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Contribution of ice sheet and mountain glacier melt to recent sea level rise

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Changes in global mean sea level primarily reflect the sum of three contributions: water mass changes in the oceans, water density changes, and variations in the volume of the ocean basins. Satellite altimetry data[1–4] suggest that sea level rose by about 2.39 ± 0.48 mm yr^{-1} between 2005 and 2011. However, previous estimates[5–9] of sea level rise from density and ocean mass changes were lower than the altimeter data indicate. Here we show that the gap in the sea level budget disappears when we combine gravity data from the GRACE (Gravity Recovery and Climate Experiment) satellite mission and temperature and salinity observations from the Argo programme collected between 2005 and 2011. The Argo data indicate a density-driven sea level rise of 0.60 ± 0.27 mm yr^{-1} throughout this period. To estimate ocean mass change from the gravity data, we developed a forward modelling technique that reduces the bleeding of terrestrial signals into the ocean data. Our reassessment suggests an ocean mass contribution of 1.80 ± 0.47 mm yr^{-1}, for a total sea level rise of 2.40 ± 0.54 mm yr^{-1}, in agreement with the altimeter-based estimates. On the basis of the GRACE data, we conclude that most of the change in ocean mass is caused by the melting of polar ice sheets and mountain glaciers. This contribution of ice melt is larger than previous estimates[10], but agrees with reports[11–13] of accelerated ice melt in recent years.

Measuring global sea level change, and understanding its causes, is a key goal in monitoring global climate. The global mean sea level (GMSL) anomaly time series from the AVISO global merged altimeter data using the three main reference satellite altimeter missions[1], TOPEX/Poseidon (T/P) and its follow-ons Jason-1/2, shows an average rate of ~3.1 ± 0.4 mm yr^{-1} for the past 20 years[2–4] (see Fig. 1a), well above the 1.7 ± 0.3 mm yr^{-1} rate from historical tide gauge data[14]. Among many possible contributors to the rate difference, accelerated continental ice melt and increase in heat content are often cited[5–9].

The Argo Project is a global array of profiling floats that measures the temperature and salinity of the upper layer of the ocean[15]. Deployment of the Argo array began in 2000, and there are now more than 3,500 floats. *In situ* temperature and salinity profiles from the Argo floats, with significantly improved spatial resolution and coverage than those of previous measurement systems (XBT, and so on), enable global-scale estimates of steric sea level change with temporal and spatial sampling approaching that of satellite altimetry, especially after 2005 (when the Argo array had reached reasonable global spatial coverage). GRACE is a satellite gravity mission that was launched in 2002 jointly by NASA and the German Aerospace Center. GRACE uses a state-of-the-art technique to observe variation of Earth's gravity with unprecedented accuracy by tracking the inter-satellite range and range rate between two coplanar, low-altitude satellites[16]. GRACE time-variable gravity observations can be used to study mass redistribution within the Earth system[17].

