

# Deep-ocean contribution to sea level and energy budget not detectable over the past decade

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**As the dominant reservoir of heat uptake in the climate system, the world's oceans provide a critical measure of global climate change. Here, we infer deep-ocean warming in the context of global sea-level rise and Earth's energy budget between January 2005 and December 2013. Direct measurements of ocean warming above 2,000 m depth explain about 32% of the observed annual rate of global mean sea-level rise. Over the entire water column, independent estimates of ocean warming yield a contribution of  $0.77 \pm 0.28 \text{ mm yr}^{-1}$  in sea-level rise and agree with the upper-ocean estimate to within the estimated uncertainties. Accounting for additional possible systematic uncertainties, the deep ocean (below 2,000 m) contributes  $-0.13 \pm 0.72 \text{ mm yr}^{-1}$  to global sea-level rise and  $-0.08 \pm 0.43 \text{ W m}^{-2}$  to Earth's energy balance. The net warming of the ocean implies an energy imbalance for the Earth of  $0.64 \pm 0.44 \text{ W m}^{-2}$  from 2005 to 2013.**

Sea-level rise is one of the most important consequences of human-caused global warming. Because sea-level rise is caused by a combination of freshwater increase (from the melting of land ice) and thermal expansion (from ocean warming), global mean sea-level change provides a powerful tool for monitoring the net impact of forcing on the climate system<sup>1</sup>. Because of their accuracy, satellite observations of sea-level rise and ocean mass change are now able to provide a new constraint on the rate of thermal expansion in the ocean, and hence on ocean heat content change. Here, we consider gridded *in situ* temperature and salinity observations from Argo in combination with global mean sea-level rise from satellite altimetry and ocean mass change estimates (that is, fresh water inputs from melting of mountain glaciers and ice sheets) from the Gravity Recovery and Climate Experiment (GRACE). By combining these three different types of observations, we quantify warming rates of the deep ocean and place upper bounds on the net rate of global warming from 2005 to 2013.

Long-term global sea-level rise has been well established<sup>2</sup>, and there have been several review papers addressing the causes of sea-level rise and their implications for global warming<sup>3,4</sup>. Since 2003, global observations of ocean temperature for depths above 2,000 m have become available on a regular basis with the advent of the Argo array of profiling floats<sup>5–10</sup>. Measurements from ships of opportunity provide observations from earlier periods but are limited to depths above 700 m (refs 3,11). Nevertheless, the ocean layers above 700 m and 2,000 m represent only 20% and 50%, respectively, of the total ocean volume<sup>11,12</sup>. Although the temperature change remains small compared to the upper ocean, the deep-ocean contribution to sea level and energy budgets might be significant because of its large volume<sup>13</sup>. Studies have demonstrated deep-ocean warming below 2,000 m depth over multi-decadal timescales<sup>13,14</sup>. For instance, it has been shown that the deep ocean (below 2,000 m depth) experienced a significant slight warming of  $0.068 \pm 0.061 \text{ W m}^{-2}$  (95% confidence), corresponding to a global mean sea-level rise of  $0.113 \pm 0.1 \text{ mm yr}^{-1}$  (95% confidence), for the 1990s–2000s period<sup>13</sup>. Decadal warming in the deep ocean has recently been discussed in a review paper<sup>12</sup>, with small but significant rates in

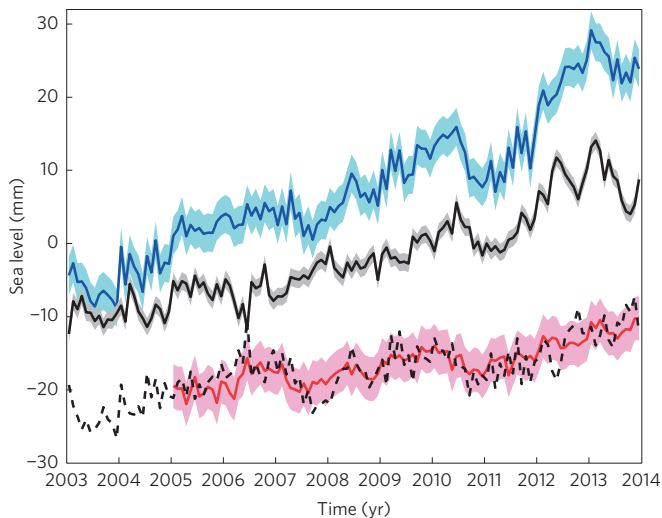
several regions that contribute to global sea-level rise and Earth's energy balance. Nevertheless, such estimates rely primarily on very sparse observations and are limited to decadal and longer-term rates of change, and periods before about 2005.

