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Global Ocean Mass Change Estimation Using Low-Degree Gravity Field From Satellite Laser Ranging

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Key Points:

- Direct use of satellite laser ranging (SLR)-derived low-degree gravity field yields significantly underestimated global ocean mass rate due to severe signal leakage
- The leakage-corrected SLR gravity field provides a realistic estimate of global ocean mass rate that agrees remarkably well with Gravity Recovery and Climate Experiment
- Forward modeling is more effective than the buffer zone technique in leakage correction for low-degree gravity field

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Satellite laser ranging (SLR) is a well-established geodetic technique for measuring the low-degree time-variable gravity field for decades. However, its application in mass change estimation is limited by low spatial resolution, even for global mean ocean mass (GMOM) change which represents one of the largest spatial scales. After successfully correcting for signal leakage, for the first time, we can infer realistic GMOM changes using SLR-derived gravity fields up to only degree and order 5. Our leakage-corrected SLR GMOM estimates are compared with those from the Gravity Recovery and Climate Experiment (GRACE) for the period 2005 to 2015. Our results show that the GMOM rate estimates from SLR are in remarkable agreement with those from GRACE, at 2.23 versus 2.28 mm/year, respectively. This proof-of-concept study opens the possibility of directly quantifying GMOM change using SLR data prior to the GRACE era.

Plain Language Summary The global mean ocean mass (GMOM) is a significant contributor to the current rise of global sea level. Satellite laser ranging (SLR) has been a proven geodetic technique that can determine low-degree time-varying gravity fields for over three decades. It is possible to derive the GMOM using only long-wavelength gravity field information from SLR because of its global nature. However, the coarse resolution of SLR gravity field makes it unable to differentiate between mass changes from land and oceans. A large portion of land signals leak into the adjacent oceans, leading to significantly underestimated GMOM change rates. To solve this problem, we incorporate geographic knowledge of ocean and land boundaries into the GMOM estimation process. This can help restore the lost land signals and results in an improved GMOM estimate. We compare the SLR estimates with the more reliable results from GRACE, which shows that the GMOM rate from SLR, after correcting for leakage, agrees remarkably well with that from GRACE. This result is encouraging because it allows for the direct quantification of GMOM change for years before 2002, which is critical for understanding long-term global sea level rise.

1. Introduction

Present-day global mean sea level (GMSL) change includes two main components: the change in seawater density due to temperature and salinity variations (the steric component), and the change in global mean ocean mass (GMOM) due to net freshwater exchange between the land and oceans (the barystatic component) (Cazenave & Moreira, 2022; Gregory et al., 2019; WCRP Global Sea Level Budget Group, 2018). Since 1992, satellite altimetry has provided accurate and continuous measurements of global and regional sea level change (Cazenave et al., 2018). The steric component of GMSL can be derived from ocean reanalysis models (Storto & Yang, 2024; Storto et al., 2015) or in situ hydrographic measurements collected from global networks such as the Argo array (Johnson et al., 2022). For GMOM change, we can infer it indirectly by summing all land mass changes in polar ice sheets, mountain glaciers, and terrestrial water storage (TWS), known as the ocean mass budget approach (Barnoud et al., 2023; Chambers et al., 2016; Dieng et al., 2017; Horwath et al., 2022; Llovel et al., 2023; WCRP Global Sea Level Budget Group, 2018). Alternatively, direct quantification has been available since the launch of the Gravity Recovery and Climate Experiment (GRACE) mission in 2002 (Tapley et al., 2004), which routinely produces high-precision, high-resolution monthly gravity field models that are widely used for GMOM estimation (Chambers et al., 2004; Chen et al., 2013, 2018; Dobslaw et al., 2020; Jeon et al., 2021; Kim et al., 2019; Rietbroek et al., 2016; Uebbing et al., 2019; Yi et al., 2015, 2017). Ideally, the sum of the barystatic and steric components should agree with the altimetry-based GMSL change within the data uncertainties, indicating that the GMSL budget is closed. It is generally accepted that GMSL closure is achieved between 2005 and 2015, when the three complementary observational techniques (GRACE, Argo, and satellite

