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Extrapolating Empirical Models of Satellite-Observed Global Mean Sea Level to Estimate Future Sea Level Change

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Key Points:
- The satellite record of global mean sea level change is quadratically extrapolated 30 years into the future
- This extrapolation agrees well with various IPCC model projections, as well as with 20th century tide gauge measurements in hindcast
- This extrapolation provides another observationally driven tool to assess ongoing and future sea level change

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Abstract We estimate a quadratic model of climate-driven global mean sea level (GMSL) change based on the satellite altimetry record (1993–2020), including a rigorous assessment of the errors in the quadratic coefficients. We then extrapolate this model 30 years into the future to 2050 and compute the 90% confidence interval. We find GMSL rise in 2050 relative to 2020 will be 16.4 cm higher, with an uncertainty range of 11.3–21.4 cm. This prediction agrees within uncertainties with IPCC SROCC and AR6 sea level projections. In addition, a hindcast extrapolation prior to 1993 agrees well with the tide gauge record of GMSL change over the 2nd half of the 20th century. We believe this shows the value of short-term observationally driven extrapolations as an additional tool for predicting future sea level change.

Plain Language Summary The satellite altimetry record of global mean sea level (GMSL) change (1993–2020) is now of sufficient length that we can begin to average through some of the natural variability and detect the climate-driven changes. If we model these changes using simple rate (mm/year) and acceleration (mm/year^2) terms, we can extrapolate the rate and acceleration into the future to predict future sea level change. This assumes that the rate and acceleration terms remain constant in the future, which probably provides a conservative assessment of future sea level change. We find extrapolated GMSL rise in 2050 relative to 2020 will be 16.4 cm higher, with a 90% uncertainty range of 11.3–21.4 cm. These numbers agree well with projections from climate models. In addition, when the rate and accelerations are extrapolated backward to 1960, we find good agreement with the tide gauge record of GMSL change.

1. Introduction

The satellite record of sea level change is now of sufficient length that we can begin to detect climate-driven signals in global mean sea level (GMSL) change (e.g., Nerem et al., 2018). Beginning with the launch of TOPEX/Poseidon in 1992, the observations have been continued with Jason-1 (2001), Jason-2 (2008), Jason-3 (2016), and Sentinel-6 (2020; Abdalla et al., 2021). Remarkably, the time series has been uninterrupted, and now this critical climate data record is 28 years in length (Figure 1). Climate-driven signals are also beginning to emerge in the observed regional sea level trends (Fasullo et al., 2020; Fasullo & Nerem, 2018; Hamlington et al., 2019), but it is still difficult to empirically model regional sea level changes (Hamlington, Frederikse, et al., 2020). Averaging regional sea level to give GMSL reduces the influence of regional sea level variability and gives a clearer picture of the climate-driven changes.

Satellite altimeter measurements give us insight into how sea level has changed over the last 3 decades, but determining how to use this information to inform future sea level change is a difficult task. One approach would be to use the observed sea level changes to improve climate models and their projections, but climate models are only beginning to be coupled to ice sheet models, one of the major contributors to future sea level change, and so they are limited in their ability to incorporate observed sea level change. Another approach is to use semi-empirical models, which combine observed sea level and surface temperature change with climate model projections (e.g., Moore et al., 2013), but the satellite record is too short of a training period for this method. Here we demonstrate a purely empirical approach using a simple mathematical model of the observed changes, and then assume that sea level changes similarly in the future. Over periods of a few decades, this approach has the advantage that it is simple to implement and modeling the uncertainty is reasonably straightforward. This approach is also independent of climate models, so it provides a useful comparison to those projections.