This lack of data has led to speculation that large amounts of heat might be entering the deep ocean undetected. For instance, it has been suggested that such deep-ocean warming (below 2,000 m) could explain the 'missing energy' in observations of the global energy budget<sup>15</sup>. Some have suggested that 30% of ocean warming on decadal timescales has occurred below 700 m depth<sup>16</sup>. Yet, direct observations of deep-ocean warming do not suggest such large amounts of warming in the deep ocean, at least before the mid-2000s<sup>12–14</sup>. Over the most recent decade, however, the GRACE and Argo observing systems have given us a new way to estimate warming in the deep ocean and the net imbalance in Earth's energy budget. To do so, we consider the total amount of sea-level rise observed by satellite altimeters between 2005 and 2013 and subtract the amount attributable to upper-ocean warming (as observed by Argo) and ocean mass increase (as observed by GRACE). The residual is then used to place a constraint on the possible range of deep-ocean warming during this period.

## Results and discussion

The global mean sea-level time series inferred by satellite altimetry (blue curve in Fig. 1) increases by approximately 30 mm from 2003 to 2013, showing some interannual variability fluctuating around a near-linear increase. This interannual variability is highly correlated to El Niño/La Niña climate variability<sup>17</sup> and is linked to fresh water exchanges between the ocean and the continents<sup>18</sup>, especially the large La Niña event of 2011<sup>19,20</sup>. From 2005 to 2013, sea level rose at a rate of  $2.78 \pm 0.32 \text{ mm yr}^{-1}$ . This rise is slightly lower than the rate of  $3.2 \pm 0.4 \text{ mm yr}^{-1}$  for the whole altimetric period (updated from refs 3,4) and has been attributed to the successive La Niña events for the recent years<sup>21</sup>. The black curve depicts the ocean mass evolution from 2003 to 2013 based on independent satellite gravimetry observations from GRACE. Similar to observed mean sea-level variations, the ocean mass signal exhibits a linear

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**Figure 1 | Global mean sea-level variations.** The estimates are observed variations by satellite altimetry (blue), ocean mass contributions based on GRACE data (solid black) and steric sea level based on *in situ* observations (red). The dashed black curve shows the indirect steric mean sea-level estimate inferred by removing ocean mass contributions from the observed sea-level time series. Seasonal signals have been removed from all curves. Curves are offset for clarity. Shading, where shown, denotes  $1\text{-}\sigma$  uncertainty of the respective estimates.

increase plus interannual variability, especially during the large La Niña event of 2011. The ocean mass variations explain 80% of the fractional variance of the observed global mean sea-level fluctuation. Formally, from 2005 to 2013, the ocean mass time series has a linear trend of  $2.0 \pm 0.1 \text{ mm yr}^{-1}$ . The uncertainties quoted here (and throughout unless otherwise noted) represent random errors plus the formal error from the linear fit estimated as described in Methods. Systematic errors (that is, temporally correlated) are dealt with separately, as discussed below and in Methods.

The globally averaged steric sea level between  $\pm 66^\circ$  of latitude and above 2,000 m depth (red curve in Fig. 1) rose with a linear trend of  $0.9 \pm 0.15 \text{ mm yr}^{-1}$  between 2005 and 2013. This value represents a mean over four data sets (see Methods). Table 1 provides the linear trend values for the 0–2,000 m layer for each analysis. This ocean warming explains 32% of the observed sea-level rise of  $2.78 \pm 0.32 \text{ mm yr}^{-1}$  inferred by satellite altimetry. Summing up the contributions over 2005–2013 and assuming that errors in GRACE and Argo analyses are uncorrelated with each other, we find that ocean mass increase and steric sea level in the upper 2,000 m account for  $2.9 \pm 0.38 \text{ mm yr}^{-1}$  of global mean sea-level rise. Considering the uncertainties, this is in excellent agreement with the observed mean sea-level trend from satellite altimetry. The sum of GRACE and Argo explains 92% of the fractional variance of global mean sea level observed by satellite altimetry.

