Authors’ response to reviewer 2 (Jianli Chen)

We thank the reviewer for the constructive and insightful comments which helped us to improve the manuscript. Following reviewer comments 9 and 10 we also updated our analysis for GRACE ocean mass change (see below).

In the following we respond to the specific comments. (Reviewer comments are repeated in *italic.*)

> *1) In the abstract, the authors discussed the SLB and OMB analyses for two periods (P1 & P2). However, for P2 only the mass term was discussed here. The steric component should be discussed as well.*

We added the numbers for the steric contribution for period P2.

> *2) Line 39: “ … sea-level change and its contributions.” “Contributors” appears to be the right word to use here.*

We replaced “contributions” by “contributors”.

> *3) Lines 108-110: References are needed to support the conclusions. “GRACE analyses suggest LWS gains and therefore a negative GMSL contribution from LWS” – I believe this was based on only one previous study (Reager et al., 2016). Some other later studies came to a completely different conclusion. In addition to the two (Cáceres et al., 2020; Gutknecht et al., 2020) cited later in Discussion by the authors, I would suggest to also cite*
> *Kim et al. (2019), the first to have reported a different and opposite GRACE LWS contribution to GMSL. A brief discussion of the different LWS estimates is needed here.*
> Kim, J.-S., Seo, K.-W., Jeon, T., Chen, J., & Wilson, C. R. (2019). Missing hydrological contribution to sea level rise. Geophysical Research Letters, 46.
> *https://doi.org/10.1029/2019GL085470*

Thank you for pointing at our omission of relevant work here. We draw a more complete picture now by writing: “Determining the LWS contribution to sea-level is a particular challenge (WCRP, 2018): Hydrological models generally suggest LWS losses and therefore a positive contribution from LWS to GMSL rise (Dieng et al., 2017; Scanlon et al., 2018; Cáceres et al., 2020). Initial GRACE-based estimates indicated a gain of LWS (Reager et al. 2016; Rietbroek et al. 2016), while newer GRACE-based estimates (Kim et al. 2019, Frederikse et al. 2020) agree with global hydrological modeling results on the sign of change (loss of LWS). Moreover, in view of the high interannual variability of LWS, the determined trend strongly depends on the selected time period and method of trend determination.”

> *4) Line 144: “other” should be added to the list, consistent with other occurrences.*

We added “or other sources” in the sentence after Eq. 6.

> *5) Line 174: “The SLB The presentation of the result needs substantial improvements. The authors should at least provide a clear definition of the two studied drainage basins, and show how the defined GRACE mascons are configured in the basins. The two maps in Figure 1 are simply not sufficient. The authors should also provide a plot showing GRACE-derived ice mass change time series for the two basins.*

In the meantime, it was clarified with the reviewer that comment 5 slipped into the review by mistake, as it did not refer to our manuscript.

> *6) Line 226: Please clarify what interpolation method(s) is (are) used here.*

We now specified that the interpolation was linear.

> *7) Lines 267-268: CMEMS provides altimeter sea level anomaly grids for the entire altimeter period, the authors need to explain why they decided to combine the two datasets (CCI sealevel record & CMEMS) to get the GMSL series and not use the CMEMS series for consistency.*

The principle of our study was to use CCI products wherever available. We now made this clear by writing: “While our study focusses on utilising CCI products, the CCI sea-level product did not cover the year 2016. We therefore extended the GMSL record with the Copernicus Marine Environment and Monitoring Service dataset (CMEMS, https://marine.copernicus.eu/) from Jan 2016 to Dec 2016."

8) Lines 365-366: "It is relatively common for there to be layers with no observations, sometimes in the upper ocean and often at depth." Please rephrase this sentence. It doesn't sound grammatically correct.

We made the sentence simpler. It now reads: "It is relatively common to have layers …"

9) Lines 494-498: The authors used CSR, JPL and GFZ GRACE RL06 SH gravity solutions (together with ITSG-Grace2018), but decided to use old generations of geocenter (Swenson et al., 2008) and SLR C20 series (GRACE TN-11), which were prepared for GRACE RL05 solutions. Are there any logical reasons for not using the RL06
supplementary datasets? Using RL05 SLR C20 may be fine, but the new RL06 geocenter series are expected to have substantially different effects on GRACE ocean mass rate estimates.

