GCL-Mascon2024: a novel satellite gravimetry mascon solution using the short-arc approach

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Responses to reviewers

Dear Chief Editor, topic editor, reviewers, and community,

On behalf of all authors, we express our great appreciation to the Chief Editor, topic editor, reviewers, and community for their constructive and valuable comments and suggestions on our manuscript entitled "GCL-Mascon2024: a novel satellite gravimetry mascon solution using the short-arc approach" [ESSD-2024-512].

We have carefully studied the comments from reviewers and the community and then tried our best to revise our manuscript according to their valuable suggestions. The black text denotes the comments, while the red text contains our responses. Modifications made to the manuscript in response to these comments are highlighted in red italics. Besides, all the revised parts are in red in the revised paper. Please find the revised version attached, which we would like to submit for your kind consideration.

Hope you can consider a possible publication. We are looking forward to hearing from you. Thank you very much.

Yours sincerely,

Jiangjun Ran

Anonymous Reviewer #1

Summary

This paper presents a novel satellite gravimetry mascon solution named GCL-Mascon2024 for recovering the mass changes on the Earth's surface, which is the first to implement the short-arc approach for Mascon solution estimation. I commend the authors for their novel approach and encourage them to continue refining and expanding upon this exciting methodology. The research findings are highly innovative and scientifically valuable and are of great significance for the research of the Earth's gravity field and the development of related fields. The paper has a complete structure, clear logic, reasonable experimental design, and detailed data, providing new ideas and methods for follow-up research. However, there is still room for improvement. I would like to recommend minor revisions of the manuscript before publication in Earth System Science Data, according to the comments as follows.

Response:

Thank you very much for your constructive comments on our manuscript. There is no doubt that these comments are valuable and very helpful for revising and improving our manuscript. We carefully modified the manuscript based on your comments and suggestions. Please kindly refer to the following text for more details. We are deeply grateful for your recognition and support of our work.

Comments

I would like to know whether the gradient correction, a well-established component of the classical short-arc approach, was incorporated into the Mascon solution process. If gradient correction was applied, I recommend the authors provide a detailed description of the strategy used. If gradient correction was not applied, the authors should justify this decision. This additional information would enhance the methodological transparency and allow readers to better evaluate the robustness of the proposed approach.

Response:

We sincerely appreciate your constructive comments. We have modified the main text to clarify the use of the gradient correction algorithm. Please kindly refer to the following text (Lines 276-284 in the revised manuscript).

To determine the appropriate arc length for GCL-Mascon2024, we conducted computations of a monthly mascon model using different arc lengths to compare the stability of the resulting estimates. Table 2 presents the condition numbers of the unconstrained normal matrices and the corresponding computational time needed for different arc lengths. From this standpoint, the 2-hr arc length corresponds to the most stable arc length in the GCL-Mascon2024 recovery. Figure 4 illustrates that increasing the arc length beyond 2 hr in the short-arc approach leads to a significant increase in noise in gravity field estimates as the normal equations become more ill-conditioned. This observation aligns closely with what we conclude from Table 2. Therefore, an arc length of 2-hr is determined to be the most suitable for the short-arc approach employed in this work. Additionally, we incorporate the gradient correction algorithm proposed by Mayer-Gürr (2008) to consider the influence of the kinematic orbit errors.

Reference

Mayer-Gürr, T.: Gravitationsfeldbestimmung aus der Analyse kurzer Bahnbögen am Beispiel der Satellitenmissionen CHAMP und GRACE, Rheinische Friedrich-Wilhelms-Universität Bonn, Landwirtschaftliche Fakultät, IGG-Institut für Geodäsie und Geoinformation, 2008.

The noise of GCL-Mascon2024 in the Caspian Sea and northern Australia is very low. This is an intriguing result that warrants further investigation. It is advisable to conduct an in-depth analysis centering around the Caspian Sea, highlighting the performance of your solution and improving the analysis.

Response:

We sincerely appreciate your valuable comments. Following your suggestion, we have explained an in-depth analysis centering around the Caspian Sea in the revised manuscript (Lines 496-509). Please kindly refer to the following text for more details.

