



# Bias in foraminiferal multispecies reconstructions of paleohydrographic conditions caused by foraminiferal abundance variations and bioturbational mixing: A model approach

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## ABSTRACT

A simple box model was applied to study the combined effect of bioturbation and foraminiferal abundance variations using synthetic isotope records constructed from the Greenland oxygen isotope record (GISP2). Apart from the well known general smoothing of the signal, the attenuation of peak heights, and the up- or downwards shift of the proxy records at intervals of changing abundance, the modeling results draw attention to two effects of special importance to climatic reconstructions based on the comparison of proxy signals from two or more planktonic foraminifer species. First, the bioturbational mixing of tests out of abundance maxima and into over- and underlying sediment can lead to the introduction of stratigraphic shifts between different species when species with opposing abundance patterns are used. This shifting of the signals can easily result in apparent increases or decreases in the isotopic gradients between different species, especially at intervals of rapidly changing climate conditions. Second, in intervals with rapidly changing environmental conditions, such as Dansgaard–Oeschger cycles, where species with different preferences often show opposing abundance patterns, the mixing of foraminifer tests out of their respective abundance maxima can result in a general, but artificial, offset between the two species. This offset then may disappear during intervals of slower variability. These artifacts have the potential of seriously biasing any paleoceanographic and paleoclimatic reconstructions based on multispecies analysis where the studied species show opposing abundance patterns. It is therefore highly recommended that species with as low abundance variations as possible, or at least with similar abundance variations, are used whenever multispecies reconstructions are attempted.

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## 1. Introduction

The most widely used archives of climatic change are records of stable isotope and element ratios in calcareous microfossils preserved in marine sediments. One recent approach that has gained importance is the use of stable oxygen and carbon isotopes from multiple species of planktonic foraminifers to reconstruct millennial to orbital scale variability in the surface water hydrography, such as thermocline depth or mixed layer depth, in regions considered essential to our understanding of the global climate system (e.g., Ravelo and Fairbanks, 1990; Ravelo and Shackleton, 1995; Lin et al., 1997; Faul et al., 2000; Hillaire-Marcel et al., 2001; de Vernal et al., 2002; Spero et al., 2003; Tedesco and Thunell, 2003; Black et al., 2004; Bostock et al., 2004; Benway et al., 2006; Kiefer et al., 2006; Lea et al., 2006; Lin et al., 2006; Rohling et al., 2006; Rashid and Boyle, 2007). The basis for the multispecies approach is the fact that different

species inhabit different habitats, resulting in slightly different isotopic values between the species. Thermocline dwelling species, for example, generally have heavier oxygen isotopes than surface dwellers because they calcify in deeper, cooler waters. Relative changes in the isotopic difference between surface and deeper dwelling planktonic species can therefore indicate changes in the arrangement of surface water hydrography, such as a thickening or thinning of the mixed layer (Spero et al., 2003; Lin et al., 2006), changes in the intensity of surface water mixing and upwelling (Black et al., 2004), surface water salinity (Rohling et al., 2006), or primary productivity (Faul et al., 2000; Spero et al., 2003). The general underlying assumption is that the foraminifer tests were deposited at the same time (seasonal and chronostratigraphic) and therefore reflect differences in physical (temperature, salinity) or chemical (e.g.  $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$ , Mg/Ca) properties between the respective water masses.

However, deep marine sediments deposited under oxic conditions are usually thoroughly mixed by the activities of benthic organisms. The thickness of this bioturbated layer varies from a few cm to more than 10 cm (DeMaster and Cochran, 1982; Officer and Lynch, 1983;

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Thomson et al., 2000). This bioturbation causes a smearing of the sedimentary record resulting in a smoothing of the proxy records used to reconstruct past environmental changes (e.g., Berger and Heath, 1968; Schiffelbein, 1984; Bard, 2001). In combination with temporal variations in the abundance of different proxy carriers, this mixing may also introduce artificial leads and lags of several thousands of years between the records of different proxies (e.g. Bard et al., 1987; Manighetti et al., 1995; Broecker et al., 1999). A drop in abundance will tend to shift the proxy values upward relative to their original position in the sediment. Conversely, an increase in the abundance of foraminifer tests will tend to shift the signal downward in the sediment relative to the level of deposition. This phenomenon can easily lead to significant artificial bias when species showing opposing trends in abundance are compared.

