

Multi-approach gravity field models from Swarm GPS data

Signal and error in the Swarm models up to 2022-09-30

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Contents

| | | |
|----------|--|-----------|
| 1 | Version history | 5 |
| 2 | Introduction | 6 |
| 3 | Source data | 6 |
| 4 | Methodology | 6 |
| 4.1 | Combination | 6 |
| 4.2 | Validation | 7 |
| 5 | Results | 10 |
| 5.1 | Spatial analysis | 10 |
| 5.2 | Temporal analysis | 13 |
| 5.3 | Low-degree zonal coefficients | 18 |
| 5.4 | Monthly models | 19 |
| 5.5 | Time series of storage catchments | 21 |
| 5.6 | Temporal variability | 39 |
| A | Kinematic Orbits | 39 |
| A.1 | Delft University of Technology | 39 |
| A.2 | Astronomical Institute of the University of Bern | 40 |
| A.3 | Institute of Geodesy Graz | 40 |
| A.4 | Common | 41 |
| B | Gravity Field Models | 41 |
| B.1 | Astronomical Institute of the University of Bern | 41 |
| B.2 | Astronomical Institute Ondřejov | 42 |
| B.3 | Institute of Geodesy Graz | 42 |
| B.4 | Ohio State University | 42 |
| B.5 | Common | 43 |
| | References | 45 |

List of Figures

| | | |
|---|--|----|
| 1 | Monthly Satellite Laser Ranging (SLR)-derived C_{20} from Loomis and Rachlin (2020) (TN-14), compared to Cheng and Ries (2018) (TN-11) and Cheng and Ries (2019) (CSR-RL06, from Gravity Recovery And Climate Experiment (GRACE)/GRACE Follow On (GRACE-FO)). | 7 |
| 2 | Deep ocean mask. | 8 |
| 3 | Temporal variability of the GRACE/GRACE-FO climatological model, including the boundaries of the regions analysed in Section 5.5.1 to Section 5.5.18. | 9 |
| 4 | Per-degree mean of the RMS difference (top) and cumulative degree-mean temporal RMS difference (bottom) between the Swarm Gravity Field Models (GFMs) and GRACE, considering 750km Gaussian smoothing. This is (an estimate of) the average per-degree quality of the various Swarm solutions in the spectral domain (top) and globally (bottom). The degree amplitudes remain relatively constant with increasing degree, instead of growing in terms of Equivalent Water Height (EWH), as the result of the smoothing. | 10 |

| | | |
|----|---|----|
| 5 | Epoch-wise cumulative spatial RMS (top) and its global average (bottom) of the difference between Swarm GFMs and GRACE, over land areas, considering 750km Gaussian smoothing. This is (an estimate of) the evolution of the ability of the various Swarm solutions to predict land mass transport processes over time (top) and its global sum (bottom). The Swarm combined model (RL01) includes the new version of the IfG and ASU individual solutions only after December 2021; this is the reason why the combined model is not below these individual solutions before 2020. | 11 |
| 6 | Epoch-wise cumulative spatial RMS (top) and its global sum (bottom) of the difference between Swarm GFMs and GRACE, over ocean areas, considering 750km Gaussian smoothing. This is the epoch-wise quality of the Swarm GFMs, and reported in the header of the combined GFMs files. The Swarm combined model (RL01) includes the new version of the IfG and ASU individual solutions only after December 2021; this is the reason why the combined model is not below these individual solutions before 2020. | 12 |
| 7 | Per-degree mean (top) and its overall cumulative (bottom) of the correlation coefficient between Swarm GFMs and GRACE, over land areas, considering 750km Gaussian smoothing. The temporal correlation at every Stokes coefficient is computed and the average over each degree is plotted at the top. It illustrates how well the temporal variations of the Swarm models agree with what is predicted from the GRACE/GRACE-FO climatological model. | 13 |
| 8 | Per-degree mean (top) and its overall cumulative (bottom) of the correlation coefficient between Swarm GFMs and GRACE, over ocean areas, considering 750km Gaussian smoothing. It illustrates that the Swarm models agree poorly with the mass variations over the ocean as predicted by the GRACE/GRACE-FO climatological model. | 14 |
| 9 | Per-degree mean (top) and its overall cumulative (bottom) of the correlation coefficient between Swarm and GRACE/GRACE-FO GFMs (not the GRACE/GRACE-FO climatological model), globally and with no smoothing. It illustrates that the Swarm models fail to represent the same temporal variations as GRACE/GRACE-FO above degree 15-20. | 15 |
| 10 | Per-coefficient RMS difference between Swarm GFMs and GRACE considering 750km Gaussian smoothing, over land (left column) and ocean (right column) areas, for AIUB, ASU, IfG, OSU and combined solutions (respectively from top to bottom). | 16 |
| 11 | Per-coefficient correlation coefficient between Swarm GFMs and GRACE considering 750km Gaussian smoothing, over land (left column) and ocean (right column) areas, for AIUB, ASU, IfG, OSU and combined solutions (respectively from top to bottom). | 17 |
| 12 | Time series of the C_{20} (top) and C_{30} (bottom) coefficients, showing coefficients in the Swarm and GRACE/GRACE-FO GFMs. The statistics in the legend consider GRACE as reference. | 18 |
| 13 | Monthly degree-RMS for Q2 of 2022, all individual and combined Swarm solutions, as well as GRACE/GRACE-FO (no smoothing). | 19 |
| 14 | Monthly degree-RMS for Q3 of 2022, all individual and combined Swarm solutions, as well as GRACE/GRACE-FO (no smoothing). | 20 |
| 15 | Time series of EWH for the Amazon basin (latitude -17 to 3 degrees, longitude -76 to -47 degrees). | 21 |

| | | |
|----|--|----|
| 16 | Time series of EWH for the Orinoco basin (latitude -3 to 12 degrees, longitude -72 to -59 degrees). | 22 |
| 17 | Time series of EWH for the La Plata basin (latitude -34 to -19 degrees, longitude -65 to -50 degrees). | 23 |
| 18 | Time series of EWH for the Mississippi basin (latitude 29 to 44 degrees, longitude -101 to -80 degrees). | 24 |
| 19 | Time series of EWH for the Columbia region (latitude 38 to 50 degrees, longitude -125 to -110 degrees). | 25 |
| 20 | Time series of EWH for the Alaska (latitude 56 to 65 degrees, longitude -151 to -129 degrees). | 26 |
| 21 | Time series of EWH for the Western Greenland region (latitude 60 to 85 degrees, longitude -60 to -37 degrees). | 27 |
| 22 | Time series of EWH for the Danube basin (latitude 43 to 48 degrees, longitude 13 to 28 degrees). | 28 |
| 23 | Time series of EWH for the Western Sub-Saharan basin (latitude 5 to 15 degrees, longitude -15 to -1 degrees). | 29 |
| 24 | Time series of EWH for the Eastern Sub-Saharan basin (latitude 1 to 13 degrees, longitude -8 to 35 degrees). | 30 |
| 25 | Time series of EWH for the Congo and Zambezi basins (latitude -23 to -3 degrees, longitude 14 to 38 degrees). | 31 |
| 26 | Time series of EWH for the Volga basin (latitude 53 to 61 degrees, longitude 34 to 56 degrees). | 32 |
| 27 | Time series of EWH for the Siberia region (latitude 57 to 72 degrees, longitude 68 to 109 degrees). | 33 |
| 28 | Time series of EWH for the Ganges-Brahmaputra basin (latitude 15 to 30 degrees, longitude 72 to 89 degrees). | 34 |
| 29 | Time series of EWH for the Indochina region (latitude 12 to 29 degrees, longitude 93 to 105 degrees). | 35 |
| 30 | Time series of EWH for the Northern Australia region (latitude -24 to -10 degrees, longitude 124 to 145 degrees). | 36 |
| 31 | Time series of EWH for the Western Antarctica region (latitude -80 to -70 degrees, longitude -140 to -85 degrees). | 37 |
| 32 | Time series of EWH for the Eastern Antarctica region (latitude -80 to -68 degrees, longitude 80 to 130 degrees). | 38 |
| 33 | Temporal variability of the Swarm combined solutions. | 39 |

List of Tables

| | | |
|---|---|----|
| 1 | Overview of the gravity field estimation approaches | 6 |
| 2 | Versions of the GFMs, and the Kinematic Orbits (KOs) used in their estimation, relevant to this report. | 6 |
| 3 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Amazon basin. | 21 |
| 4 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Orinoco basin. | 22 |
| 5 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the La Plata basin. | 23 |
| 6 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Mississippi basin. | 24 |

| | | |
|----|---|----|
| 7 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Columbia region. | 25 |
| 8 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Alaska. | 26 |
| 9 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Western Greenland region. | 27 |
| 10 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Danube basin. . | 28 |
| 11 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Western Sub-Saharan basin. | 29 |
| 12 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Eastern Sub-Saharan basin. | 30 |
| 13 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Congo and Zambezi basins. | 31 |
| 14 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Volga basin. . . | 32 |
| 15 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Siberia region. . . | 33 |
| 16 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Ganges-Brahmaputra basin. | 34 |
| 17 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Indochina region. | 35 |
| 18 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Northern Australia region. | 36 |
| 19 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Western Antarctica region. | 37 |
| 20 | Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Eastern Antarctica region. | 38 |
| 21 | Statistics of the agreement between the GRACE and Swarm time series for the regions displayed in Sections Section 5.5.1 to Section 5.5.18. | 39 |

1 Version history

Version 1, 2023-01-01

- Validation of combined models version 09, from start of mission until 2022-09-30.

2 Introduction

We report some statistics of the individual and combined GFMs produced on the context of the *Multi-approach gravity field models from Swarm GPS data* project. The approach for combining individual gravity field solutions, i.e. those produced by the various partners mentioned in Section 3, is described in Section 4.1. The procedure and assumption used to derive the statistics is described in Section 4.2. Finally, the results are presented in Section 5.

This report does not intend to draw conclusions regarding the presented statistics, it is merely a descriptive document of the signal and error in the individual and combined Swarm GFMs. For this reason, the text in Section 5 is restricted to clarifying the quantities shown in the plots.

3 Source data

The individual gravity field solutions are produced by the institutes listed in Table 1.

Table 1 – Overview of the gravity field estimation approaches

| Inst. | Approach | Reference |
|-------|------------------------------------|---------------------------------|
| AIUB | Celestial Mechanics Approach | Jäggi et al. (2016) |
| ASU | Decorrelated Acceleration Approach | Bezděk et al. (2016) |
| IfG | Short-Arcs Approach | Zehentner and Mayer-Gürr (2016) |
| OSU | Improved Energy Balance Approach | Guo et al. (2015) |

Additional details about the different gravity field approaches can be found in (Teixeira da Encarnação and Visser, 2017).

The version of the individual GFMs is listed in Table 2.

Table 2 – Versions of the GFMs, and the KOs used in their estimation, relevant to this report.

| Gravity Field Model | version | Kinematic Orbit |
|---------------------|---------|-----------------|
| AIUB | 01 | AIUB |
| ASU | 02 – 03 | IfG |
| IfG | 03 – 07 | IfG |
| OSU | 02 | AIUB |
| combined | 09 | N/A |

The version numbers listed in Table 2 are relevant within the project and are reported so that it is possible to trace back the results presented in Section 5. Particular to the combined models, version 09 relates to the chosen combination strategy, as concluded from Teixeira da Encarnação and Visser (2019).

4 Methodology

4.1 Combination

The combination of the models is conducted at the level of the solutions considering weights derived from Variance Component Estimation (VCE). As demonstrated in Teixeira da Encarnação and Visser (2019), the combination at the level of Normal Equation (NEQ) disagreed more with GRACE/GRACE-FO, as a result of the vastly different amplitudes of formal errors.

The combination considers the complete degree range (degrees 2 to 40) but the VCE weights are derived from degrees 2-20. This approach addresses the very high errors above degree 20, which would otherwise drive the value of the weights.

It is feasible to determine the VCE weights because there are two time-series based on AIUB orbits (i.e. AIUB and OSU) and two time-series based on IfG orbits (i.e. IfG and ASU). Therefore the impact of the KOs on the solutions and on the VCE weights is balanced.

4.2 Validation

The validation is done by comparing the individual and combined solutions to the Release 6 (RL06) GRACE/GRACE-FO GFMs produced at Center for Space Research (CSR), considering all solutions available at the this document is produced.

All solutions undergo a 750km radius spherical cap Gaussian filtering, unless otherwise noted, to clearly show the geophysical signal contained in the Swarm solutions. The GRACE and GOCE Gravity Model 05 (GGM05G) (Bettadpur et al., 2015) static GFM is subtracted from all models in order to isolate the time-variable component of Earth's gravity field. We chose to show the gravity field in terms of EWH, except for the statistics related to the correlation coefficient, which are non-dimensional as usual. The GRACE/GRACE-FO gravity field time series is linearly interpolated to the mid-month epoch of the Swarm solutions. The GRACE/GRACE-FO climatological model is evaluated at the same time domain. The analysis spans 2016-01-01 until 2022-09-30.

Note that there is no effort to meticulously consider or implement proper leakage reduction methods, e.g. by Guo, Duan and Shum (2010), in any of our analyses.

4.2.1 Earth's oblateness

The $C_{2,0}$ coefficient in all solutions has been replaced by the time series provided in Loomis and Rachlin (2020).

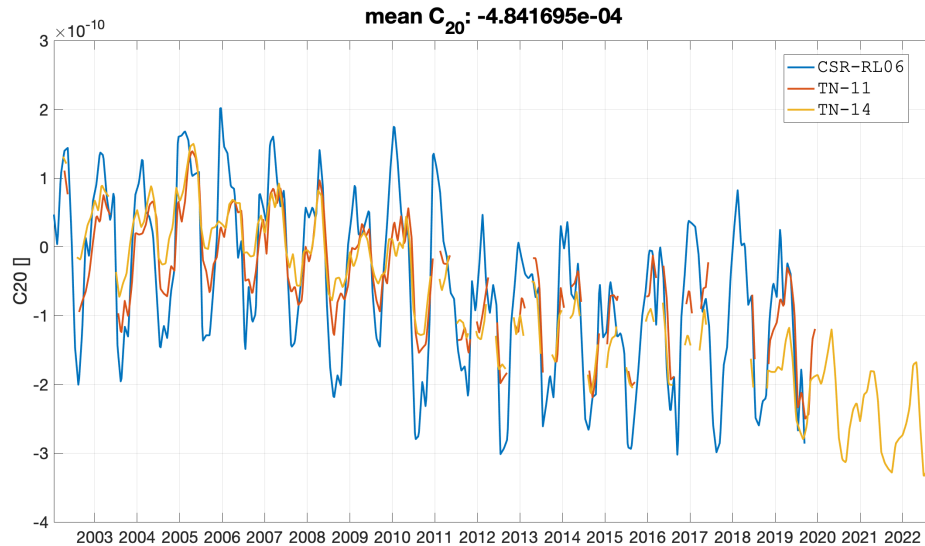


Figure 1 – Monthly SLR-derived C_{20} from Loomis and Rachlin (2020) (TN-14), compared to Cheng and Ries (2018) (TN-11) and Cheng and Ries (2019) (CSR-RL06, from GRACE/GRACE-FO).

4.2.2 Land and ocean analyses

Some analyses are restricted to either the land or ocean areas. In those cases, the land or ocean mask is applied in the spatial domain and a Spherical Harmonic (SH) analysis is done on the masked grid. The ocean mask excludes the coastal ocean areas that are roughly 1000km or less from land areas, as shown in Figure 2, while the land mask has no buffer zone.

