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Observation-based trajectory of future sea level for the coastal United States tracks near high-end model projections

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With its increasing record length and subsequent reduction in influence of shorter-term variability on measured trends, satellite altimeter measurements of sea level provide an opportunity to assess near-term sea level rise. Here, we use gridded measurements of sea level created from the network of satellite altimeters in tandem with tide gauge observations to produce observation-based trajectories of sea level rise along the coastlines of the United States from now until 2050. These trajectories are produced by extrapolating the altimeter-measured rate and acceleration from 1993 to 2020, with two separate approaches used to account for the potential impact of internal variability on the future estimates and associated ranges. The trajectories are used to generate estimates of sea level rise in 2050 and subsequent comparisons are made to model-based projections. It is found that observation-based trajectories of sea level from satellite altimetry are near or above the higher-end model projections contained in recent assessment reports, although ranges are still wide.

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Projections of future sea level generally extend to the end of the 21st century or beyond [e.g.[1–3]], a time at which differences in socioeconomic pathways become important and related uncertainties in the contributions from ocean dynamics or ice sheets grow significantly [e.g. Deconto et al.[4]; Edwards et al.[5]]. However, for certain decision types, near-term horizons are most relevant. For real estate investment and the typical lifetime of buildings and infrastructure in coastal areas, for example, a thirty-year planning horizon has particular relevance[6–9]. Additionally, flexible adaptation pathways and solutions typically require a range of lead-times on upgrades or replacements of coastal structures that lead to an emphasis on different planning horizons[10–12]. On global scales, model-based sea level projections tied to a specific socioeconomic pathway do not diverge significantly for the next thirty years and likely ranges for a given scenario generally overlap[13–15]. However, the range and uncertainty associated with these projections are greater on regional scales, and there have been relatively few studies examining the extent to which these projections are representative of recent and near-future sea-level rise [see[16] for one example]. Even if the scenario-dependent divergence is small, assessing the current and near-term trajectory of sea level rise can also be informative for the period beyond 2050 [e.g.[17]] and is necessary for informing adaptation efforts [e.g.[10,18]].

Observations provide an opportunity to assess near-term regional sea-level rise when considered alongside modeled projections [e.g.[15,16]]. Tide gauges have provided measurements of relative sea-level change extending back to the 17th century for several locations in Europe and since the 19th century across the globe. These long records have been used extensively to estimate long-term changes in coastal sea level [e.g.[19–24]]. However, tide gauges come with their own unique challenges that impact their application for understanding past, present and future sea level. The global tide gauge dataset is inconsistent in both space and time [see[25] for the description of dataset[19,26]]. Additionally, tide gauges measure relative sea level and it can be a challenge to separate the contribution of subsidence of the land upon which the tide gauge sits relative to the rise of the sea level it measures[27,28]. Furthermore, and perhaps most problematic for using the full tide gauge records as the basis for inferences about the future, the processes driving sea-level change are diverse and vary in their relative influence over time[22,29]. In other words, a rate and acceleration estimated over a 100-year tide gauge record may not be representative of a rate and acceleration estimated over the most recent thirty years.

An example of this can be found in the global mean sea level (GMSL). Between 1950-1970, the rate of GMSL rise was approximately zero due to a global increase in dam building and associated water impoundment[29]. Since the end of that time period, there has been a consistent acceleration in GMSL that persists through the present [e.g.[22,29]] and has been attributed to anthropogenic warming through thermal expansion and melt from the ice sheets and glaciers[29,30]. In other words, the estimates of the average 20th-century rate and acceleration are affected by factors not necessarily representative of the sea-level rise associated with processes we expect to drive increases in the coming years and decades. A subsequent extrapolation would be "contaminated" by the influence of these factors (e.g., dam building).

Since 1993, satellite altimeters have measured sea level with high accuracy[31,32]. In contrast to tide gauges, altimeters have provided continuous observations of sea level with near-global coverage. These measurements have led to accurate estimates of the rate of GMSL rise and a clear indication of the regional deviations from this rate [see[33], for a recent overview]. Although the now 28-year record is significantly shorter than the length offered by many tide gauges, the spatial coverage from altimetry is

much better. Recent studies have found a statistically significant increase in the rate of GMSL rise[34–36] and there are indications that the anthropogenic, or forced, pattern of sea-level rise is emerging from the internal variability [ref.[37]; Richter et al.[38]]. Building off these studies and considering the consistent acceleration on global scales found in both[22] and[29] since 1970, the satellite altimetry data provides an alternative to tide gauges when considering observation-based trajectories of sea level for the coming years.

In this study, we extrapolate satellite altimeter-measured rates and accelerations to assess the trajectory of current sea-level rise and project sea level in 2050 along the coastlines of the United States. We narrow our focus to this region both to constrain the scope of this study and also to investigate future sea level for coastal communities already experiencing ongoing and worsening impacts of increasing sea levels[15,39,40]. More specifically, with this study we attempt to address three connected questions:

1. To what extent are measured trends impacted by internal variability in the satellite altimeter record?
2. Using the answer from (1), what is the range of observation-based assessments of sea level in 2050 for the coastal United States?
3. How do the observation-based trajectories compare to those from models?

Addressing these questions requires the consideration of past, present and future sea level as estimated from tide gauges, satellite altimetry, and models. Obtaining answers has potentially high relevance both for recent scientific literature and for the coastal communities for which projections are provided. Observations can be used in other ways to improve projections of future sea level, but we consider one of the simplest: extrapolation of a rate and acceleration estimated from the satellite altimeter record. The resulting trajectory of near-term sea-level rise provides an important comparison to recent projections from assessment reports like the IPCC 6th Assessment Report and Interagency Sea Level Task Force Report[15], and gives planners an additional line of information when determining best estimates of sea-level rise in the near-term. Although it is possible that an extrapolation based on only the rate and acceleration will not be representative of the future pathways of sea-level change, we rely on this representation to match that of available model-based projections in the near-term.

