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Climate-change–driven accelerated sea-level rise detected in the altimeter era

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Using a 25-y time series of precision satellite altimeter data from TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3, we estimate the climate-change–driven acceleration of global mean sea level over the last 25 y to be 0.084 ± 0.025 mm/y². Coupled with the average climate-change–driven rate of sea level rise over these same 25 y of 2.9 mm/y, simple extrapolation of the quadratic implies global mean sea level could rise 65 ± 12 cm by 2100 compared with 2005, roughly in agreement with the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5) model projections.

sea level | acceleration | climate change | satellite altimetry

Satellite altimeter data collected since 1993 have measured a rise in global mean sea level (GMSL) of ∼3 ± 0.4 mm/y (1, 2), resulting in more than 7 cm of total sea-level rise over the last 25 y. This rate of sea-level rise is expected to accelerate as the melting of the ice sheets and ocean heat content increases as greenhouse gas concentrations rise. Acceleration of sea-level rise over the 20th century has already been inferred from tide-gauge data (3–5), although sampling and data issues preclude a precise quantification. The satellite altimeter record of sea-level change from TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3 is now approaching 25 y in length, making it possible to begin probing the record for climate-change–driven acceleration of the rate of GMSL change (6). Unlike tide-gauge data, these retrievals sample the open ocean and allow for precise quantitative statements regarding global sea level. However, detecting acceleration is difficult because of (*i*) interannual variability in GMSL largely driven by changes in terrestrial water storage (TWS) (7–9), (*ii*) decadal variability in TWS (10), thermosteric sea level, and ice sheet mass loss (11) that might masquerade as a long-term acceleration over a 25-y record, (*iii*) episodic variability driven by large volcanic eruptions (12), and (*iv*) errors in the altimeter data, in particular, potential drifts in the instruments over time (13). With careful attention to each of these issues, however, a preliminary satellite-based estimate of the climate-change–driven acceleration of sea-level rise can be obtained. This estimate is useful for understanding how the Earth is responding to warming, and thus better informs us of how it might change in the future.

The satellite altimeter record of GMSL is shown in Fig. 1 (14). These data reflect a recent update to the TOPEX measurements discussed in ref. 15 following earlier empirical work by refs. 16 and 17. The acceleration obtained by fitting a quadratic to this updated 25-y record is 0.097 mm/y². As described in ref. 12, the eruption of Mount Pinatubo in 1991 caused a decrease in GMSL just before the launch of TOPEX, followed by a slow recovery that resulted in an apparent deceleration of sea level of −0.02 ± 0.01 mm/y² over the 25-y record. To isolate the climate-change–driven acceleration, we remove this effect (Fig. 1), which increases the acceleration of the adjusted GMSL record from 0.097 to 0.117 mm/y².

There is considerable interannual variability in the GMSL time series due to changes in TWS, mainly driven by El Niño Southern Oscillation (ENSO) effects (7–9). We use a multivariable empirical orthogonal function (EOF) analysis to isolate the ENSO effects (Fig. 2) and remove them from the GMSL curve. This reduces the GMSL acceleration estimate by 0.033 mm/y², resulting in a final "climate-change–driven" acceleration of 0.084 mm/y². Climate-change–driven in this case means we have tried to adjust the GMSL measurements for as many natural interannual and decadal effects as we can to try to isolate the longer-term, potentially anthropogenic, acceleration—any remaining effects are considered in the error analysis.

We also must consider the impact of errors in the altimeter measurements, especially instrument drift. To assess instrument drift, we examine sea-level differences between altimetry and tide gauges (13) over time. This technique has been used for the last two decades to assess the instrument drift, but not to assess errors in GMSL acceleration estimates. Fig. 3 shows a time series of these differences. Using an AR1 noise model, we find that these differences imply a 1σ uncertainty in the acceleration of the instrument drift of 0.011 mm/y².

Finally, we must also consider the impact of decadal variability in GMSL on acceleration estimates derived from a 25-y record. While estimates of the impact of decadal variability on the 25-y-long time series are difficult to obtain (18), satellite altimetry is far less sensitive to decadal variability than tide-gauge measurements (19) because of its superior global coverage. Estimates of decadal variability from tide-gauge data (18) are uncertain due to their poor geographic sampling and other effects, so estimates must be assembled from measurements of the contributions to GMSL including TWS (10), the cryosphere (11), and thermosteric sea-level change (20). We have removed most of the impact of changes in TWS, but allow 0.01-mm/y² residual impact on the acceleration (based on ref. 10). Estimates of the decadal variability in ice sheet mass loss (11) suggest the impact on acceleration estimates is ∼0.014 mm/y² for a 25-y time series, in the absence of rapid dynamical changes in the ice sheets. The impact of decadal variability in thermosteric sea level was estimated at 0.01 mm/y² using a control run for the National Center for Atmospheric Research

