Response to the anonymous reviewer comments (RC1)

Interactive comment on "Mixed layer depth variability in the Red Sea" by Cheriyeri P. Abdulla et al.

Anonymous Reviewer #1

Received and published: 29 March 2018

General Comments:

The authors have used historical temperature profiles from the Red Sea to develop a monthly climatology of mixed layer depth (MLD) along the seas' central axis, and investigate the importance of wind stress, thermal buoyancy forcing and haline buoyancy forcing in controlling MLD in the northern, central and southern Red Sea. The authors also investigate the relationship between MLD and the presence of cyclonic and anticyclonic mesoscale eddies, as well as the impact of the cross-axis Tokar Gap wind jet on MLD in summer.

To my knowledge, this is the first published climatology of MLD in the Red Sea, which will be useful for verifying numerical model simulations of the basin and biogeochemical studies. The analysis of the impact of atmospheric forcing mechanisms as a function of latitude is interesting and worth publishing, in my view. The descriptions of the impacts of mesoscale eddies and the Tokar Gap wind jet are less clear and I recommend major revisions in these sections to make them truly convincing.

Answer:

We thank the reviewer for his valuable comments and suggestions. The comments and suggestion were very helpful in improving the manuscript. Necessary improvements are done in the sections explaining the effect of eddies and Tokar gap jet winds. The direct effect of wind apart from the effect of wind induced secondary circulation (the cyclonic and anticyclonic eddies) was not clear in the previous version of the manuscript, which is solved in the new version of manuscript. The answers to both specific and technical comments are given below, and required modifications are made in the manuscript.

Please note that coloured text is used in few instances of this document to represent modified/deleted text.

Red: the modified/deleted text in the previous version of the manuscript

Blue: the modified text in the new version of the manuscript.

Specific Comments:

Specific Comment-1:

Line 30 – Much of this is elementary physical oceanography, belonging in a textbook, not a scientific paper. I suggest to condense this part of the text significantly.

Answer:

We agree with the reviewer in this, our intension was to refresh the memories of the readers with the effect of each parameters on the mixed layer depth. As suggested by the reviewer, the paragraph is shortened as follows. In this, we show the two paragraphs before and after modification.

Previous version of the paragraph

Surface mixed layer is a striking and universal feature of the open ocean where the turbulence associated with various physical processes leads to the formation of a quasi-homogeneous layer with nearly uniform properties. The thickness of this layer, often named mixed layer depth (MLD), is one of the most important oceanographic parameters, as this layer directly communicates and exchanges energy with the atmosphere and therefore has a strong impact on the distribution of heat (Chen, Busalacchi, & Rothstein, 1994), ocean biology (Polovina, Mitchum, & Evans, 1995) and near-surface acoustic propagation (Sutton, Worcester, Masters, Cornuelle, & Lynch, 2014). Heat and fresh-water exchanges at the air-sea interface and wind stress are the primary forces behind turbulent mixing. Similarly, stirring associated with turbulent eddies predominantly changes the mixing process, mainly along the isopycnal surfaces where stirring may occur with minimum energy (de Boyer Montégut, Madec, Fischer, Lazar, & Iudicone, 2004; Hausmann, McGillicuddy, & Marshall, 2017; Kara, Rochford, & Hurlburt, 2003).

Oceanic heat loss cools the mixed layer and weakens the stratification, leading to strong mixing and a deeper MLD. Similarly, the heat gain warms the mixed layer and strengthens the stratification, leading to weak mixing and shallow MLDs. The fresh-water loss makes the surface water more saline and denser, leading to enhanced mixing and deeper MLDs, while the fresh-water gain makes the surface water fresher and lighter, leading to diminished mixing and shallow MLDs. The momentum transmitted to the ocean through from the wind stress acts as the primary dynamic force for the upper layer turbulence and circulation. The shear and stirring generated by the wind stress enhance the vertical mixing and play a major role in controlling the deepening of the oceanic mixed layer. In some regions, the mixed layer variability is mainly controlled by wind stress.