Results

Satellite altimeter rates and accelerations 1993 to 2020. While there are indications that the forced pattern of the rate of global sea-level rise has emerged from internal variability in the altimeter record [Fig. 1a; refs. [37,41]], an associated regional pattern of acceleration has not yet emerged [Fig. 1b; ref. [42]]. Additionally, once a portion of the internal variability is removed, the regions of statistically significant acceleration in Fig. 1b are further reduced. Around the coastlines of the U.S., the acceleration estimates from 1993 to present are large and differ from region to region and from the GMSL value[36]. Sea level for all coastlines of the U.S. has accelerated with a positive value since 1993, driven by a strong shift in the pattern of regional trends from the first half of the record to the second half of the record. Recent studies have demonstrated that these accelerations are heavily influenced by large-scale climate variability[16,33,41,43–45], contributing to changes in rate and acceleration estimates as the altimeter record has lengthened. To account for the influence of internal climate variability on altimeter-estimated regional rate and acceleration, past studies have attempted to separate and remove some portion of explainable internal variability. Specifically, interannual to
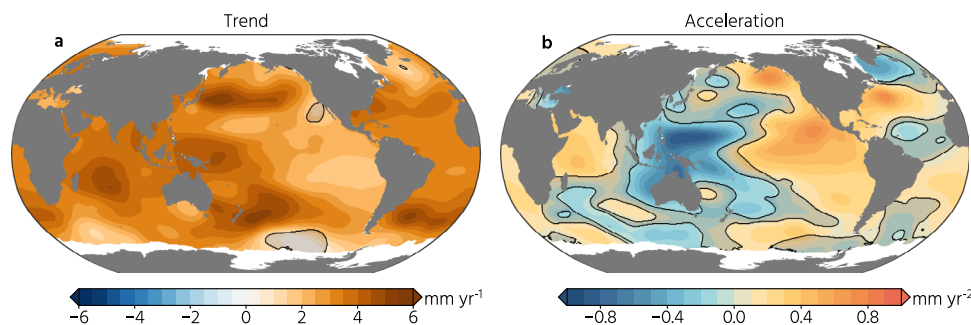
Fig. 1 Altimeter rates and acceleration. Regional rate (**a**) and acceleration (**b**) computed using the satellite altimeter data from 1993 to 2021. Gray shaded areas represent estimates that are not significant at the 95% confidence interval. Updated from[42].

decadal variability associated with large-scale climate signals can be estimated and removed using linear regression or other statistical techniques [e.g.[16,33,41,42,44,46]], potentially uncovering rate and acceleration patterns associated with external forcing. These techniques themselves add uncertainty to estimates [e.g.[41]] and there are potential limitations in the ability to fully account for internal variability associated with the large-scale climate variability that is targeted [e.g.[47]]. For example, the sea level response to a particular climate fluctuation (say El Niño) may not be perfectly linear and the regression model can underestimate the full effect.

As a starting point into the investigation of observation-based trajectories of near-term sea level, we assess how these rates and accelerations have changed over the course of the altimeter record and in doing so, provide an indication of the extent to which internal variability may still be impacting those estimates. We also assess how well the altimeter-based estimates agree with tide gauge observations along the coastlines of the United State. The focus here is on four particular coastal regions (Fig. 2 and Table S1): Northeast Coast (north of Cape Hatteras), the Southeast Coast (south of Cape Hatteras, extending to the southern edge of Florida), the Gulf Coast, and West Coast. These groupings are motivated by recent studies on the processes causing sea level change in each of these regions [e.g.[48]] and are relied on throughout the remainder of this study. This step results in consistently long records for each coastline. In Figs. 3 and 4, the evolution of the rates and accelerations estimated during the altimeter record is shown for each coastline, following the procedure used in[33]. Specifically, rates and accelerations are estimated by using the same starting year (1993) but extending the end-point of the computation from 2010-2020. This provides an indication of how these estimates have shifted as the altimeter record has lengthened. Note, the estimates are made relative to the midpoint of each time period, and the acceleration is twice the quadratic coefficient. A similar analysis performed on satellite-measured GMSL is shown in Fig. S1.

For all four coastlines, the rate estimate has increased relative to 2010 (Fig. 3; note a GIA correction has been applied; see methods for explanation). In recent years, these estimates have stabilized for the Northeast, Southeast and West Coasts, although continue to increase along the Gulf Coast. For all four coastlines, the tide gauge rate estimate from 1993 to 2020 (red) is within the 90% confidence interval of the altimeter-measured rate, although any non-GIA VLM occurring along these coastlines at some sites will contribute to differences between the two rates. The acceleration estimates, on the other hand, are similar between the tide gauges and altimetry for all four coastlines (Fig. 4). This suggests limited influence of regional non-linear vertical land motion over the time period considered here, and similar representation of the processes that drive longer accelerations in the two observational records. The acceleration estimates have

been relatively stable along the U.S. coastlines as the altimeter record has lengthened in recent years, although it is assumed as a starting point that internal variability is contributing to these estimates. Along the west coast in particular, the large El Niño in 2015/2016 caused an increase in the acceleration estimate [e.g.[33]], but the influence has diminished as the record has continued to lengthen. The rates and accelerations for the Southeast and Gulf coasts are found to be high, consistent with recent literature [e.g.[43,45]].

For both the rates and acceleration, the tide gauge envelopes (+/− one standard deviation) of possible 28-year deviations from the long term rate are shown (see Methods for details; Figs. 3 and 4; black error bar). These represent the degree to which 28-year rates and accelerations deviated from the long-term values from 1920 to the present in each region. In each case, these envelopes are larger than the uncertainty estimate (accounting for serial correlation) directly from the altimeter data. These envelopes are used for the extrapolated trajectories discussed immediately below.

Observation-based trajectories using tide gauge enveloping. As the goal of this study is to assess the trajectory of near-term sea-level rise and generate an associated observation-based estimate of future sea level that can be compared to model-based projections, it is necessary to account for the influence of internal variability both on the central projected values and associated uncertainties. We do this with two different approaches: an enveloping approach that leverages past tide gauge observations (see Methods) and an approach for removing internal variability directly. The resulting trajectories from the first of these approaches are detailed here.

In Fig. 5, the observation-based trajectories (red) associated with the enveloping approach from 2020 to 2050 for the four US Coastlines are shown along with upper and lower bounds indicating the 90% confidence interval (red shaded region). The trajectories for the Southeast Coast and Gulf Coast are substantially higher than the Northeast and West Coasts, although the higher trajectories are accompanied by a much larger uncertainty range. The large uncertainty range reflects both a large influence of internal climate variability in a 28-year record as well as other factors potentially affecting the tide gauge record (e.g non-linear vertical land motion; Kolker et al.[49]). These larger uncertainty ranges are consistent with the large tide gauge rate and acceleration envelopes shown in Figs. 3 and 4 for the Southeast and Gulf Coasts.

