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The rate of global sea level rise doubled during the past three decades

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The rise in globally averaged sea level—or global mean sea level—is one of the most unambiguous indicators of climate change. Over the past three decades, satellites have provided continuous, accurate measurements of sea level on near-global scales. Here, we show that since satellites began observing sea surface heights in 1993 until the end of 2023, global mean sea level has risen by 111 mm. In addition, the rate of global mean sea level rise over those three decades has increased from ~2.1 mm/year in 1993 to ~4.5 mm/year in 2023. If this trajectory of sea level rise continues over the next three decades, sea levels will increase by an additional 169 mm globally, comparable to mid-range sea level projections from the IPCC AR6.

With the launch of the Sentinel-6 Michael Freilich satellite in 2020, the satellite radar altimeter record of sea level has surpassed 30 years in length. This record of near-global observations of sea surface height has led to definitive measurements of not just the net increase in global mean sea level (GMSL), but also the increasing rate at which GMSL is rising. The record provides scientists with a better opportunity to now separate the expected, stochastic sea level fluctuations related to the natural variability in the climate system from the "forced" sea level changes that are mostly driven by increasing greenhouse gases[1,2]. The two main causes of the increase in GMSL are indeed both connected closely to increasing greenhouse gases in the atmosphere and the resulting planetary warming. The ocean has absorbed about 90% of the extra heat trapped by the atmosphere[3], leading to an expansion in ocean waters as it warms. Additionally, the warmer ocean and atmosphere surrounding ice sheets and glaciers has led to the loss of ice on land that has increased the mass of water in the ocean. Both processes are now well-measured with modern observing systems, with the Argo profiling floats measuring ocean warming and thermal expansion, the series of Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On satellites measuring ice and water mass redistribution at Earth's surface, and missions like Oceans Melting Greenland (OMG) helping us quantify the link between the warming oceans and disappearing land ice. While the goal of observing long-term GMSL rise is to isolate the global warming-linked rise, on shorter timescales (years to a decade), temporary shifts in the movement of water between land and ocean along with intrinsic variability in global ocean heat content can result in year-to-year variations in GMSL. These shifts are often associated with variable air-sea coupled processes, like El Niño-Southern Oscillation (ENSO)[4–7]. As the altimeter record lengthens, however, these temporary swings have a diminishing impact on the estimated trajectory of sea level rise (i.e., a trend estimated over a 15-year record is much more sensitive to a one-year swing than a trend estimated over a 30-year record).

The average rate of GMSL rise over the full length of the altimeter record - currently 3.3 mm/year - has been a widely-used metric for tracking the changes occurring to our climate system[8]. This average rate defined as a linear fit to the full record, however, is increasingly misleading. Recent studies have shown a significant acceleration in GMSL rise starting in 2017/2018, the climate equivalent of putting the "pedal to the metal"[9–11]. Even higher accelerations have been estimated regionally [e.g., refs. 12,13, but these estimates are more uncertain, since they are affected by variable processes like ocean circulation, which have no influence on GMSL. The acceleration means that the long-term average is no longer representative of the current rate of sea level rise, especially when comparing the pace at which the seas are rising today and at the beginning of the record.

The current rate and rate changes over time are important pieces of information. While the total sea level rise is generally offered in projections, information about the trajectory—here defined as a quadratic fit to a sea level time series—of this rise and its rate of change allows coastal communities to assess their ability to adapt[14]. In other words, in addition to "how much?", the question of "how fast?" is important for understanding when adaptation strategies may need to be deployed and the time horizons for worsening impacts. The observation-based trajectory also provides information on the "most likely" pathway of sea level rise for the near-term (e.g., Sweet et al., 2022)[15], giving those responsible for narrowing the range of possibilities down to a set of planning scenarios additional evidence for doing so. The most relevant information for those living at the coast is the local rate of sea level rise,

