Abstract Over the past decade, the rate of global mean sea level (GMSL) rise is about 3.5 mm/year. Terrestrial water/ice mass loss to the oceans and ocean volume expansion explain about 3.1 mm/year, indicating that the GMSL budget is not been fully understood. Past estimates from Gravity Recovery and Climate Experiment (GRACE) data have indicated that terrestrial water storage (TWS) is increasing and is thus a mitigating contributor to GMSL rise. However, TWS estimates from GRACE are uncertain mostly due to limitations in GRACE estimates of degree-1 and degree-2 order-0 spherical harmonic coefficients. We obtain an improved estimate of the TWS contribution to GMSL change using revised GRACE estimates of these low-degree coefficients. For the period 2005–2015, we find that TWS makes an additional contribution to GMSL rise of about 0.32 ± 0.02 mm/year, mostly associated with a TWS decrease. This revised estimate is sufficient to nearly balance the budget of GMSL rise.

Plain Language Summary During the last decade, the rate of global mean sea level (GMSL) rise is about 3.5 mm/year. Ocean volume increase due to thermal expansion has contributed to GMSL rise by about 1.3 mm/year. Recent estimates of terrestrial water and ice melt inflow to the oceans can explain about 1.8 mm/year, so the sum of ocean mass and volume increase (3.1 mm/year) does not explain the total observed GMSL rise (3.5 mm/year). The missing contribution to GMSL rise, about 0.4 mm/year, is a significant water volume, similar in size to the contribution from melting Antarctic ice. In this study, we show that loss of water stored on land (terrestrial water storage (TWS)) accounts for most of the missing contribution to GMSL rise (about 0.3 mm/year). Previous TWS estimates using satellite gravity data were flawed due to various limitations, which are corrected in this study.

1. Introduction

Global mean sea level (GMSL) has increased during the last century with an apparent rate acceleration during the last decade (Dieng et al., 2017; WCRP Global Sea Level Budget Group, 2018). The rate of about 3.07 mm/year between 1993 and 2015 increased to 3.5 mm/year in the period 2005 to 2015 (WCRP Global Sea Level Budget Group, 2018). Much effort has been made to understand its causes using multiple remote sensing and in situ data (Chambers et al., 2016; Dieng et al., 2017; WCRP Global Sea Level Budget Group, 2018). GMSL rise is attributed to steric effects associated with temperature and salinity change, and inflow of water mass from ice sheets, glaciers, and terrestrial water. During 2004–2015, GMSL rise associated with steric changes was estimated to be about 1.14 mm/year, about 33% of the total (Dieng et al., 2017), implying that about 67% is associated with ocean mass increase. Ice mass loss from mountain glaciers (Jacob et al., 2012) and both major continental ice sheets (Greenland and Antarctica; Forsberg et al., 2017; Velicogna & Wahr, 2013) are estimated to be major contributors to GMSL rise (Chen et al., 2013; Jacob et al., 2012) based on satellite gravity observations of the Gravity Recovery and Climate Experiment (GRACE). GRACE data have also indicated increasing terrestrial water storage (TWS), implying a contemporary GMSL change of about −0.3 mm/year (Reager et al., 2016; Rietbrock et al., 2016). However, TWS is the most uncertain contribution to sea level change (WCRP Global Sea Level Budget Group, 2018). Errors in GRACE TWS estimates might be due to poor estimates of Earth’s center of mass change (degree-1 terms, not directly observed by GRACE) and by poor determination of Earth’s dynamic oblateness changes (ΔC20; Chen et al., 2016; Seo et al., 2008). The importance of improved estimates of degree-1 spherical harmonic (SH) coefficients for regional sea level rise has been examined (Jeon et al., 2018), but the effect on continental scale and overall TWS has not yet been studied. Here we present revised values for GRACE continental-scale TWS change using improved degree-1 and ΔC20 SH coefficient estimates. Revised values indicate an overall
decrease in TWS, unlike previous GRACE estimates. As a result, TWS contributes to GMSL rise by an amount that explains the missing component of the contemporary GMSL rise budget.

2. Method

We use the ensemble mean of Center for Space Research (CSR), Geoforschungszentrum (GFZ) Potsdam, and Jet Propulsion Laboratory (JPL) release 06 monthly gravity solutions to estimate ice and water mass changes. The three solutions include SH coefficients up to degree and order 96. The decorrelation filter (Swenson & Wahr, 2006) and 500-km Gaussian smoothing were applied to suppress north-south stripes and random noise, respectively. The previous release of gravity solutions (RL05) was contaminated by pole tide error (Wahr et al., 2015) particularly in $\Delta C_{21}$ and $\Delta S_{21}$ coefficients, but these errors have evidently been suppressed in RL06, so we use reported values for $\Delta C_{21}$ and $\Delta S_{21}$ without further correction.

