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Key Points:

- This study provides a reconciled sea level budget between 2005 and 2015 in terms of acceleration
- The recent acceleration in global sea level rise is disintegrated and quantified, and its significance is testified
- An improved method to estimate continental mass changes is given, and its result can well explain sea level rise

Supporting Information:

- Supporting Information S1

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Acceleration in the Global Mean Sea Level Rise: 2005–2015

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Abstract Global mean sea level rise has been accelerating for more than 100 years, and the acceleration in the last two decades seems to further increase. The latest development in geodetic and marine observations enables us to scrutinize and understand the sources of the sea level acceleration in the last decade. For this end, observations from satellite altimetry, gravimetry, and in situ measurements of the ocean between 2005 and 2015 are combined, and their closure is examined. Our results show that the acceleration during the last decade (0.27 ± 0.17 mm/yr^2) is about 3 times faster than its value during 1993–2014. The acceleration comes from three factors, that is, 0.04 ± 0.01 mm/yr^2 (~15%) by land ice melting, 0.12 ± 0.06 mm/yr^2 (~44%) by thermal expansion of the seawater, and 0.11 ± 0.02 mm/yr^2 (~41%) by declining land water storage. Although these values in 11 years may suffer from natural variabilities, they shed light on the underlying mechanisms of sea level acceleration and reflect its susceptibility to the global warming.

Plain Language Summary This work features identification of the accelerating global sea level rise between 2005 and 2015 by using the sea level budget approach. It has been believed that we need observations of several decades or more to detect significant global sea level acceleration. This is because the sea level records are disturbed by climate variability and have an inadequate precision. Here we demonstrate that current advances in satellite gravimetry, and marine in situ measurements enable us to detect the acceleration in global sea level rise from 2005 to 2015, 11 years in total. An important factor is that we could precisely quantify different components that contribute to sea level change. Above all, we could substantially reduce the influence of climate variability in terms of the land water storage changes. This work lets us accurately understand the susceptibility of current sea level rise to global warming.

1. Introduction

Global mean sea level (GMSL) has a century-long history of measurements by tide gauges, and global satellite altimetry data cover the last two decades. GMSL has been rising with significant acceleration; that is, the rate 1.1 ± 0.3 mm/yr in 1901–1990 increased to 3.1 ± 1.4 mm/yr over 1993–2012 (Dangendorf et al., 2017) (Figure 1a). Two latest studies also showed that the rate of GMSL rise has increased in the last two decades (Chen et al., 2017; Dieng et al., 2017). The continuous and accelerating rise of GMSL deteriorates coastal habitat (Nicholls & Cazenave, 2010), and its reliable projection for the future is important to mitigate this potential threat. However, factors responsible for the acceleration have not been quantified yet due to limited accuracy and coverage of the measurements. Recent advance in space geodetic techniques (Tapley et al., 2004) and marine surveys available since 2005 (Riser et al., 2016) allowed us to scrutinize the contribution of individual factors to the current acceleration of the GMSL rise (Chen et al., 2017; Dieng et al., 2017).

Multiple factors cause sea level changes. The longer-term sea level rise is due partly to the water transport from land to ocean by the melting of continental ice sheets and mountain glaciers (Gardner et al., 2013; Shepherd et al., 2012), and partly to the thermal expansion of seawater with the global ocean temperature rise (AchutaRao et al., 2007; Rhein et al., 2013). Such multidecadal changes are significantly modulated by water exchanges between land and ocean due to various kinds of climate changes and human activities (Konikow, 2011; Wada et al., 2016). The first two factors (ice melting and thermal expansion) relate to global warming. A “hiatus” in global warming during the first decade of this century has been recognized (Bindoff et al., 2013; England et al., 2014), but the latest global surface temperature records (NASA, 2017) suggest that a new increasing stage seems to be emerging after ~2013 (Figure 1b).