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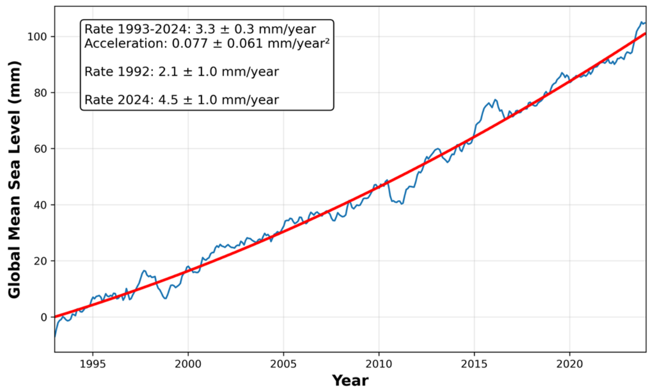

Fig. 1 | Global mean sea level rate changes. Global mean sea level time series (mm) from satellite altimetry over the time period from 1993 through 2023. The solid red line is the quadratic fit to the data and indicates the sea level change over the altimeter record relative to 1993.

but GMSL provides an integrative measure of ongoing changes in the cryosphere and large-scale ocean warming that cause sea level to rise on a near-global scale. The current methods for creating sea level projections generally rely on the regionalization of global estimates of physical processes other than ocean dynamics[16]. Tracking changes in GMSL can then still be informative for assessing more local projections and providing insight into the representativeness of sea level scenarios or projections that are currently used in planning. Assessing sea level rise on global scales also serves to improve the separation between natural and forced sea level change, as the impact of large-scale climate variability in the ocean is reduced on a global scale, which in turns amplifies the sea level rise signal associated with ongoing warming.

Results

The acceleration in GMSL was previously estimated by first accounting for and removing variability associated with several natural climate signals like ENSO[9]. It has since been shown since that a statistically significant acceleration can be inferred from the data without removing any signals related to natural and/or expected fluctuations like the inter-annual variations associated with ENSO[17]. an approach which we adopt here to estimate the acceleration. Using this acceleration, it is possible to produce an estimate of the current rate of sea level rise and understand how it compares to past rates throughout the rest of the altimeter record.

In Fig. 1, we show the quadratic fit, or trajectory, of GMSL rise from 1993 through 2023[18–20]. The acceleration is found to be 0.08 ± 0.06 mm/year^2 and the average rate is 3.3 + /− 0.3 mm/year referenced to the midpoint of the time series (see Methods for details on the uncertainty quantification; all uncertainty estimates are 90% confidence intervals). This estimate is consistent with the estimates of 0.08 + /− 0.06 mm/year^2 in Nerem et al.[8], and 0.12 + /− 0.07 mm/year^2 in Ablain et al.[10], although differ slightly as a result of the longer time series used here. Another way to view this is that it took 12 years to reach 30 mm of sea level rise, 9 more years to reach 60 mm of sea level rise, and only 7.5 more years to reach 90 mm of sea level rise. Using this trajectory and accompanying range, we can estimate the rate of GMSL rise at any particular time within this record. We find that the rate at the beginning of 1993 was 2.1 + /− 1.0 mm/year while the rate at the end of 2023 was 4.5 + /− 1.0 mm/year. This represents a more than doubling in the rate of GMSL rise over the 31-year satellite altimeter record.

As the satellite altimeter record has lengthened, the rate and acceleration estimates have evolved[8–10]. In particular, ENSO events – either El Niño or La Niña – occurring at the end of the available record can temporarily increase or decrease the rate and acceleration. In 2023, the fourth strongest El Niño during the satellite altimeter record occurred, following three successive years of La Niña-like conditions. This series of events provides an opportunity to test the robustness of the rate and acceleration estimates in the current record. To do so, we fix the start year of the record in 1993, but shorten the record at the end point successively by 1 year. Table 1 shows the results using endpoints from 2017 to 2024. The rate of the full record (varying between 25 and 31 years in length in this test) is constant at 3.3 mm/year. The influence of the ENSO variability can be seen more clearly in the acceleration, although the estimates vary only between 0.08 mm/year^2 and 0.09 mm/year^2. Notably, the uncertainty estimate continues to decrease with the lengthening record (from 0.09 mm/year^2 to 0.06 mm/year^2 for the acceleration), and there no significant difference between any of those acceleration estimates. Additionally, the impact of the 2023 El Niño is minor, demonstrating that the currently measured acceleration is unlikely to vary significantly in the immediate future.