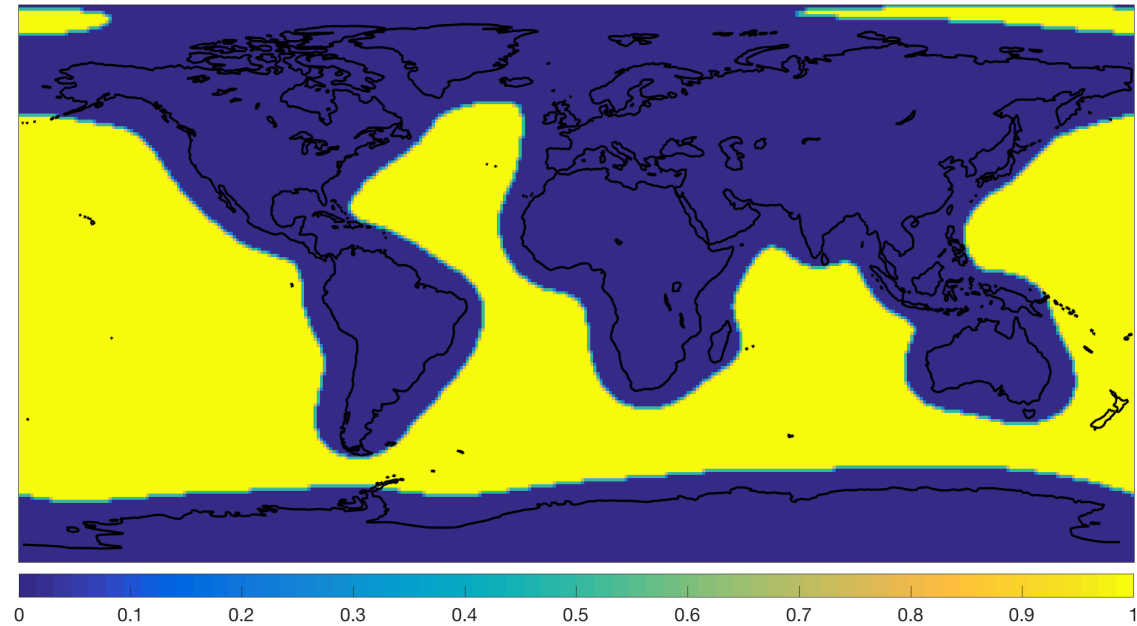


Figure 2 – Deep ocean mask.

4.2.3 Catchment time series

In Section 5.5, the geophysical signal represented by the Swarm solutions is evaluated on the basis of the time series of average EWH over restricted geographical locations, shown in Figure 3. Each averaging is done over the corresponding spatial truncation of an equiangular grid representation of the SH coefficients. The locations shown in Sections 5.5.1 to 5.5.18 are related to the largest hydrological basins and polar regions with the highest signal variability observed by GRACE/GRACE-FO. We perform a parametric regression on the time series of all geographical regions considering a constant and drift terms, along with annual and semi-annual sine and co-sine terms to improve the robustness. We plot the linear part of this regression, in order to quantify the accuracy of Swarm-derived climatological trends. The time series are plotted along with tables presenting some statistics. The values of the constant and linear terms for the Swarm and GRACE/GRACE-FO solutions (column 1) are shown in terms of EWH (columns 2 and 4). Additionally, the difference of these parameters between the Swarm and GRACE/GRACE-FO solutions relative to the GRACE/GRACE-FO climatological model is listed in columns 3 and 5 (the values for the latter data set in these columns is zero). Finally, the correlation coefficients is presented in the last column (the value for GRACE/GRACE-FO climatological model is 1). The constant term is the average basin storage over the relevant data period.

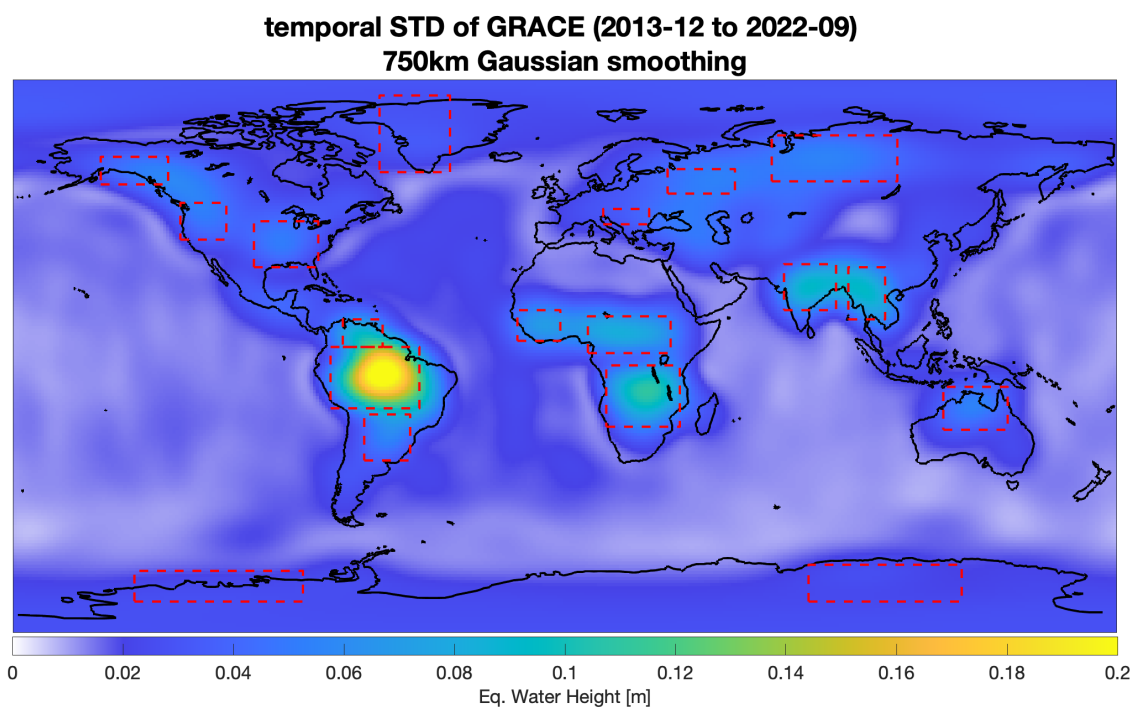


Figure 3 – Temporal variability of the GRACE/GRACE-FO climatological model, including the boundaries of the regions analysed in Section 5.5.1 to Section 5.5.18.

5 Results

5.1 Spatial analysis

5.1.1 Degree-mean RMS difference

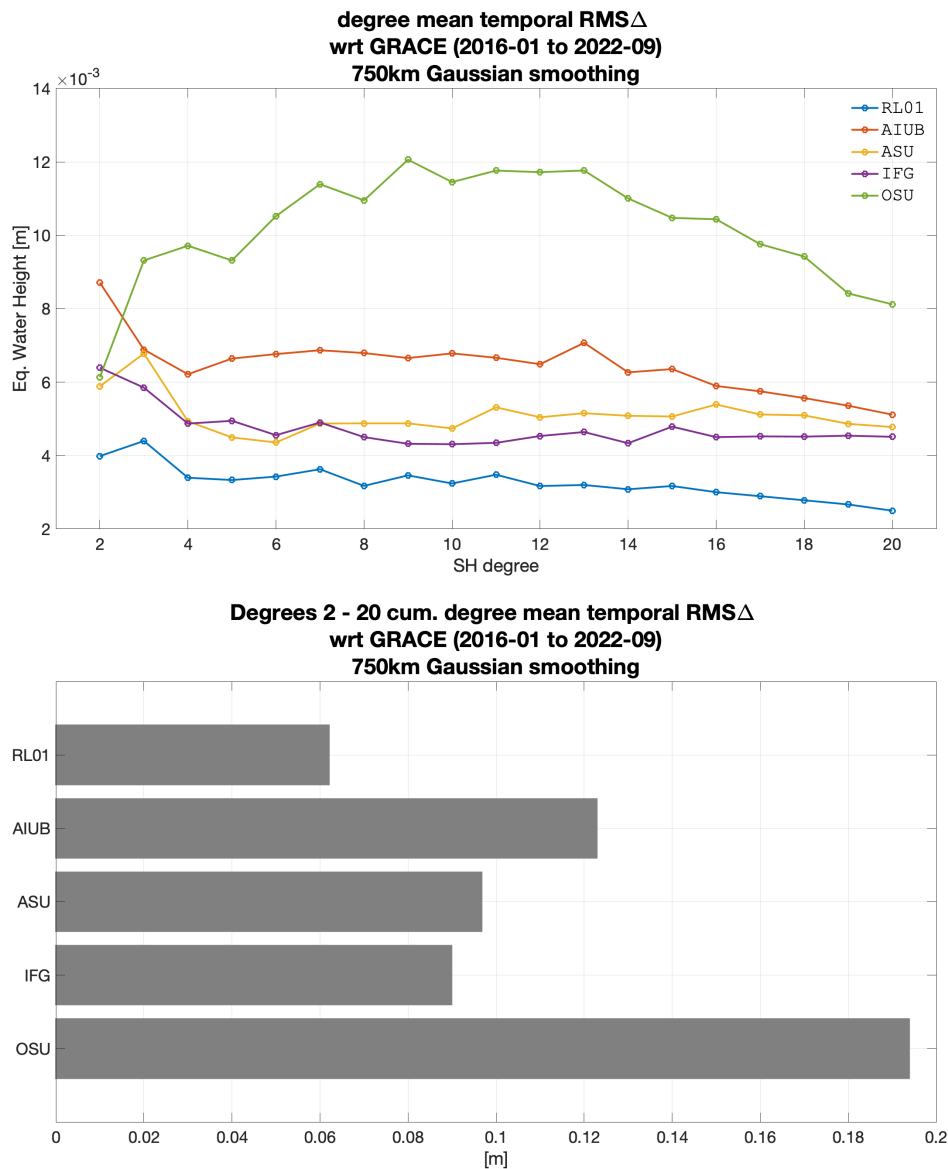


Figure 4 – Per-degree mean of the RMS difference (top) and cumulative degree-mean temporal RMS difference (bottom) between the Swarm GFMs and GRACE, considering 750km Gaussian smoothing. This is (an estimate of) the average per-degree quality of the various Swarm solutions in the spectral domain (top) and globally (bottom). The degree amplitudes remain relatively constant with increasing degree, instead of growing in terms of EWH, as the result of the smoothing.

5.1.2 Cumulative degree amplitude difference over land

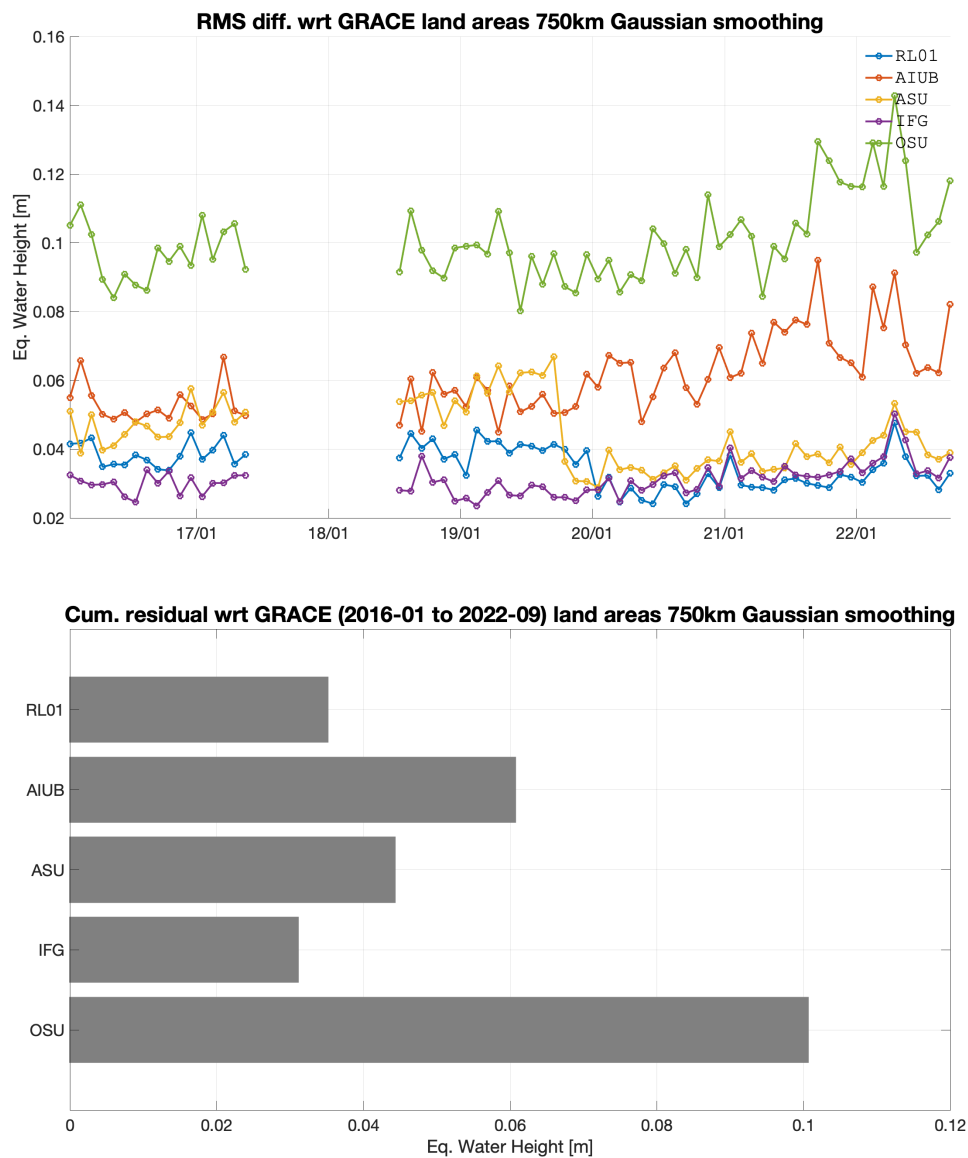


Figure 5 – Epoch-wise cumulative spatial RMS (top) and its global average (bottom) of the difference between Swarm GFMs and GRACE, over land areas, considering 750km Gaussian smoothing. This is (an estimate of) the evolution of the ability of the various Swarm solutions to predict land mass transport processes over time (top) and its global sum (bottom). The Swarm combined model (RL01) includes the new version of the IfG and ASU individual solutions only after December 2021; this is the reason why the combined model is not below these individual solutions before 2020.

5.1.3 Cumulative degree amplitude difference over oceans

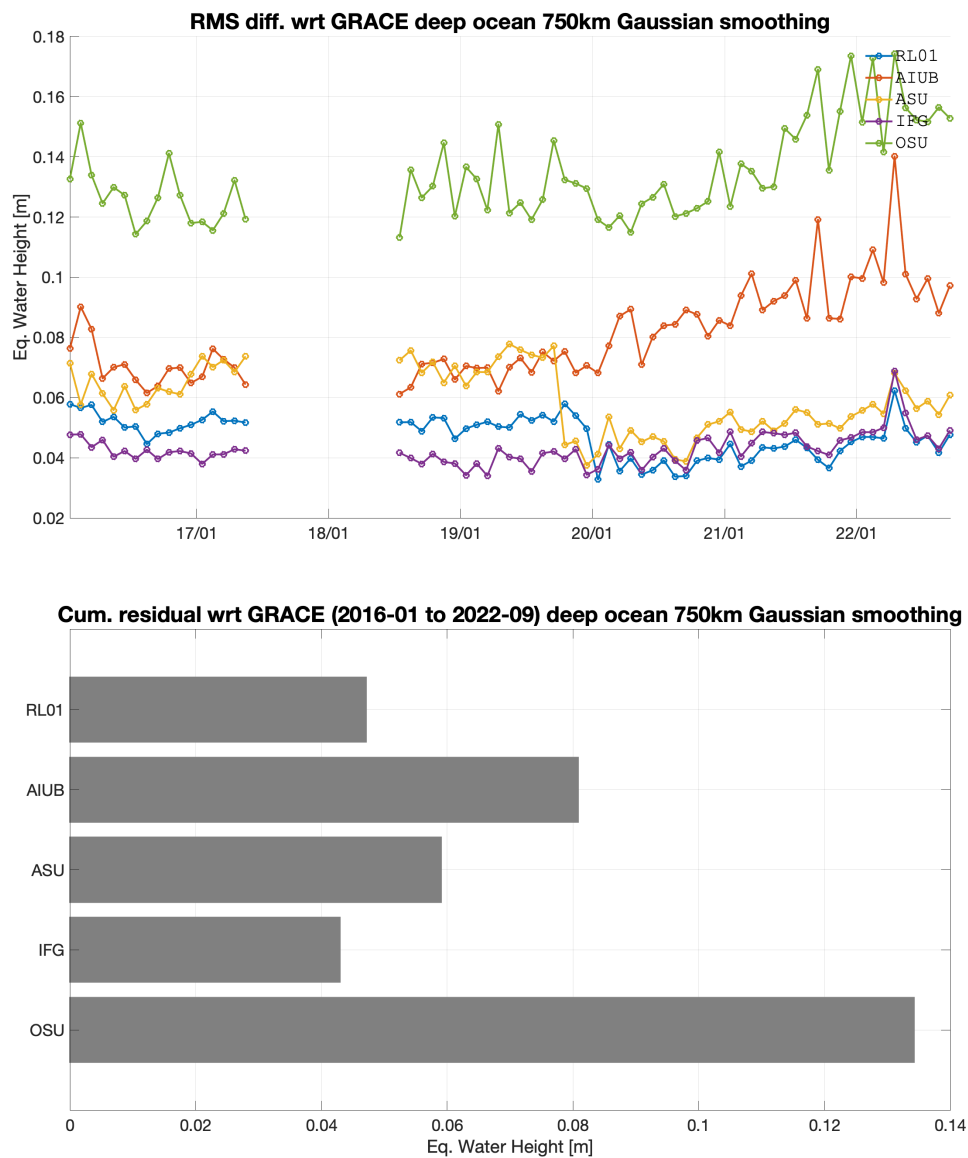


Figure 6 – Epoch-wise cumulative spatial RMS (top) and its global sum (bottom) of the difference between Swarm GFMs and GRACE, over ocean areas, considering 750km Gaussian smoothing. This is the epoch-wise quality of the Swarm GFMs, and reported in the header of the combined GFMs files. The Swarm combined model (RL01) includes the new version of the IfG and ASU individual solutions only after December 2021; this is the reason why the combined model is not below these individual solutions before 2020.