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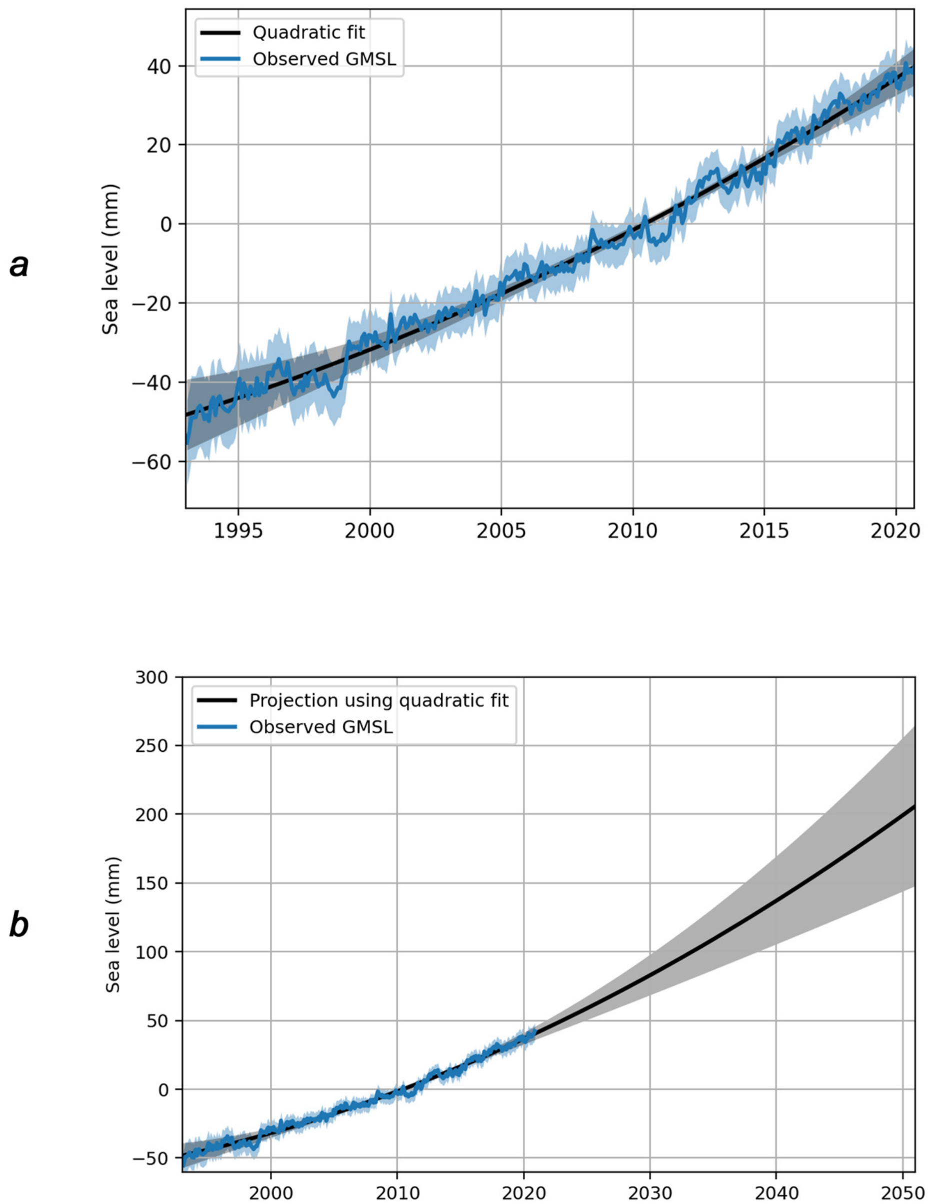

Figure 1. Global mean sea level observations (Beckley et al., 2017) and estimated errors (Ablain et al., 2019), fit with a 2nd order quadratic. (b) Same as (a), but showing the extrapolation of the quadratic to 2050 with 90% uncertainty bounds.

The observation-driven predictions are unlikely to be effective beyond a few decades, but the need for near-term assessments is high, and observations can be especially useful in assessing sea-level rise on these shorter timescales. As a result of the sea-level rise that has taken place both during and before the altimeter record, coastal impacts have increased in frequency and severity in recent years (see Oppenheimer et al., 2019 for summary), and will likely continue to increase in the next couple of decades (e.g., Thompson et al., 2021; Sweet et al., 2022) Planning decisions are also increasingly being made on these shorter time horizons. For real estate investment and the typical lifetime of buildings and infrastructure in coastal areas, a 30 year planning horizon has a particular relevance. Additionally, flexible adaptation pathways and solutions typically require significant lead-times on upgrades or replacements of coastal structures that lead to an emphasis on shorter planning horizons (Bloeman et al., 2018; Hall et al., 2019; Werner et al., 2021). Assessing the current and near-term trajectory of sea level rise is both informative for the period beyond 2050 (e.g., Little et al., 2019) and necessary for informing adaptation efforts (e.g., Haasnoot et al., 2013; Ranger et al., 2013).

