a strong $\Delta^{14}$C gradient (0.2 permille change per meter) and a highly variable calcification depth (uniform probability of calcifying between 0 and 100 m), the resulting heterogeneity ($\sigma = 50$ years) is small compared to the age-heterogeneity found in this study. Over most of the ocean the $\Delta^{14}$C gradient is weaker than this (Key, 2001), and individual foraminifera may incorporate carbon over a range of depths during their calcification.

4.2 Practical Considerations When Applying This Method

We have demonstrated the use of small-$n$ radiocarbon measurements to estimate site and core-depth specific bioturbational mixing. This knowledge is especially important when a high-resolution analysis or the analysis of individual foraminifera (IFA) is planned, and it is our hope that bioturbation estimates will become routine in these applications. However, there are some practical considerations when applying this method.

Firstly, the estimation only works if the age-heterogeneity is larger than the measurement error. For the data presented here, measurement error ranged from about 80 to 400 years. At sedimentation rates below about 2 cm kyr$^{-1}$, age-heterogeneity from bioturbation will far exceed this measurement error, even for relatively small bioturbation depths. However, as $s$ rises, the expected age-heterogeneity between individuals (Figure 5, dashed lines), or samples (Figure 7, contour lines), falls rapidly. Furthermore, for many foraminifera taxa, single specimens cannot be dated, even with MICADAS, and...
Figure 8. Coefficient of variation for estimates of $\sigma_{age}$ or the implied bioturbation depth $L$ as a function of the number of dated samples $n_{rep}$. Dashed lines indicate that for 9 replicated $^{14}$C measurements there would be a 25% uncertainty in the estimated values of $\sigma_{age}$ and $L$.

so the approach of dating small-$n$ samples has to be used - reducing the signal of age-
384 heterogeneity by a factor of $n_f$.

Secondly, the uncertainty, or standard error ($SE$), of a standard deviation depends on the number of samples measured (Equation 6), hence a sufficient number of small-
387 $n$ samples needs to be measured in order to get a reliable estimate of $\sigma_{ind}$, and in turn to estimate $L$ with a given precision. For example, with approximately 9 samples, the proportional uncertainty (or coefficient of variation) of the standard deviation is approximately 1/4 (Figure 8), therefore with true bioturbation depths of 10 or 2 cm we would expect estimates of 10 ± 2.5 cm or 2 ± 0.5 cm respectively.

$$SE_{\sigma_{ind}} = \frac{\sigma_{ind}}{\sqrt{2(n_s - 1)}}$$ (6)

5 Conclusions

An awareness of bioturbation and its potential influence on sedimentary proxy records due to the age-heterogeneity it causes is not new (e.g., Schiffelbein, 1985; Andree, 1987; Keigwin & Guilderson, 2009; Steiner et al., 2016; Goreau, 1980); however, it has only recently become possible to directly measure the age-heterogeneity in sediment slices of the medium that is radiocarbon dated, e.g. foraminifera. We measured age-heterogeneities that imply much deeper mixing than is typically assumed in the paleo-climate literature. At the same time, we found that between core variation in age-heterogeneity could largely be explained by sedimentation rates, which implies a relatively consistent mixed layer depth. It is conceivable that the ”paleo” bioturbation depth is larger and less variable than measurements of contemporary bioturbation depths would imply (e.g., Solan et al., 2019), as integrated over time, a long period of shallow mixing would be obliterated by a subsequent period of deep mixing; where ”long” is relative to the sedimentation rate.

The availability of small-$n$ radiocarbon dating will allow us to assess how consistent bioturbation depths really are, in addition to obtaining independent estimates of age-heterogeneity to aid our interpretation of proxy climate records.
Acknowledgments

We thank the scientists and crew members on board the research vessels R/V Sonne and Ocean Researcher 1 who helped with sample retrieval, especially M. Mohtadi (all GeoB cores), F. Lamy (SO213-84-2), and C.-C. Su and A. Zuhr (OR1-1218-C2-BC). Thanks are owed to R. De Pol-Holz for help with radiocarbon measurements carried out at Keck-Carbon Cycle AMS facility, and to H. Grotheer, E. Bonk and T. Gentz who carried out the MICADAS AMS analyses. N. Behrendt and L. Kafemann assisted with sample preparation. T. Ronge is acknowledged for discussion, without implying agreement on what is written in this manuscript.

