Biogeosciences
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Interactive comment on "Repercussions of differential settling on sediment assemblages and multi-proxy palaeo-reconstructions" *by* A. G. M. Caromel et al.

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Received and published: 11 July 2013

General comment: This study deals with an interesting and rarely considered issue of the degree to which microfossil assemblages deposited at the sea floor are autochthonous in the sense of consisting exclusively of individuals that inhabited the overlying water column. In theory, during transit from the surface layer, these fossils can be displaced by currents. This phenomenon is known as expatriation. The degree of expatriation is a function of residence time in the water column, which in turn is a function of settling velocity. At sub-millimeters scales, the latter becomes a complex function of size and shape and because different microfossils differ by size

and shape, they are likely to experience differential expatriation. This issue has been recognized many years ago by workers like Berger (1970), Berger and Piper (1972) and thoroughly conceptualized by Weyl (1978). It is a pity that the authors do not seem to be aware of that study, because it might have guided them in a different direction in their research.

Comment: This brings me to the main problem I have with the paper. In my opinion, the approach is inappropriate because it only considers transport during settling. Yet, by far the most important component of transport occurs during life. Microplankton organisms have no means of propulsion to counteract passive transport by currents. Since during their life they inhabit the most dynamic surface layer and because their lifespan can range from weeks to months, the distance they travel during life will inevitably be many times longer than the amount of lateral displacement during settling. I am afraid the authors have focused on the wrong aspect of expatriation and their conclusions and calculations are only really useful for a case where one would attempt to compare microfossil assemblages intercepted by a series of vertically arranged sediment traps. I note that the authors us the example of the Agulhas leakage as a process expatriating microfossils into an entirely different ecological context (Peeters et al. (2004)), noting that the Agulhas leakage transports life assemblages of plankton, but then this issue is not developed any further.

Response: While the referee raises an interesting topic for investigation, that of lateral transport and drift during life, as well as the potential variation and turnover in assemblages resulting from the changing conditions experienced by a drifting assemblage in the surface waters which was explored in Weyl (1978), quantifying this was not the intent of the current paper, as we feel that this is not at present feasible. As the referee states, "residence time in the water column, [...] in turn is a function of settling velocity". When considering the settling velocities we obtain, the residence time in the surface layers should be on the order of a few days, yet as they pointed out, the lifespan of

foraminifera can range from weeks to months. There are therefore other processes at work to maintain the living organisms in the upper water column for longer, whether cellular processes such as amount of lipids in the cytoplasm, or through upper water turbulent resuspension (as exemplified in Sciascia et al. (2013)). Until these processes and, more importantly, their differential effects on different species, are identified and quantified, it remains impossible to estimate settling velocity of the living organisms and to subsequently calculate any potential bias arising in surface waters in living assemblages and to integrate this into our consideration of expatriation.

We cannot even answer the simple question at the moment if there still is a difference in settling velocity between different species under such conditions of turbulence, or whether foraminifera are neutrally buoyant, in which case all species would undergo the same lateral transport during a specific timespan, irrespective of shape. Such a scenario would result in the residence time and consequent transported distance centring on the differences in lifespan between different species, and their turnover associated with encountering different environments during the drift. Much also remains to be discovered about the lifespan of different species of foraminifera; integrating turnover adds another level of complexity to the problem, and on the whole we feel that, should all the information be eventually made available, the problem would be best addressed by more complex particle tracking and turnover models (such as in Follows et al. (2007), for example).

We therefore purport to demonstrate a bias that may be introduced between death and reaching the sediment floor. We acknowledge that drift during life is an essential component of expatriation, reference to which is lacking in the paper, and consequently the introduction was amended to make mention of this and make the focus of the paper clearer.

General comment: Thus, although I appreciate that the research is tackling a relevant and interesting issue, I feel the paper does not do justice to the topic and that the

authors could do better to bring their assessment closer to reality. In addition to the major issue outlined above, I have identified several minor points, which I feel should be addressed as well.

Comment: The authors apparently carried out settling experiments to determine terminal settling velocities of foraminifera of various sizes and shapes. I wonder a) why and b) how. There are numerous earlier studies, based on various approaches that have determined in detailed settling velocities of foraminifera and their relationship to size and shape. A good example is the study by Fok-Pun and Komar (1983). A cursory look at their results reveal identical range of values as that reported here in Table 1. Why was the new experimental determination of the velocities necessary? More importantly, how were the experiments carried out? It does not seem appropriate to me to refer to unpublished work in this context.

Response: The reason new experiments were carried out to determine settling velocities, rather than using previously published values from Fok-Pun and Komar (1983) or Takahashi and Bé (1984), was to broaden the range of morphologies used, to determine whether shape and density introduce any bias in settling. The study by Fok-Pun and Komar (1983) used only 4 species, the spherical *Orbulina universa* and 3 ellipsoidal forms; that of Takahashi and Bé (1984) was more extensive, but did not represent conical forms such as *G. truncatulinoides*, or make use of more heavily calcified species such as *G. conglobatus* or *G. tumida*.

