GRACE and GRACE-FO Mascons for Ocean Dynamic Applications

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Response to Reviewer 1:

Thank you for your helpful and detailed review. We have made many changes to the text in response, and also wish to reply to each comment (repeated in bold-face) in turn:

"I find the lack of treatment of GRD effects from atmospheric mass changes over land a major shortcoming of this dataset. It is unclear why these effects are not included. They are clearly important around Eurasia and Antarctica at the annual time scale, judging from previous works including the cited paper by Tamisiea et al. (2010). Just because they are not provided in other GRD calculations, as stated in lines 363-364, is not a good justification for leaving those potentially important effects out of this dataset. Quite the contrary!
An implementation of such a correction could use surface atmospheric fields from the AOD model or some other atmospheric reanalysis product of choice. I strongly recommend that the authors update their dataset with this extra correction."

The decision to include only the continental water mass changes as a driver in the GRD calculations was a purposeful one. We have another paper in preparation that does explicitly include the atmospheric and oceanographic (AO) effects on the GRD, and the calculations were finished prior to this submission. The quantitative benefit or degradation of including the AO forcing depends on how it is assessed. Because the benefits are not clear, the results raise questions as to whether some of the fundamental assumptions behind the GRD calculations are satisfied when including these AO mass changes. Below, we discuss some of the results that motivated our future GRD manuscript.

As the reviewer points out, the largest benefits of reduced ocean mass variability are in the Mediterranean, and the effect of the annual component is most notable in the oceans near Eurasia and Antarctica. Indeed, assessed globally, the total (mascons that include the GAD component) ocean mass variability shows a slightly larger reduction, calculated by removing the GRD estimate, when the AO forcing is included. However, if the GAD component is removed prior to calculating the mass variability reduction, then GRD results show a slightly smaller reduction than the case where the AO forcing is not included. To address the reviewer's specific suggestion of only using the atmospheric component, we verified that this mixed set of results is also replicated in that case.

This mixed set of results may have two causes. Firstly, it is known that the GAD does not adequately reflect all dynamic ocean variability, and thus, it may not be adequate to drive the estimate. When the GRD estimate is removed from the total signal, we note an improvement. However, if the GAD estimate in a given region was corrected by the GRACE measurement, then the GRD with the AO forcing will amplify that incorrect estimate, resulting in a degradation when it is removed from the GRACE-GAD residual. Secondly, and perhaps more fundamentally, the GAD component can vary rapidly from month to month. Even moving the epoch of a 30-day average by 15 days can produce a dramatically different GAD estimate in some regions. Thus, it is not clear that fundamental assumption going into the GRD calculations, that the barotropic redistribution of ocean mass has occurred, is satisfied. As the atmospheric-only results mirror those of the full AO and atmospheric estimates over the continents are generally considered good, this later explanation seems more likely.

We wish to withhold detailed description of these complex issues until a future GRD-focused publication. However, we have added the following few lines to the current text, such that readers know for certain that the AOD signal was not incorporated in the current GRD estimate, and why:

As in many GRD calculations, the contribution of dynamic ocean and atmospheric mass changes to the GRD estimate are not considered for two reasons. First, relative to the barystatic-GRD signal caused by land/ice changes, the impact of the ocean and atmosphere mass change on the barystatic-GRD is small. The most significant impact is on the annual amplitudes, with dfferences in the barystatic-GRD estimates generally less than 0.5 cm except around the coasts of Eurasia and Antarctica. Second, because results incorporating the GRACE AOD1B RL06 into the barystatic-GRD estimate were ambiguous as to whether improvement was achieved. We choose to omit that relatively small contribution here.

"Another important issue is the characterization of uncertainty for the newly applied corrections or in some sense the remaining GRD and earthquake signals after correction. In this regard, a number of other similar products, dealing with these corrections, have been recently made available (e.g., Landerer and Wiese, https://doi.org/10.5067/HMOGD-4JM01; Dahle et al. 2025, https://doi.org/10.5194/essd-17-611-2025). Discussion of the new dataset in the context of other similar products would be very useful. Moreover, comparisons with these other corrections, particularly for the case of GRD, could provide a measure of uncertainty. The only quantitative discussion of uncertainty refers to the DOM fields and is based on crude comparisons with ECCO (lines 437-441). Any measure of uncertainty for the corrections provided would be useful when applying the DOM fields to ocean circulation and data assimilation studies."

Thank you for the suggestion of comparing to other products. We have added an appendix with a comparison of the annual and trend estimates of the GRD products. We believe that, for the most part, the differences are associated with the underlying estimates of mass changes over the continents. Those differences are small between our DO mascon GRD and the JPL GRD. The difference is larger with the GRAVIS estimate, since it is generated from spherical harmonics. Producing such an estimate with spherical harmonics is more difficult, in that they are attempting to provide an estimate over the entire ocean while also needing to restore the signal leakage from the continents.

We have produced the following comparison plots with the JPL and GravIS GRD series, which we are placing in a new Appendix B:

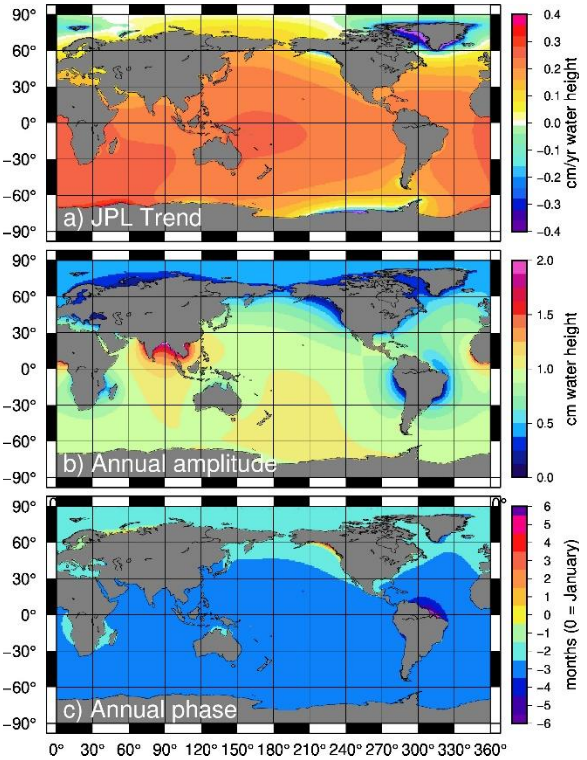

Figure B1: The linear trend (a), annual amplitude (b), and annual phase (c) of the JPL barystatic-GRD estimate. The ocean mask used was the CSR mascon mask (to ½° resolution). Phases in (c) are defined such that 0 refers to an annual maximum in January, and ±6 refers to a maximum in July.

