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Key Points:

- GRACE/GFO-derived global ocean mass change agrees generally well with Altimeter-Argo estimates at seasonal and long-term scales
- The GRACE/GFO and Altimeter-Argo GMOM differences become substantially larger and systematic during the late-stage GRACE and GFO periods
- The discrepancy is likely related to the single accelerometer mode of the late-stage GRACE and GFO and/or errors of Argo and altimeter data

Supporting Information:

- Supporting Information S1

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Global Ocean Mass Change From GRACE and GRACE Follow-On and Altimeter and Argo Measurements

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Abstract Satellite altimeter sea surface heights, in combination with Argo ocean temperature and salinity observations, provide an independent measure of global mean ocean mass (GMOM) change. Over the period January 2005 to April 2020, GMOM rates observed by the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GFO) range from 1.88 ± 0.10 to 2.63 ± 0.10 mm/year, compared to 2.85 ± 0.37 mm/year from Altimeter-Argo. Over much of the GRACE era, GRACE GMOM estimates agree well with Altimeter-Argo over a broadband of frequencies. However, during the late stage of the GRACE mission (after August 2016) and into the GFO era, differences between GRACE/GFO and Altimeter-Argo GMOM estimates become substantially larger and systematic, which may be related to the single accelerometer mode of operation during late-stage GRACE and GFO missions and/or errors of Argo and altimeter data.

1. Introduction

The Gravity Recovery and Climate Experiment (GRACE) satellite gravity mission launched in 2002 has provided a revolutionary means for measuring temporal variations of the Earth's gravity field with unprecedented accuracy, serving as a tool for studying mass redistribution and movement within the Earth system (Tapley et al., 2019). GRACE was decommissioned in November 2017, and the GRACE Follow-On (GFO) mission was launched in May 2018 to continue the endeavor. Over the past 18 years, GRACE/GFO time-variable gravity measurements have been widely used to study mass redistribution of mobile components of the Earth system within the hydrosphere, cryosphere, oceans, and solid Earth. GRACE has greatly improved our understanding of large-scale water mass variations in the climate system (e.g., Cazenave & Chen, 2010; Tapley et al., 2019). Given the uniqueness of the measurement, a major challenge is validating GRACE/GFO time-variable gravity solutions and associated mass changes at varied local, regional, and global spatial scales. Many of the reported signals lack independent measurements of gravity (or mass) change with spatial resolution comparable to GRACE/GFO, but global mean ocean mass (GMOM) is an exception.

GRACE/GFO satellite gravimetry provides the means to quantify GMOM change by measuring changes in Earth's gravity field. Independent estimates of GMOM change can also be determined from satellite altimetry global mean sea level (GMSL) and Argo floats observations. GMSL is an important measure of global climate change as well as the global hydrologic cycle. GMSL change is driven by two major forces, ocean mass change due to water mass redistribution between the oceans and land (including polar ice sheets) and ocean volume or density change (the so-called steric sea level change) due to ocean temperature and salinity variations. Satellite altimetry has been a well-established technique for accurately measuring global sea level change since 1992 (Cazenave et al., 2018). Over the past three decades, GMSL is rising at an estimated rate of 3.1 ± 0.3 mm/year (WCRP, 2018), on top of strong seasonal variations with an annual amplitude of ~ 10 mm (Chen et al., 2018). Steric contributions to GMSL change can be estimated from global ocean temperature and salinity observations from the Argo float array (Argo, 2000), for periods since ~ 2005 when Argo global coverage became relatively complete. The difference between GMSL change from altimetry and steric changes from Argo (Altimeter minus Argo or Altimeter-Argo) is an independent estimate of GMOM change to validate GMOM from GRACE/GFO satellite gravimetry.

Continuing advancement of the three observational techniques (GRACE/GFO gravimetry, satellite altimetry, and Argo floats) has led to improved understanding of GMSL change. Previous studies (Chambers et al., 2017; Chen et al., 2013; Dieng et al., 2017; Rietbroek et al., 2016; WCRP, 2018; Yi et al., 2015) focused on closing the sea level rise budget, reconciling trends in GMSL estimates from altimetry, GRACE, and Argo. Good agreement was found in GMSL trends from altimeter and the sum (GRACE + Argo). Other studies (e.g., Chen et al., 2018, 2019; Llovel et al., 2019) compared GRACE-estimated GMOM changes with altimetry and Argo using the difference (Altimeter-Argo) seeking validation of both GRACE and Altimeter-Argo estimates. GRACE- GMOM changes were found to agree well with Altimeter-Argo over a broadband of frequencies, from seasonal, interannual, and longer time scales (Chen et al., 2018).