Even though the problem of bioturbation and abundance variations in the proxy carriers is well known and there is a large literature dealing with the effect on the environmental signals recorded in the sediments (see overview by Matisoff, 1982), these results have found little application in paleoceanographic research. The aim of this modeling study is to explore the nature of potential errors that may arise from the combination of bioturbational mixing and abundance variations in the foraminifer species, and to highlight two effects of particular interest when a multispecies approach is used for paleohydrographic reconstructions.

## 2. The bioturbation model and the synthetic data set

For our simulation we used a simple box model consisting of a homogeneously mixed layer (cf. Berger and Heath, 1968; Manighetti et al., 1995). Consequently, there is a sharp boundary to underlying preserved historical layers and no consideration is given to the potential effects of deep reaching burrows penetrating into the sediment below the mixed layer (the transitional layer). The model starts with a mixed layer with homogeneous abundance and isotope values. As one layer of new sediment is deposited on top of the column, the lowermost slice of the mixed layer is transferred to the historical layer, and the remaining sediment of the mixed layer is homogeneously mixed with the new sediment, resulting in a new homogeneous layer with slightly different abundance and isotope values. This process is then repeated, gradually shifting the mixed layer upwards through the addition of sediment at the top of the column until the top of the sediment record is reached. The model itself does not require the input of sedimentation rates, rather the sedimentation rate is determined by the sedimentation rate of the modeled data set.

The model used is of course an extreme simplification of the bioturbation process. In reality, the mixed layer is not always homogeneously mixed, the transition to the historical layer, where the isotope signal is preserved, is gradual and not sharp, and deep reaching burrows may pipe sediment over significant vertical distances. More complex models can be applied to simulate more realistic types of bioturbation (e.g. Trauth, 1998). However, burrow type, burrowing intensity, and burrowing depth are controlled by a number of interrelated factors such as bottom and pore water oxygenation, food flux and food availability, sedimentation rate and substrate consistency (Wetzel, 1991). Predictions of spatial and temporal variations in the bioturbational mixing are therefore difficult. Furthermore, the difference in effect on the sediment between a simple box model and more elaborate models is rather small (Meysman et al., 2003), and no model can accurately accommodate the effect of deep reaching single burrows, which also show considerable spatial and temporal variability (Löwemark and Werner, 2001; Leuschner et al., 2002; Löwemark and Grootes, 2004; Hughes et al., 2005). Our modeling study differs from previous modeling studies (e.g. Bard et al., 1987; Anderson, 2001; Barker et al., 2007) in that it explicitly addresses how the interpretation of

multispecies records is affected by the combined effect of bioturbation and opposing abundance variations.

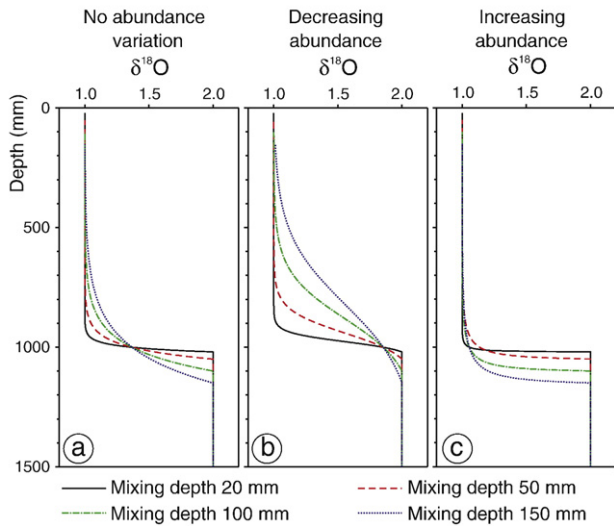
As input data synthetic records of unmixed abundance and isotope values with 1 mm sampling intervals were used (corresponding to a temporal resolution of 10 yr at a sedimentation rate of 10 cm  $\text{ky}^{-1}$ ). For a demonstration of the bioturbation model we first created simple synthetic records where isotope values and foraminifer abundances shift stepwise from one level to another. The effect of bioturbation was then modeled for different mixing depths (Fig. 1). It is important to note that it is the variations in absolute abundance (number of tests/mass unit sediment) that were used to model the effect of bioturbation on the proxy records, in contrast to relative abundance, which is the generally reported parameter in micropaleontological studies.