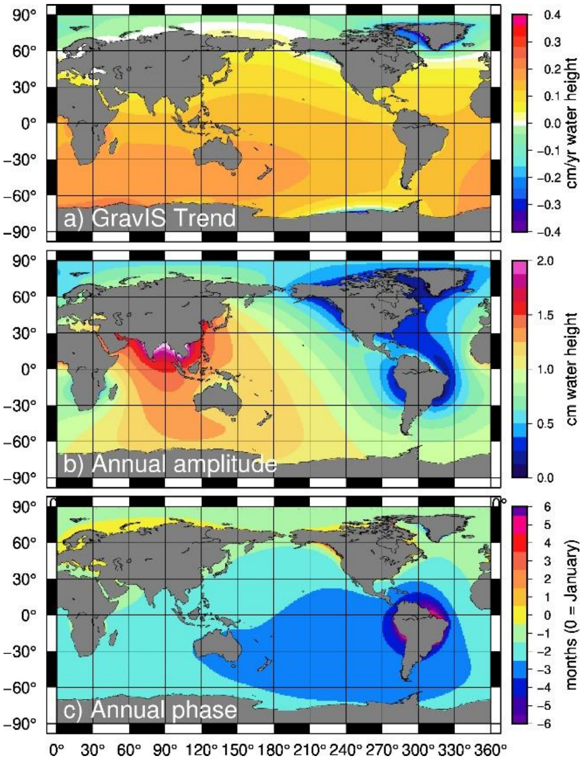

Figure B2: The linear trend (a), annual amplitude (b), and annual phase (c) of the GravIS barystatic-GRD estimate. The ocean mask used was the CSR mascon mask (to 1° resolution). Phases in (c) are defined such that 0 refers to an annual maximum in January, and ±6 refers to a maximum in July.

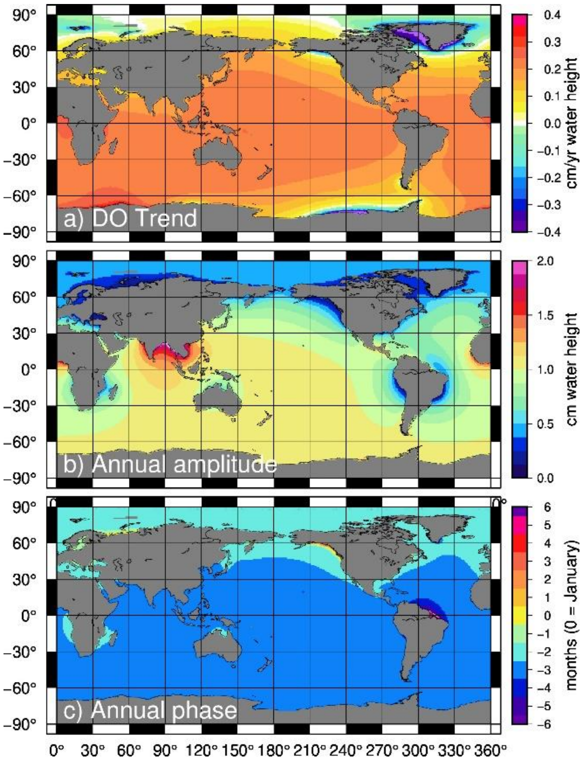

Figure B3: The linear trend (a), annual amplitude (b), and annual phase (c) of the DO mascon barystatic-GRD estimate. The trend and annual amplitude are identical to those shown in Fig. 7, and are repeated here for ease of comparison. Phases in (c) are defined such that 0 refers to an annual maximum in January, and ±6 refers to a maximum in July.

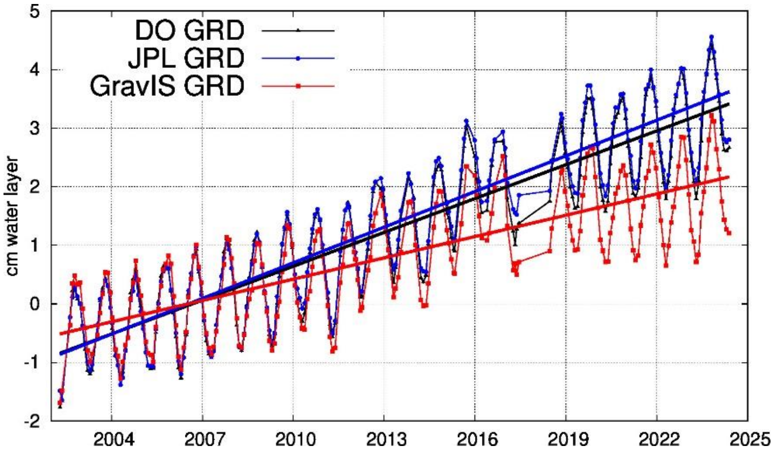

Figure B4: The mean signal over the global oceans (as defined by the CSR mascon mask), for the barystatic-GRD estimates from the new DO mascons, the JPL mascons, and the COST-G GravIS spherical harmonics.

We added the following lines describing this in the main text:

The GRD series which results is similar to the recent JPL barystatic-GRD series (Landerer and Wiese, 2025), but computed using the land input from the DO mascons rather than the JPL mascons. Average differences between these barystatic-GRD series (Fig. B1) are only 0.01 cm yr^{-1} in trend and 0.06 cm in annual amplitude. The recent GravIS barystatic-GRD series (Fig. B2) is substantially different from either the DO or JPL barystatic-GRD series, probably because it is based on spherical harmonic input rather than mascon input (see Appendix B).

And this info in the new Appendix B, which also contains the new images:

Recently, two other barystatic-GRD series have been released. JPL's barystatic-GRD series (Landerer and Wiese, 2025) is based on their RL06.3 version 4 mascons with coastal resolution improvement (CRI) filter. The GravIS barystatic-GRD series (Dahle et al. 2025, Dobslaw et al., 2025) is based on the COST-G RL02 spherical harmonic series. Both barystatic-GRD series were made via the same mathematical theory as our DO mascon barystatic-GRD series, but use the JPL or COST-G land data to define the mass inputs. The GravIS barystatic-GRD series also allows the atmosphere to drive their barystatic-GRD response, which the DO and JPL mascon barystatic-GRD estimates do not.

Directly subtracting the barystatic-GRD files is not recommended, since the JPL output as defined is smoothly spread across ½°x½° grids and the GravIS output is given on 1°x1° grids, while the DOM barystatic-GRD is averaged over the larger CSR mascons. However, the three barystatic-GRD series' trend, annual amplitude, and annual phase maps (Fig. B1, B2, and B3) can be directly compared. Additionally, the ocean-averaged timeseries over the CSR mascon ocean mask (Fig. B4) can be fairly compared between the series.

The DO mascon and JPL barystatic-GRD estimates are very similar in overall shape and have nearly identical annual phases, when averaged over the global oceans. The JPL barystatic-GRD estimate has a slightly higher trend (0.203 cm yr^{-1} compared to 0.193 cm yr^{-1}) and a slightly lower globally-averaged annual amplitude overall (0.87 cm vs 0.93 cm). These differences (0.01 cm yr^{-1} in trend and 0.06 cm in annual amplitude) do not define an error estimate of the barystatic-GRD method itself, but are a reflection of the level of difference between the JPL and CSR mass estimates over land.

The GravIS barystatic-GRD series is markedly different from either the DO or JPL mascon barystatic-GRD series. GravIS mapped trends (Fig. B2) are generally smaller, leading to an ocean-averaged trend (Fig. B4) of only 0.121 cm yr^{-1}, considerably lower than the DO (0.193 cm yr^{-1}) and JPL mascon (0.203 cm yr^{-1}) trends. The use of spherical harmonics, which lose some of their coastal land/ice signal into ocean grids as leakage, may explain some of this difference. The annual amplitude of the globally-averaged GravIS barystatic-GRD series (0.877 cm) is of similar those of the DO and JPL series. Inclusion of the atmospheric forcing leads to higher annual amplitudes around Eurasia. However, even given this additional forcing, the differences appear larger than we might expect from the results of Tamisiea et al. (2010).