GRACE solutions are reported in a Center-of-Mass frame, thus lacking information about degree-1 SH coefficients. Conventional practice has been to estimate degree-1 coefficients using GRACE terrestrial water and ice mass changes assuming uniform distribution over the oceans of water mass discharged from land (Swenson et al., 2008). However, leakage contamination causes signals over land to spread to adjacent oceans (and vice versa) due to the limited range of SH coefficients. Leakage is a particular problem near coastlines, where relatively small ocean signals tend to be contaminated by typically larger terrestrial hydrologic signals. Furthermore, the assumption of uniform water distribution over the oceans is incorrect. Instead, the distribution of water over the oceans should conform to a changing geoid, including self-attraction and loading (SAL) effects (Tamisiea et al., 2014). SAL effects cause sea level to rise or fall by about 20–25% on a regional scale when compared with a uniform distribution (Clark & Lingle, 1977; Mitrovica et al., 2011).

GRACE $\Delta C_{20}$ is vulnerable to tide aliasing error and is often replaced by a value determined from satellite laser ranging (SLR) measurements (Cheng et al., 2013; Loomis et al., 2019). However, a recent study of regional sea level change using CSR RL05 showed that, after $S_2$ and $K_2$ tide alias correction, GRACE $\Delta C_{20}$ was superior to SLR $\Delta C_{20}$ (Jeon et al., 2018). Tide aliasing error has evidently been suppressed in RL06, so now we might simply retain the GRACE RL06 value for $\Delta C_{20}$. Another choice is to adopt an estimated $\Delta C_{20}$ based on the method of Sun et al. (2016) which also provides degree-1 SH coefficients and considers SAL effects. We use this approach to find degree-1 and $\Delta C_{20}$ SH coefficients, but unlike Sun et al. (2016) who dealt with spatial leakage using an empirical buffer zone, we use forward modeling (FM) to obtain leakage corrected GRACE mass fields.

FM was developed to resolve the spatial leakage problem at continent-ocean boundaries (Chen et al., 2013). FM uses known locations of continent-ocean boundaries in an iterative process to separate land and ocean signals, providing estimates of both continental and ocean mass changes. In the original method, ocean mass changes were assumed to be uniformly distributed (Chen et al., 2013), but here we use a revised FM procedure that incorporates SAL effects (Jeon et al., 2018). For more details about FM and estimating low-degree SH coefficients, see supporting information.

Post-Glacial Rebound (PGR) models are used to remove the viscoelastic mantle response to the last glaciation from GRACE data. A PGR model contains linear rates of change of Earth gravity field SH coefficients. Many PGR models are available, and their predictions are diverse (WCRP Global Sea Level Budget Group, 2018). The choice of a PGR model has a major effect on estimates of regional to continental scale water and ice mass changes, and identifying the best PGR model is difficult. In this study we correct GRACE data using the Peltier et al. (2018) model (hereafter Peltier18). Peltier18 has been used in the latest GRACE products such as CSR (Save, 2019) and JPL mascon (RL06) solutions (Tellus, 2018). We also examine two other models by A et al. (2013) (hereafter A13) and Caron et al. (2018) (hereafter Caron18). A13 has been widely used in GRACE studies (Adhikari & Ivins, 2016; Chen et al., 2013; Johnson & Chambers, 2013; Yi et al., 2015). Caron18 is a very recent model.

3. Results

3.1. Continental Water and Ice Mass Change

As a first look at total terrestrial water and ice mass effects we use conventional degree-1 and SLR $\Delta C_{20}$ SH coefficients, but do not correct for leakage using FM. The consequent barystatic sea level (BSL; the negative
of total terrestrial ice and water mass changes) is about 0.70 mm/year, much less than a recent estimate using the JPL mascon solution, 1.78 mm/year (Tellus, 2018). The smaller value is attributable to spatial leakage (Chen et al., 2013), and demonstrates the importance of addressing the leakage problem, which we do using revised FM.