In addition to satellite altimetry, two new types of observations enable assessments of individual factors responsible for GMSL changes and can help us examine the closure of the sea level budgets. Thousands of floats are deployed to make in situ temperature and salinity profiles in the global ocean since 2005

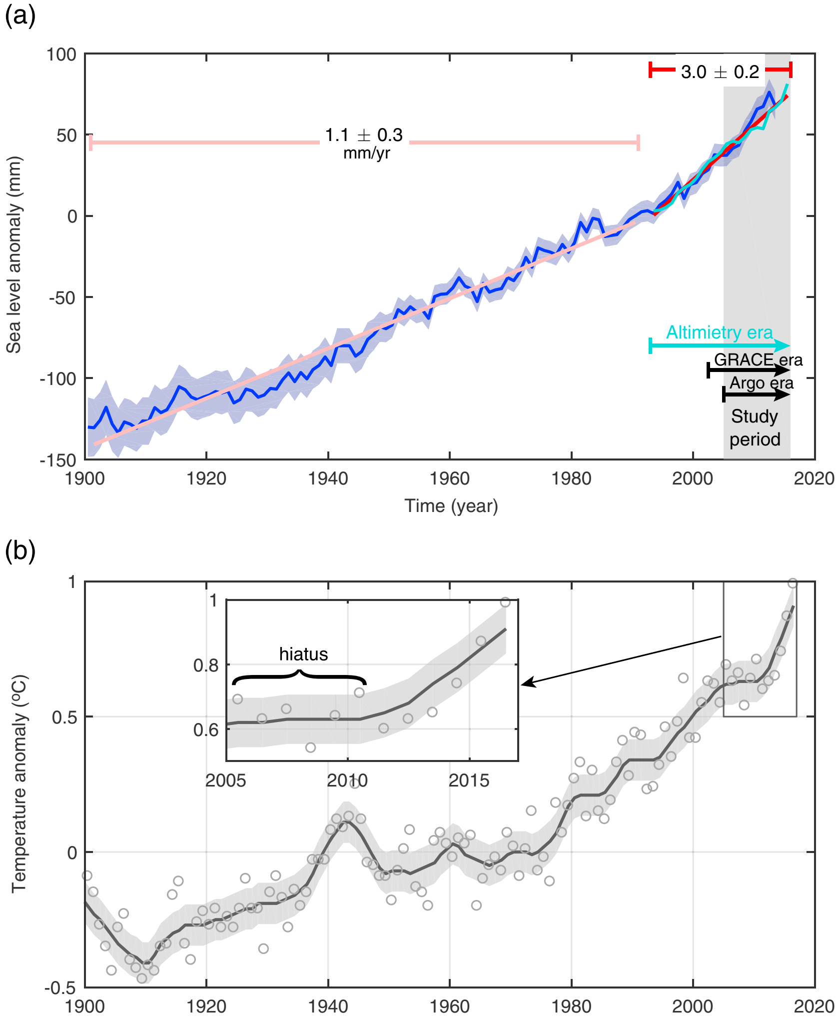

Figure 1. Records of (a) GMSL and (b) global mean surface temperature from 1900 to 2015. In Figure 1a, the blue curve is from tide gauges (Church & White, 2011) and the green curve is from satellite altimetry (refer to supporting information). Trends in three different time periods are annotated, and the gray patch marks the period studied here. The deployment of the Argo floats began in 1999, but we think its spatial coverage became dense enough around 2005. In the global mean surface temperature Figure 1b, we show the black curve as the 5 year moving average. We roughly indicate the period of the hiatus in the inset.

(Riser et al., 2016), and they allow us to calculate thermosteric sea level changes from the surface down to the depth of ~2 km. Gravity Recovery and Climate Experiment (GRACE) satellites, launched in 2002, are designed to study temporal variations of the Earth's gravity field (Tapley et al., 2004) and help us study dynamic water redistribution in oceanic regions (Rietbroek et al., 2016) and changing land water storages for individual continents. Assuming the conservation of the total water mass, the global continental water storage decreases from GRACE are expected to be equal to the barystatic sea level increases (Church et al., 2013).