The trajectories can perhaps best be understood by considering the enveloping approach and the underlying rate and acceleration values. The objective of this approach is to determine the extent to which the altimeter-measured rates and acceleration may deviate from the forced, long-term values, and then to use this to assess uncertainty in the projected ranges. The envelopes
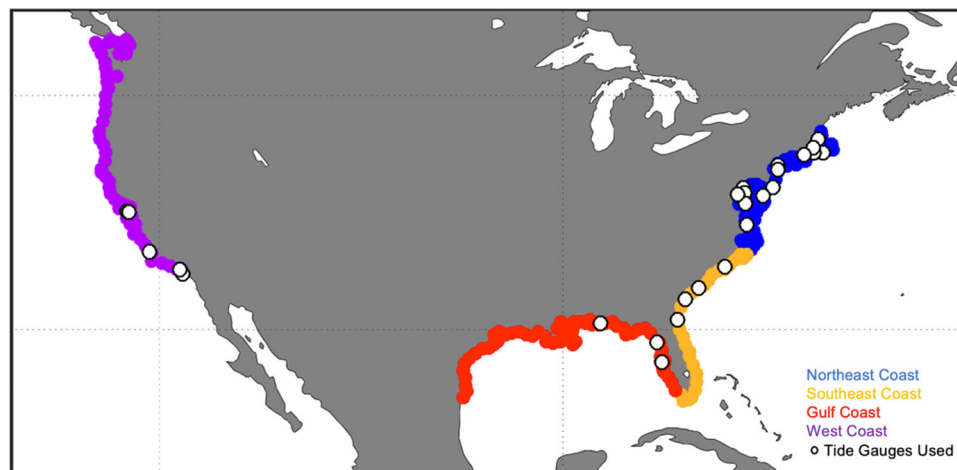
Fig. 2 United States coastal regions. Definition of the coastal regions used in this study: Northeast (blue), Southeast (orange), Gulf (red), West (purple). Tide gauges used are shown as white markers.
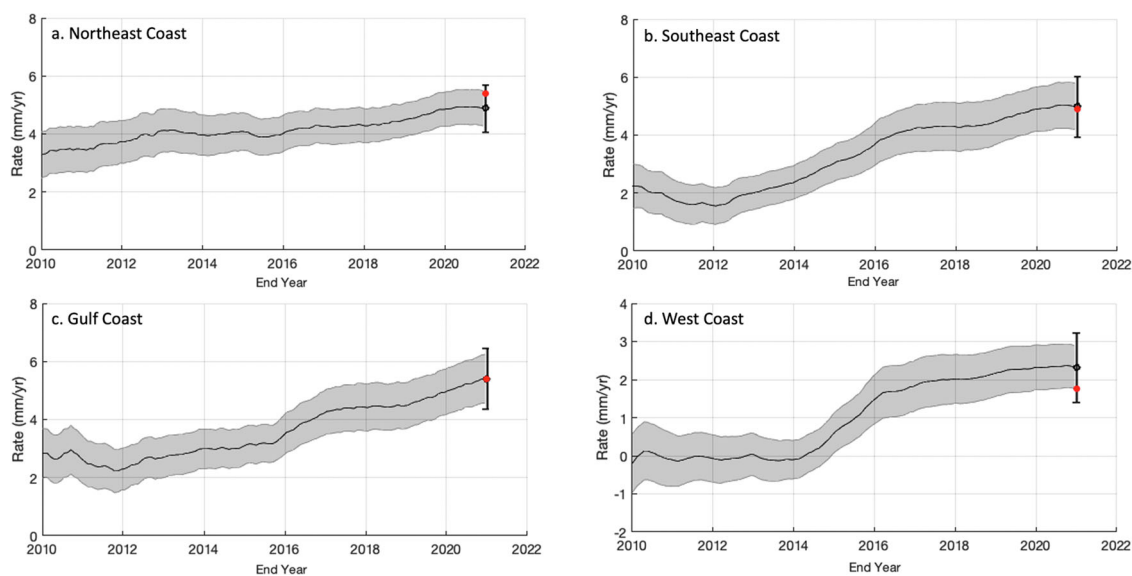

Fig. 3 Evolution of altimeter rates. For the time-period from 1993 to 2020, the evolution of rate estimates from the satellite altimeter record for four different regions along the coastlines of the United States: (**a**) Northeast Coast, (**b**) Southeast Coast, (**c**) Gulf Coast, (**d**) West Coast. The start year for each estimate is 1993, and the end year for the estimate is given on the x-axis. The shading provides the 90% confidence interval. The corresponding tide gauge estimates from 1993 to 2020 are shown in red, and the tide gauge envelope of possible estimates is provided by the solid black error bar.

computed from the tide gauges are an estimate of the possible size of these deviations and can be placed in the context of the altimeter-measured rates and accelerations. If the altimeter-measured rate and acceleration from 1993 to 2020 are anomalously high and driven upward by internal variability, it is probable that a shift will occur in the future and the rates and accelerations will become smaller. It would then be expected that the acceleration and rate estimates would revert towards a lower value as the altimeter record lengthened. This would be reflected in the lower-end of the range (red shaded area). Similarly, the upper bounds in Fig. 5 would suggest the current altimeter-measured rates and acceleration have actually been suppressed by internal variability and would increase in the coming years by a shift in variability. These bounds then provide a useful constraint on the possible sea-level rise by 2050. Based on the possible variations in the trend and acceleration observed in the historical tide gauge record, it is unlikely (at the 90% confidence interval) that sea-level rise in 2050 would fall outside of these bounds.

In interpreting the trajectories and accompanying estimates of future sea level shown in Fig. 5, it is important to note that the direct contribution of internal variability is not represented and needs to be considered separately. These estimates are for the long-term baseline mean sea level only and will not reflect interannual variations that can be substantially larger than the baseline mean sea level value and persist for several years, or subannual variations related to storms that can be even larger for days at a time (e.g.[48]). The estimates are intended for comparison to model-based projections and potentially in application to be used to adjust the means of probability distribution functions used for flood probability forecasting; they should not be interpreted as sea level in the region will never be higher than the upper envelope.