New version of the paragraph (modified text in blue colour)

The surface mixed layer is a striking and universal feature of the open ocean where the turbulence associated with various physical processes leads to the formation of a quasi-homogeneous layer with nearly uniform properties. The thickness of this layer, often named mixed layer depth (MLD), is one of the most important oceanographic parameters, as this layer directly communicates and exchanges energy with the atmosphere and therefore has a strong impact on the distribution of heat (Chen et al., 1994), ocean biology (Polovina et al., 1995) and near-surface acoustic propagation (Sutton et al., 2014). Heat and fresh-water exchanges at the air-sea interface and wind stress are the primary forces behind turbulent mixing. The loss of heat and/or freshwater from the ocean surface can weaken the stratification and enhance the mixing and vice versa. The shear and stirring generated by the wind stress enhance the vertical mixing and play a major role in controlling the deepening of the oceanic mixed layer. Further, the stirring associated with turbulent eddies predominantly changes the mixing process, mainly along the isopycnal surfaces where stirring may occur with minimum energy (de Boyer Montégut et al., 2004; Hausmann et al., 2017; Kara et al., 2003).

[Lines: 20-33]

Specific Comment-2:

Line 43 – Bower and Farrar (2015) have direct estimates of evaporation rates that should be mentioned and referenced here.

Answer:

The suggested reference of Bower and Farrar (2015) is appropriate to the context and added to the manuscript.

[Lines: 50]

Specific Comment-3:

Line 148 and following – 85 m ± what? Need to add standard deviations to these mean values, in this line and all the following instances of reporting mean values. This is essential to understanding the statistical significance of the mean values. I realize some statistics are included in the supplementary material, but *they should be included in the main document. Similar for lines 152–153, line 175 and line 197 (plotted lines need error bars or similar).*

Answer:

The range of observed MLD values and the standard deviation from mean value are included at appropriate instances. The text is modified accordingly. The error-bars are added to the figure describing the monthly climatology of NHF, evaporation and precipitation, and wind stress (Figure 5).

The figure 4 shows monthly values from a single year (2016), with one value for each month. Therefore, we have not included the error bars.

Modified text

A Hovmoller diagram of the monthly MLD climatology is presented in Fig. 3. The deepest MLD is observed in February and the shallowest during May-Jun. A significant annual variability is observed in the Red Sea. The maximum value of climatological mean MLD is observed in February at the northern Red Sea while the minimum noticed at various instances, especially during summer months. The MLD of individual profiles in the northern Red Sea has a wide range of values from 40 to 120 m mainly due to the presence of active convection process, while some of the profiles show MLD deeper than 150 m in consistence with Yao et al., (2014). Apart from the northern deep convection region, the south-central Red Sea between 18 °N-21 °N (53±5 m) and 14 °N-16 °N (48±9 m) also experienced deeper MLDs during the winter, which is separated by a shallower MLD around 17 °N (44±14 m). During July to September, the region around 19 °N experienced a deeper mixed layer in contrast with the general pattern of summer shoaling over the entire Red Sea.

[Lines: 187-197]

Specific Comment-4:

Line 214 – It wasn't obvious to this reviewer how the authors chose the latitudes where there were supposedly reductions in correlation between MLD and all forcing mechanisms. For some of the gray bars, the coincidence of lower correlations is obvious, but not in all. Would be good to define more clearly how these latitudes were chosen, hopefully using some objective criteria.

Answer:

As pointed out by the reviewer, we have selected the latitude bands (13.5 °N, 17.5 °N, 19 °N, 23 °N, and 26.5 °N) based on the observed drop in correlation for all the forces. We agree that there is a small difference in the case of 23 °N. At this latitude, the heat flux and wind stress have a clear coinciding drop in correlation while correlation for freshwater has a small increase. But, considering the correlation values for freshwater from 22 °N and 24 °N, the correlation is dropped around 23 °N (between 22 °N and 24 °N), even though a small local increase is seen at 23 °N. Therefore, we considered 23 °N as the region of coinciding drops in correlation.

[Lines:293]

Specific Comment-5:

Line 243 – References are needed here to validate the authors' description of the relationship between mesoscale eddies and MLD.

Answer:

Appropriate references were added to the text (Dewar, 1986; Fox-Kemper, Ferrari, & Hallberg, 2008; Hausmann et al., 2017; Smith & Marshall, 2009; de Boyer Montégut et al., 2004; Chelton et al., 2004, 2011).

[Lines: 328-333]

Specific Comment-6:

Line 267 - The authors are implicitly arguing that the upwelling and downwelling associated with the secondary circulation of cyclonic and anticyclonic eddies is more important in determining MLD in the eddies than direct wind forcing and buoyancy forcing. Is there any literature to support this? I'm guessing there is, and the authors need to add some references here to this point.