Direct measurements of GMSL have been performed by satellite altimetry over the last two decades. By correcting for the steric contributions from the Argo data (Roemmich et al., 2015; Wijffels et al., 2016), we can isolate the barystatic sea level changes. Steric contributions from the part below the Argo maximum depth (~2 km) are considered negligible during the recent decades (Dieng, Palanisamy, et al., 2015). If the barystatic sea level increase is equivalent to the decrease of the land water and ice storage, the seawater budget should close. Such a test allows us to assess the reliability of the obtained GMSL changes, and recent studies with this approach discuss contemporaneous sea level changes not only in trends but also in seasonal/interannual variabilities (Chambers et al., 2017; Chen et al., 2013; Yi et al., 2015). However, up to now, only a few studies focused on quantifying the acceleration term in the sea level budget (Chen et al., 2017), and the acceleration plays a crucial role in projecting the future GMSL rise in conjunction with the increasing atmospheric greenhouse gas concentrations (Church et al., 2013). The acceleration term is also free from model errors in glacial isostatic adjustments (GIAs), which would occur at constant rates in the timescale studied in this paper. Here we use the Argo, GRACE, and satellite altimetry data sets to estimate the acceleration term in GMSL and its closure in the sea level budget.

2. Data and Method

2.1. Altimetric Sea Level Change

Global sea level altimetry data by TOPEX/Poseidon and Jason satellites have been available since 1993. Here we used products processed by five different organizations: University of Colorado (CU; http://sealevel.colorado.edu/); Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO; http://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html); Commonwealth Scientific and Industrial Research Organisation (CSIRO; http://www.cmar.csiro.au/sealevel/sl_hist_last_decades.html); National Aeronautics and Space Administration, Goddard Space Flight Center (NASA-GSFC; http://podaac-ftp.jpl.nasa.gov/dataset/MERGED_TP_J1_OSTM_OST_GMSL_ASCII_V3); and National Oceanographic and Atmospheric Administration (NOAA; http://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/). We used their averages as the data and found their monthly dispersion ~1.0 mm. This is an underestimate as no systematic errors in the observations are considered. Here we assumed the monthly uncertainty as 17.3 mm, and this makes their annual uncertainty 5 mm as recommended by Church and White (2011).

2.2. Steric Changes

In the Argo project, they deploy floats over the global ocean to monitor its variability in salinity and temperature in the upper 2,000 m. The floats achieved a dense spatial coverage around 2005. Here we estimate steric changes of the global mean sea level from 2005 to 2015 based on monthly products from the International Pacific Research Center (IPRC), the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), and the Scripps Institution of Oceanography (SIO) (http://www.argo.ucsd.edu/Gridded_fields.html). These data sets have 1° × 1° spatial resolution between 65°S and 65°N from the surface to the depth of 2,000 m. We adopted their spatial average as the final estimate and their dispersion as their uncertainty.

2.3. Mass Changes

GRACE data are used to estimate contributions of land water and land ice to GMSL. The averages of the solutions from Center for Space Research, University of Texas (CSR), Jet Propulsion Laboratory, California Institute of Technology (JPL), and Deutsche GeoForschungsZentrum, Potsdam (GFZ) are used to alleviate errors in the individual solutions. These data sets are available at http://icgem.gfz-potsdam.de/ICGEM/. Special treatments are performed for the low degree components, and the contributions from GIA are corrected (Peltier et al., 2015).

The forward modeling method was proposed by Chen et al. (2013) to restore the leakage of land signals to oceans. The ocean mass correction was introduced to bring the change in the degree-0 term (total mass of the Earth) to zero. The degree-1 terms (geocenter position) were also fixed to zero because GRACE is not sensitive to them. However, this step could introduce a systematic bias in the final estimate, because the output models are derived only from signals on land rather than from the whole Earth, and the consequent degree-1 terms may not follow those in the input model. Here we used the method to process degree-1 terms further modified by Yi et al. (2015).

The forward modeling method has the following three steps:

Spherical harmonic coefficients (SHCs) of the GRACE monthly solutions are smoothed and converted into space domain values of equivalent water height σ_1.

All grids of σ_1 on the land are integrated based on an area-weighted matrix (suppose the total mass is m), and a uniform value of a is given to all the grids in the ocean so that the integration of a is equal to $-m$. Therefore, the sum of global mass is zero and we get a new set of water height at global grids, σ_2. This process is named as the ocean mass correction.

