

Authors' Response to Reviewer's Comments

Reviewer's Comment: Saraswat et al. present an extensive core-top compilation of new and published $\delta^{18}\text{O}$ values of the species *Globigerinoides ruber*. *G. ruber* is the most commonly measured planktic species and the new data set has the potential to improve the coverage in the Indian Ocean and can complement existing global compilations (i.e., Waelbroeck et al. 2005). The data set itself would benefit from additional documentation (data source, sampling depth, $\delta^{13}\text{C}$ of *G. ruber*) that can be added with minimal effort. As outlined below, the scientific analysis and interpretation of the data need revision:

Authors' Response: Thank you very much for appreciating our effort. We have added the details (data source, sampling depth), wherever available. As the $\delta^{13}\text{C}$ of *G. ruber* is missing for a majority of the previous data points, we have not included it, at this point. We have incorporated all the suggestions regarding the scientific analysis and interpretation and hope the revised manuscript will be accepted for publication.

Reviewer's Comment: Title/L18, 20, 23, 25, 34...This is probably only a wording issue but "salinity" is not influencing or controlling the $\delta^{18}\text{O}$ of carbonate, $\delta^{18}\text{O}$ of sea water is. The authors probably use "salinity" because salinity is often reconstructed from $\delta^{18}\text{O}$ of seawater and because both parameters are locally highly correlated and influenced by precipitation and evaporation. However, I think the authors should be precise. Salinity and $\delta^{18}\text{O}$ are related but can be decoupled to some extent, i.e., if the source of the freshwater endmember changes, the same salinity might be associated with different $\delta^{18}\text{O}$ seawater values. This is demonstrated by the large scatter of the the $\delta^{18}\text{O}$ -salinity relationships in Figure 8 and the different freshwater endmembers in the Arabian Sea (-2.84 ‰) and the BOB (-4.23 ‰).

Authors' Response: We agree with the reviewer that $\delta^{18}\text{O}$ carbonate depends on $\delta^{18}\text{O}$ sea water. However, as pointed out by the reviewer, huge riverine influx and direct precipitation strongly influence the salinity as well as the $\delta^{18}\text{O}$ sea water in the northern Indian Ocean. In view of the strong influence of the fresh water influx on both the salinity and $\delta^{18}\text{O}$ sea water, $\delta^{18}\text{O}$ carbonate is often used to reconstruct the salinity changes in the northern Indian Ocean. It was to highlight this close relationship between fresh water influx induced salinity and $\delta^{18}\text{O}$ carbonate, that we stated it in the title. As the reviewer has rightly suggested that the change in endmember $\delta^{18}\text{O}$ can affect the $\delta^{18}\text{O}$ carbonate without a concomitant change in salinity, we have rephrased the title as given below.

'Large fresh water influx induced salinity gradient and diagenetic changes in the northern Indian Ocean dominate the stable oxygen isotopic variation in *Globigerinoides ruber*'

Reviewer's Comment: L39: There are earlier examples of $\delta^{18}\text{O}$ seawater reconstructions based on *G. ruber* that should be cited here including Wang et al. (1995), Kallel et al. (1997) and Schmidt et al. (2004).

Authors' Response: The suggested references have been added.

Reviewer's Comment: L44: I disagree with this statement. The relationships between the physicochemical conditions and foraminiferal $\delta^{18}\text{O}$ seems to be quite constant since we have a very good agreement between laboratory derived equations and field data when the ambient conditions of shell formation are known. The reasons why there are offsets in different basins is that, particularly

when core tops are used, the exact conditions of shell formation ($\delta^{18}\text{O}$ sea water, light intensity, temperature, depth of calcification, seasonal flux, pH...) are not well constrained.

Authors' Response: The sentence has been deleted.

Reviewer's Comment: L113/Methods: I suggest to show a table with all the relevant information, the expeditions, number of samples, region etc.

Authors' Response: The following table with all the details, has been added.