Answer:

As mentioned in the reply to comment #5, appropriate references discussing the importance and dominance of eddy effect on MLD variability are added to the manuscript. The results from the literature (de Boyer Montégut et al., 2004; Chelton et al., 2004, 2011; Dewar, 1986; Fox-Kemper et al., 2008; Hausmann et al., 2017; Smith & Marshall, 2009) have shown that eddies can efficiently re-stratify the ocean, dominating over the existing effect of wind stress and net heat flux over the region. The studies also show that the resultant effect of eddy is largely dependent on the eddy amplitude, and the mixing intensity is largest at the centre of eddy.

[Lines: 329-333]

Specific Comment-7:

Line 322 - It is not clear to me here if the region to the south of the jet axis is well-mixed because of wind-induced turbulent mixing, or because of the secondary circulation associated with the wind stress curl-induced formation of the anticyclonic eddy, or both. the authors need to clarify this, or, if it is ambiguous, say that they are not sure which mechanism dominates.

Answer:

It is true that the wind-induced turbulent mixing obviously exists on both side of the Tokar jet axis. The secondary circulation formed by the Tokar winds, with different polarities on both side, cyclonic to the north of the Tokar-axis and anticyclonic to the south, acts in opposite direction to the vertical mixing. The mixing in the Tokar region is the sum of both the wind-induced turbulent mixing and the secondary circulation (eddies). A proper quantification of the contribution each mechanism needs further investigations.

[Lines: 439-443]

Specific Comment-8:

Line 326 - If this is a summary sentence, I suggest to start it with "In summary. . ."

Answer:

The text is changed accordingly.

[Lines: 443-444]

I'm left with uncertainty about the authors' claim regarding the role of the TG jet in increasing MLD. As questioned above, does the upwelling and downwelling associated with the eddies overwhelm the direct mixing impact of the wind jet? Presumably the direct impact of the winds would be felt on both sides of the wind jet axis, but it's not clear if the authors are making this point for the cyclonic as well as anticyclonic eddy. Clarification needed here.

Answer:

As mentioned in the reply to comment #7, we agree that the turbulence is present on both sides and enhances mixing. But eddy effect is in opposite directions in the northern and southern sides of Tokar-axis, and therefore the signature is evident in the mixed layer depth structure, with enhancement of mixing in the southern side and reducing the mixing in the northern side (please refer to Figures 10 and 11).

[Lines: 412, 424, 439-446]

Specific Comment-9:

Line 346 – It was not clear to me if the deeper MLD was due to the direct impact of the winds or the formation of the anticyclonic eddy. Needs clarification.

Answer:

As mentioned in the reply to comment #7 and #8, the contribution of both the wind and secondary circulation are simultaneously existed in the Tokar region. In the previous version of the manuscript, the contribution of direct wind turbulence was not clearly mentioned in the conclusion part. In the revised version of the manuscript, we corrected the text and clearly stated that the mixing in the region is a combination effect of both wind turbulence and eddies.

[Lines: 478-480]

Specific Comment-10:

Line 350 - I think this is the best result of the paper.

Answer:

We thank the reviewer for appreciating this part of the result.

Specific Comment-11:

Line 357 - As remarked on above, why would the winds enhance ML development south of the wind axis but not north? Maybe the deepening to the south is due mostly/only to the formation of the anticyclonic eddy?

Answer:

As stated in replies to comments#7 to 9, the wind enhance mixing on both side of the Tokar-axis. The text also corrected accordingly.

The deepening in the south of Tokar axis is the combined effect of both wind and anticyclonic eddy, while shoaling in north is due to the opposite (diminishing) effect of the cyclonic eddy.

[Lines: 490-492]

Technical comments:

Technical comment-1:

Line 20 – Should read “The surface mixed layer . . .” (i.e., add “the”)

Answer:

The manuscript is corrected as suggested.

[Lines: 20]

Technical comment-2 to 4:

Line 30 – Should read “Oceanic heat loss. . ..” (i.e., delete “The”)

Line 30 – “to strong mixing. . .” “Strong”? Compared to what?

Line 35 – “through from. . ...” Extra word here.

Answer to *Technical comment-2 to 4*:

The manuscript is corrected accordingly. This paragraph is modified and summarised.

[Lines: 27-30]

Technical comment-5:

Line 39 – “The Red Sea is a typical. . ...” How is it typical?

Answer:

The text is corrected and removed the usage “typical”.

We have used this word considering that the Red Sea is a typical inverse estuarine system, where the evaporation is dominated over the precipitation.