Expand σ_2 into SHC, then smoothed SHCs are forwarded back to spatial observations σ_3. The difference between σ_1 and σ_3 is $\Delta\sigma$. Then update σ_2 in two steps. First, $\sigma_2 = \sigma_2 + 1.5 \times \Delta\sigma$, where a factor of 1.5 is introduced to accelerate the convergence; Second, apply the ocean mass correction in Step 2.

We repeated Step 3 until $\Delta\sigma$ on the land becomes small enough, which means the mass distribution σ_2 shares the similar gravity signal as the GRACE observations.

3. Results

After seasonal variations are removed, altimetric GMSL records show large interannual variations superposed on the background persistent rise with small but significant acceleration (yellow curve in Figure 2a). Cazenave et al. (2014) showed that these interannual variations are largely driven by the land-ocean water exchanges associated with ENSO (El Niño–Southern Oscillation). Land water storage revealed by the GRACE observations indeed exhibits strong variations, especially since ~2010 (Figure 2a). It made a negative contribution to GMSL from 2005 to 2010 because of increasing land water storage (Reager et al., 2016). However, intense oscillations after 2010 reversed the trend to a large positive contribution, with the cumulative increase exceeding the negative contribution before 2011. This results in a large acceleration over the whole 2005–2015 period, accounting for approximately two-fifth of the contemporaneous acceleration in GMSL.

Note that this land water contribution is likely not related to long-term global warming but changes with natural interannual-to-decadal variability, such as ENSO and Pacific Decadal Oscillation phases (Cazenave et al., 2014). Therefore, such short-term contribution from land water storage makes the long-term climate changes ambiguous and should be removed. Reager et al. (2016) applied the JPL mascon products (Watkins et al., 2015) (also based on GRACE observations) to study changes in land water storage and suggested that short-term natural variability up to 2014 has slowed down the sea level rise. Our result supports this conclusion for the first half of study period. However, in its second half, our results suggest a faster decline of the land water storage, which is underestimated in the JPL mascon products. This is confirmed in the sea level budget in Figure 3, in which an extra rise of 4 ± 2 mm in GMSL record during 2010–2015 is not found in the JPL mascon products. Moreover, amplitudes of seasonal variations in the JPL mascon solutions are significantly weaker. In terms of acceleration, the budget based on the JPL mascon products only explains 85% of the altimetry observation (Figure 2b). We think this underestimation reflects the leakage from ocean to land, which has not been recognized adequately. The recent water storage losses mainly come from coastal areas (refer to supporting information), and the leakage from the increasing gravity of ocean would have caused the underestimation of the land water loss in these areas. This leakage correction also improves the annual variations and long-term trends in GMSL. The details can be found in the supporting information (Chen et al., 2013; Cheng et al., 2011; Peltier et al., 2015; Reager et al., 2016; Swenson et al., 2008; Wahr et al., 2015; Wouters et al., 2013; Zhang et al., 2009).

The interannual fluctuation in altimetry-based GMSL 2005–2015 is much reduced after we removed the contribution from land water storage. Such a "land-water-corrected" GMSL curve (red curve in Figure 2a) is more suitable for discussing the long-term trend and acceleration due to land ice melting and thermal expansion. This quantity can be independently measured by combining the GRACE and Argo observations (black curve in Figure 2). These two curves agree well with each other, indicating the closure of the sea level budget and mutual consistency of the three different data sets.

Steric change and land ice, respectively, contribute to GMSL acceleration by 0.12 ± 0.06 mm/yr^2 and 0.04 ± 0.01 mm/yr^2, whose sum coincides with 0.16 ± 0.17 mm/yr^2 from land-water-corrected GMSL (despite its large uncertainty). Figure 2b suggests that the acceleration in altimetric GMSL is inflated by natural variability of land hydrological storage. The acceleration is much reduced by this correction but still holds a significant value of 0.16 ± 0.06 mm/yr^2, with approximately one-fourth coming from ice melting and approximately three-fourth from steric change.