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altimetry) are all in nominal operation, providing data with sufficient accuracy and coverage (Chen et al., 2018; WCRP Global Sea Level Budget Group, 2018). There are notably large discrepancies between GRACE (plus GRACE Follow-On (FO), launched in 2018) observed GMOM change and estimates from satellite altimetry and Argo, which were likely attributed to errors in Argo and GRACE/GRACE-FO estimates (Barnoud et al., 2021, 2023; Chen et al., 2020; Horwath et al., 2022; Johnson et al., 2023).

Prior to the GRACE era, satellite laser ranging (SLR) played a key role in determining the low-degree time-variable gravity field, starting with the launch of LAGEOS-1 and Starlette in the 1970s (Pearlman et al., 2019). Since the 1990s, with several dedicated SLR satellites in orbit, the spherical harmonic (SH) expansion of gravity field models derived from SLR can reach up to degree and order (d/o) 5, corresponding to ∼4,000 km spatial resolution (half wavelength) (Cheng et al., 1997, 2011; Löcher & Kusche, 2020; Loomis et al., 2019, 2020; Matsuo et al., 2013; Sośnica et al., 2015). Numerous studies have focused on analyzing the temporal variations of these low-degree coefficients, particularly the zonal term J2 that reflects the dynamic oblateness of the Earth. Specifically, various geophysical models are used to explain the observed changes, which are associated with large-scale mass redistribution in the Earth system, from seasonal to long-term scales (Chao et al., 2020; Cheng & Ries, 2018; Cheng & Tapley, 2004; Cheng et al., 2013; Cox & Chao, 2002; Nerem & Wahr, 2011; Nerem et al., 2000; Yoder et al., 1983). However, the inverse process, that is, using the SLR-derived gravity field to directly infer regional mass change, is challenging due to its very limited spatial resolution, even for regions as large as the Greenland ice sheet (GrIS) and the Antarctic ice sheet (AIS) (Bonin et al., 2018; Matsuo et al., 2013; Meyer et al., 2019). To improve estimates of regional mass change, it is often necessary to incorporate a prior information using various methods: spatially via the least-squares Mascon approach (Bonin et al., 2018), spectrally via the scaling factor technique (Gałdyn et al., 2024), or spatiotemporally via empirical orthogonal function projection (Löcher & Kusche, 2020; Talpe et al., 2017). While these approaches improve interpretability for regional studies, they reduce the independency of SLR from other observational techniques.

The situation is different for the global ocean, which covers about 70% of the Earth's surface, a spatial scale large enough to allow, in principle, the use of the low-degree gravity field for direct mass change estimation. In practice, however, there is significant signal leakage between land and oceans due to the rather limited spatial resolution. Without effectively addressing signal leakage, it is unlikely to derive realistic GMOM estimates from the low-degree SLR solutions. This also explains why SLR is rarely, if not impossible, used to directly infer GMOM changes, even though the global nature of GMOM implies that only long-wavelength information is sufficient. We address this problem by correcting for signal leakage using the global forward modeling (FM) technique (Chen et al., 2015). The leakage-corrected SLR solutions are then used to estimate the GMOM change and are validated with GRACE estimates. To our knowledge, this is the first study to use an independent low-degree (5 d/o) SLR gravity field for GMOM estimation. Our proof-of-concept study opens the possibility of directly estimating GMOM change using SLR for the pre-GRACE era.

