Interactive comment on "Re-examining the 4.2 ka BP event in foraminifer isotope records from the Indus River delta in the Arabian Sea" by Alena Giesche et al.

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Comment on Giesche et al. by L. Giosan (Woods Hole Oceanographic Institution) and K. Thirumalai (Brown University):

Giesche et al. present a valuable new dataset of planktonic foraminifer isotopic time series from core 63KA in the Arabian Sea. The authors briefly mention our recent paper on a similar topic (Giosan et al., 2018, Climate of the Past, in press). Giesche et al. expand on the original study by Staubwasser et al. (2003), but similar to this previous work, the new data exhibit low signal-to-noise ratio in a very complex coastal region. We argue that a more conservative interpretation is required to take into account this.

We thank L. Giosan and K. Thirumalai for taking the time to write a comment for the discussion of this manuscript and challenging us to sharpen our arguments.

Addressing uncertainties is needed to convincingly show that salinity signals, which are indicative of a "4.2 ka event", or any such millennial/centennial events in the late Holocene for that matter, are detectable in the foram 18O (and 13C) composition in this region.
Surface water masses in the NE Arabian Sea at core 63KA location may be affected by (a) advection of waters from NW Arabian Sea that have a variable upwelling-modified composition;

We acknowledge that our site location can be affected by multiple water masses and processes, but the existing paleo-SST records from the region favor a salinity-based explanation for the *G. ruber* $\delta^{18}O$ record and difference between *G. sacculifer* and *G. ruber* ($\Delta\delta^{18}O_{s-r}$). As discussed in the original paper of Staubwasser et al. (2003), we point to the data from core M5-422 off the coast of N. Oman in the NW Arabian Sea (Cullen et al., 2000) showing a decrease in *G. ruber* $\delta^{18}O$ over the 4.2 ka BP event, indicating that SSTs are warmer rather than cooler over this time. If anything, higher SSTs would suppress the signal of increased salinity we note in the surface-dwelling foraminifera. Similarly, it argues against the influence of cold upwelling water, because M5-422 is located downstream between the zone of upwelling and core 63KA. Finally, the SSTs recorded in the nearby core 56KA from the NE Arabian Sea (Doose-Rolinski et al., 2001), also show that temperature does not greatly change the salinity signal over 4.2 ka BP, which was discussed and shown in Figure 1 a-c of Staubwasser (2012).

(b) fluvial discharge from the Indus but also from River Hub that is proximal to the core (figure 1 in Giesche et al. supplementary materials);

We agree that the Hub River may also contribute freshwater, but the Indus river discharge (>100 km^3 per year before ~1950) is orders of magnitude greater than the Hub River (0.1 km^3 per year) (Milliman et al., 1984). Although the Hub river may contribute sediment, the relative amount of freshwater discharge is much smaller than the Indus. The arrival of freshwater at the coring location during summer months can be seen in the supplemental Figure S1 of the manuscript – this large plume extends along the entire coastline. Additionally, the salinity maps provided in Figure S1 include an important caveat in their caption – over the time window of this map (1955-2012), modern Indus River discharge has been reduced by >50% due to barrages and irrigation (Ahmad et al., 2001). This means that the freshwater plume seen in the summer map is artificially reduced compared to the discharge before 1955. We conclude that the Indus River freshwater discharge is the most significant factor influencing surface water salinity at our coring location during summer months when *G. ruber* and *G. sacculifer* have peak abundances.

(c) changes in winter to summer rain and snow/ice meltwater with variable isotopic signal that feed the Indus;

Isotope mass balance calculations suggest that the ratio of winter to summer rain or snow/ice/meltwater to direct runoff in the Indus river is unlikely to influence the isotopic signal of the Indus to the degree that would be needed to impact the signal of the foraminifera. The isotopic composition of the Indus River is -11.1‰$_{VSMOW}$ (Karim and Veizer, 2002) compared to the Arabian Sea surface waters of ~1‰$_{VSMOW}$ (LeGrande and Schmidt, 2006). The interannual $\delta^{18}O$ variability of Indus river discharge, ranging <2‰ (Lambs et al., 2005), mixed throughout ~20 m depth in the coastal NE Arabian Sea region would have a minor impact the $\delta^{18}O$ of the foraminifera (we estimate no more than ±0.05‰ for a ±1‰ change in river composition). In contrast, the increase in $\delta^{18}O$ of *G. ruber* at 4.1 ka BP exceeds the mean value by +0.38‰.

