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COMMENTARY

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Evaluating IPCC Projections of Global Sea-Level Change From the Pre-Satellite Era

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Key Points:

- IPCC projections in the mid-1990s of global sea-level change over the next 30 years were remarkably robust
- The largest disparities between projections and observations were due to underestimated dynamic mass loss of ice sheets
- Comparison of past projections with subsequent observations gives confidence in future climate projections

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract With an acceleration of global sea-level rise during the satellite altimetry era (since 1993) firmly established, it is now appropriate to examine sea-level projections made around the onset of this time period. Here we show that the mid-range projection from the Second Assessment Report of the IPCC (1995/1996) was strikingly close to what transpired over the next 30 years, with the magnitude of sea-level rise underestimated by only ∼1 cm. Projections of contributions from individual components were more variable, with a notable underestimation of dynamic mass loss from ice sheets. Nevertheless—and in view of the comparatively limited process understanding, modeling capabilities, and computational resources available three decades ago—these early attempts should inspire confidence in presently available global sea-level projections. Such multidecadal evaluations of past climate projections, as presented here for sea-level change, offer useful tests of past climate forecasts, and highlight the essential importance of continued climate monitoring.

Plain Language Summary The ultimate test of climate projections occurs by means of subsequent observations. Three decades of satellite-based measurements of global sea-level change now enable such a comparison and show that early IPCC climate projections were remarkably accurate. Predictions of glacier mass loss and thermal expansion of seawater were comparatively successful, but the ice-sheet contributions were underestimated. Nevertheless, these findings provide confidence in model-based climate projections.

1. Main Text

Perhaps one of the most powerful ways to demonstrate the impact of human activity on Earth's climate is to evaluate—by means of subsequent observations—projections of future climate that were made decades ago (Hausfather et al., 2020). Within this context, sea-level projections are challenging because they depend on disparate elements of the climate system (e.g., thermal expansion of seawater and land-based ice loss), which are often modeled separately. Comparisons of sea-level records with Intergovernmental Panel on Climate Change (IPCC) projections have been made before, but the shortness of overlapping projection timelines and observational time series, which ended in 2006 or 2011 in previous assessments (Rahmstorf et al., 2007, 2012), has been a limitation. Similarly, more recent analyses of this nature focused on the time interval 2007–2018 only (Slangen et al., 2023; Wang et al., 2021).

The satellite altimetry record of global mean sea-level change, now more than 30 years long, has enabled recent progress by demonstrating a doubling of the rate of sea-level rise between 1993 and 2023 (Hamlington et al., 2024). The beginning of this record occurred during the time of the first IPCC assessment reports, which featured continuous sea-level projections until 2100. As a result, an excellent opportunity now exists to assess the validity of sea-level projections made three decades ago.

We examined the first two IPCC projections because, unlike all subsequent assessment reports, they were made entirely independently from the satellite altimetry record of sea-level change. The First Assessment Report (IPCC-FAR; Houghton et al., 1990) is based on emission scenarios that deviate substantially from what has been observed since 1990 and it was therefore not further considered. Here we focus specifically on Scenario IS92a from the 1995/1996 Second Assessment Report (IPCC-SAR; Warrick et al., 1996). This emission scenario projected globally averaged atmospheric CO_2 concentrations that match observations exceptionally well (427 vs. 423 ppmv in 2024; inset in Figure 1). Thus, not only was IS92a the most frequently used "middle of the road" scenario in IPCC-SAR, it has so far also largely materialized.