5.2 Temporal analysis

5.2.1 Per-degree mean correlation coefficient over land

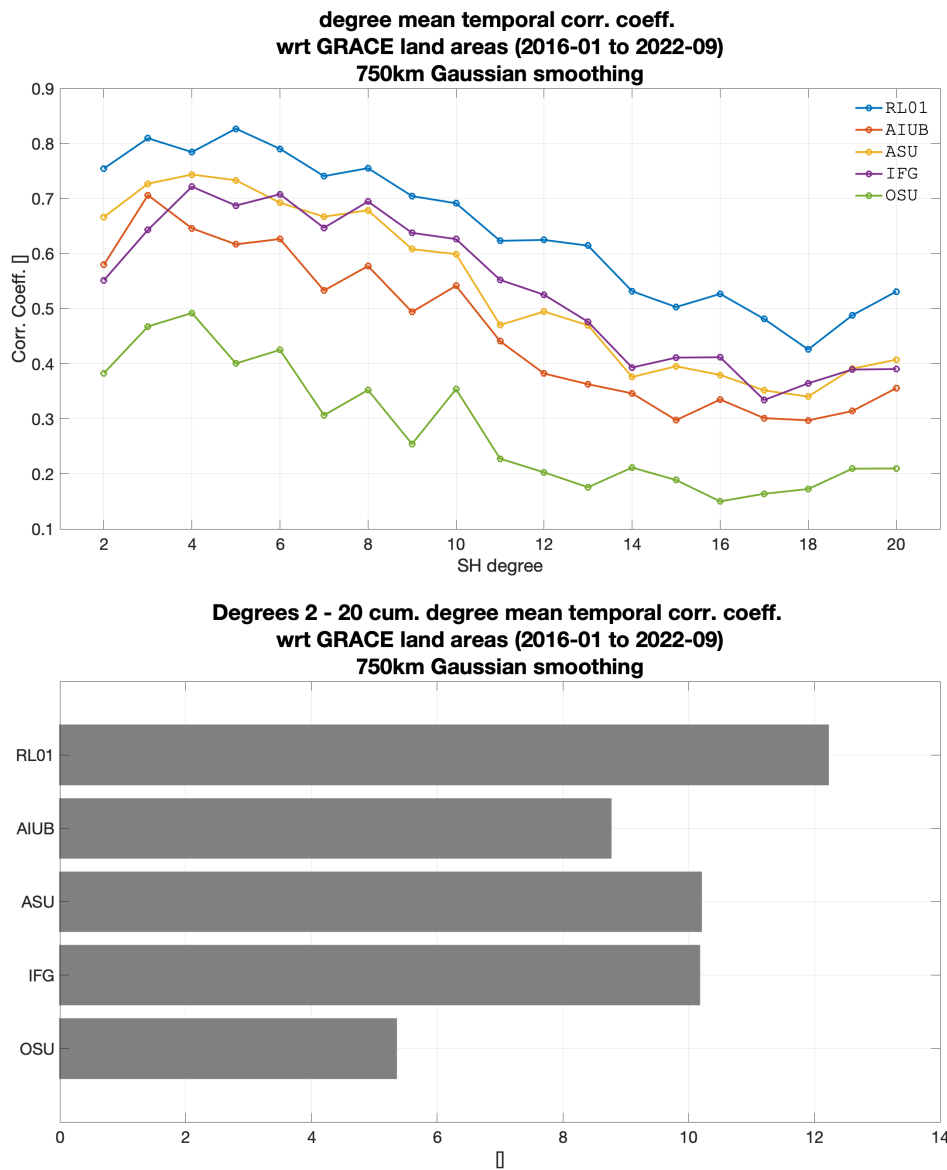


Figure 7 – Per-degree mean (top) and its overall cumulative (bottom) of the correlation coefficient between Swarm GFMs and GRACE, over land areas, considering 750km Gaussian smoothing. The temporal correlation at every Stokes coefficient is computed and the average over each degree is plotted at the top. It illustrates how well the temporal variations of the Swarm models agree with what is predicted from the GRACE/GRACE-FO climatological model.

5.2.2 Per-degree mean correlation coefficient over oceans

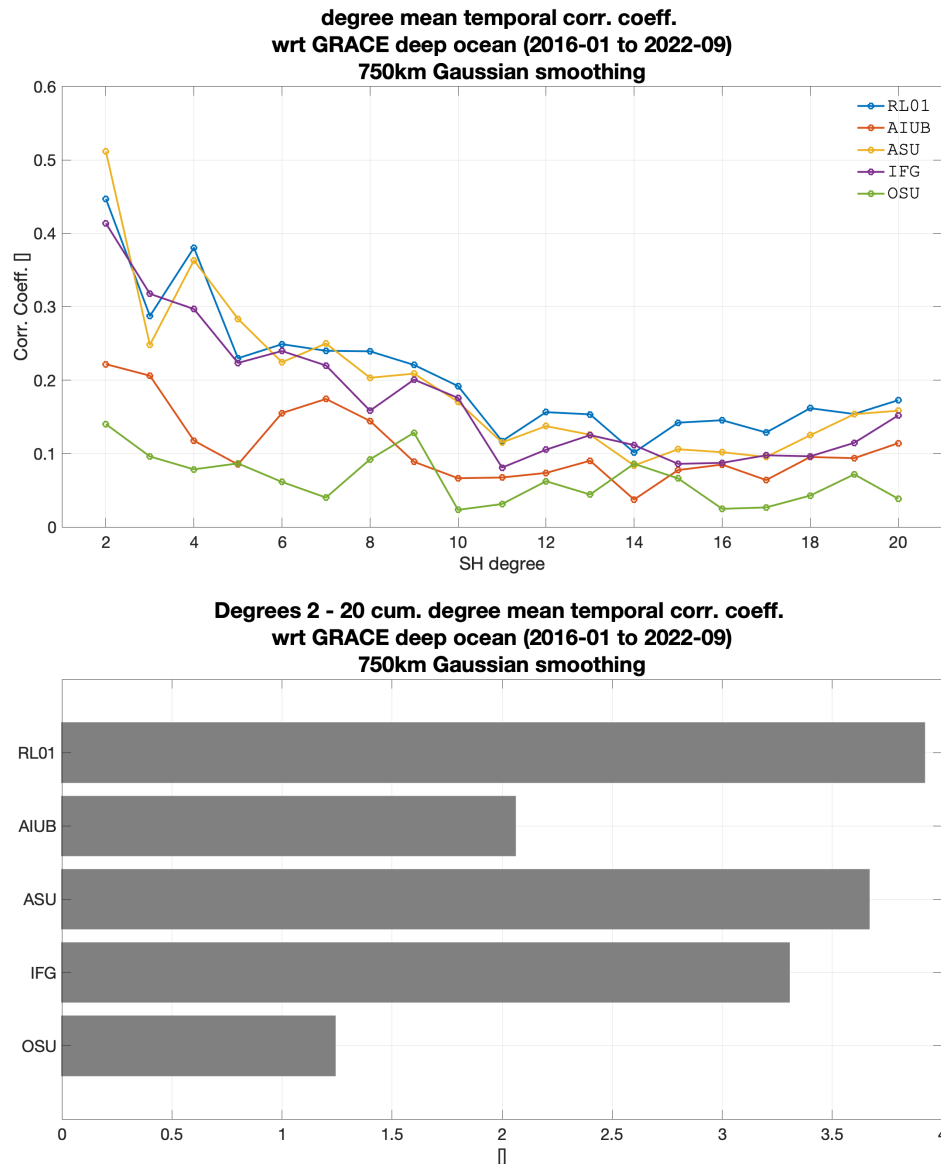


Figure 8 – Per-degree mean (top) and its overall cumulative (bottom) of the correlation coefficient between Swarm GFMs and GRACE, over ocean areas, considering 750km Gaussian smoothing. It illustrates that the Swarm models agree poorly with the mass variations over the ocean as predicted by the GRACE/GRACE-FO climatological model.

5.2.3 Global unsmoothed per-degree mean correlation coefficient

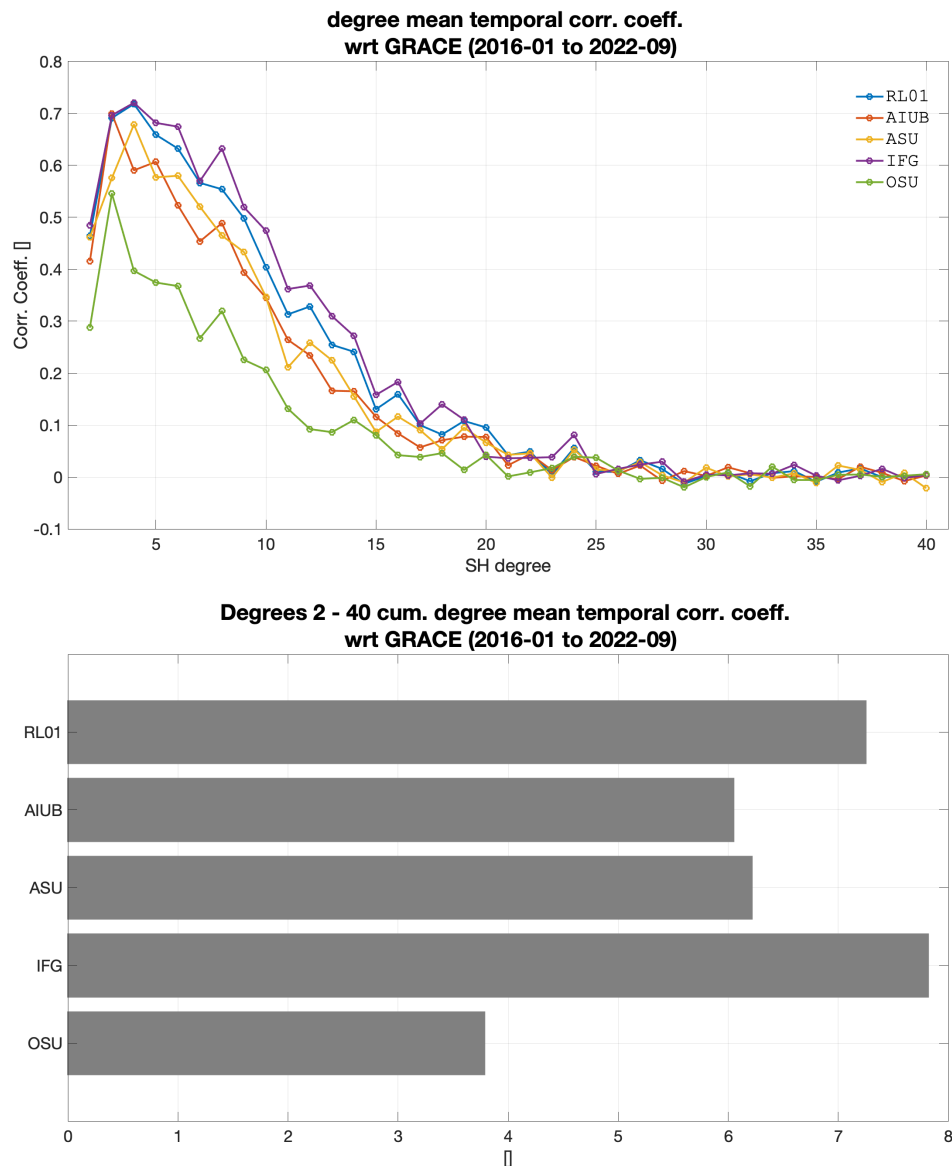


Figure 9 – Per-degree mean (top) and its overall cumulative (bottom) of the correlation coefficient between Swarm and GRACE/GRACE-FO GFMs (not the GRACE/GRACE-FO climatological model), globally and with no smoothing. It illustrates that the Swarm models fail to represent the same temporal variations as GRACE/GRACE-FO above degree 15-20.

5.2.4 Triangular plots of the RMS differences

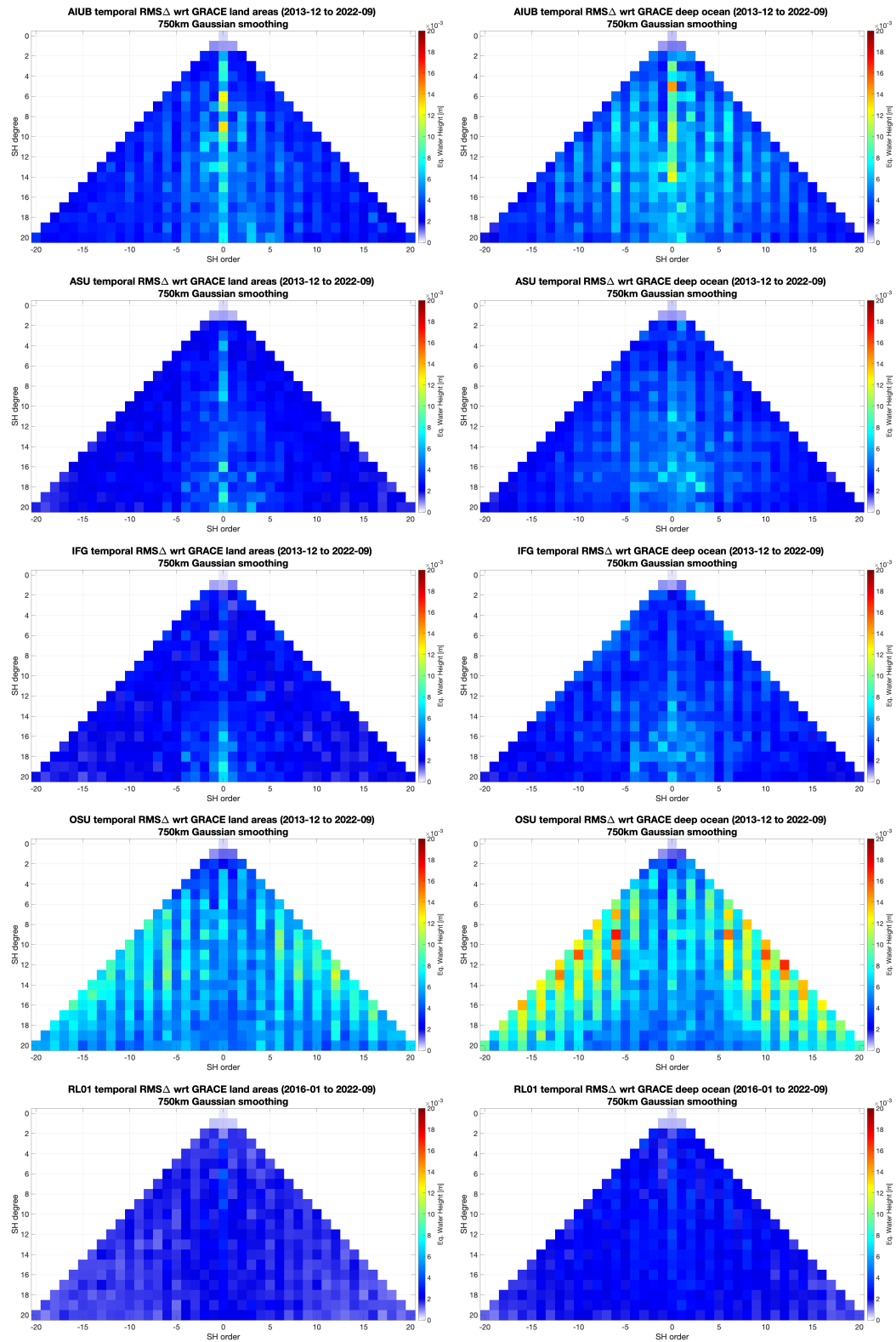


Figure 10 – Per-coefficient RMS difference between Swarm GFMs and GRACE considering 750km Gaussian smoothing, over land (left column) and ocean (right column) areas, for AIUB, ASU, IfG, OSU and combined solutions (respectively from top to bottom).