(d) deep winter mixing bringing Arabian Sea High Salinity Water Mass (ASWHSW) to the surface. All these potential sources and/or modifiers affect the isotopic signal in planktonic forams. For example, ASWHSW mixing would increase the salinity and decrease the temperature of surface waters.

Arabian Sea High Salinity Water (ASHSW) can be an important factor in the region. ASHSW forms in the surface waters of the northern Arabian Sea during winter due to intensified evaporation and cooling (Kumar and Prasad, 1999). This is the source of the highly saline surface waters in this part of the Arabian Sea. Two relevant points emerge from Kumar and Prasad's (1999) analysis: first, there is a northward current along the west coast of India during winter months that initially prevents the spreading of the high-salinity water onto the shelf (our coring location), and second, the high salinity water is then pushed northeast in the summer by the ISM. In fact, this is the highly saline water that provides the crucial contrast to the primarily summertime freshwater discharge of the Indus River. Additionally, our difference proxies ($\Delta^{18}O$) monitor changes in the water column regardless of the water mass composition throughout time. Differencing reduces the effect of ASHSW because the surface and deep waters are equally affected, but a freshwater plume would have a much greater impact on the surface. For example, the difference between surface dwelling species *G. sacculifer* and *G. ruber* ($\Delta\delta^{18}O_{s-r}$) would reflect the relative impact of the summertime freshwater plume (affecting *G. ruber* more than *G. sacculifer*). Additionally, the amount of warmer surface water mixing deep in the water column during winter (when ASHSW does not reach the coring location) would be reflected in the absolute $\delta^{18}O$ of the thermocline-dwelling *N. dutertrei*.

The dynamics of these waters masses is also complex near the coast. For example, the effect of the Indus freshwater plume at the core location is uncertain as summer coastal circulation is directed in the opposite direction along the coast of India. In fact, this is obvious in the modern salinity map provided by the authors (figure 1 in Giesche et al. supplementary materials) where the change in *signal at the core location is close to none between summer and winter (< 0.2 psu). If anything, River Hub discharge could affect the salinity at the core site more than the Indus (same figure).*

See above response to point b).

Given this complexity, despite any statistical tests, we argue that interpreting a signal of 0.04-0.07‰ as "significant" or "weakly significant" when intra-sample standard deviation is on the order of 0.12‰ is misleading. Smoothing of the signal and ulterior correlation at a subjectively-chosen window is bound to produce some degree of significance even in random data. The fact that there is no significant correlation in sample-to-sample comparison of the same species (G. ruber) at different size fractions is unsettling and should be taken as a warning signal.

We agree that the statistics must be carefully interpreted, but they cannot be ignored. The statistical tests take into account the variability of populations within the dataset. The Welch's t-test comparing the mean values for *N. dutertrei* pre- and post-4.1 ka BP shows that the +0.08‰ shift in $\delta^{18}O$ is statistically significant (t value = 6.2, $p < 0.01$, n = 132), along with the +0.07‰ shift in mean $\delta^{13}C$ (t value = 3.3, $p < 0.01$, n = 132). This proxy, which we relate to winter mixing and IWM, shows a clear step change at 4.1 ka BP. The t-test for *G. sacculifer* also shows that the +0.08‰ shift in mean $\delta^{18}O$ values is statistically significant (t value = 3.8, $p < 0.01$, n = 128). Although these changes in mean $\delta^{18}O$ are small and on the order of the reproducibility of individual $\delta^{18}O$ measurements, they are significant when the variance of the population consisting of 60+ samples before and after 4.1 ka BP is considered. The shifts in mean $\delta^{18}O$ are also visually obvious in the records.

In addition, the SiZer analysis (Figure 4) objectively shows increases and decreases in the data that are significant (Chaudhuri and Marron, 1999), and both *G. sacculifer* and *N. dutertrei* exhibit significant increases at 4.1 ka BP for all smoothing bandwidths. We acknowledge that the t-tests for mean $\delta^{18}O$ of *G. ruber* pre- and post-4.1 ka BP are not significant (the 0.04-0.07‰ numbers referred to in this comment). We are not arguing for a stepped change in *G. ruber* $\delta^{18}O$ at 4.1 ka BP, but rather a period of increased values between 4.8 and 3.9 ka BP. The new $\delta^{18}O$ record of *G. ruber (*400-500µm) shows a double-peak maximum occurring at 4.1 and 3.95 ka BP that is related to seven discrete measurements with high $\delta^{18}O$ values (see Figure 1 below). These maxima are offset from the average $\delta^{18}O$ value by +0.18‰ (smoothed average), or up to +0.38‰ when considering the maximum individual measurement at 4.1 ka BP. The offsets from the average values exceed one standard deviation of the entire record from 5.4-3.0 ka BP, which is 0.13‰.