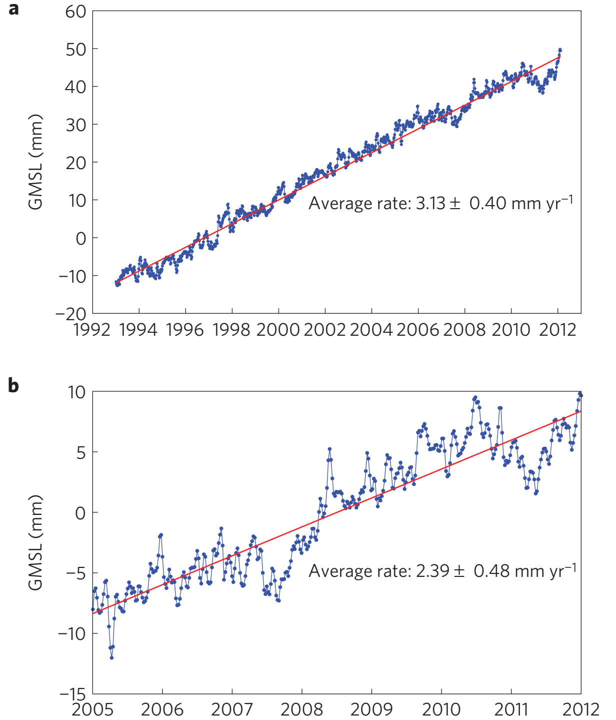

Figure 1 | Global mean sea level (GMSL) change. a, GMSL change observed by the TOPEX/Poseidon and Jason-1/2 satellite altimeters during the period 1993–2012. Seasonal (including annual and semiannual) variations have been removed using an unweighted least-squares fit. Computation is based on the AVISO weekly global merged mean sea level anomaly grids (derived from the three main reference missions, T/P and its follow-ons Jason-1/2; available at http://www.aviso.oceanobs.com/en/data/products/sea-surface-height-products.html). The red line represents the linear trend estimated from a least-squares fit. **b**, The same as in **a**, but for the most recent 7-year period (January 2005–December 2011). A PGR correction of −0.3 mm yr^{-1} has been applied to the altimeter data[18].

A number of previous studies[5–9] have investigated closure of the global sea level rise budget by comparing the satellite altimetry rate with the sum of an Argo steric rate and the ocean mass rate from GRACE. Table 1 summarizes some published estimates. GRACE estimates (which have typically been combined with a

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calculated post-glacial rebound (PGR) contribution) show greatest variability. The Peltier09 PGR model[18], which includes a rotational feedback effect, has been used in some estimates (Table 1), but recent studies[19,20] indicate that this feedback term leads to an overestimated PGR rate (of $\sim -2\,\mathrm{mm\,yr^{-1}}$), compared with the $\sim -1\,\mathrm{mm\,yr^{-1}}$ from the Paulson07 PGR model[21] (the rotational feedback effect was inappropriately applied in the ICE5G PGR model (leading to overestimation of contributions to GRACE-observed mean sea level), and the issue has been identified and will be addressed in the upcoming ICE6G model (personal communications with W.R. Peltier and Y. Liu at the 2012 AGU Fall Meeting)). Some of the good agreements as listed in Table 1 seem to be coincident owing to the use of an overestimated PGR correction. After revised PGR estimates are applied, the published results (Table 1) show that the Argo plus GRACE rate is below the satellite altimetry rate by about $1\,\mathrm{mm\,yr^{-1}}$, although one previous study[7] does show agreement between the sum of steric and mass contributions and altimetry estimates within the applicable error bounds (but the error bounds are considerably larger than those of other studies).

Given the longevity of altimetry observations, and careful attention to their calibration, ground-truth and data processing, rate discrepancy is more likely due to deficiencies in Argo and GRACE estimates. Argo data lack deep ocean sampling (below 2,000 m), poorly sample polar regions, and are subject to calibration and interpolation errors. In addition to these problems, Argo spatial coverage before about 2005 was uneven, especially in the Southern Hemisphere, while the system was being deployed, and for this reason, we examine here only the period January 2005–December 2011. In this 7-year period, the altimeter rate is $2.39 \pm 0.48\,\mathrm{mm\,yr^{-1}}$ (Fig. 1b), well below the $3.13\,\mathrm{mm\,yr^{-1}}$ rate for the period 1993 to 2011 (Fig. 1a). The lower rate over 2005–2011 is apparently related to two major La Niña events (2007/2008 and 2010/2011)[22] (see Supplementary Information for more details).

The global mean steric sea level rate of $0.60 \pm 0.27\,\mathrm{mm\,yr^{-1}}$ used here is the simple average of three estimates based on the International Pacific Research Center (IPRC), Japan Agency for Marine-Earth Science and Technology (JAMS), Scripps Institution of Oceanography (SIO) Argo data sets (see Methods and Supplementary Information for details). The uncertainty ($\pm 0.27\,\mathrm{mm\,yr^{-1}}$) includes the formal error ($\pm 0.25\,\mathrm{mm\,yr^{-1}}$) with 95% confidence from a least-squares fit of the Argo time series using Monte Carlo tests, and possible error ($\pm 0.1\,\mathrm{mm\,yr^{-1}}$) from the deep ocean (below 2,000 m; ref. 23) that is not included in the Argo data. Despite the variability among the three, it is clear that for 2005–2011, the steric rate is a relatively small contributor (about 25%) to the total altimetry rate ($2.39 \pm 0.48\,\mathrm{mm\,yr^{-1}}$). This is consistent with previous studies[5].