5.2.5 Triangular plots of the correlation coefficients

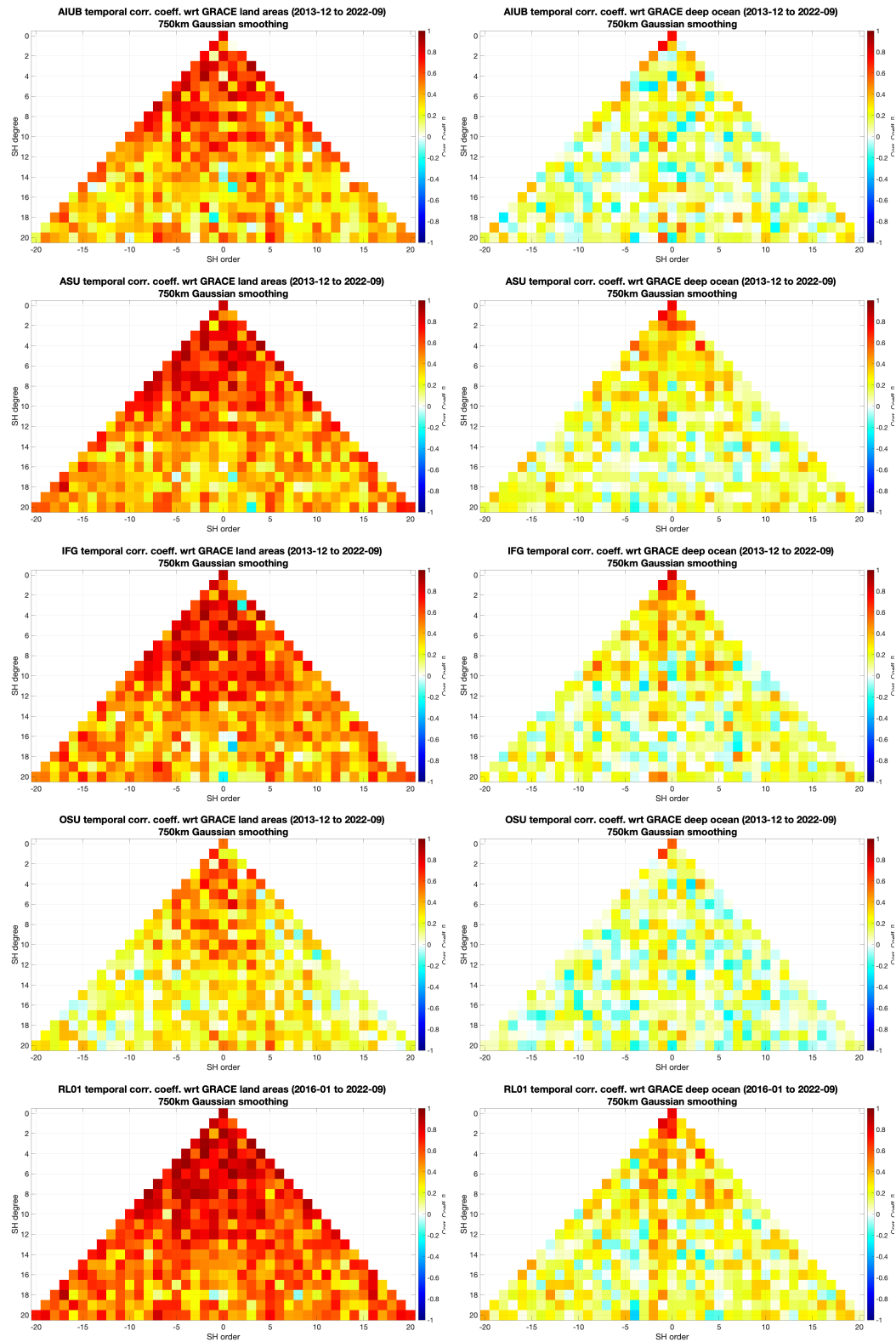


Figure 11 – Per-coefficient correlation coefficient between Swarm GFMs and GRACE considering 750km Gaussian smoothing, over land (left column) and ocean (right column) areas, for AIUB, ASU, IfG, OSU and combined solutions (respectively from top to bottom).

5.3 Low-degree zonal coefficients



Figure 12 – Time series of the C_{20} (top) and C_{30} (bottom) coefficients, showing coefficients in the Swarm and GRACE/GRACE-FO GFMs. The statistics in the legend consider GRACE as reference.

5.4 Monthly models

5.4.1 Monthly degree-RMS

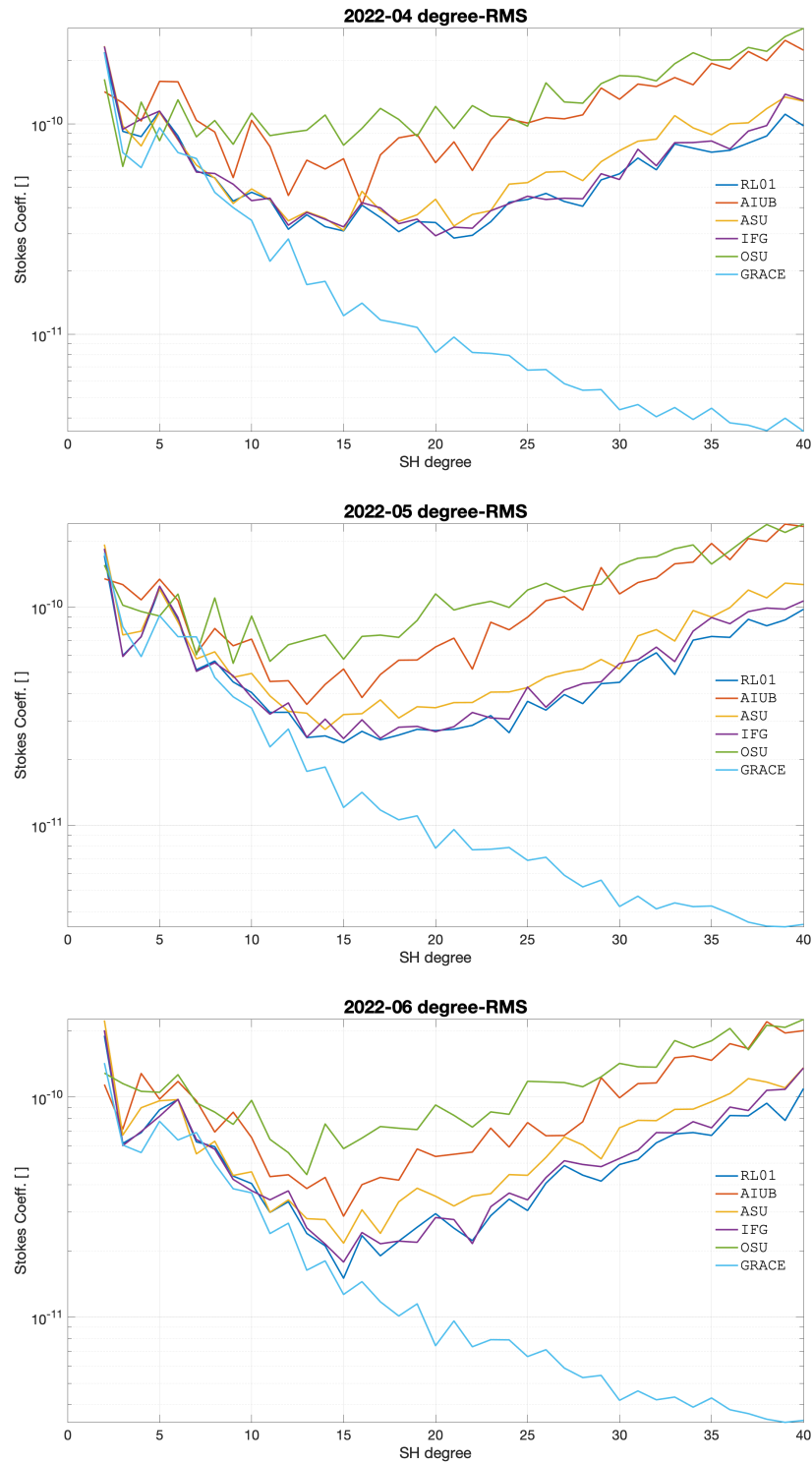


Figure 13 – Monthly degree-RMS for Q2 of 2022, all individual and combined Swarm solutions, as well as GRACE/GRACE-FO (no smoothing).

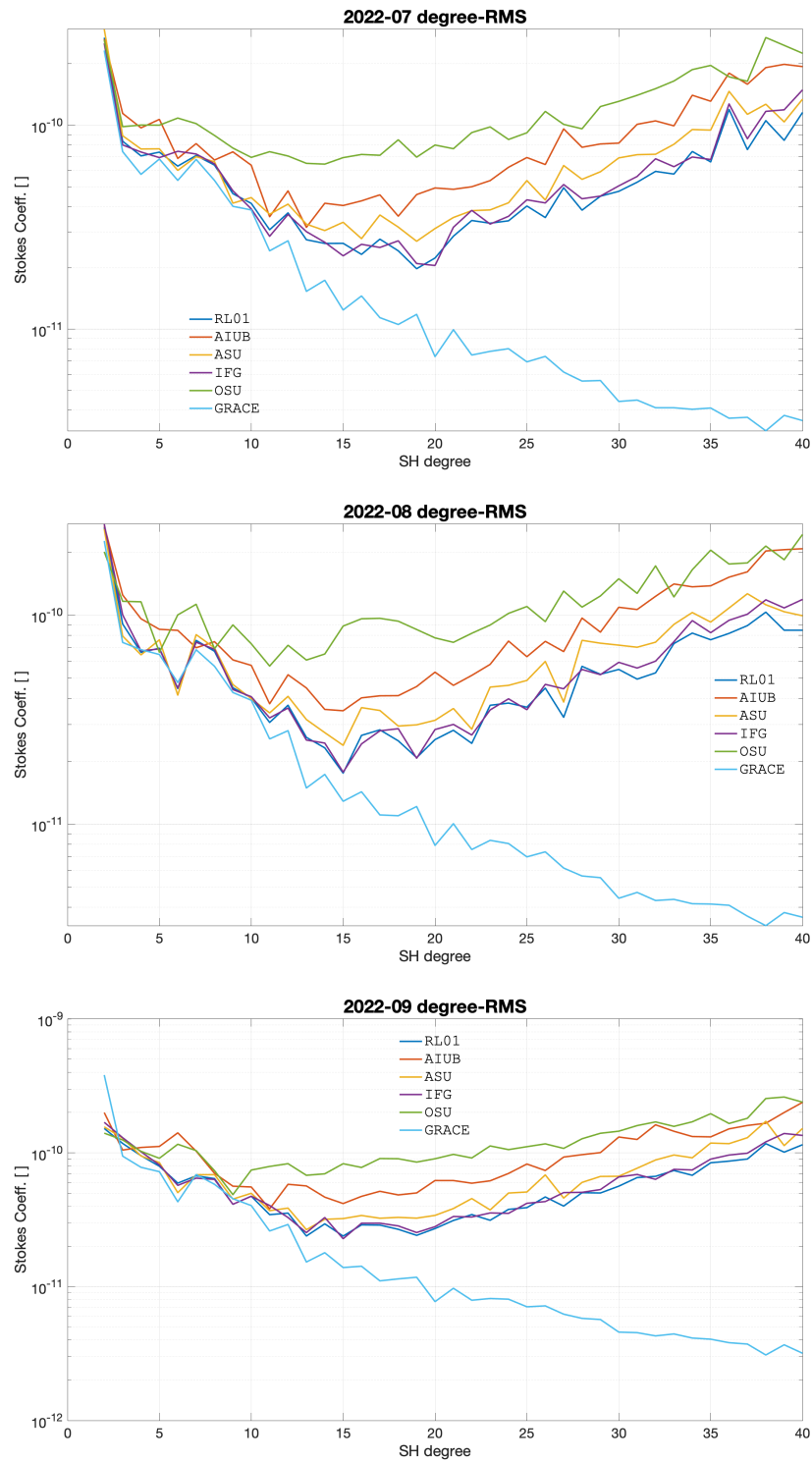


Figure 14 – Monthly degree-RMS for Q3 of 2022, all individual and combined Swarm solutions, as well as GRACE/GRACE-FO (no smoothing).

5.5 Time series of storage catchments

5.5.1 Amazon basin

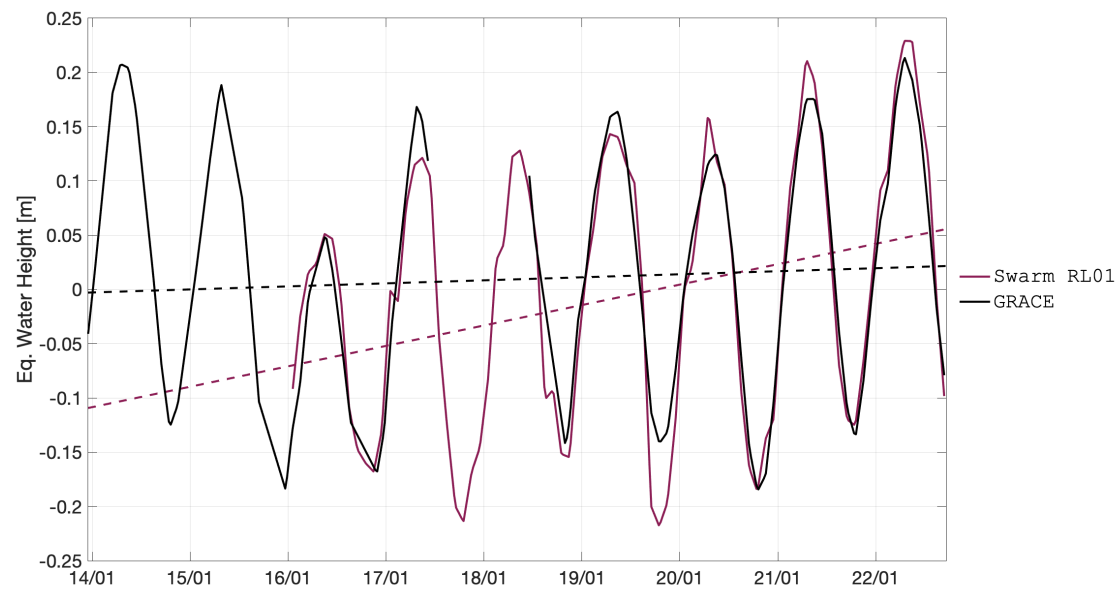


Figure 15 – Time series of EWH for the Amazon basin (latitude -17 to 3 degrees, longitude -76 to -47 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|--------------------|-----------------------------|-----------------------|--------------------------------|------------------|
| Swarm RL01 | -0.21 | -2.43 | 1.88 | 1.60 | 0.97 |
| GRACE | 2.22 | 0.00 | 0.28 | 0.00 | 1.00 |

Table 3 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Amazon basin.