Despite the low signal to noise ratio of the *G. ruber* records, the long-term trends for both size fractions of *G. ruber* are similar. In fact, compared to the previously published $\delta^{18}O$ of *G. ruber* (315-400µm), the larger size fraction makes an even stronger case for the increased $\delta^{18}O$ spanning ~4.8-3.9 ka BP with a strong peak at 4.1 ka BP exceeding 1SD of the record, which is also apparent in the SiZer analysis.

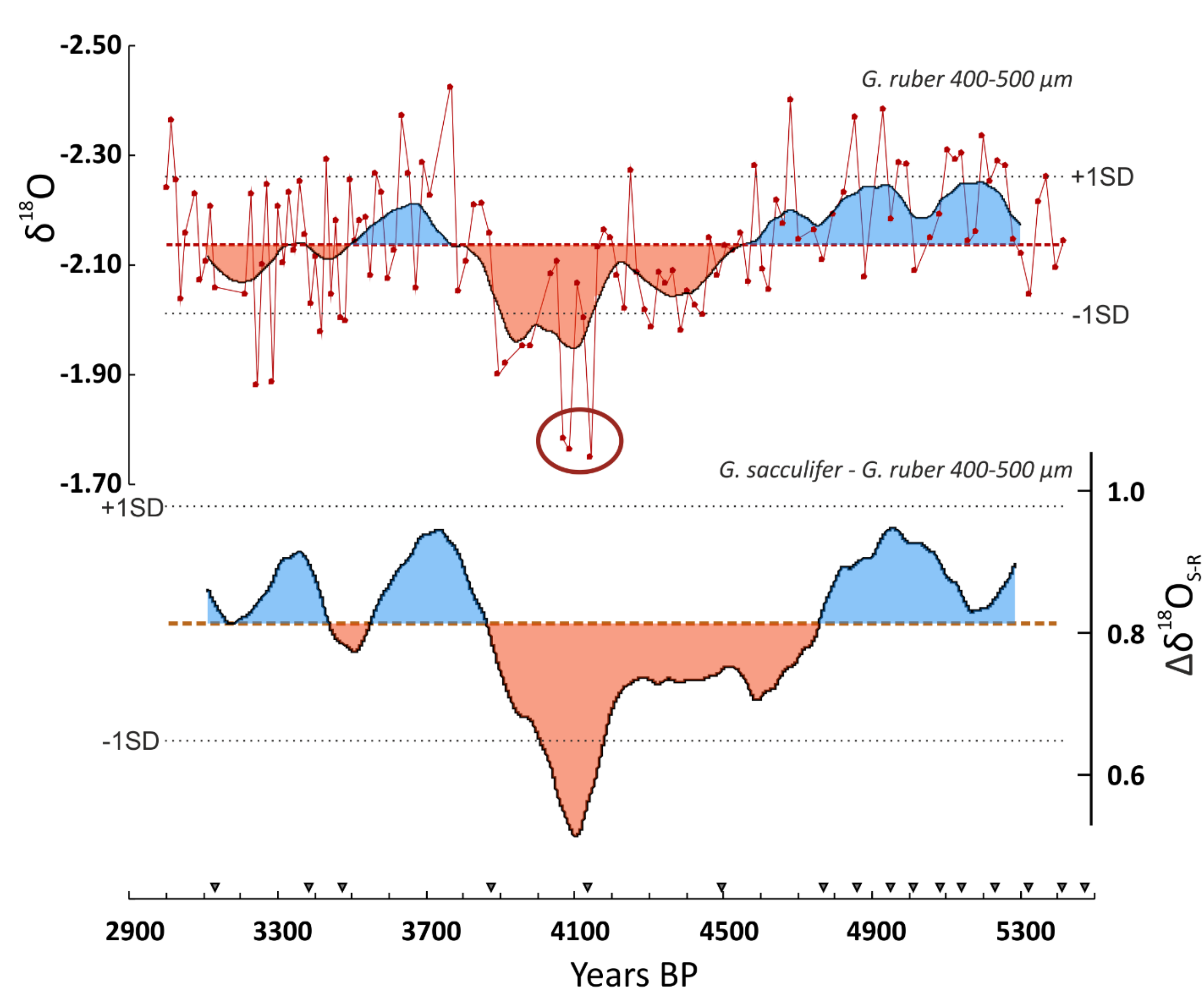

Figure 1. Top: *G. ruber* (400-500µm) $\delta^{18}O$ shown with ±1SD, with three points around 4.1 ka BP circled. Bottom: $\Delta\delta^{18}O_{s-r}$ shown with ±1SD.