Accurate quantification of GMOM changes using GRACE/GFO is difficult. GMOM changes include the largest spatial scales that GRACE/GFO can measure and are subject to uncertainties related to several aspects of GRACE/GFO postprocessing. Among these are signal leakage between land and oceans due to the limited degree and order range of GRACE/GFO gravity spherical harmonic (SH) coefficients, which is mainly controlled by the altitude (~500 km at launch) of GRACE/GFO satellites and the intersatellite distance (~220 km); needed spatial filtering to suppress noise in GRACE/GFO gravity solutions; uncertainty in GRACE/GFO low-degree SH coefficients (especially the degree 2 zonal coefficient ΔC_{20} , also termed as ΔJ_2 by a scale factor); the need to independently determine geocenter motion (or equivalently degree 1 SH coefficients, ΔC_{11} , ΔS_{11} , and ΔC_{10}); and the need to model and remove solid Earth geophysical signals, including Glacial Isostatic Adjustment (GIA) and earthquake-related deformation.

There has been continued progress in addressing these and other postprocessing issues over time. For example, a recent study (Chen et al., 2019) demonstrated that appropriately enforcing total mass conservation in GRACE solutions led to notably improved agreement between GRACE and Altimeter-Argo GMOM estimates. After a 1-year gap between GRACE and GFO missions, GFO data are now available through April 2020. Preliminary analysis indicates that GFO solutions have comparable precision and spatiotemporal resolution as GRACE (Landerer et al., 2020). However, the accelerometer onboard one GFO satellite is not functioning correctly (upon launch), and the impact of this hardware issue on gravity solutions remains unclear. A likely effect would be the particularly large uncertainties in ΔC_{20} and ΔC_{30} (noted as ΔJ_2 and ΔJ_3 hereafter), consistent with late-stage GRACE solutions (after August 2016) when one accelerometer failed.

The motivation of this study is to continue independent validation of satellite gravimetry solutions into the GFO era. GMOM change is estimated using the extended records of GRACE and GFO and Altimeter-Argo estimates, and they are compared at various time scales. This continues the effort to validate GRACE/GFO GMOM estimates and, additionally, reveals increasing disagreement between Altimeter-Argo and GRACE/GFO solutions during late stages of GRACE and early years of GFO missions.

2. Data Processing

2.1. GRACE/GFO Gravity Solutions

GRACE/GFO gravity solutions as fully normalized SH coefficients (up to degree and order 60 or 96) are provided by three GRACE/GFO data processing centers, including the Center for Space Research (CSR) at the University of Texas at Austin, German Geoforschungszentrum (GFZ), and NASA Jet Propulsion Laboratory (JPL). SH solutions are referred to as GSM solutions (see Yuan, 2019 for GRACE/GFO file name conventions). GRACE/GFO Release 6 (RL06) GSM solutions used in the present analysis include 133 monthly solutions (up to degree and order 60) from GRACE covering the period January 2005 to June 2017 and 21 solutions from GFO covering the period June 2018 to April 2020 (after the gap of about 1 year between GRACE and GFO). The selection of this time span (after 2005) is based on the availability of Argo data. The GRACE and GFO RL06 solutions from CSR, JPL, and GFZ are obtained with the same data processing standards and background geophysical models (except for the tide models) but using different processing strategies and software (Bettadpur, 2018). Independent ΔJ_2 and ΔJ_3 solutions estimated from Satellite Laser Ranging (SLR) data are provided by the GRACE/GFO project (GRACE Technical Note 14), as recommended replacements of GRACE/GFO values (Loomis et al., 2019). Estimated geocenter motion time series are also provided by the GRACE/GFO project as supplementary data sets (GRACE Technical Note 13) (Landerer, 2019). GIA corrections to GRACE/GFO GMOM estimates are computed from the ICE6G-D model (Peltier et al., 2018).

In addition to the GRACE/GFO CSR, JPL, and GFZ RL06 gravity SH solutions, two GRACE/GFO RL06 mascon (mass concentration) solutions covering the same period (January 2005 to April 2020) provided by CSR and JPL are also used in the study to estimate GMOM change. Mascon solutions offer improved spatial resolution and data quality and reduce the effect of the longitudinal striping (found in the SH solutions) (Save et al., 2016; Wiese et al., 2016). The CSR RL06 mascon solutions (Version 2) are determined for $1^\circ \times 1^\circ$ equal-area elements and represented on $0.25^\circ \times 0.25^\circ$ grids. The JPL RL06 mascons are determined for $3^\circ \times 3^\circ$ equal-area elements, represented on $0.5^\circ \times 0.5^\circ$ grids. For GRACE/GFO SH solutions, the GMOM changes are estimated using an ocean mask with a 500-km buffer zone (excluding coastal ocean areas within 500 km of coastlines). This is to reduce leakage error in GRACE/GFO GMOM estimates (Chambers et al., 2010; Chen et al., 2018). Leakage error is also expected in the CSR GRACE/GFO mascon solutions (Save et al., 2016), and here we use an ocean mask with a 200-km buffer zone to minimize leakage error in the associated GMOM estimates. Leakage effects in the JPL mascon solutions were addressed by the Coastal Resolution Improvement (CRI) filter (Wiese et al., 2016).