5.5.2 Orinoco basin

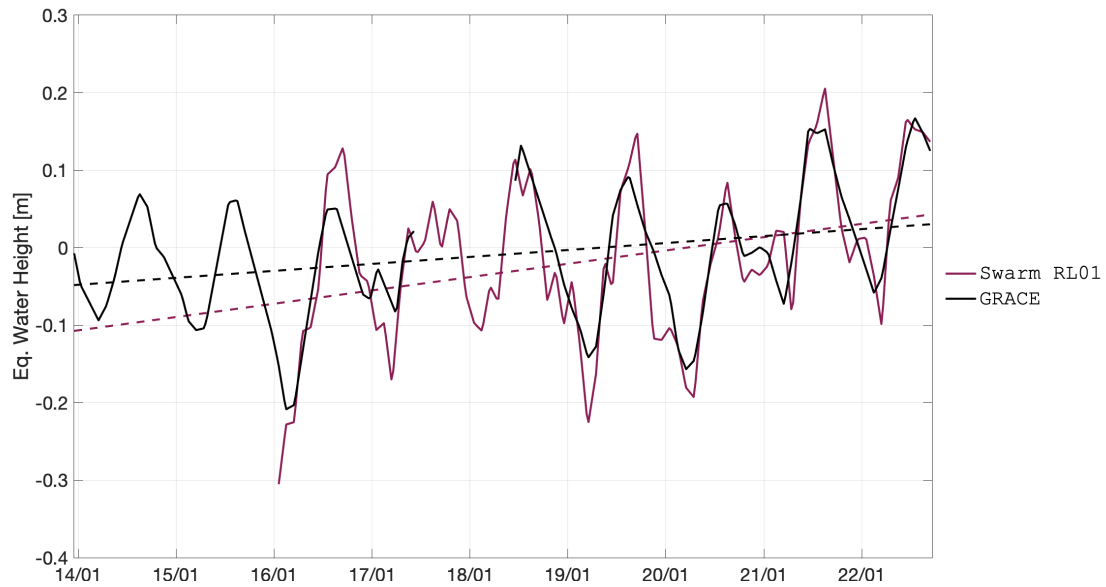


Figure 16 – Time series of EWH for the Orinoco basin (latitude -3 to 12 degrees, longitude -72 to -59 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|--------------------|-----------------------------|-----------------------|--------------------------------|------------------|
| Swarm RL01 | -1.45 | -0.57 | 1.72 | 0.82 | 0.91 |
| GRACE | -0.88 | 0.00 | 0.90 | 0.00 | 1.00 |

Table 4 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Orinoco basin.

5.5.3 La Plata basin

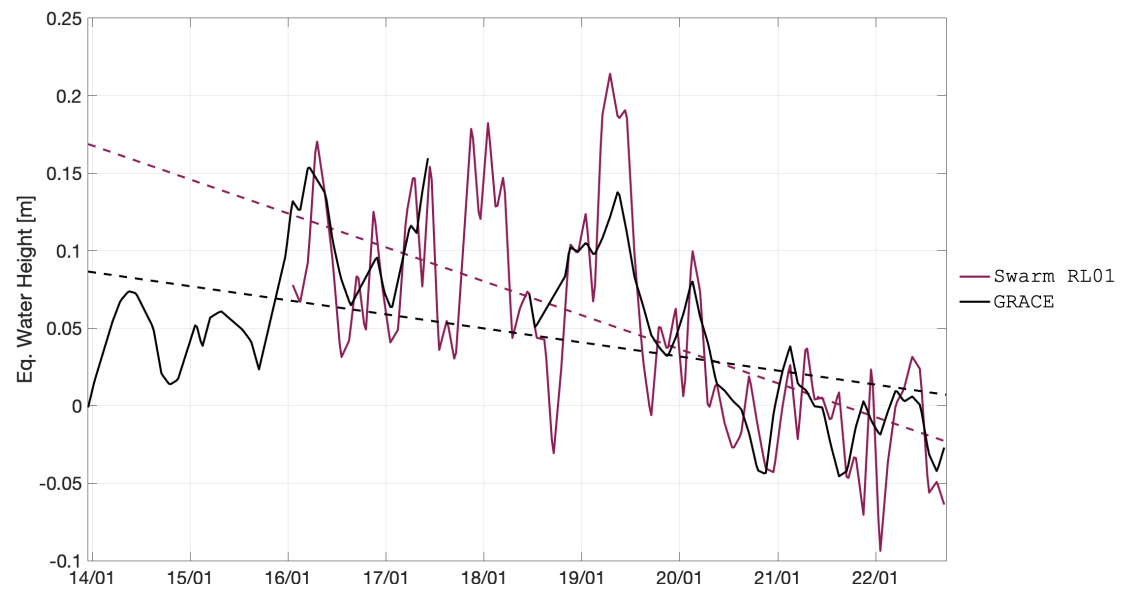


Figure 17 – Time series of EWH for the La Plata basin (latitude -34 to -19 degrees, longitude -65 to -50 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|--------------------|-----------------------------|-----------------------|--------------------------------|------------------|
| Swarm RL01 | 5.04 | 0.43 | -2.19 | -1.28 | 0.85 |
| GRACE | 4.61 | 0.00 | -0.91 | 0.00 | 1.00 |

Table 5 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the La Plata basin.

5.5.4 Mississippi basin

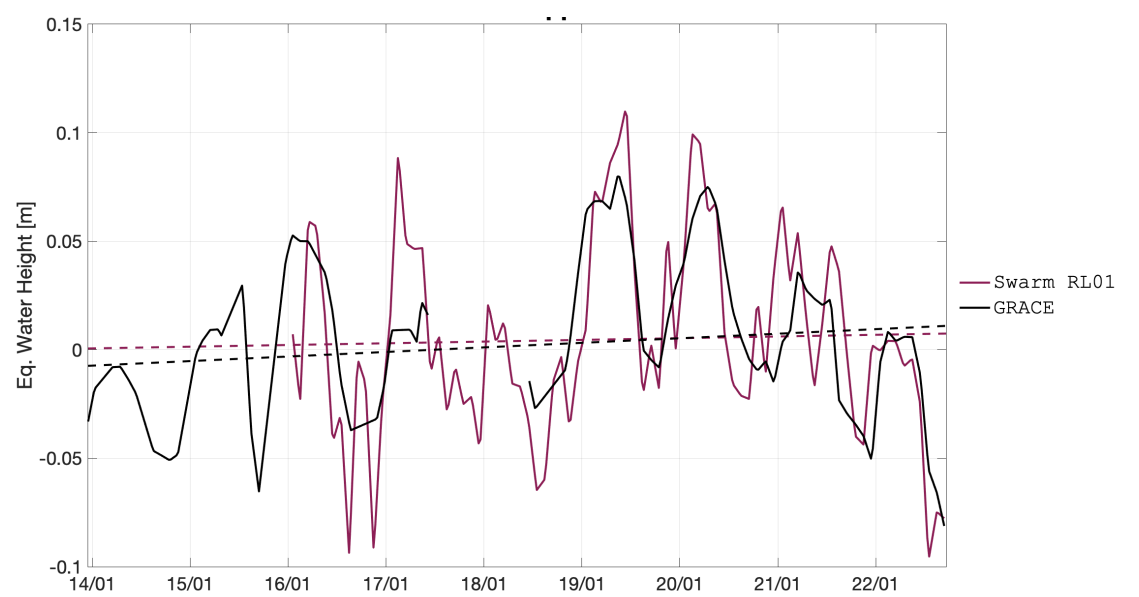


Figure 18 – Time series of EWH for the Mississippi basin (latitude 29 to 44 degrees, longitude -101 to -80 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|--------------------|----------------------|-----------------------|-------------------------|------------------|
| Swarm RL01 | 0.57 | 0.04 | 0.08 | -0.13 | 0.75 |
| GRACE | 0.53 | 0.00 | 0.21 | 0.00 | 1.00 |

Table 6 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Mississippi basin.

5.5.5 Columbia region

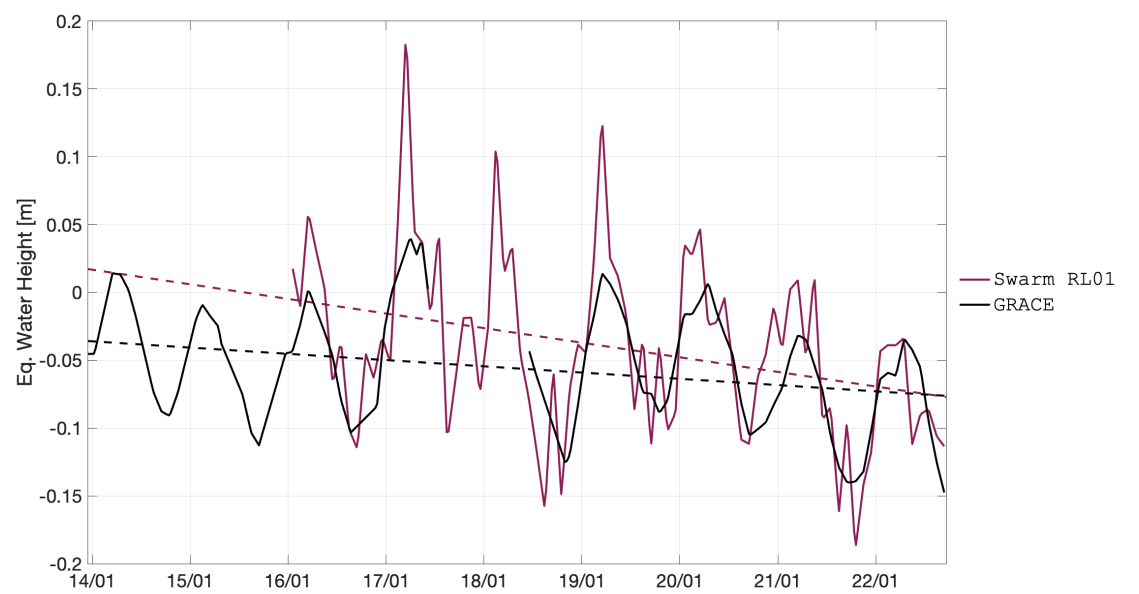


Figure 19 – Time series of EWH for the Columbia region (latitude 38 to 50 degrees, longitude -125 to -110 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|-----------------------|--------------------------------|--------------------------|-----------------------------------|---------------------|
| Swarm RL01 | -3.94 | 1.40 | -1.08 | -0.62 | 0.80 |
| GRACE | -5.34 | 0.00 | -0.46 | 0.00 | 1.00 |

Table 7 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Columbia region.

5.5.6 Alaska

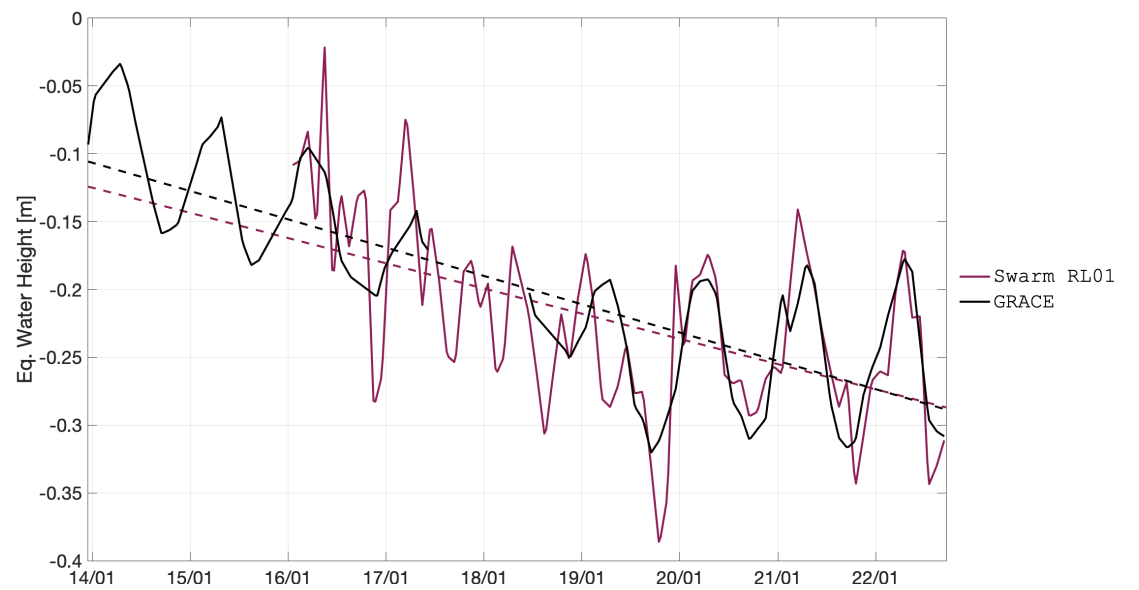


Figure 20 – Time series of EWH for the Alaska (latitude 56 to 65 degrees, longitude -151 to -129 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|-----------------------|-------------------------|--------------------------|----------------------------|---------------------|
| Swarm RL01 | -22.36 | -2.33 | -1.86 | 0.23 | 0.83 |
| GRACE | -20.03 | 0.00 | -2.09 | 0.00 | 1.00 |

Table 8 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Alaska.

5.5.7 Western Greenland region

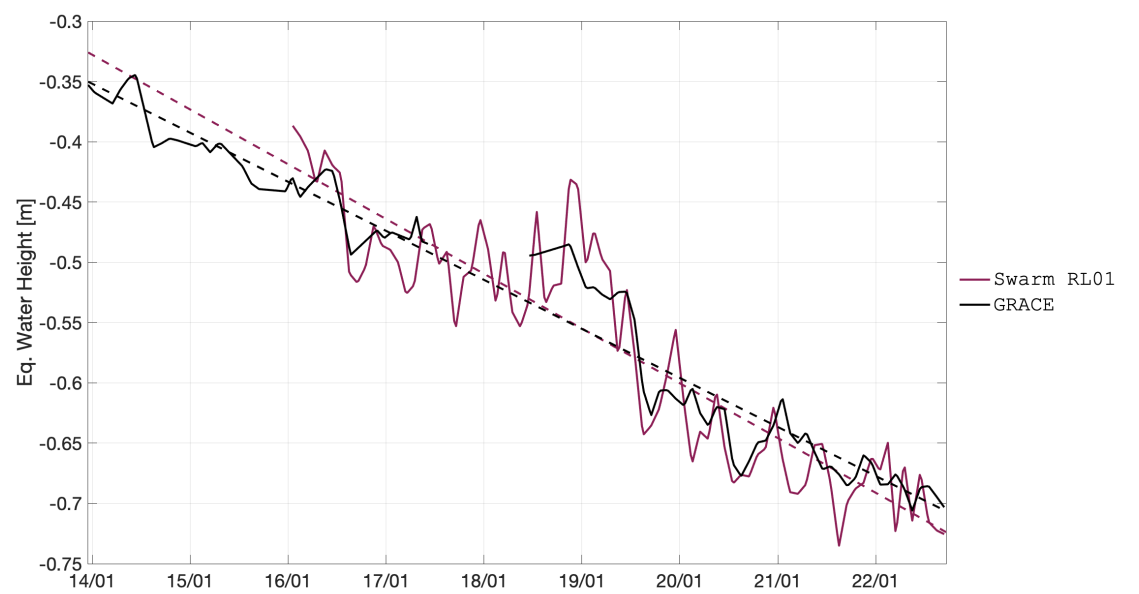


Figure 21 – Time series of EWH for the Western Greenland region (latitude 60 to 85 degrees, longitude -60 to -37 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|--------------------|-----------------------------|-----------------------|--------------------------------|------------------|
| Swarm RL01 | -57.23 | -3.10 | -4.54 | -0.47 | 0.96 |
| GRACE | -54.13 | 0.00 | -4.07 | 0.00 | 1.00 |

Table 9 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Western Greenland region.