We should note that the land-water-corrected GMSL shows a clear acceleration; that is, the linear trend 2011–2015 is 65% faster than the trend in 2005–2010 (Figure S12 in the supporting information). We also confirmed with the *L*-curve method that the quadratic function is the most appropriate (Figure 4); that is, the introduction of acceleration reduces the postfit residuals by 25%, while the higher-order terms do not further improve the fit. Similar conclusions could also be found in other components and their combinations, justifying the quadratic polynomial fit for the observed GMSL changes.

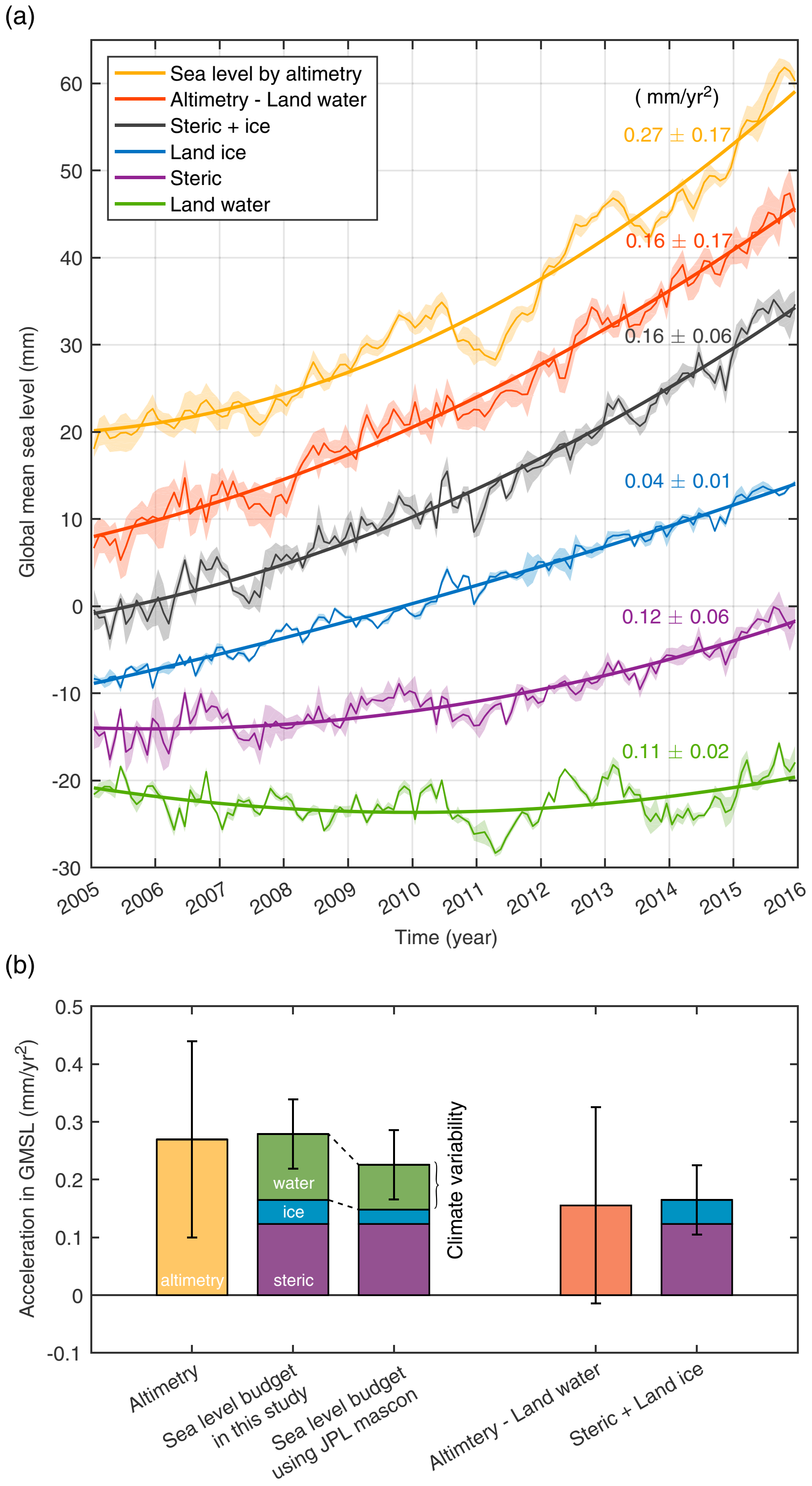

Figure 2. Acceleration of GMSL change and its breakdown. (a) Time series of all components. The results of land water and land ice are derived from GRACE observations, and the steric change is based on Argo observations. The average seasonal variations have been removed. Time series are modeled by quadratic polynomials of time, and the estimated accelerations (mm/yr^2) are annotated alongside. Details about the