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Investigating the Acceleration of Regional Sea Level Rise During the Satellite Altimeter Era

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Key Points:
- Internal variability is removed from the satellite altimeter record, and the impact on trends and accelerations is assessed
- For most locations, a significant acceleration or deceleration still has not emerged, despite removing some amount of internal variability
- Many of the large-amplitude signals have been removed, narrowing the range of accelerations that could be associated with a forced response

Supporting Information:
- Supporting Information S1

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Abstract The 25-year record of satellite altimeter-measured sea level has led to improvements in the understanding of sea level change on both regional and global scales. However, the extent to which the pattern of regional sea level rise measured by altimeters is representative of the forced sea level response remains an open question. Internal variability both contributes to regional sea level changes on short time scales and masks the pattern of forced trend and acceleration associated with anthropogenic global warming. Recent studies have demonstrated that the forced trend pattern of regional rise has begun to emerge, although there has been no assessment of a possible associated acceleration. Here, the regional acceleration pattern is estimated from the altimeter sea level record and assessed with regard to the influence of internal variability. While the dominant features in the acceleration pattern can be attributed to internal variability, there is an indication that the forced acceleration pattern may emerge as the record continues to lengthen.

1. Introduction

The separation of the long-term trend and acceleration in sea level rise from naturally occurring variability has been a frequently studied problem (Calafat & Chambers, 2013; Chen et al., 2017; Fasullo et al., 2016; Haigh et al., 2014; Hamlington et al., 2014; Jevrejeva et al., 2008; Merrifield, 2011; Nerem et al., 2018; Palanisamy et al., 2015). Identifying and estimating the trend and acceleration in sea level rise is required for the validation of model projections and would aid in planning efforts where an understanding of internal versus forced variability is important. Relatedly, discussion of an acceleration in sea level is often unclear, conflating short-term swings associated with internal variability with longer-lasting rate shifts that may be indicative of a response to anthropogenic forcing. Indeed, internal sea level variability on a wide range of time scales serves to obscure the underlying anthropogenic or forced change, either impacting the trend estimation directly or providing noise that increases the uncertainty (e.g., Calafat et al., 2013; Calafat & Chambers, 2013; Chambers et al., 2012; Dangendorf et al., 2014; Haigh et al., 2014; Hamlington et al., 2014; Han et al., 2017). This is particularly problematic in the case of determining if there is a long-term acceleration (note that we use the term acceleration to refer to both positive and negative values) in sea level rise from the sea level records that are currently available. Efforts have been made to quantify the length of record needed to extract an acceleration from the background noise (Calafat & Chambers, 2013; Haigh et al., 2014; Jordá, 2014). A central idea of such efforts is that a sufficiently long record (with the needed length varying from location to location) would lessen the impact of internal variability and allow for an improved estimate of the acceleration. These studies have focused on available tide gauge records that extend back to the start of the twentieth century and provide the long records needed to make such an assessment. The use of tide gauges to estimate long-term rates and accelerations, however, will always be limited due to their sparse spatial coverage, inconsistent sampling in time, and the fact that tide gauge measurements are impacted by the movement of the land upon which they sit and thus represent relative sea level.

Sea level measured by satellite altimeters provides fewer challenges given the near-global and continuous coverage, although with a significant drawback of still having a relatively short record extending back to only 1993. Studies in recent years have convincingly shown that the altimeter-measured trends are heavily influenced by internal variability (e.g., Bromirski et al., 2011; Hamlington et al., 2014; Hamlington et al.,

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2016; Han et al., 2017). While estimates of sea level acceleration based on tide gauge records clearly show that longer records are needed for the 25-year satellite altimeter period, few attempts have been made to assess these conclusions directly on the satellite altimeter data. Indications are that the record is reaching a sufficient length that the pattern of forced regional trends (Fasullo & Nerem, 2018) and a significant global acceleration may be emerging from the noise of internal variability. Furthermore, using a sea level reconstruction, Dangendorf et al. (2019) demonstrate that this global acceleration and associated geographic pattern may have persisted over the past several decades. Given these recent findings, it is important to examine the acceleration estimated directly from the altimeter record and determine whether an improved understanding of the regional acceleration of sea level rise may now be possible. In doing so, we also attempt to distinguish between short-term shifts in internal variability that lead to an apparent acceleration in regional sea level rise and a longer, underlying acceleration potentially linked to a forced response.