While the estimated values of future sea level provide potentially useful information for tracking ongoing and near-term sea-level rise, the range is still large and limits the ability to make comparisons to model-based projections. The envelopes established for each coastline from the available tide gauges can
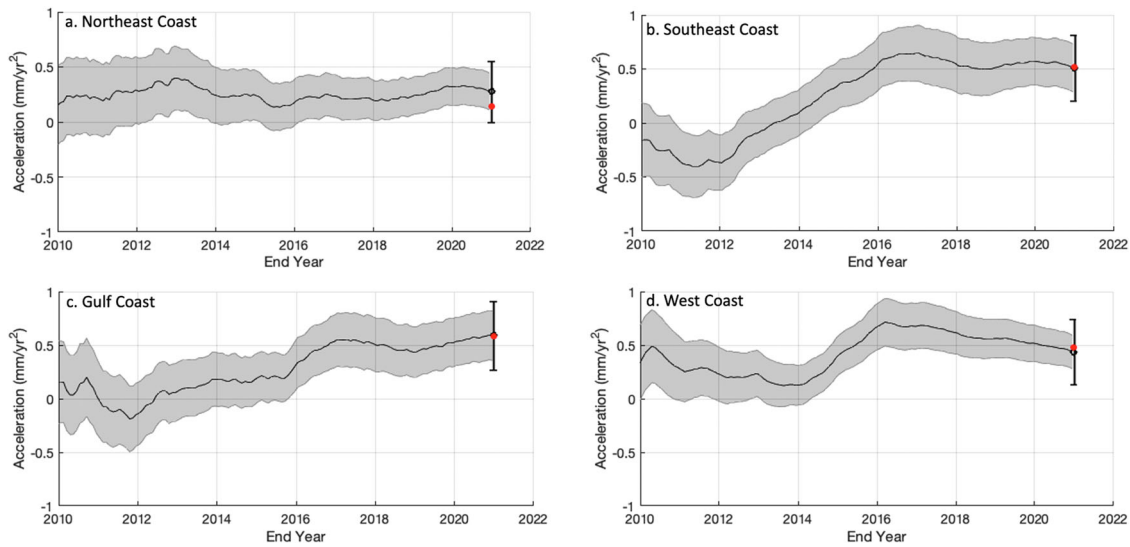
Fig. 4 Evolution of altimeter acceleration. For the time-period from 1993 to 2020, the evolution of acceleration estimates from the satellite altimeter record for four different regions along the coastlines of the United States: (**a**) Northeast Coast, (**b**) Southeast Coast, (**c**) Gulf Coast, (**d**) West Coast. The start year for each estimate is 1993, and the end year for the estimate is given on the x-axis. The shading provides the 90% confidence interval. The corresponding tide gauge estimates from 1993 to 2020 are shown in red, and the tide gauge envelope of possible estimates is provided by the solid black error bar.
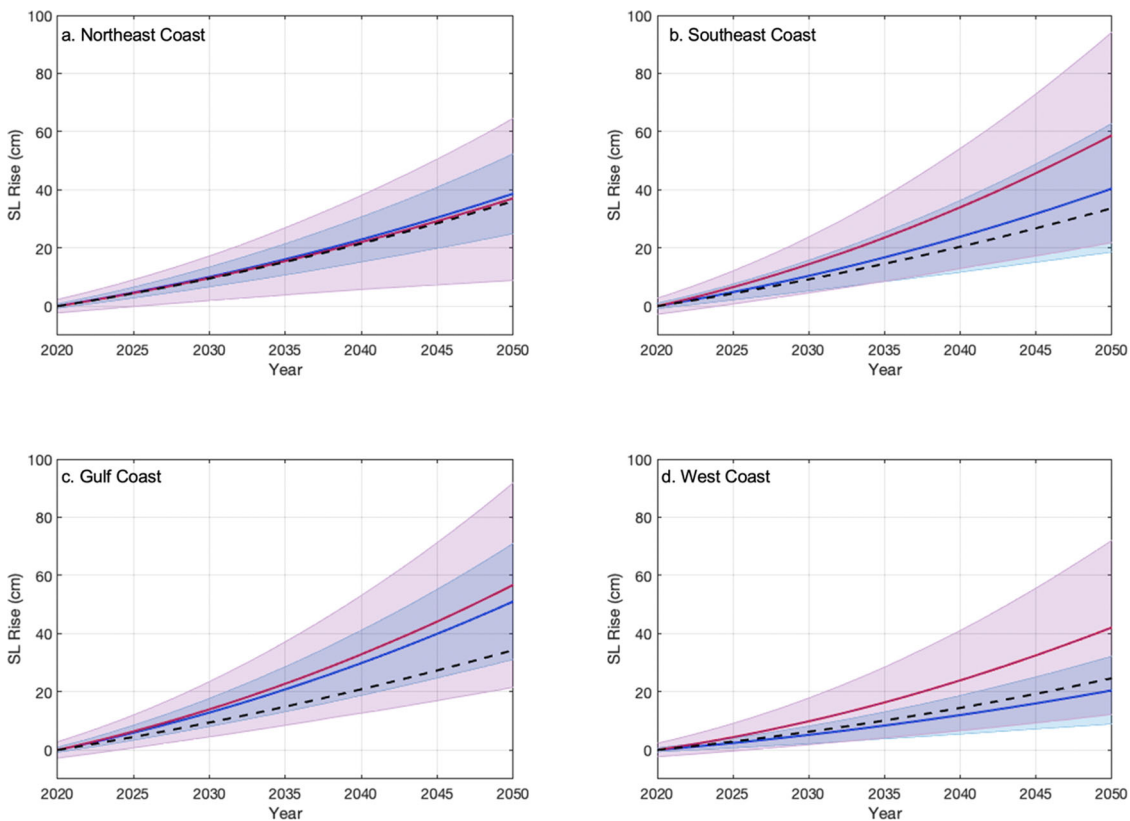

Fig. 5 Observation extrapolations, 2020-2050. Altimeter-based extrapolated trajectories. from 2020 to 2050 for four different regions along the coastlines of the United States: (**a**) Northeast Coast, (**b**) Southeast Coast, (**c**) Gulf Coast, (**d**) West Coast obtained using both the enveloping approach (red) and the approach of correcting for internal variability and accounting for serial correlation and altimeter measurement error (blue). The shaded regions bound the 90% confidence interval for the projections. Also shown are the projections (black dotted line) after adjusting the altimeter-measured trends using a correction based on the tide gauge acceleration and rate envelopes.

also be used themselves to improve the projection to 2050. By comparing the deviation of the tide gauge-estimated acceleration and rate from 1993 to 2020 to the deviations that have occurred since 1920, we can evaluate whether the values from the most recent 28-year time-period are likely above or below the long-term values. From this assessment, we can create a correction for the altimeter-measured trend and acceleration. Stated another way, a new estimate can be obtained that has been corrected for the influence of internal variability using these envelopes. The resulting estimate for each coastline is shown by the dotted black line in Fig. 5. For the Northeast, the original and corrected estimates are very similar. For the other three coastlines, the estimated future sea level is now lower after performing the correction based on the historical record. This indicates that the current rates and accelerations shown in Figs. 3 and 4 are likely higher than the expected long-term, forced rate, and have been driven higher by internal variability.