See our response to comment 10

10) Lines 499-509: Please clarify which ICE6G GIA model was used. The authors cited Peltier et al. (2015), which is an outdated version. After fixing some error(s), Peltier et al. (2018) released an updated version of the model, ICE6G_D.

As seen from the two comments above (9 & 10), the GRACE related analyses in the current study are not up to the current standards. The authors need to either provide a convincing reasoning or update the analyses using the current standards.

We agree that the standards on degree-one time-series and some other aspects of GRACE analysis have changed since the time when our original GRACE-based OMC products were generated.

Given the pertinent comments by two reviewers (Reviewer 2 comments #9 and #10; Reviewer 3 comment on line 495) we decided to perform a major update of the GRACE-based OMC analysis according to more recent standards. The update concerns GIA corrections, Degree-one solutions, and C20 series. The update includes updates of the related uncertainty assessment. The update has resulted in an increase of the linear trends for GRACE ocean mass change in the order of several tenths of millimetres per year. The updated standard uncertainties are also increased slightly.

This update entailed a complete re-work of the budget analysis and a change to many numbers. We believe that it was worth the effort and that the dataset and assessment thus provided may serve the community as a longer-lasting reference.

Some more details on the update are appended at the end of this reply.

We have updated the pertinent text in Sect. 3.3 as well as all numbers and figures in Sections 4, 5, 7, and 8 that depend on the OMC products.

11) Figure 10: The authors may choose some colors to better distinguish the curves (red and magenta are not a good pair).

We have changed the colors. They are now dark red and light red and should be better distinguishable than previously

12) Line 1144: "We cannot attribute the misclosures in the budgets of linear trends, …" Please consider rephrasing this sentence. "We cannot attribute the misclosures in the budgets of linear trends to any particular error source, …" ?

We rephrased the sentence accordingly.

13) Lines 115-1156: "The unassessed atmospheric water content contribution (cf. Sect. 3.8) could add to the misclosure, though." Please consider rephrasing this sentence. "The unassessed atmospheric water content contribution (cf. Sect. 3.8) could contribute to the misclosure, though."?

Well observed. We rephrased the sentence accordingly.

14) Line 1182: “are0.26” -> “are 0.26”

Thanks for spotting this. We added the space

15) Lines 1216-1220: “Errors in …” It is unclear what are really discussed here. Do those cited values (e.g., -1.37 ± 0.17 mm yr^{-1}) represent estimates rates with uncertainties? If so, the values for Antarctic (-0.14 ± 0.09) and Greenland (0.02 ± 0.02) do not sound right.

We reworded this part and put it into two separate sentences. They should now be clearer. We also checked the numbers. The part now reads:

In our study, the GIA corrections and their uncertainties are -1.37 ± 0.19 mm yr^{-1} for the GRACE OMC estimate, -0.14 ± 0.09 mm yr^{-1} and -0.02 ± 0.02 mm yr^{-1} for the GRACE-based assessment of the Antarctic and Greenland mass contribution, respectively, and -0.30 ± 0.05 mm yr^{-1} for the altimetric GMSL change. (These numbers are subtracted from the uncorrected results.) The errors in these GIA corrections to different budget elements are likely correlated among each other.

16) Lines 1284-1287: “we have provided …” It is not clear what the “start of our survey” is referred to. Please be more specific.

Thanks four pointing on this. We rephrased the sentence. It now reads:

This new dataset (cf. Shepherd et al., 2019) shows that ice losses are dominated by the Pine Island Glacier and Thwaites Glacier basins in West Antarctica, where mass losses (expressed as equivalent GMSL contribution) have increased from 0.04 ± 0.01 mm yr^{-1} in 1992–1997 to 0.36 ± 0.03 mm yr^{-1} in 2012–2017.

Additional background information on the GRACE ocean mass change analysis update

The following information is given as part of the response to the reviewers, in addition to the information given in the revised manuscript.

Approach to assessment of trend uncertainty associated to degree-one, C20, and GIA

Trend uncertainties associated go degree-one, C20, and GIA were assessed individually based on the spread of a small ensemble of different options to incorporate these effects.