5.5.8 Danube basin

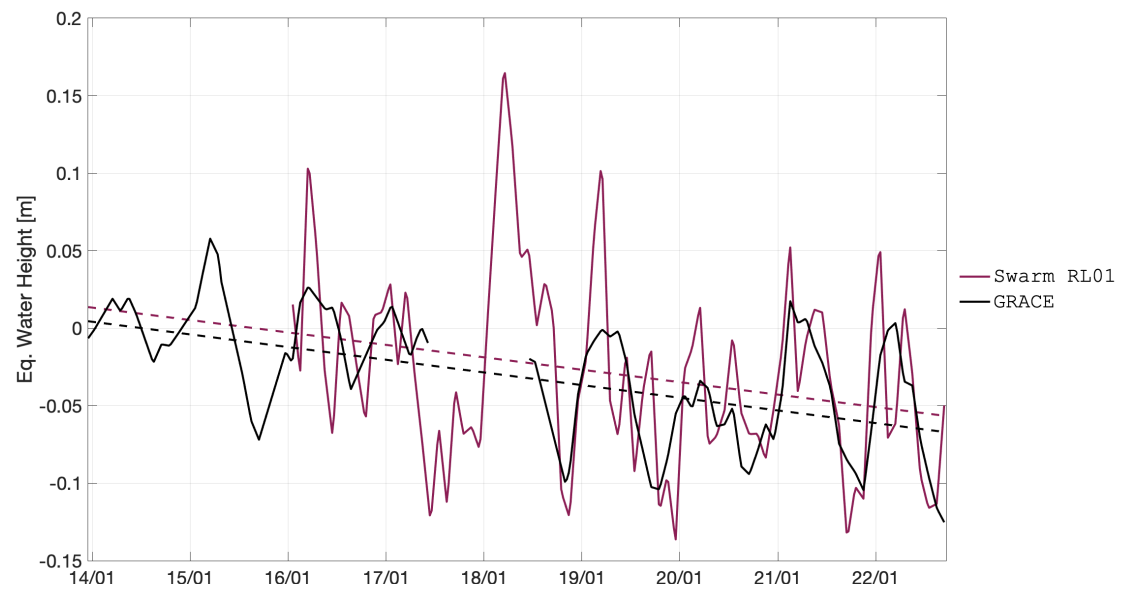


Figure 22 – Time series of EWH for the Danube basin (latitude 43 to 48 degrees, longitude 13 to 28 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|-----------------------|--------------------------------|--------------------------|-----------------------------------|---------------------|
| Swarm RL01 | -2.81 | 0.28 | -0.80 | 0.02 | 0.61 |
| GRACE | -3.09 | 0.00 | -0.82 | 0.00 | 1.00 |

Table 10 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Danube basin.

5.5.9 Western Sub-Saharan basin

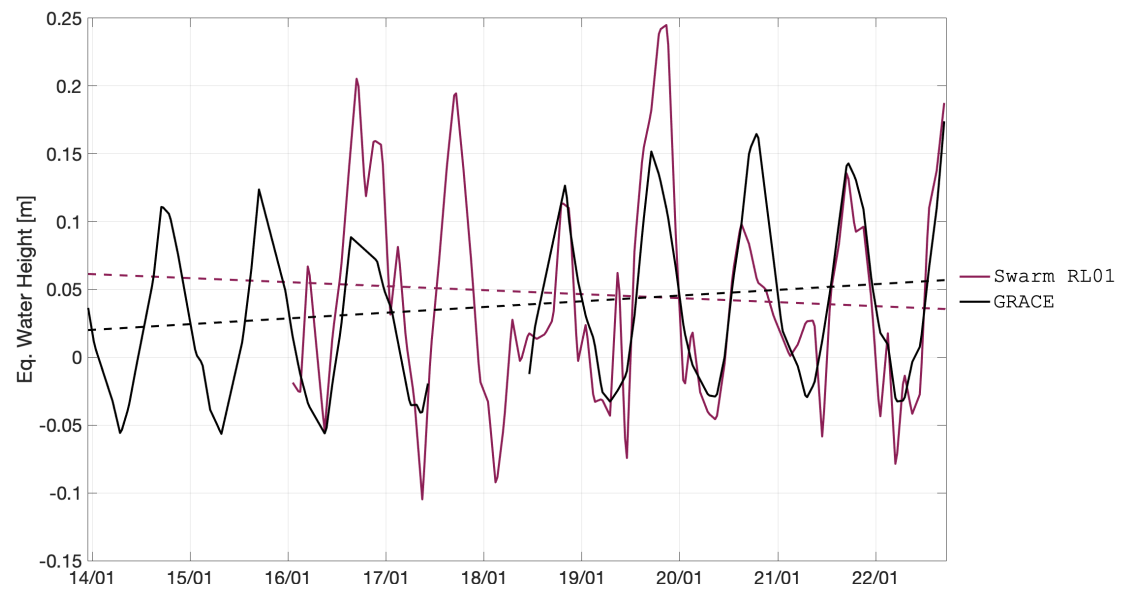


Figure 23 – Time series of EWH for the Western Sub-Saharan basin (latitude 5 to 15 degrees, longitude -15 to -1 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|--------------------|-----------------------------|-----------------------|--------------------------------|------------------|
| Swarm RL01 | 4.32 | 1.05 | -0.30 | -0.72 | 0.77 |
| GRACE | 3.27 | 0.00 | 0.42 | 0.00 | 1.00 |

Table 11 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Western Sub-Saharan basin.

5.5.10 Eastern Sub-Saharan basin

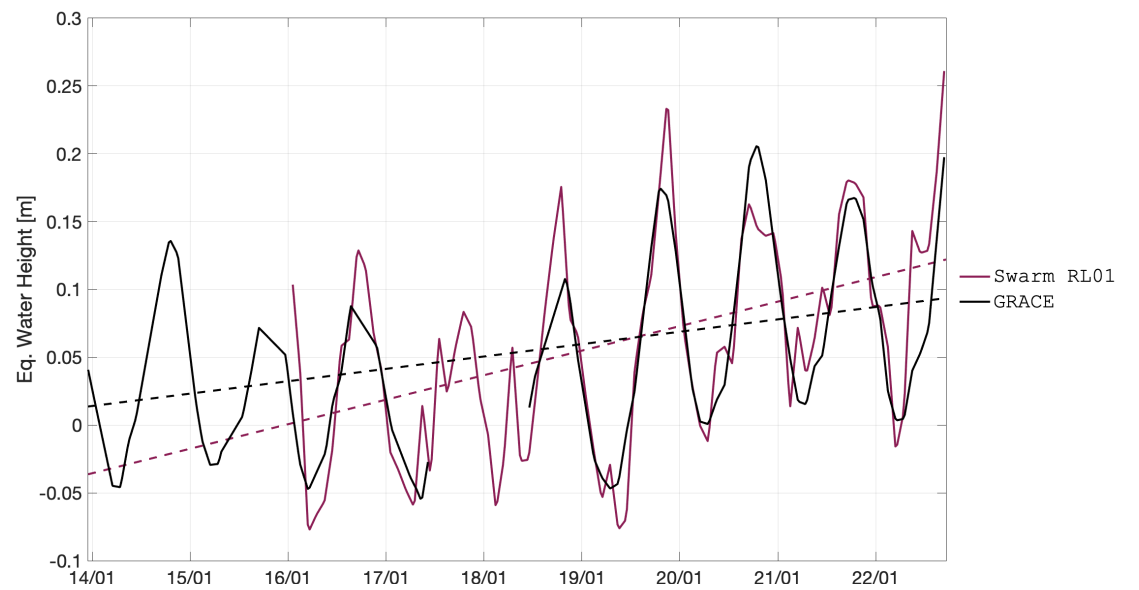


Figure 24 – Time series of EWH for the Eastern Sub-Saharan basin (latitude 1 to 13 degrees, longitude -8 to 35 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|--------------------|-----------------------------|-----------------------|--------------------------------|------------------|
| Swarm RL01 | 5.90 | 0.93 | 1.81 | 0.90 | 0.89 |
| GRACE | 4.97 | 0.00 | 0.91 | 0.00 | 1.00 |

Table 12 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Eastern Sub-Saharan basin.

5.5.11 Congo and Zambezi basins

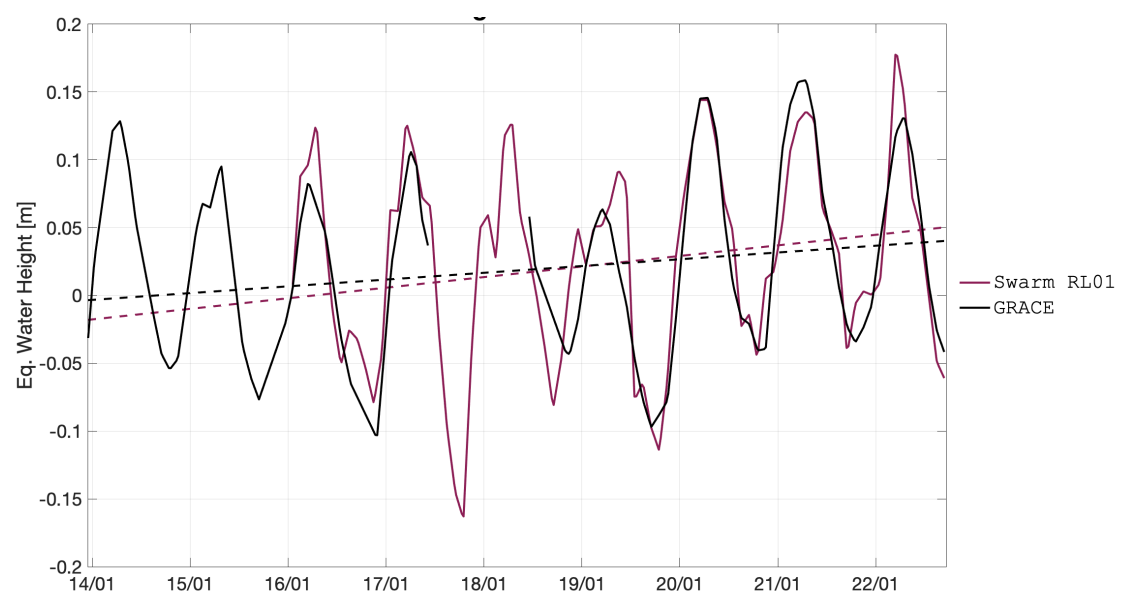


Figure 25 – Time series of EWH for the Congo and Zambezi basins (latitude -23 to -3 degrees, longitude 14 to 38 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|--------------------|-----------------------------|-----------------------|--------------------------------|------------------|
| Swarm RL01 | 2.66 | -0.01 | 0.78 | 0.28 | 0.91 |
| GRACE | 2.66 | 0.00 | 0.50 | 0.00 | 1.00 |

Table 13 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Congo and Zambezi basins.

5.5.12 Volga basin

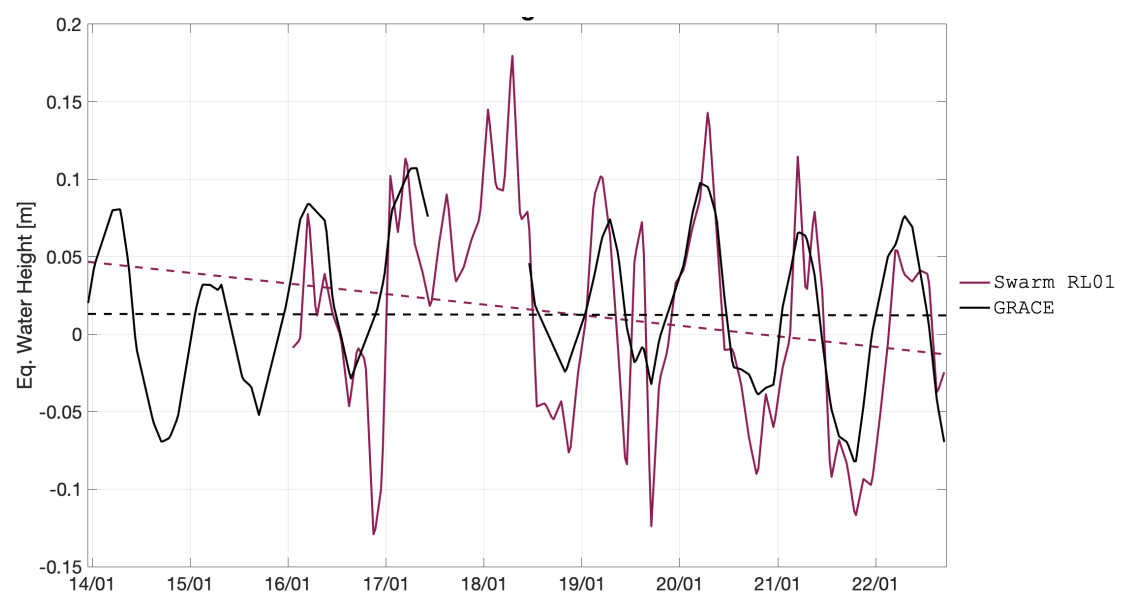


Figure 26 – Time series of EWH for the Volga basin (latitude 53 to 61 degrees, longitude 34 to 56 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|-----------------------|--------------------------------|--------------------------|-----------------------------------|---------------------|
| Swarm RL01 | 1.19 | -0.54 | -0.68 | -0.67 | 0.77 |
| GRACE | 1.73 | 0.00 | -0.01 | 0.00 | 1.00 |

Table 14 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Volga basin.

5.5.13 Siberia region

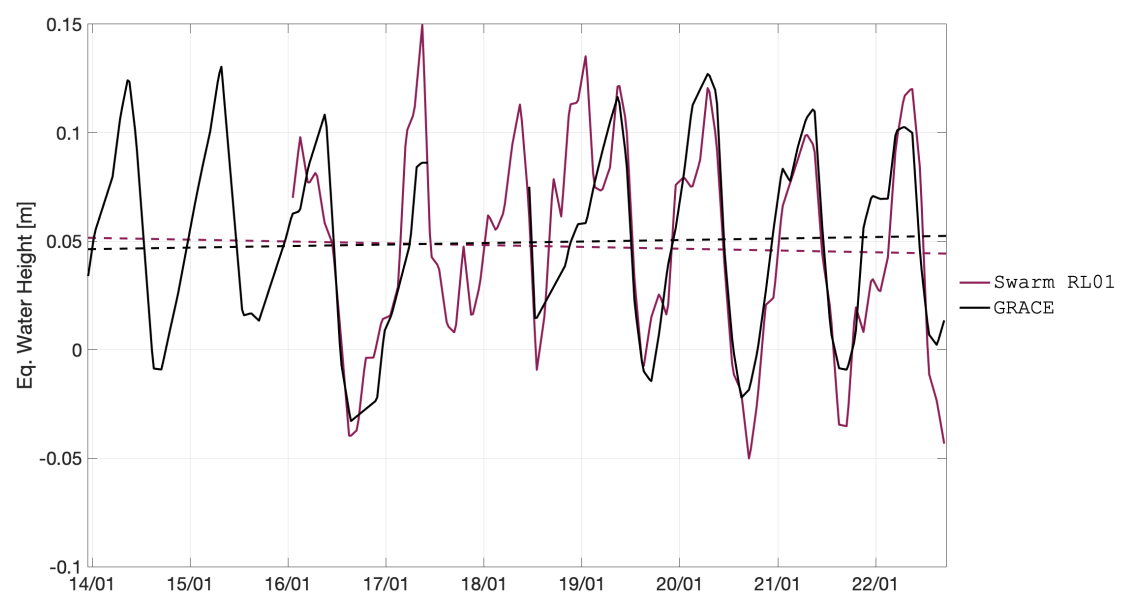


Figure 27 – Time series of EWH for the Siberia region (latitude 57 to 72 degrees, longitude 68 to 109 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|--------------------|-----------------------------|-----------------------|--------------------------------|------------------|
| Swarm RL01 | 4.77 | -0.59 | -0.08 | -0.15 | 0.82 |
| GRACE | 5.36 | 0.00 | 0.07 | 0.00 | 1.00 |

Table 15 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Siberia region.