2. Data and Methods

2.1. Gravity Field Models

For SLR gravity field models, we use two operational data sets: one from the Center for Space Research (CSR) at the University of Texas at Austin (Cheng & Ries, 2017) and the other from NASA Goddard Space Flight Center (GSFC) (Loomis et al., 2019, 2020). Both solutions are estimated up to 5 d/o (plus additional SH coefficients C_{61} and S_{61}) based on tracking data from multiple SLR satellites, including LAGEOS-1/2, Stella, Starlette, Ajisai and LARES (see Table S1 in Supporting Information S1 for information on satellites). The GSFC solution additionally includes the Larets satellite (Loomis et al., 2020). The CSR solution is sampled monthly and spans from 2002 to the present, while the GSFC solution is weekly starting from 2000. We resample the weekly GSFC solutions to their monthly averages. To reduce data noise, we use the ensemble mean of the two data sets. For the GRACE gravity field models, we use the Level-2 SH solutions up to 60 d/o provided by CSR (Release 6.0). As recommended, the J_2 coefficients in GRACE solutions are replaced by those derived from SLR given in Technical Note TN-14 (Loomis et al., 2019). We note that GRACE Mascon solutions are less affected by signal leakage, whereas GMOM estimates from either SH or Mascon solutions are generally consistent (Barnoud et al., 2023; Chen et al., 2020; Horwath et al., 2022).

10.1029/2024GL109717

The time span for our investigations is January 2005 to December 2015, and the static gravity field is removed using the GOCO06s model to derive anomaly fields (Kvas et al., 2021). We also remove the glacial isostatic adjustment signals using the ICE6G-D model (Peltier et al., 2018). The non-tidal dynamic ocean signals, represented as the GAB component of the Atmosphere and Ocean De-Aliasing Level-1B (AOD1B) product, are not restored because they have minimal impact on the GMOM estimates since Release 06 (Dobslaw et al., 2017, 2020). For geocenter motions (degree-1 spherical harmonics), there are notable inconsistencies between estimates based on different techniques, such as GRACE (plus ocean models), SLR, and Global Navigation Satellite Systems, which contribute to one of the largest uncertainties in GMOM estimates (Blazquez et al., 2018; Chen et al., 2018; Horwath et al., 2022; Kim et al., 2022). Furthermore, the widely used GRACE-based geocenter estimates (Sun et al., 2016; Swenson et al., 2008) are not available in the pre-GRACE era, while there is still room for improvement in the SLR-based geocenter estimates (Cheng, 2024). Therefore, like previous studies (Bonin et al., 2018; Löcher & Kusche, 2020; Meyer et al., 2019; Talpe et al., 2017), we omit them for GRACE and SLR solutions, which has a common impact on both and is subject to further investigation. The anomaly SH coefficients are transformed into gridded equivalent water heights (Wahr et al., 1998), which are used for GMOM estimation.

2.2. Leakage Correction

Due to the truncated SH expansion, satellite-based gravity field models are generally limited in their ability to separate signals from different source locations, leading to so-called signal leakage in regional mass change estimation (Swenson & Wahr, 2002). Signal leakage is further exacerbated by the spatial filtering required to suppress high-frequency noise. For the global ocean, signal leakage mainly occurs along coastlines, where much stronger land signals, for example, from melting ice sheets, leak into the surrounding oceans, leading to a general underestimation of ocean mass (Chen et al., 2013). A widely used method for leakage correction in GMOM estimation is to apply a buffer zone that extends the coastline hundreds of kilometers into the ocean to mask out areas near land, for example, 300–500 km typically for GRACE (Barnoud et al., 2023; Chambers et al., 2007, 2016; Chen et al., 2018; Uebbing et al., 2019). However, for the SLR solutions of only 5 d/o, the leakage problem is much more severe than for GRACE (60 d/o), indicating that an extremely large buffer zone is needed.