For example, for degree-one, ten different degree-one time series were used. There temporal sampling was identical to that of the GRACE solutions. They were treated in the same way as the GRACE solutions (synthesis into the spatial domain, weighted integration with a buffered ocean kernel, scaling to account for the buffer). In this way, time series of the degree-one contribution to the OMC estimate were derived. Linear trends of these time series were calculated according to Section 2.2. The standard deviation of the ten linear trend values was calculated and taken as the standard error associated to Degree-one. We did not adjust the calculation of the standard deviation to effects of the low sample size (e.g., with t-Student distributions). The same procedure was used for C20. For GIA, the procedure was performed immediately on the level trends, rather than by generating time series and fitting trends to them.

Differences between GIA models affect differences between GIA corrections as well as differences between degree-one solutions. The former were addressed by the GIA uncertainty assessment, while the latter were included in the degree-one uncertainty assessment.

Degree-one

We agree that the formerly used geocenter time series are outdated from today's perspective. The choice had been a question of project timelines (involving "freezing" of data products) rather than of awareness. For our update, we skip the former single degree-1 solution and use coefficients according to more recent standards, which indeed affects trends significantly. However, we do not simply take the TN13 products (which basically is Sun et al. (2016) with ICE-6G_D GIA), but we compute our own in-house solution according to Sun's method. We do this because, first, TN13 does not provide an individual degree-one product for ITSG-Grace2018, and second, it allows us to be consistent with varying GIA choices. It means we have a dedicated degree-one correction for each combination of GRACE solution {ITSG, CSR, GFZ, JPL} and GIA model {A2013, Caron, Peltier}.

As expected, using these degree-one solutions instead of those in the previous manuscript version results in a notable increase of OMC trends in the order of tenths of a millimetres per year. Now all tested combinations result in a linear global ocean mass trend of more than 2 millimetres per year over the period P2.

We reran the degree-one uncertainty assessment and found an increase of the 1-sigma standard deviation of trends from 0.14 mm/a (old) to 0.18 mm/a (new). This time we picked a variety of ten different solutions out of a total pool of twenty options and tried to keep a balance between age, choice of method, data centres and GIA models:

- Swenson 08, CSR RL05, Tellus (A2013)
- Rietbroek 2016 (combination approach)
- Cheng 2010 SLR
- Sun 2016, CSR RL06, orig. (A2013)
- 3 x TN13 (CSR, GFZ, JPL), with ICE-6G_D
- 3 x TUDresden GEF, ITSG-Grace2018, GIA from {A2013, Caron18, ICE-6G_D}

Figure 1 compares our degree-one time-series (when employing CSR RL06 and ICE-6G_D) to the degree-one time-series provided at Tellus for CSR RL05 and CSR RL06. Figure 2 shows the degree-one contributions to the global OMC estimate according to the ten solutions that underlie our uncertainty assessment. Figure 3 shows the distribution of associated linear trends.