By subtracting the GRACE-based ocean mass signal from the satellite altimeter-observed sea-level rise we create an inferred estimate of steric sea level for the whole water column. This inferred steric sea-level estimate (dashed black curve in Fig. 1) is overlaid on the independently observed 0–2,000 m Argo thermal expansion estimate. Agreement with the Argo-based estimate is striking, and well within the estimate of random error plus the formal error from the linear fit (see Methods). The trend of altimetry minus GRACE is  $0.77 \pm 0.28 \text{ mm yr}^{-1}$ , which is statistically significant at a  $1\text{-}\sigma$  confidence interval relative to random errors plus the formal error from the linear fit. We assume that random errors in GRACE and satellite altimetry observations are not auto-correlated over periods

**Table 1 | Global mean steric sea-level trends.**

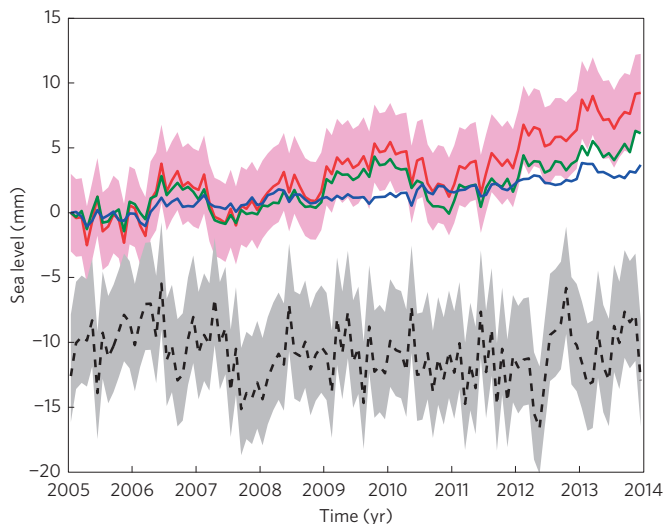
Sea-level trend (mm yr <sup>-1</sup> )	0–2,000 m	0–700 m	700–2,000 m
SCRIPPS	$0.93 \pm 0.21$	$0.51 \pm 0.17$	$0.42 \pm 0.07$
IPRC	$0.80 \pm 0.19$	$0.50 \pm 0.15$	$0.31 \pm 0.07$
JAMSTEC	$0.96 \pm 0.19$	$0.65 \pm 0.16$	$0.34 \pm 0.06$
NOAA	$0.93 \pm 0.12$	$0.48 \pm 0.10$	$0.45 \pm 0.05$
Mean	$0.90 \pm 0.15$	$0.53 \pm 0.13$	$0.38 \pm 0.05$

The estimates are computed over 2005–2013 at different layers, as quoted in the table. The last row is the mean estimated on the basis of the four data sets we have considered in the study. Errors are estimated to be at  $1\text{-}\sigma$  uncertainty. We assumed that the random error for the 0–2,000 m depth range is similar to the errors for the other two layers in computing the linear trend estimates.

longer than one month, which is supported by previous estimates of uncertainty<sup>22</sup>. The two estimates exhibit similar behaviour, although the inferred estimate has slightly larger interannual variability. The inferred thermal expansion estimate explains 54% of the fractional variance of the 0–2,000 m observed steric sea-level variations. Note that the random error estimates for the GRACE-based ocean mass component of global mean sea level are smaller than those of either the altimeter-measured mean or the Argo-based estimate of mean steric sea level. This difference can be explained in part by the presence of baroclinic mesoscale eddies, which have a larger effect on the observed and steric mean sea-level contributions than the ocean mass component.

Argo can be used to estimate warming in different layers of the upper ocean, as shown in Fig. 2. For example, the green and blue curves are for the 0–700 m and 700–2,000 m layers, respectively. The choice of 0–700 m in the upper layer reflects historical changes in sampling by *in situ* observations<sup>23</sup>. Interannual variability in the upper 700 m layer is large, and in fact accounts for 85% of the fractional variance of the entire 0–2,000 m layer variations. Thus, changes in the upper layer explain most of the interannual variability of net steric mean sea-level fluctuations<sup>11</sup>. As for the linear trend, the upper 700 m layer accounts for 58% of the 0–2,000 m layer change, with a linear trend of  $0.53 \pm 0.13 \text{ mm yr}^{-1}$  indicating a significant rise during this period. The 700–2,000 m depth layer shows a near-linear increase with a rate of  $0.38 \pm 0.05 \text{ mm yr}^{-1}$ , and has smaller interannual variability than the top layer. We assume the random error (that is, the data accuracy) for the 0–2,000 m layer is the same as the other two layers, a conservative interpretation given that uncertainties due to unresolved eddy-variability should decrease with depth. Our estimate of warming in this lower layer is somewhat larger than previous studies, which found that the 700–2,000 m layer accounted for only one third of the net 0–2,000 m ocean thermal expansion over 1955–2010<sup>24</sup>. This difference may be due to decadal variations in the rate of warming in this mid-depth layer, including a gradual penetration of heat into greater depths of the ocean.