To create a realistic picture of the effect of abundance variations on multiproxy records, the GISP2 record (Meese et al., 1994, 1997; Grootes and Stuiver, 1997) was used to generate both a synthetic unmixed isotope record and two antiphased synthetic abundance records, referred to as subpolar (cold-adapted species) and subtropical (warm-adapted species). The GISP2 ice core isotope record was converted to a synthetic sediment record with a sedimentation rate of 10 cm  $\text{ky}^{-1}$ , which is considered to be a typical value for piston and gravity cores used in paleoceanographic studies. Thus, one year in the GISP2 record corresponds to 0.1 mm in the synthetic sediment record. Following Anderson (2001), the GISP2 isotope record was scaled to 2‰ amplitude to allow direct comparison with typical open marine glacial–interglacial variability in planktonic foraminifer records.

The abundance of foraminiferal tests in marine sediment commonly varies rapidly over short vertical distances. Records from the Santa Barbara basin show changes in foraminifer flux on the scales of an order of magnitude over time spans shorter than a decade for several planktonic species (Field et al., 2006), and changes of one order of magnitude over intervals less than 10 cm are not uncommon in marine records (e.g. Pflaumann and Jian, 1999; Chen et al., 2003; LoDico et al., 2006; Vautravers and Shackleton, 2006; Rashid and Boyle, 2007). Moreover, variations in foraminiferal abundances have been shown to closely respond to the Dansgaard–Oeschger cycles recorded in the Greenland ice cores (Hendy and Kennett, 2000). We therefore used the GISP2 isotope record to construct two antiphased abundance records representing a subpolar (cold-adapted) species and a subtropical (warm-adapted) species. The abundances of the two synthetic species are controlled by variations in the isotope record and were set to vary stepwise between 10 and 100 tests per g sediment, with highest abundances for the subpolar species corresponding to the heaviest isotope values, and vice versa for the subtropical species (Fig. 2a and b). This artificial record is extreme in that it shows so consequent antiphasing between warm and cold species, but as demonstrated by many foraminiferal faunal records, this kind of rapid antiphased abundance variations is not uncommon. (e.g. Chen et al., 2003; Ujjié, 2003; Rogerson et al., 2005).