[Lines: 34]

Technical comment-6:

Line 45 – "regions in the world. . .." Referring to the water in the Red Sea? Maybe use "ocean basin" instead of "region."

Answer:

The manuscript is corrected as suggested.

[Lines: 40]

Technical comment-7:

Line 48 – What about Yao et al. references? Shouldn't they be included here? They represent some of the most comprehensive modeling studies of the Red Sea to date (after Sofianos' papers).

Answer:

The manuscript is corrected as suggested and the references are added.

[Lines:42-43]

Technical comment-8:

Line 49 – The increase in the number of temperature. . .." (add "the number of")

Answer:

The manuscript is corrected as suggested.

[Lines: 44]

Technical comment-9:

Line 55 – the authors should consider adding reference to Bower and Farrar (2015) paper and Yao et al. papers.

Answer:

The manuscript is corrected as suggested and the references *are added.*

[Lines: 49-50]

Technical comment-10:

Line 77 – Over what depth range are inversions flagged?

Answer:

Over upper 500 meters, which could be sufficient for the MLD estimation in the Red Sea.

Technical comment-11:

Line 89 – What does "spread" mean? I think the word to be used is "distribution."

Answer:

The text corrected as suggested.

[Lines: 83]

Technical comment-12:

Line 110 – "Traon" Check spelling. I think it's "LaTraon".

Answer:

The text corrected as suggested.

[Lines: 113]

Technical comment-13:

Line 118 – What is meant by short-range disturbances? A sentence or two more on how the method works will save the reader from having to look it up elsewhere.

Line 121 – Would be helpful to the reader to give an example. How exactly does this work?

Answer:

A brief description on the estimation of MLD using "segment method" is added in the manuscript, with the help of a sample profile.

The text added in the manuscript:

The MLD can be estimated based on different methods. The Fig.2 shows a sample temperature profile collected on 19th January 2015 from Red Sea (24.9° N, 35.18 °E), with short-range gradients within the mixed layer. This gradient could rise from instrumental errors or turbulence in the upper layer. The curvature method (Lorbacher et al., 2006) identified MLD at 32 m, due to the presence of a short range gradient at this depth. Threshold method (de Boyer Montégut et al., 2004) detected MLD at 130 m (threshold = 0.2 °C), while segment method identified MLD at 120 m. The segment method based MLD could be considered as a reliable estimate comparing to both curvature (under estimation) and threshold method (over estimation). The segment method first identifies the portion of the profile with significant inhomogeneity where the transition from a homogeneous layer to inhomogeneous layer occurs. Then, this portion of the profile is analyzed to determine the MLD (detailed procedure of the estimation technique is given Abdulla et al., 2016). In the present study, MLD is estimated based on the segment method, which is found to be less sensitive to short-range disturbances within the mixed layer (Abdulla et al., 2016). This method first identifies the portion of the profile (segment) where the transition from a homogeneous layer to inhomogeneous layer occurs. Then, this segment is analyzed to determine the MLD.