Sr.No.	Cruise	Month/Year	Area	Total Samples
1.	SK117	September-October 1996	Eastern Arabian Sea	27
2.	SK175	April-May 2002	North-eastern Bay of Bengal	45
3.	SK237	August 2007	South-eastern Arabian Sea	26
4.	SK308	January 2014	Northwestern Bay of Bengal	29
5.	SSD004	October-November 2014	Gulf of Mannar, Lakshadweep Sea	41
6.	SSD055	August 2018	North-eastern Arabian Sea	11
7.	SSD067	November-December 2019	South-western Bay of Bengal, Lakshadweep Sea, Eastern Arabian Sea	45
8.	SSK035	May-June 2012	Western Bay of Bengal	13
9.	SSK098	January-February 2017	Andaman Sea	15

Reviewer's Comment: L131: There seems to be a small discrepancy between the values obtained from published sources and the original data. According to PANGAEA and the appendix in the cited thesis by Sirocko (1989), the core top value for MD76-135 is -1.81‰ (this paper: -1.89‰) and for MD76-136 -1.78‰ (this paper: -1.82‰). Perhaps this offset is just due to a different sampling depth or averaging. I have not checked the other sites. Please check and document the sampling depth in the core and the actual source of the data (table in paper, supplement or data base with doi/link)

MD76-136: <https://doi.org/10.1594/PANGAEA.77485>

MD76-135: <https://doi.org/10.1594/PANGAEA.77484>

Sirocko (1989): <https://doi.org/10.2312/reports-gpi.1989.27>

Authors' Response: We have used MARGO compilation (Waelbroeck et al., 2005, <https://doi.pangaea.de/10.1594/PANGAEA.227321>) for the previously published northern Indian Ocean core-top/Late Holocene *G. ruber* $\delta^{18}\text{O}$ data. We checked the individual core δ data available on PANGAEA and observed small difference in the values due to different core depths, as stated by the reviewer. The values have been corrected for the top 2 cm of the core, wherever the data is available (e.g. MD76-135, -1.89 replaced with -1.81).

Reviewer's Comment: Figure 1, 2, 7: The maps have been produced with OceanDataView. Please give proper credit to the author of the software and cite Schlitzer, R., Ocean Data View, <https://odv.awi.de>, 2018. What kind of interpolation technique has been used to produce the maps?

Authors' Response: The following sentence has been added in all the maps and reference has been added in the list.

'The map has been prepared by using Ocean Data View software (Schlitzer, 2018).'

Reviewer's Comment: L146: State the laboratory where the samples have been measured.

Authors' Response: The following details have been added.

'The samples were analyzed in the Alfred Wegner Institute for Polar and Marine Research, Bremerhaven, MARUM, University of Bremen, Bremen, Germany and the Stable Isotope Laboratory (SIL) at Indian Institute of Technology, Roorkee, India.'

Reviewer's Comment: Figure 4: The relation of $\delta^{18}\text{O}$ with water depth is interesting. To what extent is this relation influenced by the fact that shallow sites are more exposed to freshwater input (=lower $\delta^{18}\text{O}$) than the more remote deeper sites? To isolate the effect of water depth, it might help to plot the difference to the predicted $\delta^{18}\text{O}$ vs water depth rather than absolute $\delta^{18}\text{O}$.

Authors' Response: Thank you very much for the suggestion. We have added a plot of the difference between the measured $\delta^{18}\text{O}_{ruber}$ and expected $\delta^{18}\text{O}_{calcite}$.