estimated errors are given in section 2 and the supporting information. The curves have been offset for clarity. (b) Sea level budget in terms of acceleration. (left) Accelerations in the observed global mean sea level by satellite altimetry and those disaggregated into three components (land water, land ice, and steric) using data from GRACE/Argo. The result using the JPL mascons is also shown. The large contribution from continental water is driven by natural variability other than the current global warming. (right) The sea level acceleration budget after removing the land-water contributions.

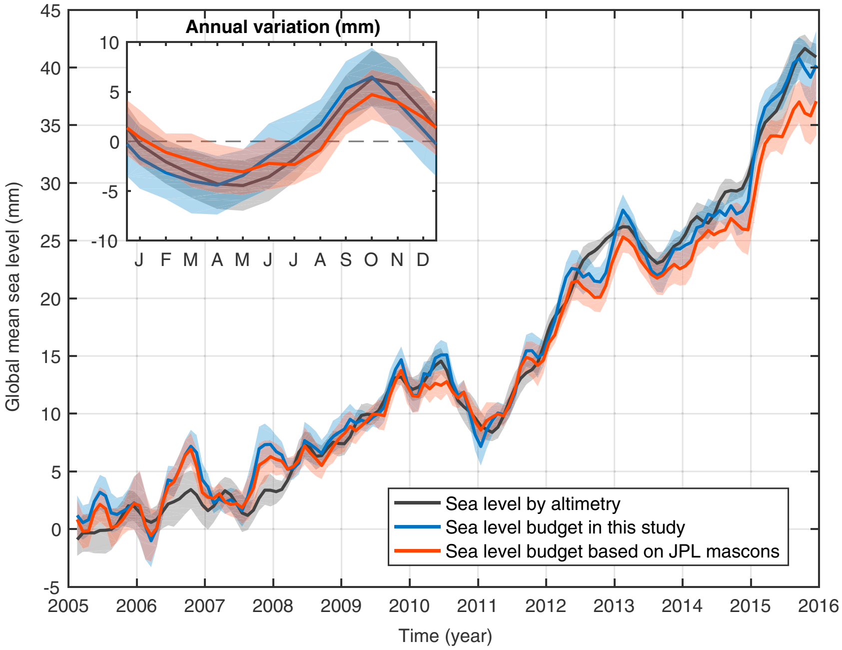

Figure 3. Sea level budget in this study and based on JPL mascons. The annual variations are removed and plotted in the inset. The interannual time series are smoothed by a 3 month sliding window. The sea level budget curves are based on the GRACE (land water and ice) and Argo (thermosteric) observations. Uncertainties in the interannual/annual variations are calculated by the dispersion among different data sets/years.