Observation-based trajectories using internal variability correction. As a second approach to accounting for the impact of internal variability, interannual to decadal variability associated with large-scale climate signals can be estimated and removed [e.g.[33,41,42,44,46]]. In this study, we rely primarily on the modal decomposition approach described in[41]; see Methods for details]. The two statistical modes of variability are associated with large-scale climate variability related to El Nino-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) and centered in the Pacific Ocean, and thus have the largest magnitude contribution for the West Coast region. The contribution is, however, non-zero for the other coastlines. This is expected as ENSO is known to have an impact on the east coast of the U.S. [e.g.[50]]. Alternate approaches that rely on climate indices have also been used for a similar purpose [e.g.[16,33,44,46,51]]. Following on from these same studies, we also fit an index tracking the North Atlantic Oscillation (NAO; Hurrell[52]) after removal of the statistical modes, and subsequently remove the associated NAO variability from the data prior to estimating rates and acceleration.

We estimate and remove internal variability and compute uncertainty by accounting for both serial correlation of the residuals, uncertainty in the GIA correction and altimeter measurement uncertainty[53]. The resulting trajectories and associated estimates for each coastline are shown in Fig. 5. A notable difference from the estimates using the enveloping approach (red) is the smaller 90% confidence interval by 2050 for all four regions. Similar to the values shown in the enveloping approach, the Gulf Coast has the highest estimated sea level in 2050 and the West Coast has the lowest. The mean value for the Northeast and West coastlines agrees well with the envelope-corrected projection (dotted black line). For the Southeast and Gulf Coasts, however, the estimate exceeds the corrected value from the enveloping approach. It should be noted that while some portion of the internal variability has been removed, the full influence of internal variability has not been accounted for and likely plays a role in the higher projections for the Gulf Coast[43,45,54]. This variability will also be captured in the tide-gauge envelopes and likely contributes to the large range for the two coastlines shown in Fig. 5.

Comparison to model-based projections. The observation-driven trajectories produced here can be compared to model projections and subsequently used to evaluate the possible trajectory of ongoing sea-level rise. Specifically, we compare them to climate model projections used in the IPCC 6th Assessment Report (AR6[13]); and to the sea level scenarios in the U.S.-focused

Interagency Sea Level Task Force Technical Report[15]. The values for the projected sea level for 2050 relative to the start of 2020 are shown (labeled "medium" in Table S2) for each coastal region along with the associated 90% confidence interval (labeled as "high" and "low" in Table S2) (Fig. 6). We show the estimates from the two different observation-based extrapolation approaches along with the modeled projections for the SSP1-2.6, SSP3-7.0 and SSP5-8.5 scenarios from the IPCC AR6. We also provide the values from the Interagency Sea Level Task Force Technical Report for the Intermediate Low, Intermediate High, and tide gauge-based observation extrapolations. Additionally, the median values for the enveloping approach after performing the correction of historical 28-year periods (black dashed lines in Fig. 5) are provided. Note, there is a discrepancy between the observation-based estimates and those from the other two reports. Specifically, with the observation-based approaches, only VLM associated with GIA is considered, whereas the other projections include contributions from more localized processes. Given that these non-GIA processes only contribute linearly in the AR6 projections, the possible contribution for the next three decades is generally small for these regions, although could be larger for the Gulf Coast. The total VLM (including GIA and non-GIA) estimates in both the AR6 and Technical Report are similar across scenarios for each region, with contributions of 6, 3, 5, and 0 cm from 2020-2050 for the Northeast, Southeast, Gulf and West Coasts, respectively. If the Gulf Coast region was not constrained to only the locations east of the Grand Isle tide gauge, the VLM contribution would be higher.

The 90% confidence intervals for both observation-based approaches are generally larger than those associated with the model projections. This is expected given the influence of internal variability that the two approaches are trying to account for in the uncertainty estimation. In general, the median observation-based estimates are higher than the median projections from the models. There is overlap between the 90% confidence intervals across all regions and projections, however. The Southeast, Gulf and West Coast median values for both observation-based approaches are higher than the upper end 90% confidence interval for the SSP5-8.5 scenario. This is particularly notable for the Gulf Coast, where the lower end of the interval variability-corrected estimate only narrowly overlaps the higher end of the SSP5-8.5 projection. While the projections for Northeast demonstrate the correspondence between the observation-based trajectories and AR6 projections, the other three regions have observation-based estimates that are higher – although not necessarily significantly different statistically – than the projected sea level from the AR6. For the Interagency Technical Report[15], there is also overlap between the 90% intervals across all approaches. The Technical Report includes an observation extrapolation using tide gauge records from 1970 to present and the same approach used here to correct for internal variability before extrapolating. In all four regions, the extrapolation using the satellite altimetry data results in higher values, but there is considerable overlap in the 90% confidence intervals.

One important feature to consider is the impact of variability that we do not account for in the internal variability-correction approach but do attempt to capture in the enveloping approach. As discussed above, recent studies have discussed shorter-term variability that substantially impacts the Southeast and Gulf Coasts. This variability will result in the wider confidence intervals shown in Fig. 6. However, the corrected estimate using the enveloping approach (Fig. 6, red) does attempt to account for such variability, and the resulting estimate of future sea level is in better agreement with the model-based projections.