Table 1 | Changes in rates and accelerations during the altimeter record

End Date	Rate (mm/year)	Acceleration (mm/year^2)	2020–2050 Sea Level Change (mm)
2017.99	3.3 ± 0.4	0.09 ± 0.09	171 ± 77
2018.99	3.3 ± 0.4	0.09 ± 0.08	168 ± 71
2019.99	3.3 ± 0.4	0.09 ± 0.08	174 ± 64
2020.99	3.3 ± 0.4	0.09 ± 0.07	169 ± 60
2021.99	3.3 ± 0.3	0.08 ± 0.07	165 ± 57
2022.99	3.3 ± 0.3	0.08 ± 0.06	158 ± 55
2024.00	3.3 ± 0.3	0.08 ± 0.06	169 ± 52

Rate and acceleration estimates for different lengths of the satellite altimeter record. The start year is fixed in 1993 but the end year of the record used varies from 2017.99 to 2024. The last row indicates the rate and acceleration estimates over the current full record. Uncertainty estimates denote the 90% confidence interval. Additionally, the extrapolation of the measured rate and acceleration is used to project the sea level change from 2020–2050.

We can use the rate and acceleration to assess the near-term trajectory of future sea level rise and provide an observation-driven estimate of sea level rise in 2050. Figure 2A shows the extrapolation of the current trajectory, centered on the midpoint of the satellite record, yielding an estimate of 205 + /− 54 mm from 2008 to 2050. This can then be compared to model-based projections from the IPCC 6th Assessment Report[16]. over the same time period. The IPCC AR6 created a series of sea level projections for different Shared Socioeconomic Pathways (SSPs). SSPs are scenarios that explore possible future global developments, considering factors like population growth, economic trends, and climate policies. These pathways are used in climate modeling to project different levels of greenhouse gas emissions, which, in turn, influence sea level rise. Sea level projections derived from SSPs provide a range of possible outcomes, from lower rise under strong mitigation efforts to higher rise in scenarios with continued high emissions. These projections do not directly integrate observations, so the observation-based extrapolations made here represent an independent comparison.

As seen in Fig. 2B, there is substantial overlap in likely ranges of the projections, although the observation-based estimate closely reflects the median estimate and likely range of the SSP2-4.5 scenario. The choice to only extend the observation extrapolation to 2050 is intentional and driven by the understanding of the processes expected to contribute to sea level rise in the near future. It is unlikely that, over the next three decades, ice sheet instabilities will be initiated that make outsized contributions to sea level rise. This is reflected in the range of the SSP5-8.5 Low Confidence (LC) scenario in Fig. 2, which has a higher upper end but is still similar to the SSP5-8.5 scenario that does not include the low confidence (e.g., ice sheet instability) processes. Table 1 also includes the results of the extrapolation done using rates and accelerations determined from shorter altimetry record lengths, demonstrating again relatively little variation in the observation-driven projection from 2020 to 2050 as the altimeter record continues to increase.

Discussion

With plans in place to continue the satellite altimetry record with the launch of Sentinel-6B in 2025 and potentially Sentinel-6 C in 2030, we will continue to monitor the progression of global sea level rise from space for the next decade. This monitoring will be essential to both provide a window into our changing climate and support coastal communities that are adapting or