The utilization of mass variations in large lakes (e.g., the Caspian Sea) to assess noise levels in GRACE solutions is a well-established approach (e.g., Loomis and Luthcke, 2017; Ditmar, 2022). Herein, we choose the largest lake on Earth, the Caspian Sea, as *an example for verification. We follow the approach proposed by Ditmar (2022), wherein the mass anomaly time series derived from GRACE is compared with the water level time series obtained from satellite altimetry observations. The latter time series is empirically rescaled (with a scaling factor of 0.687 for the Caspian Sea provided by Ditmar (2022)) to account for signal damping in the GRACE solution. Figure 12 presents the mass anomaly time series over the Caspian Sea derived from various mascon solutions and satellite altimetry data. As illustrated, the GCL-Mascon2024 solution shows strong consistency with the other models in capturing mass variations in this region. Using satellite altimetry-derived mass variations, scaled by a factor of 0.687, as the reference, the noise SD for the GSFC, CSR, JPL, and GCL-Mascon2024 mascon solutions are 5.7 cm, 5.8 cm, 5.6 cm, and 5.2 cm, respectively.*

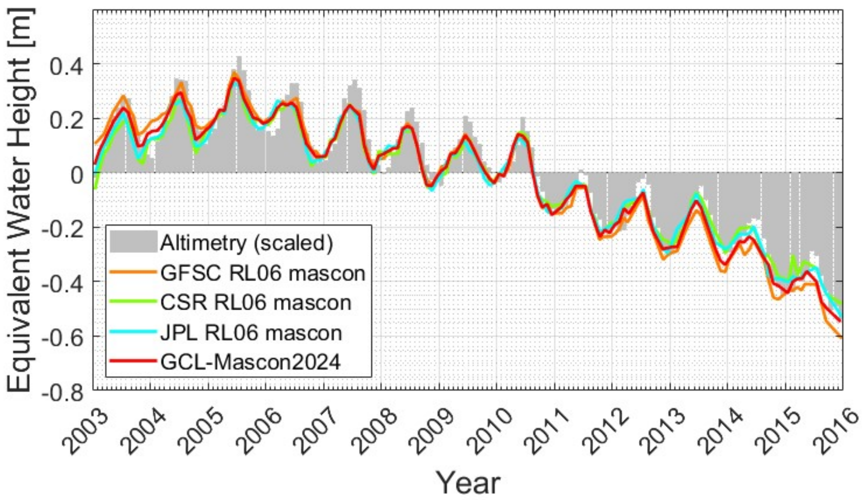

Figure 12. Comparison of GRACE-derived mass anomaly time series (expressed in equivalent water height, EWH) from different mascon solutions with satellite altimetry-based water level variations over the Caspian Sea. The time series derived from satellite altimetry has been downscaled using a scale factor of 0.687 to account for signal attenuation (Ditmar, 2022).

It is recommended to add comparisons of the residuals in the open ocean.

Response:

We sincerely appreciate your valuable comments. Following your suggestion, we have supplemented the comparison in the time series of ocean mass. Please kindly refer to the following text (Lines 510-517 in the revised manuscript) for more details.

GRACE satellite gravity measurements over oceanic regions directly correspond to ocean bottom pressure variations at spatial scales of ~300 km (Watkins et al., 2015).

Figure 13 illustrates the time series of basin mass variations derived from different mascon solutions. To assess the quality of our solutions for ocean signals, we compute the correlation coefficients between GCL-Mascon2024 and the RL06 mascon solutions released by GSFC, CSR, and JPL. The resulting correlations are 95.7%, 98.0%, and 98.2%, respectively, indicating a high level of consistency between our products and official mascon products.

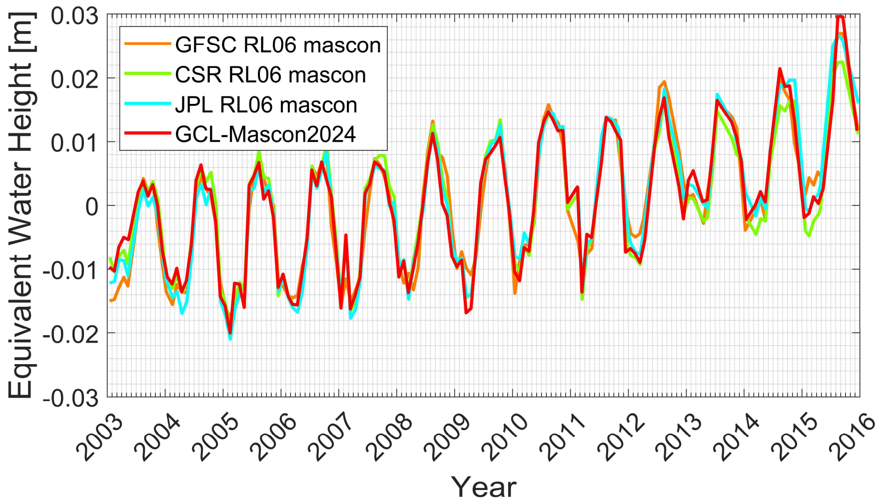

Figure 13. Comparison of GRACE-derived mass anomaly time series (expressed in equivalent water height, EWH) over the global sea from different mascon solutions.

Reference

Watkins, M. M., Wiese, D. N., Yuan, D.-N., Boening, C., and Landerer, F. W.: Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons, Journal of Geophysical Research-Solid Earth, 120, 2648-2671, https://doi.org/10.1002/2014jb011547, 2015.