2. Removing Internal Variability From Altimeter Record

Haigh et al. (2014) showed that records longer than the altimetry record would be needed to estimate a significant acceleration associated with a forced response, albeit with the important caveat that properly accounting for internal variability could reduce this detection time. Here, we attempt to account for and remove some of this internally occurring variability to improve the interpretation of the regional acceleration pattern in the satellite altimeter record and examine the results in the light of recent studies. A number of methods have been applied to the satellite record of sea level to separate and remove internally occurring variability and gain a better understanding of the background trend (e.g., Royston et al., 2018; Zhang & Church, 2012). A detailed description on the approach used here for removing internal variability from the satellite altimeter record is given in the supporting information, but an overview is provided in this section. To remove sea level variability associated with internally occurring signals, a cyclostationary empirical orthogonal function (CSEOF; for more details the reader is referred to Kim et al., 2015) decomposition is performed on gridded satellite altimetry data from 1993 to mid-2018. CSEOFs have been used in recent years to explain and quantify internal variability in a wide range of climate records. CSEOF analysis is designed to capture the time-varying spatial patterns and longer-time scale fluctuations present in geophysical signals, relying on the quasiperiodic nature of well-known climate signals. The primary reason for its use here is the evaluation of the technique conducted in prior studies as applied to sea level records. It is noted that other techniques could lead to similar results (e.g., Royston et al., 2018) but are not applied here (as discussed in more detail below). After the trend and seasonal signal, the next two dominant global modes of variability are associated—in part—with decadal variability centered in the Pacific (referred to here as the decadal mode) and the biennial oscillation of El Nino–Southern Oscillation (ENSO) (referred to here as the biennial mode, but noting that this mode only represents a component of ENSO variability) [see Hamlington et al., 2019 for extended discussion of this designation]. The acceleration during the satellite altimeter time period (1993 to 2018) imparted by each of these modes is shown in Figure 1. The decadal mode is closely related to the Pacific Decadal Oscillation (PDO), although the variability contained in the mode is not restricted to the northeast Pacific. The associated acceleration pattern (Figure 1a) shows a dipole-like pattern in each of the Atlantic, Indian, and—particularly prominently—Pacific Oceans, with large positive accelerations in the western Atlantic, Indian, and Southern Oceans. The second mode (Figure 1b), on the other hand, shows smaller-magnitude accelerations outside of the Pacific Ocean. In the Pacific, there is a large area of positive acceleration centered in the Nino 3.4 region (equatorial Pacific) and separated from the coast.

A critical component of this approach is in evaluating the extent to which the variability removed is truly representative of internal variations. As with any modal decomposition, however, assessing whether the resulting modes are associated with internal variability and do not contain a portion of the forced secular trend is a challenge, particularly when the forced pattern may be unknown. To address this particular challenge, a model comparison is performed. Using a large ensemble model—the Community Earth System Model (Kay et al., 2015)—these two modes were compared to similar modes from an unforced control run and extracted from individual ensemble members containing both internal variability and forced trends (Hamlington et al., 2019). While these modes were shown to be both representative of internal variability, the extent to which they were separable from the forced response in a 25-year record was assessed. To do this, the modes obtained from each ensemble member were projected onto the altimeter data, and the