The main focus here is improving the GRACE global ocean mass rate estimate. The problem is challenging for a number of reasons. One is that the ocean mass rate ($\sim 2\,\mathrm{mm\,yr^{-1}}$) is far smaller than long-term rates or month-to-month terrestrial signals, either from terrestrial hydrology or ice melt ($\sim$20–200 $\mathrm{mm\,yr^{-1}}$). As GRACE spatial resolution is fundamentally limited by satellite altitude and the distance between the two satellites, and spatial filtering or smoothing is needed to suppress the dominated spatial noise (that is, the stripes) in GRACE data, there is significant leakage of relatively large ice mass or terrestrial water storage (TWS) signals into the oceans. The analysis below indicates that this causes underestimation of ocean mass rates. Direct computation of oceanic mass change (by summing up estimates over ocean area or modified ocean area) can be problematic if the leakage effect is not appropriately addressed. A second challenge is that the large spatial extent of the oceans leaves mass rate estimates vulnerable to errors in both GRACE and PGR low-degree spherical harmonic coefficients.

Previous studies have attempted to reduce terrestrial leakage into the oceans[6] by excluding ocean regions near land, within 300 or 600 km, for example. This approach is reasonable but *ad hoc*. Another method[11,12] has been to employ iterative forward modelling to separate the terrestrial from the ocean signal, using known locations of terrestrial mass sources, especially melting ice sheets and glaciers. Iterative forward modelling has previously been applied at regional scales to improve estimates of ice mass loss rates in Greenland and other regions, but here we apply it on a global scale. The advantage is that all mass change rates for the global oceans, polar ice sheets, mountain glaciers and other TWS changes are estimated simultaneously in a coherent mass-conserving way.

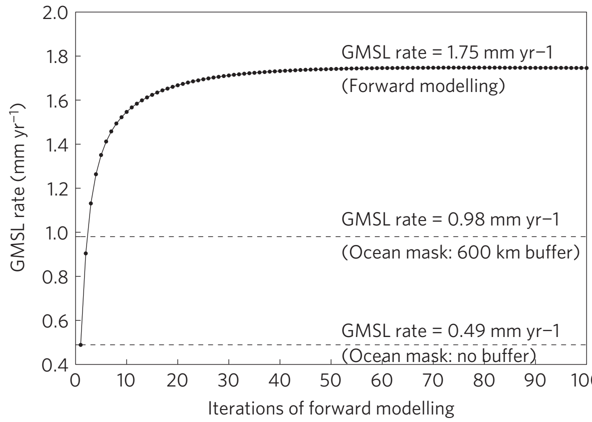

Figure 2 | GRACE non-steric GMSL rates (black line with dots) for the period 2005–2011, as a function of number of iterations in the global forward modelling process. The two horizontal lines show GRACE estimates (of non-steric GMSL rates) for the cases of excluding ocean regions within 600 km of the coast, and including all ocean regions. A decorrelation filter and 500 km Gaussian smoothing have been applied to the GRACE data (CSR RL05).

We use GRACE Release 05 (RL05) solutions available from the Center for Space Research (CSR), University of Texas, and from GeoForschungsZentrum, Potsdam. Our average GRACE oceanic mass rate is $1.80 \pm 0.47\,\mathrm{mm\,yr^{-1}}$. This is substantially larger than near $\sim 1\,\mathrm{mm\,yr^{-1}}$ rates in the Mass column of Table 1. Figure 2 is helpful in understanding why the estimates differ. Figure 2 shows how forward modelling estimates vary with increasing iterations. The other two lines on this figure show simple computations of rates (from the same data) excluding ocean regions within 600 km of land, and including all ocean regions. These values depend on details of the decorrelation and smoothing filters. Here a decorrelation filter and 500 km Gaussian smoothing are used. The forward modelling estimates do not, in principle, depend on the spatial filtering because the same filtering steps are used to match predicted with observed GRACE data during the forward modelling process.