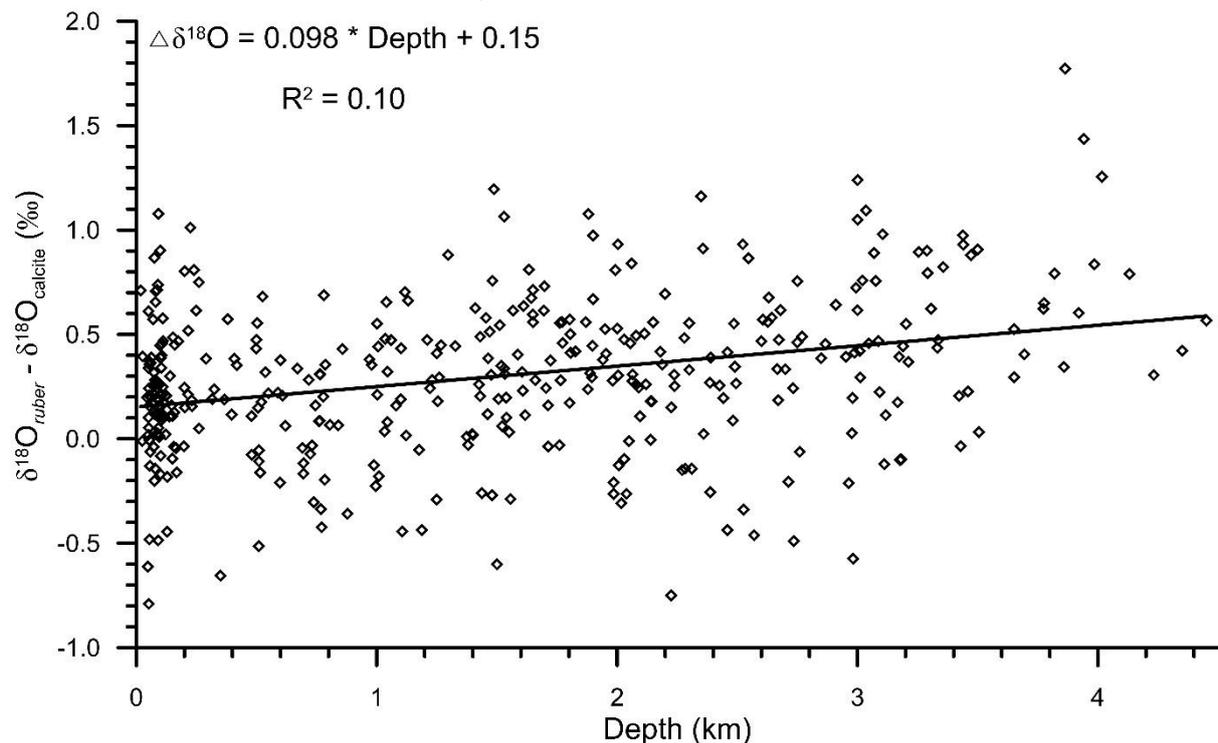


Figure 11: The relationship of the difference between measured $\delta^{18}\text{O}_{ruber}$ and expected $\delta^{18}\text{O}_{calcite}$ with the water depth from which the surface samples were collected, in the northern Indian Ocean. The $\delta^{18}\text{O}_{ruber} - \delta^{18}\text{O}_{calcite}$ increases with increasing water depth.

The following text has also been added.

'The large influence of the terrestrial fresh water influx in the shallower region, as compared to the deeper parts of the northern Indian Ocean, is also likely to contribute to the observed increase in $\delta^{18}\text{O}_{ruber}$ with depth. The fresh water is depleted in heavier oxygen isotope as compared to the seawater (Bhattacharya et al., 1985; Ramesh & Sarin, 1992). Thus, the foraminiferal shells secreted in the shallow waters are likely to be enriched in the lighter oxygen isotope, resulting in a depth related bias. Therefore, to delineate the influence of depth related diagenetic alteration and secondary calcification in $\delta^{18}\text{O}_{ruber}$, we subtracted the expected $\delta^{18}\text{O}_{calcite}$ from the measured $\delta^{18}\text{O}_{ruber}$. The difference between the measured $\delta^{18}\text{O}_{ruber}$ and expected $\delta^{18}\text{O}_{calcite}$ was plotted with water depth (Figure 11). The difference (measured $\delta^{18}\text{O}_{ruber} - \text{expected } \delta^{18}\text{O}_{calcite}$) increased with depth, suggesting a strong influence of the depth related processes in $\delta^{18}\text{O}_{ruber}$.'

Reviewer's Comment: Figure 5 & 6: What is the purpose of showing separate relations with temperature and salinity (must be $\delta^{18}\text{O}$ of sea water, see above) when we know that both factors influence the $\delta^{18}\text{O}$ of foraminiferal carbonate? Temperature and salinity are also spatially related and it is impossible to quantify the relative influence of both factors in the plots. In my opinion, Figures 5 and 6 and the corresponding discussion can be omitted.

Authors' Response: We agree with the reviewer that $\delta^{18}\text{O}_{\text{sw}}$ depends on both the salinity and temperature. However, we hope the reviewer will agree with us that the relative influence of salinity and temperature on $\delta^{18}\text{O}_{\text{sw}}$, will depend on the extent of variation in these parameters. A large range of seawater salinity is observed in the northern Indian Ocean, as compared to the limited variation in temperature. Also, many researchers have used the salinity estimated from the residual $\delta^{18}\text{O}_{\text{sw}}$ to reconstruct past salinity and in turn monsoon intensity. In view of the difference in the range of variation in the salinity and temperature, we plotted the $\delta^{18}\text{O}$ separately, to understand the relative influence of these two parameters. Therefore, we have retained the figure and discussion. However, if the reviewer insists, we'll remove this section.