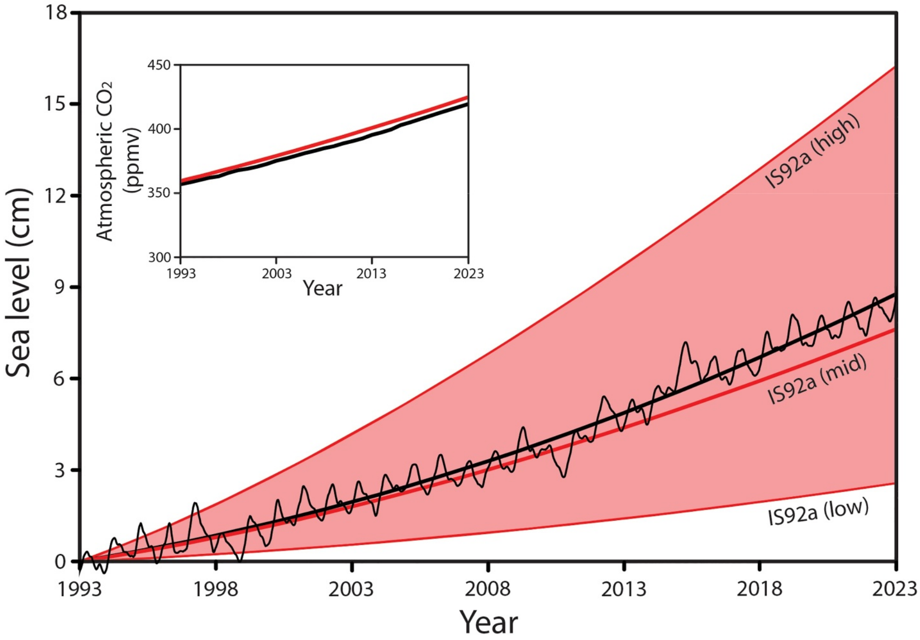

Figure 1. Global mean sea-level projections versus observations for the satellite altimetry era (1993–2023). Low, mid, and high projections (red, with associated equilibrium climate sensitivities of 1.5, 2.5, and 4.5°C, respectively) from Scenario IS92a in IPCC-SAR (including aerosol changes) (Warrick et al., 1996) compared to globally averaged sea-level measurements (thick black line is a quadratic fit through the high-resolution time series shown by the thin black line) based on satellite altimetry (without correction for glacial isostatic adjustment) (Hamlington et al., 2024). Projections have been normalized to zero in 1993 to place them on the same scale as the observations. Inset shows projected (Schimel et al., 1996) (red, 1992 budget) versus observed (black, data from Lan et al., 2025) globally averaged atmospheric CO_2 for the same time interval. Further details can be found in Supporting Information S1.

Scenario IS92a includes a low, mid, and high projection of sea level, defined primarily by equilibrium climate sensitivity (ECS; 1.5, 2.5, and 4.5°C, respectively). We consider all three in comparison with the 1993–2023 global sea-level record (Hamlington et al., 2024). As shown (Figure 1), the observed sea-level acceleration follows the mid (or "best estimate") of Scenario IS92a quite closely, although sea level has been rising slightly faster than projected (an underprediction of ∼1 cm by 2023). One potential explanation is the difference between the ECS in IPCC-SAR (2.5°C) compared to more recently proposed numbers. For example, a value of 3.4°C (2.4–4.5°C, 95% confidence interval) was inferred from a comprehensive examination of the Last Glacial Maximum (Tierney et al., 2020). Because ECS correlates with Earth's transient climate response (Meehl et al., 2020), we cannot rule out that the smaller ECS used in IPCC-SAR may have contributed to its underprediction of sea level. The key finding, however, is that while these early projections faced a host of limitations compared to what is presently achievable, they nevertheless did an impressive job. On the other hand, the fact that sea level has been rising slightly faster than projected motivates a closer examination of the main contributors to sea-level rise during this time interval.

Scenario IS92a included a breakdown between thermal expansion, glaciers/ice caps, Greenland, and Antarctica. Terrestrial water storage, while recognized, was at the time considered too uncertain and too small to be explicitly modeled (Warrick et al., 1996). Thermal expansion and glaciers/ice caps were expected to account for nearly all sea-level rise by 2023, with a negligible contribution from the large ice sheets (Antarctica was even projected to see a slight mass increase). Taking advantage of a recently published sea-level budget that extends to 2021 (Dangendorf et al., 2024), we assess the component processes modeled in IPCC-SAR (Figure 2). The steric component of sea level (thermal expansion) as well as the contribution from shrinking glaciers and ice caps were predicted well, although steric sea-level rise was slightly overestimated. On the other hand, terrestrial water storage and the contribution from the ice sheets were either neglected or projected to be negligible. In fact, sea-level equivalent mass losses from Greenland (10.8 ± 0.9 mm, 1992–2018) (The IMBIE Team, 2020) and Antarctica (7.6 ± 3.9 mm, 1992–2017) (The IMBIE team, 2018) represent ∼25% of the 6–7 cm of global sea-level