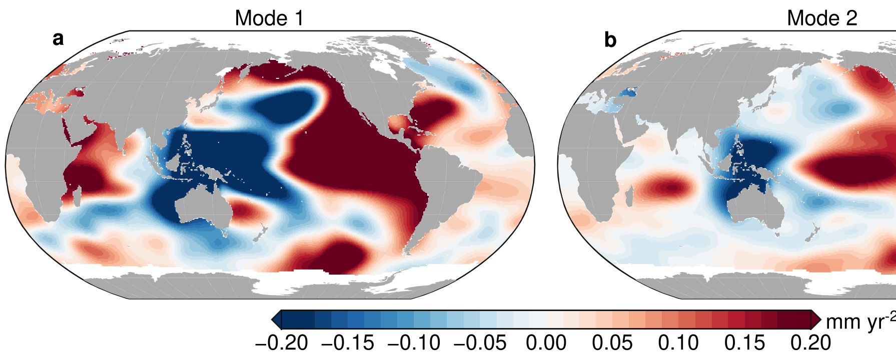

Figure 1. Regional accelerations associated with (a) the decadal CSEOF mode and (b) the biennial/interannual CSEOF mode estimated from 1993 to 2018.

uncertainty associated with the technique itself for removing internal variability was computed by estimating the acceleration spread that resulted at each location. Other approaches to the removal of internal variability typically hinge on the use of climate indices. Both Zhang and Church (2012) and Royston et al. (2018) rely on climate indices to remove variability associated with the PDO and ENSO in the Indo-Pacific. Our goal here, however, is to not rely on a climate index to remove the internal variability and instead to assess the extent to which we are able to represent and remove the internal variability. In other words, the CSEOF analysis takes advantage of the large-scale patterns associated with climate signals like ENSO and PDO and not just the temporal variations as represented by a climate index. Coupled with the ability to assess the acceleration uncertainty associated with the estimation technique itself, it is thus viewed as the preferred method for the removal of internal variability. We do note, however, that other techniques—including those referenced above—could serve a similar purpose of removing internally occurring modes of variability. Finally, the method for assessing the uncertainty on the trend and acceleration estimates given here follows Royston et al. (2018) and is detailed in the supporting information.

3. Contribution of Internal Variability to Trends

By correcting for internally occurring signals that impact sea level during the satellite altimeter record, a significant acceleration in global mean sea level from 1993 to 2017 was recently found at 0.084 ± 0.025 mm/yr^2 (Nerem et al., 2018). WCRP Global Sea Level Budget Group (2018) estimated a similar acceleration from a separate analysis of the altimetry data, while Frederikse et al. (2018) and Dangendorf et al. (2019) provided further support for this result using longer sea level reconstructions that incorporate tide gauge information. In addition, using a large ensemble model, Fasullo and Nerem (2018) demonstrated that the forced sea level trend pattern is emerging in the 25-year altimeter record. The estimated acceleration in global mean sea level is expected given the accelerating mass loss in Greenland and Antarctica measured by the Gravity Recovery and Climate Experiment satellites, over the past ~15 years (Chen et al., 2017). This acceleration in ice mass loss would also have an associated regional signature in sea level (Adhikari et al., 2016).

With the absence of an observational assessment of a regional sea level acceleration pattern and given the studies indicating the emergence of forced trends and accelerations, we compute the accelerations on a regional level from the altimeter data, investigate the causes of the returned pattern, and determine the extent to which signals are separable. Simply looking at the evolution of trend patterns during the altimeter record (Figures 2a and 2b) reveals that a large acceleration is implied in many locations. The regional trend pattern during the altimeter record has shifted dramatically from the first half (1993 through 2005) to the second half (2006 into 2018) (Figures 2a and 2b). In addition to a reversal of the trend pattern in the Pacific Ocean, the trends in the Indian Ocean and north Atlantic show large changes from the first period to the second. For the full record, this pattern is flattened out with greatly reduced spatial variability (Figure 3a). Other than an area in the eastern tropical Pacific, the majority of the trends are significant at the 95% confidence level. Although longer-term variability could still impact these 25-year trends, this result coupled with the analysis of Fasullo and Nerem (2018) supports the assertion that this trend may be representative of a forced response, at least in some areas.