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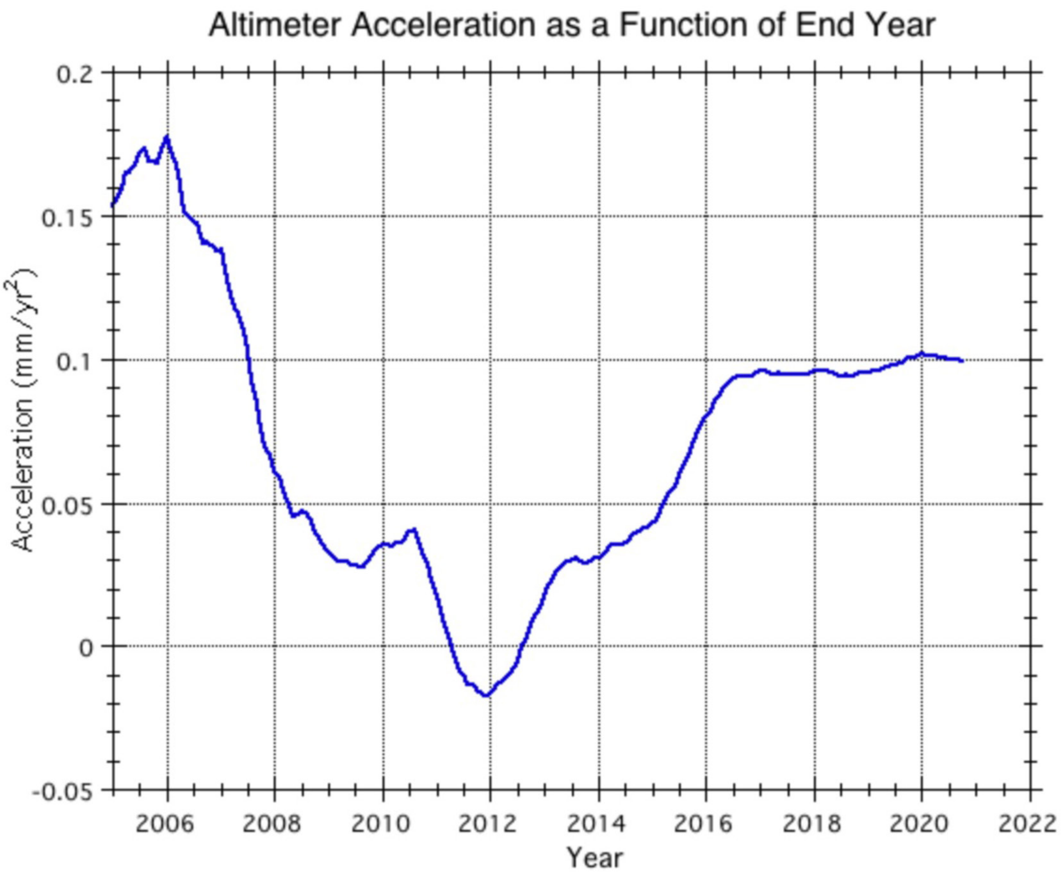

Figure 2. Acceleration coefficient versus the end date of the fit interval (start date is 1993.0). As the length of the time series gets longer, the acceleration coefficient becomes stable after 2017.

The time series of GMSL is well-approximated by a quadratic plus interannual variability mainly associated with ENSO (Figure 1). Nerem et al. (2018) attempted to isolate the climate-driven rate and acceleration of GMSL. Here we update those results and focus on extrapolating this quadratic sea level model to predict future sea level change in 2050.

2. Estimates of the Rate and Acceleration of GMSL

Estimates of the rate of GMSL change from satellite altimetry have been made for many years, but only recently has it become possible to reliably estimate the climate-driven acceleration of GMSL with sufficient confidence (e.g., Ablain et al., 2019; Nerem et al., 2018). Estimates of the acceleration as a function of the length of the time series have stabilized (Figure 2), suggesting that the impacts of interannual and decadal variability have lessened over a 28 year time series. Here we use updated 10-day GMSL estimates from Beckley et al. (2017), where seasonal variations have been removed and monthly averages computed.

