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Key Points:

- The sea level rise rate has increased since 2010
- A reconciled sea level budget is achieved
- The mechanism underlying the increase sea level rate is discussed

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An increase in the rate of global mean sea level rise since 2010

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Abstract The global mean sea level (GMSL) was reported to have dropped 5 mm due to the 2010/2011 La Niña and have recovered in 1 year. With longer observations, it is shown that the GMSL went further up to a total amount of 11.6 mm by the end of 2012, excluding the 3.0 mm/yr background trend. A reconciled sea level budget, based on observations by Argo project, altimeter, and gravity satellites, reveals that the true GMSL rise has been masked by El Niño–Southern Oscillation-related fluctuations and its rate has increased since 2010. After extracting the influence of land water storage, it is shown that the GMSL has been rising at a rate of 4.4 ± 0.5 mm/yr for more than 3 years, due to an increase in the rate of both land ice loss and steric change.

1. Introduction

Global mean sea level (GMSL) is an indicator of global climate and environment changes. It is a result of global warming, ice melting, and water exchange between land and sea. The GMSL rise directly influences the coastal environment, such as erosion in coastal areas and higher flood risk [Cazenave and Cozannet, 2014]. In the last 100 years, GMSL has been rising in response to “global warming” caused by accumulation of anthropogenic greenhouse gases in the atmosphere [Intergovernmental Panel on Climate Change (IPCC), 2014]. Historical tide gauge data show a GMSL trend of 1.7 ± 0.2 mm/yr from 1900 to 2009 and 1.9 ± 0.4 mm/yr since 1961 [Church and White, 2011]. The satellite altimetry missions since 1993 provide a nearly global coverage of the ocean and show a rate of 3.2 ± 0.4 mm/yr in the last 20 years. A recent study using probabilistic technique declared that these values are somehow overestimated but the acceleration is underestimated: the GMSL rising rate is 1.2 ± 0.2 mm/yr from 1900 to 1990 and 3.0 ± 0.7 mm/yr from 1993 to 2010 [Hay et al., 2015]. In spite of this, it is well accepted that the GMSL has been rising slower since the start of 21st century, which coincides with a hiatus in the Earth’s warming [Cazenave et al., 2014; England et al., 2014].

We compute the GMSL rate from altimetry data over 5 year long moving windows to show the interannual variance in the period 1993–2014 and depict the results in Figure 1. The average trend from 1993 to 2014 is 3.2 ± 0.4 mm/yr. Rates faster/slower than the whole-period average are expressed in red/blue. Figure 1 shows that the GMSL rate was fast in 1996–2004 and slow in 2005–2010. Since then, the 5 year trend appears to be accelerating again, indicating that the GMSL is rising faster since 2010.

The 2010/2011 La Niña, the strongest El Niño–Southern Oscillation (ENSO) cold event in the past eight decades, caused a drop of 5 mm in GMSL [Boening et al., 2012]. The drop is a result of excesses of terrestrial water storage in Australia, northern South America, and Southeast Asia, within which Australia had a dominant contribution [Fasullo et al., 2013]. Their studies showed that this event seemed to end and the GMSL rate recovered from the drop in late 2011. In this work we extend the time period to mid-2014. It shows that the GMSL went further up rather than just recovering from the drop and the fluctuation brought by this La Niña episode lasted longer to late 2013.

We adopt a line with annual-semiannual periods to fit the GMSL records in the recent 10 years, and after removing the background rate (3.0 mm/yr, 2005–2014) and periods, we find that the GMSL has experienced large fluctuation since 2010. The GMSL dropped 7.9 mm from the start of 2010 to the start of 2011, and rose 11.6 mm afterward to the end of 2012, then dropped 4.4 mm in half a year. To understand the mechanism responsible for the GMSL rise, a reconciled sea level budget is achieved. The contributions from land water, land ice, and steric change are discussed.