In this study, we correct the signal leakage by FM, which has been proven effective in various regional GRACE applications (Chen et al., 2007, 2009; Jiao et al., 2022; Long et al., 2015). For GMOM estimation, only the geographic knowledge of land and ocean boundaries is required (Chen et al., 2013; Jeon et al., 2021; Kim et al., 2019; WCRP Global Sea Level Budget Group, 2018; Yi et al., 2015). This is an important feature of our leakage correction method, which does not use GRACE information to spatially or temporally constrain the mass change patterns of low-resolution SLR gravity field. By assuming that the signals come mainly from land, the global FM iteratively updates the land signals to match the original "apparent" model when applying the same truncation and filtering process. A 4,000 km Gaussian filter is applied to suppress noise in the SLR gravity coefficients (Matsuo et al., 2013). The ocean mass is simultaneously adjusted for the global mass conservation at each iteration. When converged, it produces the leakage-corrected land mass distribution as well as the associated ocean mass; the latter, when integrated over the global ocean, naturally provides the desired GMOM estimate. We outline the processing steps of the FM for GMOM estimation in Text S1 in Supporting Information S1, and further details can be found in Chen et al. (2013, 2015). Moreover, if the focus is regional instead of global mean ocean mass changes, sea-level fingerprints can be inferred from the leakage-corrected land mass by solving the sea-level equation (Adhikari et al., 2019; Farrell & Clark, 1976; Hsu & Velicogna, 2017; Riva et al., 2010).

3. Results and Discussion

Figure 1a shows the GMOM change time series derived from GRACE (60 d/o) and SLR (5 d/o) from 2005 to 2015. The leakage-corrected GRACE solution using global FM is used as the benchmark for comparison. Both SLR solutions, with and without leakage correction, are computed for comparison. All solutions show clear seasonal signals, even for the raw SLR estimate without leakage correction, that is, SLR (w/o FM). However, the long-term change is significantly underestimated in the raw SLR solution. This is expected because the GMOM rate of change is primarily driven by changes in land ice mass, including polar ice sheets and mountain glaciers, which typically occur along coastlines. The low resolution of the SLR gravity field makes it difficult to accurately locate these ice-melt signals, which leak into adjacent oceans and are misinterpreted as changes in ocean mass. As

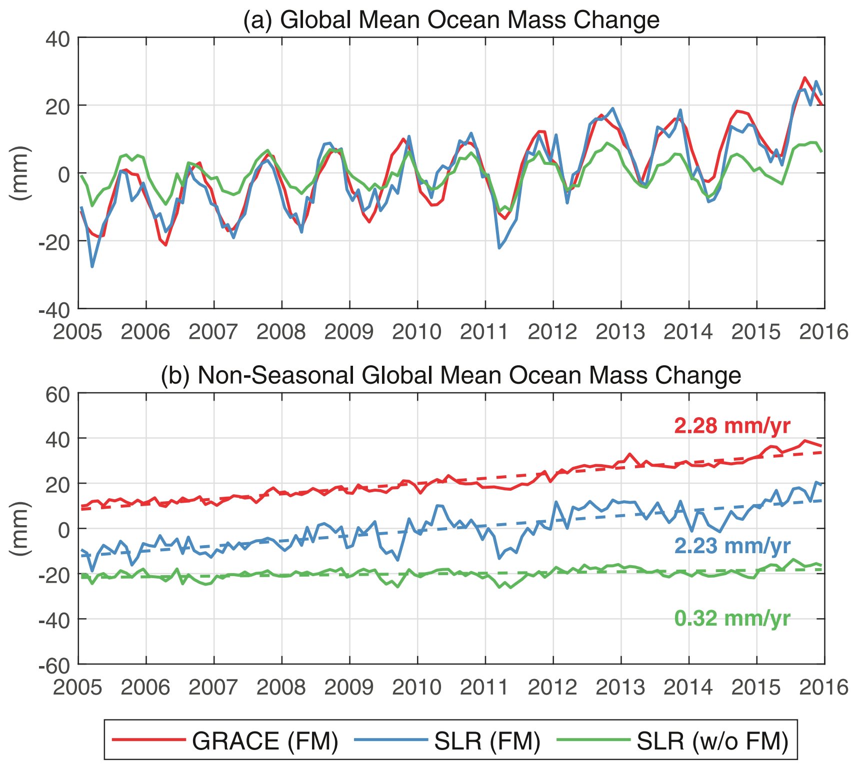

Figure 1. (a) Global mean ocean mass change from the Gravity Recovery and Climate Experiment (60 d/o) and satellite laser ranging (5 d/o) gravity fields with and without (w/o) leakage correction using global forward modeling. Panel (b) same as (a), but with the seasonal terms (annual and semi-annual) removed, and the dashed lines represent the estimated trends from least-squares fits.

the FM technique is particularly effective in recovering land ice signals, the leakage-corrected SLR solution is in remarkably good agreement with GRACE for long-term signals.