Reviewer's Comment: Figure 9: I suggest to have the same ranges/limits for x and y axis and to indicate the 1:1 relation with an additional line. Is the slope of the shown regression statistically significantly different from 1? To assess whether the derived linear equations will help to improve paleoclimatic reconstructions (as stated in L27), it would be important to quantify the error of the regression equations.

Authors' Response: As advised, same range has been used for both the x and y axes. We have also added a line representing 1:1 relationship between the measured and expected $\delta^{18}\text{O}$.

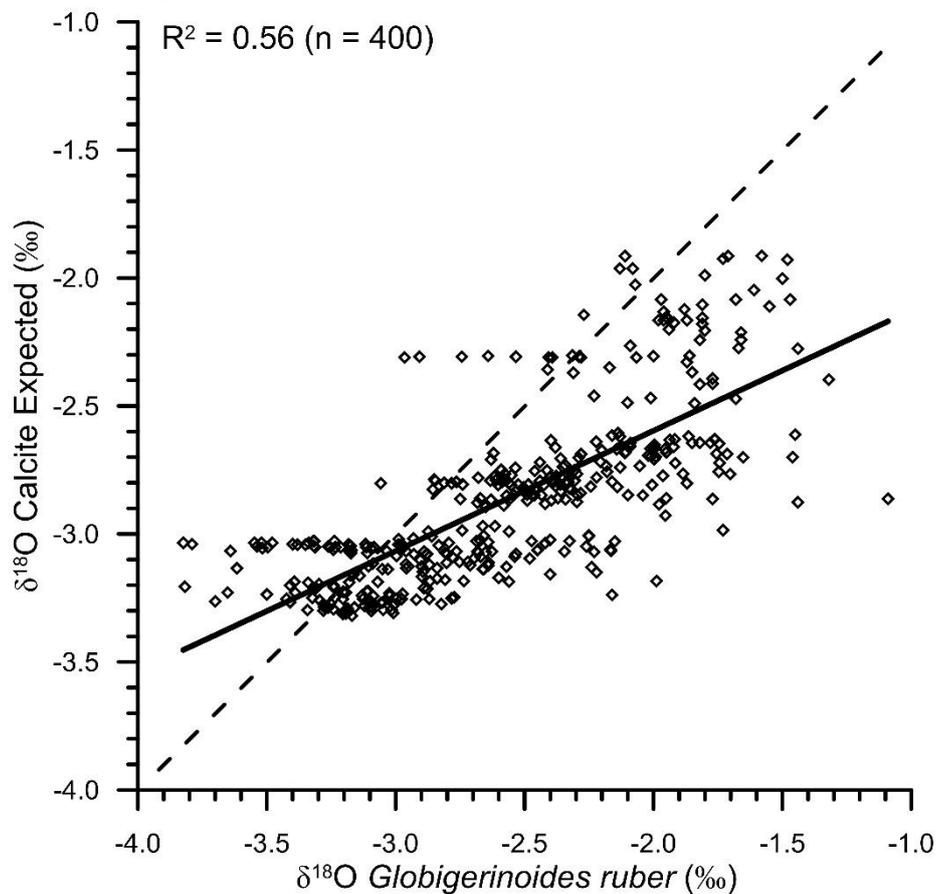


Figure 9: The scatter plot of expected $\delta^{18}\text{O}$ calcite as estimated from the ambient salinity-temperature and the analyzed $\delta^{18}\text{O}_{\text{ruber}}$. The two are significantly correlated ($R^2 = 0.56$), suggesting that *Globigerinoides ruber* correctly represents the ambient conditions. The dotted line represents the 1:1 relationship between the measured and expected $\delta^{18}\text{O}$.

Reviewer's Comment: L155: Salinity from the World Ocean Atlas is provided on a grid. How exactly was salinity estimated at the core location? From the nearest grid point?

Authors' Response: Yes, the salinity and temperature at the core location was extrapolated from the nearby grid points, using the Live Access Server at the National Institute of Oceanography, Goa, India. The details have been added in the manuscript.

Reviewer's Comment: L218/Discussion: It should be mentioned that stratigraphic information is not provided for most of the core tops. Core top sediments can represent older time slices when the sedimentation rates are low or when older sediments are exposed due to erosional processes. This does not matter so much if the Holocene is present and stable. However, in the Indian Ocean large Holocene $\delta^{18}\text{O}$ variations are expected due to variations in Monsoon precipitation.