GRACE/GFO GSM estimates are based on the GSM solutions only, without adding back the GAD fields (representing dynamic ocean signal and atmospheric loading over the ocean). Using GSM only or using GSM + GAD (but removing the GAD mean over the ocean) leads to very similar GMOM estimates, introducing a slight 0.03-mm/year difference in estimated GMOM rates for the period January 2005 to April 2020, which is consistent with findings of Chen et al. (2019). Neglecting the GAD mean (GAD) effect may cause some inconsistency with altimeter-observed GMOM, but the difference is rather small and does not affect the conclusions of this study.

2.2. Satellite Altimeter and Argo Data

The satellite altimetry GMSL series is provided by the French AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic Data) processing center. The AVISO series is calculated using data from multiple satellite altimeters (merged altimeter products) on 10-day intervals covering the period 1993 to the present (see Ablain et al., 2018, 2019 for details of AVISO processing). A monthly GMSL series from January 2005 to April 2020 is derived from the 10-day series by resampling at the middle of the month, and a GIA correction of ~ -0.3 mm/year was applied (Peltier, 2009).

Argo estimates are derived from three different data products, provided by the Scripps Institution of Oceanography (SIO) at the University of California at San Diego, the International Pacific Research Center (IPRC) at the University of Hawaii, and the Agency for Marine-Earth Science and Technology (JAMS) of Japan. Estimates include ocean depths to about 2,000 m, starting in 2004 (for SIO) or 2005 (for IPRC and JAMS). Monthly steric contributions to GMSL change from January 2005 to April 2020 are computed from the three Argo data sets. Steric effects from the deep oceans (below 2,000 m) are expected to be small (~ 0.1 mm/year) (Llovel et al., 2019) and are not included in the present study due to lack of reliable observations.

3. Results

3.1. GMOM Changes From GRACE/GFO and Altimeter-Argo

Figure 1a compares GRACE/GFO GMOM estimates with comparable estimates from Altimeter-Argo measurements for the period January 2005 to April 2020. The three GRACE/GFO series are derived from the CSR RL06 GSM solutions with a 500-km ocean mask, CSR RL06 GSM solutions using forward modeling (FM, an alternative method to reduce leakage error) (see Text S1 in supporting information [SI] for details), and CSR RL06 mascons (labeled MC in plots and tables). In general, the three GRACE/GFO GMOM estimates agree well with Altimeter-Argo, especially at seasonal time scales, consistent with findings from previous studies (e.g., Chen et al., 2018, 2019). However, significant discrepancies are observed during the GFO period (June 2018 to April 2020). There is also a slight phase difference between the GRACE/GFO and Altimeter-Argo GMOM estimates, which is believed to be related to the absence of degree-0 (ΔC_{00}) SH terms in GRACE/GFO SH and MC solutions (Chen et al., 2019). During most of the GRACE time span, the three GRACE/GFO GMOM series and Altimeter-Argo estimates also agree well at interannual and long-term time scales (see Figure 1b). The discrepancies between GRACE/GFO and Altimeter-Argo estimates during GFO and late GRACE periods are more obvious when seasonal variations are removed.