In terms of estimating the uncertainty near the earthquakes, we have added Table 1 (below), in which we divide up the differences with ECCO into regions, including one over the area the earthquake model was produced over. The "DO-ECCO" residual standard deviation in the "earthquakes" region shows the stdev(DO – ECCO) after the bias, trend, annual, and semiannual has been fit and removed. Whereas the standard CSR mascons have a 3.32cm residual stdev, the DO mascons have a 1.42cm stdev – and we expect that roughly 0.8cm of that is caused by non-earthquake-related differences (i.e.: the stdev in the "open-equatorial" ocean region).

Averaging Area	**ECCO v4r4**	**DO Mascons**	**RL06.3* Mascons**	**DO - ECCO**	**RL06.3* - ECCO**
Standard Deviation over Time (cm)					
Global Oceans	1.63	1.88	2.02	**1.33**	1.49
Open Ocean	1.40	1.60	1.66	**1.12**	1.19
Arctic	3.27	3.52	3.88	**2.69**	3.26
Earthquakes	2.36	3.11	6.00	**1.88**	4.77
Linear Trends (cm yr^{-1})					
Global Oceans	0.00	0.00	0.00	0.00	**0.00**
Open Ocean	-0.01	0.00	0.02	**0.01**	0.04
Arctic	0.15	-0.02	-0.30	**-0.17**	-0.45
Earthquakes	-0.09	-0.14	0.11	**-0.05**	0.21
Annual Amplitudes (cm)					
Global Oceans	1.17	1.27	1.32	**0.61**	0.66
Open Ocean	0.97	0.96	1.01	**0.41**	0.45
Arctic	1.71	2.47	2.29	1.47	**1.28**
Earthquakes	2.40	2.81	3.05	**1.07**	1.32
Residual Standard Deviation over Time (cm)					
Global Oceans	1.21	1.45	1.52	**1.12**	1.18
Open Ocean	1.07	1.32	1.33	**1.00**	1.01
Open Equatorial	0.68	0.98	0.99	**0.81**	0.83
Arctic	2.79	2.69	2.75	**2.04**	2.06
Earthquakes	1.18	1.68	3.61	**1.42**	3.32

Table 1: Comparison of standard deviations, linear trends, annual amplitudes, and residual standard deviation (after the removal of trends, annuals, and semiannuals) of the ECCOv4r4, DO mascon, and CSR RL06.3 with mean ocean mass uniformly removed, as well as the same statistics for the differences between each mascon series and ECCOv4r4. The "open ocean" is defined as CSR ocean mascons more than 300 km, exclusive of the Arctic and earthquake regions. The "open equatorial" is defined as the subset of the "open ocean" within 30° of the equator. The "earthquakes" region is defined as the broader regions near Japan and Andaman Bay modelled in Bonin et al (2025).

"A final concern is the DOM evaluations performed using comparisons with ECCOv4r4. First, such comparisons need to acknowledge that the ECCOv4r4 solution is itself constrained by GRACE data (in that case JPL mascons). Thus, interpreting similarities between GRACE and ECCOv4r4 as a sign of the quality of DOM derived in the paper (e.g., lines 425-429) is at best ambiguous."

Thank you. We are aware of the assimilation of GRACE data into ECCO and have now added lines concerning it into the text:

We want to note that ECCOv4r4 incorporates GRACE data as constraints to their bottom pressure estimates during their weighted-least-squares optimization process, in which they adjust boundary conditions, initial conditions, and model parameters to best minimize the model-minus-observation misfit. Due to this, there is some concern that the ocean bottom pressure estimates of ECCOv4r4 could be pulled towards GRACE by the optimization process itself, even if GRACE is more incorrect than the unconstrained model. Two facts convince us that a similarity with ECCOv4r4 is not merely an echoed recognition of GRACE's assimilation into the state estimate, however. First, the assimilation uses the 2002-2016 GRACE JPL RL05 mascon data, which is significantly different in both mascon averaging size and detailed ocean statistics from our 2002-2024 CSR RL06-based DO mascons. Second, ECCOv4r4 also simultaneously assimilates millions of non-GRACE observations (ECCO Consortium, 2021), and the assimilation method finds the state variables that statistically optimize the residuals between all assimilated observations, not just GRACE. Thus, if ECCOv4r4 agrees with GRACE mascons, it means that the model physics and other (more numerous) observations were statistically consistent with the GRACE data, not that ECCOv4r4 is automatically adjusted toward GRACE. For example, the strong difference between ECCOv4r4 and our GRACE/FO DO maps in the eastern Atlantic (Figs. 9 and 10; discussed below) is an indication that the assimilation rejected the GRACE observations there as being inconsistent with the model physics and other observations and so did not significantly adjust the estimated result toward GRACE.

"Second, perhaps more important is to show quantitatively whether DOM estimates are more or less consistent with the ECCO fields than the regular (uncorrected) mascons. Similar attempts are reported by Ponte et al. (2024, https://doi.org/10.1029/2024EA003661) for the seasonal cycle. See also comment on Figure 11 below."

Figure 11/ Do the DOM behave differently compared to the regular mascons? The focus should be on what improvements are brought by the DOM and this figure and its discussion do not address the key reason for the analysis.

397/ Effects of GRD and comparisons with ECCO are also discussed by Ponte et al. (2024; https://doi.org/10.1029/2024EA003661) in the context of the seasonal cycle. A discussion of how the current results relate to their findings would be useful to add in section 3.

Thank you. We have added more explicit comparisons between the DOM-ECCO residuals and the RL06.3-ECCO residuals, including a new figure in Appendix C and a Table 1 (shown above) in the main document:

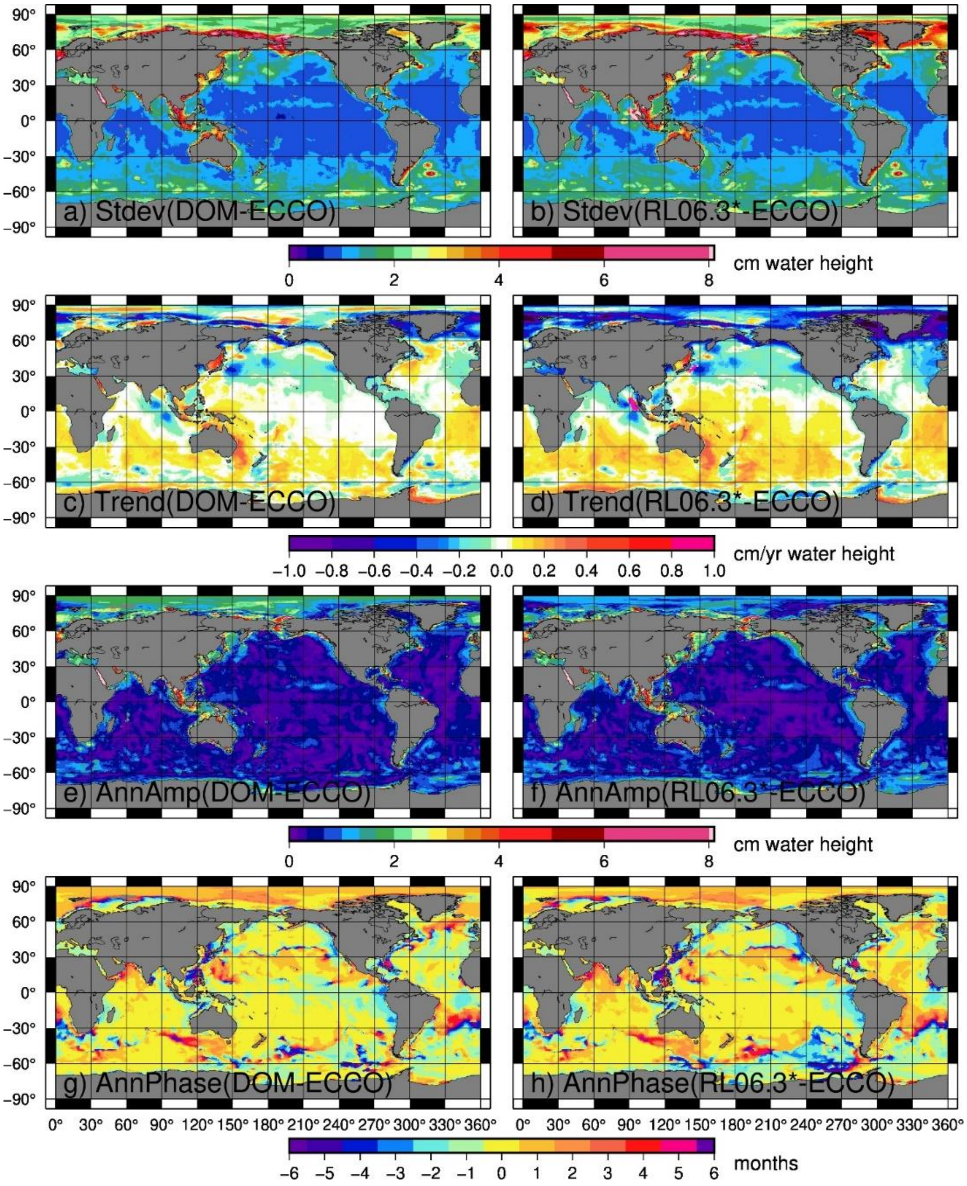

Figure C1: The differences between the DO mascons and ECCOv4r4 (left) compared to the difference between the CSR RL06.3 mascons and ECCOv4r4 (right), for the following statistics: standard deviation (a,d), linear trend (b,e), annual amplitude (c,f), and phase of the annual signal (d,g). The phase difference is given in months relative to the respective GRACE mascon annual phase.

The text throughout Section 3 (the comparisons with ECCO) has been reorganized and added to. Some of the most changed text now reads:

Maps of the differences between the DO mascons and ECCOv4r4, and between the RL06.3 comparison and ECCOv4r4, are shown in Appendix C, with only the averaged statistics given here.

Trend reductions across the Pacific Ocean are also visible. Most of this change is due to the removal of the barystatic-GRD signal, as opposed to the simpler technique of merely removing an ocean-wide mean for each month. Such changes are anticipated – for example, Ponte et al. (2024) demonstrated that incorporating a barystatic-GRD signal (their "GAL" or "Gravitational Attraction and Loading") improved the fit between the JPL GRACE mascons and ECCO over 56% of the ocean's area, and made particularly large improvements in coastal regions near large land/ice mass sources like Greenland and coastal Alaska, similar to what we see here.

Overall, we find that the DO mascon trends are generally both nearer to zero and more similar to ECCO than the RL06.3 trends are (Figure C1, Table 1), with an improvement of 0.022 cm yr^{-1} in the non-arctic open ocean (defined as ocean grids more than 300 km from land, exclusive of the Arctic Ocean and the regions involved in the earthquake modelling). In the Arctic Ocean, the trend reduction from RL06.3 is more pronounced: a difference of 0.28 cm yr^{-1}. Near the earthquakes, the change is 0.26 cm yr^{-1}. In all cases, these differences are larger than the trends in each area seen in ECCO alone, and in each area, the change drives the trends both closer to ECCO and closer to zero. We therefore assume that the trends of the DO mascons represent improvements over the RL06.3 trends with a uniform ocean mean removed.

Across the global oceans, the annual amplitude of the differences between the DO mascons and ECCOv4r4 is slightly smaller (0.61 cm) than the similar difference between the RL06.3 mascons and ECCO (0.66 cm). A similar 0.04 cm improvement exists in the open ocean, and a larger 0.25 cm improvement near the earthquakes (Table 1). The 2002-2017 phase of the annual (not shown) closely matches that of the 2002-2024 series (Fig 8e), which are also similar to phase maps found in the modern JPL and GSFC GRACE/FO mascons (Ponte et al., 2024), with phases consistent across latitudes through the Indian and Pacific Oceans, and the Atlantic and Arctic differing from both. In most places, the annual phase of the DO mascons is within half-month (±15°) of the ECCO state estimate (Fig C1g), though there are stripes of considerable phase variability throughout the ocean, where a simple annual amplitude difference may not fully explain the errors. However, phase differences of more than half a month typically occur in regions where the annual amplitude is small. The average absolute value non-Arctic, open-ocean phase difference from ECCO, in places with over 1 cm annual amplitude, is 0.36 months for the DO mascons versus 0.43 months for the RL06.3 mascons (Fig C1h). This suggests that the DO mascons improve the annual phase resolution in places where the annual signal is strongest.

In the Arctic, however, the amplitude of the residual annual signal is 0.19 cm smaller when differencing ECCO from RL06.3, than from the DO mascons (Figure C, Table 1), and the DO mascon phase there is slightly more offset from ECCO's as well (Figure C1g,h). We believe that this shows that the DO mascons capture an Arctic signal that is not represented in the ECCO model, rather than evidence of enhanced errors in the DO mascons over the standard CSR mascons. Previously, the ocean near the North Pole has been shown to have large seasonal mass variations and compare well between pressure gauges and early GRACE data (Peralta-Ferriz and Morison, 2010; Peralta-Ferriz et al., 2016), which are not well-estimated by ECCO. The ECCO state estimate peaks in June and decays rapidly thereafter, while the central-Arctic DO monthly climatological signal ramps up until June but remains high from then through October (Fig. 12). Considering the limited observations that ECCO runs can assimilate in the Arctic (compared to the rest of the ocean) and the fact that previous studies have shown strong agreement between bottom pressure recorders and GRACE, we assume this reflects a true ocean signal observed in the DO mascons that is not captured by ECCO, and captured less well by the standard RL06.3 CSR mascons.