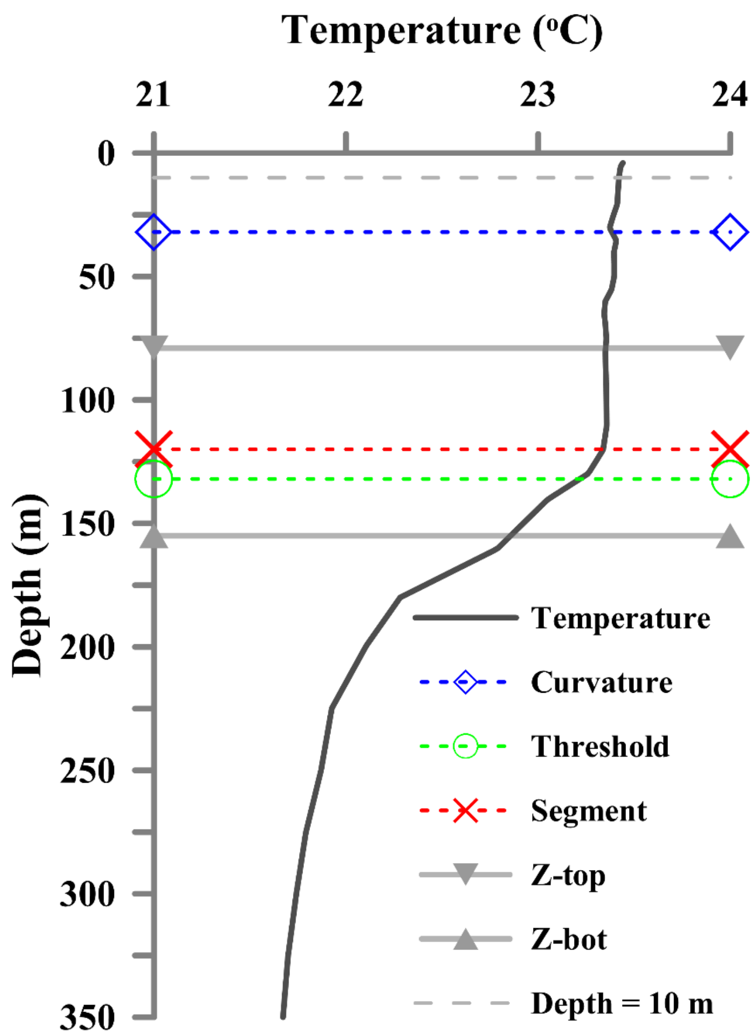

Figure. The MLD estimated for a schematic temperature profile based on curvature, threshold, and segment methods. Z-top and Z-bot represents the top and bottom ends of the portion of the profile with significant inhomogeneity.

[Lines: 119-161]

Technical comment-14:

Line 149 – Are these numbers from individual profiles? Please clarify.

Answer:

Yes, these numbers are from individual profiles. The same is mentioned in the text also.

The text from the manuscript

The MLD of individual profiles in the northern Red Sea has a wide range of values from 40 to 120 m mainly due to the presence of active convection process, while some of the profiles show MLD deeper than 150 m in consistence with Yao et al., (2014).

[Lines: 191-193]

Technical comment-15:

Line 158 – This sentence is confusing. What is meant by the "other regions"?

Answer:

The sentence is corrected. "other regions" is replaced with "other parts of the Red Sea"

The text from the manuscript

Compared to other parts of the Red Sea, during November and December, relatively shallower MLDs were witnessed at approximately 16 °N-17 °N, and 24.5 °N-26.5 °N.

[Lines: 218-220]

Technical comment-16:

Line 168 – I would say April to June is more like the monsoon transition (probably low winds), not summer.

Answer:

The text is corrected accordingly.

[Lines: 229-230]

Technical comment-17:

Line 174 – "net heat loss" (loss not lose)

Answer:

The text is corrected accordingly.

[Lines: 236]

Technical comment-18:

Line 180–181 – Rather than "enhance mixing," which should be "enhances mixing" to be grammatically correct, I would suggest saying "supports vertical mixing through buoyancy loss" or something similar.

Answer:

The text is corrected accordingly

[Lines: 242-243]

Technical comment-19:

Line 181 – "slightly diminishes mixing. . ." And here I would say "opposes vertical mixing due to buoyancy gain."

Answer:

The text is corrected accordingly

[Lines: 243-244]

Technical comment-20:

Line 184 – Would be helpful to define acronyms in figure caption.

Answer:

The figure caption is corrected accordingly

<u>The changes caption from the manuscript</u>

Figure 3. Time series of heat flux components (incoming shortwave radiation (SWR), long wave radiation (LWR), latent heat flux (LHF), sensible heat flux (SHF) and net heat flux (NHF)) for the year 2016 in the central Red Sea.

[Lines: 251-253]

Technical comment-21:

Line 190 – "support vertical mixing" (add "vertical")

Answer:

The text is corrected as suggested.

[Lines: 204]

Technical comment-22:

Line 192 – Shouldn't it be "net buoyancy flux" ?

Answer:

The text corrected accordingly.

[Lines: 259]

Technical comment-23:

Line 194 – Isn't there a Sofianos paper to be referenced here too? Figures 3 and 4 – It would be helpful to add a zero Line on Figs. 3 and 4.

Answer:

The reference of *Sofianos paper* is included accordingly.

[Lines: 264-265]

The zero lines are inserted in the figure 3 and 4

[Lines: 250, 266]

Technical comment-24:

Line 200 – I suggest that the authors mention the wind direction as well as stress amplitude variations through the seasons. Also, shouldn't wind stress in the winter be negative? All wind stress values are presented as positive. This is okay since it is only the magnitude (not direction) that impacts vertical mixing, but the authors need to say they are showing absolute value only.

