Author Response to Reviewer Comment 2: Anonymous Reviewer 2

Key:

- Review comment is in **bold**
- Author response is in normal text
- Changes made are in *italics*

We thank Reviewer 2 for their contribution to the review process of this paper. We have considered the reviewers comments carefully and incorporated their feedback in the below dialogue.

General comments: In this paper, Baldry et al. combine carbon measurements from the open ocean and east coastal areas in the Red Sea to model ecosystem-driven changes on the carbon system of coral reefs, mangrove forest, and seagrass meadows. In this region, oceanographic studies in general as well as carbon and ecosystem studies are heavily underrepresented, despite its extreme conditions regarding hydrography and vulnerable ecosystems. The paper by Baldry et al. represent an important contribution to the biogeochemical research from the Red Sea, and by using novel data, historical data, and a model tool, they increase our knowledge about driving forces for coastal ecosystems.

More specific comments:

The word "trend" is used but the word refers to change over time, and you do not use the word this way. As I understand, you simply mean linear relationship between e.g. offshore salinity and distance from a point in the southern Red Sea, or alkalinity and the mentioned distance.

This is correct. We are describing linear relationships and not trends with time

The terms "trends" and "linear trends" have been replaced with "linear relationships", except when used in the context of seasonal changes. Here, the term "seasonal trend" has been changed to "seasonal dependency"

Every now and then you put up statements and explain them later in the manuscript, e.g. P2, L22 about linear trends, P4, L18 where you introduce D without explaining it until later in the text. I encourage you to gather the statement and explanation, to make the reading easier.

We agree these issues need be addressed. We have altered the identified problems as outlined in the specific comments, in particular introducing and explaining D. The f*irst paragraph of 2.4(now 2.5) now reads:*

"A single-end-member mixing model was used to model conservative TA (cTA) and conservative DIC (cDIC) for coastal observations. First, the distance of a point along the central axis of the Red Sea in km (D) was calculated for each observation. This was done using the "alongTrackDistance" function (default settings) in the R package "geosphere" (Hijmans, 2017) with the reference point 12.7737°N 43.2618°E to represent D = 0 and the reference point 28.2827°N 34.0694°E to define position of the central south-north axis. The single-end-member model was then implemented by 1) describing the linear variations of offshore S, TA and DIC with D, so that predictions of offshore S (S_O), offshore TA (TA_O) and offshore DIC (DIC_O) can be made from the value of D corresponding to coastal observations, and then 2) calculating cTA and cDIC for observations according to Equations 1-2, which predict the simple dilution and concentration (SDC) effects of evaporation (Figure 2)."

You refer to numerous interesting papers, please include a separation between ";" and the following author name. This comment is valid for the whole paper. E.g. L 28: (Bauer et al., 2013; Camp et al., 2016; Cyronak et al., 2018; Gattuso et al., 1998; Guannel et al., 2016; Unsworth et al., 2012) – here I have added space.

Noted.

A space has been added between ";" and the following author name.

You discuss several limitations with the single-end-member model, but you actually did choose this model. Please add an argument stating why, despite all its limitations, you made this decision.

Noted.

We have adjusted section 2.6 as follows:

2.6 Model Assumptions and Limitations

The single-end-member mixing model assumes simple two-dimensional circulation in a region that exhibits more complex flow. The modelled flow follows a south-north trajectory along the central axis of the Red Sea, with perpendicular coastal flushing from offshore waters located at similar distances along the central axis (Figure 2). This allows changes in the carbonate chemistry of offshore waters, due to both conservative and non-conservative processes, and conservative coastal evaporation to be modelled.

It is well known that this is not the case and the Red Sea has a complex surface flow displaying multiple dynamic eddies along its length (Sofianos and Johns, 2003; Zhan et al., 2014). Depending on the direction of flow, these eddies promote coastal flushing from offshore waters originating further north or further south along the central axis of the Red Sea, mixing in a way the simple single-end-member mixing model cannot capture. Other limitations of the simple single-end-member model include its inability to account for coastal upwelling along the continental shelf, variable mixing of Gulf of Aden waters with Red Sea offshore waters and changes in basin-scale evaporation and calcification which have been documented in previous studies (Anderson and Dyrssen, 1994; Churchill et al., 2014; Krumgalz et al., 1990; Papaud and Poisson, 1986; Steiner et al., 2018).