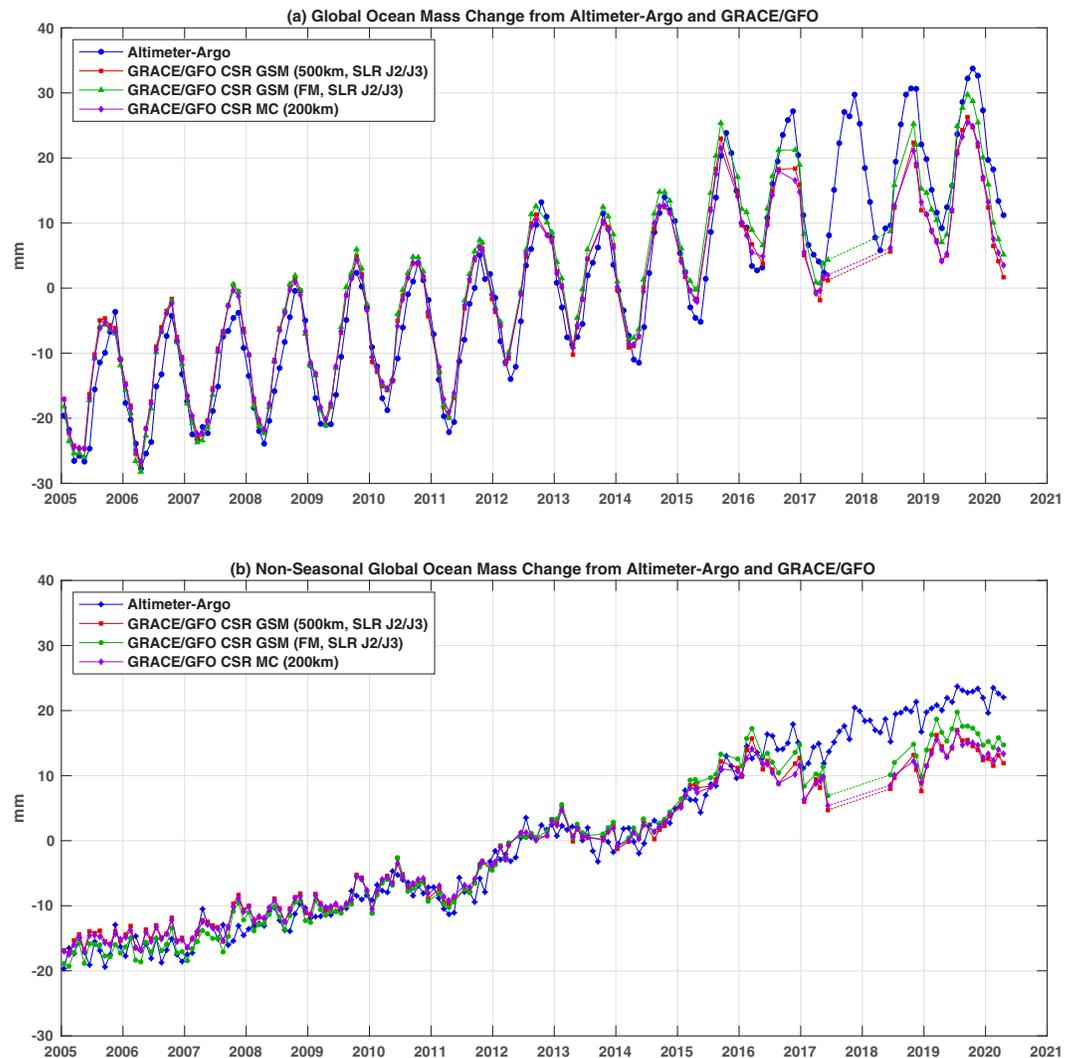


Figure 1. (a) Monthly global mean ocean mass change (in mm of equivalent sea level change) derived from altimeter minus Argo (Altimeter-Argo) and three GRACE/GFO estimates based on CSR RL06 GSM and MC solutions over the period January 2005 and April 2020. The two CSR GSM estimates are computed from 500-km ocean basin kernel and forward modeling (FM), and the CSR MC estimates are computed from 200-km ocean basin kernel (i.e., Cases 2, 8, and 5 in Table 2, all with J2/J3 replacements). (b) Same as (a) but with annual and semiannual variations removed.

Table 1 gives amplitudes and phases of annual and semiannual variations and linear trends of GMSL change from altimetry and from a combination of Argo, with each of eight different GRACE/GFO GMOM estimates for the period January 2005 to April 2020. In addition to the three GRACE/GFO estimates in Figure 1, the other five GRACE/GFO estimates include three (CSR, JPL, and GFZ) SSH solutions with ΔJ_2 and ΔJ_3 replaced by SLR solutions (Loomis et al., 2019), JPL MC, and CSR GSM from FM with ΔJ_2 and ΔJ_3 replaced by SLR data. The results (Table 1) for altimeter, Argo, and Argo ensemble mean are calculated from monthly series over the entire time period (January 2005 to April 2020). Because missing months (and the 1-year gap) in GRACE/GFO series may affect Table 1 values, a separate calculation using Altimeter-Argo series resampled at GRACE/GFO epochs is also given in Table 1 [noted as Altimeter-Argo (SIO/JAMS/IPRC)*]. Differences in sampling times affect estimated seasonal terms and trends. The resampled Altimeter-Argo series is used in the following comparison with GRACE/GFO.

Seasonal terms of the eight GRACE/GFO GMOM estimates are similar, with the exception of JPL MC, with a smaller annual amplitude, and $\sim 5^\circ$ phase difference relative to the others. The source of this difference is unknown but may be related to the CRI filter suppressing leakage between land and oceans in JPL MC

Table 1

Amplitudes and Phases of Annual and Semiannual Components and Linear Trends of Global Mean Sea Level Change From Satellite Altimeter, Steric Contributions From Argo Observations, Ocean Mass Estimates From Altimeter-Argo, and Eight Different GRACE/GFO Ocean Mass Estimates (Cases 1–8) for the Period January 2005 to April 2020