Please clarify the time interval used for constructing the observation equation, particularly in light of the differing sampling rates between the kinematic orbit (10 seconds) and other L1B data (5 seconds). Specifically, address how these discrepancies in sampling rates are reconciled.

Response:

We sincerely appreciate your valuable comments. As your comments pointed out, the kinematic orbit sample rate is different from the other L1B data. The integration time interval is 5 seconds for the observation equation using the rangerate observation, while the integration time interval of the observation equation based on the orbit is the same as the kinematic orbit sample rate. The purpose of this strategy is to include as much rangerate data as possible into the GCL-Mascon2024 temporal gravity field determination.

Kindly provide a detailed explanation of the error assessment strategy employed for the kinematic orbits. This should include the following: -The criteria used to identify and classify errors, -Whether interpolated epochs are incorporated into constructing the observation equation, etc.

Response:

We sincerely appreciate your valuable comments. It is well-established that kinematic orbits contain a lot of gross errors. Firstly, we use the Pauta criterion to give a quality flag to the kinematic orbit. The gross error data quality mark is 0, and the normal data quality mark is 2. Secondly, as for the gap in the kinematic orbits, we fill the gap with the reduced dynamic orbit (i.e., GNV1B data), and its quality mark is 1. Lastly, different weights are assigned to orbit data with different quality tags to construct the observation equation: 2 corresponds to the maximum weight, 1 to an intermediate weight, and 0 to the minimum weight.

Minor comments

Page 3, Lines 93-95: Section 5 is information on the dataset, and section 6 is the conclusion. These two parts are reversed in the text. Please adjust the order to ensure consistency.

Response:

We sincerely appreciate your valuable comments. We have adjusted the order of sections 5 and 6 in the revised version of the manuscript (Lines 99-101 in the revised manuscript).

Page5, Line 157, Table 1: Please explain the similarities and differences between the background force model in the Mascon solution and the spherical harmonic solution.

Response:

We sincerely appreciate your valuable comments. Both the Mascon and spherical harmonic solutions utilize identical background force models during the processing of Level-1B data. These shared models include the solid (pole) Earth and ocean (pole) tides, nontidal atmosphere and ocean dealiasing, Atmospheric tides, third-body attractions, and general relativity. The consistency in these foundational models ensures that both approaches adhere to the same standards for gravity field recovery. While the core background force models remain aligned, the Mascon solution requires five additional corrections to account for specific geophysical and geometric effects not inherently resolved by the unfiltered spherical harmonic approach:

(1) Earth’s Elastic Response

Mascon solutions explicitly incorporate the elastic response of the solid Earth to surface mass redistribution. This correction accounts for instantaneous crustal deformation induced by surface loading, which is critical for isolating true mass signals from geometric displacements.

(2) Glacial Isostatic Adjustments

GIA correction is applied to mitigate the viscoelastic rebound of the Earth's mantle due to Pleistocene deglaciation. This long-term signal, often conflated with contemporary mass changes in gravity solutions, is explicitly modeled and removed in Mascon recovery.

(3) Earth Ellipsoidal Corrections

The Earth's oblate shape necessitates ellipsoidal corrections to accurately represent mass anomalies on the reference ellipsoid rather than a spherical surface. These geometric adjustments ensure consistency with the Earth's true gravitational potential field.

(4) Low-degree Term Corrections

Mascon solutions apply targeted corrections to low-degree spherical harmonic terms (e.g., degree-1 and degree-2 coefficients) to address systematic errors arising from satellite orbit parameterization and reference frame uncertainties.

(5) GAD Corrections

To explicitly contain seafloor pressure anomalies in the corrected mascon solutions, the AOD1B RL06 GAD product (Dobslaw et al., 2017) is reintegrated into the mascon calibration framework.

Following a standardized processing workflow (Watkins et al., 2015; Save et al., 2016; Loomis et al., 2019; Tregoning et al., 2022), the uncorrected mascon solutions (i.e., $\mathrm{MASCON}_{Uncorrected}$, we will return to that point in Sect. 2.5) are systematically integrated with the aforementioned corrected components to generate corrected mascon grids. The formula to generate the corrected mascon grid is

$$\mathrm{MASCON}_{Corrected} = \mathrm{MASCON}_{Uncorrected} - \mathrm{MASCON}_{C_{20}} + \mathrm{SLR}_{C_{20}} + \mathrm{DEG1} - \mathrm{GIA} + \mathrm{GAD}\,. \quad (4)$$

Reference

Dobslaw, H., Bergmann-Wolf, I., Dill, R., Poropat, L., Thomas, M., Dahle, C., Esselborn, S., Koenig, R., and Flechtner, F.: A new high-resolution model of non-tidal atmosphere and ocean mass variability for de-aliasing of satellite gravity observations: AOD1B RL06, Geophysical Journal International, 211, 263-269, https://doi.org/10.1093/gji/ggx302, 2017.