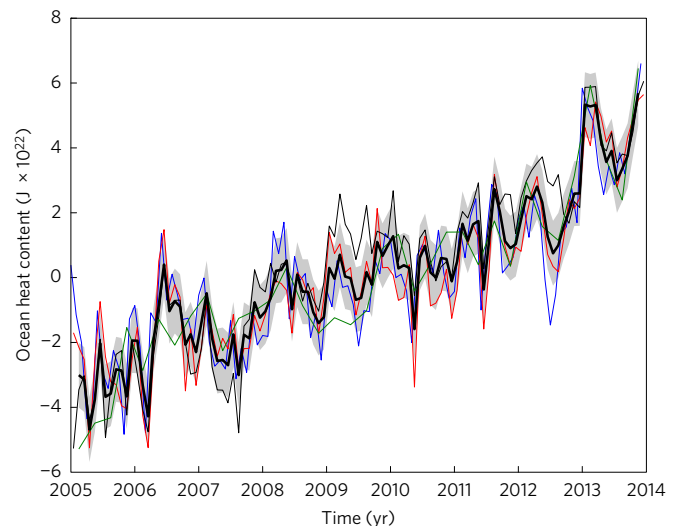
The steric sea level inferred by combining satellite altimetry and GRACE observations represents the ocean's thermal expansion over the entire water column. Argo, however, provides a direct estimate of thermal expansion of the upper water column only. By subtracting the Argo estimate from the inferred estimate of full-depth steric height, it is possible to estimate steric sea-level contributions below 2,000 m (dashed black line, Fig. 2). In doing so, we obtain a new estimate of the deep-ocean contribution to global mean sea-level change. This estimate shows large interannual variability and a cooling trend of  $-0.13 \pm 0.34 \text{ mm yr}^{-1}$ . Again, the uncertainty quoted here represents the combination of random errors plus the formal error from the linear fit, assuming that each observing system is independent and that errors are uncorrelated over timescales longer than one month. Neither the trend nor the



**Figure 2 | Global mean steric sea-level change contributions from different layers of the ocean.** 0–2,000 m (red), 0–700 m (green), 700–2,000 m (blue). The dashed black curve shows an estimate for the remainder of the ocean below 2,000 m computed by removing the 0–2,000 m estimate from the GRACE-corrected observed mean sea-level time series. Seasonal signals have been removed from all curves. Curves are offset for clarity. Shading, where shown, denotes  $1\text{-}\sigma$  uncertainty of the respective estimates.

interannual variability of the deep-ocean warming is statistically significant. Therefore, we find no significant global ocean warming below 2,000 m. Nevertheless, by performing a more rigorous and conservative error analysis, it is possible to estimate an upper bound on the rate of deep-ocean warming (2,000–bottom) in terms of its contribution to global mean sea-level rise and Earth's energy budget from 2005 to 2013.

To provide such bounds, we consider additional systematic uncertainties in the estimates, including those that are correlated over time and are not included in the discussion above. In the GRACE data, this includes a long-term, secular uncertainty related to the correction for crustal movements associated with the end of the Last Glacial Maximum. This correction is referred to as the glacial isostatic adjustment (GIA). Because removal of the GIA signal results in a secular correction to the GRACE observations, GIA uncertainty is correlated over the entire length of the record. For the ocean mass signal inferred by GRACE, the GIA uncertainty has been estimated to be  $\pm 0.4 \text{ mm yr}^{-1}$  (ref. 25). In the altimeter data, uncertainties in the stability of the reference frame also limit the accuracy of the estimated trends. Such uncertainty amounts to  $\pm 0.5 \text{ mm yr}^{-1}$  in the rate of sea-level rise observed by satellite altimeters<sup>26</sup>. Assuming the GRACE and altimeter errors are uncorrelated with each other, we estimate the net trend error of the thermal expansion in the deep ocean to be  $\pm 0.72 \text{ mm yr}^{-1}$ . Therefore, our estimate of deep-ocean contribution to sea level becomes  $-0.13 \pm 0.72 \text{ mm yr}^{-1}$ . This yields an upper bound for global mean sea-level rise due to deep-ocean warming below 2,000 m of  $0.59 \text{ mm yr}^{-1}$  for the period from 2005 to 2013. To estimate the equivalent change in heat content, we assume that heat content and thermal expansion in the layer from 2,000 m to the bottom of the ocean are related to each other (a reasonable assumption given that actual temperature changes in the deep ocean on these timescales are much less than  $1^\circ\text{C}$ ). Assuming that a  $1 \text{ mm yr}^{-1}$  steric sea-level rise is equivalent to a heating rate of  $0.6 \text{ W m}^{-2}$  for the layer below 2,000 m (see Table 1 from ref. 13), we estimate deep-ocean heat content change to be  $-0.08 \pm 0.43 \text{ W m}^{-2}$ . The uncertainty implies an upper bound of  $0.35 \text{ W m}^{-2}$  warming. For the decade from 1990 to 2010, previous