5.5.14 Ganges-Brahmaputra basin

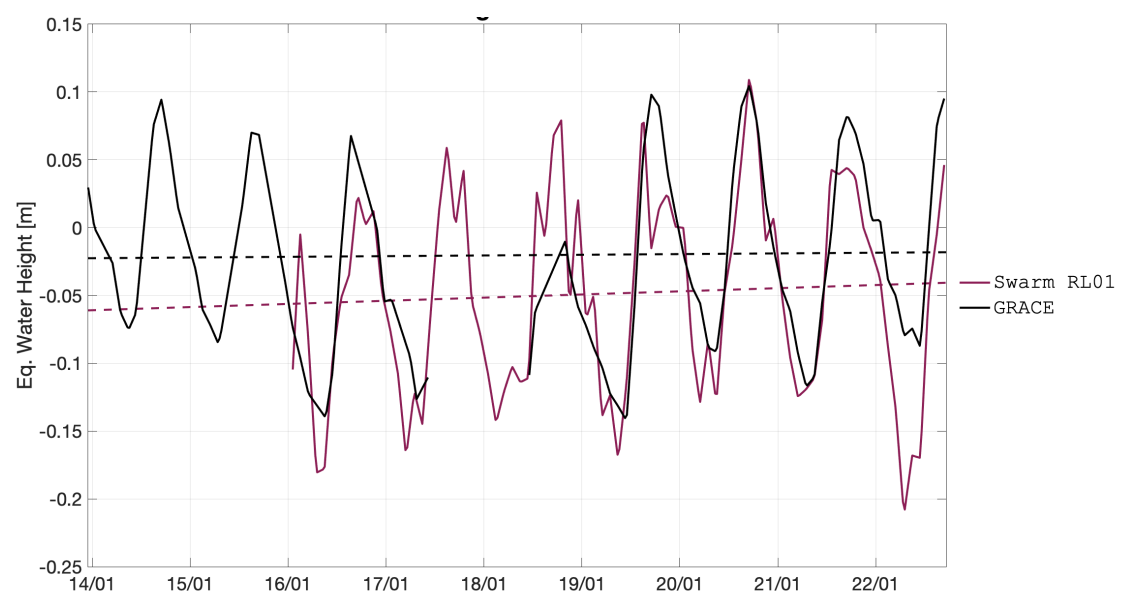


Figure 28 – Time series of EWH for the Ganges-Brahmaputra basin (latitude 15 to 30 degrees, longitude 72 to 89 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|--------------------|-----------------------------|-----------------------|--------------------------------|------------------|
| Swarm RL01 | -5.05 | -2.25 | 0.23 | 0.18 | 0.81 |
| GRACE | -2.79 | 0.00 | 0.05 | 0.00 | 1.00 |

Table 16 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Ganges-Brahmaputra basin.

5.5.15 Indochina region

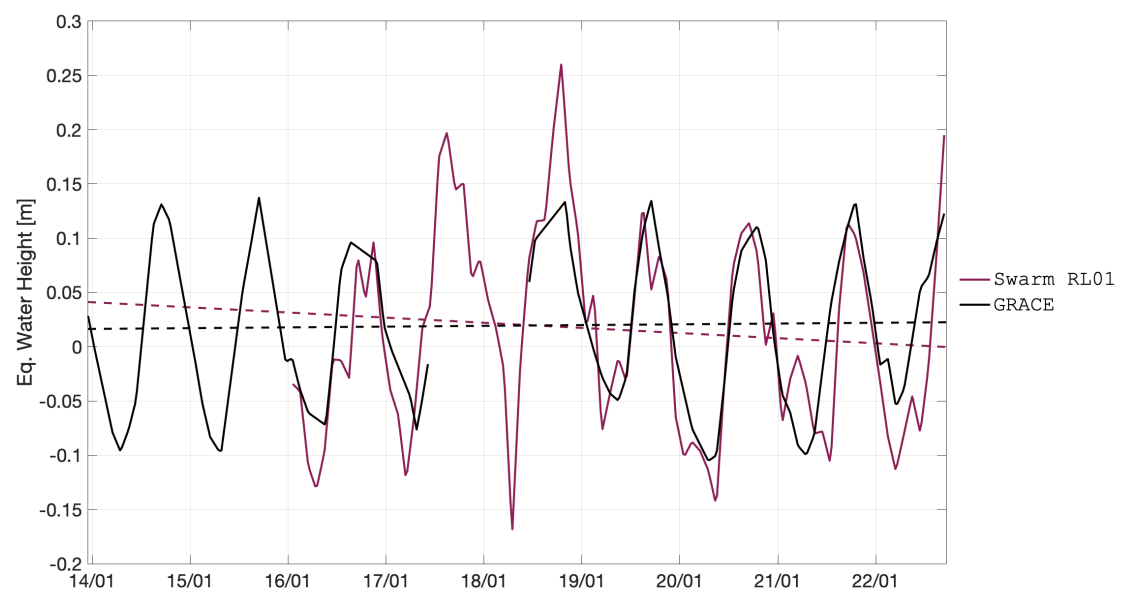


Figure 29 – Time series of EWH for the Indochina region (latitude 12 to 29 degrees, longitude 93 to 105 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|-----------------------|--------------------------------|--------------------------|-----------------------------------|---------------------|
| Swarm RL01 | 1.30 | 0.09 | -0.47 | -0.54 | 0.80 |
| GRACE | 1.21 | 0.00 | 0.07 | 0.00 | 1.00 |

Table 17 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Indochina region.

5.5.16 Northern Australia region

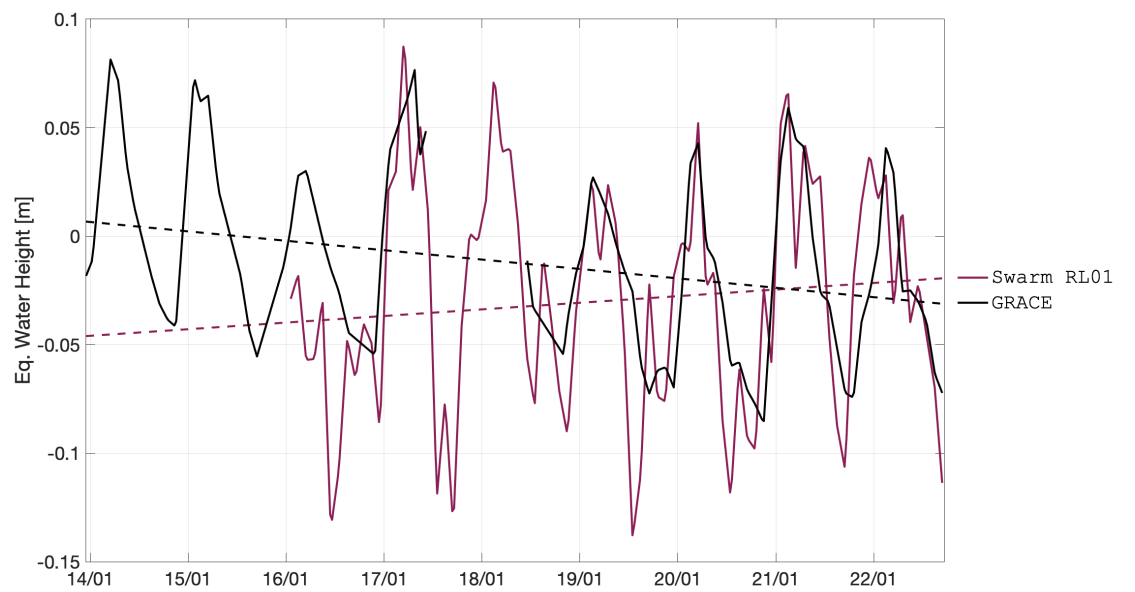


Figure 30 – Time series of EWH for the Northern Australia region (latitude -24 to -10 degrees, longitude 124 to 145 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|--------------------|-----------------------------|-----------------------|--------------------------------|------------------|
| Swarm RL01 | -2.89 | -1.89 | 0.30 | 0.74 | 0.65 |
| GRACE | -1.00 | 0.00 | -0.43 | 0.00 | 1.00 |

Table 18 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Northern Australia region.

5.5.17 Western Antarctica region

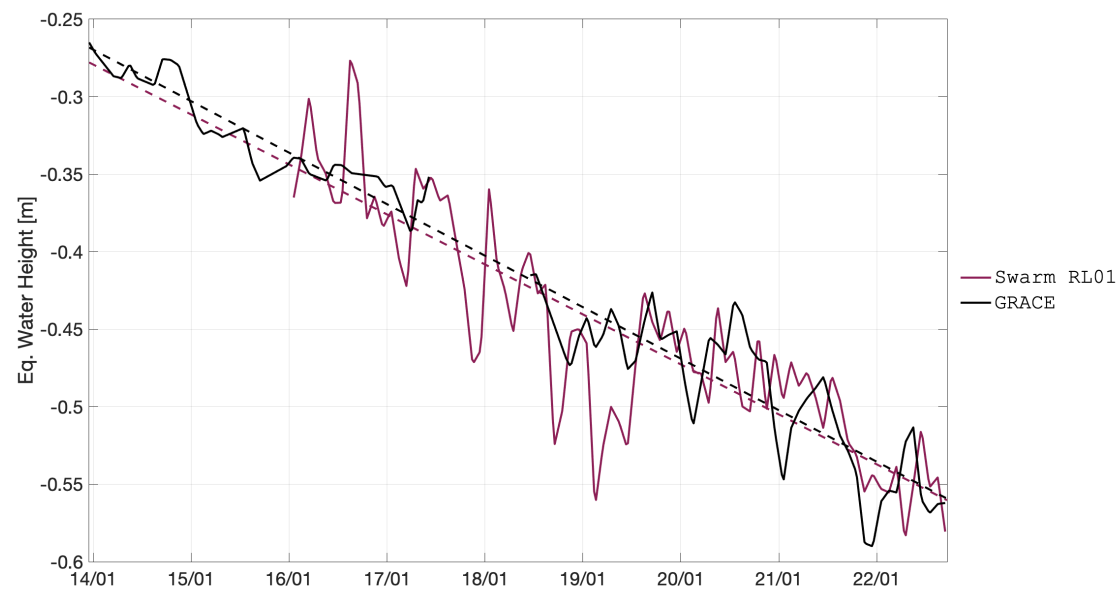


Figure 31 – Time series of EWH for the Western Antarctica region (latitude -80 to -70 degrees, longitude -140 to -85 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|-----------------------|--------------------------------|--------------------------|-----------------------------------|---------------------|
| Swarm RL01 | -45.23 | -2.69 | -3.22 | 0.10 | 0.88 |
| GRACE | -42.54 | 0.00 | -3.32 | 0.00 | 1.00 |

Table 19 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Western Antarctica region.

5.5.18 Eastern Antarctica region

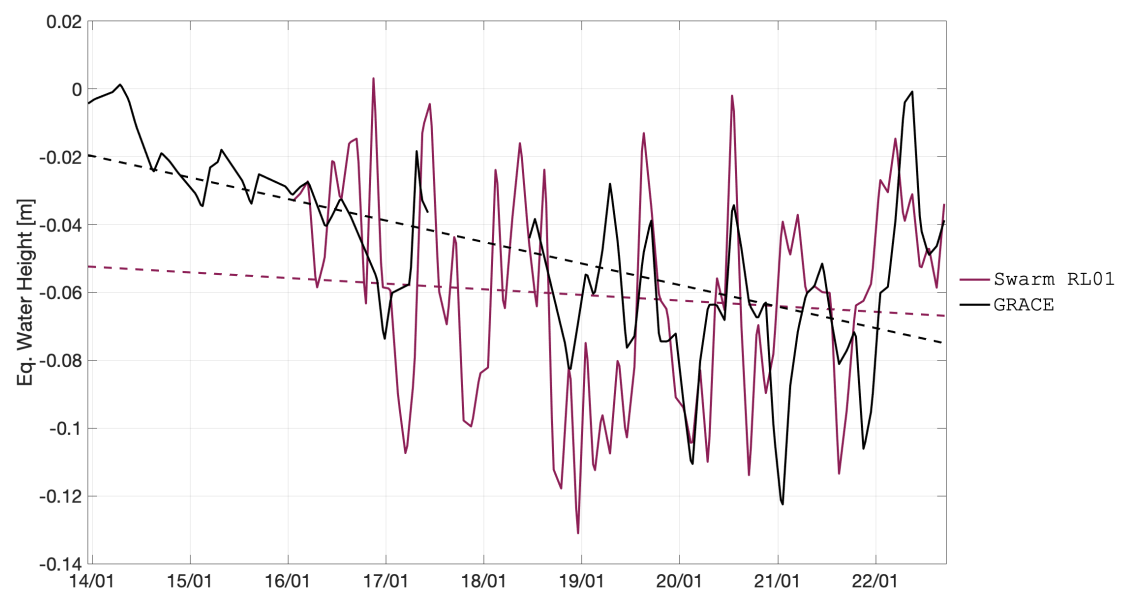


Figure 32 – Time series of EWH for the Eastern Antarctica region (latitude -80 to -68 degrees, longitude 80 to 130 degrees).

| solution | constant term [cm] | constant term Δ [cm] | linear term [cm/year] | linear term Δ [cm/year] | corr. coeff. [] |
|------------|--------------------|-----------------------------|-----------------------|--------------------------------|------------------|
| Swarm RL01 | -6.09 | -1.18 | -0.17 | 0.47 | 0.45 |
| GRACE | -4.91 | 0.00 | -0.63 | 0.00 | 1.00 |

Table 20 – Statistics of the agreement between GRACE/GRACE-FO and Swarm time series relative to the GRACE/GRACE-FO climatological model for the Eastern Antarctica region.

5.5.19 Overview

| solution | constant term Δ RMS [cm] | linear term Δ RMS [cm/year] | corr. coeff. mean [] |
|------------|---------------------------------------|--|--------------------------|
| Swarm RL01 | 1.55 | 0.69 | 0.80 |
| GRACE | 0.00 | 0.00 | 1.00 |

Table 21 – Statistics of the agreement between the GRACE and Swarm time series for the regions displayed in Sections 5.5.1 to 5.5.18.

5.6 Temporal variability

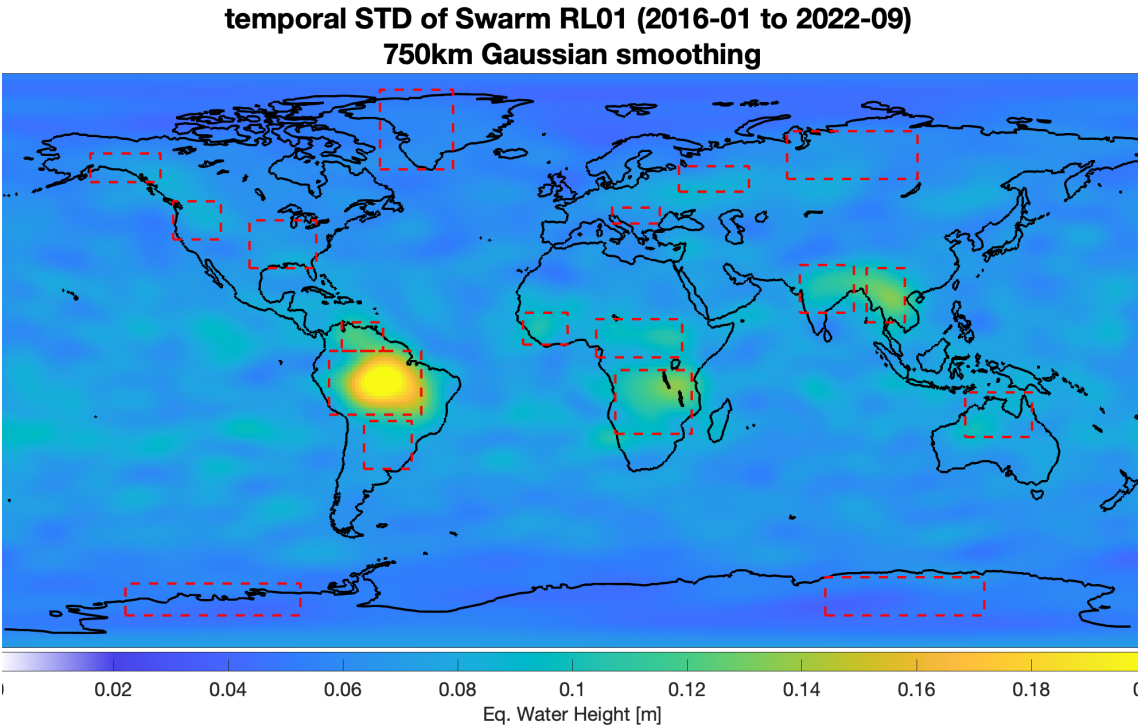


Figure 33 – Temporal variability of the Swarm combined solutions.