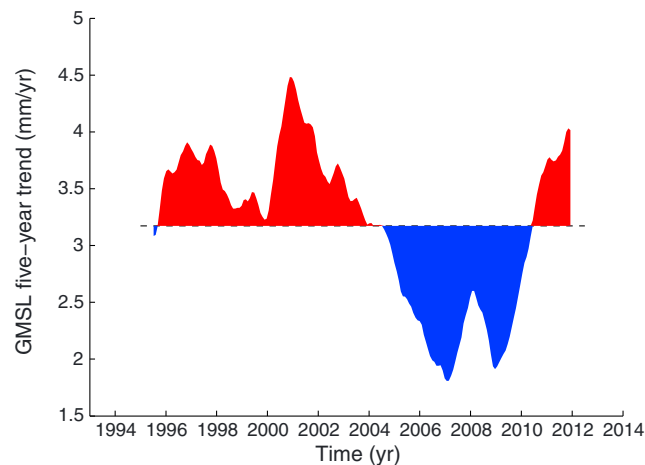


Figure 1. Temporal evolution of the GMSL rate computed over 5 year long moving windows. The horizontal line represents the average rate of 3.2 mm/yr from 1994 to 2014. The red and blue areas indicate the fast and slow rates with respect to the average rate, respectively. The GMSL rate behavior was fast from 1996 to 2004, slow from 2005 to 2010, and then fast again.

2. Data and Methods

The variation in GMSL is dominated by two factors: the steric change and mass contribution. The first concerns density change caused by thermal expansion and salinity change, which can be measured by the Argo project; the second includes water contribution from land water and land ice, covering polar ice sheets and glaciers and ice caps (GICs), which can be measured by Gravity Recovery and Climate Experiment (GRACE). Assuming that water interchange between land and oceans is subject to conservation of mass, the mass increase in oceans equals the mass loss on land and vice versa. Theoretically, the GMSL change calculated from Argo and GRACE should approximate the altimetry observations, excluding the defect of Argo in the

space coverage. In this study, the GMSL rise rate is computed using the latest GRACE, altimetry, and Argo data, to investigate the current status of GMSL change and discuss the mechanism for its fluctuation.

2.1. GRACE

To determine how mass migrates on the Earth surface, GRACE Release 05 data sets covering from January 2003 to July 2014 are here used to compute ice melting and land water storage changes. The data sets come from three organizations: the Center for Space Research at the University of Texas, GeoForschungsZentrum, Potsdam, and Jet Propulsion Laboratory (<http://icgem.gfz-potsdam.de/ICGEM/>). Their mean values are taken as our final estimation. We process the GRACE data by applying a 500 km Gaussian smoothing filter [Wahr *et al.*, 1998], replacing all the degree 2 coefficients with satellite laser ranging ones [Cheng *et al.*, 2011] and adding back the degree 1 (geocenter) coefficients [Swenson *et al.*, 2008]. The postglacial rebound effect is corrected by a 3-D Geruo13 PGR model [Geruo *et al.*, 2013].

The uncertainty of GRACE data is estimated as introduced in Wahr *et al.* [2006], and the monthly uncertainties of the land water, land ice, and their sum to GMSL are 3.9 mm, 1.8 mm, and 4.5 mm, respectively. All uncertainties in the paper are in 95% confidence intervals. The difference among the three models is also compared. On average, their monthly observations of land mass are varied at a level of 1.0 mm. This difference is comparatively smaller, so we declare that the choice of processing group will not bias our conclusion. The Glacial Isostatic Adjustment (GIA) uncertainty for Greenland and Antarctica is estimated as 21 Gt/yr and 72 Gt/yr, respectively [Velicogna and Wahr, 2013]. These observation uncertainties are included in the uncertainties of the secular trend.

2.2. Altimetry

The altimetry data are produced by five processing groups: 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 Organization (CSIRO; http://www.cmar.csiro.au/sealevel/sl_hist_last_decades.html); National Aeronautics and Space Administration (NASA; http://podaac-ftp.jpl.nasa.gov/dataset/MERGED_TP_J1_OSTM_OST_GMSL_ASCII_V2); and National Oceanographic and Atmospheric Administration (NOAA; <http://www.star.nesdis.noaa.gov/sod/Isa/SeaLevelRise/>). These data are based on Topex/Poseidon and Jason-1/2 missions. The mean values of the five organizations from January 2003 to July 2014 are adopted.