## 3. Results and discussion

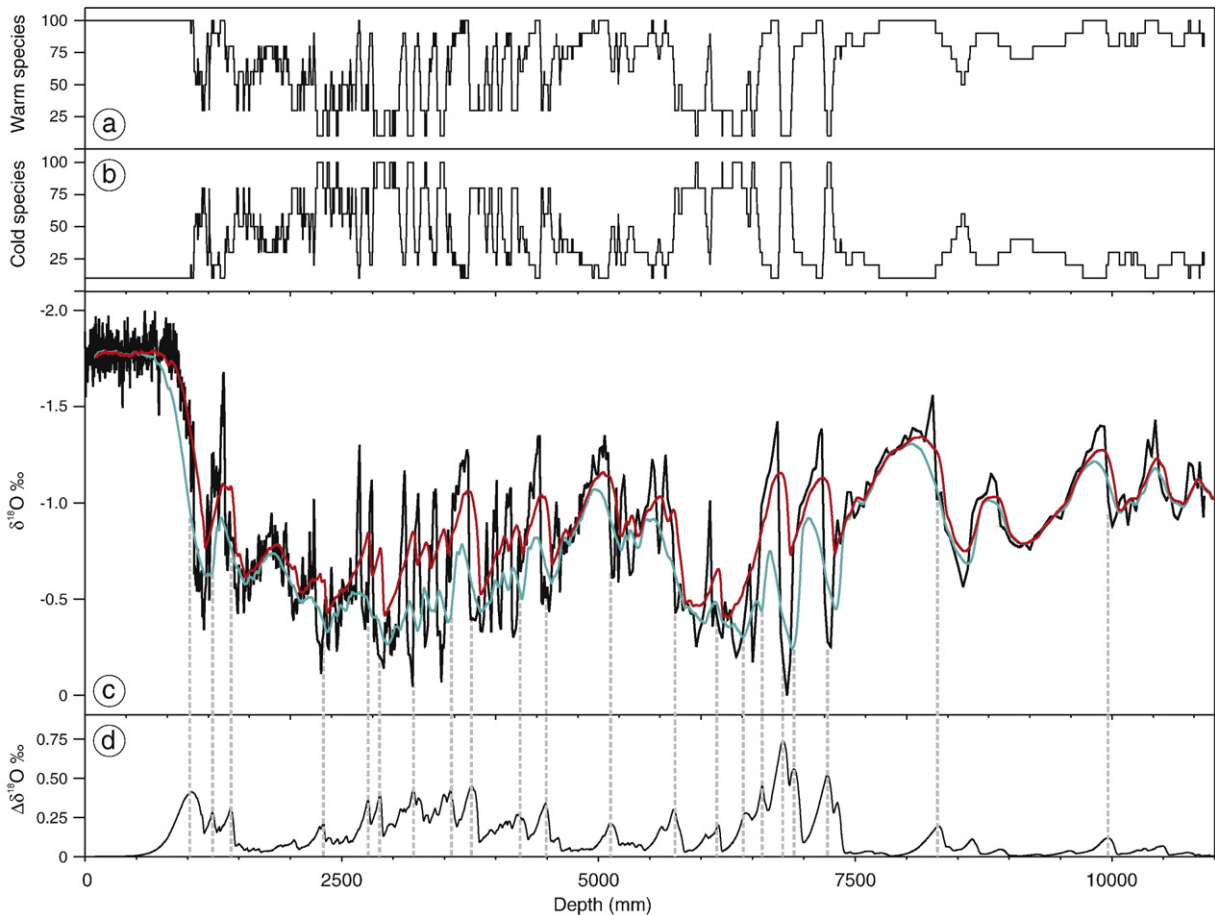
We first used the model to show how an abrupt change in isotope signal is altered by the bioturbation. The original isotope values were set to change instantaneously from 2‰ to 1‰ and then the effect of four different mixed layer thicknesses was modeled: 20, 50, 100, and 150 mm (Fig. 1a). The results show that the onset of the changing isotope values is shifted downward to a depth corresponding to the thickness of the mixed layer, and then the values drop exponentially towards 1‰. The thicker the mixed layer is, the wider the affected zone will be, and the gentler the slope. Our modeled changes agree with earlier modeling results (Berger and Heath, 1968; Matisoff, 1982), and also show a strong similarity to the redistribution of distinct marker horizons observed in the deep sea (e.g., radioactive isotopes; Carpenter et al., 1982; DeMaster and Cochran, 1982; Thomson et al., 2000), tephra layers (Ruddiman and Glover, 1972; Officer and Lynch, 1983), microtectites (Glass, 1969), and



**Fig. 1.** Modeling results illustrating the effect of bioturbation on an isotopic record that originally show a stepwise change from 2.0 to 1.0‰ (black line). Four different mixed layer depths were modeled: 20 mm, 50 mm, 100 mm, and 150 mm. a) No change in the abundance of the proxy carrier. b) Decreased abundance, shifting the isotope curve upward, and c) increased abundance shifting the curve downward.

natural and artificial chemical substances (Mahaut and Graf, 1987; Conte et al., 1994; Wheatcroft et al., 1994).

In a second step, simple stepwise changing records were used for a conceptual visualization of the combined effect of bioturbation on concomitant variations in foraminifer abundance and isotope signal. Isotope values were set to change instantaneously from 2‰ to 1‰ and abundances were set to increase (from 10 to 100 tests  $g^{-1}$ ) or decrease (100 to 10 tests  $g^{-1}$ ) at the same stratigraphic level. The effect of bioturbation was then modeled using different mixed layer depths (20, 50, 100, and 150 mm). Again the resulting curves showed exponential changes, the gentler the thicker the mixed layer was (Fig 1b and c). The most striking aspect of these simple records is the relatively large difference in effect on the isotope data between an increase and a decrease in foraminifer test abundance. With increasing abundance, the isotope curves are shifted downward in the record. In contrast, a decrease in abundance leads to an upward shift of the isotope curves and to much gentler slopes as foraminifers from deeper levels, where abundances are high, keep getting mixed into overlying sediment for a long distance above the initial position of the abundance shift. This clearly demonstrates that two foraminifer species that originally have exactly the same isotopic values, but opposing abundance trends, would become artificially separated by the bioturbational mixing process. The isotope curve of the species experiencing a decrease is shifted upward, whereas the curve of the species with increasing abundance is shifted downward. The resulting isotope gradient between the two species may be almost as large as the original