Global mean sea level	Annual		Semiannual		Linear trend (mm/year)
	Amplitude (mm)	Phase (deg)	Amplitude (mm)	Phase (deg)	
GMSL: Altimeter	6.28 ± 0.32	148 ± 3	1.29 ± 0.32	222 ± 14	3.92 ± 0.30
Steric: Argo (SIO)	4.80 ± 0.24	4 ± 3	1.36 ± 0.24	213 ± 10	1.25 ± 0.04
Steric: Argo (JAMS)	4.89 ± 0.22	8 ± 23	1.47 ± 0.22	213 ± 9	0.87 ± 0.04
Steric: Argo (IPRC)	5.67 ± 0.22	3 ± 22	1.23 ± 0.22	227 ± 10	0.88 ± 0.04
Steric: Argo (SIO/JAMS/IPRC)	5.12 ± 0.19	5 ± 2	1.35 ± 0.19	217 ± 8	1.00 ± 0.22
GMOM: Altimeter-Argo (SIO/JAMS/IPRC)	10.82 ± 0.30	165 ± 2	0.13 ± 0.30	334 ± 132	2.92 ± 0.37
GMOM: Altimeter-Argo (SIO/JAMS/IPRC)*	10.47 ± 0.32	165 ± 2	0.33 ± 0.32	49 ± 54	2.85 ± 0.37
GMOM Case 1: CSR GSM (500 km)	10.57 ± 0.34	176 ± 2	1.00 ± 0.34	13 ± 20	2.43 ± 0.05
GMOM Case 2: CSR GSM (500 km, SLR J2/J3)	10.43 ± 0.30	177 ± 2	1.15 ± 0.30	34 ± 15	2.22 ± 0.05
GMOM Case 3: JPL GSM (500 km, SLR J2/J3)	10.43 ± 0.30	177 ± 2	1.07 ± 0.30	39 ± 16	2.23 ± 0.05
GMOM Case 4: GFZ GSM (500 km, SLR J2/J3)	10.48 ± 0.32	176 ± 2	1.29 ± 0.32	55 ± 14	2.15 ± 0.05
GMOM Case 5: CSR MC (200 km)	10.04 ± 0.26	176 ± 2	1.12 ± 0.26	34 ± 13	2.24 ± 0.04
GMOM Case 6: JPL MC	8.70 ± 0.22	171 ± 2	0.83 ± 0.22	37 ± 15	2.21 ± 0.04
GMOM Case 7: CSR GSM (FM)	10.86 ± 0.33	176 ± 2	1.04 ± 0.33	17 ± 18	2.72 ± 0.5
GMOM Case 8: CSR GSM (FM, SLR J2/J3)	10.74 ± 0.31	177 ± 2	1.18 ± 0.30	35 ± 15	2.54 ± 0.05

Note. Most of the listed uncertainties represent only the formal least squares fitting error (1 sigma for amplitudes, phases, and trends), except for the altimeter trend (± 0.30 mm/year from WCRP, 2018) and Argo ensemble mean trend (± 0.22 mm taken as the standard deviation of the three Argo estimates, as well as Altimeter-Argo (square root of the sum of the two)). Phase ϕ is defined for the annual term as $\sin[2\pi(t - t_0) + \phi]$, where t_0 refers to t_0^0 on 1 January and similarly for the semiannual term.

Because missing months (and the 1-year gap) in GRACE/GFO series may affect Table 1 values, a separate calculation using Altimeter-Argo series resampled at GRACE/GFO epochs is also given as Altimeter-Argo (SIO/JAMS/IPRC)*.

solutions. Additional analysis (not shown here) suggests that even when a 200-km ocean kernel is used to minimize residual leakage error, JPL MC estimates still retain a relatively smaller annual amplitude. The annual phases of the other seven GRACE/GFO GMOM estimates are virtually the same ($\sim 176^\circ$), with a phase lag (of $\sim 12^\circ$) compared to Altimeter-Argo, consistent with our visual examination discussed above. However, linear trends of the eight GRACE/GFO GMOM estimates differ substantially, ranging from 1.97 to 2.72 mm/year. Replacing GRACE/GFO ΔJ_2 and ΔJ_3 with SLR solutions reduces the GMOM trends by ~ 0.4 mm/year (when 500-km basin kernel is used). The two MC estimates show similar trends (~ 2.24 and 2.21 mm/year), and the two FM trends are notably larger (by ~ 0.3 mm/year) than the ocean basin kernel estimates. One finds the best agreement with Altimeter-Argo (2.72 vs. 2.85 mm/year) when GRACE/GFO ΔJ_2 and ΔJ_3 are retained and FM is used to suppress land-ocean leakage.

As noted by Chen et al. (2019), improved results are obtained by enforcing global water mass conservation. This means that the sum of water mass in the atmosphere, hydrosphere, cryosphere, and ocean is constant, and the condition is implemented by adding the negative of ΔC_{00} coefficients from GRACE/GFO GAC fields. GAC fields are supplementary GRACE/GFO project data sets representing atmospheric and oceanic signals removed from GRACE/GFO solutions. We recomputed CSR and JPL MC GMOM estimates by enforcing mass conservation in a similar way. Table 2 shows Altimeter-Argo (resampled to GRACE/GFO epochs) and eight updated GRACE/GFO GMOM estimates. After enforcing mass conservation, the $\sim 12^\circ$ annual phase lags between GRACE/GFO and Altimeter-Argo time series are greatly diminished. Mass conservation also causes minor changes (decreases) in GRACE/GFO GMOM trends. Listed uncertainties are formal least squares fitting errors (1 sigma for amplitudes, phases, and trends), except for the Altimeter-Argo trend. The eight GRACE/GFO GMOM rates range from 1.88 ± 0.10 to 2.63 ± 0.10 mm/year. True uncertainties of GRACE/GFO estimates are difficult to quantify but are expected to be larger than the formal errors.