Authors' Response: The following details have been added.

'It should however, be noted here that the stratigraphic information is not provided for most of the core tops. Core top sediments can represent older time slices when the sedimentation rates are low or when older sediments are exposed due to erosional processes. This does not matter so much if the Holocene is present and stable. However, in the Indian Ocean large Holocene $\delta^{18}\text{O}$ variations are expected due to variations in monsoon precipitation. Therefore, the uncertain age of the core tops can affect the results stated above.'

Reviewer's Comment: L 245: Explain how mixed layer depth has been defined/determined?

Authors' Response: The following details have been added.

'The mixed layer was defined as the top 25 m of the water column following Narvekar and Prasanna Kumar (2014). Although the mixed layer depth varies regionally as well as during different seasons, the average mixed layer depth was used to compare the calcification conditions.'

Reviewer's Comment: L246: Provide more context. Why has the O. universa low light equation been used if G. ruber $\delta^{18}\text{O}$ is better described with the high-light equation (see Thunell et al. 1999)? How big are the constant offsets to the published equations?

Authors' Response: The following details have been added.

'We also estimated the expected $\delta^{18}\text{O}$ calcite by using the high-light equation of Bemis et al (1998), as *G. ruber* $\delta^{18}\text{O}$ is better described with the high-light equation (Thunell et al. 1999). The choice of equation used to estimate the expected $\delta^{18}\text{O}$ calcite did not make any difference other than a small offset. The difference between expected $\delta^{18}\text{O}$ calcite estimated using paleotemperature equation of Mulitza et al., (2003) and the high-light equation of Bemis et al., (1998) varied from -0.33 to -0.41‰. The expected $\delta^{18}\text{O}$ calcite estimated using Mulitza et al., (2003) paleotemperature equation provided values close to the measured *G. ruber* $\delta^{18}\text{O}$.'

Reviewer's Comment: L247/Discussion/Figure 9: It would be very interesting to see a map of the residual $\delta^{18}\text{O}$ (predicted-observed). Any spatial pattern in the residuals might point to the environmental/ecological reason for the deviations from expected $\delta^{18}\text{O}$. For example, the chlorophyll

maximum is very shallow in the coastal areas of the BOB and the Arabian Sea whereas it is deep in the central Indian ocean. If *G. ruber* exploits the chlorophyll maximum as a food source (Fairbanks and Wiebe, 1980) it might record higher $\delta^{18}\text{O}$ due to lower temperatures and lower light levels (i.e., Spero et al., 1997). Likewise, the deeper central areas should show lower sedimentation rates and stronger signals from dissolution and sediment mixing.

Authors' Response: We gained a lot of insight after plotting the map of expected-observed $\delta^{18}\text{O}$. We have discussed the same in the revised manuscript and added the following text and figure.

The deviation of the expected $\delta^{18}\text{O}_{\text{calcite}}$ from the observed $\delta^{18}\text{O}_{\text{ruber}}$ ($\delta^{18}\text{O}_{\text{residual}}$) can be because of several factors including the difference in the ambient conditions at the time of secretion of the primary calcite during the lifetime and the diagenetic changes post death and burial. The observed $\delta^{18}\text{O}_{\text{ruber}}$ was close to the expected $\delta^{18}\text{O}_{\text{calcite}}$ in the shallower waters, especially the Bay of Bengal, Andaman Sea and northeastern Arabian Sea (Figure 10). The difference was large in the deeper Arabian Sea and the equatorial Indian Ocean. *Globigerinoides ruber* is suggested to inhabit chlorophyll maximum for easy availability of food (Fairbanks and Weibe, 1980). In such a scenario, $\delta^{18}\text{O}_{\text{ruber}}$ is expected to be higher due to lower temperatures and lower light levels at relatively deeper depths (Spero et al., 1997). The depth of chlorophyll maximum is shallower in the marginal marine waters of both the Bay of Bengal and the Arabian Sea (Sarma & Aswanikumar, 1991; Madhu et al., 2006). If *G. ruber* thrived at chlorophyll maximum depths, the $\delta^{18}\text{O}_{\text{ruber}}$ should be enriched in heavier isotope and thus $\delta^{18}\text{O}_{\text{residual}}$ should be negative. The positive $\delta^{18}\text{O}_{\text{residual}}$ in the shallower regions, however, suggests that *G. ruber* thrives in the warmer upper parts of the mixed layer. Alternatively, the large influence of the depleted fresh water $\delta^{18}\text{O}$ dominates the chlorophyll maximum influence on the observed $\delta^{18}\text{O}_{\text{ruber}}$ in the shallower regions of the northern Indian Ocean. The concentration of positive $\delta^{18}\text{O}_{\text{residual}}$ values close to the riverine influx regions confirms the strong influence of depleted fresh water $\delta^{18}\text{O}$ in modulating $\delta^{18}\text{O}_{\text{ruber}}$ in the northern Indian Ocean. The negative $\delta^{18}\text{O}_{\text{residual}}$ at deeper stations is attributed to a combination of factors including deeper chlorophyll maximum depth habitat of *G. ruber*, reduced influence of fresh water, lower sedimentation rate resulting in mixing of older and younger fauna, and post depositional diagenetic changes.'

