Reply to William Howard (reviewer 2).
We are grateful for the reviewer's supportive comments on our manuscript. Below we respond to the reviewer's comments (in *italics*). Judging from the comments, it seems that our response to the previous (technical) review did not reach the reviewer, so for completeness we append our previous reply below.

I think the implications of this study could be explored a bit further, perhaps in a future study.

We agree with the reviewer that the implications of (variable) seasonality need to be better accounted for in paleoceanographic studies. In the final section of out manuscript we have tried to mention some of these implications and outline potential directions for future research. We will try to make these points even more explicit in the revised version.

1) For example species with strong peaks in seasonal production might have different patterns in the range of seasonality they reflect in their isotopic or trace-metal variability. This could be another interesting test. Mix (1987) explored this idea in concept, and others have tried to apply it, sometimes coming up with surprising interspecific offsets in isotopic composition due to differences in seasonal production (e.g. King and Howard, 2005).

Indeed different species can have different seasonality at the same location (SFig. 1), which lead to different flux-weighted offsets in their fossil proxy signal (Fig. 9). Our model also predicts that such situation is likely to occur at mid-range temperatures where warm-water taxa will be more strongly biased towards summer and cold-water taxa more biased towards winter.
We have added a sentence to the third paragraph of section 4.2 to explicitly mention this effect. The start of the paragraph now reads (change in italics):

"The temperature offsets due to seasonality vary between +4 and -4 °C and may range by as much as 6°C within one species (Fig. 9). *At a single location, species with a different seasonality mode may show different flux-weighted offsets. This is more likely to occur at intermediate temperatures where warm and cold-water species mix and has been observed previously (Jonkers et al., 2013; King and Howard, 2005).* Large positive offsets are generally found at higher latitudes, reflecting a preference for summer flux in colder regions."

2) It would be interesting to see if, in aggregate, the offsets of individual taxa's peaks from mean temperatures drive biases in multivariate paleotemperature estimates. In principle multivariate biotic approaches can only work well if the taxa have distinct and only partially-overlapping environmental optima (expressed through seasonality or abundance variation against other environmental variable).

This is an interesting point indeed. In principle, the fossil record integrates seasonality over many years and any assemblage-based paleoclimate inference would therefore reflect the mean seasonality (of course as long as this mean seasonality remained constant over time). However, most, if not all, empirical calibrations between an environmental parameter and fossil species abundance overlook seasonal (and depth) habitats and thus probably infer an environmental niche that is too wide (i.e. a winter species can be very abundant in the sedimentary record, but its abundance would be driven by conditions in winter rather than mean annual conditions. In theory, changes in its abundance could thus occur in response to changing winter conditions even when mean annual conditions remain constant.)
This could affect assemblage-based calibrations/reconstructions and better understanding of planktonic foraminiferal ecology is definitively required to improve reconstructions of past climate. (And our paper exactly aims at this.)
In addition to the previous change (see supplement) we have made some more changes to the first paragraph of section 4.2, which now reads (change in *italics*):

"The existence of a significant seasonal component in the shell flux pattern of extant planktonic foraminifera has implications for the interpretation of the fossil record. Since seasonality is species-

specific and spatially variable, fossil assemblages of the same species collected at different locations contain in the composition of their shells a different amount of seasonal bias. Firstly, this may affect proxy calibrations based on sediment core tops, which depending on their location will reflect a variable amount of seasonal bias and not reflect mean annual conditions. *Because of such seasonal bias, determining the environmental niche of a certain species using mean annual conditions leads to an overestimation of the width of this niche. Consequently, under these assumptions, calibration based on mean annual environmental conditions may not be meaningful*. *Hönisch et al. (2013) provide an instructive example on how seasonality may affect Mg/Ca-temperature calibration, but seasonal biasing may also affect multivariate biotic approaches based on foraminiferal assemblages*."