Significance

Satellite altimetry has shown that global mean sea level has been rising at a rate of ∼3 ± 0.4 mm/y since 1993. Using the altimeter record coupled with careful consideration of interannual and decadal variability as well as potential instrument errors, we show that this rate is accelerating at 0.084 ± 0.025 mm/y², which agrees well with climate model projections. If sea level continues to change at this rate and acceleration, sea-level rise by 2100 (∼65 cm) will be more than double the amount if the rate was constant at 3 mm/y.

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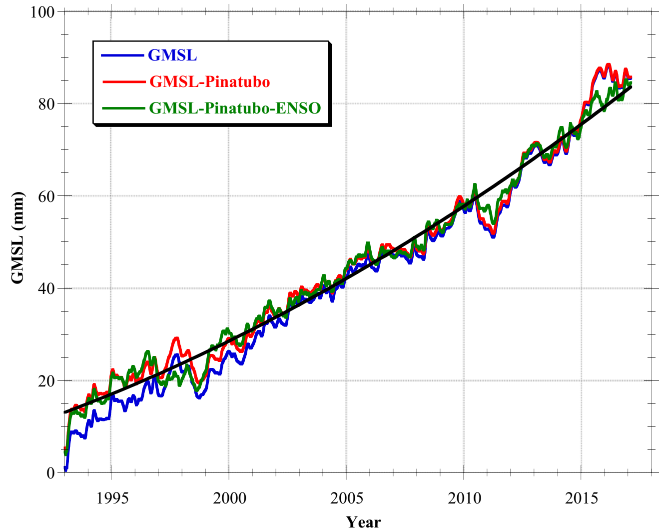

Fig. 1. GMSL from the adjusted processing of ref. 15 (blue) and after removing an estimate for the impacts of the eruption of Mount Pinatubo (12) (red), and after also removing the influence of ENSO (green), fit with a quadratic (black). The acceleration (0.084 mm/y^2) is twice the quadratic coefficient.

(NCAR) Large Ensemble (LE) (21). We also include an estimate from the NCAR LE of the impact of decadal variability in precipitable water in the atmosphere, which can impact GMSL. Therefore, a conservative estimate of the total impact of decadal variability on our acceleration estimate is the root sum square (RSS) of these contributions, which is 0.017 mm/y^2.

Table 1 shows a summary of the different error estimates. The final error estimate for the climate-change–driven GMSL acceleration is the RSS of the measurement errors (0.011 mm/y^2), the error in the Pinatubo correction (0.01 mm/y^2), the error in the ENSO correction (0.01 mm/y^2), and the errors due to decadal variability (0.017 mm/y^2). Their joint consideration yields a final acceleration estimate of 0.084 $\pm$ 0.025 mm/y^2.

We can perform an approximate validation of the altimeter-based GMSL acceleration estimate by examining other satellite and in situ

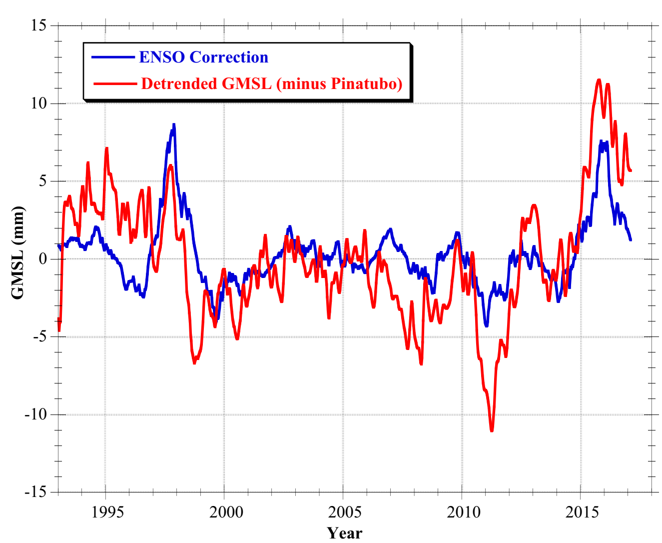

Fig. 2. ENSO GMSL correction (blue) compared with detrended GMSL (red, Pinatubo effects removed).