The Argo rate of $0.60 \pm 0.27\,\mathrm{mm\,yr^{-1}}$ plus our GRACE rate of $1.80 \pm 0.47\,\mathrm{mm\,yr^{-1}}$ yields a rate of $2.40 \pm 0.54\,\mathrm{mm\,yr^{-1}}$ for GMSL from 2005 to 2011. This agrees very well with the $2.39 \pm 0.48\,\mathrm{mm\,yr^{-1}}$ from altimetry (Fig. 3). The uncertainty ($\pm 0.47\,\mathrm{mm\,yr^{-1}}$) of the GRACE rate is given by considering the formal error in GRACE mass rates (with 95% confidence interval), standard deviations among the six GRACE estimates, PGR model error, and the potential long-term geocentre effect (see Supplementary Information for details on uncertainty assessment). Nevertheless, Fig. 2 suggests that simple exclusion of regions near land is likely to underestimate the ocean mass rate, and that deficiencies in previous GRACE estimates using this approach are probably responsible for the consistently smaller ocean mass rates (than those from the present study).

The GRACE ocean mass rate ($1.80 \pm 0.47\,\mathrm{mm\,yr^{-1}}$) is dominated by losses from Antarctica, Greenland and mountain glaciers, with

Table 1 | Published estimates of GMSL rates from satellite altimetry (Altimetry), Argo (Steric), GRACE with PGR corrections (Mass) and the sum (Steric + mass).

GMSL rates (mm yr^{-1})	Time period	Steric	Mass	Steric + mass	Altimetry
Willis *et al.*[6] (Paulson07 PGR)	May 2003–May 2007	−0.5 ± 0.5	0.8 ± 0.8	0.3 ± 0.6	3.6 ± 0.8
Leuliette *et al.*[7] (Paulson07 PGR)	Jan. 2004–Dec. 2007	0.8 ± 0.8	0.8 ± 0.5	1.5 ± 1.1	2.4 ± 1.1
Cazenave *et al.*[8] (Peltier09 PGR)	Jan. 2003–Dec. 2007	0.37 ± 0.1	1.9 ± 0.1	2.3 ± 0.1	2.5 ± 0.4
Cazenave *et al.*[8] (Paulson07 PGR)	Jan. 2003–Dec. 2007	0.37 ± 0.1	0.9 ± 0.1	1.3 ± 0.1	2.5 ± 0.4
Cazenave *et al.*[5] (Peltier09 PGR)	Jan. 2003–Dec. 2007	0.25 ± 0.8	2.1 ± 0.1	2.4 ± 0.8	2.5 ± 0.4
Cazenave *et al.*[5] (Paulson07 PGR)	Jan. 2003–Dec. 2007	0.25 ± 0.8	1.1 ± 0.1	1.4 ± 0.8	2.5 ± 0.4
Leuliette & Willis[9] (Paulson07 PGR)	Jan. 2005–Sep. 2010	0.5 ± 0.5	1.1 ± 0.6	1.6 ± 0.6	2.2 ± 0.8
This study (Geruo13 PGR)	Jan. 2005–Dec. 2011	0.6 ± 0.3	1.8 ± 0.5	2.4 ± 0.5	2.4 ± 0.4

The low rate reported by Willis *et al.*[6] was later determined to be tied to errors in Argo data[29]. Altimetry estimates (including those for Leuliette & Willis[9]) are all from Jason-1 (or Jason-1/2) observations. The error bounds represent the 95% confidence interval. The Argo data used in some previous studies cover only the top 900 m of the ocean, whereas Leuliette & Willis[9] and the present study cover the top 2,000 m.