Non-seasonal variability in the DO mascons has similar magnitude and locations as that seen in ECCO (Fig. 13), with the largest variability at high latitudes and lower values at the equator. The equatorial variance away from the coastlines ("open-equatorial" in the bottom of Table 1) is often used as a standard measure of the noise floor in the DO mascons. The level of high-frequency (non-annual) variability there should be quite small, with standard deviation well below 1 cm. Average ECCO open-equatorial RMS residuals are 0.68 cm (Fig. 13b, Table 1), confirming the approximate RMS of the expected signal. The DO mascons have a value 0.30 cm higher than this (average values 0.98 cm). Based on the residual of the DO mascons and ECCO (Fig 13c, Table 1), ~0.8 cm RMS is a reasonable approximation of the month-to-month uncertainty in the DO mascons. We do note, however, that this estimate could underestimate the errors, if the assimilation of GRACE/FO causes larger artificial similarities than we assume.

In reality, the uncertainty as measured by comparison with ECCO varies with region, with differences larger at higher latitudes due to greater ocean model uncertainty, near coastlines (especially Arctic/Antarctic ones) due to GRACE/FO ice/land leakage, and near the major earthquakes due to earthquake model uncertainty. Based on the differences with ECCO (Table 1), we estimate DO mascon uncertainties near the earthquakes to be 1.42 cm (much smaller than the RL06.3 uncertainties of 3.32 cm). The Arctic area uncertainties for the DO mascons are found to be 2.04 cm (compared to a similar 2.06 for RL06.3). These differences with ECCO represent an expected upper bound on the DO mascon uncertainties, because they include any errors in the state estimate as well as the GRACE/FO errors. For example, we suspect the Arctic uncertainties to be overstated, because we anticipate that a large part of the differences in the Arctic are due to missing signal in ECCO. Another signal seen in the DO mascons and not ECCO is the high variability in the Argentine basin east of Brazil (Fig. 13), which has a known, sub-annual barotropic variation (Fu, 2007; Hughes et al., 2007; Yu et al., 2018). It is greatly damped in ECCO (and the ocean dealiasing product used for GRACE/FO processing), but is recovered better by GRACE/FO mascons, both the original and the DO versions. In locations such as this, the difference between ECCO and the mascons will overstate the DO uncertainties.

8/ Capitalize "arctic" here and elsewhere when referring to region, ocean, etc.

Done.

50/ Sounds too "assertive". You have tried to remove non-oceanographic signals from earthquakes, but not all earthquakes. Moreover, there are possibly other non-oceanographic signals (e.g., Mandea et al. 2015; https://doi.org/10.1002/2015JB012048) that are ignored in this work. While outside the scope of this paper, these signals could be mentioned to provide broader context.

We have altered the text to read:

To improve the utility of GRACE/FO data for oceanographic applications, we have created a set of gridded mascons where the largest known non-oceanographic geodetic signals have been explicitly removed, such that the remaining ocean mass variability is predominantly driven by ocean circulation changes.

We are aware of the potential for deep-earth signals to contaminate ocean signal in the mascons. We elect not to discuss this complex topic in the introduction, but instead cover it a few paragraphs later (see line 118 comment response), and also extend the line in the discussion section concerning it instead. The discussion section now reads:

> Thus, we conclude that the bottom pressure trend observed in all GRACE (and presumably GRACE-FO) data in the northeast Atlantic cannot be oceanographic in nature. It is beyond the scope of this study to determine what could be responsible for the signal, but we suspect it is more likely a solid earth gravity signal that deserves further investigation, potentially a mass redistribution signal from inside the mantle (Gouranton, 2025) or along the core-mantle boundary (Mandea, 2015).

52/ Define mascon at first mention (line 36?).

Done.

80/ Define ECCOv4r4.

Done, and the relevant citation was pointed to there also.

118-119/ This statement also seems too assertive (see comment on line 50).

Our apologies. The line now reads:

> This removes the most visible solid earth signal in the ocean mascons, though we note that residual signal from these earthquakes and signal from other quakes remains in the DO mascons, as do other types of deeper solid earth mass signals (Mandea et al., 2015; Gouranton et al., 2025). By removing these few quakes by a simple model, as described in Section 2.3, we remove a large fraction of the ocean-area signal that is not related to oceanographic processes.

139/ Define ellipsoid correction.

This is explained a few paragraphs later in Section 2.1. We have now added a note expressly pointing to Section 2.1 on this earlier line.

135/ What "idea across"? Too colloquial? It would be more informative to say that the approximation is good to within some percentage number or something equivalent.

Done. The new wording is:

The equation is not exact due to changes in regularization weights, masking, geocenter updates, and implementation of the ellipsoid correction (Section 2.1). The globally-averaged RMS error (RMSE) relative to the real DO mascons (weighted by latitude) is 0.49 cm. Much of that is due to large differences near the modeled earthquakes (RMSE > 15 cm; see Section 2.3) and in the Arctic near Franz Josef Land (RMSE > 4 cm; see Section 2.2). Coastal RMSE are typically 0.5-2.0 cm. Open ocean (exclusive of the Arctic and earthquake zones) differences between the actual DO mascons and the approximation given by Equation 5 are 0.35 cm water height on average.

346-347/ Could be written more clearly.

The line has been altered to read:

The combined barystatic-GRD signal will not cause significant dynamic ocean signals, since redistribution of mass within the ocean occurs rapidly, leading ocean pressure to reach equilibrium (meaning negligible horizontal pressure gradients) far faster than the seasonal or longer timescale characteristic of barystatic-GRD effects (Ponte, 2006).

355/ Imprecise phrasing: pressure variations do not arise from geostrophic balance, instead they lead to geostrophic balance as currents driven by those pressure variations feel the Coriolis force in a rotating planet.

Thank you, you are correct. We have revised this section (based on several of your comments) to read:

A related signal arises from global ocean-area atmospheric pressure variations, seen as the average of the GAD product over the oceans (Fig. 7a, blue line). This signal is defined to be uniform over the ocean. Its inclusion in the standard mascons means that the standard mascons represent both internal ocean pressure variations (which drive geostrophic balance), GRD mass signals, and this atmospheric pressure variation. Because internal pressure variations should average out to zero, global averages of the standard mascons reflect a combination of GRD and this atmospheric pressure signal (e.g., Chambers & Schröter, 2011). We intend the DO mascons to reflect only the portions of the ocean pressure signal that impacts geostrophic balance, and thus remove both the barystatic-GRD signal and the mean atmospheric pressure signal over the global oceans, resulting in monthly global ocean mean values of zero at all times in the DO mascons (Fig. 7a, black line).

356/ "Because internal pressure variations should average out to zero,..."

Corrected.

Figure 7/ It is not easy to see the subtle differences in these panels. Perhaps showing a difference of trends and amplitudes can provide a better quantitative assessment of the importance of a spatially varying GRD vs spatially constant correction. The differences in annual amplitude can also miss possible differences coming from changes in phase. If

differences in phase are important, showing the root-mean-square difference of the annual cycles might be a better alternative.

We assume you mean Figure 8, not Figure 7? We agree that showing the difference between the plots is perhaps easier to read, and have done so. We also now include the phase plot.

Phase differences are mostly small (within a month), but not always. The DOM phases (Fig 8e) are similar to what Ponte 2024 saw in ECCO (more on that later). The changes in annual amplitudes and stdev(annual) signals are qualitatively similar to what they found also. We now cite that paper in the GRD discussion (and again later during the comparison with ECCO).