3.2. Comparing Altimeter-Argo and GRACE/GFO Residuals

To better understand differences between Altimeter-Argo and GRACE/GFO GMOM estimates, we show in Figure 2a residual time series between Altimeter-Argo and three GRACE/GFO estimates similar to Figure 1a but with global mass conservation enforced. Residual series between Altimeter-Argo and the

Table 2

Amplitudes and Phases of Annual and Semiannual Components and Linear Trends of Global Mean Ocean Mass Change From Altimeter Minus Argo (Altimeter-Argo) and Eight Different GRACE/GFO Estimates (Cases 1–8) for the Period January 2005 to April 2020, With Global Mean Atmospheric Mass Change Effect (i.e., the ΔC_{00} Terms) Considered Using the GRACE/GFO GAC Fields

Global mean sea level	Annual		Semiannual		Linear trend (mm/year)
	Amplitude (mm)	Phase (deg)	Amplitude (mm)	Phase (deg)	
GMOM: Altimeter-Argo	10.47 ± 0.32	165 ± 2	0.33 ± 0.32	49 ± 54	2.85 ± 0.37
GMOM Case 1: CSR GSM (500 km)	10.39 ± 0.34	168 ± 2	0.53 ± 0.34	15 ± 36	2.34 ± 0.05
GMOM Case 2: CSR GSM (500 km, SLR J2/J3)	10.23 ± 0.31	168 ± 2	0.74 ± 0.31	49 ± 24	2.13 ± 0.05
GMOM Case 3: JPL GSM (500 km, SLR J2/J3)	10.22 ± 0.31	169 ± 2	0.69 ± 0.31	57 ± 26	2.14 ± 0.05
GMOM Case 4: GFZ GSM (500 km, SLR J2/J3)	10.28 ± 0.33	169 ± 2	1.00 ± 0.32	74 ± 19	2.07 ± 0.05
GMOM Case 5: CSR MC (200 km)	9.85 ± 0.27	168 ± 2	0.71 ± 0.27	49 ± 22	2.15 ± 0.04
GMOM Case 6: JPL MC	8.67 ± 0.27	161 ± 2	0.45 ± 0.23	64 ± 29	2.12 ± 0.04
GMOM Case 7: CSR GSM (FM)	10.67 ± 0.33	168 ± 2	0.57 ± 0.33	23 ± 33	2.63 ± 0.05
GMOM Case 8: CSR GSM (FM, SLR J2/J3)	10.54 ± 0.31	169 ± 2	0.78 ± 0.31	49 ± 23	2.45 ± 0.05