Figure 1b shows the leakage-corrected ocean mass variations (annual and semi-annual terms removed) together with the linear trends (dashed lines) obtained by unweighted least-squares fits. On the one hand, the leakage-corrected SLR solution not only provides consistent trend estimates with GRACE, but also captures interannual signals mainly related to the El Nino-Southern Oscillation events, such as the well-observed ocean mass decrease in 2011 due to La Niña (Boening et al., 2012). On the other hand, it has more variability than the other two solutions. The observational data for SLR are much sparser and more inhomogeneous than those for GRACE, which results in higher noise and correlations in the estimated gravity field parameters. The noise is further amplified by the leakage correction using FM, which is essentially an inversion process. Nevertheless, the trend estimation is less affected in our case because the 10-year period is not too short to distinguish between trend and interannual variability (Cazenave et al., 2014; Moreira et al., 2021).

Figure 2 shows the gridded mass change rates estimated from GRACE and SLR gravity field solutions. Regional ice melt patterns in the GrIS, AIS, and mountain glaciers are well observed by GRACE and dominate the current ocean mass increase (Bamber et al., 2018). The raw SLR gravity field captures some of these signals, as seen near GrIS and the West AIS, but they are scattered far from the source with significantly reduced magnitudes. In contrast, the global FM successfully relocates the leaked land signals and largely restores their magnitudes, which is critical for deriving a reliable GMOM rate. In addition, the leakage-corrected SLR solution can qualitatively distinguish the mass gain in the East AIS from the mass loss in the West AIS. However, given its native spatial resolution of only 5 d/o, we cannot expect it to reveal regional details like GRACE, for example, the distinct patterns between inland and coastal regions of the GrIS are not separated. However, this will have minimal impact on our GMOM estimate, since at such a global scale only the total amount of land-ocean mass exchange is relevant.