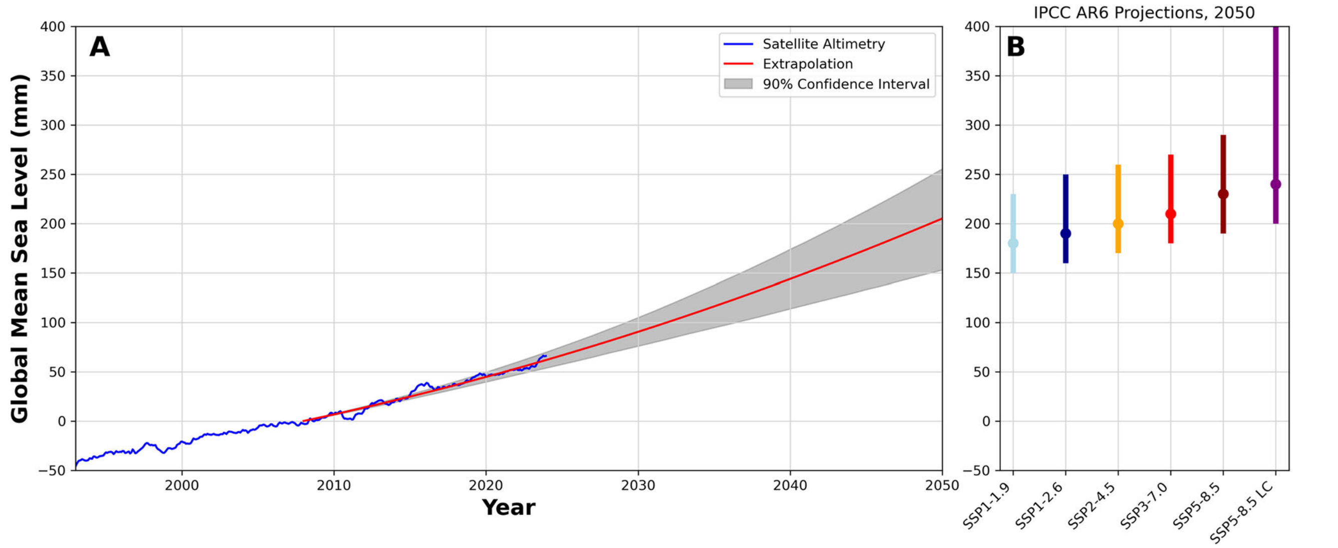

Fig. 2 | Extending the Satellite Record into the Future. A Extrapolation of the quadratic fit to the satellite altimeter record to 2050. The gray shaded area reflect the 90% confidence interval on the extrapolated sea level. **B** the model-based projections from the IPCC AR6 for six of the different scenarios considered. Error bars on the projections indicate the likely range for each scenario. The SSP5-8.5 LC scenario indicates the Low Confidence scenario used in the IPCC AR6.

preparing to adapt to increasing impacts along their coastlines. The simple analysis of the current GMSL record conducted here suggests two key takeaways that highlight the extent of changes occurring in our climate system and how those changes are reflected in global sea level.

1. Over the 31-year satellite altimeter record, the rate of global sea level rise has more than doubled from 2.1 mm/year to 4.5 mm/year.
2. Global sea levels increased by 111 mm from 1993 to 2024. If the current trajectory continues, global sea levels will increase by more than 169 mm over the next three decades.

Looking further into the future, the current trajectory suggests rates of 5.0 +/− 1.4 mm/year by 2030, 5.8 +/− 2.0 mm/year by 2040 and 6.5 +/− 2.6 mm/year by 2050. Such rates would represent an evolving challenge for adaptation efforts, and a shift in this trajectory could indicate the need to accelerate or adjust plans that are being put into place[14]. With the methodology used to produce the updated projections within the IPCC 6th Assessment Report[16] and the connection between some of the global processes and regional sea level rise, tracking GMSL over time also provides important information at the local level. Specifically, it can provide an indication of the overall changes in the climate system that are driving broadscale sea level rise that then combines with more local signals to increase the threat posed by rising oceans. Additionally, the observation-based estimate discussed here is an important and useful complement to the model-based projections, giving an independent check on such projections and providing an additional line of evidence for the narrowing range of near-term sea level rise. With total sea level rise measured by satellite altimetry surpassing 100 mm in 2023, global observations from satellites will continue to increase in importance and relevance as humanity prepares for the impact of increasing sea levels at the coast and it is critical that these observations be continued in the future.