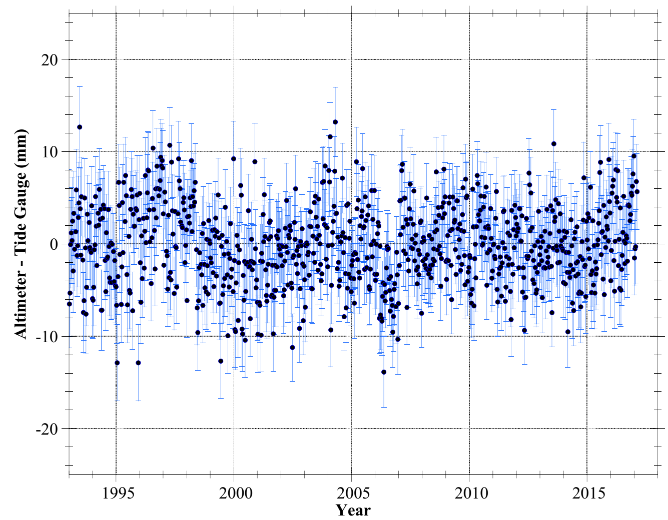

Fig. 3. Differences between altimeter and tide gauge observed sea level used to estimate the error in the acceleration estimate (13).

measurements of the components that contribute to the GMSL acceleration. The Gravity Recovery and Climate Experiment (GRACE) mission provides estimates of the cryospheric contributions to the acceleration of sea-level rise, including Greenland, Antarctica, and small ice caps and mountain glaciers (22), although these measurements only start in 2002. As shown in Table 2, Greenland and Antarctica account for most of the observed GMSL acceleration (6). The acceleration of thermosteric sea level was determined from an update to ref. 23. The thermosteric acceleration is small compared with the ice sheets, but on par with the acceleration from mountain glaciers and small ice caps.

Table 2 summarizes estimates of the contribution of these components to the acceleration of GMSL. While the time periods are shorter than covered by the altimetry record, they provide a rough validation of the altimeter-based acceleration estimate. Shortening the altimeter record to match GRACE increases the acceleration, but also significantly increases the error bar. The main consequence of the shorter time periods is the potential influence of interannual and decadal variability. Nevertheless, the agreement between the climate-change–driven acceleration (adjusted for ENSO and Pinatubo effects) observed from 25 y of satellite altimetry and independent acceleration estimates from the components contributing to GMSL is quite good.

Our estimate of the 25-y GMSL acceleration is 0.084 $\pm$ 0.025 mm/y^2 (1σ) after removing the Pinatubo effect and accounting for the impact of ENSO variations. The probability that the acceleration is actually zero is less than 1%. The error includes both the altimeter drift error and the impact of decadal variability.

Table 1. Components of acceleration error (1σ)

Error	Source	Acceleration error, mm/y^2
Altimeter measurement errors	Tide-gauge validation	0.011
Decadal variability	Cryosphere (11)	0.014
	TWS (NCAR LE)	0.0054
	Thermosteric (NCAR LE)	0.0075
	Precipitable water (NCAR LE)	0.0013
Pinatubo correction error	NCAR LE	0.01
ENSO/PDO correction error	Joint EOF analysis	0.01
Total	RSS	0.025

Table 2. Validation of acceleration estimate

Component	Time period	Rate, mm/y; Epoch 2005.0	Acceleration, mm/y^2
Greenland	2002.3–2017.0	0.66	0.0236
Antarctica	200.32–2017.0	0.19	0.0332
Mountain glaciers and small ice caps	2002.3–2017.0	0.51	0.0094
Thermosteric*	1993.0–2016.0	1.65	0.0076
Components total		3.01	0.074
Altimeter observed	1993.0–2017.0	3.1	0.097
Altimeter observed*	1993.0–2017.0	2.9	0.117
Altimeter observed†	1993.0–2017.0	2.9	0.084

*Corrected for Pinatubo.

†Corrected for Pinatubo and ENSO effects (climate-change–driven acceleration).

When taken with a rate of sea-level rise of 2.9 ± 0.4 mm/y (epoch 2005.0), the extrapolation of the quadratic gives 654 ± 119 mm of sea-level rise by 2100 relative to 2005, which is similar to the processed-based model projections of sea level for representative concentration pathways 8.5 in the IPCC Fifth Assessment Report (24). Stated alternatively, the observed acceleration will more than double the amount of sea-level rise by 2100 compared with the current rate of sea-level rise continuing unchanged. This projection of future sea-level rise is based only on the satellite-observed changes over the last 25 y, assuming that sea level changes similarly in the future. If sea level begins changing more rapidly, for example due to rapid changes in ice sheet dynamics, then this simple extrapolation will likely represent a conservative lower bound on future sea-level change. In contrast, few potential processes exist to suggest that this estimate is too high. Projections over shorter time frames (25, 50 y, etc.) are therefore likely more reliable, but will also be more sensitive to internal climate variability and volcanic eruptions.