This is a contribution to the SPACE ERC project; this project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement no. 716092). Additionally, this work was supported by German Federal Ministry of Education and Research (BMBF) as Research for Sustainability initiative (FONA); www.fona.de through Palmod project (FKZ: 01LP1509C). Samples from core SO213-84-2 were processed and analysed while Sze Ling Ho was supported by the Initiative and Networking Fund of the Helmholtz Association Grant VG-NH900.

Radiocarbon dates have been submitted to Pangaea (www.pangaea.de - DOI pending). Additionally, the data and R code to reproduce the analyses are supplied as Supporting Material to this manuscript (Data Set S1).

References

Anderson, D. M. (2001). Attenuation of millennial-scale events by bioturbation in marine sediments. *Paleoceanography, 16*(4), 352–357. doi:10.1029/2000PA000530

Andree, M. (1987). The Impact of Bioturbation on AMS 14C Dates On Handpicked Foraminifera: A Statistical Model. *Radiocarbon, 29*(2), 169–175. doi:10.1017/S0033822200056927

Berger, W. H., & Heath, G. R. (1968). Vertical mixing in pelagic sediments. *Journal of Marine Research, 26*(2), 134–143.

Boudreau, B. P. (1998). Mean mixed depth of sediments: The wherefore and the why. *Limnology and Oceanography, 43*(3), 524–526. doi: 10.4319/lo.1998.43.3.0524

Dolman, A. M., Kunz, T., Groeneveld, J., & Laepple, T. (2020). Estimating the timescale-dependent uncertainty of paleoclimate records - a spectral approach. Part II: Application and interpretation. *Climate of the Past Discussions, 1–22*. doi: 10.5194/cp-2019-153

Dolman, A. M., & Laepple, T. (2018). Sedproxy: A forward model for sediment-archived climate proxies. *Climate of the Past, 14*(12), 1851–1868. doi: 10.5194/cp-14-1851-2018

Goreau, T. J. (1980). Frequency sensitivity of the deep-sea climatic record. *Nature*, 287(5783), 620. doi: 10.1038/287620a0

Groeneveld, J., Ho, S. L., Mackensen, A., Mohtadi, M., & Laepple, T. (2019). Deciphering the variability in Mg/Ca and stable oxygen isotopes of individual foraminifera. *Paleoceanography and Paleoclimatology, 0*(ja). doi:10.1029/2018PA003533

Guinasso, N. L. G., & Schink, D. R. (1975). Quantitative Estimates of Biological Mixing Rates in Abyssal Sediments. *Journal of Geophysical Research, 80*(21), PP. 3032-3043. doi: 1975010.1029/JC080021p03032

Haslett, J., & Parnell, A. (2008). A simple monotone process with application to radiocarbon-dated depth chronologies. *Journal of the Royal Statistical Society: Series C (Applied Statistics), 57*(4), 399–418. doi: 10.1111/j.1467-9876.2008.00623.x
Hebbeln, D., & cruise participants. (2006). Report and preliminary results of RV Sonne Cruise SO-184, Pabesia, Durban (South Africa) - Cilacap (Indonesia) - Darwin (Australia), July 8th - September 13th, 2005 (Vol. 246). Department of Geosciences, Bremen University.

Heegaard, E., Birks, H. J. B., & Telford, R. J. (2005). Relationships between calibrated ages and depth in stratigraphical sequences: An estimation procedure by mixed-effect regression. *The Holocene, 15*(4), 612–618. doi: 10.1191/0959683605h36r

Keigwin, L. D., & Guilderson, T. P. (2009). Bioturbation artifacts in zero-age sediments. *Paleoceanography, 24*(4), PA4212. doi: 10.1029/2008PA001727

Key, R. (2001). Radiocarbon. In *Encyclopedia of Ocean Sciences* (pp. 2338–2353). Elsevier. doi: 10.1006/rwos.2001.0162