A number of non-climate related factors can influence the acceleration of GMSL. Fasullo et al. (2016) showed that the eruption of Mount Pinatubo and the associated cooling effects of the aerosols injected into the stratosphere caused a deceleration of GMSL of about 0.017 mm/yr^2 over 1993–2020. We removed this effect using a model as described in Fasullo et al. (2016). Removing these effects increases the climate-driven acceleration. In addition, the interannual ENSO impacts, due to both shifts in land/ocean precipitation and thermosteric changes, can influence the acceleration estimate (Boening et al., 2012; Hamlington, Piecuch, et al., 2020; Llovel et al., 2011; Moreira et al., 2021; Ngo-duc et al., 2005; Piecuch & Quinn, 2016). Here, we use an observation-driven and model-assessed ENSO correction derived by Hamlington, Piecuch, et al. (2020) to remove ENSO variability from the GMSL time series. The Pinatubo and ENSO-corrected GMSL variations are shown in Figure 1. The

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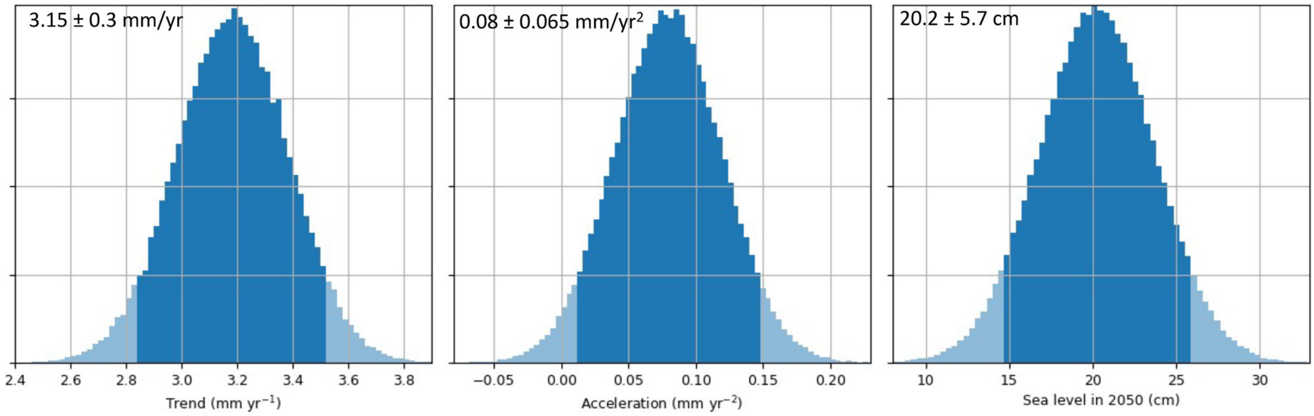

Figure 3. Histograms of (a) the trend estimate, (b) the acceleration estimate, and (c) extrapolated sea level rise in 2050 relative to the mean over 1993–2020 using the Monte Carlo method to assess the errors as discussed in the text.

correction for ENSO is directly related to the analysis done in Hamlington, Piecuch, et al. (2020). A regional pattern is generated using cyclostationary empirical orthogonal functions and then averaged globally to produce the GMSL correction. Uncertainty estimates are obtained through the model comparisons discussed in Hamlington, Piecuch, et al. (2020). A regression of ENSO and PDO climate indices on GMSL along the lines of Zhang and Church (2012) would produce similar results although without a clear way of assessing the uncertainty. The ENSO correction does not capture all the variability, especially during strong La Nina events, but it still reduces the error in the quadratic fit.

Figure 2 shows estimates of the acceleration versus the length of the data record after removing the Pinatubo and ENSO corrections. The acceleration has been stable at around ~0.08 mm/yr^2 since 2017. This suggests the impacts of interannual and decadal variability (not accounted for by our Pinatubo and ENSO corrections) are being sufficiently averaged in a 28 year time series for our purposes. After removing the Pinatubo and ENSO contributions, we obtain an average rate and acceleration of 3.3 mm/yr and 0.083 mm/yr^2 over 1993–2020. As discussed in Nerem et al. (2018), most of this acceleration is attributed to ice mass loss in Greenland and Antarctica.