These limitations cannot be addressed within the present study and require a sustained observational effort to address knowledge gaps in the carbon chemistry of the Red Sea, combined with more complex circulation models. Complex circulation models could capture some large-scale variance in circulation, but they are costly simulations that may still produce questionable results due to the unresolved coastal bathymetry of the Red Sea. Instead, we use the 99% P.I. of offshore carbonate chemistry residuals as a bound of model error, and to capture deviations from modelled carbonate chemistry due to variations in circulation.

You use the words strong or weak linear increase when you actually mean high or low r2. Just be aware that strong/weak linear increase might also be understood as a line with high or low slope.

We have attempted to make the association between strong/weak to r2 in the text by referencing to r2 values in parentheses more often. We have also edited section "2.7 Statistical tests" to read

"All statistical tests were performed using R software (R core team, 2017) with a 95% confidence level. Least squares regression analysis was used to calculate linear relationships with D for S, temperature and carbonate variables, thus determining how S, temperature and carbonate variables vary along the central axis from south to north. Least squares regression analysis was also used to

calculate relationships between rTA and rDIC. The square of Pearson's correlation coefficient (r^2) of linear relationships was used to evaluate the strength of the relationships."

Detailed comments:

P1 L16: you introduce the word "trend", which refer to change over time. But this is not what you mean, right? Rather use "linear relationship"

Addressed above

P2 L11: I suggest a more direct language: As such, these non-conservative changes can be measured as anomalies from the carbonate system which has experienced conservative mixing.

Thank you.

This suggestion has been taken throughout the paper, and the use of the term "norm" removed from the text throughout.

L22: You state "The linear trend in offshore carbonate system concentrations..." without explaining or showing what you mean by this. Again, I suspect that you mean simply linear relationship and not trend.

Addressed above.

L23: suggest to not use the word "norm" but only "expected conservative behaviour"

Changed.

"norm" replaced with "expected conservative behaviour"

P3 L27: second last word: switch "a" with "an"

Changed.

"a" replaced with "an"

L27: please add if this method also use non-linear curve fitting

Changed.

"and TA was measured by open-cell titration with 0.1 M hydrochloric acid using a Mettler Toledo T50 Autotitrator equipped with an InMotion Pro Autosampler" to "and TA was measured by open-cell titration with 0.1 M hydrochloric acid using a Mettler Toledo T50 Autotitrator equipped with an InMotion Pro Autosampler using non-linear curve fitting to determine an equivalence point"

L29: add full address of Dr. A. Dickson the first time he is mentioned

Addressed

"Dr. A. Dickson" changed to "Dr. Andrew Dickson (Scripps Institution of Oceanography)" on first occurrence

L35: which type of CTD is used

We cannot address this point; we do not know the make and model of the ship's CTD. We do not see this as a critical lack.**L36: I guess you used a plastic tube to transfer the water from the water samples to the glass bottle?**

Yes. Words added to text.

P4 L1: add reference for VINDTA-3C

The text states the make (Marianda) and model (VINDTA-3C) of the instrument that was used. There is no "reference" for the instrument.

L11: references for long-term changes: it seems like you have older refs than Steiner et al. 2018, please add

This is the only reference showing long-term changes in the Red Sea. Older references include older Red Sea data or some other aspect of Red Sea carbonate chemistry, but the aim of those studies was not to show long-term changes.

No changes made

L17: add the word "observed" so the sentence reads "describing the linear variations of observed S, TA and DIC ..."

Changed.

"describing the linear variations of S, TA and DIC ..." to "describing the linear variations of observed S, TA and DIC ..."

L19: define D here (distance from a defined zero point in the southern Red Sea)

Changed.

D is now defined earlier.

First paragraph of 2.4 now reads:

"A single-end-member mixing model was used to model conservative TA (cTA) and conservative DIC (cDIC) for coastal observations. First, the perpendicular distance of a point along the central axis of the Red Sea in km (D) was calculated for each observation. This was done using the "alongTrackDistance" function (default settings) in the R package "geosphere" (Hijmans, 2017) with the reference point 12.7737°N 43.2618°E to represent D = 0 and the reference point 28.2827°N 34.0694°E to define position of the central south-north axis. The single-end-member model was then implemented by 1) describing the linear variations of S, TA and DIC with D, so that predictions of offshore S (S_O), offshore TA (TA_O) and offshore DIC (DIC_O) can be made from D corresponding to coastal observations, and then 2) calculating cTA and cDIC for coastal observations according to Equations 1-2, which predict the simple dilution and concentration (SDC) effects of coastal evaporation (Figure 2)."

L19: explain difference between observed S, TA and DIC and predictions of So, Tao, and DICo (both along the north south axis). Why don't you use observed offshore values in Eq 1 and 2?