As one additional comparison between the observations and models and to assess the degree to which the two may be
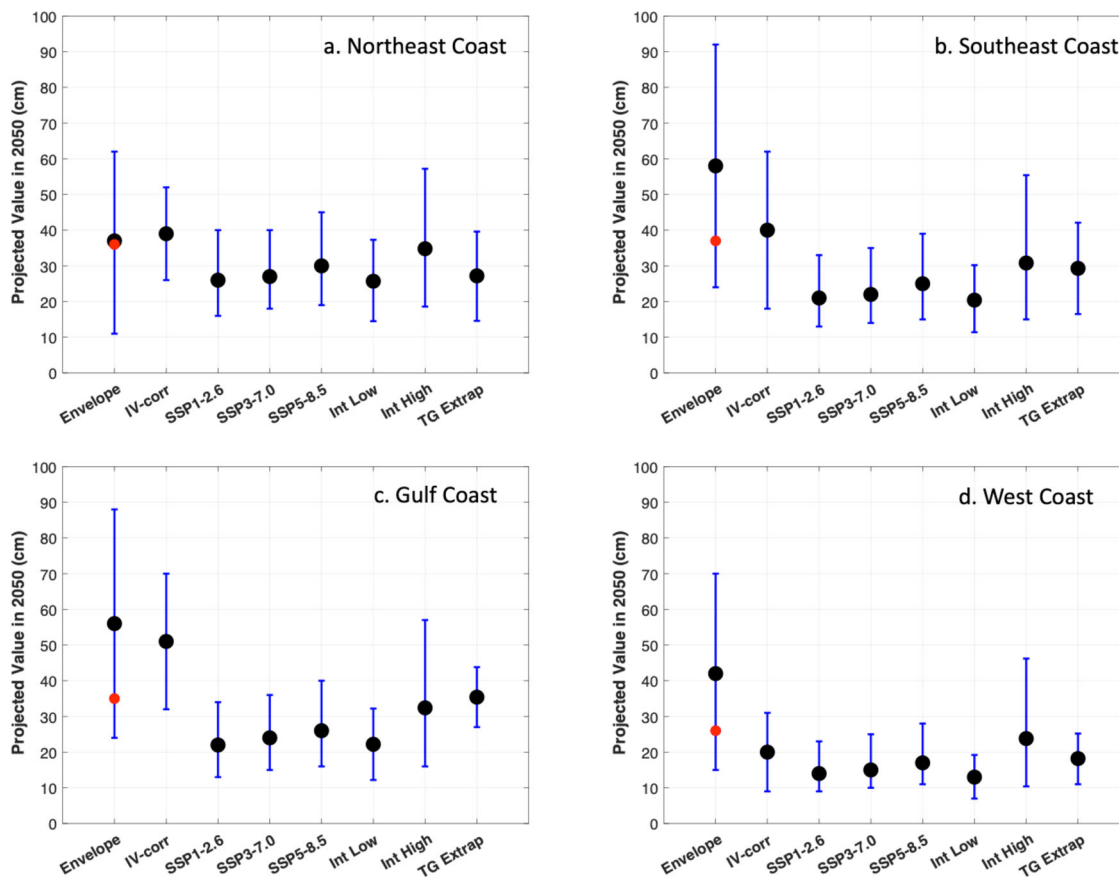
Fig. 6 Future sea level change estimates, 2020-2050. Sea level change from 2020 to 2050 for four different regions along the coastlines of the United States: (**a**) Northeast Coast, (**b**) Southeast Coast, (**c**) Gulf Coast, (**d**) West Coast obtained from the observations and IPCC AR6 and Interagency Task Force Technical Report. Black circles indicate median estimates and blue lines indicate the 90% confidence interval on each estimate. Two observation-based approaches are shown: the enveloping approach and the internal variability (IV-corr) approach. The red circle represents the internal variability correction value using the enveloping approach (using black dashed lines in Figs. 3 and 4). TG Extrap is the tide gauge extrapolation from the Interagency Sea Level Task Force report for the U.S. coastlines.

diverging, we can estimate the sea-level change from the time period now covered by the observational record. From 2007 to 2020, the median value of the sea-level rise projected for the AR6 SSP5-8.5 was less than 1 cm higher than the observed sea-level rise estimated from the rate and acceleration fit to the altimeter-data corrected for internal variability for the Northeast Coast, and approximately 1 cm lower than the Southeast and West Coasts. For the Gulf Coast, however, the observed sea-level rise is approximately 3 cm or almost 50% higher than the modeled sea-level rise over the same period. To arrive at the AR6 projected values, there would have to be a large (but possible; Fig. 4c) reduction in the rate and acceleration estimated from the satellite altimeter record. These results are consistent with[16], although different methodological comparisons and different region definitions should be considered when comparing directly.

Outlook for lengthening satellite altimeter record. With the launch of Sentinel-6A/Michael Freilich in late 2020, the modern satellite altimeter record will soon exceed three decades in length. The launch of Sentinel-6B will follow in the coming years, and the satellite altimeter record should exceed four decades in length by 2032 as a result of ongoing and planned missions. As the record increases, the influence of internal variability occurring on interannual to decadal timescales that is impacting the rate and acceleration estimates discussed in this paper will be reduced. To test this, we repeat the enveloping approach but successively increase the length of the record used to create the rate and

acceleration envelopes from 30 to 50 years. For each yearly interval, the size of the 90% confidence interval for a 30-year estimate is computed for each coastal region. Even though a longer window is used to compute the envelope, we are still only assessing sea level over a 30-year time period, matching the estimates from 2050 relative to 2020.

The results are shown in Fig. 7. The width of the 90% confidence interval decreases rapidly as the record length increases for all four coastal regions. Once the record length reaches 40 years, all four coastal regions have similar confidence interval widths, and all are less than 50 cm. This confidence interval is still large, although it should be noted that this is largely a result of the enveloping approach adopted in this study. The primary takeaway for this test is that based on the decreasing impact of internal variability on rate and acceleration estimates, the utility of the observational record in assessing future sea level and comparing to model-based projections will only increase as the satellite altimeter record continues to lengthen.

Discussion
Before summarizing and contextualizing the observation-based trajectories and projections presented here, there are a number of caveats and limitations of this study that must be discussed. First, the mean of extrapolated trajectories presented here are necessarily tied to the altimeter-measured rates and accelerations and based on recent studies, and it is clear that these accelerations are still heavily impacted by internal variability. We attempt to
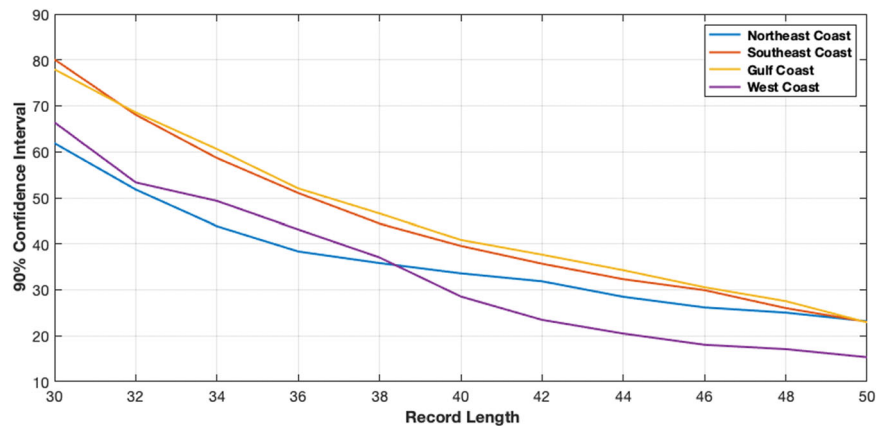
Fig. 7 Narrowing ranges. Width of the 90% confidence interval in centimeters for increasing record lengths used in the enveloping approach. Values represent the confidence interval width for a 30-year projection, reflecting the 30-year projection time period from 2020 to 2050 considered in this study.