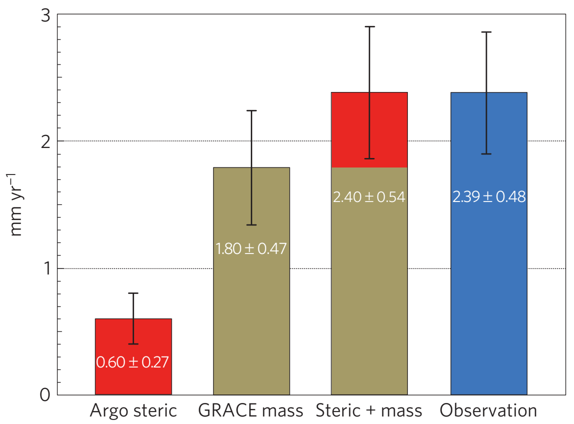

Figure 3 | Global sea level rise budget. Summary of the GMSL rise budget for the period January 2005–December 2011, with an observed sea level rate of 2.39 ± 0.48 mm yr^{-1} from satellite altimeter observations (AVISO T/P and Jason-1/2 mean sea level anomaly grids), a steric contribution of 0.60 ± 0.27 mm yr^{-1} from Argo float ocean temperature and salinity observations, and a non-steric (mass) contribution 1.80 ± 0.47 mm yr^{-1} from GRACE satellite gravity measurements. The sum of steric and non-steric contributions is 2.40 ± 0.54 mm yr^{-1}.

comparable contributions from each of these three sources. Our Greenland mass rate (−0.69 ± 0.05 mm yr^{-1}, or −250 ± 18 Gt yr^{-1}) agrees well with those from previous studies, and the Antarctic rate (−0.50 ± 0.26 mm yr^{-1}, or −180 ± 94 Gt yr^{-1}) falls into the lower bound of those from previous studies[24]. Argo and GRACE results together show that melting ice sheets and mountain glaciers are about three times larger than steric influences on global sea level rise for this period. In contrast, the Intergovernmental Panel on Climate Change Assessment Report 4 estimated that between 1993 and 2003, steric and ice melting effects on global sea level rise were comparable, with rates ∼1.6 ± 0.5 mm yr^{-1} (steric) and ∼1.2 ± 0.5 mm yr^{-1} (ice melting from Antarctica, Greenland and mountain glaciers)[10]. Differences are certainly tied to the fact that the earlier assessment was made without the critical new information from Argo and GRACE, and in addition, it covers an entirely different time period. Another difference may be tied to accelerated melting of polar ice sheets and mountain glaciers (since 2005; refs 11–13), which has been observed with GRACE data. Here, we examine the global sea level rise budget for only a relatively short 7-year period (2005–2011). The estimated sea level rates (from GRACE, Argo and altimetry) are probably affected by the strong interannual variability, and may not really represent the real long-term trend.

The uncertainty of the GRACE oceanic mass rate in the present study represents potential contributions from the formal error in the GRACE apparent mass rate estimate (from a least-squares fit of the GRACE time series at each grid point), standard deviation among six GRACE estimates modifying low-degree spherical harmonic coefficients in various ways, PGR model error, and long-term geocentre motion (see Supplementary Information for details). The assumed PGR model uncertainty may underestimate the true model error. The improvement in the upcoming ICE6G model is expected to significantly reduce the discrepancy among PGR models, in terms of contributions to GRACE-estimated oceanic mass rates. We have assumed that oceanic mass rates are uniform over the global ocean, but this is not the case when considering the self-gravitation effect[25]. However, we have demonstrated (through an experiment discussed in the Supplementary Information) that whether self-gravitation is considered or not in the forward modelling does not affect the estimated mass rates over land and/or the mean rate over the ocean. The comparison between GRACE oceanic mass (+Argo steric) rates with altimeter data is also affected by the different spatial coverages of the data. The Jason-1/2 altimeter data cover the global ocean only between ∼66° S and 66° N (and the Argo data reach up to ∼65° S–65° N), whereas GRACE covers the global ocean. The inclusion of the Arctic Ocean introduces an effect of only ∼0.07 mm yr^{-1} on global sea level rate, which is well below the estimated error bounds (±0.47 mm yr^{-1}) of GRACE estimates, and neglected in the error budget (see Supplementary Information for more on error analysis).