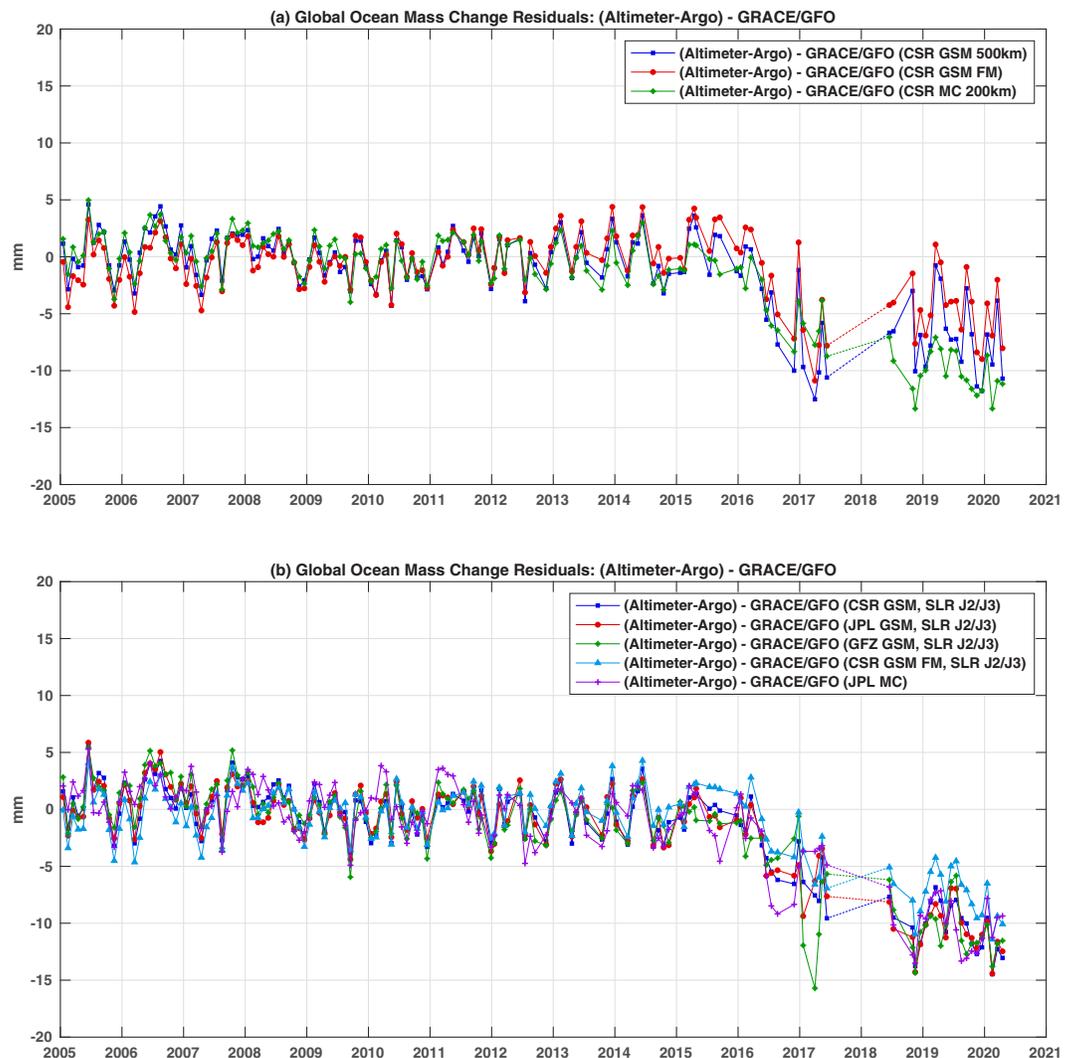


Figure 2. (a) Monthly global mean ocean mass change residuals (in mm of equivalent sea level change) between altimeter minus Argo (Altimeter-Argo) and three GRACE/GFO estimates (Cases 1, 5, and 7) based on CSR RL06 GSM and MC solutions over the period January 2005 and April 2020. Atmospheric mass change effects (i.e., the C_{00} contributions) are considered in GRACE/GFO estimates using the GAC fields. (b) Similar to (a) but for residuals between Altimeter-Argo and five other GRACE/GFO estimates (Cases 2, 3, 4, 6, and 8).

Table 3

RMS Residuals (in Units of mm) of Differences Between Altimeter-Argo and GRACE/GFO GMOM Estimates (Cases 1–8) Over Five Periods January 2005 to April 2020, January 2005 to August 2016, November 2016 to April 2020, November 2016 to June 2017, and June 2018 to April 2020 (Labeled as Periods 1–5)

RMS pairs and periods	Period 1 2005.01 to 2020.04	Period 2 2005.01 to 2016.08	Period 3 2016.11 to 2020.04	Period 4 2016.11 to 2017.06	Period 5 2018.06 to 2020.04
Altimeter-Argo/Case 1	3.93 (3.55)	2.11 (2.06)	8.06 (7.08)	9.27 (8.46)	7.62 (6.56)
Altimeter-Argo/Case 2	4.60 (3.78)	2.10 (1.95)	9.81 (7.84)	6.79 (5.28)	10.63 (8.53)
Altimeter-Argo/Case 3	4.60 (3.83)	2.11 (1.97)	9.82 (7.95)	6.24 (4.81)	10.76 (8.75)
Altimeter-Argo/Case 4	4.88 (3.76)	2.22 (1.94)	10.42 (7.80)	9.16 (7.41)	10.81 (7.92)
Altimeter-Argo/Case 5	4.44 (3.64)	1.98 (1.82)	9.32 (7.61)	6.68 (5.21)	10.30 (8.26)
Altimeter-Argo/Case 6	4.55 (3.52)	2.42 (2.18)	9.34 (6.84)	4.89 (3.04)	10.41 (7.70)
Altimeter-Argo/Case 7	3.09 (3.48)	2.07 (1.99)	5.76 (6.99)	7.05 (8.04)	5.27 (6.60)
Altimeter-Argo/Case 8	3.53 (3.74)	1.94 (1.92)	7.17 (7.76)	4.83 (5.72)	7.81 (8.43)

Note. Similar RMS estimates with trends removed are listed in parentheses for comparisons. The removed trends are estimated over the period January 2005 to August 2016 (to avoid effects on RMS residuals from potential biases in single ACC mode GRACE/GFO observations). Dates are formatted as YYYY.MM.

other five GRACE/GFO estimates are shown in Figure 2b. The mean of each residual series (estimated over the period January 2005 through August 2016) has been removed. After mid-2016 (late GRACE and into GFO missions), differences between Altimeter-Argo and GRACE/GFO become larger in magnitude and systematic. After mid-2016 GRACE/GFO GMOM, trends are substantially smaller. Over most of the GRACE era (January 2005 through mid-2016), GRACE trends agree fairly well with Altimeter-Argo (see Figure 1b), with only minor long-term variability in the residuals (see Figure 2). Increasing differences after mid-2016 coincide with the single accelerometer mode near the end of the GRACE mission and a similar condition for GFO.