address this limitation in a couple of different ways, one of which leads to a very wide confidence interval (the enveloping approach) that reflects our uncertainty in how representative the altimeter-estimated acceleration is of a long-term, forced acceleration. We can and do use this uncertainty to create a tide-gauge-based correction to our extrapolation, but the confidence interval on this corrected estimate will still be large. A second limitation of this study is associated with the approach of accounting for internal variability. We consider and remove only the two statistical modes that are investigated in[41,42], which are largely representative of Pacific-centered large-scale climate variability. In other words, this is an incomplete account of the variability that may be impacting trend and acceleration estimates, particularly for the coastal regions other than the West Coast and there are recent studies documenting the influence of internal variability in these regions [e.g.[45,54]]. Indeed, many other processes impact the open ocean sea level signal[14,42] that we do not explicitly account for here but may be driving regional differences in the rates and accelerations. A more detailed study of each of these coastlines is needed and could lead to changes in both the extrapolated estimates and associated uncertainties. This study is also not (and is not intended to be) a detection and attribution effort for the sea-level change measured during the altimeter record. It is possible that a more formal detection and attribution study could lead to better observation-based assessments of future sea level. Additionally, observations of the individual processes contributing to sea-level change and subsequent analysis could improve projections beyond those produced here. As stated in the introduction, however, our goal is to understand what can be determined about near-term future sea level from the nearly three decade-long altimeter record. Finally, the focus area here is on the coastlines of the United States. To extend this to other regions or even global scales, consideration of local factors and regional similarities is necessary. As a specific example, the impact of natural signals like ENSO and PDO are accounted for here but will not be as relevant or important in other parts of the ocean.

Despite these limitations and caveats, there are a number of important conclusions that can be drawn from this work:

1. The satellite altimeter-based extrapolated trajectories are tracking near or above the AR6 SSP5-8.5 scenario and U.S. Technical Report Intermediate Low and High scenarios for all four coastlines of the United States, although importantly future ranges in 2050 do overlap across all techniques and reports.

2. The Gulf Coast of the U.S. has experienced a high rate and acceleration during the satellite-altimeter era that leads to a median estimate of increasing sea level from 2020 to 2050 that exceeds 30 cm across all observation-based approaches considered here.

3. In order to not exceed the RCP8.5 high-end projections for 2050, the rate and/or acceleration will have to decrease in magnitude relative to the rate and acceleration estimated from the 1993 to 2020 for all four coastlines, although such decreases are not without historical precedent.

4. The uncertainty in future observation-based estimates in 2050 for the coastlines of the U.S. is large, although it will decrease with the lengthening satellite altimeter record due to reduced influence of internal variability.

The primary goal of this work is not to provide an alternative to model-based projections. Instead, the observations are used here for comparison to the models and to provide an ongoing assessment of the possible trajectory of future sea-level rise. This assessment suggests that the current trajectory of sea-level rise along the coastlines of the U.S. is currently more closely aligned with the SSP5-8.5 scenario in the near-term (which is itself an unlikely scenario, see Hausfather and Peters[55]) than to other scenarios with lower projections of future sea level. This result is in alignment with the results of[16], although we note there are different methodological choices including the treatment of the observational data (both altimetry and tide gauges) and internal variability. Additionally, the smaller region of focus has highlighted the Southeast and Gulf Coasts of the U.S. as experiencing particularly high rates and accelerations during the past three decades that subsequently lead to high estimates of sea level in 2050. It is important to keep in mind that the projections discussed here only address the increase in the height of the ocean. When making an assessment of what may happen at the coast, it is necessary to account for additional subsidence beyond GIA that may be occurring and leads to an increase in relative sea level [see[56] for discussion]. Shorter-timescale variability like that we have attempted to remove here can also exacerbate or diminish the impacts of the projected sea level-rise by leading to periods of substantially higher or lower sea level along all coastlines of the U.S. As an example, the average seasonal cycle contributes an additional 8 cm (Northeast), 10 cm (Southeast and Gulf Coast), and 4 cm (West Coast) in any given year, with potential modulation of this contribution on a year-to-year basis[57]. Along the west coast, ENSO variability can contribute greater than 20 cm on an interannual basis. These factors, along with shorter-term

signals like tides, must be considered along with the projections discussed here when assessing future flood threats[48,58,59].

Lastly, this study and those of[16] and[15] provide important comparisons between models and sea-level observations, but really represent the first in what should be a series of ongoing assessments. The trajectory of ongoing sea level should be evaluated on a regular basis, and direct comparisons to the different modeled scenarios should be performed. In order to conduct this regular evaluation, uninterrupted continuity of the satellite altimetry record is critical. The usefulness of the satellite altimetry record in understanding long-term sea-level rise will only increase as the record lengthens.

Methods

Tide gauge enveloping approach. We rely on two separate approaches for accounting for the influence of internal variability on our rate and acceleration estimates, one based on similar efforts in prior studies and one based on historical observations. In the first approach, we estimate and remove the contribution of internal variability and assesses the impact of both serial correlation and measurement errors on the projected uncertainty, following a similar approach to[42] and[15]. As an alternative approach, we rely on the tide gauge record to constrain the possible contribution of internal variability in what is referred to here as an "enveloping approach". To do this, we estimate the envelope of possible rate and acceleration estimates across any given 28-year period (matching the record length of the satellite altimetry) using the historical tide gauge record. This envelope provides an indirect measure of uncertainty for the altimeter-estimated rate and acceleration caused by unaccounted for climate variability and is used as the basis for our uncertainty estimates in the extrapolation.