Methods

Steric sea level changes from Argo data. Ocean temperature (T) and salinity (S) fields from the three Argo data sets (IPRC, JAMS, and SIO) are provided on 1° × 1° grids, covering the global oceans from the sea surface to about 2,000 m depth, and between about 65° S and 65° N. At each grid point, steric sea level change (Δh) can be computed as vertical integration of seawater density change of all the layers from the surface to ∼2,000 m depth (numbers of layers N vary in different Argo data sets),

$$\Delta h = -\sum_{i=1}^{N} \frac{\rho - \rho_0}{\rho} \cdot h_i$$

Seawater density ρ is computed as a function of T, S and pressure (P), using the SeaWater Library, which is based on the UNESCO 1983 algorithms[26], and $\rho 0$ represents the mean density of sea water at a given grid point depth. Global mean steric sea level changes are estimated by averaging the steric rate at each grid point with the cosine of latitude as weighting, and the steric rate is estimated by using a least-squares fit of a linear trend, after annual and semiannual variations have been removed.

Argo steric sea level rates. Three different sets of monthly 1° × 1° gridded Argo temperature and salinity fields are used in the present study, which are from the

IPRC at the University of Hawaii, the JAMS and SIO (see http://www.argo.ucsd.edu/Gridded_fields.html). Each data set covers the latitude range 65° S–65° N and depths 0–2,000 m. The global mean steric sea level rates are 0.48 ± 0.22, 0.78 ± 0.35 and 0.54 ± 0.22 mm yr^{-1} for the IPRC, JAMS and SIO estimates, respectively. The averaged Argo steric sea level rate of 0.60 ± 0.27 mm yr^{-1} used here is the simple average of the three (IPRC, JAMS and SIO) rates (see Supplementary Information for more information on Argo data processing and uncertainty assessment).

GRACE oceanic mass rate from global forward modelling. From the two GRACE RL05 solutions (CSR and GeoForschungsZentrum), we estimate global mean ocean mass rates through global forward modelling, with three different treatments of GRACE degree-2 gravity coefficients: replacing GRACE degree-2 order 0 (C_{20}) with SLR estimates[27]; replacing all GRACE degree-2 coefficients (C_{20}, C_{21}, S_{21}, C_{22}, S_{22}) with SLR estimates; retaining all GRACE degree-2 coefficients. A modified version of the Paulson07 PGR model (noted as Geruo13 in Table 1; refs 21,28) is used to remove the PGR effect from the GRACE mass rates. From the two RL05 solutions and 3 treatments of degree-2 coefficients there are six mass rates for the global ocean, with separate estimates for Antarctica, Greenland, mountain glaciers, and all other TWS sources. Rates are summarized in Supplementary Table S1. We take the mean of the six rates (1.80 ± 0.47 mm yr^{-1}) as our GRACE estimate. The estimated uncertainty includes contributions from the standard deviation of the six GRACE estimates, PGR model error, and long-term geocentre motion (see Supplementary Information for details on error assessment).

The global forward modelling can more effectively reduce the leakage effect between terrestrial and ocean signals, and help reconstruct true mass rates of the ocean, polar ice sheets, mountain glaciers and TWS at the same time. Full details of the forward modelling approach are provided in the Supplementary Information. A brief synopsis is as follows: on a global $1° \times 1°$ grid, we first assign initial trial mass rates (for example, GRACE apparent mass rates after filtering and smoothing) to each grid point over land, and a uniform layer of water is added to the oceans to conserve total mass. The trial mass rate grid is converted into spherical harmonics (with the same resolution as GRACE data); we then convert the spherical harmonics of the trial mass rate grid back to a spatial grid after applying GRACE data processing procedures to the spherical harmonic representation of the trial mass field (including truncation and smoothing); we compare the processed trial spatial grid with the GRACE apparent mass rate grid and adjust the trial mass rates accordingly. These three steps are repeated iteratively, until the processed trial mass rate grid matches the GRACE apparent mass rate grid. This provides a single mass rate estimate for the oceans, which conserves mass globally, because terrestrial rates are estimated simultaneously. Averages for specific regions (such as Antarctica) can also be calculated.

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Author contributions

J.L.C. planned analyses, acquired and prepared data, implemented the computation, and wrote the paper. C.R.W. and B.D.T. analysed the data and results.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.L.C.

Competing financial interests

The authors declare no competing financial interests.