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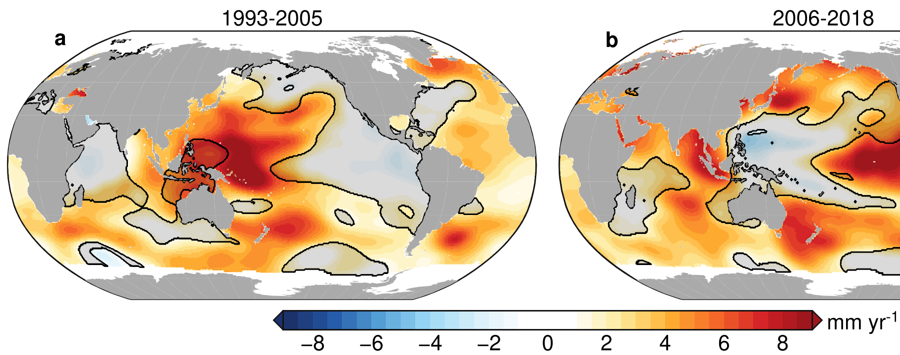

Figure 2. Satellite-measured regional rates of sea level change from (a) 1993–2005 and (b) 2006–2018. Areas shaded gray represent trends that are not significant at the 95% confidence level.

Recent studies have suggested that much of the trend reversal seen from the first half of the altimeter record to the second (e.g., Figures 2a and 2b) is explainable through internal variability (e.g., Hamlington et al., 2016; Han et al., 2017; Peyser et al., 2016), providing an initial indication of the extent to which internally occurring signals obscure a possible background acceleration in the altimeter record. To evaluate this, the variability associated with the decadal and biennial modes are removed, and the trend patterns over the first half, second half, and full satellite altimeter record are recomputed. The resulting trend patterns are compared to one another by computing spatial correlations, which are shown in supporting information Table S1. Before removing the variability described by the CSEOF modes, the correlation between the first half and second half spatial trend patterns is found to be −0.21, and the correlations with the trend pattern from the full record computed as 0.41 and 0.21, respectively. Once the internal variability is removed, the three trend patterns are in better agreement, with a correlation of 0.41 between the first and second halves and correlations of 0.61 and 0.71 with the full trend pattern, respectively. In other words, the variability described by the two modes considered here drives much of the difference seen between the trend patterns estimated from the first and second halves, and their removal returns a residual trend pattern computed over