**Fig. 2.** Synthetic abundance records used as input function for the modeling: a) subtropical (warm-adapted), and b) subpolar (cold-adapted) foraminifer species. c) Synthetic isotope record constructed from the GISP2 ice core record compared to the isotope signal of the subtropical (red curve) and subpolar (blue curve) species after bioturbation with a 10 cm thick mixed layer. Both records show a smoothing and decreased amplitude compared to the original signal. In intervals with rapid isotopic changes, there is also a significant offset between the two species, and the maxima and minima show considerable phase shifts. d) Maximum differences are observed in intervals with large and rapid changes, such as D/O events or Termination 1. Original data provided by the National Snow and Ice Data Center, University of Colorado at Boulder, and the WDC-A for Paleoclimatology, National Geophysical Data Center, Boulder, Colorado. <ftp://ftp.ncdc.noaa.gov/pub/data/paleo/icecore/greenland/summit/gisp2/isotopes/gispd18o.txt>.

isotopic shift. The outcome also shows that this artificial difference between the two species may stretch over several tens of centimeters (Fig. 1).

Finally we used this model to study the effect on the more realistic synthetic isotope and abundance records constructed from the GISP2 record. Fig. 2c shows the resulting isotopic records of the subpolar and subtropical species after mixing, compared to the original signal. The modeled records reveal several distinct changes compared to the original record. The most obvious effect of the mixing is the well-known smoothing and the decreased amplitude of short term events (cf. Anderson, 2001). However, as pointed out in several earlier studies on the effect of bioturbation (e.g. Peng and Broecker, 1984; Bard et al., 1987), there is also an introduction of artificial leads and lags between species with opposing abundance trends. Because the subpolar species has its maximum abundance during cold events, large numbers of ‘cold’ tests will be mixed downwards in the record, making the subpolar species’ heavy isotopes occur earlier in the record than the cold signal recorded by the subtropical species. Conversely, because the warm species show maximum abundances during warm intervals, large numbers of isotopically light foraminifers will be mixed downwards, resulting in earlier light isotope peaks in the subtropical species, compared to the subpolar species (Fig. 2c). The size of these isotopic offsets and phase shifts between the species is depending on depth of bioturbation, abruptness and magnitude of abundance variations and abruptness of isotope changes; the largest offsets occur between foraminifers with opposing abundance trends at rapid, high amplitude isotopic and abundance shifts. These artificial leads and lags between the two species could easily be misinterpreted as a difference in phase of the forcings controlling the individual water layers.

A largely overlooked effect of this stratigraphic offset between the two curves is that calculated isotopic gradients between two species may show erroneously increased values during phases of rapid and large climatic changes (when abundance and isotope values shift the fastest). This could easily give the false impression that there is an alteration in surface water hydrography, or a change in calcification depth (or season) during times of rapid climatic changes, such as Dansgaard–Oeschger events or terminations. Although the isotopic

input signal for the two species was identical, bioturbation in combination with abundance changes have shifted the isotopic signal of the warm species downwards while the cold species is shifted upwards. However, from the irregular shape of the curves it is not immediately obvious that there is a stratigraphic shift between the two species, and the resulting increase in isotopic gradient between the two species could easily be erroneously interpreted as a true change in surface water hydrography. As can be seen from the curve in Fig. 2d, the gradient is the largest where isotope and abundance changes are abrupt, but rather small where changes are gradual. At very abrupt changes the artificial gradient may reach a value close to half the amplitude of the initial isotopic change.

A second striking effect of the mixing of tests out of the abundance maxima is the fact that the two species, although initially having exactly the same isotopic composition, may become distinctly separated with the subpolar species showing generally heavier values than the subtropical one (Figs. 2 and 3). This effect is caused by the antiphased variations in abundance. During cold times the abundances of subpolar species are high, while the abundance of subtropical species is low, and vice versa during warm times. During intervals of rapid climate change, such as Dansgaard–Oeschger cycles, foraminifers with ‘warm’ isotope signals are mixed into cold intervals both from the abundance peak above and below. Conversely ‘cold’ foraminifera are mixed into warm intervals from above- and below lying cold intervals. This leads to a constant overrepresentation of “cold” isotope values in the subpolar tests in “warm” intervals, and an overrepresentation of “warm” values in the subtropical tests during the “cold” intervals. This effect is largest in intervals with rapidly changing abundances, but small in intervals where the abundance shows little variability. This kind of offset between the two curves could erroneously be interpreted as representing different calcification depths or seasons. The results also show that warm-adapted species will be closer to the true signal during warmer intervals, while cold-adapted species will be closer during cold intervals. It is particularly important to take this kind of offset between different species into account when attempting down core calibrations in between different species and proxies (cf. Skinner and Elderfield, 2005).