Koutavas, A., & Joanides, S. (2012). El Niño–Southern Oscillation extrema in the Holocene and Last Glacial Maximum. *Paleoceanography, 27*(4), PA4208. doi: 10.1029/2012PA002378

Kunz, T., Dolman, A. M., & Laepple, T. (2020). A spectral approach to estimating the timescale-dependent uncertainty of paleoclimate records – Part 1: Theoretical concept. *Climate of the Past, 16*(4), 1469–1492. doi: 10.5194/cp-16-1469-2020

Küssner, K., Sarnthein, M., Lamy, F., & Tiedemann, R. (2018). High-resolution radiocarbon records trace episodes of Zoophycos burrowing. *Marine Geology, 403*, 48–56. doi: 10.1016/j.margeo.2018.04.013

Lea, D. W. (2014). Elemental and Isotopic Proxies of Past Ocean Temperatures. In *Treatise on Geochemistry* (Second ed., Vol. 1-16, pp. 373–397). Elsevier.

Longheud, B. C. (2020). SEAMUS (v1.20): A ∆¹⁴C-enabled, single-specimen sediment accumulation simulator. *Geoscientific Model Development, 13*(1), 155–168. doi: 10.5194/gmd-13-155-2020

Longheud, B. C., Metcalfe, B., Ninnemann, U. S., & Wacker, L. (2018). Moving beyond the age–depth model paradigm in deep-sea palaeoclimate archives: Dual radiocarbon and stable isotope analysis on single foraminifera. *Climate of the Past, 14*(4), 515–526. doi: 10.5194/cp-14-515-2018

Matisoff, G. (1982). Mathematical models of bioturbation. In P. L. McCall & M. J. S. Tevesz (Eds.), *Animal-sediment relations: The biogenic alteration of sediments* (pp. 289–300). New York: Springer.

Nürnberg, D., Bijma, J., & Hemleben, C. (1996). Assessing the reliability of magnesium in foraminiferal calcite as a proxy for water mass temperatures. *Geochimica et Cosmochimica Acta, 60*(5), 803–814. doi: 10.1016/0016-7037(95)00446-7

Officer, C., & Lynch, D. (1983). Determination of mixing parameters from tracer distributions in deep-sea sediment cores. *Marine Geology, 52*(1-2), 59–74. doi: 10.1016/0025-3227(83)90021-X

R Core Team. (2019). *R: A language and environment for statistical computing*. Vienna, Austria.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Ramsey, C. B., ... van der Plicht, J. (2013). IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP. *Radiocarbon, 55*(4), 1869–1887. doi: 10.2458/azu_js_rc.55.16947

Rosenthal, Y., Lohmann, G. P., Lohmann, K. C., & Sherrell, R. M. (2000). Incorporation and preservation of Mg in Globigerinoides sacculifer: Implications for reconstructing the temperature and 18O/16O of seawater. *Paleoceanography, 15*(1), 135–145. doi: 10.1029/1999PA000415

Ruff, M., Szidat, S., Gaggele, H. W., Suter, M., Synal, H. A., & Wacker, L. (2010). Gaseous radiocarbon measurements of small samples. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 268*(7), 790–794. doi: 10.1016/j.nimb.2009.10.032
Schiffelbein, P. (1985). Calculation of error measures for deconvolved deep-sea stratigraphic records. *Marine Geology*, 65(3), 333–342. doi: 10.1016/0025-3227(85)90063-5

Schiffelbein, P., & Hills, S. (1984). Direct assessment of stable isotope variability in planktonic foraminifera populations. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 48(2), 197–213. doi: 10.1016/0025-3227(84)90044-0

Solan, M., Ward, E. R., White, E. L., Hibberd, E. E., Cassidy, C., Schuster, J. M., ... Godbold, J. A. (2019). Worldwide measurements of bioturbation intensity, ventilation rate, and the mixing depth of marine sediments. *Scientific Data*, 6(1), 58. doi: 10.1038/s41597-019-0069-7