**Figure 3 | Ocean heat content change above 2,000 m depth.** Curves show estimates based on data products from Scripps (blue), IPRC (red), JAMSTEC (black) and NOAA (green). The thick black curve depicts the mean among these estimates. The grey envelope denotes one standard error around this mean, based on an error estimate in ref. 27.

studies<sup>13</sup> estimate a slight warming of  $0.068 \pm 0.061 \text{ W m}^{-2}$  for the layer below 2,000 m, which is roughly five times smaller than our upper-bound estimate.

As for upper ocean steric height changes, Argo and other *in situ* observations are used to estimate ocean heat content change in the top 2,000 m from 2005 to 2013 (Fig. 3). Analyses from several different centres all show interannual variability and a rise since 2005. Furthermore, all curves are almost always within  $1\text{-}\sigma$  uncertainty of the mean ocean heat content change (thick black curve). We find a linear increase ranging from  $6.76$  to  $9.37 \times 10^{21} \text{ J yr}^{-1}$ , depending on the hydrographic analysis used, with a mean value of  $7.95 \times 10^{21} \text{ J yr}^{-1}$ . This corresponds to an ocean heat uptake between  $0.61$  and  $0.85 \text{ W m}^{-2}$ , with a mean value of  $0.72 \text{ W m}^{-2}$  and a dispersion that matches the one standard error of  $0.1 \text{ W m}^{-2}$  (ref. 27). Therefore, we estimate the heat uptake by the upper 2,000 m of the global ocean to be  $0.72 \pm 0.1 \text{ W m}^{-2}$ . Our estimate is slightly larger than the recently reported estimate of  $0.54 \pm 0.1 \text{ W m}^{-2}$  for the upper 1,500 m layer<sup>27</sup> computed over 2005–2010 and the estimate of  $0.56 \text{ W m}^{-2}$  for the 0–1,800 m layer<sup>23</sup> over 2004–2011. The differences may, in part, be due to differences in the period and/or depth over which they were analysed; note that our time period is longer than the two previous studies.

Finally, we combine our estimate of upper-ocean warming (above 2,000 m) with the ocean heat content change in the lower layer (below 2,000 m) to estimate the heat uptake by the entire ocean. We find a net ocean warming equivalent to a radiative imbalance of  $0.64 \pm 0.44 \text{ W m}^{-2}$  since 2005. Here we have included the potential systematic uncertainties and assume that errors are uncorrelated between estimates of warming above and below 2,000 m depth. Our estimate of full-depth ocean warming is in good agreement with a recent estimate of Earth's net energy imbalance of  $0.50 \pm 0.43 \text{ W m}^{-2}$  for the period from 2001 through 2010<sup>28</sup>. Nevertheless, our full-depth ocean heat content change and its contribution to global mean sea level relies on a strong hypothesis. We have assumed that each observing system is independent and that errors are uncorrelated over timescales longer than one month. If this assumption is invalid then the error bounds quoted in our analysis might be underestimated.



## Methods

Total sea level has been continuously observed by satellite altimetry since 1992 with the launch of TOPEX/Poseidon followed by Jason-1 and -2, launched in 2001 and 2008, respectively. This family of satellites provides a near-global coverage ( $\pm 66^\circ$  of latitude) of the oceans every ten days. We have considered here the global mean sea-level time series from the University of Colorado<sup>17</sup>, available at <http://sealevel.colorado.edu/>. These data have been processed by applying geophysical corrections and verified using independent tide gauge records. (For more information about data processing, see ref. 17.) For a period of ten days, random errors in the global average are estimated to be about 4 mm and have been verified through comparison with tide gauges<sup>9,22,29</sup>. To compute monthly error averages, we assume that these ten-day averaged altimetric data have an e-folding correlation time of ten days. Then, the accuracy of the monthly global mean sea level is estimated to be  $\pm 2.6$  mm (which represents random measurement error).