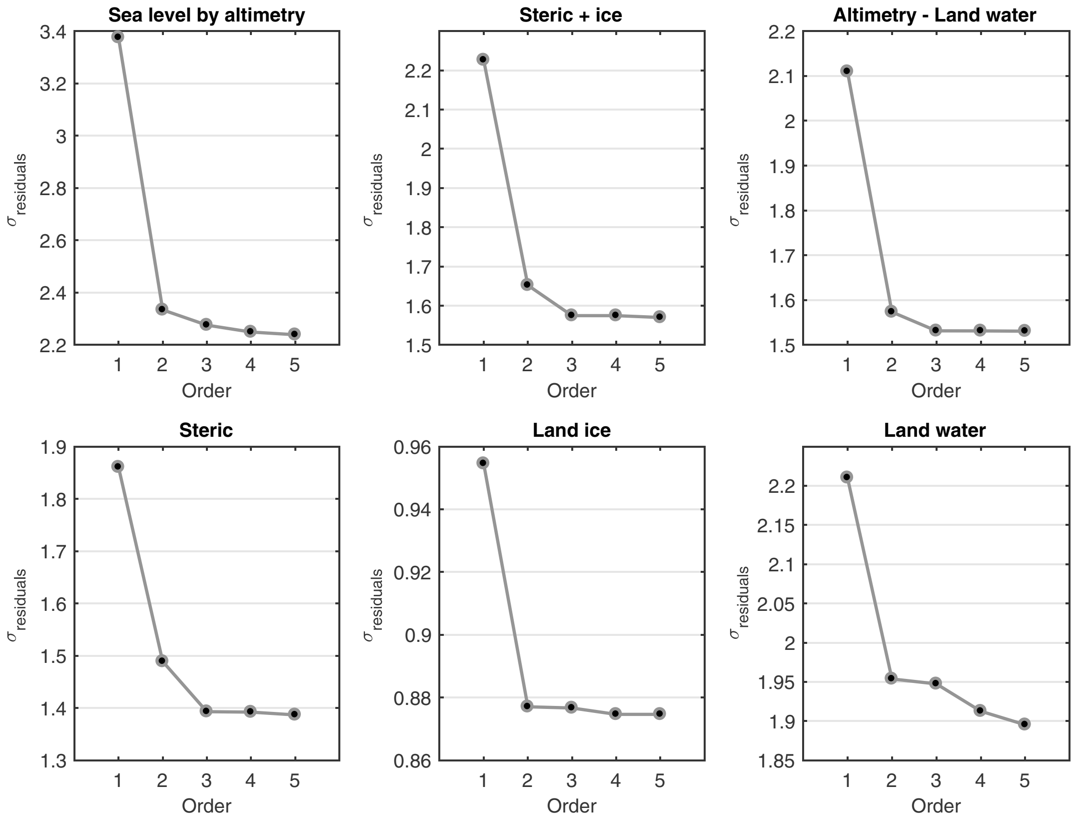

Figure 4. Dependence of the standard deviation of the postfit residuals of various quantities (unit: mm) on the degree of polynomials used to model their time series. All show sharp drops by adding the quadratic (degree-2) terms and insignificant decrease by further adding higher-order terms.

4. Discussion and Conclusion

The large acceleration in steric change is likely related to the restart of global warming in recent years (Figure 1b), as an immediate response of the surface mixed layer to the warming. On the other hand, the melting of land ice is a multidecadal consequence of the global warming with a delayed response. A simulation study showed that observations spanning at least 20 years are necessary for reliable separation of the long-term acceleration in ice melting from short-term natural variability (Wouters et al., 2013). We can easily confirm this by comparing the acceleration in different periods, especially for the Greenland ice sheet (see section 6.2 in the supporting information). However, short-term variations of individual ice sheets and mountain glaciers seem to cancel each other to some extent, and the acceleration of the melting of the global land ice robustly falls within the range 0.03–0.07 mm/yr^2 for periods exceeding 7 years (Figure S14). This agrees with the acceleration 0.04 mm/yr^2 obtained here for 2005–2015 despite the relatively short time span.

The acceleration in sea level rise derived here has sound implication from multiple viewpoints. At first, the sea level budget approach is essential to study the acceleration in GMSL in a period as short as a decade. Altimetry records have an uncertainty so large that the determination of their acceleration over just a decade is not reliable, but the uncertainty can be largely reduced after justification with independent observations by GRACE and Argo. Second, approximately three-fourth of the acceleration directly comes from the accelerating global temperature rise, and the contribution from land ice only accounts for approximately one-fourth (0.04 ± 0.01 mm/yr^2). Studies using GRACE and Satellite Laser Ranging reported significant acceleration in melting of Greenland and Antarctic ice sheets in the last two decades (Chen et al., 2009; Matsuo et al., 2013; Velicogna & Wahr, 2006), and the acceleration could reach 0.1 mm/yr^2 for specific periods such as 1992–2009 (Rignot et al., 2011) or 2003–2013 (Velicogna et al., 2014). However, such acceleration would decrease by extending the time window to more recent years, as seen in the slowdown of melting in Greenland ice sheet from 2013 to 2015 due to surface mass gains (van den Broeke et al., 2016).