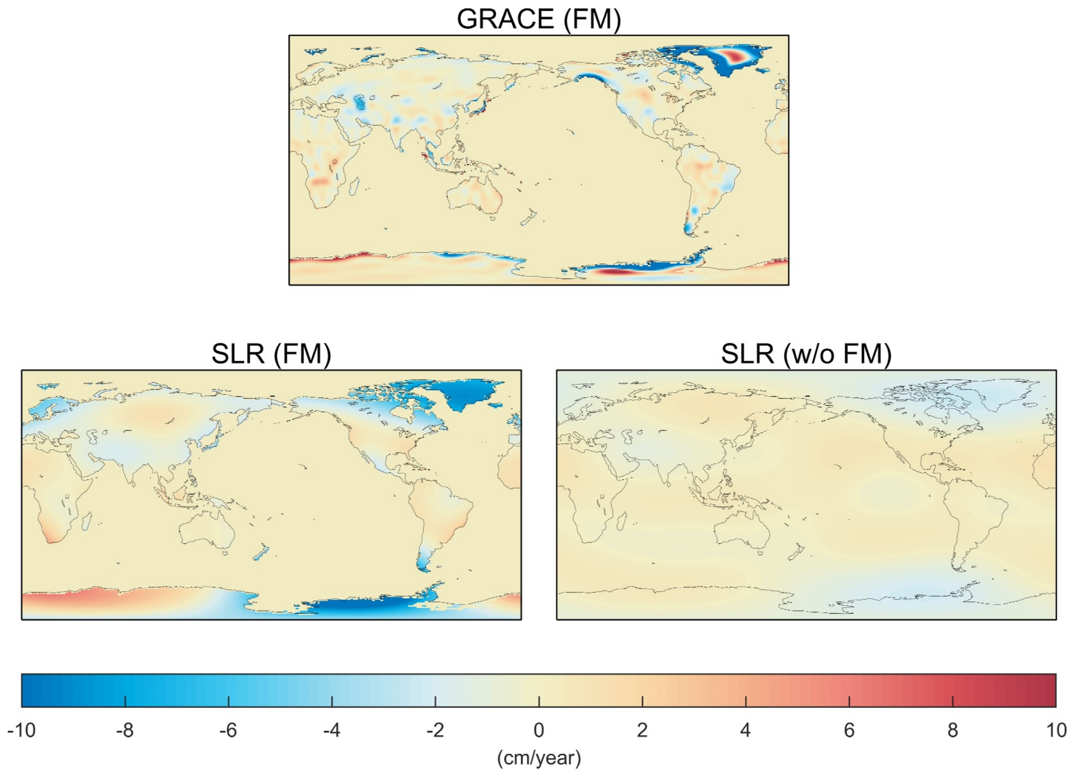

Figure 2. Gridded trends of mass changes (in terms of equivalent water heights) estimated from Gravity Recovery and Climate Experiment (60 d/o) and satellite laser ranging (SLR) (5 d/o) after leakage correction using the global forward modeling (FM). The raw SLR solution without leakage correction, that is, SLR (w/o FM), is also shown. A uniform layer of water mass is assigned over the oceans for global mass conservation in the FM.

Figure 3 shows the gridded annual amplitudes of the three solutions, which mainly show seasonal variations in TWS. As observed by GRACE, large annual signals are present in large river basins, particularly in tropical regions (Scanlon et al., 2019). Changes in TWS are the main contributor to the seasonal variations in GMOM, as the atmospheric and dynamical ocean signals are removed during the gravity field recovery process (Willis et al., 2008). Again, the leakage-corrected SLR solution can generally recover annual signals at the continental scale.

Table 1 lists the estimated trends and seasonal amplitudes and phases of GMOM changes from 2005 to 2015, as well as their formal one-sigma uncertainties obtained from least-squares fits. In addition, SLR estimates using different leakage-correction buffers are presented for comparison. The Gaussian filter is not applied for the case using buffer zone. For linear rates, the leakage-corrected SLR solution (2.23 mm/year) agrees remarkably well with GRACE (2.28 mm/year), mainly due to the effectiveness of the FM in recovering land ice mass change signals, as shown in Figure 2. Without any correction for leakage, the 5 d/o SLR solution obviously cannot be used to derive the GMOM rate, as it gives an estimate of only 0.32 mm/year. The use of a buffer zone can recover some of the long-term signals, and the estimated rates are 0.98, 1.21, and 1.27 mm/year for buffer zones of 500, 800, and 1,000 km, respectively, gradually increasing with the size of the buffer zone. However, even for a 1,000 km buffer zone, the estimated rate is still about half that of GRACE and SLR when using FM. Given the spatial resolution of only 5 d/o for the SLR gravity field, the widely used buffer zone technique in GRACE cannot provide realistic GMOM rate estimates.

For the annual signals, all SLR solutions are in good phase agreement with GRACE, which benefits from the combination of the two SLR solutions from CSR and GSFC. As shown in Fig. S1 in Supporting Information S1, the phasor plot indicates that the combination of the two SLR solutions brings the annual phase closer to that of GRACE. The amplitudes of all SLR solutions in Table 1 are conservative, while FM gives the largest estimate of 9.11 mm, but is still about 10% smaller than the 10.14 mm of GRACE. The individual GMOM estimates of CSR