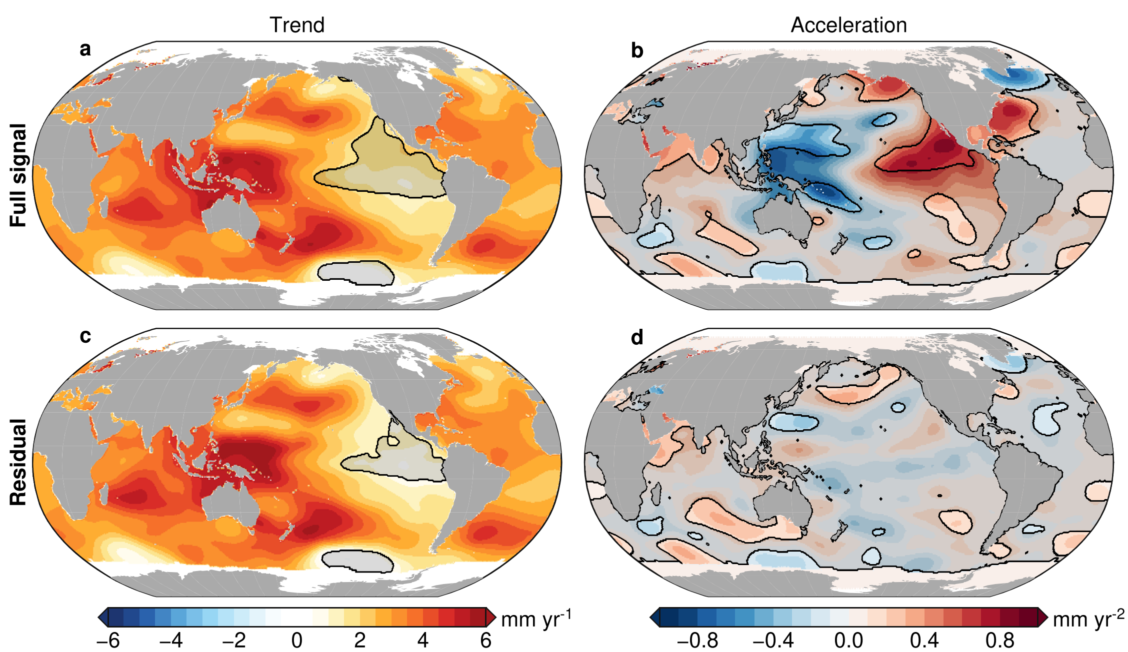

Figure 3. Regional rate (a) and acceleration (b) computed using the full satellite altimeter data, and rate (c) and acceleration (d) computed using the residual data after removal of two modes of internal variability. All estimates are computed over the time period from 1993 to 2018, and gray shaded areas represent estimates that are not significant at the 95% confidence interval.

the full length of the record that is much less impacted by interannual to decadal variability (Figures 3a vs. 3b). The effects of removing internal variability on the trend and acceleration are more fully described in the next section.

4. Influence of Removing Internal Variability on Trend and Acceleration Estimates

The regional patterns of trends and accelerations computed from the full gridded data set (minus the seasonal signal) are shown in Figures 3a and 3b. In the Pacific Ocean, there are large areas of strong, significant acceleration in the eastern Pacific extending into the northeastern Pacific and along the West Coast of the United States, before removal of the internal variability (Figure 3b). This pattern bears a strong resemblance to the expression of PDO in sea level and the first mode (Figure 1) (Cummins et al., 2005). During the altimeter record, indices tracking the PDO exhibit a phase shift from positive to negative before shifting again toward the positive phase in the last decade (Mantua & Hare, 2002). This temporal evolution imparts an acceleration pattern resembling the positive phase of the PDO. The change in trend pattern in the Pacific Ocean from the first half of the altimeter record to the second half of the record (Figure 2) is further evidence of this shift. Once the CSEOF modes associated with decadal and biennial modes are removed and the trend and acceleration are recomputed, this dipole acceleration pattern in the Pacific is dramatically reduced (Figures 3c and 3d). The large acceleration along the west coast of the Americas in Figure 3b is mainly explained by internal variability (e.g., PDO and ENSO), while the deceleration in the western tropical Pacific around the Philippines and Indonesia is entirely removed. Additionally, the large acceleration off the East Coast of the United States is reduced, as is the deceleration off the southern coast of Greenland (although areas of significant acceleration and deceleration remain). The impact of the mode removal on the Atlantic Ocean also underscores the fact that the variability is not distinguished by an index-based description but instead reflects a common time scale of variability across the globe. Lastly, the trend pattern (Figures 3a and 3c) is little changed with or without the influence of this internal variability, consistent with the correlation analysis results shown in Table S1 and indicative of a global sea level rise signal. While longer-term variability may still impact the satellite altimeter trend pattern, it is now reaching a length where interannual- to decadal-scale variability is having a reduced effect.

Although areas of moderate acceleration and deceleration are still present in Figure 3d, most of the strong signals in Figure 3b are dampened. There are two implications of this dampening: (Adhikari et al., 2016) for most locations across the globe, a significant acceleration or deceleration still has not emerged, despite removing some amount of internal variability; and (Austermann et al., 2017) many of the large-amplitude signals have been removed, narrowing the range of accelerations that could be associated with a forced response. This is similar to the argument of Fasullo and Nerem (2018), specifically that patterns associated with the forced regional response may emerge before the forced response evaluated on a location-by-location basis. To further assess this interpretation, the histograms of the accelerations in both cases (with and without the modes of internal variability) are generated. The narrowing spread of regional accelerations is evident (Figure 4). The mean of the distribution of the acceleration (note, not the area-weighted mean) when using the full altimeter data is found to be 0.10 mm/yr^2, while the mean value after removing the decadal and biennial modes is 0.086 mm/yr^2. Importantly, the standard deviation has a significant reduction (from 0.48 to 0.36 mm/yr^2), reflecting the possible beginning emergence of a more spatially consistent level of acceleration that is visible in Figure 3d and the removal of large accelerations associated with the shorter-term shifts of internal variability. The global mean acceleration can be computed by area-weighting the acceleration map in Figure 3d prior to averaging and is estimated to be 0.088 $\pm$ 0.027 mm/yr^2 (1-sigma), consistent with the acceleration from Nerem et al. (2018). For a more direct comparison to the previous study, the regional acceleration associated with the Mt. Pinatubo eruption has also been removed in Figure 3d and prior to the computation of the global mean acceleration. The uncertainty on this global mean estimate is given by the standard error of the mean, and the effective degrees of freedom are computed using the empirical orthogonal function-based technique outlined in Bretherton et al. (1999).