Are the proxies chosen by Giesche et al. appropriate in these conditions to the task of reconstructing the summer and winter monsoons? We argue that the authors do not make a convincing case for this. First, their indicator for winter mixing, N. dutertrei, does not preferentially live in winter. Assuming that the limited sediment trap data cited by the authors is correct, the summer peak abundance in N. dutertrei is as important quantitatively as the winter peak due to its more extended temporal range (4 months compared to 1-2 months in winter). Thus isotopic signals in this species will be a mixed summer-winter 18O and not appropriate for detecting a winter monsoon signal.

The available foraminifer trap data (Curry et al., 1992; Zaric, 2005) is limited in both temporal (1986-87) and spatial extent (1000 km SW of our coring location). We show the trap data as overlapping peaks in Figure 2: there are 2 traps (shallow and deep), and the deep trap has the longest time series (660 days). Unfortunately, the data collection of the deep trap stops just before the second winter season (end of October). This means that our summary figure shows foraminifera counts over 1 winter (2 traps) and 2 summers (2 traps). If we only compared the total sum of *N. dutertrei* from the shallow trap over 1 year, we would see 38% of total numbers stemming from summer months (JJA) and 62% in winter months (DJF) – indeed, the growth of this species is not restricted to one season. However, this would effectively only dampen the temperature signal recorded by *N. dutertrei* during winter mixing. Furthermore, the temperature signal from winter mixing likely persists well beyond the winter months (Deser et al., 2003; Hanawa and Sugimoto, 2004), and therefore also affects the $\delta^{18}O$ of thermocline-dwelling species throughout the summer. The exceptionally low $\delta^{18}O$ values of *N. dutertrei* around 4.3 ka BP are best explained by warmer surface waters reaching deeper in the thermocline, and the differences between *N. dutertrei* and both *G. sacculifer* and *G. ruber* ($\Delta\delta^{18}O_{d-s}$, $\Delta\delta^{18}O_{d-r}$) suggest that cooler water may also be reaching the surface. Therefore, despite the scarcity of foraminifer trap data from our study area, we believe that our knowledge about winter mixing and foraminifer depth habitats provides sufficient information to interpret the $\delta^{18}O$ signal of *N. dutertrei* in relation to winter mixing.

Furthermore, interpretation of 13C values in this and other planktonic species is too simplistic given their known problems (e.g., possible shift in habitat, vital effects). Such problems are not discussed in the paper and interpretation is not even supported in the only cited reference (encyclopedia entry by Lynch-Stieglitz, 2006).

Admittedly, the $\delta^{13}C$ values of planktonic foraminifera are difficult to interpret. The basic principle is that surface waters of the ocean will have higher $\delta^{13}C$ than deeper water due to uptake of more ^{12}C by photosynthesis (Ravelo and Hillaire-Marcel, 2007), however, surface productivity is also increased by the upwelling of nutrient-rich bottom waters. With this in mind, lower $\delta^{13}C$ values in the thermocline at 4.3 ka BP could reflect increased presence of deeper water (Sautter and Thunell, 1991), or possibly a decrease in productivity. We are not confident about the interpretation of the $\delta^{13}C$ values, but its correlation to the $\delta^{18}O$ signal of *N. dutertrei* warrants mention.

In these conditions it is not productive to extend further our analysis of the paper as all interpretation and conclusions are vitiated by inappropriate basic assumptions. We urge the authors to consider a more conservative approach in interpreting this new data. It is evident to us that solving the salinity signal using forams in this region needs a more sophisticated approach (e.g., Ba/Ca in planktonics; temperature correction from Mg/Ca measurements, etc.). The alkenone-based SST estimates from Doose-Rolinski et al. can only be used to understand a qualitative indicative range of cooling as we now know that the high temperature plateau of the alkenone method limits its usefulness given the high SSTs in the region.