3. Assessing the Errors in the Rate and Acceleration Estimates

There are a variety of errors that must be considered when evaluating the possible range of sea-level change in 2050. We consider uncertainties due to measurement errors, Glacial Isostatic Adjustment (GIA), and serial correlation. To account for all the different error sources, we generate a 100,000-member Monte-Carlo ensemble. For each ensemble member, we start with the GMSL curve from altimetry, and use all the error sources to perturb the GMSL curve. Next, we fit a quadratic to each ensemble member, and extrapolate this quadratic to 2050. Finally, we use the ensemble-mean and the 5th and 95th percentile as our projection mean and lower and upper bounds. The statistics of these calculations are shown in Figure 3.

First, there are the measurement errors in the altimetry. One approach is to compare altimeter-measured sea level to a set of global tide gauge sea level measurements and use the statistics of the differences to build an error model for altimeter-measured GMSL, as was done in Nerem et al. (2018). A second approach is to build an error model for the altimetry by modeling the errors in each of the potential error sources, which vary for each satellite mission (TOPEX, Jason-1, etc.). This is the approach implemented by Ablain et al. (2019) and tends to give a more conservative error estimate than the first approach. We use the second approach here, as described by Ablain et al. (2019), which includes uncertainties arising from high-frequency errors due to altimetry noise, geophysical corrections, orbit determination, wet troposphere corrections, gravity fields, inter-mission biases, large scale drifts due to reference frame uncertainties, and the instabilities in the TOPEX/Poseidon record. This approach gives an error in the measured acceleration (0.056 mm/yr^2 90% CI) about 36% higher than the first approach (0.041 mm/yr^2 90% CI). We assess the uncertainties of the quadratic fit to the altimeter record by taking both the measurement uncertainties and the autocorrelated residuals due to internal variability into account.

Table 1
Global Mean Sea Level Change in 2050.0 Relative to 2020.0 (cm)

	Extrap	SSP5-8.5	SSP2-4.5	SSP1-2.6	SROCC RCP 8.5	SROCC RCP 4.5	SROCC RCP 2.6
Low	11.3	14.1	11.0	10.2	13.5	10.8	9.5
Mid	16.4	18.2	15.5	14.0	18.3	14.7	13.4
High	21.4	27.9	24.4	22.9	23.4	18.9	17.4

Note. SSP projections are from Fox-Kemper et al. (2021) and SROCC projections are from Oppenheimer et al. (2019).

For the former, we use the estimates of Ablain et al. (2019) and Caron et al. (2018) for the GIA. For the latter we use Bos et al. (2013). We generate a 100,000 member ensemble of perturbed estimates of the GMSL curve. These perturbations are created by generating auto-correlated random noise with the noise parameters for each included process as described in Ablain et al. (2019). We consider all the measurement error sources mentioned in Ablain et al. (2019), except for the GIA term, for which we use a different approach, described below.

Glacial Isostatic Adjustment causes a net subsidence of the global sea floor. If not accounted for, this subsidence leads to an underestimation of the GMSL rate from altimetry (Gregory et al., 2019; Tamisiea, 2011). The magnitude of this effect can be deduced from GIA models by computing the modeled geocentric sea-level change (which is equal to the sum of the predicted relative sea-level change and vertical land motion) and averaging this change over the global oceans. To account for this effect on our GMSL estimates and its uncertainty we use the relative sea-level and vertical deformation trends from the ensemble of GIA models from Caron et al. (2018). We compute the GIA correction term by adding the relative sea-level and solid-earth deformation terms and averaging this sum over the altimetry domain. For each ensemble member, we use a random realization of a 5,000-member subset from the GIA ensemble.

Finally, we have to account for the serial correlation in the GMSL time series. The GMSL time series exhibits clear interannual and decadal variability, even after removing the impact of ENSO and Pinatubo. Due to this variability, the uncertainties in the estimated quadratic coefficients will be larger than when the variability can be approximated as a white noise process (e.g., Bos et al., 2014; Royston et al., 2018). To account for this uncertainty in the Monte-Carlo procedure, we estimate the noise parameters of the GMSL curve (after applying the corrections for ENSO and Pinatubo and removing a quadratic) under the assumption that the noise spectrum can be described by a Generalized Gauss-Markov process (Langbein, 2004). We then generate random noise using this spectrum and add that noise to the time series for each ensemble member. Both the estimation of the noise parameters and random noise generation has been performed with the Hector software (Bos et al., 2013).