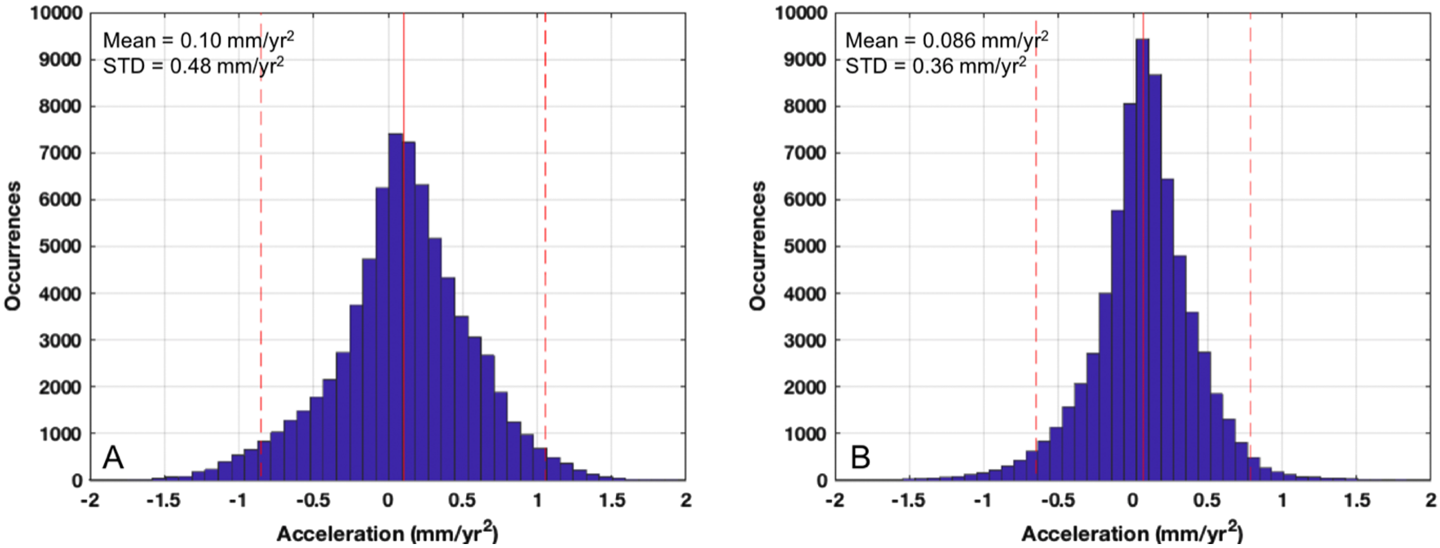

Figure 4. Histograms of regional accelerations for (a) full altimetry data and (b) altimetry data minus modes representing ENSO and the PDO. Solid red line represents the mean acceleration, while the dashed red lines represent 2-sigma departures from the mean.

5. Discussion

From a practical or planning perspective, both the long-term trend and the variability that occurs about this trend are important. While much of the focus here is on removing the influence of the internal variability to better estimate this underlying trend, the large short-term changes in sea level associated with internal variability can cause dramatic shifts in sea level (as seen in Figure 2) that can heighten the risk of coastal flooding from one year to the next (e.g., Sweet et al., 2018). Internally occurring climate variability can contribute to large short-term changes in sea level—both increases and decreases—and will continue to do so in the future. To provide a full assessment of possible future sea level change on a range of time scales, however, it is also important to quantify both the trend and the acceleration of sea level rise on regional levels.