It is true we do use offshore observations in the methods to calculate 99% P.I. Thus the specification of only coastal observations being used in the model has been removed.

Section 2.4 (now 2.5) now reads:

2.5 Implementing a single-end-member mixing model

A single-end-member mixing model was used to model conservative TA (cTA) and conservative DIC (cDIC) for coastal observations. First, the perpendicular distance of a point along the central axis of

the Red Sea in km (D) was calculated for each observation. This was done using the "alongTrackDistance" function (default settings) in the R package "geosphere" (Hijmans, 2017) with the reference point 12.7737°N 43.2618°E to represent D = 0 and the reference point 28.2827°N 34.0694°E to define position of the central south-north axis. The single-end-member model was then implemented by 1) describing the linear variations of observed offshore S, TA and DIC with D, so that predictions of offshore S (S_O), offshore TA (TA_O) and offshore DIC (DIC_O) can be made from D corresponding to coastal observations, and then 2) calculating cTA and cDIC for observations according to Equations 1-2, which predict the simple dilution and concentration (SDC) effects of evaporation (Figure 2).

Equation 1: $cTA = (S/S_O)*TA_O$

Equation 2: $cDIC = (S/S_O) DIC_O$*

Where S is the observed salinity at a coastal observation point and S_O, TA_O and DIC_O are calculated for a distance D corresponding to the observation point from the linear relationships found in step 1.

Other carbon parameters, the partial pressure of CO_2 (pCO_2), pH, the saturation state of aragonite (Ω_{Ar}), were calculated with the R package "seacarb" (Gattuso et al. 2018) assuming silicate and phosphate concentrations of zero, employing the total scale for pH and using the carbonate constants from Millero et al. (2010). Both conservative values and observed values were calculated for other carbon parameters, from cTA and cDIC, and observed TA and DIC, respectively.

Residual TA (rTA) and residual DIC (rDIC) were then calculated by subtracting cTA and cDIC from observed TA and observed DIC, respectively. Residual other carbon parameters ($rpCO_2$, rpH, $r\Omega_{Ar}$) were calculated by subtracting conservative values of other carbon parameters (calculated from cTA and cDIC) from observed values of other carbon parameters (calculated from TA and DIC observations).

L31: "All other open waters" means 200m< transition<coastal? And would you please define coastal?

A new section 2.4 has been added into the manuscript:

2.4 Definition of the coastal zone

Offshore observations used to describe the offshore end-member were those (from KAUST, WHOI and published sources) with bathymetry > 200 m below sea-level according to the General Bathymetry Chart of the Oceans (GEBCO) gridded bathymetry with a 30s resolution (BODC, https://www.bodc.ac.uk/). All other open-water observations not collected over a coastal habitat were labelled as coastal, transition waters. Samples collected over a coastal habitat were classified by the corresponding habitat, either coral reef, seagrass meadow or mangrove forest.

P5 L2: what is an "observed estimate"

Changed to "observed value"

Now reads:

Other carbon parameters, the partial pressure of CO_2 (pCO_2), pH, the saturation state of aragonite (Ω_{Ar}), were calculated with the R package "seacarb" (Gattuso et al. 2018) assuming silicate and phosphate concentrations of zero, employing the total scale for pH and using the carbonate constants from Millero et al. (2010). Both conservative values and observed values were calculated for other carbon parameters, from cTA and cDIC, and observed TA and DIC, respectively.

Residual TA (rTA) and residual DIC (rDIC) were then calculated by subtracting cTA and cDIC from observed TA and observed DIC, respectively. Residual other carbon parameters ($rpCO_2$, rpH, $r\Omega_{Ar}$) were calculated by subtracting conservative values of other carbon parameters (calculated from cTA and cDIC) from observed values of other carbon parameters (calculated from TA and DIC observations).

L6: to ensure clarity, add "coastal" to "observed TA and observed DIC"

Not changed as coastal specification removed as above.

L18: change "two-end-member" with "single-end-member"

Thankyou

Changed "two-end-member" to "single-end-member"

L20: as above

Thank you

Changed "two-end-member" to "single-end-member"

L29: suggest changing "linear trends with D for S ...variables" with "how S, temperature and carbonate variables vary along the central axis from south to north".

The sentence has been adjusted to make it more explicit what linear relationships with D mean.

This sentence now reads:

Least squares regression analysis was used to calculate linear relationships with D for S, temperature and carbonate variables, thus determining how S, temperature and carbonate variables vary along the central axis from south to north

L30: add "to" between the words "used investigate"

Thank you!