The trend error of the altimetry result in 20 years is 0.4 mm/yr (1 standard deviation) in all five groups. The discussion on this problem can be found in Church and White [2011]. The error of trend in a dedicated time period is estimated from the variance of trends among the five groups. It turns out that a shorter time period

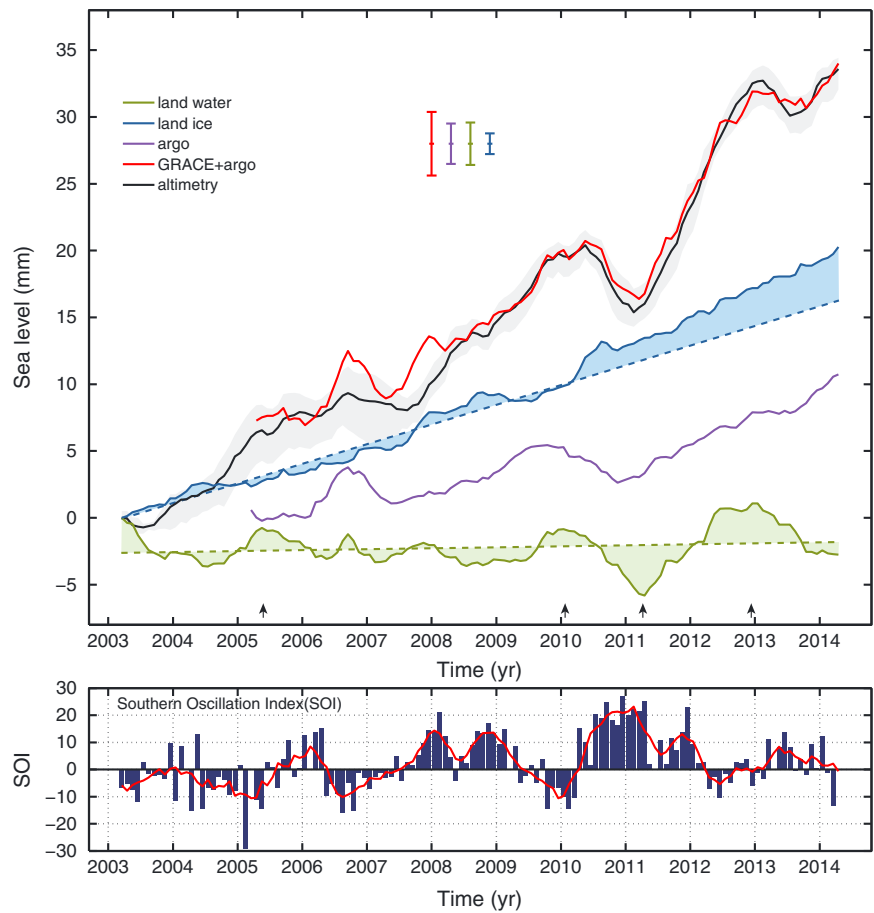


Figure 2. GMSL from altimetry (in black, variance range in gray shading), steric (in magenta), and mass contribution estimated from GRACE (green for terrestrial water storage contribution and blue for land ice contribution). The red line is the combined effect of GRACE and Argo. Trend of land ice from 2003 to 2014 is in blue dashed line. The trend of land water from 2003 to 2014 is in green dashed line. The error bar of each plot is shown. The annual and semiannual periods are removed, and a half-year sliding window smoothing is applied. The four arrows indicate the four specific times in Figure 4. The time series of Southern Oscillation Index (SOI) is shown in the bottom figure. The red curve is a smoothed result from 5 month long moving windows.

results in a larger error range. In a period of 5 years, the uncertainty is about 0.5~0.8 mm/yr. In Figure 2, the variance range is taken from the minimum and maximum values of observations from five groups in each epoch.