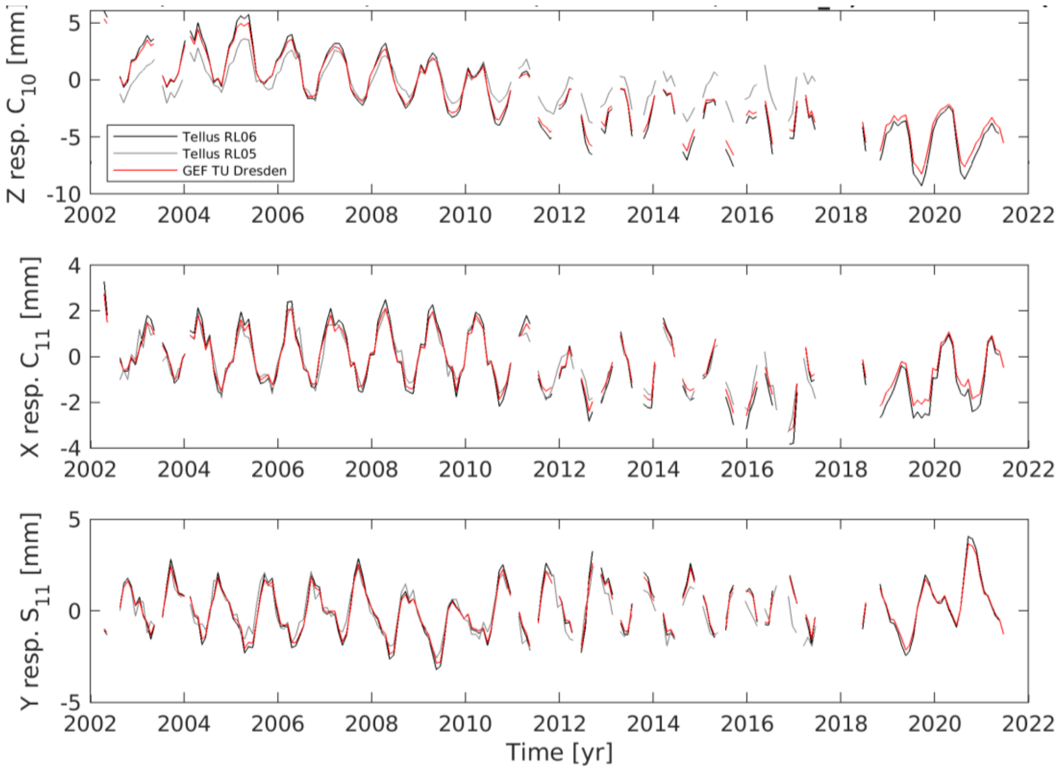

Figure 1: Degree-one time-series expressed in terms of geocenter motion [mm]. Comparison between Tellus RL05, Tellus RL06 and our dedicated solution (red) based on an approach comparable to the TN-13 approach (based on Sun et al., 2016); in this case for the combination of GRACE RL06 CSR with ICE-6G_D.