To create the envelope of possible rate and acceleration estimates in a 28-year record, we rely on available long tide gauge records along the U.S. coastlines (Table S1). The rate and acceleration estimated from the tide gauge records are not the same as those estimated from the satellite altimeter data. This is because tide gauges measure relative sea level, which is the movement of the ocean relative to land. In other words, tide gauge measured rates and accelerations will include the contribution from vertical land motion while the altimeter-measured rates and accelerations will not. To address this discrepancy between the measurements, the long-term rate and acceleration estimated from 1920 to present (or the longest available record) is removed from the tide gauges. The goal of creating the envelope is to capture the extent to which a 28-year rate or acceleration can deviate from the long-term values. These deviations can be estimated once the long-term rates and acceleration are removed. In other words, the tide gauges are not being used to provide an estimate of the long-term rate and acceleration. Instead, the tide gauges are being used to determine how much sea level can deviate from the long-term rate and acceleration in any 28-year record, subsequently providing an alternative assessment of uncertainty in the altimeter-measured rate and acceleration.

Once the long-term rate and accelerations are removed, the resulting tide gauge records are grouped and used to generate a "virtual station" [e.g. Jevrejeva et al.[60]] for four different segments of the US coastlines (Fig. 2 and Table S1). After removal of the long-term rate and acceleration (creating residuals with a long-term mean of zero) and formation of a single time series for each region, a sliding 28-year window is applied to the residuals; rate and acceleration values are estimated in each window using least squares to determine the range of variation of the rate and acceleration for all 28-year periods within the tide gauge record. It should be noted that any sustained deviation from the rate and acceleration estimated over 1920 to 2020 will influence the magnitude of the values in the envelope. Such deviations could result from non-linear vertical land motion, volcanic events, or the aforementioned dam building, among other factors. Consequently, the envelopes estimated here and subsequent uncertainty estimates are likely larger than what would be expected from internal variability alone. After producing normal distributions based on the spread of the 28-year rate and acceleration values, we use the altimeter-measured rate and acceleration to extrapolate and generate mean regional projection out to 2050 and use the tide gauge envelopes for the spread about these values. Specifically, for each coastline, we create 1000 trajectories from 1993 to 2050 by adjusting the altimeter-measured rate and acceleration with randomly selected values from the tide gauge-defined rate and acceleration envelopes. Since the tide-gauge envelopes are computed as 28-year deviations from long-term values, we can use them to create similar-scale deviations in the altimeter record. Finally, we do apply a glacial isostatic adjustment (GIA) correction[61] to the altimeter-measured rate. The primary reason for applying this correction is to provide a more direct comparison to the model-based projections, although the effect on the projections is not large. This correction does add uncertainty to our estimates, which we account for in the extrapolation process.

Satellite altimetry data. The European Copernicus Marine Environment Monitoring Service (CMEMS) multi-mission gridded sea surface heights were used for the satellite altimeter data in this study. Other satellite altimeter data (including from NASA JPL PO.DAAC) was analyzed without noticeable impacts on the rates and accelerations. This gridded data has monthly temporal resolution and half-degree spatial resolution and covered the time period from January 1993 to June 2020. The dataset used is corrected for the inverse barometer effect, but no additional adjustments were made to the data prior to use. To create the regional time series for each of the four coastlines (Fig. 1), the grid point nearest to the coastline along the extent of the region was subsampled and averaged together. Larger swaths of coastal data (e.g, nearest three grid points) were also selected without noticeable impact on the results contained in the paper. It should be noted that the satellite altimeters do not provide measurements directly at the coast, potentially adding to a mismatch between altimeter-measured estimates and the rates and accelerations occurring at the coast. Given the structure of our analysis, this does not significantly impact our results for two reasons. First, the tide gauge data are only used to establish deviations from the long-term rates and accelerations. Second, the modeled projections from the AR6 similarly do not provide rates and accelerations for processes directly at the coast.

Tide gauge data. Monthly tide gauge records for the United States coastlines were retrieved from the National Oceanic and Atmospheric Administration (NOAA), covering the time period from January, 1920 to December, 2020. Only gauges with records more than 70% complete during this time period were used. Tide gauges were grouped into four different regions (shown in Fig. S2). Tide gauges south of Sewells Point were considered to be part of the Southeast region. Along the Gulf Coast, only tide gauges east of Grand Isle (not included) were used due to the possible large influence of non-linear vertical land motion (see[48] for discussion). Once grouped, the retained tide gauges were averaged together after the mean, rate and acceleration of each individual tide gauge was removed. This removed the possible influence of long-term vertical land motion which does not similarly influence the satellite altimeter measurements.

Rate and acceleration estimates. Rates and accelerations were estimated in all instances using a quadratic fit. Any acceleration estimates given here are defined as twice the quadratic coefficient. All estimates are referenced to the midpoint of the time period considered. In the case of the rate and acceleration evolution shown in Fig. 2, this results in a shifting midpoint as the record length is increased. The uncertainty in the rate and acceleration is estimated by assuming that the temporal autocorrelation spectrum of the altimetry observations can be described by a Generalized Gauss Markov (GGM) noise model[44]. The parameters of the GGM model and the resulting rates and accelerations and associated uncertainties have been computed using the Hector software[62]. The altimeter measurement uncertainty is also accounted for in all estimates[53].

Data availability

Monthly tide gauge records for the United States coastlines were retrieved from the National Oceanic and Atmospheric Administration (NOAA), covering the time period from January, 1920 to December, 2020 (https://tidesandcurrents.noaa.gov/). The European Copernicus Marine Environment Monitoring Service (CMEMS) multi-mission gridded sea surface heights were used for the satellite altimeter data in this study (https://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/gridded-sea-level-heights-and-derived-variables.html). The projections for the IPCC 6th Assessment Report can be downloaded here: https://podaac.jpl.nasa.gov/announcements/2021-08-09-Sea-level-projections-from-the-IPCC-6th-Assessment-Report. The scenarios from the Interagency Sea Level Task Force Technical Report can be downloaded from https://sealevel.nasa.gov/task-force-scenario-tool.

Code availability

Codes to reproduce the results in this publication using the datasets listed above can be found here: https://zenodo.org/record/5951626#.YrYVt-zMJaY.

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Author contributions

B.D.H. conceived of the experiment, performed the core analysis, interpretation of results, and writing. D.P.C. helped conceive of the experiment, and assisted interpretation of results and writing. T.F. performed analysis, assisted in generating figures, and helped with interpretation of the results and writing the manuscript. B.B. helped generate figures, assisted in interpreting the results and assisted in writing the manuscript. S.D, S.F. and R.S.N assisted in interpretation of results and writing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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