Figure 1 shows oceanic and continental water and ice mass changes using revised FM for leakage correction with various degree-1 and ΔC20 SH coefficients. For continents excluding Antarctica and Greenland estimates also include ice mass loss associated with melting glaciers. Black lines in Figure 1 employ conventional low-degree SH coefficients, yielding a BSL rise rate of 1.76 mm/year (an increase of 1.06 mm/year relative to the result when we did not correct for leakage). This is close to the recent JPL mascon estimate, 1.78 mm/year, which also used conventional degree-1 and ΔC20 SH coefficients. Although the time series (in black) in Figure 1 are corrected for spatial leakage, they remain contaminated by an error in conventional degree-1 SH coefficients due to the assumption of uniform water distribution over the oceans and the leakage caused by a limited range of SH coefficients. The blue lines in Figure 1 are obtained by replacing conventional degree-1 SH coefficients with those that consider SAL and leakage effect as explained above. These revised estimates differ significantly in Eurasia and North America relative to the black lines in Figure 1. The revised mass loss rate for Eurasia is near −220 Gt/year, about twice that for Antarctica.

As discussed above, various choices exist for ΔC20 including the conventional one of replacing the GRACE value with a satellite laser ranging (SLR) solution (Cheng et al., 2013), as used for black and blue lines in Figure 1. Figure S1 shows four different ΔC20 time series, including the conventional SLR ΔC20, which has a much smaller rate than the other three (ΔC20 from GRACE, updated-SLR and this study). Red lines in Figure 1 show estimates based upon our ΔC20, as described above. Compared to the blue lines in Figure 1, rates of change are greater, except for South America. Other ΔC20 from GRACE and updated-SLR (Loomis et al., 2019) show linear trends similar to our ΔC20. Therefore, continental water and ice mass changes using them (Figure S2) show mass change rates similar to red lines in Figure 1.
The red line in Figure 1h, incorporating our new degree-1 and $\Delta C_{20}$ coefficients, indicates a BSL rate of 2.07 mm/year, or 0.31 mm/year larger than with conventional degree-1 and SLR $\Delta C_{20}$ coefficients. Thus, using conventional low-degree coefficients leads to a smaller GRACE value for BSL rise. We use synthetic data (Eom et al., 2017; Marzeion et al., 2015; Noël et al., 2015; van Wessem et al., 2014) to support this statement, showing that accurate estimates of terrestrial water and ice storage and consequent BSL are obtained using our new low-degree SH coefficients (see supporting information). As in Figure 1, the synthetic experiment also shows that the decreasing rate of terrestrial water and ice mass and the increasing rate of BSL are underestimated when conventional low-degree SH coefficients are used. The synthetic data study also reveal limitations of previous methods, including use of a buffer zone for leakage correction, and FM without considering SAL (see the supporting information).

### 3.2. GMSL Budget 2005–2015

Since 1993, satellite altimeters have measured near-global sea level rise associated with both ocean mass and steric changes. To appraise each contributor to altimetry measurements of GMSL rise, we examine the period 2005–2015 when Argo float data have been available to provide a global steric sea level change estimate (Chen et al., 2013). From 2005 to 2015, the total GMSL rise rate, after correcting bias in satellite altimeters, was 3.5 mm/year, and the steric sea level rise estimated by ensemble means of 11 data sets was 1.3 mm/year (WCRP Global Sea Level Budget Group, 2018). Therefore, the residual, 2.2 mm/year (GMSL minus steric sea level), is due to water mass inflow to the oceans. The sum of GRACE estimates of ice mass loss from both ice sheets, glaciers, and continental TWS change ought to be close to 2.2 mm/year, if the GRACE data are properly corrected. Our improved FM solution including our new values for degree-1 and $\Delta C_{20}$ SH coefficients predicts the BSL rise rate to be 2.07 mm/year. These BSL values differ by about 0.1 mm/year, a small amount that is likely due to limitations in altimeter satellite coverage. Altimetry satellites survey the oceans between latitudes 66°N to 66°S, approximately. In contrast, GRACE measures properties of the global oceans. Another cause may be related to ocean dynamics, which are not important for global ocean mass estimates, but should be considered for regional studies (Uebbing et al., 2019).

We can examine the question of differing spatial coverage by looking at the GRACE ocean mass rise rate over the latitudinal band seen by altimeters. Since ocean dynamic effects have been removed using numerical models in GRACE data processing, we restore them to obtain regional ocean mass changes, adding to the improved FM results presented above. Considering latitudes from 66°N to 66°S and including ocean dynamic effects, the BSL rate is 2.12 mm/year, closer to the 2.2 mm/year GMSL altimeter rate minus steric effects.

Figure 2 shows each budget element of BSL rise from the conventional FM solution and our improved FM solution.