The importance of the climate-driven effect has not been recognized until recently (Reager et al., 2016; Wada et al., 2016), so GRACE-derived land water storage changes may be quite different from results that only focus on groundwater depletion (e.g., Döll et al., 2014; Famiglietti, 2014). Besides, the different strategies in processing of GRACE and separation of ice and water signals may cause inconsistencies even with similar data sources (Dieng, Champollion, et al., 2015; van Dijk et al., 2014). Our method indicates that the contribution from land water storage in 2003–2013 has a weak negative trend (−0.12 ± 0.06 mm/yr), and this agrees well with −0.06 ± 0.09 mm/yr in the same period using a different mascon approach (Schrama et al., 2014).

Two recent studies reported the acceleration in GMSL over the last two decades (Chen et al., 2017; Dieng et al., 2017). They incorporated various observations and models to extend their study period back to 1993 to make their data sets longer and robust against natural variabilities in decadal timescales. Dieng et al. (2017) investigated changes in the sea level rate between the last two decades and identified a significant acceleration; that is, the rate 2.67 ± 0.19 mm/yr in 1993–2004 increased to 3.49 ± 0.14 mm/yr in 2004–2015. Nevertheless, they did not constrain the acceleration in shorter timescales. Our results generally agree with their rates in 2005–2015. However, a large discrepancy exists in the mass balance of the Antarctic ice sheet; that is, our results show the rate of 0.55 mm/yr while they found it only 0.33 mm/yr. The difference reflects their use of the incorporation of various observations including satellite altimetry, GRACE, and interferometric synthetic aperture radar in contrast to our approach based only on GRACE. Our results agree well with those using the JPL mascons (Table S2 in the supporting information).

Chen et al. (2017) adopted an ensemble empirical mode decomposition method to extract the intrinsic trend 1993–2014 and found a gradual increase of the sea level rate from 2.2 ± 0.3 mm/yr in 1993 to 3.3 ± 0.3 mm/yr in 2014. However, studies over such a long period may underestimate the influence of the rapid warming after the recent hiatus. This underestimation appears in their average GMSL trend of 3.0 mm/yr in 2004–2014, which is only 85% of the value obtained by Dieng et al. (2017) and by us. As shown in Figure 1, global warming is resumed only in recent years, and averaging over a longer period will reduce the acceleration. After all, Chen et al. (2017) found a significant acceleration only in Greenland ice sheet melting (0.03 mm/yr^2), and not in the steric sea level change.

In conclusion, we have confirmed the consistency of the acceleration in the GMSL change 2005–2015 from satellite altimetry (0.27 ± 0.17 mm/yr^2) with data from GRACE and Argo. This supports the accelerating sea level rise in the last two decades reported by Chen et al. (2017) and Dieng et al. (2017). We also found that the acceleration mainly comes from terrestrial water storage (0.11 ± 0.02 mm/yr^2) and steric change (0.12 ± 0.06 mm/yr^2), and the latter is probably related to the recent restart of global warming. The contribution of the acceleration in the melting land ice is only 0.04 ± 0.02 mm/yr^2, which may possibly increase in the future because of its delayed response. After removing the contribution of natural variability of hydrological storage, the remaining acceleration is 0.16 ± 0.06 mm/yr^2, which is by 1 order of magnitude larger than 0.02 ± 0.015 mm/yr^2 over 1920–2011 (Calafat & Chambers, 2013) and 3 times as fast as 0.055 mm/yr^2 during 1993–2014 (et al., 2017). We should be aware that the large acceleration only reflects the period 2005–2015, and we need longer observations to sufficiently remove the influence of decadal and multidecadal variabilities. Nevertheless, it is important to recognize that this acceleration indicates the susceptibility of GMSL to the recent resumption of global warming after the hiatus.

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