"to" added between "used" and "investigate"

P7 L3: suggest a simpler language: "The offshore carbonate system of the Red Sea was characterized along the south-north ...".

Thank you!

P7 L3 now reads:

The offshore carbonate system of the Red Sea was characterized along the south-north central axis.

L4: suggest "Offshore waters exhibited significant and strong (highr2) linear increase in S ...". This sequence of words should be use all over , because the words "strong" or "weak" are connected to the linearity and only indirectly to significance.

Noted.

Changed "....strong (high r^2), significant…." *to ".... Significant and strong (high* r^2)….." *(and variations with "weak") everywhere.*

L6, L9, L10, L11: as above Are the strong/weak linear trend values summarized in a Table? If so , this should be announced early in paragraph 3.1.

Noted.

Table S3 reference added at the start of Section 3.1

L32: you describe the "Coastal observations", but then the word "central axis" should be exchanged with something else, since the coast is not along the central axis. Maybe just use "from south to north".

Noted.

Sentence now reads:

Coastal observations also displayed significant linear relationships with S from south-north along the Red Sea (Figure 3-5).

L37: change "end-member" with "waters"

Noted.

Changed "end-member" to "waters"

P8L7, L10, L14, L18, L19, L22andmore: as above. In general, I advise you to not use "end-member" when you mean "saters". It is just confusing.

Noted.

Changed "end-member" to "waters" in section 3.2 and where appropriate in the text. "offshore end-member" is now only used when referring to the single-end-member mixing model and not when comparing to offshore observations.

L31: do you really mean "trend", if so, over which time. If not, change with "linear relationship"

Addressed above

P9 L15: you are comparing to a "norm", are you referring to anomalies (P2, L12) or expected conservative behaviour (P2, L23)?

Comparing to the expected conservative behaviour using a 99% P.I. for error

Changed to 99% P.I.

L18: as above

As above

L22: delete "norm or"

Changed.

L24 and 25 ant the rest of this and next paragraphs: use other words for "norm"

Changed.

Here we are comparing to 99% P.I. so we have now changed the language to directly say this by replacing "norm" with "99% P.I.".

P10 L15: you write "seasonal trend", do you actual mean "seasonal variation"? If so, change all over

Addressed above.

Changed to "seasonal dependency"

P21 L5: change "The latitude at which time series stations are at is indicated by the text"Ts"" with "Time series stations are indicated as TS". Refer to Figure S1 in the figure text

Changed as suggested.

P22, Figure 2: define Oi earlier in figure text.

We have mentioned Oi earlier in the text

Now reads:

"……Flow axis 1 is along the south-north central axis where waters experience cumulative changes due to basin-scale evaporation and calcification. Flow axis 2 is perpendicular to this axis, where it is assumed that evaporative effects prevail as waters transition from offshore locations (Oi) to coastal regions."

L7: change "estimate" with "determine"

Changed as suggested.

L9: after "central axis at distance Di" add "from a fixed reference point in the southern Red Sea"

Changed as suggested.

P23, Figure 3: L3: suggest text " Offshore observations of S, T and carbon variables (left) and four coastal ..."

Changed as suggested.

P24, Figure 4: L3: change "end-members" with "waters"

Changed as suggested.

L4: after "included" add "in the"

Changed as suggested.

P26, Figure 6: A, B, C, D, AB, BC, CD are not explained

Noted.

Figure 7 caption changed from "Grouping letters indicate the results of post-hoc bootstrapped t-tests, summarized from statistics presented in Table S5. If tests showed significant similarities at the 0.05 significance level with another habitat across a variable they were assigned the same letter." to "Grouping letters (A-D) assigned above boxplots indicate the results of post-hoc bootstrapped t-tests, summarized from statistics presented in Table S5. If tests showed significant similarities at the 0.05 significance level with another habitat across a variable they were assigned the same letter."

Table S2: in the footnote you use a * as a multiplicator, this is confusing since the same sign is used as footnote numbering.

Noted

Changed footnotes [+]

Please change Table S3 and S4: please include units where you can (T, TA, DIC, pCO2 etc).

Noted.

Added unit references. Also added unit references to Table S2.

Table S4: change title from "By Habitat descriptive statistics for carbon variable habitat groups for all coastal ..." to "Descriptive statistics for carbon variable habitat groups for all coastal ..."

Noted.

Reviewer suggested change implemented.

Table S5: add units where feasible

Noted.

Added unit references

Table S7: as above

Noted.

Added unit references