3) The authors could stand to add references to (or better yet, in further development, data from) some studies that reinforce their point about strong seasonality.
Eguchi, N. O., H. Ujiie, H. Kawahata, and A. Taira (2003), Seasonal variations in planktonic foraminifera at three sediment traps in the Subarctic, Transition and Subtropical zones of the central North Pacific Ocean, Mar. Micropaleontol., 48(1-2), 149-163
Chapman, M. R. (2010), Seasonal production patterns of planktonic foraminifera in the NE Atlantic Ocean: Implications for paleotemperature and hydrographic reconstructions, Paleoceanography, 25, PA1101, doi:10.1029/2008PA001708.
Sagawa, T., A. Kuroyanagi, T. Irino, M. Kuwae, and H. Kawahata (2013), Seasonal variations in planktonic foraminiferal flux and oxygen isotopic composition in the western North Pacific: Implications for paleoceanographic reconstruction, Mar. Micropaleontol., 100, 11-20, doi:10.1016/j.marmicro.2013.03.013.
King, A. L., and W. R. Howard (2001), Seasonality of foraminiferal flux in sediment traps at Chatham Rise, SW Pacific: implications for paleotemperature estimates, Deep-Sea Research Part I-Oceanographic Research Papers, 48(7), 1687- 1708, doi:10.1016/S0967-0637(00)00106-0.
Pilskaln, C. H., S. J. Manganini, T. W. Trull, L. Armand, W. Howard, V. L. Asper, and R. Massom (2004), Geochemical particle fluxes in the Southern Indian Ocean seasonal ice zone: Prydz Bay region, East Antarctica, Deep-Sea Research I, 51, 307-332, doi:10.1016/j.dsr.2003.10.010.

We would like to thank the reviewer for his suggestions of additional sediment trap studies. The main reason why these have not been included in the database is because of their duration of less than a year a criterion we used to select time series for the database (see section 2: Data and methods). Please also refer to our previous response (see below) to this comment.

References

Mix, A. C. (1987), The oxygen-isotope record of glaciation, in North America and Adjacent Oceans During the Last Deglaciation, edited by W. F. Ruddiman and H. Wright, pp. 111-135, Geological Society of America, Boulder.
Hönisch, B., Allen, K. A., Lea, D. W., Spero, H. J., Eggins, S. M., Arbuszewski, J., deMenocal, P., Rosenthal, Y., Russell, A. D., and Elderfield, H.: The influence of salinity on Mg/Ca in planktic foraminifers - Evidence from cultures, core-top sediments and complementary $\delta^{18}O$, Geochimica et Cosmochimica Acta, 121, 196-213, http://dx.doi.org/10.1016/j.gca.2013.07.028, 2013.
Jonkers, L., van Heuven, S., Zahn, R., and Peeters, F. J. C.: Seasonal patterns of shell flux, $\delta^{18}O$ and $\delta^{13}C$ of small and large N. pachyderma (s) and G. bulloides in the subpolar North Atlantic, Paleoceanography, 28, 164-174, 10.1002/palo.20018, 2013.
King, A. L., and Howard, W. R.: $\delta^{18}O$ seasonality of planktonic foraminifera from Southern Ocean sediment traps: Latitudinal gradients and implications for paleoclimate reconstructions, Marine Micropaleontology, 56, 1-24, 2005.

REPLY TO TECHNICAL REVIEW:

Dear professor Kitazato,

Thank you for accepting our paper on shell flux seasonality in BGD. Both reviewers have received the manuscript positively, but one of them suggests some corrections. We would like to thank the reviewer for his/her comments, which we have copied below in red. We have made some change to the manuscript (explained below) and provide a response to the comments below.

Kind regards,

Lukas Jonkers & Michal Kucera.

Reviewer 2:

This is a really good compilation, synthesis, and analysis of planktonic foraminiferal flux seasonality.

In further revisions, it would be good to see some more rigorous analysis and demonstration of *how* paleoceanographic reconstructions might be biased, unless they are talking about paleo-estimates based on single-species abundance variations. In this version the biases introduced by the seasonality of individual taxa are clearly demonstrated, but the effect on multivariate biotic paleo-estimation is not. Indeed multivariate biotic approaches depend upon strong specific dependencies on temperature and/or other properties to work, and are based upon sedimentary assemblages which are flux-weighted aggregations of multiple years (if not centuries or millennia!) of shell production and sedimentation.