4. Extrapolation of Observed GMSL Into the Future

Simple extrapolation of a quadratic model of past sea level change into the future assumes that the estimated rate and acceleration terms in the model are constant over the observation period and the period of the extrapolation. In a sense, we are extrapolating the trajectory of observed sea level change. Here, we extrapolate the rate and acceleration found from 28 years of altimeter data to 2050 and we use the estimated errors in these coefficients to establish a range for potential 2050 sea level rise (Figure 1 and Table 1). We do not extrapolate beyond 2050 because the uncertainty in the extrapolations increases and exceeds the likely ranges across the SSP scenarios used in the IPCC AR6.

Figure 4 shows the results of the extrapolation backwards in time prior to 1993 compared to the tide gauge GMSL record. Although the errors on the extrapolation are large, the differences with the tide gauge record have a standard deviation of only 5 mm. Since our quadratic model performs well for the period 1960–1993, it can reasonably be expected to perform similarly for the next 30 years.

The process-based argument for using a quadratic model is as follows. The concentration of GHGs is increasing exponentially in the atmosphere (but perhaps more recently quadratically). The radiative forcing increases as the logarithm of the GHG concentration, so the Earth's radiation imbalance increases linearly (Kramer et al., 2021; Raghuraman et al., 2021). The heat accumulation is approximately the integral of the radiative forcing, thus resulting in a quadratic. Therefore, the ocean heat content contributions to sea level change should roughly increase quadratically. A similar argument can be made for the contributions of mountain glaciers, because they are linearly dependent on surface temperature (Edwards et al., 2021). Greenland and Antarctica are more complex. Only SMB in Greenland has been related to a quadratic (Noël et al., 2021). Antarctic SMB is projected to increase linearly as a function of surface temperature (Lenaerts et al., 2016). Discharge from Antarctica and Greenland is harder to predict, but we feel it is a reasonable assumption that discharge will continue on its same trajectory over the next 30 years. So, while other representations could be used, we prefer the quadratic model. Beyond this,

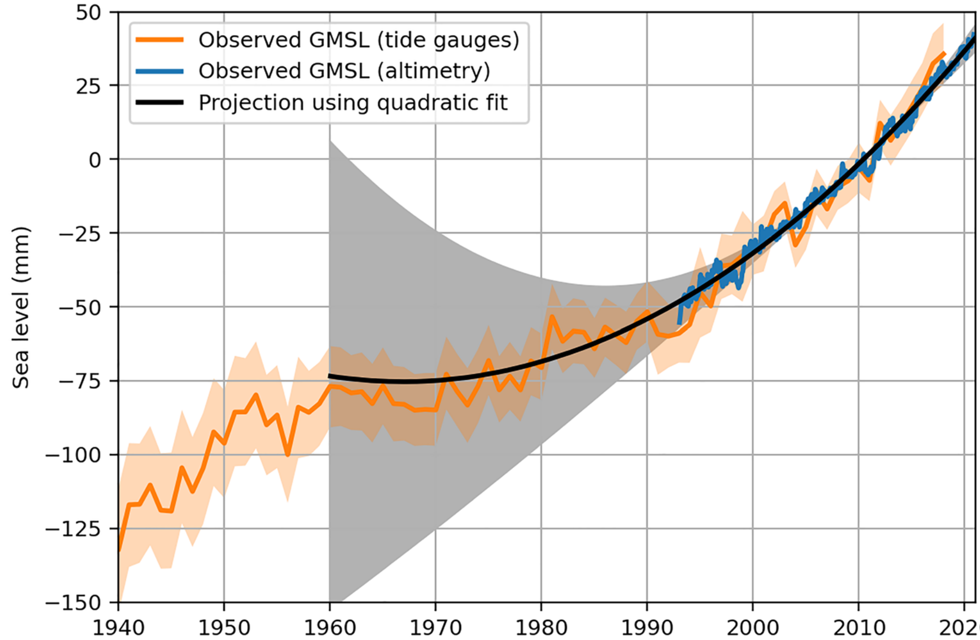

Figure 4. Extrapolation of the quadratic fit back in time prior to the altimeter era as compared to the tide gauge record of global mean sea level change (Frederikse et al., 2020).

the projections and associated pathways in the AR6 can be reasonably approximated by a quadratic model in the next 30 years. As an objective is to compare observation extrapolation to model-based projection, we also use this similarity as motivation for adopting a quadratic model. Lastly, the recent AR6 performed a similar altimeter-derived GMSL extrapolation out to 2100 using a quadratic model (although without any of the uncertainty analysis performed in the present study).