Loomis, B. D., Luthcke, S. B., and Sabaka, T. J.: Regularization and error characterization of GRACE mascons, Journal of Geodesy, 93, 1381-1398, https://doi.org/10.1007/s00190-019-01252-y, 2019.

Save, H., Bettadpur, S., and Tapley, B. D.: High-resolution CSR GRACE RL05 mascons, Journal of Geophysical Research-Solid Earth, 121, 7547-7569, https://doi.org/10.1002/2016jb013007, 2016.

Tregoning, P., McGirr, R., Pfeffer, J., Purcell, A., McQueen, H., Allgeyer, S., and McClusky, S. C.: ANU GRACE Data Analysis: Characteristics and Benefits of Using Irregularly Shaped Mascons, Journal of Geophysical Research-Solid Earth, 127, https://doi.org/10.1029/2021jb022412, 2022.

Watkins, M. M., Wiese, D. N., Yuan, D.-N., Boening, C., and Landerer, F. W.: Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons, Journal of Geophysical Research-Solid Earth, 120, 2648-2671, https://doi.org/10.1002/2014jb011547, 2015.

Page12, Line 320: annual amplitude -> annual amplitudes

Response:

We sincerely appreciate your valuable comments. We have corrected this typo in the revised version of the manuscript (Line 338 in the revised manuscript).

Page 16, Table 5: The table currently presents with four decimal places. However, such precision does not appear necessary for this study's context. To improve clarity and readability, it is recommended to round the values to 1 decimal place or, at most, 2 decimal places.

Response:

We sincerely appreciate your valuable comments. As recommended, we have revised Table 5 by rounding all numerical values to two decimal places. Please kindly refer to the revised manuscript (Line 405) for more details.

Page 19, Table6: Similar to the above comment. Please revise the table 6 accordingly.

Response:

We sincerely appreciate your valuable comments. Following your suggestion, we have revised Table 6 by rounding all numerical values to two decimal places. Please kindly refer to the revised manuscript (Line 481) for more details.

Page 18, section 4.2.3: Please explain why the climate component needs to be removed from the desert for the Mascon solutions validation and assessment and add the necessary references.

Response:

We sincerely appreciate your valuable comments. We have supplemented the reasons why the climate component needs to be removed from the desert. Please kindly refer to the following text (Lines 448-452 in the revised manuscript) for more details.

Our impetus stems from an understanding that precipitation within desert regions is limited. It is critical to emphasize that aridity cannot be equated with negligible temporal mass variations (e.g., Scanlon et al., 2022). Conversely, low precipitation may stimulate an extensive consumption of groundwater. To that end, the residuals, calculated after removing the climatological components (i.e., bias, trend, and amplitude) from the mass variations, can be regarded as mis-modeling signals or temporal noise that persist in the temporal gravity fields (e.g., Zhou et al., 2024).

Reference

Scanlon, B. R., Rateb, A., Anyamba, A., Kebede, S., MacDonald, A. M., Shamsudduha, M., Small, J., Sun, A., Taylor, R. G., and Xie, H.: Linkages between GRACE water storage, hydrologic extremes, and climate teleconnections in major African aquifers, Environmental Research Letters, 17, https://doi.org/10.1088/1748-9326/ac3bfc, 2022.

Zhou, H., Zheng, L., Li, Y., Guo, X., Zhou, Z., and Luo, Z.: HUST-Grace2024: a new GRACE-only gravity field time series based on more than 20 years of satellite geodesy data and a hybrid processing chain, Earth System Science Data, 16, 3261-3281, https://doi.org/10.5194/essd-16-3261-2024, 2024.

Page 20, section 6: I recommend including the access dates for all datasets, which ensures readers and future researchers can trace the exact versions of the data used in the study.

Response:

We sincerely appreciate your valuable comments. Following your suggestion, we have supplemented the access dates for all datasets. Please kindly refer to the following text (Line 551 in the revised manuscript).

All datasets used in this study were last accessed on 25 May 2025. The specific data repositories include: …

P25, Lines 794-796: The manuscript generally maintains a high referencing standard; however, I noticed inconsistencies in the formatting of author names in the reference list. e.g., in Line 794, the author is cited as "Wiese, D.," while in Line 796, the same author is cited as "Wiese, D. N.". I recommend carefully reviewing the entire reference list and standardizing the formatting of author names.

Response:

We sincerely appreciate your valuable comments. Following your suggestion, we have thoroughly reviewed the entire reference list and corrected all inconsistencies in the formatting of author names. Please kindly refer to the revised manuscript for more details.