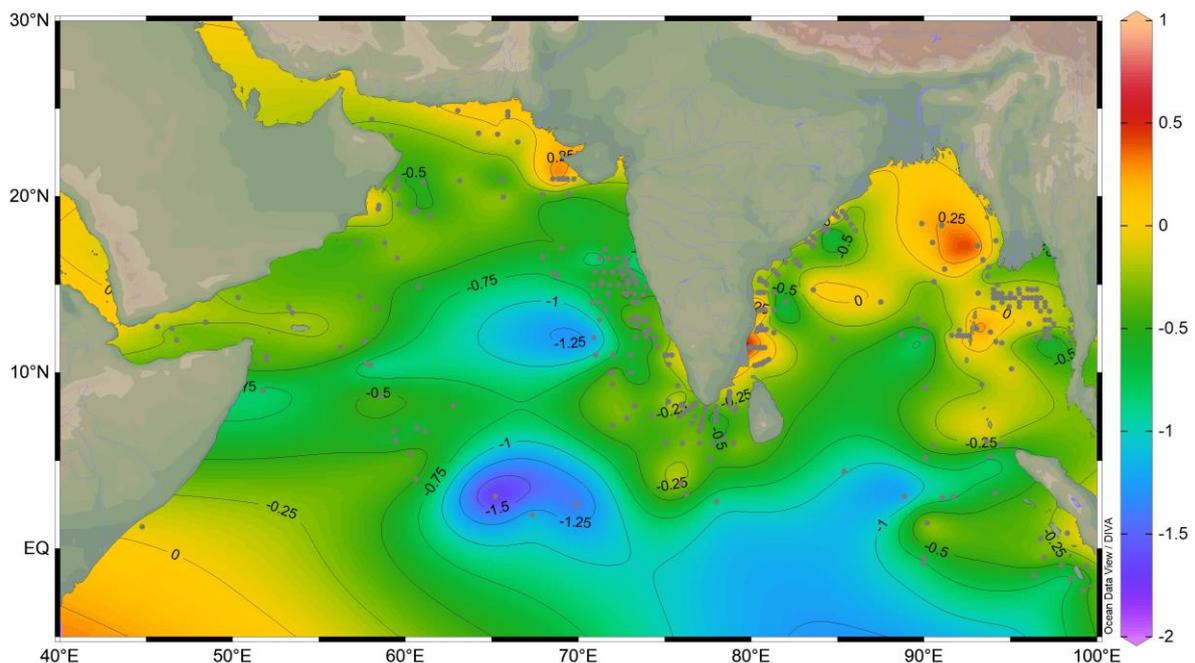


Figure 10: The difference in the expected $\delta^{18}\text{O}_{\text{calcite}}$ and observed $\delta^{18}\text{O}_{\text{ruber}}$ in the surface sediments of the northern Indian Ocean. The grey filled squares are the sample locations. The thin blue lines are the major rivers draining in the northern Indian Ocean. The thin black lines mark the contours at 0.25‰ interval. The map has been prepared by using Ocean Data View software (Schlitzer, 2018).

Reviewer's Comment: L270. The authors attribute the increase of $\delta^{18}\text{O}$ with water depth to diagenesis and partial dissolution. This is certainly a possible explanation. However, it seems very likely that the deep basins receive much less terrigenous matter than the shallow slope/shelf sites and that the sedimentation rates are significantly lower in the deep parts of the Indian Ocean. When the sedimentation rates are lower than ~ 2 cm/kyr (quite common in deep pelagic basins) it is likely that the the Holocene is mixed with isotopically heavier material from the last glacial/deglaciation (Broecker 1986), which might also explain the relationship of $\delta^{18}\text{O}$ with water depth. Is anything known about the sedimentation rates in the deep basins?