Steiner, Z., Lazar, B., Levi, S., Tsroya, S., Pelled, O., Bookman, R., & Erez, J. (2016). The effect of bioturbation in pelagic sediments: Lessons from radioactive tracers and planktonic foraminifera in the Gulf of Aqaba, Red Sea. *Geochemistry et Cosmochimica Acta*, 194, 139–152. doi: 10.1016/j.gca.2016.08.037

Teal, L., Bulling, M., Parker, E., & Solan, M. (2010). Global patterns of bioturbation intensity and mixed depth of marine soft sediments. *Aquatic Biology*, 2(3), 207–218. doi: 10.3354/ab00052

Thirumalai, K., DiNezio, P. N., Tierney, J. E., Puy, M., & Mohtadi, M. (2019). *An El Niño mode in the glacial Indian Ocean?* https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019PA003669. doi: 10.1029/2019PA003669

Thirumalai, K., Partin, J. W., Jackson, C. S., & Quinn, T. M. (2013). Statistical constraints on El Niño Southern Oscillation reconstructions using individual foraminifera: A sensitivity analysis. *Paleoceanography*, 28(3), 401–412. doi: 10.1002/palo.20037

Thomson, J., Cook, G. T., Anderson, R., MacKenzie, A. B., Harkness, D. D., & McCave, I. N. (1995). Radiocarbon Age Offsets in Different-Sized Carbonate Components of Deep-Sea Sediments. *Radiocarbon*, 37(2), 91–101. doi: 10.1017/S0033822200030526

Tiedemann, R., Lamy, F., Molina-Kescher, M., Tapia Arroyo, R., Poggemann, D. W., & Nürnberg, D. (2014). FS Sonne Fahrbericht / Cruise Report SO213 - SOPATRA: South Pacific Paleoceanographic Transsects - Geodynamic and Climatic Variability in Space and Time, Leg 1: Valparaiso/Chile - Valparaiso/Chile, 27.12.2010 - 12.01.2011 and Leg 2: Valparaiso/Chile - Wellington/New Zealand, 12.01.2011 - 07.03.2011 (Report). doi: 10.2312/cr_so213

Trauth, M. H., Sarnthein, M., & Arnold, M. (1997). Bioturbational mixing depth and carbon flux at the seafloor. *Paleoceanography*, 12(3), 517–526. doi: 10.1029/97PA00722

Wacker, L., Bonani, G., Friedrich, M., Hajdas, I., Kromer, B., Nemec, N., ... Vockenhuber, C. (2010). MICADAS: Routine and High-Precision Radiocarbon Dating. *Radiocarbon*, 52(2), 252–262. doi: 10.1017/S0033822200045288

Wetzel, A., & Werner, F. (1980). Morphology and ecological significance of Zoophycos in deep-sea sediments off NW Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 32, 185–212. doi: 10.1016/0025-3227(80)90040-1

Wheatcroft, R. A. (1992). Experimental tests for particle size-dependent bioturbation in the deep ocean. *Limnology and Oceanography*, 37(1), 90–104. doi: 10.4319/lo.1992-37.1.0090

Wit, J., Reichart, G., & Ganssen, G. (2013). Unmixing of stable isotope signals using single specimen δ18O analyses. *Geochemistry, Geophysics, Geosystems*, 14(4), 1312–1320. doi: 10.1002/ggge.20101
Supporting Information for ”Estimating bioturbation from replicated small-sample radiocarbon ages”
Andrew M. Dolman¹, Jeroen Groeneveld¹,², Gesine Mollenhauer³,⁴,⁵, Sze Ling Ho⁶, Thomas Laepple¹,⁴,⁵

¹Alfred-Wegener-Institut Helmholtz-Zentrum für Polar-und Meeresforschung, 14473 Potsdam, Germany
²Institute of Geology, Hamburg University, 20146 Hamburg, Germany
³Alfred-Wegener-Institut Helmholtz-Zentrum für Polar-und Meeresforschung, 25570 Bremerhaven, Germany
⁴Department of Geosciences, University of Bremen, 28359 Bremen, Germany
⁵University of Bremen, MARUM – Center for Marine Environmental Sciences and Faculty of Geosciences, 28334 Bremen, Germany
⁶Institute of Oceanography, National Taiwan University, 10617 Taipei, Taiwan

Contents of this file
1. Text S1
2. Figures S1 to S3

Additional Supporting Information (Files uploaded separately)
1. Captions for Dataset S1

Introduction
Text S1 and Figure S1 contain extended results of the simulation study to examine the bias in the estimation of age-heterogeneity due to the non-linear relationship between $F^{14}C$ and age. In this supporting material we examine the behaviour of the bias over a wide parameter space that exceeds the range of age-heterogeneities that would be encountered in real samples - but that allows the full shape of the function to be characterised.