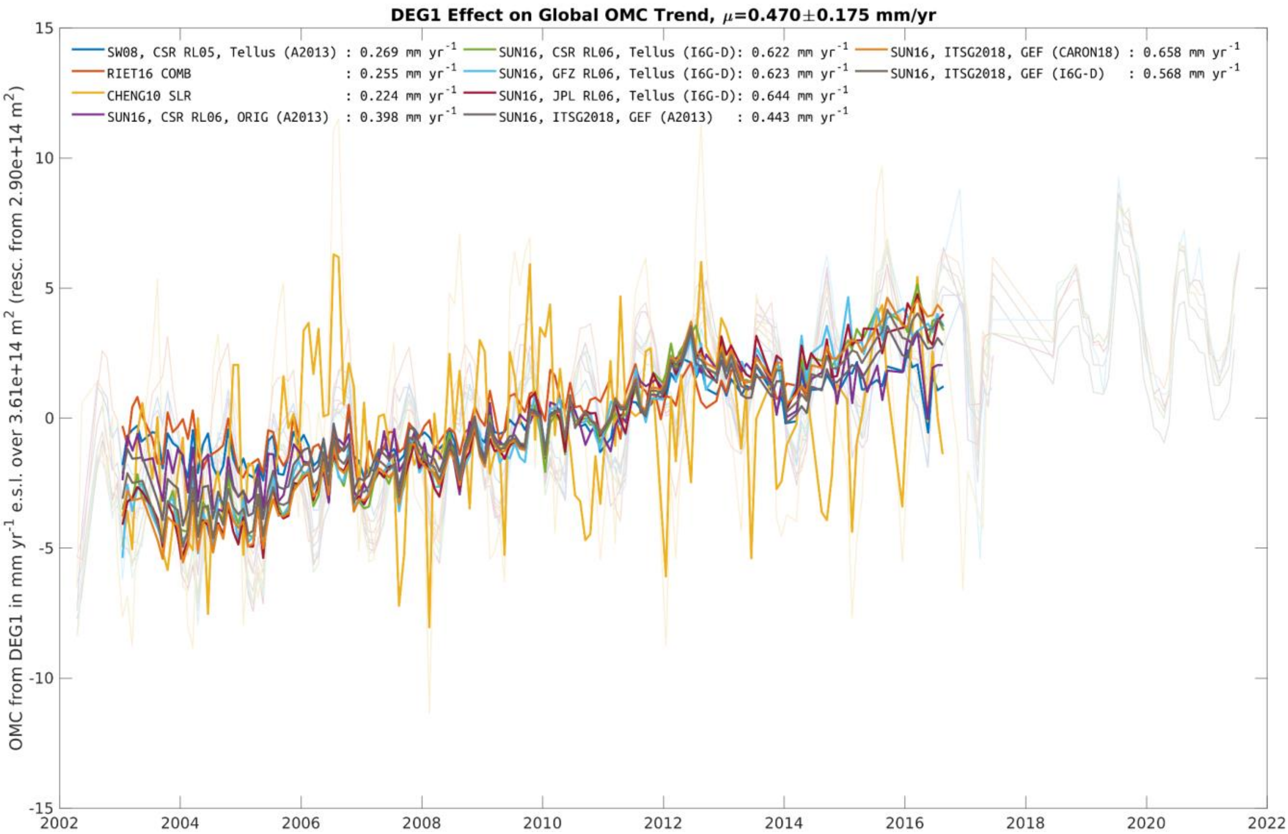

Figure 2: Contribution to the global OMC from ten different degree-1 solutions. SW08 is the Swenson 2008 RL05 Tellus product, RIET16 the series by Rietbroek et al. The three GEF solutions were computed by us according to the Sun et al. (2016) method, which is also used in the three official TN13 ("RL06, Tellus") solutions in combination with ICE-6G_D GIA. The original data (faint in background) minus the approximated seasonal signal from the multi-parameter least-squares fit is shown as bold lines.

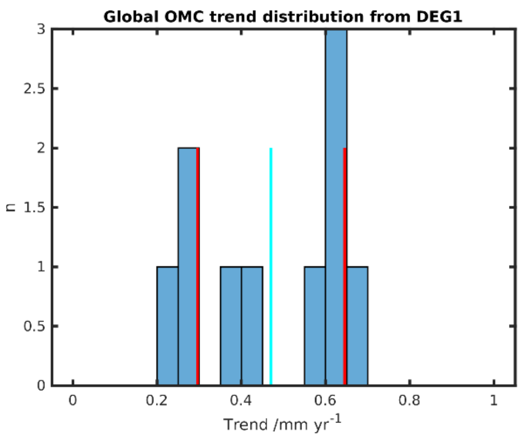

Figure 3: Distribution of linear trends of the degree-one contribution to global OMC (in terms of mm yr^{-1} sea-level equivalent) according to ten analysed degree-one products. Resulting trends appear rather clustered in (a) deprecated: low trend, (b) degree-one series that use the GIA model by A et al. (2013): low-to-mid trend and (c) more recent: TN13 and solutions generated in our study, with ICE-6G_D and Caron18 GIA: largest trends. The light blue line represents the mean linear trend of the ten analysed solutions, the red lines indicate the corresponding 1-sigma standard deviation around the mean.

C20 / C30

We have updated our GRACE analysis for C_{20}. We now replace C_{20} coefficients in all solutions with values according to GRACE Technical Note 14 (TN14).

We have also updated our C_{20} uncertainty assessment. We compare the linear trends of seven different solutions:

- CSR SLR RL05
- TU Delft GRACE/models
- CNES/GRGS GRACE/LAGEOS RL04
- GFZ SLR RL06
- DGFI SLR
- CSR SLR RL06
- GSFC SLR RL06

Figures 4 and 5 show the C_{20} contribution to global OMC according to these C_{20} series and the trend distribution, respectively.

The standard deviation of the linear trends remains almost unchanged (w.r.t. our previous solution) at 0.049 mm yr^{-1}. The TN14 C_{20} solution is – out of all seven solutions – the closest to the mean trend.

C_{30} coefficients are not replaced in the GRACE solutions, as the associated accelerometer problems arose after Aug 2016, which is the end of the period assessed in our study.