Due to a delay in the publication of the other paper in which the methodology is described, we agree that a description of the settling experiments used to generate the values for the settling speeds of individual species of planktic foraminifera is needed here. The following paragraphs were added to the Materials and Methods after the first sentence: "Specimens from nine species of planktic foraminifera, representing a broad range of morphologies, were picked from the >250μm size fraction from deep-sea core samples: near-spherical *Globigerinoides conglobatus* (n=29) and *Orbulina universa* (n=30); globular *Globigerinoides trilobus* (n=26), *Globigerinoides sacculifer*

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(n=28), and *Globigerinoides ruber* (n=24); discoidal *Globorotalia menardii* (n=30), and *Globorotalia tumida* (n=30); lowly conical *Globorotalia hirsuta* (n=29); and highly conical *Globorotalia truncatulinoides* (n=29). For each specimen, a maximum diameter measurement was taken using ImageJ (version 1.44p; National Institutes of Health, USA).

The specimens were soaked for two weeks to remove air bubbles, and were then allowed to settle individually in a cylindrical tube of 155mm depth and 140mm diameter. This setup was deemed sufficient for the foraminifera to reach terminal velocity with negligible wall effects (calculated following Di Felice (1996)), and this was verified by measuring settling velocity over several depth intervals. Settling was recorded using a high-speed camera (Vision Research Phantom v.9.1 at a sampling rate of 100pps with a 1440x720 pixel resolution and 3000μs exposure) and terminal velocity was confirmed by calculation from 20 consecutive image frames from the lowest 30mm."

In addition, we add the following to the Results and Discussion section to reflect the reviewer's comment and acknowledge previous work: "Our results generally agree well with previous work of settling foraminiferal shells; for example, settling velocities between 0.02 and 0.06 m/s for *Orbulina universa* are comparable to those obtained by (Fok-Pun and Komar, 1983). Minor differences in settling velocities, for example for *G. sacculifer*, can readily be explained by differences in the size fraction used for the experiment, previous studies having used a proportion of smaller specimens (Fok-Pun and Komar, 1983; Takahashi and Bé, 1984)."

Comment: I am worried about the calculations being based on empty specimens with no cytoplasm inside and without spines. This does not reflect the typical state of foraminifera after death. Also, the work is based on the assumption that most foraminifera sink individually. This remains to be established.

Response: We recognise that these represent two further simplifications to our calcu-

lations, that we feel are justified and have little impact on the calculations. Previous published sinking experiments have shown that dead cytoplasm-filled tests have settling velocities similar to empty tests (Takahashi and Bé, 1984). While the spines may indeed generate additional drag that decreases settling velocity (Takahashi and Bé 1984), it is rare to find specimens in sediment assemblages that have preserved spines, as many species resorb their spines during gametogenesis (Hemleben et al., 1989), prior to the sinking in the watercolumn with which we are concerned. The work is indeed based on the assumption that most foraminifera sink individually, but until evidence for flocculation into aggregates as is reported in diatoms (Alldredge and Gotschalk, 1989) is established, we think that this is a necessary and reasonable assumption.

Comment: The effect of turbulence in the surface layer, which is not considered here, may be larger than the authors expect, making the displacement estimates presented here far too conservative (Sciascia et al., 2013).

Response: We already acknowledge in our paragraph detailing the simplifications of the ocean model, that our estimates are minimum settling times. In addition, as explained above, beyond the effects of size presented in Sciascia et al. (2013), it remains speculation as to how differently turbulence may act on particles of different shape and density. Should foraminiferal species higher in the watercolumn experience more resuspension post-mortem, which would extend their residence time compared to the species living lower in the watercolumn, this has the potential to introduce a bias, but the effect of turbulence is so far unquantified and therefore cannot be integrated here. We speculate that turbulence may have a larger effect on the smaller or less dense particles such as diatoms and radiolaria, which additionally reside higher in the watercolumn and are therefore more exposed to the turbulence; as these particles already travel further than the foraminifera, this would have the effect of amplifying the bias between different proxies.

Comment: The discussion where the authors consider the effects of lateral displacement of microfossils and other particles on proxy calibration is correct in principle but it misses the point that the effect of lateral transport is already contained in the existing calibrations. These are based on relating sediment parameters to surface water properties at the same location, thus assigning environmental values to assemblages irrespective of the degree of lateral transport.

Response: The referee's comments would be correct if there were no change in flow over time. Certainly, transfer functions are calibrated against the modern conditions which include lateral transport. As geostrophic flow changes, for example between glacial and interglacial conditions (e.g. Lynch-Stieglitz et al., 2011), these changes in current velocities, and therefore transport potential, could have an influence and this is what we went out to test. We have clarified this in the text.

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Interactive comment on Biogeosciences Discuss., 10, 6763, 2013.