5. Comparison to Climate Model Projections

The extrapolation of the altimetry record we have done here can be directly compared to climate model projections used in the IPCC Assessments. Table 1 and Figure 5 shows these comparisons for the year 2050 relative to 2020. The range of the extrapolated model predictions is comparable to the climate model projections, suggesting that observationally based extrapolations have a role to play in understanding future sea level change. The extrapolation lies between RCP 4.5 and 8.5 for the SROCC projections and SSP2-RCP4.5 and SSP5-RCP8.5 for the AR6 projections, though statistically we cannot rule out any of the scenarios, similar to the results found by Wang

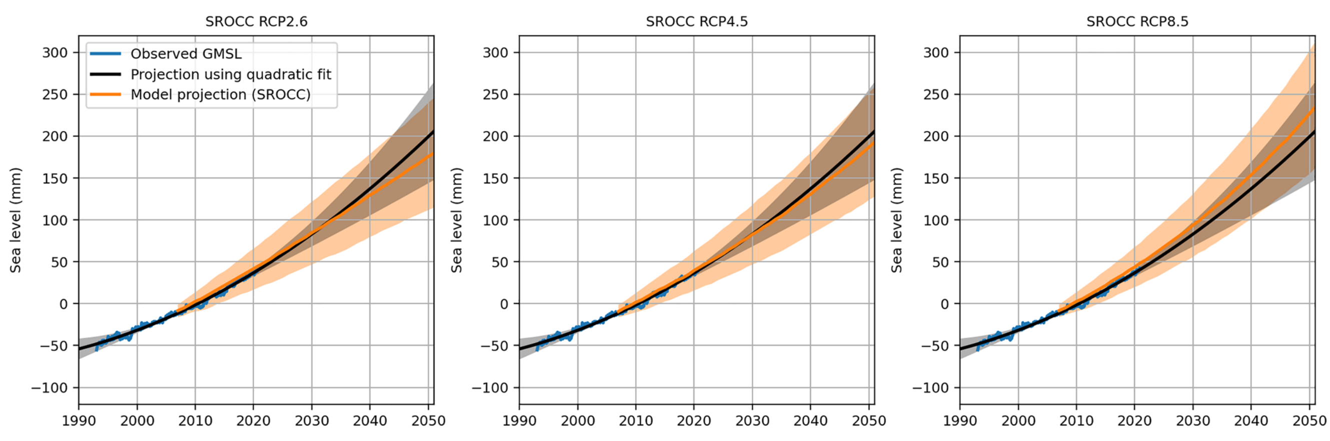

Figure 5. Comparison of the altimeter-derived global mean sea level extrapolation to the SROCC projections (Oppenheimer et al., 2019).

et al. (2021). Our extrapolation is lower than one presented in the IPCC AR6 (Fox-Kemper et al., 2021) largely because of the ENSO correction we have applied.

6. Discussion

We have constructed a quadratic model of climate-driven GMSL change from the satellite altimetry record and assessed the errors in this model. We then used this model to extrapolate forward 30 years to estimate GMSL change in 2050 relative to 2020, finding a central value of 16.4 cm with a 90% confidence interval of 11.3–21.4 cm. We found good agreement between these extrapolations and projections from climate models used by the IPCC assessments. In addition, we found reasonable agreement when extrapolating backward in time prior to the altimeter era and comparing to tide gauge estimates of GMSL over 1960–1993.

We chose not to extrapolate beyond 2050 in this work because the errors become large quickly and the assumption of stationarity in the model parameters (rate and acceleration) becomes more suspect. However, extrapolating to 2100 does still give reasonable agreement with the IPCC projections (which themselves closely follow a quadratic).

We believe the altimeter sea level record is now of sufficient length that short-term extrapolations over a few decades can be used as an additional tool when trying to assess ongoing and future GMSL change, in addition to the standard approaches based on climate models and semi-empirical methods. The next step will be to extend this type of method to regional sea level change when the observational record can support such work (Hamlington, Frederikse, et al., 2020).

Data Availability Statement

The software and data from this study can be downloaded at https://doi.org/10.5281/zenodo.6265943.

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