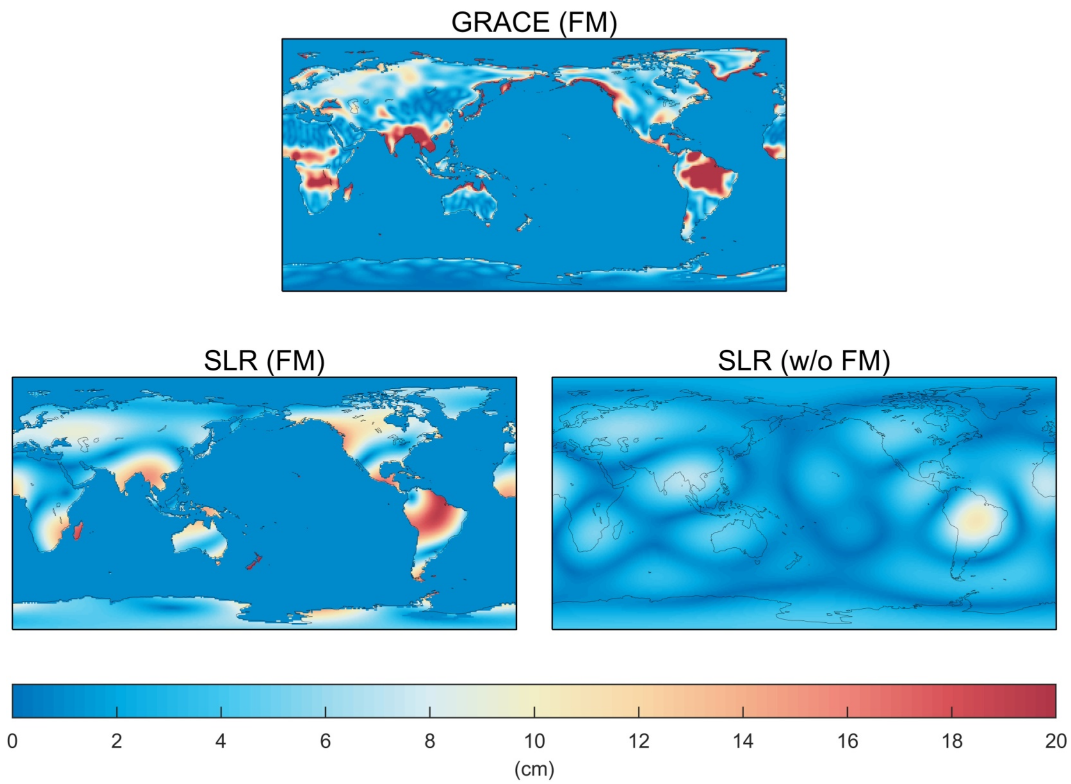

Figure 3. Gridded annual amplitudes of mass changes (in terms of equivalent water heights) estimated from Gravity Recovery and Climate Experiment (60 d/o) and satellite laser ranging (SLR) (5 d/o) after leakage correction using the global forward modeling (FM). The raw SLR solution without leakage correction, that is, SLR (w/o FM), is also shown. A uniform layer of water mass is assigned over the oceans for global mass conservation in the FM.

and GSFC in Table S2 in Supporting Information S1 show that the GSFC solution has a smaller annual amplitude than CSR, but a larger semi-annual amplitude. This may be related to their specific SLR data processing strategies, for example, background models and/or parameterizations, in gravity field modeling (Cheng & Ries, 2023), which requires further investigation. In contrast to rate estimation, the buffer zone can bring back the annual signals, for example, 8.91 mm for the 1,000 km case. This can be explained by the fact that most basins with significant seasonal signals, such as the Amazon, are located inland (see Figure 3). Therefore, the use of a sufficiently large buffer zone around land can account for the leakage signals. However, long-term mass changes occur mainly along narrow coastlines, especially for melting ice sheets. As a result, they naturally leak further out into the oceans than annual signals from inland areas and require an extremely large buffer zone to be effectively

Table 1
Linear Trends and Seasonal Signals of Global Mean Ocean Mass (GMOM) Changes From Gravity Recovery and Climate Experiment (60 d/o) and Satellite Laser Ranging (5 d/o) for the Period 2005–2015