2.3. Argo

The temperature and salinity of the upper layer of the ocean measured by the Argo profiling floats are used to estimate the steric contribution. The Argo project started in 2000, but only after 2005 was the spatial coverage globally dense enough to guarantee a reasonable evaluation [Chen *et al.*, 2013]. The Argo data used here are 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). Their mean value is adopted as our steric estimation. These data have a spatial resolution of 1° between about 65°S and 65°N and range from the surface to about 2000 m in depth. The details about the Argo data processing and data error discussion can be found in Chen *et al.* [2013]. The uncertainty of data is based on the fitting residue of the periodicity and is estimated as 3.6 mm. The contribution from below the observation depth of Argo is 0.11 mm/yr [Purkey and Johnson, 2010], which is included in our trend error.

2.4. Global Forward Modeling Method

A global forward modeling method introduced by Chen *et al.* [2013] is adopted to alleviate the signal leakage problem in GRACE. The step-by-step instructions can be found in their supplementary information. In brief, in each

Table 1. Trends of GMSL From Altimetry, Argo, and GRACE With GIA Corrected (mm/yr)

	Jan 2005 to Dec 2009	Jan 2010 to Jul 2014	Jan 2005 to Jul 2014
Altimetry	2.49 ± 0.85	4.49 ± 0.62	3.13 ± 0.44
Argo + GRACE	2.39 ± 0.56	4.33 ± 0.60	3.00 ± 0.31
Argo	0.98 ± 0.44	1.77 ± 0.23	0.97 ± 0.18
GRACE	1.41 ± 0.35	2.56 ± 0.55	2.03 ± 0.25
Land water	-0.27 ± 0.25	0.38 ± 0.48	0.07 ± 0.13
Land ice	1.69 ± 0.25	2.18 ± 0.28	1.96 ± 0.22
Greenland	0.57 ± 0.09	0.89 ± 0.09	0.77 ± 0.06
Antarctica	0.45 ± 0.23	0.71 ± 0.25	0.60 ± 0.21
GICs	0.67 ± 0.05	0.58 ± 0.08	0.58 ± 0.04

step of the iterative fitting, the difference between the observation and the model is added back in the next step. As a result, the modeled mass change becomes closer and closer to the GRACE observations. This process is repeated for all monthly solutions from the three groups. We only take one modification that the degree 1 coefficients are included in the iteration. The results with and without degree 1 are compared, and the former gave a slightly better sea level budget. The land water and land ice are separated based on their spatial locations.

3. Results

With a reconciled GMSL budget, it is necessary to understand the mechanisms underlying the changes in GMSL. Some previous studies [Cazenave *et al.*, 2009; Chen *et al.*, 2013; Leuliette and Miller, 2009; Leuliette and Willis, 2011] investigated this budget, but only Chen *et al.*'s [2013] result agreed well, with the help of a more realistic GIA model and a global forward modeling method, which is also adopted in this paper. The time series of GMSL from altimetry, the steric change from Argo, and mass change from GRACE are depicted in Figure 2 and their trends listed in Table 1. The annual and semiannual periods are removed using the method described above, and a half-year sliding window smoothing is applied. The error bars have been reduced by $\sqrt{6}$ to account for the half-year smoothing. Variations in GMSL shown by Argo and GRACE are closely consistent with altimetry observations (the red and black curves in Figure 2).

The sea level budget is better established ever since 2008, while the result between 2005 and 2008 is not so good. Considering that during the studied period the altimeter and GRACE satellites were under stable condition while the Argo project was in a development stage, we speculate that this mismatch is due to the flaw in the Argo early observation.

Table 1 indicates that from January 2005 to July 2014, the steric change contributes 25%–35%, land water contributes less than 7%, and land ice contributes 55%–70%. The ocean mass contributions of Greenland, Antarctica, and the glaciers and ice caps to GMSL rise are 23%–27%, 13%–26%, and 17%–20%, respectively. The huge ice volume of Greenland (equals 7 m sea level) and West Antarctica (the instable part of the continent, equals 3–5 m [Cazenave and Cozannet, 2014]) has higher potential of contributing to the GMSL than the GICs, whose share of contribution is declining now as a result.

Table 1 and Figure 2 show that the GMSL rising rate increases 80% from 2.5 mm/yr to 4.5 mm/yr after 2010. The abnormal terrestrial water storage, accelerated melting in land ice, and steric changes are all the contributors. The blue curve in Figure 2 represents the contribution of global ice melting, and it shows an increase since 2010.