Answer:

The Figure in the previous version of manuscript show the "magnitude of wind stress" alone. As mentioned by the reviewer, the East and North components of wind stress along with absolute wind stress are presented in the figure 5.

[Lines:266]

Technical comment-25:

Line 206 – I'm not sure what the authors mean here by "phase." I think they are referring to negative and positive correlation; e.g., MLD and NHF are negatively correlated since as NHF (into the ocean) increases, MLD decreases.

Answer:

The text is corrected accordingly as follows.

The wind stress and E-P are positively correlated with MLD while the NHF is negatively correlated since as NHF (into the ocean) increases, MLD decreases. For simplicity of the figure (Figure 5), the correlation values of all parameters are presented as positive.

[Lines: 279-282]

Technical comment-26:

Line 229 - How were eddies identified? If some eddies or sub-gyres are semi-permanent, how do you decide when one 'dies' and a new one is formed? If the histogram is from another paper, it should be referenced here.

Answer:

Eddies are identified based on "winding angle" method. The identification is done by Zhan et al., 2014. The reference is mentioned in the text as well as in the caption of the histogram (Fig. 7).

[Lines: 308-309 and 335]

Technical comment-27:

Line 258 - I think 'curve' should be 'curves,' because the point is (I think) that at these latitudes, correlations between MLD and all the forcing factors (wind, thermal buoyancy, haline buoyancy) are reduced.

Answer:

The text is corrected accordingly

[Lines: 362]

Technical comment-28:

Line 260 - Zhai and Bower 2013 should be added to this list, and Bower and Farrar 2015.

Answer:

These references are added to the list.

[Lines: 364]

Technical comment-29:

Line 289 – Authors should indicate data source in figure caption.

Answer:

The wind data is CFSR hourly wind product. The same mentioned in the caption also.

[Lines: 394]

Technical comment-30:

Line 291 – What is the data source for the T S profiles?

Answer:

The temperature and salinity profiles are from Sofianos and Johns, 2007, and the same is mentioned in the figure cation.

Caption

Figure 9. (a) The CTD measured temperature and salinity profiles during 13-14 Aug 2001. (b) SLA maps and (c) wind speed and direction (averaged for the previous one week) in the Tokar region, before, during and after the Tokar event. The temperature and salinity profiles are received through personal communication from (Sofianos & Johns, 2007).

[Lines: 412-416]

Technical comment-31:

Line 293 - This year (2001) was also highlighted and described by Zhai and Bower 2013, which should be referenced here.

Answer:

The suggested reference is added in the manuscript.

Text from the manuscript

The temperature and salinity profiles measured during summer 2001 (13-14 Aug 2001), which coincided with the Tokar event are shown in Fig. 9a-b (Sofianos and Johns, 2007; Zhai and Bower, 2013).

[Lines: 397-398]

Technical comment-32:

Line 333 - "slightly lower" than what? Lower than some individual measurements? If that is what is meant, that is obvious and this phrase should be deleted, or replaced with the actual extreme values.

Answer:

The text is corrected accordingly.

[Lines:453]

Technical comment-33:

Line 334 - Rather than 'general picture', authors should say something more concrete like 'climatological mean."

Answer:

The text is corrected accordingly.

[Lines: 454]

Technical comment-34:

Line 340 - I would say that shallow MLD and increased stratification are the same thing. Authors could consider 'associated with increased short-wave radiation' instead.

Answer:

The text is corrected accordingly.

[Lines: 459-460]

Technical comment-35:

Line 343 - Suggest to add "...is not linear with increasing latitude."

Answer:

The text is corrected accordingly.

[Lines: 475]

Technical comment-36:

Line 345 - This phrase is confusing. Suggest to say "deeper MLD than typical of elsewhere in the Red Sea" or something similar.

Answer:

The text is corrected accordingly.

[Lines: 478]

Answer to reviewer comments-Supporting information

SI-Comment-1:

Figure S1 – I think "distribution" is a better word than "spread."

Answer:

The text is corrected accordingly.

[Lines: 27 and 45]

SI-Comment-2:

Table S1 – I don't think it's necessary to include this table. It was sufficient to describe the end result of the QC in the manuscript.

Answer:

This Table is removed. The manuscript is modified accordingly.

SI-Comment-3 and 4:

Table S2 – Could this information be summarized more efficiently with a plot of some kind?

Table S3 – Similar comment for this table. Change to a plot?

Answer:

As suggested by the reviewer, the tables S2, S3 and S4 are converted into plots.

[Lines: 52, 61, and 70]