This is a valid point, however, as the reviewer mentions, the focus of our paper is to explain the seasonality in individual species and the discussing the effects thereof on paleo-estimates. We completely agree that seasonality (and flux variability on longer time-scales) may also have affected proxy-calibrations based on core tops (not only assemblage-based proxies) that integrate years to millennia. While a rigorous analysis of this effect goes beyond the scope of our paper (and, perhaps, a technical comment), we have changed the introduction of section 4.2 to:

'The existence of a significant seasonal component in the shell flux pattern of extant planktonic foraminifera has implications for the interpretation of the fossil record. Since seasonality is species-specific and spatially variable, fossil assemblages of the same species collected at different locations contain in the composition of their shells a different amount of seasonal bias. *Firstly, this may affect proxy calibrations based on sediment core tops, which depending on their location will reflect a variable amount of seasonal bias and not reflect mean annual conditions. This affects both multivariate biotic approaches based on foraminiferal assemblages as well as single species geochemical calibrations. Secondly*, this spatial bias may translate into a temporal bias in records straddling climatic transitions.' (change in *italics*).

The work could also stand to include more data sets, especially as they note most of the data are from the Northern Hemisphere. There are a couple more Southern Hemisphere studies in the list below. These would tend to reinforce the authors' point that many taxa show strong flux seasonality. Studies from which these data could be drawn include:

We would like to thank the reviewer for the suggestions for additional studies for inclusion in seasonality the database since we agree that more data, particularly from under-sampled regions, would improve our study. Below we explain why some of these suggested studies did not make it into the compilation.

Eguchi, N. O., H. Ujiie, H. Kawahata, and A. Taira (2003), Seasonal variations in planktonic foraminifera at three sediment traps in the Subarctic, Transition and Subtropical zones of the central North Pacific Ocean, Mar. Micropaleontol., 48(1-2), 149-163

An important criterion for inclusion in the data set was that the time series of shell fluxes is at least one year (page 5: line 3). We deem this necessary to infer seasonality from the time series. Unfortunately the data presented by Eguchi et al span less than one year.

Chapman, M. R. (2010), Seasonal production patterns of planktonic foraminifera in the NE Atlantic Ocean: Implications for paleotemperature and hydrographic reconstructions, Paleoceanography, 25, PA1101, doi:10.1029/2008PA001708.
Unfortunately the data from this study that are available on the NOAA website appear to contain some serious errors. We have not been able to get a clarification from Mark Chapman regarding these issues and therefore not included these data. We will once more try to sort this out in order to include this study in a revised version of the manuscript.

Sagawa, T., A. Kuroyanagi, T. Irino, M. Kuwae, and H. Kawahata (2013), Seasonal variations in planktonic foraminiferal flux and oxygen isotopic composition in the western North Pacific: Implications for paleoceanographic reconstruction, Mar. Micropaleontol., 100, 11-20, doi:10.1016/j.marmicro.2013.03.013.
Just like the Eguchi et al dataset, this time series spans < 1 year.

King, A. L., and W. R. Howard (2001), Seasonality of foraminiferal flux in sediment traps at Chatham Rise, SW Pacific: implications for paleotemperature estimates, Deep-Sea Research Part I-Oceanographic Research Papers, 48(7), 1687-1708, doi:10.1016/S0967-0637(00)00106-0.
These time series are shorter than one year.

Pilskaln, C. H., S. J. Manganini, T. W. Trull, L. Armand, W. Howard, V. L. Asper, and R. Massom (2004), Geochemical particle fluxes in the Southern Indian Ocean seasonal ice zone: Prydz Bay region, East Antarctica, Deep-Sea Research I, 51, 307-332, doi:10.1016/j.dsr.2003.10.010.
Although this study presents total foraminiferal counts, they are not presented on species level, which prevents inclusion in our data set.