Other methods such as Ba/Ca and Mg/Ca were explored on a few samples of *G. ruber* (315-400µm). Preliminary results show that Ba/Ca supports the $\Delta\delta^{18}O_{d-r}$ used to infer Indus River discharge, with very low Ba/Ca around 4.2 ka BP suggesting reduced freshwater discharge (see Figure 2 below) (Bahr et al., 2013). The Mg/Ca measurements lack a data point around 4.1 ka BP, but overall temperatures appear to be increasing between 4.2 and 3.8 ka BP. Additionally, using $\Delta\delta^{18}O_{d-r}$ would reduce the influence of a temperature signal on our proxies. It is premature to include these scarce measurements in this manuscript but we intend to develop these records further in the near future.

Evidence supports the basic assumptions made in the interpretation of the data, and statistics have demonstrated that these changes are significant. We have phrased our interpretations carefully to reflect uncertainities where they exist and have taken a conservative approach in interpreting the data. The signals we discuss exceed the 1SD variability of the data from 5.4-3.0 ka BP, and the technique of differencing $\delta^{18}O$ minimizes influence of other factors. We reject the claim that our study (and that of Staubwasser et al., 2003) is built on inappropriate basic assumptions and stand by our interpretation of the $\delta^{18}O$ and $\Delta\delta^{18}O$ signals in core 63KA.

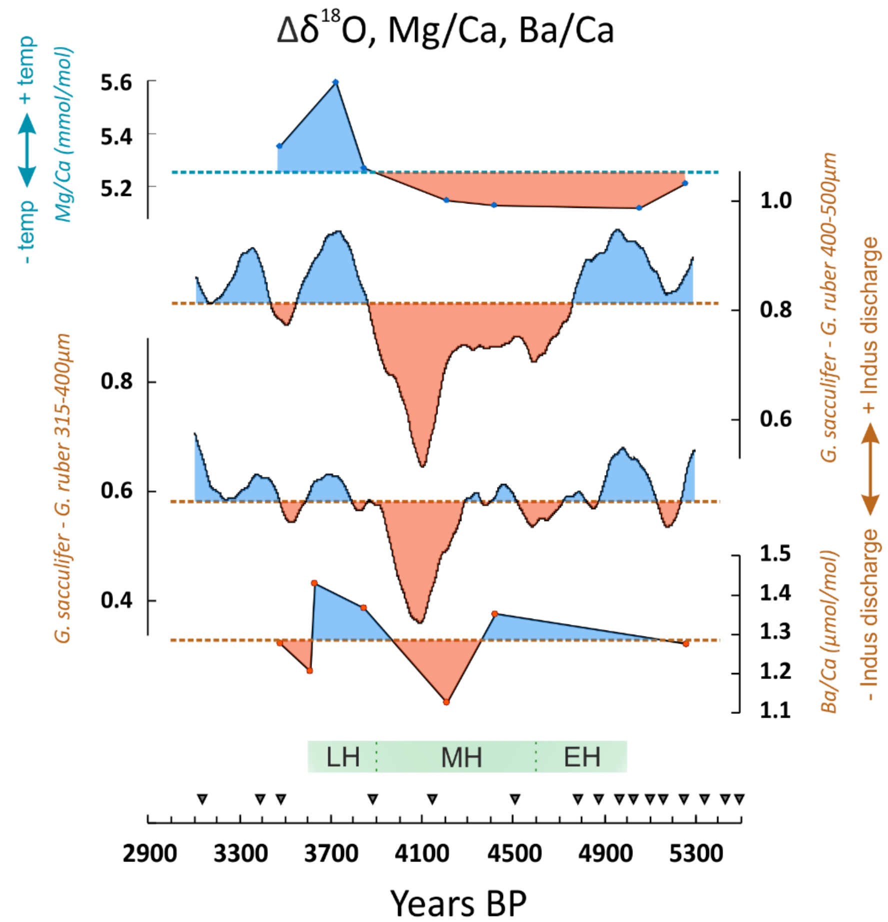

Figure 2. Preliminary results from Mg/Ca and Ba/Ca measurements on *G. ruber* (315-400µm) indicate increasing temperatures over 4.2-3.8 ka BP, as well as lower river input around 4.2 ka BP, supporting the interpretations of Indus River discharge inferred from $\Delta\delta^{18}O_{d\text{-}r}$.

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