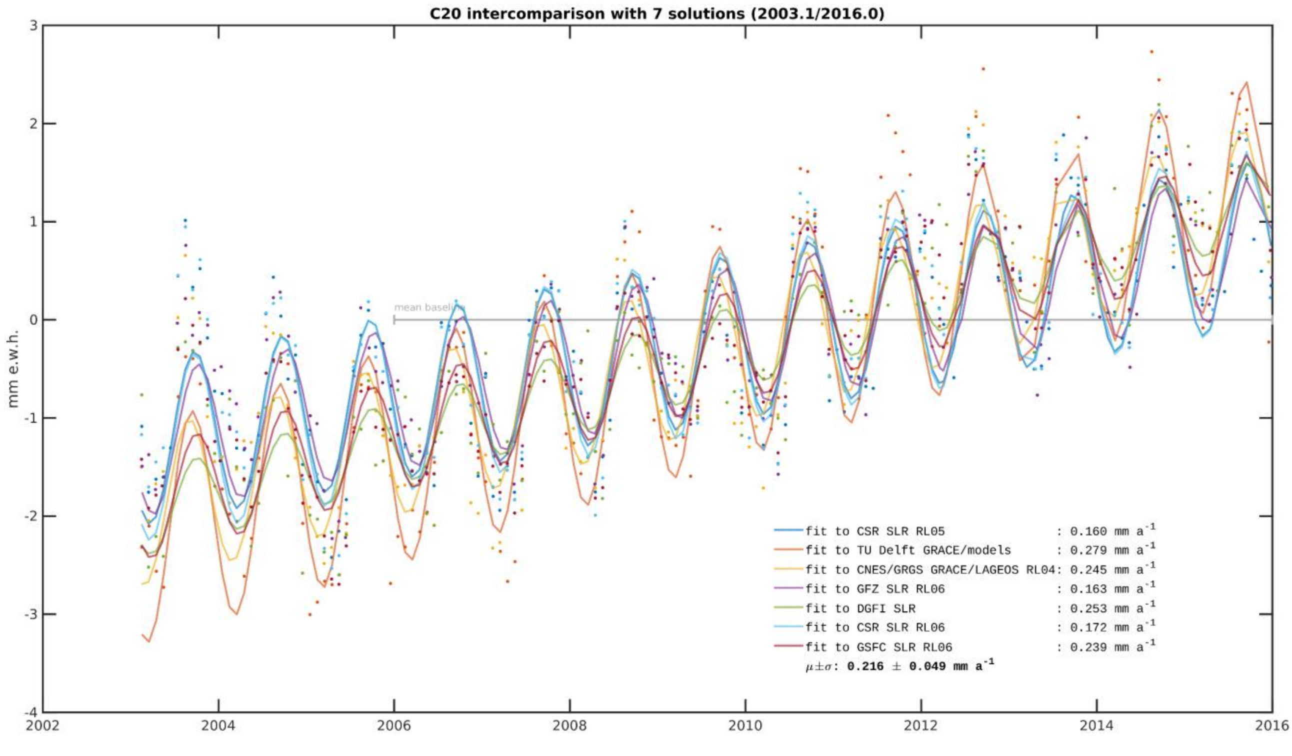

Figure 4: Comparison of the C_{20} contribution on global OMC (in terms of mm sea-level equivalent) according to seven different solutions spanning the 2003.1/2016.0 period. The bold curves represent the multi-parameter least-squares fit to the time series at approximately monthly resolution (dots). Linear trends are indicated in the legend.

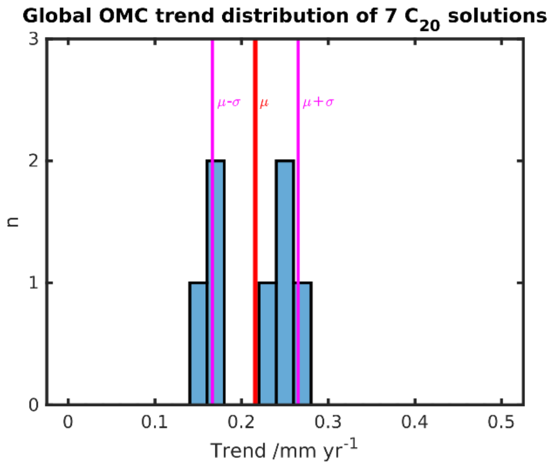

Figure 5: Distribution of linear trends of the C_{20} contribution to global OMC (in terms of mm yr^{-1} sea-level equivalent) according to seven analysed C_{20} products for the 2003.1/2016.0 period. The currently used TN14/GSFC solution is closest to the mean linear trend (red line) of the seven solutions.

GIA

The original submission used ICE-6G_C in the ensemble of GIA models to be compared with our preferred GIA solution. We now replaced this by ICE-6G_D.

We found that the switch from ICE-6G_C to ICE-6G_D (while keeping all other post-processing steps fixed) leads only to a small of assessed linear OMC trends by 0.047 mm/a.

As this switch also affected the uncertainty analysis, we have updated that as well and come up with a slightly increased OMC uncertainty contribution from GIA. GIA uncertainties are of the same order as for degree-one, which makes both of them the largest sources of uncertainty in our analysis.