Authors' Response: Thank you very much for pointing out this aspect. We have added the following details.

'Additionally, the gradual decrease in the sedimentation rate with increasing depth and distance from the continental margins can also cause a depth related trend in $\delta^{18}\text{O}_{\text{ruber}}$. The bioturbation disturbs the top few cm sediments (Gerino et al., 1998) resulting in the mixing of older shells with comparatively younger shells (L6wemark, and Grootes, 2004). In high sedimentation rate regions of the shelf and slope, the mixing is restricted to the shells deposited in a shorter climatologically stable interval. However, in the deeper regions, it is likely that the shells deposited during the colder glacial interval or deglaciation with relatively higher $\delta^{18}\text{O}_{\text{ruber}}$ gets mixed with the younger shells, as it is available close to the surface due to the low sedimentation rate (Broecker, 1986; Anderson, 2001). The mixing of shells with a relatively higher $\delta^{18}\text{O}$ with the modern shells having lighter $\delta^{18}\text{O}$ can also result in the depth related increasing trend of $\delta^{18}\text{O}_{\text{ruber}}$. The sedimentation rate is very high on the slope and decreases in the deeper regions of both the Arabian Sea (Singh et al., 2017) and Bay of Bengal (e.g. Bhonsale and Saraswat, 2012; Suokhrie et al., 2022).'

Reviewer's Comment: L291-293: Unfortunately, $\delta^{13}\text{C}$ of *G. ruber* has not been not reported and shown along with $\delta^{18}\text{O}$. As DIC in river water is very depleted in carbon-13, since it derives from the remineralized organic matter, it provides additional information on freshwater input (see for example Pastouret et al. 1978). If freshwater from river input is the reason for some of the low $\delta^{18}\text{O}$ values in *G. ruber* in the BOB, $\delta^{13}\text{C}$ values should be low as well. Since $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ of foraminiferal carbonate are always measured together it should be straightforward to add $\delta^{13}\text{C}$ of *G. ruber* to the data set.

Authors' Response: We agree that the fresh water influx also affects the carbon isotopic ratio of the foraminiferal shells. However, a larger variation in the carbon isotopic ratio in the northern Indian Ocean is due to the large productivity changes. The productivity is invariably high in the marginal marine regions as compared to the open ocean, mainly due to the upwelling and nutrient input. Therefore, it is difficult to delineate the relative contribution of the fresh water influx and productivity in the carbon isotopic ratio of the foraminifera in the northern Indian Ocean. Additionally, the $\delta^{13}\text{C}$ of a majority of the previously published records is not available. Therefore, it is difficult to add the $\delta^{13}\text{C}$ data.

Reviewer's Comment: L306-313: Please review and revise the reasons for the different slopes in the North Atlantic and the Indian Ocean. The higher slope of the $\delta^{18}\text{O}$ /salinity relationship in the North Atlantic is due to the fact that precipitation/freshwater in high latitudes is depleted in oxygen-18 (\sim -35 ‰) compared to tropical areas (\sim -5 ‰) (see for example Figure 10 in Rozanski et al., 1993).

Authors' Response: We have added the following lines.

'The heavier oxygen isotope depleted precipitation/fresh water influx in the higher latitudes (\sim -35 ‰) as compared to the tropical areas (\sim -5 ‰) also results in a higher slope of the $\delta^{18}\text{O}$ -salinity relationship in the North Atlantic Ocean (Rozanski et al., 1993).'

Reviewer's Comment: L324: Except for upwelling regions, the variations in surface water pH are indeed small. However, the pH at the foraminiferal shell is strongly influenced by light intensity in the presence of symbionts (see Jorgensen et al. 1985, Fig 6). Small variations in turbidity or calcification depth can therefore influence the stable isotope ratio of *G. ruber* via the pH effect.

Authors' Response: We have added the following text in the revised manuscript.

'The seawater pH in the immediate vicinity of the foraminiferal shell is strongly influenced by the light intensity in the presence of symbionts (Jorgensen et al., 1985). The riverine influx in the northern Indian Ocean makes the surface waters turbid reducing the light penetration depths (Prasanna Kumar et al., 2010). Therefore, riverine influx induced variations in turbidity in the northern Indian Ocean can influence the $\delta^{18}\text{O}_{\text{ruber}}$ via the pH effect.'