Dataset S1 contains R code and the radiocarbon age measurements to replicate the analyses in this study. These data have been submitted to the Pangaea archive (DOI PENDING) but are additionally supplied here in a form that will work directly with the supplied R code.

**Text S1.**

Here we examine the behaviour of the bias in age-heterogeneity estimates, due to the non-linear relationship between $F^{14}C$ and age, over a wide parameter space that exceeds the range of age-heterogeneities that would be encountered in real samples.

Our bias simulation study indicates that, expressed as a proportion of the true age-heterogeneity, estimated age-heterogeneity decreases non-linearly with the true age-heterogeneity. This proportion tends towards a value of $\frac{1}{\sqrt{n_f}}$ at the limit of infinite age-heterogeneity, i.e. an infinitely low sedimentation rate (Figure S1). The vertical line in Figure S1 indicates an age-heterogeneity of 10 kyr, which corresponds to a bioturbation depth of 10 cm with a sedimentation rate of 1 cm kyr$^{-1}$. In most practical cases, samples that are being radiocarbon dated would fall to the left of this line, as cores with sedimentation rates of 1 cm kyr$^{-1}$ can only be radiocarbon dated down to a depth of about 50 cm, as material that is deeper than this will be beyond the age limit for reliable...
radiocarbon dating. Therefore the maximum bias we are likely to observe would be a factor of approximately 1/2.

**Data Set S1.** R code and the radiocarbon age measurements required replicate the analyses in this study. These data have been submitted to the Pangaea archive (DOI pending) but are additionally supplied here in a form that will work directly with the supplied R code.
Figure S1. Simulation of the bias in the estimation of age-heterogeneity due to the exponential relationship between F\(^{14}\)C and age, expressed as a proportion of the true value. The blue lines show the bias for samples with different numbers of individual foraminifera per radiocarbon date. As the true age-variance increases (as \(L\) increases or \(s\) decreases), the estimate becomes a smaller proportion of the true value and tends towards the square root of the inverse of the number of individuals per sample. The true \(\sigma_{age}\) values correspond to a core with bioturbation depth of 10 cm and sedimentation rates shown in the upper horizontal axis. The dashed vertical orange line indicates \(\sigma_{age}\) for a core with a 10 cm bioturbation depth and sedimentation rate of 1 cm kyr\(^{-1}\).
Figure S2. Additional reference charts to obtain estimates of the age-uncertainty $\sigma_{\text{age}}$ for a sample measured on a given number of foraminifera, from the sedimentation rate of the core $s$, and assuming bioturbation depths $L$ of 5, 10, 15 and 20 cm. Or alternatively, estimates of the number of foraminifera per sample needed to reduce $\sigma_{\text{age}}$ below a given level.
Figure S3. An illustration of the exponential and gamma probability distributions as applied to the age distribution of foraminifera from mixed sediment. Under a simple model of sediment mixing, the age distribution particles is an exponential distribution with standard deviation equal to $L/s$, where $L$ is the bioturbation depth and $s$ is the sedimentation rate (blue shaded area). When means of samples of $n$ values are taken from an exponential distribution, these means are gamma distributed, with shape parameter = $n$. As $n$ increases, the gamma distribution rapidly approximates a symmetrical distribution. Here the standard deviation (scale) of the exponential is set to 2000 years, the theoretical value for a sediment core with a bioturbation depth $L$ of 10 cm and sedimentation rate $s$ of 5 cm kyr$^{-1}$. The mean age (dashed vertical line) remains constant as $n$ increases, but the standard deviation shrinks with $\sqrt{n}$. 

October 6, 2020, 11:23am