		Annual		Semiannual	
GMOM	Trend (mm/year)	Amplitude (mm)	Phase (deg)	Amplitude (mm)	Phase (deg)
GRACE (FM)	2.28 ± 0.07	10.14 ± 0.29	273 ± 2	1.01 ± 0.29	39 ± 17
SLR (FM)	2.23 ± 0.14	9.11 ± 0.63	275 ± 4	0.99 ± 0.63	32 ± 36
SLR (w/o FM, no BUF)	0.32 ± 0.06	5.71 ± 0.26	279 ± 3	0.31 ± 0.26	34 ± 48
SLR (BUF 500 km)	0.98 ± 0.10	7.85 ± 0.43	277 ± 3	0.35 ± 0.43	27 ± 70
SLR (BUF 800 km)	1.21 ± 0.11	8.50 ± 0.50	278 ± 3	0.37 ± 0.50	17 ± 78
SLR (BUF 1,000 km)	1.27 ± 0.12	8.91 ± 0.54	279 ± 3	0.39 ± 0.54	12 ± 79

Note. FM means the global forward modeling for leakage correction, and BUF means the buffer zone.

accounted for. For the semi-annual signals, the use of FM allows very close SLR estimates to GRACE, while setting different buffer zones cannot resolve the amplitude underestimation.

4. Concluding Remarks

We investigate the potential of using the low-degree SLR gravity field for GMOM estimation. Given its very limited spatial resolution of 5 d/o, direct use results in significant underestimation of GMOM change rates and seasonal signals due to strong signal leakage between land and oceans. We apply global FM to correct for leakage by incorporating geographic information on land-ocean boundaries. The leakage-corrected SLR gravity field is used for GMOM estimation and compared with GRACE (60 d/o) over the period 2005 to 2015, during which GRACE estimates can be considered reliable. Without leakage correction, the SLR gives a GMOM rate of only 0.32 mm/year, which is significantly lower than the GRACE reference of 2.28 mm/year. Using global FM, the estimated rate is improved to 2.23 mm/year, which agrees remarkably well with GRACE, though the formal uncertainty is larger than that of GRACE. The finding that a low-degree gravity field is capable of deriving realistic GMOM trend may initially seem surprising. However, it is important to note that the GMOM represents one of the largest spatial scales, so long-wavelength gravity change information is adequate provided that signal leakages along the coastlines are sufficiently corrected. By assuming most of signals come from the land, which is the case for long-term trends in general, the FM successfully restores the land signals, especially polar ice mass changes that drive the GMOM trend. This explains the good agreement between the 5 d/o SLR and 60 d/o GRACE solutions with FM. For regional applications, however, high-degree information is required for signal separation even with FM. Establishing a buffer zone up to 1,000 km from the coastlines cannot resolve the leakage as it gives a rate of ∼1.27 mm/year, which is still significantly underestimated. This indicates that the buffer zone technique is less effective than the FM technique given the coarse spatial resolution of the continental-scale SLR gravity field. For seasonal variations, both buffer zone and FM techniques can recover the signals, but the latter provides a better estimate of the semi-annual amplitude. Our proof-of-concept study gives encouraging results based on the 5 d/o SLR gravity field for GMOM estimation, which was previously considered infeasible or not even discussed. This opens up a potential new scientific application aspect of the long-standing and well-established SLR technique. In the future, when operational SLR gravity solutions are available for the pre-GRACE period, a more comprehensive analysis of the global ocean mass budget can be performed by reconciling direct SLR estimates with those synthesized from various mass balance data sets of ice sheets, glaciers, and TWS.

Data Availability Statement

The SLR gravity field models are available from https://ftp.csr.utexas.edu/pub/slr/degree_5/CSR_Monthly_5x5_Gravity_Harmonics.txt (CSR) and https://earth.gsfc.nasa.gov/sites/default/files/geo/slr-weekly/gsfc_slr_5x5c61s61.txt (GSFC). GRACE CSR RL06 models are from GRACE (2018). The J2 estimates from TN-14 are provided at https://archive.podaac.earthdata.nasa.gov/podaac-ops-cumulus-docs/gracefo/open/docs/TN-14_C30_C20_GSFC_SLR.txt.

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