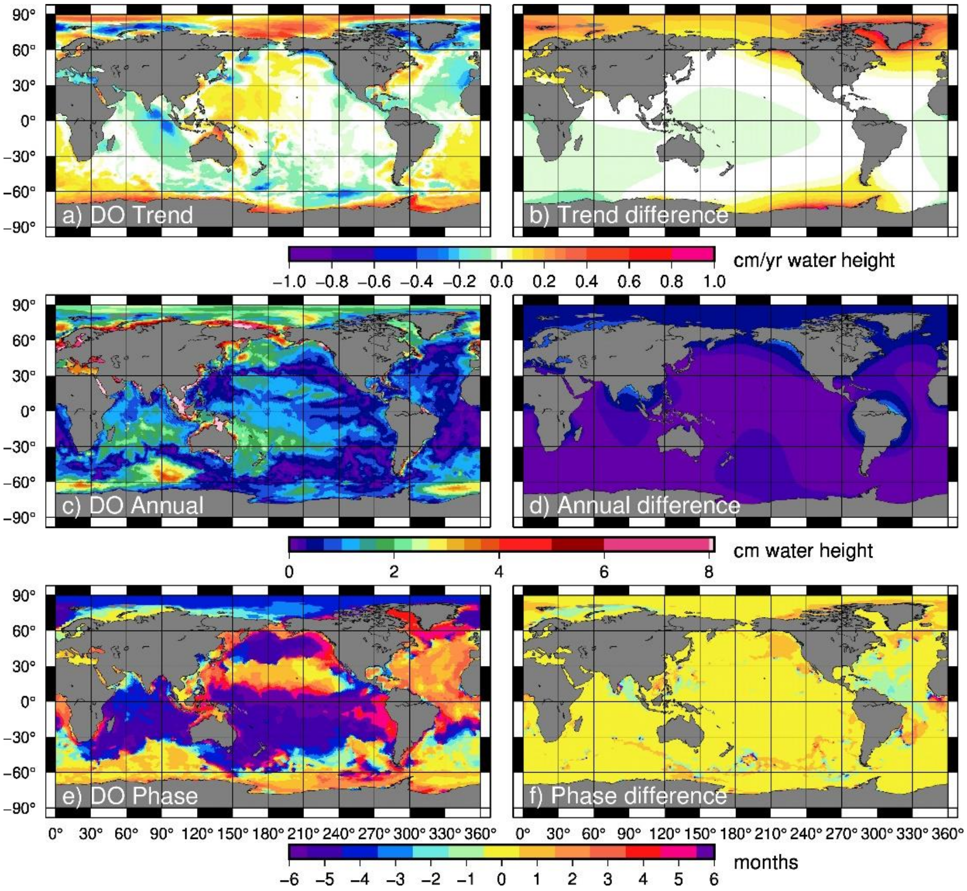

Figure 1: The 2002-2024 trends (a), annual amplitudes (c), and annual phases (e) of the DO mascons, compared to the changes away from a comparison case where a uniform global ocean average is removed rather than the GRD estimate (b, d, f). Phases in (e) are defined such that 0 refers to an annual maximum in January, and ±6 refers to a maximum in July. Phase differences in (f) are the number of months that the comparison series' phase is shifted away from the DOM phase.

The following text has been added in regards to the altered figure:

Previous studies have attempted to estimate such grids for ocean applications (Song & Zlotnicki, 2008; Chambers & Willis, 2009; Landerer et al., 2015) by removing a uniform ocean mass signal (i.e., the time series shown in Fig. 7a applied uniformly for each grid cell). In Fig. 8 (right), we depict the errors caused by removing such a uniform ocean mass signal to approximate from land/ice drainage, rather than removing the full barystatic-GRD estimate of ocean mass redistribution. These errors are a substantial fraction of the full DO mascon signal (Fig. 8, left) for the trend and annual amplitude, and (unsurprisingly) have the same spatial patterns as the GRD trend and annual amplitude (Fig. 7). Maximum trend differences are greater than 1 cm yr^{-1} just off the coast of Antarctica and Greenland (Fig. 8b), compared to local DO mascon trends less than half that size. Changes in the annual signal amplitude exceed 1 cm near the Amazon, the Ganges, and the Alaskan glaciers (Fig. 8d), similar to what Ponte et al. (2024) noted when using the recent JPL GRD estimate (Landerer and Wiese, 2025). While, in most places, changes in the phase of the annual signal (Fig. 8f) are less than a month, using a simplified uniform distribution instead of a true barystatic-GRD approach shifts the timing of the annual by a month or more over substantial fractions of the ocean. These differences are seen as non-oceanographic artifacts left in any GRACE/FO series that does not remove a barystatic-GRD estimate. By estimating and removing GRD from the DO mascons, we avoid such artifacts (Fig. 8a,c,e).

420-421/Remaining earthquake signals can be seen in side lobes away from the epicenter in both trend and rms plots (figure 6b,d). Is a linear trend the best model to remove? Some more insight into this would be useful for the user, including some discussion of why the current models seem to miss significant parts of the earthquake signal.

Sorry; you're right that we should explain this better, and not depend on people to read the earthquake model paper. We've added the following text in the document to explain this:

While the model used in the DO processing has removed most of the variance caused by the earthquakes near the epicenters, some trends remain in the northern Indian Ocean and the northwestern Pacific Ocean that are not entirely consistent with the larger-scale ocean trends in the area. These questionably large trends are most obvious 5-15° away from each earthquake epicenter, well outside the region of greatest impact, and explain a significant fraction of the DOM signal in these regions (over 70% of the signal west of the Andaman quakes, and 20-40% near Japan). Long-term signals, especially linear trends, are expected to be the least accurate part of the earthquake model (Bonin et al, 2025), because the EOF method used to construct the model cannot easily distinguish between a trend caused by ocean dynamic changes, a trend caused by solid-earth post-seismic motion of a prior earthquake, and a 'trend' which is really a sudden co-seismic jump during an earthquake. The majority of this confusion was treated during a pre-processing step to the earthquake modelling (Bonin et al., 2025), but we expect that some misappropriated long-term solid-earth signal remains in the DOM due to an imperfect earthquake fit. An unknown but probably large percentage of the near-earthquake DOM trends (and potentially other long-period signals) are likely to be residual long-wavelength solid earth signals not removed by the earthquake model. We recommend oceanographers working in these regions consider removing trends from the DO mascons and only use the residuals in their analysis. In the northern Indian ocean, west of the Andaman-Sumatra sequence of earthquakes, a smaller change in trend seems to occur after the final April 2012 quake, which some users may find beneficial to fit and remove locally as well. (This 2012 trend change will not impact the Japanese quake area, nor will the earthquake model trend uncertainty impact any area away from the earthquakes.)

428/ Define f/H.

Thanks. The line now reads:

…and closed potential vorticity (f/H) contours in the Southern Ocean.

459-463/ The Argentine basin issue has been noted and discussed before in several papers. Moreover, the DOM dataset does not bring anything new to this issue, as far as I can grasp from this brief discussion. I suggest deleting this text.

> We have revised that section so that (hopefully) the issue reads more as a known example, not anything new (which, we agree, it isn't).

512/ "…and the effect of global atmospheric pressure"

> Text altered.

516/ The text here reads "mascons are designed to be comparable to ocean models" but two lines below we have "mascons should not be compared to…models of ocean bottom pressure". Please rewrite more clearly.