To compare our results with previous studies, we also computed the trends during 2003 to 2009. The total contribution of Greenland and Antarctic ice in our study is 0.89 ± 0.25 mm/yr, and this agrees with 0.82 ± 0.16 mm/yr from Hanna *et al.* [2013]; our total land ice estimation (1.47 ± 0.23 mm/yr) agrees well with 1.51 ± 0.16 mm/yr from Gardner *et al.* [2013]. The contribution of ocean warming during 1993 to 2010 is 1.1 ± 0.3 mm/yr [IPCC, 2014], which is almost constant in recent decades, except the speed up in the last few years. It, however, needs more observations to tell it a long-term interannual variance.

3.1. Land Ice

The melting rate of land ice shows an increase since 2010. After extending the 2003–2009 trend, we find that the land ice trend since 2010 shows an apparent deviation from it, as represented by the light blue shading in Figure 2.

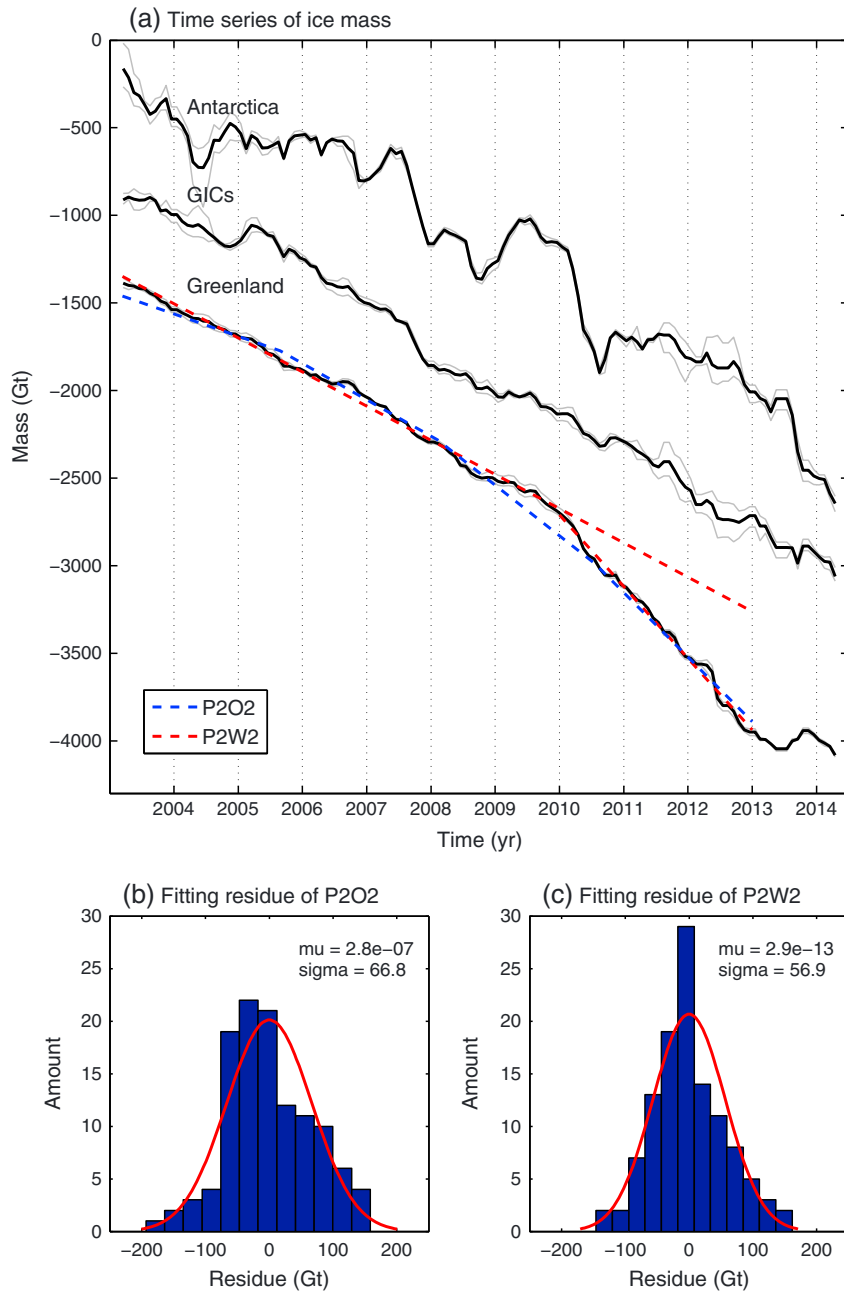


Figure 3. (a) Time series of mass in Antarctic, GICs, and Greenland. The variances among the three GRACE models are shown in gray lines. The time series of Greenland mass is fitted by two strategies, P2O2 (polynomial of order 2 with two periods) and P2W2 (two-piecewise line with two periods) in blue and red dashed lines, respectively. (b and c) Their fitting residues are shown; in each the red line represents the theoretical Gaussian distribution of the residuals. Mu and sigma are the expectation and standard deviation of the Gaussian distribution.

To find the acceleration in melting of land ice, we extract the three components: Antarctica, Greenland, and GICs. The results are shown in Figure 3. In the last decade the ice melt in Greenland is regarded to be accelerated [Velicogna, 2009; Velicogna et al., 2014; Wouters et al., 2013]. This work put a check on the acceleration of the mass change of Greenland. Because the giant mass loss in Greenland has largely stopped since 2013, here we only recheck its changing characteristic from 2003 to 2012. Traditionally, its mass change is fitted by a quadratic polynomial with annual and semiannual periods (hereinafter P2O2). However,

with a closer inspection, we find that the P2O2 does not fit well from 2009 to mid-2010, during which a sharp change in trend is discernible.

Therefore, we tried a different fitting strategy, a two-piecewise linear fitting with a break in January 2010 and with annual and semiannual periods (hereinafter P2W2). For a better comparison with the linear trend after 2010, the trend from 2003 to 2009 is extrapolated. Compared with the residue of P2O2, the result of P2W2 has a 15% lower standard variance and shows a closer pattern to Gaussian distribution (red lines), the statistical behavior of a