A Kinematic Orbits

A.1 Delft University of Technology

| | |
|----------------------|---|
| Software: | GPS High precision Orbit determination Software Tool (GHOST) (Helleputte, 2004; Wermuth, Montenbruck and Helleputte, 2010) |
| Preprocessing: | None |
| Differencing Scheme: | Undifferenced |
| Linear combination: | Ionosphere-free |

| | |
|-----------------------------------|--|
| Differential code bias: | N/A |
| Ionosphere model: | N/A |
| GPS observations: | Code and carrier phase |
| Carrier phase ambiguities: | Float |
| Estimator: | Bayesian weighted LS |
| Arc length: | 30 hours |
| Observation weighting: | A-priori weights equal to 1m and 1mm for code and phase observations (resp.) |
| Data screening: | Minimum SNR of 10, minimum of 6 GPS satellites, code and phase outlier editing threshold of 2 m and 3.5 cm, respectively, 1 meter or larger difference between estimated KO positions and with Reduced-Dynamic PSO |
| Transmitter PCV: | Official IGS08 ANTEX (Schmid et al., 2007) up to day 17/028, official IGS14 ANTEX (Rebischung and Schmid, 2016) afterwards |
| Receiver PCV: | Empirically determined from stacking of reduced-dynamic POD residuals with 1° binning |
| GPS orbits and clocks: | Final orbits and 5 seconds clocks of CODE (Dach et al., 2017) |
| Earth precession model: | IAU 1976 (Lieske et al., 1977) |
| Earth nutation model: | IAU 1980 (Seidelmann, 1982) |
| Earth orientation model: | CODE final ERP |

A.2 Astronomical Institute of the University of Bern

| | |
|-----------------------------------|---|
| Software: | Bernese v5.3 (Dach et al., 2015) |
| Preprocessing: | Cycle slip detection based on epoch-difference solution |
| Differencing Scheme: | Undifferenced |
| Linear combination: | Ionosphere-free |
| Differential code bias: | N/A |
| Ionosphere model: | N/A |
| GPS observations: | Code and carrier phase |
| Carrier phase ambiguities: | Float up to 26 January 2020, ambiguity-fixed afterwards |
| Estimator: | Batch LS |
| Arc length: | 24 hours |
| Observation weighting: | Constant |
| Data screening: | 2 cm/s or larger time-differences of the geometry-free |
| Transmitter PCV: | Official IGS08 ANTEX (Schmid et al., 2007) up to day 17/028, official IGS14 ANTEX (Rebischung and Schmid, 2016) afterwards |
| Receiver PCV: | Stacking of carrier phase residuals from reduced-dynamic POD of approx. 120 days, 9 iterations, 1° binning linear combination of L1B GPS carrier phase observations |
| GPS orbits and clocks: | Final orbits and 5 seconds clocks of CODE (Dach et al., 2017) |
| Earth precession model: | IERS 2010 Conventions (Petit and Luzum, 2010) |
| Earth nutation model: | IERS 2010 Conventions (Petit and Luzum, 2010) |
| Earth orientation model: | CODE final ERP |

A.3 Institute of Geodesy Graz

| | |
|------------------|--|
| Software: | Gravity Recovery Object Oriented Programming System (GROOPS) (Mayer-gürr et al., 2020) |
|------------------|--|

| | |
|-----------------------------------|--|
| Preprocessing: | Cycle slip detection based on Melbourne-Wuebbena combination |
| Differencing Scheme: | Raw undifferenced |
| Linear combination: | None (the ionospheric influence is co-estimated) |
| Differential code bias: | Graz University of Technology (TUG) daily estimated absolute biases |
| Ionosphere model: | Slant total electron content (STEC) 1st, 2nd and 3rd order effects (Hoque and Jakowski, 2008) estimated in each epoch for each receiver-transmitter pair |
| GPS observations: | Code and carrier phase |
| Carrier phase ambiguities: | MLAMBDA (Chang, Yang and Zhou, 2005) |
| Estimator: | LS |
| Arc length: | 24 hours |
| Observation weighting: | Elevation and azimuth-dependent, ROTI dependent |
| Data screening: | Implicit in VCE |
| Transmitter PCV: | Empirical, estimated from 5.5 years of data, including data from several LEO missions (GRACE, Jason 2 & 3, MetOp-A & -B, Sentinel 3A, Swarm, TanDEM-X, TerraSAR-X) (Zehentner, 2016) |
| Receiver PCV: | Empirical, spherical harmonics (maximum D/O 100), derived from 38 months of data |
| GPS orbits: | TUG, estimated using ≈ 200 daily IGS stations |
| GPS clocks: | TUG 30 seconds, interpolated using CODE 5 seconds finals to a sampling of 5 seconds |
| Earth precession model: | IAU 2006/2000A precession-nutation model (Coppola, Seago and Vallado, 2009) |
| Earth nutation model: | IAU 2006/2000A precession-nutation model (Coppola, Seago and Vallado, 2009) |
| Earth orientation model: | IERS EOP 08 C04 (Petit and Luzum, 2010) |

A.4 Common

| | |
|------------------------------------|---|
| Receiver clock corrections: | Co-estimated |
| Phase wind-up: | Correction applied |
| Sampling rate: | 10 seconds up to 15 July 2014, 1 seconds afterwards |
| Receiver antenna offset: | satellite specific values |
| Elevation cut-off angle: | 0° |
| Swarm attitude: | L1B attitude data |
| GPS attitude model: | (Kouba, 2009) |

B Gravity Field Models

B.1 Astronomical Institute of the University of Bern

| | |
|---------------------------------|---|
| Software: | Bernese v5.3 (Dach et al., 2015) |
| Approach: | Celestial Mechanics Approach (CMA) (Beutler et al., 2010) |
| Reference GFM: | AIUB-GRACE03S (Jäggi et al., 2011) |
| Empirical Parameters: | Daily and 15 minutes, both piecewise-constant (constrained) |
| Coord. Axis Combination: | TBD |
| Single Sat. Combination: | NEQ, equal weights |

| | |
|---------------------------------|--|
| Temporal correlations: | None |
| Drag Model: | None |
| EARP and EIRP Models: | None |
| Non-tidal Model: | Unti Nov 2017: AOD1B (Flechtner, Schmidt and Meyer, 2006; Flechtner, 2007; Flechtner, 2011) After Nov 2017: AOD1B-RL06 (Dobslaw et al., 2017) |
| Atmospheric Tidal Model: | TBD |
| Ocean Tidal Model: | EOT11a (Savcenko and Bosch, 2012) |
| Permanent Tide System: | tide-free |

B.2 Astronomical Institute Ondřejov

| | |
|---------------------------------|---|
| Software: | (developed in-house) |
| Approach: | Decorrelated Acceleration Approach (DAA) (Bezděk et al., 2014; Bezděk et al., 2016) |
| Reference GFM: | ITG-GRACE2010s (Mayer-Gürr et al., 2010) |
| Empirical Parameters: | Daily constant-piecewise |
| Coord. Axis Combination: | TBD |
| Single Sat. Combination: | NEQ, equal weights |
| Temporal correlations: | Empirical decorrelation filter |
| Drag Model: | NRLMSISE (Picone et al., 2002) |
| EARP and EIRP Models: | Knocke, Ries and Tapley (1988) |
| Non-tidal Model: | AOD1B-RL06 (Dobslaw et al., 2017) |
| Atmospheric Tidal Model: | Biancale and Bode (2006) |
| Ocean Tidal Model: | FES2004 (Lyard et al., 2006) |
| Permanent Tide System: | tide-free |

B.3 Institute of Geodesy Graz

| | |
|---------------------------------|--|
| Software: | Gravity Recovery Object Oriented Programming System (GROOPS) (Mayer-gürr et al., 2020) |
| Approach: | Short-Arcs Approach (SAA) (Mayer-Gürr, 2006) |
| Reference GFM: | GOCO05S (Mayer-Gürr, 2015) |
| Empirical Parameters: | Piecewise linear for each arc (ranging from 15 to 45 minutes) |
| Coord. Axis Combination: | TBD |
| Single Sat. Combination: | NEQ, relative weighting from VCE |
| Temporal correlations: | Empirical covariance function |
| Drag Model: | JB2008 (Bowman et al., 2008) |
| EARP and EIRP Models: | Rodriguez-Solano et al. (2012) |
| Non-tidal Model: | AOD1B-RL06 (Dobslaw et al., 2017) |
| Atmospheric Tidal Model: | Biancale and Bode (2006) |
| Ocean Tidal Model: | FES2014 (Carrere et al., 2015) |
| Permanent Tide System: | zero tide |

B.4 Ohio State University

| | |
|-----------------------|--|
| Software: | (developed in-house) |
| Approach: | Improved Energy Balance Approach (IEBA) (Shang et al., 2015) |
| Reference GFM: | GIF48 (Ries et al., 2011) up to D/O 200 |

| | |
|---------------------------------|--|
| Empirical Parameters: | 2nd order polynomial every 3 hours, 1-CPR sinusoidal every 24 hours |
| Coord. Axis Combination: | TBD |
| Single Sat. Combination: | NEQ, equal weights |
| Temporal correlations: | None |
| Drag Model: | NRLMSISE (Picone et al., 2002) |
| EARP and EIRP Models: | Knocke, Ries and Tapley (1988) |
| Non-tidal Model: | AOD1B (Flechtner, Schmidt and Meyer, 2006; Flechtner, 2007; Flechtner, 2011) |
| Atmospheric Tidal Model: | Biancale and Bode (2006) |
| Ocean Tidal Model: | EOT11a (Savcenko and Bosch, 2012) |
| Permanent Tide System: | tide-free |

B.5 Common

| | |
|--|---|
| Regularization: | none |
| Solid Earth Tidal Model: | IERS2010 |
| Pole Tidal Model: | IERS2010 |
| Ocean Pole Tidal Model: | IERS2010 |
| Third body perturbations: | Sun, Moon, Mercury, Venus, Mars, Jupiter and Saturn, following the JPL-PLS (Folkner et al., 2014) |
| $C_{2,0}$ coefficient: | estimated alongside other coefficients |

Acronyms

| | |
|----------------------|--|
| AA | Acceleration Approach, Rummel (1979) |
| AIUB | Astronomical Institute of the University of Bern, Switzerland, www.aiub.unibe.ch |
| AIUB-GRACE03S | AIUB GRACE-only static model, version 3, Jäggi et al. (2011) |
| AOD1B | Atmosphere and Ocean De-aliasing Level 1B product, Flechtner, Schmidt and Meyer (2006), Flechtner (2007) and Flechtner (2011) |
| AOD1B-RL06 | Atmosphere and Ocean De-aliasing Level 1B RL06 product, Dobslaw et al. (2017) |
| ASU | Astronomical Institute (Astronomický ústav), AVCR, Ondřejov, www.asu.cas.cz/en |
| AVCR | Czech Academy of Sciences (Akademie věd České Republiky), Czech Republic, www.avcr.cz/en/ |
| CODE | Centre for Orbit Determination in Europe, Dach et al. (2017) |
| CMA | Celestial Mechanics Approach, Beutler et al. (2010) |
| CPR | Cycle Per Revolution |
| CSR | Center for Space Research, UT Austin, USA, www.csr.utexas.edu |
| D/O | Degree and Order |
| DAA | Decorrelated Acceleration Approach, Bezděk et al. (2014) and Bezděk et al. (2016) |
| EARP | Earth Albedo Radiation Pressure |
| EIRP | Earth Infrared Radiation Pressure |
| EBA | Energy Balance Approach, O'Keefe (1957) and Jekeli (1999) |
| EOT | Empirical Ocean Tide model |
| EOT11a | 2011 Empirical Ocean Tide model, Savcenko and Bosch (2012) |
| EWB | Equivalent Water Height |
| EOP | Earth Orientation Parameter |
| ERP | Earth Rotation Parameters |

| | |
|-----------------------|---|
| FES | Finite Element Solution global tide model |
| FES2004 | 2004 Finite Element Solution global tide model, Lyard et al. (2006) |
| FES2014 | 2014 Finite Element Solution global tide model, Carrere et al. (2015) |
| GFM | Gravity Field Model |
| GIF48 | GRACE Intermediate Field 48, Ries et al. (2011) |
| GNSS | Global Navigation Satellite System |
| GOCE | Gravity field and steady-state Ocean Circulation Explorer, Balmino et al. (1999) and Floberghagen et al. (2011) |
| GOCO | Gravity Observation COmbination |
| GOCO05S | GOCO release 05 satellite-only gravity field model, Mayer-Gürr (2015) |
| GPS | Global Positioning System |
| GRACE | Gravity Recovery And Climate Experiment, Tapley, Reigber and Melbourne (1996) and Tapley (2004) |
| GRACE-FO | GRACE Follow On, Kornfeld2019 |
| IAU | International Astronomical Union |
| IEBA | Improved Energy Balance Approach, Shang et al. (2015) |
| IERS | International Earth Rotation Service |
| IERS2010 | IERS Conventions 2010, Petit and Luzum (2010) |
| ifG | Institute of Geodesy, TUG, Graz, www.ifg.tugraz.at |
| IGS | International GNSS Service, Dow, Neilan and Gendt (2005) |
| ITG | Institut für Geodäsie und Geoinformation, Germany |
| ITG-GRACE2010s | ITG GRACE-only static model, 2010, Mayer-Gürr et al. (2010) |
| JB2008 | Jacchia-Bowman 2008, Bowman et al. (2008) |
| JPL | Jet Propulsion Laboratory, USA, www.jpl.nasa.gov |
| JPL-PLE | JPL Planetary and Lunar Ephemerides, Folkner et al. (2014) |
| KO | Kinematic Orbit |
| L1B | Level 1B data |
| LAMBDA | Least-squares Ambiguity De-correlation Adjustment, Teunissen (1995) |
| LEO | Low-Earth Orbit |
| LS | least-squares |
| MLAMBDA | Modified LAMBDA method, Chang, Yang and Zhou (2005) |
| N/A | Not Applicable |
| NEQ | Normal Equation |
| NRLMSISE | US Naval Research Laboratory Mass Spectrometer and Incoherent Scatter radar atmospheric model, Picone et al. (2002) |
| OSU | Ohio State University, www.osu.edu |
| PCV | Phase Center Variation |
| POD | Precise Orbit Determination |
| PSO | Precise or Post-processed Science Orbit |
| RL06 | Release 6 |
| ROTI | Rate of TEC Index |
| RMS | Root Mean Squared |
| SAA | Short-Arcs Approach, Mayer-Gürr (2006) |
| SH | Spherical Harmonic |
| SLR | Satellite Laser Ranging, Smith and Turcotte (1993) and Combrinck (2010) |
| SNR | Signal-to-Noise Ratio |
| TEC | Total Electron Content |
| TU Delft | Delft University of Technology, Netherlands, www.tudelft.nl |
| TUG | Graz University of Technology, Austria, www.tugraz.at |

| | |
|-----------|---|
| UT Austin | University of Texas at Austin, www.utexas.edu |
| USA | United States of America |
| VCE | Variance Component Estimation |
| WP | Work Package |

Symbols

C Stokes coefficient.

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