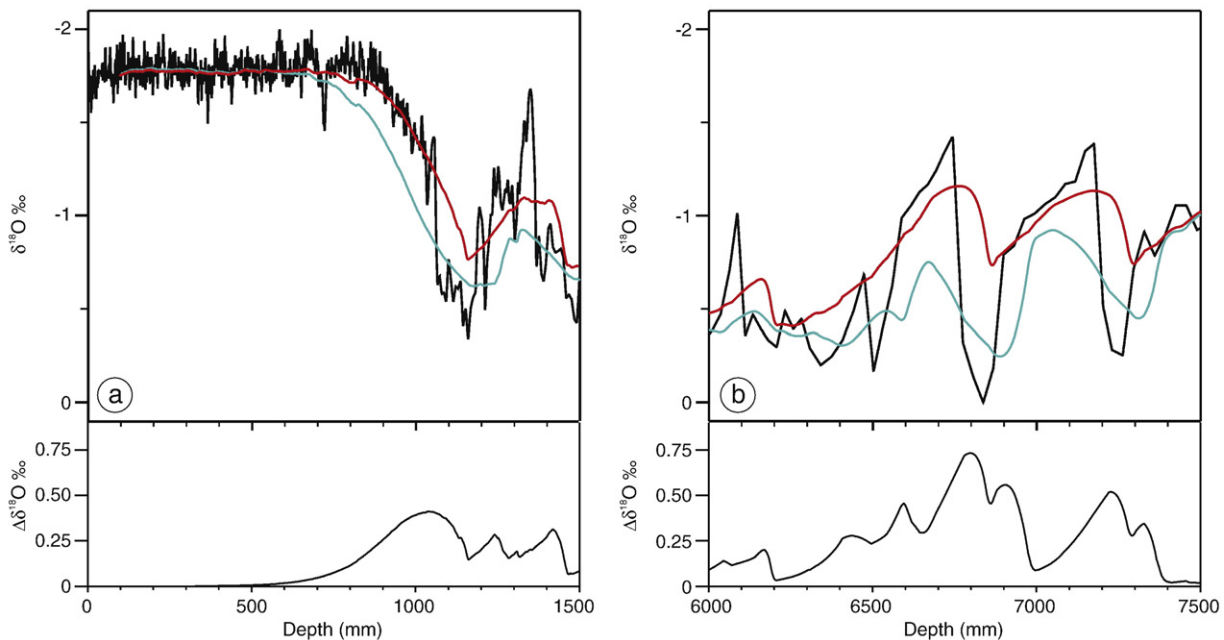


Fig. 3. Close up of Termination 1 and Dansgaard–Oeschger cycles 10–12, clearly showing the general offset between the subtropical (red curve) and subpolar (blue curve) species, as well as the phase shifts between the peaks.

#### 4. Conclusions

Besides showing the well-known general attenuation and smoothing of the proxy signals, the results from the modeling study also demonstrate how the bioturbational mixing of tests out of abundance maxima results in a phase shift of warm and cold species in opposite directions, causing large leads and lags between different species during intervals of rapidly changing environmental conditions. This shifting of the proxy records is well known from earlier studies, but our results high-light two previously largely ignored effects of particular interest to paleoceanographic reconstructions based on the multispecies approach:

- The shifting of the proxy signals can result in apparent increases or decreases in the isotopic gradients between different species, especially during intervals of rapidly changing climate conditions.
- In intervals with rapid climatic oscillations, such as Dansgaard–Oeschger cycles, the bioturbational mixing of tests out of abundance maxima into over- and underlying sediment with lower abundances will result in a general offset between “cold” and “warm” species. That this offset decreases in intervals with smaller variability, such as the Holocene, can easily be interpreted as a change in the hydrographic structure of the water column.

These artifacts have the potential of seriously biasing any paleoceanographic and paleoclimatic reconstructions based on multispecies analysis where the species show opposing abundance variations. It is therefore highly recommended that records of species showing small abundance variations are used whenever multispecies reconstructions are attempted. Preferably, species displaying opposing abundance patterns should be avoided.

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