set of random data. Based on these two reasons, we conclude that P2W2 is a better choice. The change pattern of Greenland ice mass from 2003 to 2012 is closer to piecewise linear; i.e., the time series is relatively linear before 2010 and an increase of 100% afterward (1.1 ± 0.1 mm/yr in 2010–2012 compared to 0.54 ± 0.1 mm/yr in 2003–2009). This acceleration is due mainly to the loss of ice from the southwest coast of Greenland.

Greenland did not show mass loss from 1990 to 2002 [Matsuo *et al.*, 2013], but from 2010 to 2012 it was melting more than twice faster than Antarctica (1.1 ± 0.1 mm/yr compared to 0.4 ± 0.3 mm/yr). This tremendous mass losing rate has stopped abruptly since 2013. But the whole land ice is still losing mass quickly because this alleviation in Greenland is counteracted by a simultaneously accelerated ablation in the Antarctic ice (Figure 3).

The mass balance status in Antarctica is less well determined because of the large fluctuation in only 11 years. However, the Antarctic ice was melting slower before 2006 [Chen *et al.*, 2009], and an acceleration seems to have started recently.

3.2. Land Water

Previous studies showed that the interannual variance of GMSL is related to ENSO [Nerem *et al.*, 2010; Cazenave *et al.*, 2014] and land water storage [Llovel *et al.*, 2011]. Here the relationship between ENSO and the land water storage is checked. The SOI data are taken from <http://www.bom.gov.au/climate/current/soi2.shtml>. The land water storage is positively correlated with SOI; i.e., a positive SOI (La Niña event) corresponds to a mass increase on land to a drop in GMSL and vice versa. The large and long-sustaining La Niña event from mid-2010 to the start of 2012 together with abnormal Indian Ocean Dipole and Southern Annular Mode [Fasullo *et al.*, 2013] caused the largest excess in land water storage ever since 2003, contributing to the GMSL a drop of 3.8 mm, compared with the linear trend in the whole range. This value is 5.1 mm when compared with January 2010, the same as in [Boening *et al.*, 2012]. However, straight after this mass accumulation and starting in mid-2012, the land water storage shows a giant mass loss, contributing to GMSL a rise of 3.0 mm. This mass loss lasted for more than 1 year and ended in the end of 2013. One noteworthy phenomenon is that this mass loss on land is unrelated to ENSO, which is too moderate during this period to cause such an extreme condition. The mass loss may be explained by a subsequent undulation resulted from the tremendous mass loss around 2011, or other climatic factors, some of which were observed to have a key role in the drop of GMSL in 2010/2011 [Fasullo *et al.*, 2013].