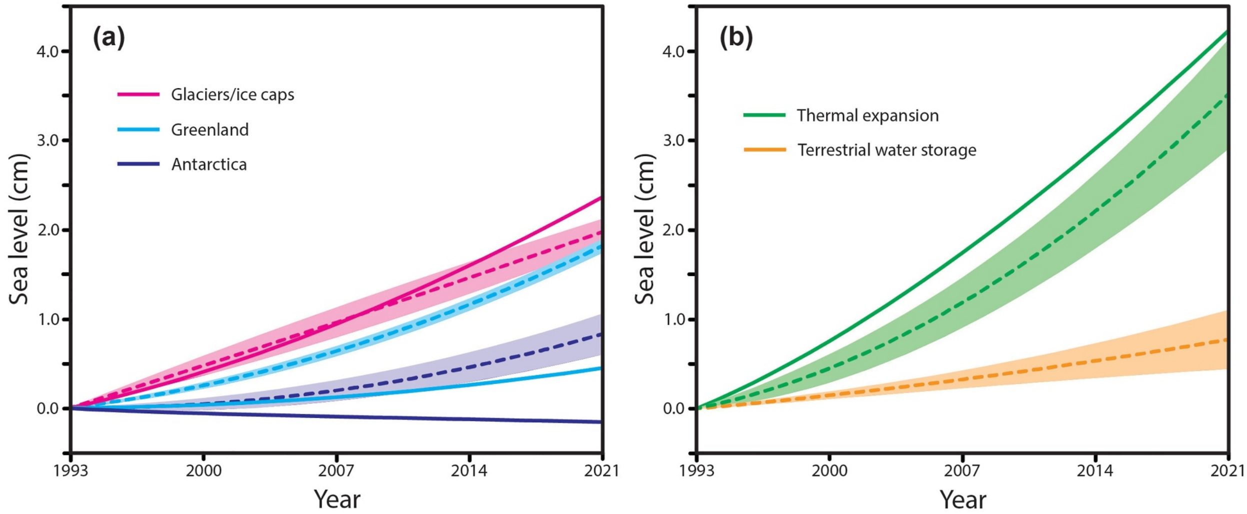

Figure 2. Projections versus observations of the contributors to global sea-level rise (1993–2021). (a) Land-based ice, (b) liquid water. Projections from IPCC-SAR (Warrick et al., 1996) (solid lines) compared to observations synthesized by Dangendorf et al. (2024) (dashed lines plus one sigma uncertainties). Note that IPCC-SAR did not project changes in terrestrial water storage. Further details can be found in Supporting Information S1.

rise seen during that time period. Likewise, the net transfer of groundwater to the ocean has proven to be a larger factor than previously believed (Wada et al., 2017).

An important reason for the underprediction is the fact that early IPCC reports treated ice sheets by means of mass balance models only; as stated in IPCC-SAR "the dynamic response can be ignored on the time-scale of decades to a century" (Warrick et al., 1996). This shortcoming persisted and came to the forefront in IPCC-AR4 (Meehl et al., 2007) where this component was largely excluded, resulting in the lowest sea-level projections among the full sequence of IPCC reports (Garner et al., 2018; Oppenheimer & Alley, 2016). A variety of recent studies have emphasized the important role of dynamic ice loss (i.e., ice flow), both in Greenland (e.g., King et al., 2020) and Antarctica (e.g., Diener et al., 2021). As a result, when dynamic ice-sheet change was explicitly included in IPCC-AR5 (Church et al., 2013), projected sea-level rise increased compared to IPCC-AR4. Subsequent reports have even acknowledged the "deep uncertainty" associated with ice sheet disintegration processes (Oppenheimer et al., 2019) and the potential for a "low-likelihood, high-impact storyline" with sea level rising much faster than projected (Fox-Kemper et al., 2021). The most recent assessment (IPCC-AR6) therefore included low-confidence projections reflecting processes like Antarctic marine ice-cliff instability. Because these scenarios begin to diverge away from their higher confidence counterparts within the next few decades, future evaluations of IPCC-AR6 projections could forewarn a high-impact sea level future.

As mentioned, thermal expansion was overestimated in IPCC-SAR, partly offsetting the low projections for ice-sheet contributions. As a result, one could argue that the relatively accurate net result was somewhat fortuitous. While this may be true, we would emphasize here that future studies should continue to examine projections of component processes of sea-level change (e.g., Felikson et al., 2025). We also recognize that meaningful sea-level projections are conditional on accurate atmospheric CO_2 projections, something IPCC-SAR did successfully and, going forward, needs to be accomplished again.

As was inferred previously (Rahmstorf et al., 2007, 2012), IPCC projections have tended to slightly underestimate the rate and magnitude of global sea-level rise. Evaluation of a time series that is now twice as long indicates that this finding remains intact. Our overarching conclusion is that the satellite-era record of global sea-level change lends credence to early sea-level projections based on modeling capabilities available three decades ago. These models possessed a level of skill on par with what has been shown with respect to temperature, dating back to the earliest model predictions from the 1970s (Hausfather et al., 2020). Despite its shortcomings regarding ice sheets and terrestrial water storage, IPCC-SAR deserves credit for the validity of its sea-level projections, not least in view of the stated caveat that "future projections are likely to be underestimated" (Warrick et al., 1996). Given the advances in both resolution and process understanding since the 1990s, the early success of the IPCC-SAR projection gives considerable confidence to climate projections for the future. Meanwhile, the importance of continued monitoring of all relevant components of the climate system by key agencies cannot be understated.

Data Availability Statement

This study contains no new data. The data used are available through Schimel et al. (1996), Warrick et al. (1996), Dangendorf et al. (2024), Hamlington et al. (2024), and the National Oceanic and Atmospheric Administration (https://gml.noaa.gov/ccgg/trends/gl_data.html).

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