RMS values for the eight residual series (Figure 2) are computed for five different time spans: January 2005 to April 2020 (the entire period), January 2005 to August 2016 (GRACE prior to accelerometer failure), November 2016 to April 2020 (GRACE and GFO single accelerometer era), November 2016 to August 2016 (GRACE single accelerometer period), and June 2018 to April 2020 (GFO era). Results are in Table 3. RMS values are also calculated with linear trends (over January 2005 to August 2016) of the residual series removed and listed in parentheses for comparisons. The reason for removing the trends over the period January 2005 to August 2016 (instead of the whole time span) is to avoid effects on RMS residuals from potential biases in GRACE/GFO observations in single accelerometer mode (after August 2016). For all eight cases, with or without trends removed, RMS values during the single accelerometer mode period are 2 to 4 times larger than during the GRACE period (January 2005 to August 2016). Estimates using FM (Cases 7 and 8) yield the smallest RMS for the entire time span (Period 1) when trends are not removed, indicating the value of FM in reducing leakage error over longer time scale (Chen et al., 2015).

4. Conclusions and Discussion

GMOM changes have been estimated from three different GRACE/GFO GSM (SH) solutions and from CSR and JPL MC solutions for the period January 2005 to April 2020 and compared with independent satellite altimeter and steric changes from Argo observations (Altimeter-Argo). GRACE/GFO GMOM rates range from 1.88 to 2.63 mm/year, compared with ~ 2.85 mm/year from Altimeter-Argo. During the late stage of GRACE (after August 2016) and into the GFO mission, differences between GRACE/GFO and Altimeter-Argo GMOM estimates become substantially larger and systematic.

GMOM changes are susceptible to uncertainties and errors in low-degree gravity SH coefficients obtained from GRACE/GFO. After mid-2016, GRACE/GFO low-degree SH coefficients, in particular ΔJ_2 and ΔJ_3 , have relatively poor quality, most likely related to loss of one satellite accelerometer for each mission. However, replacing GRACE/GFO ΔJ_2 and ΔJ_3 coefficients with SLR solutions did not reduce (and actually increased) the discrepancy between GRACE/GFO and Altimeter-Argo estimates. One possible explanation is that there may be some correlations of errors in GRACE/GFO ΔJ_2 and ΔJ_3 estimates with other low-degree SH terms at long-term scales. Geocenter motion also plays an important role in GRACE/GFO GMOM estimation. Long-term geocenter motion accounts for ~ 0.6 mm/year to GRACE/GFO observed GMOM rates

over the studied period (January 2005 to April 2020). Uncertainties in estimated geocenter series may also contribute to discrepancies between GRACE/GFO and Altimeter-Argo.

A firm cause of large and systematic discrepancies after mid-2016 is not known, but the time span coincides with the single accelerometer mode of the late-stage GRACE mission and into the GFO era, suggesting this as a likely cause. Uncertainties in Argo observations may also contribute. The three Argo data sets all show clear coolings of the ocean during 2016 but with fairly large discrepancies among the three estimates (see Figure S1 and Text S2 in SI for additional information). Further studies of Argo temperature and salinity changes are needed to better understand the Argo uncertainty.

Potential errors in altimeter data may also play a role. We show in SI a comparison of three independent GMSL series provided by AVISO (used in the present analysis), NASA JPL, and NOAA Laboratory for Satellite Altimetry (see Figure S2 and Text S3). The three GMSL series agree very well. The slight differences in estimated GMSL rates (3.92, 3.99, and 3.84 mm/year, respectively) cannot explain the observed discrepancy between GRACE/GFO and Altimeter-Argo since 2016. The Jason-3 altimeter was launched in January 2016. A slight radiometer drift of Jason-3 is under investigation by researchers at CNES Collecte Localisation Satellites (in charge of processing altimeter data). Preliminary assessment indicates that the impact on GMSL change series is minor and negligible.

GIA models are excluded as potential error sources because they affect only the linear trend during this period and could not introduce a change in trend. Sea floor deformation due to present-day mass redistribution is estimated to make a very small contribution (~ 0.1 mm/year) to altimeter-observed GMSL rate (Frederikse et al., 2017) and if included in the analysis would slightly amplify the discrepancies. With only 2 years of GFO it is clear that further investigations using longer records will be important in resolving such discrepancies.

Data Availability Statement

The GRACE and GFO RL06 GSM solutions, other auxiliary GRACE/GFO data products, and JPL mascon solutions are available at the NASA Physical Oceanography Distributed Active Archive Center (<https://podaac.jpl.nasa.gov/grace>, and <https://podaac-tools.jpl.nasa.gov/drive/files/allData/tellus/L3/mascon/RL06>). The AVISO GMSL series can be downloaded online (<ftp://ftp.aviso.altimetry.fr/pub/ocean/AVISO/indicators/msl/>), and the Argo gridded data products are available online (<https://argo.ucsd.edu/data/argo-data-products/>). The NOAA and JPL altimeter GMSL series are available online (https://www.star.nesdis.noaa.gov/socd/lisa/SeaLevelRise/LSA_SLR_timeseries_global.php and https://podaac.jpl.nasa.gov/dataset/MERGED_TP_J1_OSTM_OST_GMSL_ASCII_V42).

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