To estimate global mean ocean mass variations, we use GRACE CSR Release-05 time-variable gravity observations from April 2002 through to December 2013 (available at <ftp://podaac-ftp.jpl.nasa.gov/allData/grace/L2/CSR/RL05/>). Standard processing steps were followed (details can be found in ref. 30) by accounting for geocentre motion<sup>31</sup>, glacial isostatic adjustment<sup>32</sup> and changes in Earth's dynamic oblateness (that is,  $C(2,0)$  coefficients)<sup>33</sup>. The impact of land signals on GRACE ocean mass is reduced by omitting data within 300 km of land. The resulting ocean average represents ocean mass changes and can thus be directly compared to the steric-corrected sea level. We estimate the accuracy (which represents random measurement error) of the monthly ocean mass estimates to be  $\pm 1.2$  mm (ref. 30). Additional GRACE solutions from GFZ (available at <ftp://podaac-ftp.jpl.nasa.gov/allData/grace/L2/GFZ/RL05/>) and JPL (available at <ftp://podaac-ftp.jpl.nasa.gov/allData/grace/L2/JPL/RL05/>) were also analysed. The standard deviation among the three solutions is  $\pm 0.4$  mm, which indicates that the formal error estimate above is conservative.

Gridded temperature and salinity estimates used in this study are obtained from four separate groups: Scripps Institution of Oceanography (updated from ref. 34), International Pacific Research Center (IPRC), Japan Agency for Marine-Earth Science and Technology (JAMSTEC, ref. 35) and National Oceanic and Atmospheric Administration (NOAA, ref. 24). These data can be downloaded at [www.argo.ucsd.edu/Gridded\\_fields.html](http://www.argo.ucsd.edu/Gridded_fields.html) for SCRIPPS, IPRC and JAMSTEC data sets and [www.nodc.noaa.gov/OC5/3M\\_HEAT\\_CONTENT/](http://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/) for the NOAA data set. Contrary to the others, the NOAA and JAMSTEC data sets combine not only Argo floats, but also other *in situ* measurements (for example, expendable bathythermograph (XBT), CTD and mooring data). Temperature and salinity data have been passed through many quality control checks (see the Argo quality control manual for more details, ref. 36). Steric sea-level time series are computed by using temperature and salinity fields from each data product. (Further details of this computation can be found in ref. 11, section 2.1.1.) On a monthly basis, the global mean steric sea-level evolution of the upper 2,000 m of the ocean is estimated with an accuracy of  $\pm 3$  mm (refs 5,9). As for altimetry and GRACE, this uncertainty represents an estimate of random measurement error in estimating the global mean using available observations. The partitioning of heat content change above and below 700 m has been motivated because of the historical sampling for the past decades<sup>23</sup>.

All estimates in the present study are anomalies with respect to the time-mean over their respective periods (that is, 2003–2013 for altimetry and GRACE time series and 2005–2013 for steric sea level inferred by Argo data sets). Because we are focusing on interannual to decadal changes, we have removed a monthly-climatology defined as the time-mean over the respective time periods for each calendar month. The curves are offset for clarity.

The error estimates for each observing system previously described in this section represent the accuracy of the measurement at a monthly basis. We assume that these errors are random and uncorrelated over timescales longer than one month. This is a good assumption, given that none of the analyses use data collected over a period longer than one month. To estimate uncertainty in the trend, we perform a weighted least-squares fit to the monthly observations, where the weights are chosen to equal the reciprocal of the square of the measurement accuracy for each month (as in ref. 27; Appendix A). The formal error from the fit, which represents the misfit of the observations to the trend, is added to the individual random error for each month to compute the trend uncertainty quoted throughout the manuscript. As well as the trend errors, we add systematic uncertainty for GRACE and satellite altimetry.

Coherence between two time series is quantified in terms of explained variance (EV), defined as:

$$EV = 1 - \frac{\text{var}(A - B)}{\text{var}(A)}$$

where  $\text{var}(A - B)$  and  $\text{var}(A)$  denote the variance of  $A - B$  and  $A$  respectively. The measure will be equal to 1 when  $B$  completely accounts for variations of  $A$ , and less than 1 otherwise.

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## Author contributions

W.L. and J.K.W. conceived the study. W.L. conducted the calculations and led the writing of the manuscript. F.W.L. computed the ocean mass time series inferred by GRACE data. All authors contributed to the analysis and participated in its discussion.

## Additional information

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## Competing financial interests

The authors declare no competing financial interests.