Methods

Data

The global mean sea level time series was generated using the Integrated Multi-Mission Ocean Altimeter Data for Climate Research (https://podaac.jpl.nasa.gov/NASA-SSH; 18–19). It combines Sea Surface Heights from the TOPEX/Poseidon, Jason-1, OSTM/Jason-2, Jason-3, and Sentinel-6 Michael Freilich missions. The GMSL time series used here has the correction for glacial isostatic adjustment (GIA; 18) applied and the seasonal cycle is removed prior to estimation. The GIA correction ensures that the observed sea level changes are reflective of actual water volume and mass changes, and to allow for direct comparisons to the projections from the IPCC AR6.

Rate, acceleration, uncertainty estimates and trajectory estimates

The rate and accelerations were estimated with quadratic fit to the GMSL time series from January, 1993 to December, 2023, referenced to the mid-point of the record (2008.5). The acceleration values in this study are twice the quadratic coefficient, a, in the approximation to GMSL given as ½*at^2 + bt + c. The rate at a given time t is calculated as at + b. The approach adopted here follows Nerem et al.[9]. Sources of error that we assess include (i) the serially-correlated residuals, (ii) the uncertainties associated with the GIA correction applied to the NASA SSH data, and (iii) the measurement errors associated with altimetry, which are satellite mission-dependent (e.g., TOPEX, Jason-1, etc.). We follow the methods of Maul & Martin[21] to account for the lag-1 serial correlation of the formal errors, which are enhanced by the autocorrelated residual variability that remains in the data after removing the quadratic trajectory[22,23]. Errors associated with GIA are based on a Bayesian inversion that considers varying ice loading histories and Earth structures. Measurement errors are assumed to be uniform across the global oceans and modeled based on each potential error source, where we include altimeter noise, geophysical corrections, orbit determination, wet troposphere corrections, precision orbit determination, inter-mission biases, large-scale drifts associated with reference frame uncertainties, and the instabilities of TOPEX/Poseidon[9,10].

The extrapolated 90% confidence limits are determined using a Monte Carlo simulation with 10,000 members in which the rate is subject to three perturbations based on the three sources of error we consider: GIA, measurement errors, and serially correlated formal errors. We construct a normal distribution with standard deviation equal to the 1-sigma error for each of the three error sources, sample randomly from each normal distribution, and add the sum of each error triplet to the rate. The procedure is the same for the acceleration, except that GIA can be neglected since there is no acceleration associated with GIA. Then, 10,000 pairs of perturbed rate and acceleration are extrapolated and the 90% confidence limits are given by the bounds which contain 90% of the extrapolations

Data availability

Global mean sea level time series from Integrated Multi-Mission Ocean Altimeters TOPEX/Poseidon, Jason-1, OSTM/Jason-2, and Jason-3 Version 5.1. Ver. 5.1 PO.DAAC, CA, USA is available https://podaac.jpl.nasa.gov/NASA-SSH and from https://doi.org/10.5067/GMSLM-TJ151.