As discussed in Fasullo and Nerem (2018), the pattern of forced trend response should be emerging from the short altimeter record, but there is still little information about the expected acceleration (expected because of accelerated ice mass loss) that accompanies this trend pattern. Here, we demonstrate that with the current length of the altimeter record, and accounting for and removing internal variability, the spatial variability of accelerations is, at least, reduced. Consistent with other studies, however, most locations do not display a significant acceleration, and many locations that do are likely still influenced by unaccounted for internal variability. While there is no currently published map of regional accelerations over the same time period that can be used for comparison of the results shown here, there are comparisons that can be made that provide a check on the present analysis (detailed computation details given in the supporting information). A forced pattern of acceleration is likely to arise from two main contributors: changes in ocean dynamics and gravitation, rotation, and deformation patterns associated with accelerated ice mass loss. The latter can be roughly approximated using spatial information from the Gravity Recovery and Climate Experiment satellites coupled with estimates of accelerations from the relevant cryospheric sources during the satellite altimeter period and provides a likely range of accelerations (Adhikari et al., 2016). It should be noted that these estimates are not free from accelerations associated with internal variability but do provide an expected order of magnitude. As seen in Figure S1a, this pattern is spatially flat for most of the ocean with little variation around a value of approximately 0.1 mm/yr^2, consistent with the mean of the distributions described here. The pattern associated with changes in ocean dynamics is harder to assess, but large ensemble models can be used to determine if the signal-to-noise characteristics obtained as part of this study are indeed reasonable. Here we use the large ensemble of the Community Earth System Model to compute the acceleration associated with the forced response from 1993 to 2018 (Figure S1b). We apply the same procedure described above to remove biennial and decadal variability, following the methods of Hamlington et al. (2019), and compute the acceleration for each of the individual ensemble members. While there is greater spatial variability when compared to Figure S1a, the accelerations are generally small with few locations exceeding a magnitude of 0.1 mm/yr^2. These two patterns are not directly combined but indicate that likely forced accelerations should be expected to be within $\pm$0.3 mm/yr^2, consistent with the narrowing range shown in Figure 3d. Finally, the lack of spatial variability in the pattern associated with ice mass loss makes detection of the pattern challenging in areas away from the melt source, but if it is beginning to emerge, we would expect reduced spatial variability and a convergence toward values around ~0.1 mm/yr^2 in areas with expected smaller dynamical accelerations (e.g., off the southwest coasts of South America and Africa).

In summary, although it could be rightfully argued that estimating and interpreting regional accelerations from a 25-year record that contains variability occurring at many different time scales is speculative, investigating the acceleration pattern in the altimeter record has potentially important implications for our understanding and views of ongoing sea level change. For example, there has been a notable shift in the trends measured by the altimeters in recent years, made clear by the trend patterns in Figure 2 but quantified by the acceleration pattern in Figure 3b. The perception of the significance of ongoing sea level rise can be influenced by these short-term changes and trends (e.g., internal signals suppressing sea level rise for an extended period in a particular location), but it is important to emphasize that such variability generally oscillates on top of a background trend and acceleration. Examining the acceleration in the altimeter record allows us to both highlight the influence of internal variability and assess the degree to which we can uncover the forced, underlying acceleration by attempting to remove it. As mentioned above, understanding the internal and forced components of sea level rise will be important going forward as both serve to narrow the gap between flooding and nonflooding conditions along the coast.

6. Competing Interests

The authors declare no competing interests.

7. Materials and Correspondence

All materials and correspondence requests can be directed to B. D. H. (at benjamin.d.hamlington@jpl.nasa.gov).

8. Data Availability Statement

Gridded Surface Height Anomalies Version 1801. Ver. 1801 available from NASA JPL PO.DAAC, CA, USA (at https://doi.org/10.5067/SLREF-CDRV1).

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