The water storage in land had little net mass change from 2003 to 2014. Even the strongest ENSO cold event in 80 years could only cause a temporary water surplus. IPCC [2014] gave the contribution of land water to GMSL at a longer term: the trend is -0.11 ± 0.5 mm/yr for 1901 to 1990 but 0.38 ± 0.12 mm/yr for 1993 to 2010. The current balance may be a result of counteraction of the progress of anthropogenic processes, like groundwater withdrawal and impoundment in reservoirs [Chao *et al.*, 2008; Konikow, 2011]. This fluctuation in land water should be excluded when evaluating the secular GMSL trend.

To show the change of land water storage in the SOI extreme episodes, the mass anomalies in four specified times are demonstrated in Figure 4. Here “anomaly” means the deviation from the secular trend, after the annual and semiannual periods are removed. The four epochs are 2005AMJ (mean of Apr, May, and June and so on), 2010JFM, 2011MAM, and 2012NDJ, which are marked out with arrows in Figure 2.

The 2005AMJ, 2010JFM, and 2012NDJ show a land water storage loss, contributing to a rise in GMSL. The 2011MAM shows a land water storage increase. The anomalies concentrate mainly in equatorial areas (between 30° north and south) and North America, where relatively heavy precipitation occurs. As has been mentioned above, the 2012NDJ is not related to ENSO but is a result from anomalies in 2011MAM. The other three related to ENSO have a consistent mass status in the equatorial area, although local contrast can be