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References

1. Fasullo, J. T. & Nerem, R. S. Altimeter-era emergence of the patterns of forced sea-level rise in climate models and implications for the future. *Proc. Natl. Acad. Sci. USA* **115**, 12944–12949 (2018).
2. Richter, K. et al. Detecting a forced signal in satellite-era sea-level change. *Environ. Res. Lett.* **15**, 094079 (2020).
3. Von Schuckmann, K. et al. Heat stored in the earth system: where does the energy go? The GCOS earth heat inventory team. *Earth Syst. Sci. Data Discuss.* **2020**, 1–45 (2020).
4. Boening, C., Willis, J. K., Landerer, F. W., Nerem, R. S. & Fasullo, J. The 2011 La Niña: So strong, the oceans fell. *Geophys. Res. Lett.* **39** https://doi.org/10.1002/2017GL072845 (2012).
5. Fasullo, J. T., Boening, C., Landerer, F. W. & Nerem, R. S. Australia's unique influence on global sea level in 2010–2011. *Geophys. Res. Lett.* **40**, 4368–4373 (2013).
6. Piecuch, C. G. & Quinn, K. J. El Niño, La Niña, and the global sea level budget. *Ocean Sci.* **12**, 1165–1177 (2016).
7. Hamlington, B. D. et al. Origin of interannual variability in global mean sea level. *Proc. Natl. Acad. Sci. USA* **117**, 13983–13990 (2020).
8. Nerem, R. S., Frederikse, T. & Hamlington, B. D. Extrapolating empirical models of satellite-observed global mean sea level to estimate future sea level change. *Earth's. Future* **10**, e2021EF002290 (2022).
9. Nerem, R. S. et al. Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proc. Natl. Acad. Sci. USA* **115**, 2022–2025 (2018).
10. Ablain, M. et al. Uncertainty in satellite estimates of global mean sea-level changes, trend and acceleration. *Earth Syst. Sci. Data* **11**, 1189–1202 (2019).
11. Chen, X. et al. The increasing rate of global mean sea-level rise during 1993–2014. *Nat. Clim. Change* **7**, 492–495 (2017).
12. Hamlington, B. D. et al. Observation-based trajectory of future sea level for the coastal United States tracks near high-end model projections. *Commun. Earth Environ.* **3**, 230 (2022).
13. Davis, J. L. & Vinogradova, N. T. Causes of accelerating sea level on the East Coast of North America, *Geophys. Res. Lett*. **44**, https://doi.org/10.1002/2017GL072845 (2017).
14. Haasnoot, M., van't Klooster, S. & Van Alphen, J. Designing a monitoring system to detect signals to adapt to uncertain climate change. *Glob. Environ. change* **52**, 273–285 (2018).
15. Sweet, W. V. et al. Ocean, Global and regional sea level rise scenarios for the United States: Updated mean projections and extreme water level probabilities along US coastlines. *National Oceanic and Atmospheric Administration* (2022).
16. Fox-Kemper, B. et al. Ocean, cryosphere and sea level change. in *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Masson-Delmotte, V. et al.) 1211–1362 (Cambridge University Press, 2021). https://doi.org/10.1017/9781009157896.011.
17. Guérou, A. et al. Current observed global mean sea level rise and acceleration estimated from satellite altimetry and the associated measurement uncertainty. *Ocean Sci.* **19**, 431–451 (2023).
18. Willis, J. K., Hamlington, B. D., & Fournier, S. Global mean sea level time series, trajectory and extrapolation. Dataset access [2023-03-01] at https://doi.org/10.5281/zenodo.7702315.
19. Beckley, B. D., Callahan, P. S., Hancock Iii, D. W., Mitchum, G. T. & Ray, R. D. On the "Cal-Mode" correction to TOPEX satellite altimetry and its effect on the global mean sea level time series. *J. Geophys. Res. Oceans* **122**, 8371–8384 (2017).
20. GSFC. Global mean sea level trend from integrated multi-mission ocean altimeters TOPEX/Poseidon, Jason-1, OSTM/Jason-2, and Jason-3 Version 5.1. Ver. 5.1 PO.DAAC, CA, USA. https://doi.org/10.5067/GMSLM-TJ151 (2021).
21. Maul, G. A. & Martin, D. M. Sea level rise at Key West, Florida, 1846-1992: America's longest instrument record? *Geophys. Res. Lett.* **20**, 1955–1958 (1993).
22. Bos, M. S., Williams, S. D. P., Araújo, I. B. & Bastos, L. The effect of temporal correlated noise on the sea level rate and acceleration uncertainty. *Geophys. J. Int.* **196**, 1423–1430 (2014).
23. Royston, S. et al. Sea-level trend uncertainty with Pacific climatic variability and temporally-correlated noise. *J. Geophys. Res. Oceans* **123**, 1978–1993 (2018).

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Author contributions

B.D.H. conceived of the concept for the paper, performed the initial data analysis, and led writing and editing. A.B.-M. performed the data analysis on the extrapolations and uncertainty estimates. J.K.W., S.F., N.V., and R.S.N. contributing to the original draft of the paper, interpretation of the results and editing and revision. C.G.P., P.R.T., and R.K. contributed to interpretation of the results, in addition to reviewing, editing and finalizing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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