> Sorry. The line has been amended to read:
>
> The dynamic ocean mascons should not be directly compared to ocean bottom pressure recorders or models of ocean bottom pressure (unless the impact of water mass addition to the ocean via barystatic-GRD has been considered).

Appendix/ Substantial text in the appendix is basically a repetition word for word of the main text. This is a bad practice and really unnecessary. All repeated text should be deleted.

> We have removed the two middle paragraphs that contained the repeated information. Sorry.

References/ Please double check your list for completeness. I could not find Pie et al. (2025), Ponte et al. (2018), Save (2019), Sun et al. (2016).

> Thanks. Corrected.

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Response to Reviewer 2:

Thank you for your helpful advice and questions . We have made changes to the text in response, and also wish to reply to each comment (repeated in bold-face) in turn:

The authors compare the DO dataset with ECCOv4.4. However, if I understand correctly, ECCOv4.4 already assimilates a version of GRACE/GRACE-FO data, but the ECCOv4.4 website does not indicate which. While the authors make efforts to ensure a consistent comparison (for example by removing atmospheric signals from ECCOv4.4), it would be helpful to briefly discuss the implications of ECCOv4.4 already assimilating GRACE ocean bottom pressure – likely a JPL mascon version.

I recommend that the authors add a brief explanation (max 2-3 sentences) describing, to the best of their knowledge, which GRACE product is assimilated in ECCOv4.4 and how this may affect the comparison presented in the manuscript. Clarifying this point would help readers better interpret the similarities or differences between the datasets. It would also likely make a stronger case for the use of this new product to be assimilated in modeling efforts like future versions of ECCO, which would likely yield an improved representation of the real world compared to what ECCOv4.4 and others currently do.

> Thank you. We are aware of the assimilation of GRACE data into ECCO, and have now added the following lines concerning that into the text:
>
> We want to note that ECCOv4r4 incorporates GRACE data as constraints to their bottom pressure estimates during their weighted-least-squares optimization process, in which they adjust boundary conditions, initial conditions, and model parameters to best minimize the model-minus-observation misfit. Due to this, there is some concern that the ocean bottom pressure estimates of ECCOv4r4 could be pulled towards GRACE by the optimization process itself, even if GRACE is more incorrect than the unconstrained model. Two facts convince us that a similarity with ECCOv4r4 is not merely an echoed recognition of GRACE's assimilation into the state estimate, however. First, the assimilation uses the 2002-2016 GRACE JPL RL05 mascon data, which is significantly different in both spatial resolution and detailed ocean statistics from our 2002-2024 CSR RL06-based DO mascons. Second, ECCOv4r4 also simultaneously assimilates millions of non-GRACE observations (ECCO Consortium, 2021), and the assimilation method finds the state variables that statistically optimize the residuals between all assimilated observations, not just GRACE. Thus, if ECCOv4r4 agrees with GRACE mascons, it means that the model physics and other (more numerous) observations were statistically consistent with the GRACE data, not that ECCOv4r4 is automatically adjusted toward GRACE. For example, the strong difference between ECCOv4r4 and our GRACE/FO DO maps in the eastern Atlantic (Figs. 9 and 10; discussed below) is an indication that the assimilation rejected the GRACE observations there as being inconsistent with the model physics and other observations and so did not significantly adjust the estimated result toward GRACE.

The manuscript would benefit from a brief mention of the density used for the conversion from pressure to water equivalent thickness. I recognize that the dataset itself already includes this information (i.e., 1025 kg/m^3) within the list of data attributes, but since this product is strongly targeting an oceanography audience, I think it would be relevant to mention this upfront in the manuscript.

We have added this clarification to the end of Section 2.0:

Like all other CSR GRACE/FO mascon products, mass changes estimated in the DO mascons are presented in units of equivalent water height, relative to the 2004-2009 DO mascon mean. A saltwater estimate of density (1025 kg m^{-3}) is used to compute the height (in cm) of water which, spread over a given area, which would equate to the mass anomaly observed by GRACE/FO.

The manuscript emphasizes that several sources of noise – such as earthquake signals and Arctic leakage effects – have been mitigated in this product. I appreciate the estimate of average uncertainty of ~0.8 cm equivalent water thickness for the DO product. However, it would be helpful if the authors could clarify whether this estimate refers to the global oceans or specifically to equatorial regions. In addition, could the authors provide an estimate of the uncertainty specific to the Arctic and subarctic regions? The improvement of the ocean bottom pressure product appears to be particularly significant in these areas, in addition to the lower-latitude regions with the earth-quake-related signals removed.

We have now provided much more information on the comparison with ECCO, including specific numbers about the Arctic, which led to a big reorganization of Section 3. The differences with ECCO are now shown in Figure C1, and averages over regions (including the Arctic) are in Table 1. Additionally, the following section now exists at the end of Section 3:

Non-seasonal variability in the DO mascons has similar magnitude and locations as that seen in ECCO (Fig. 13), with the largest variability at high latitudes and lower values at the equator. The equatorial variance away from the coastlines ("open-equatorial" in the bottom of Table 1) is often used as a standard measure of the noise floor in the DO mascons. The level of high-frequency (non-annual) variability there should be quite small, with standard deviation well below 1 cm. Average ECCO open-equatorial RMS residuals are 0.68 cm (Fig. 13b, Table 1), confirming the approximate RMS of the expected signal. The DO mascons have a value 0.30 cm higher than this (average values 0.98 cm). Based on the residual of the DO mascons and ECCO (Fig 13c, Table 1), ~0.8 cm RMS is a reasonable approximation of the month-to-month uncertainty in the DO mascons. We do note, however, that this estimate could underestimate the errors, if the assimilation of GRACE/FO causes larger artificial similarities than we assume.

In reality, the uncertainty as measured by comparison with ECCO varies with region, with differences larger at higher latitudes due to greater ocean model uncertainty, near coastlines (especially Arctic/Antarctic ones) due to GRACE/FO ice/land leakage, and near the major earthquakes due to earthquake model uncertainty. Based on the differences with ECCO (Table 1), we estimate DO mascon uncertainties near the earthquakes to be 1.42 cm (much smaller than the RL06.3 uncertainties of 3.32 cm). The Arctic area uncertainties for the DO mascons are found to be 2.04 cm (compared to a similar 2.06 for RL06.3). These differences with ECCO represent an expected upper bound on the DO mascon uncertainties, because they include any errors in the state estimate as well as the GRACE/FO errors. For example, we suspect the Arctic uncertainties to be overstated, because we anticipate that a large part of the differences in the Arctic are due to missing signal in ECCO. Another signal seen in the DO mascons and not ECCO is the high variability in the Argentine basin east of Brazil (Fig. 13), which has a known, sub-annual barotropic variation (Fu, 2007; Hughes et al., 2007; Yu et al., 2018). It is greatly damped in ECCO (and the ocean dealiasing product used for GRACE/FO processing), but is recovered better by GRACE/FO mascons, both the original and the DO versions. In locations such as this, the difference between ECCO and the mascons will overstate the DO uncertainties.