Methods

Altimeter Data Processing. The altimeter data were processed following the recommendations set forth in ref. 15, including the latest orbits, tide models, sea-state bias models, water vapor corrections, etc. Following ref. 15, the "cal mode" correction to the TOPEX data was not applied, because the correction degraded comparisons to tide-gauge sea-level measurements, and because later investigation showed it should not have been applied in the first place. Not applying the cal-mode correction slightly increases the estimated sea-level acceleration. Measured GMSL was corrected for the effects of Glacial Isostatic Adjustment with a global model, which increased the GMSL rate by 0.25 mm/y (25).

Pinatubo GMSL Contribution. The computation of the effects of the eruption of Mount Pinatubo on GMSL using the NCAR LE of models (21) is described in ref. 12. Because this model ends in 2010, we assumed an exponential decay from 2010 to the present. This correction increases the quadratic acceleration estimate by 0.02 mm/y^2. The error in this correction was estimated from the variance of the NCAR LE at 0.01 mm/y^2.

Computation of the ENSO GMSL Contribution. We removed the effects of ENSO and Pacific Decadal Oscillation (PDO)-related variations on GMSL by computing a correction. This correction was computed via a joint cyclostationary empirical orthogonal function (CSEOF) analysis of altimeter GMSL, GRACE land water storage, and Argo-based thermosteric sea level from 2005 to present. The physical interpretation of these two modes is discussed in ref. 26, although here the understanding of the modal decomposition is extended through the inclusion of additional variables. The two leading CSEOF modes were subsequently projected onto the altimeter data from 1993 to present and averaged over the global ocean to arrive at what we refer to as a GMSL ENSO correction. Applying this correction reduced the quadratic acceleration value by 0.033 mm/y^2. Based on the ENSO and PDO variability during the altimeter record, a positive acceleration is expected due both to the presences of two large El Niños at either end of the record and the recent shift from the positive to negative phase of the PDO. To allow for the possibility that this correction might have not removed all of the ENSO signal and also based on sensitivity tests of the decomposition, we carry an error estimate of 0.01 mm/y^2 for this correction.

Calculation of Acceleration. We perform a least-squares fit of a quadratic using a time epoch of 2005.0 (the midpoint of the altimeter time series), where acceleration is twice the quadratic coefficient. All of the data were weighted equally—weighting the data based on error estimates from tide-gauge differences did not appreciably change the results.

Tide-Gauge–Based Altimeter Acceleration Error Estimate. The altimeter sea-level measurements were differenced with individual tide-gauge sea-level measurements, and then stacked and globally averaged to detect changes in the altimeter instrument behavior, assuming the tide-gauge measurements are perfect, following ref. 13. While there are overlaps between each of the four satellites in the time series, allowing instrumental biases to be determined and removed, there was no overlap in early 1999 when the TOPEX altimeter was switched from Side A to Side B of its electronics. As a consequence we estimated a bias here of 5.7 mm by leveling the TOPEX Side A tide-gauge differences to an average of the Jason-1–3 differences. This is a slightly different value than was found in ref. 15 (5 mm) because our analysis technique was different. Once this adjustment was made, an AR1 noise model was used to estimate the 1σ error in the quadratic acceleration coefficient of 0.011 mm/y^2. This is almost certainly a conservative error estimate because it assumes the tide-gauge sea-level measurements are perfect.

Acceleration Validation. We computed a rough validation (Table 2) of the altimeter-based acceleration estimate by comparing to other datasets, although they cover different time periods. We used the GRACE mascon data from ref. 27 and computed time series by averaging the mascons over (*i*) Greenland, (*ii*) Antarctica, and (*iii*) mountain glaciers and small ice caps (areas updated from ref. 28).

Constraining the thermosteric contribution to sea-level acceleration is hampered by the large discrepancies and related uncertainties that exist in ocean heat content datasets (20, 29). The root cause of these discrepancies has been attributed to errors in the raw data and mapping methods used to infill data gaps, which are particularly large in the southern oceans, but substantial progress has been made recently in dealing with these issues (30, 31). Given the systematic biases imparted by both data errors and infilling methods, a simple averaging across available datasets is not an effective means of minimizing bias (32). Rather, the optimization of mapping methods is likely to offer a suitable best estimate for quantifying both thermosteric contributions to acceleration and their uncertainty. Here we use the estimate provided from ref. 23. Comparison with independent data, such as the top of atmosphere (TOA) radiative balance also provides insight (32). We find the TOA reconstruction of ref. 33 to be broadly consistent with the value of acceleration derived from ref. 23.

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