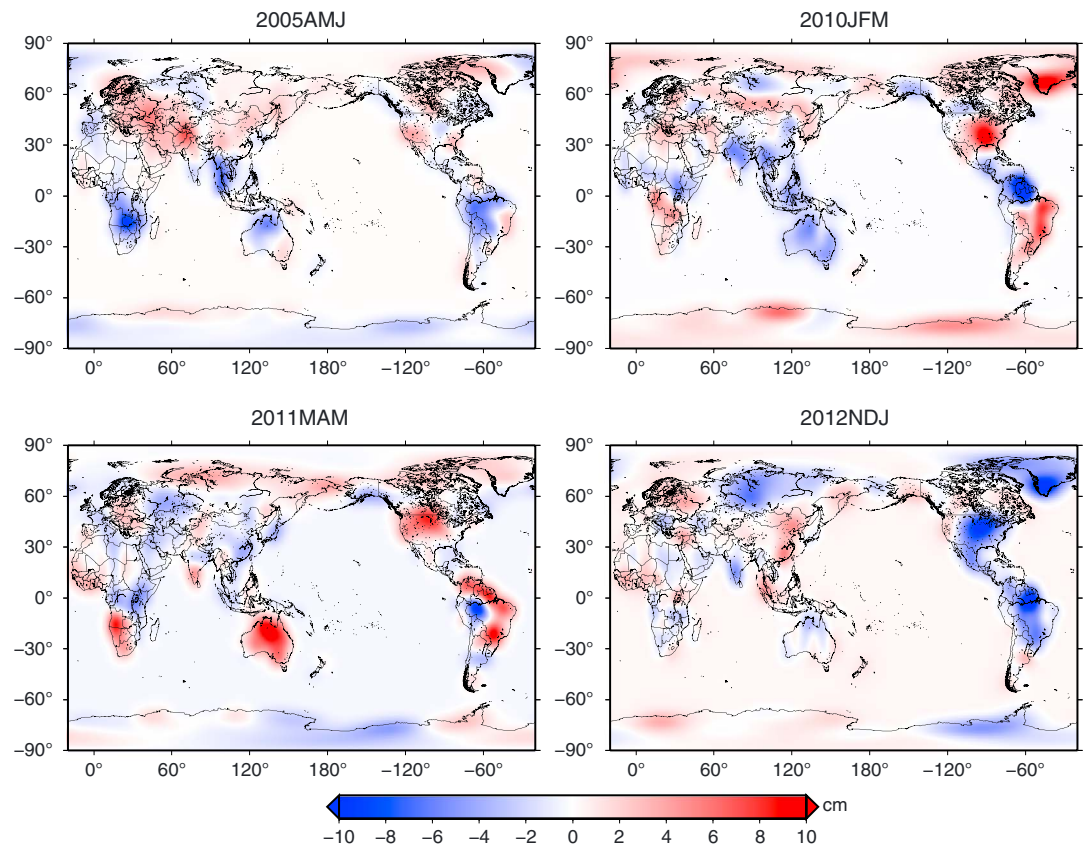


Figure 4. Global mass anomalies in four specific epochs. They are also annotated with arrows in Figure 2. The equal water depth on land is a recovered result from GRACE observations, while the ocean is assigned with a uniform mass layer to guarantee the mass conservation.

found in South America and Africa. The abnormal GMSL rise in 2012 was caused by the water storage loss in Siberia, North America, and South America. It is interesting that Australia, who played a dominant role in the fall of the ocean in the 2010/2011 La Niña, is absent in the mass loss area in 2012NDJ, probably due to its unique surface hydrology [Fasullo *et al.*, 2013]. By subtracting 2011MAM from 2010JFM, we can get a similar result as in Boening *et al.* [2012].

4. Discussions and Conclusions

It is no surprise that the rate of GMSL rise accelerated after the ~ 5 mm drop in the 2010/2011 La Niña event, as it did after the 1998 El Niño. Thus, the apparent acceleration in the following several years is a matter of course. However, whether it is underrecovering or overrecovering is hard to discriminate based solely on altimetry data. With the help of GRACE data, we can extract individual components and learn their mechanisms.

In conclusion, the increase in GMSL rate can be explained by three factors: from the start of 2011 to the end of 2012, the land water storage went from a minimum to a peak, contributing 6.8 mm in 2 years; the land ices, especially those in Greenland, have been melting 30% faster ever since 2010 (2.2 ± 0.3 mm/yr compared to 1.7 ± 0.3 mm/yr); and a speed up in rise from steric change also makes a contribution.

Our work goes further ahead of Boening *et al.* [2012]. Not only we have a longer study period but also we give a more self-consistent sea level budget. The GRACE + Argo in their Figure 2 failed to catch up with the rise of altimeter observations since mid-2011. We adopt a different method to process GRACE models to circumvent the signal leakage problem, and the Argo data we used have a better spatial resolution and cover larger depth (to about 2000 m). With longer observations, we find that there is a large land water storage deficit irrelevant to ENSO that lasted from 2012 to 2013.

Our results of sea level steric change, mass change, and altimetry observation are very similar with the curves shown in Llovel *et al.* [2014], except that we smooth the data and also separate the components of land water and land ice. Their steric and mass contributions are 0.9 ± 0.15 mm/yr and 2.0 ± 0.1 mm/yr between 2005 and 2013, very close to our 0.97 ± 0.18 mm/yr and 2.0 ± 0.2 mm/yr during January 2005 to July 2014.

From Figure 2 we can find that ever since 2011, the contributions from land ice and steric change have been in a fast and steady increase. Since 2011, the steric change, at a value of 2.2 ± 0.4 mm/yr, with the 2.2 ± 0.3 mm/yr from the land ice melt, has made the GMSL rise rate as high as 4.4 ± 0.5 mm/yr. More records are needed to tell whether this high rate will continue or not. The drop of GMSL in mid-2013, a transient result of the recharge of the land water, has blinded us to an upcoming faster GMSL rise rate, which has actually been on its way for more than 3 years.

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