Averaging Area	ECCO v4r4	DO Mascons	RL06.3* Mascons	DO - ECCO	RL06.3* - ECCO
Standard Deviation over Time (cm)					
Global Oceans	1.63	1.88	2.02	**1.33**	1.49
Open Ocean	1.40	1.60	1.66	**1.12**	1.19
Arctic	3.27	3.52	3.88	**2.69**	3.26
Earthquakes	2.36	3.11	6.00	**1.88**	4.77
Linear Trends (cm yr^{-1})					
Global Oceans	0.00	0.00	0.00	0.00	**0.00**
Open Ocean	-0.01	0.00	0.02	**0.01**	0.04
Arctic	0.15	-0.02	-0.30	**-0.17**	-0.45
Earthquakes	-0.09	-0.14	0.11	**-0.05**	0.21
Annual Amplitudes (cm)					
Global Oceans	1.17	1.27	1.32	**0.61**	0.66
Open Ocean	0.97	0.96	1.01	**0.41**	0.45
Arctic	1.71	2.47	2.29	1.47	**1.28**
Earthquakes	2.40	2.81	3.05	**1.07**	1.32
Residual Standard Deviation over Time (cm)					
Global Oceans	1.21	1.45	1.52	**1.12**	1.18
Open Ocean	1.07	1.32	1.33	**1.00**	1.01
Open Equatorial	0.68	0.98	0.99	**0.81**	0.83
Arctic	2.79	2.69	2.75	**2.04**	2.06
Earthquakes	1.18	1.68	3.61	**1.42**	3.32

Table 1: Comparison of standard deviations, linear trends, annual amplitudes, and residual standard deviation (after the removal of trends, annuals, and semiannuals) of the ECCOv4r4, DO mascon, and CSR RL06.3 with mean ocean mass uniformly removed, as well as the same statistics for the differences between each mascon series and ECCOv4r4. The "open ocean" is defined as CSR ocean mascons more than 300 km, exclusive of the Arctic and earthquake regions. The "open equatorial" is defined as the subset of the "open ocean" within 30° of the equator. The "earthquakes" region is defined as the broader regions near Japan and Andaman Bay modelled in Bonin et al (2025).

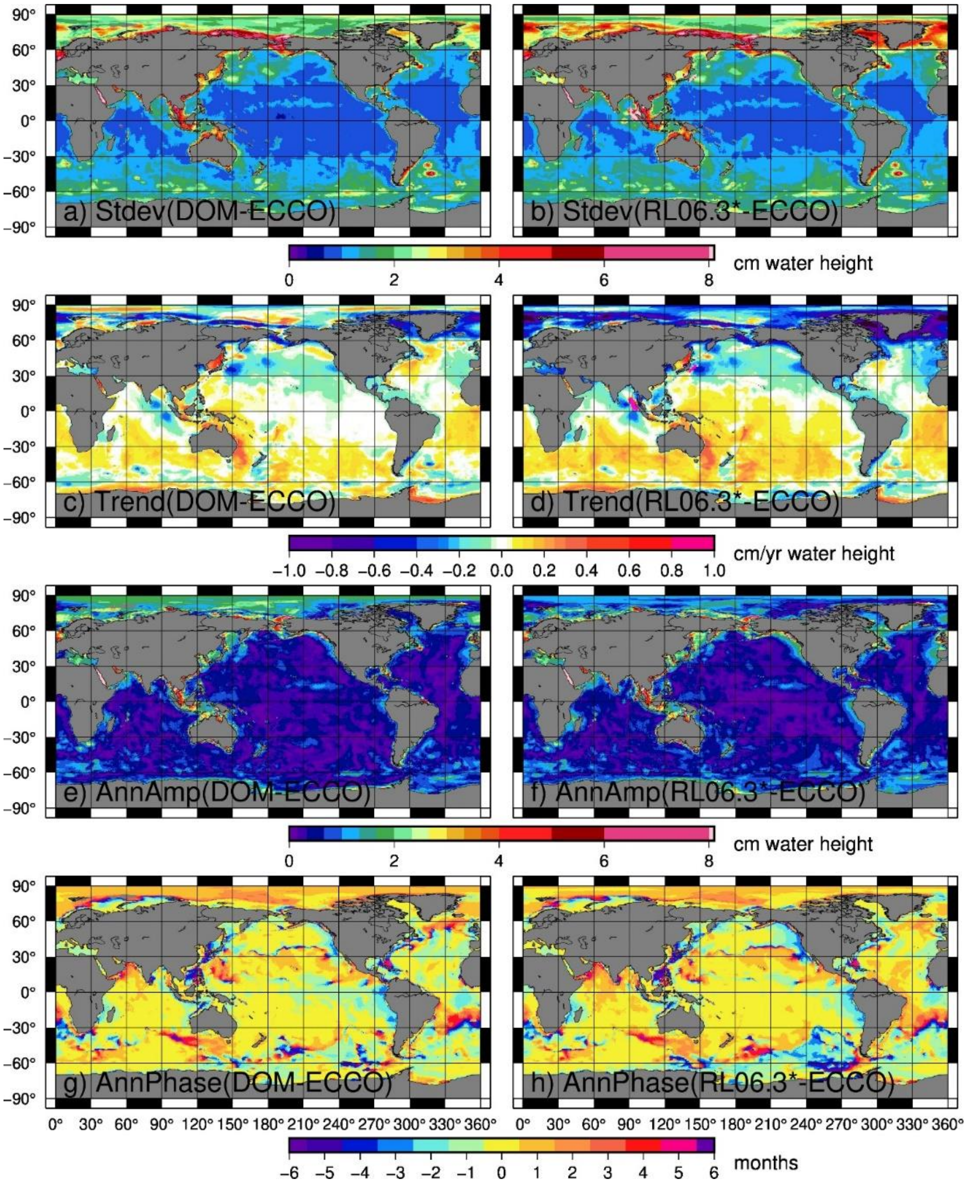

Figure C1: The differences between the DO mascons and ECCOv4r4 (left) compared to the difference between the CSR RL06.3 mascons and ECCOv4r4 (right), for the following statistics: standard deviation (a,d), linear trend (b,e), annual amplitude (c,f), and phase of the annual signal (d,g). The phase difference is given in months relative to the respective GRACE mascon annual phase.

Overall, this measure of uncertainty is broadly consistent with improvements reported in previous GRACE/-FO solutions. For example, JPL mascons RL05 report a global ocean average uncertainty of ~1cm after applying a Coastline Resolution Improvement filter by Wiese et al. (2016); CSR RL05 mascons consider a global average of 2cm by Save et al. (2016); and Chambers and Bonin (2012), find standard error of Rel05 spherical harmonics -based solution to be ~1cm in low-mid latitudes, and between 1.5-2cm in the polar and subpolar regions. Given the limited availability of multi-year in situ bottom pressure records, it is understandable that the uncertainty estimate relies on comparisons with ocean models.

However, as noted above, the ECCOv4.4 solution is not fully independent of GRACE data. I suggest that the authors include a brief cautionary note in the manuscript indicating that, because ECCOv4.4 assimilates GRACE, the estimated uncertainty of ~0.8 cm may not be entirely independent of the product being evaluated.

> Thank you. In addition to the longer explanation in regards to your first comment, we have also added a reminder concerning this in Section 3:
>
> We do note, however, that this estimate could underestimate the errors, if the assimilation of GRACE/FO causes larger artificial similarities than we assume.