Both conventional and our improved FM solutions predict similar ice mass loss rates in Antarctica and Greenland. They differ mainly in continental mass change (glacier and TWS) excluding Antarctica and Greenland. The difference is evidently related to degree-1 SH coefficients. Because these low-degree SH coefficients have little effect on small-scale glacier contributions, the BSL difference (0.31 mm/year) mostly results from large-scale TWS change. The net TWS contribution to BSL rise would be estimated by correcting the glacier contribution from the continental mass change (glacier and TWS). However, estimates of the glacier contribution range over 0.61–0.84 mm/year (WCRP Global Sea Level Budget Group, 2018; Zemp et al., 2019), and thus, the estimated net TWS contribution to GMSL rise also varies from 0.08 to 0.31 mm/year. Furthermore, uncharted glaciers may contribute additional uncertainty to the BSL budget, although their effect on BSL rise during the GRACE era would be minor (Parkes & Marzeion, 2018). The main point is that the new degree-1 and $\Delta C_{20}$ coefficients lead to an upward revision in the TWS contributions to BSL rise of about 0.32 mm/year, relative to previous GRACE value. A similar result is obtained using the A13 PGR model, but the Caron18 model (Figure S6) predicts a much larger BSL rate. The larger BSL rate is due to larger estimates of $\Delta C_{10}$ from both conventional and improved methods. However, upward revision of continental water and ice contributions to BSL rise is found using two other PGR models, confirming again that conventional low-degree SH coefficients lead to an underestimate.

We estimate contributions to the 0.32 mm/year BSL rate from major river basins (Oki & Sud, 1998) (see supporting information for details) using our improved FM solutions (Figure 3). We excluded largely glaciated
regions such as Alaska, the Himalayas, Patagonia, and many Arctic islands in order to focus on other TWS sources. Figure 3 shows that TWS losses over high-latitude basins in the northern hemisphere have contributed to BSL rise. Lena, Mackenzie, and Volga basins are important contributors. At lower latitudes, there is also TWS depletion in Sao Francisco and Euphrates basins. TWS over Amazon, Congo, and Zambeze basins has increased, mitigating BSL rise. On the other hand, the conventional FM solutions (Figure S7) do not show such large TWS decline at high latitudes, and negative TWS rates in Lena, Mackenzie, and Volga

Figure 2. BSL budget. BSL rise is attributed to Greenland (blue), Antarctica (pink), and Glacier and TWS (brown). The leakage errors in both solutions were corrected by revised FM, and PGR effect was removed by Pelter18 model. Conventional FM solution (left bar) uses SLR (Cheng et al., 2013) $\Delta C_{20}$ and degree-1 SH coefficients by Swenson et al. (2008). The improved FM solution (right bar) incorporates newly estimated degree-1 and $\Delta C_{20}$ SH coefficients. White numbers show rates of each component, and black numbers are the sum of all contributors. Black lines represent a confidence interval of each component within 95%.

Figure 3. TWS contributions from large river basins to BSL rise rate using the improved FM solutions. Red (blue) colors represent BSL rise (drop) associated with TWS decrease (increase).
basins are smaller than those in Figure 3. In Ob and Yenisei basins, conventional solutions also yield larger TWS increases than our improved solution. We also examined the TWS contribution using the global land data assimilation system (GLDAS; Rodell et al., 2004). GLDAS models components of surface water storage, such as soil moisture, snow, and canopy water. TWS contributions to BSL rise predicted by GLDAS (Figure S8) and observed by GRACE differ significantly, suggesting a need for improvement in GLDAS and probably other hydrological models. However, both GLDAS and GRACE show that TWS declines in basins over Eurasia and North America.

4. Conclusion

For the period 2005–2015, the satellite altimeter rate of GMSL rise is 3.5 mm/year. This rise is due both to steric effects (observed by Argo) and mass changes (observed by GRACE). Previous GRACE mass and Argo steric estimates explained only about 3.1 mm/year, with a missing amount of 0.4 mm/year. In this study, we show that the contribution of terrestrial water storage (TWS) obtained using conventional GRACE mass fields has been underestimated. The underestimation is due to errors in degree-1 SH coefficients due to leakage contaminated mass fields and an incorrect assumption of uniform changes in sea level. We developed revised degree-1 SH coefficients by correcting for leakage while considering water distribution over the oceans governed by SAL. These revised coefficients indicate a global decline in TWS. Various estimates of the ΔC20 coefficient produce minor changes in estimated TWS. The revised GRACE estimate of decline in TWS predicts an increase in the BSL rate (0.32 mm/year) that largely accounts for the missing amount in previous estimates. Globally, TWS trends, possibly modulated by climate variability (Reager et al., 2016; Rodell et al., 2018) or anthropogenic activity (Chao et al., 2008; Wada et al., 2012), contribute significantly to GMSL rise. The important conclusions are that satellite altimetry and GRACE observations are in good agreement and that TWS is a significant cause of contemporary GMSL rise, with a magnitude similar to the contribution of Antarctica.

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