Earth's Future

RESEARCH ARTICLE

10.1029/2020EF001839

Past, Present, and Future Pacific Sea-Level Change

B. D. Hamlington[1], **T. Frederikse**[1], **P. R. Thompson**[2], **J. K. Willis**[1], **R. S. Nerem**[3], and **J. T. Fasullo**[3]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [2]Department of Oceanography, University of Hawaii at Manoa, Honolulu, HI, USA, [3]Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, CO, USA

Key Points:

- The western tropical Pacific and the northeastern Pacific off the west coast of the US have seen shifts in sea-level in the past decade
- Sea-level trends in these regions have evolved during the 26-year satellite-altimeter record, reflecting natural and forced contributions
- The altimetry record is still too short to rule out natural variability contributions to the 26-year trend on the order of 1 mm/yr

Supporting Information:

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

Correspondence to:

B. D. Hamlington,
bhamling@jpl.nasa.gov

Citation:

Hamlington, B. D., Frederikse, T., Thompson, P. R., Willis, J. K., Nerem, R. S., & Fasullo, J. T. (2021). Past, present, and future Pacific sea-level change. *Earth's Future*, *8*, e2020EF001839. https://doi.org/10.1029/2020EF001839

Received 5 OCT 2020
Accepted 17 DEC 2020

Author Contributions:

Conceptualization: B. D. Hamlington
Formal analysis: B. D. Hamlington, T. Frederikse
Methodology: B. D. Hamlington
Writing – original draft: B. D. Hamlington
Writing – review & editing: T. Frederikse, P. R. Thompson, J. K. Willis, R. S. Nerem, J. T. Fasullo

Abstract Satellite altimeters have provided near-global coverage of the ocean with a continuous record now approaching 3 decades. These observations have led to definitive evidence of an increase in global mean sea-level, while offering a depiction of the spatial variability in sea-level change. As a result of the increasing length of the altimeter record, studies have sought to understand and detect the emergence of a forced or anthropogenic response in sea-level. The central idea behind these studies is that the altimeter record is now long enough that the influence of interannual to decadal variability is reduced and does not obscure underlying regional trends in the way that it did for the early part of the altimeter record. Two locations—the western tropical Pacific and the northeastern Pacific off the west coast of the United States—are noteworthy for their sea-level variations during the altimeter era, exhibiting large departures from the global average albeit in opposite directions. In this study, we examine satellite altimeter-measured sea-level in these two regions. The goals are to understand the evolution of the sea-level trend, and determine what can be inferred about future sea-level change from the satellite altimeter record. We find that in the two locations considered here the altimetry record is still too short to rule out natural variability contributions to the trend on the order of 1 mm/yr. Using longer records from tide-gauge observations and models, an assessment of the potential future changes in both regions is made for both regions.

Plain Language Summary Satellite altimeters have provided near-global coverage of the ocean with a continuous record now approaching 3 decades in length. With this length of record, the influence of shorter-term variability is reduced and it is possible a trend associated with anthropogenic forcing may emerge. Two locations—the western tropical Pacific and the northeastern Pacific off the west coast of the United States—are particularly noteworthy for their sea-level variations during the altimeter era, exhibiting large departures from the global average albeit in opposite directions. Here, we find that the altimeter-measured trends in these two regions are still impacted by natural variability, while also finding that the anthropogenic-related sea-level signal will likely emerge in coming years.

1. Introduction

Since 1993, satellite altimeters have provided continuous measurements of sea-level with near-global coverage. These measurements have led to the first precise estimates of global mean sea-level (GMSL) rise and acceleration (WCRP Global Sea Level Budget Group., 2018; Nerem et al., 2018). Satellite altimeter measurements have also provided a clear indication of the regional variability of sea-level rise across the ocean (B. D. Hamlington et al., 2020; Stammer et al., 2013). The spatial pattern of trends (used here to refer to the linear rate) and changes this pattern has undergone during the altimeter record offer valuable clues into the relative roles of natural variability versus sea-level changes associated with anthropogenic climate change and the timescales over which these contributions vary (e.g., B. D. Hamlington et al., 2014, 2016; Meyssignac et al., 2012; Palinisamy et al., 2015; Zhang & Church, 2012). Recent studies have demonstrated that the altimeter record is sufficiently long for the anthropogenic—or forced, as used here—sea-level trend pattern to emerge from natural variations, although there are still questions about the global extent of this emergence (Fasullo & Nerem, 2018; B. D. Hamlington et al., 2019; Richter et al., 2020). For much of the altimeter record, the regional pattern of trends has been heavily impacted by the presence of natural climate variability. The most prominent feature has been a zonal "seesaw" signature in the Pacific Ocean (e.g., Bromirski et al., 2011; Merrifield 2011; Merrifield & Maltrud, 2011, Merrifield, Thompson, & Lander, 2012; Meyssignac et al., 2012; Moon et al., 2015;

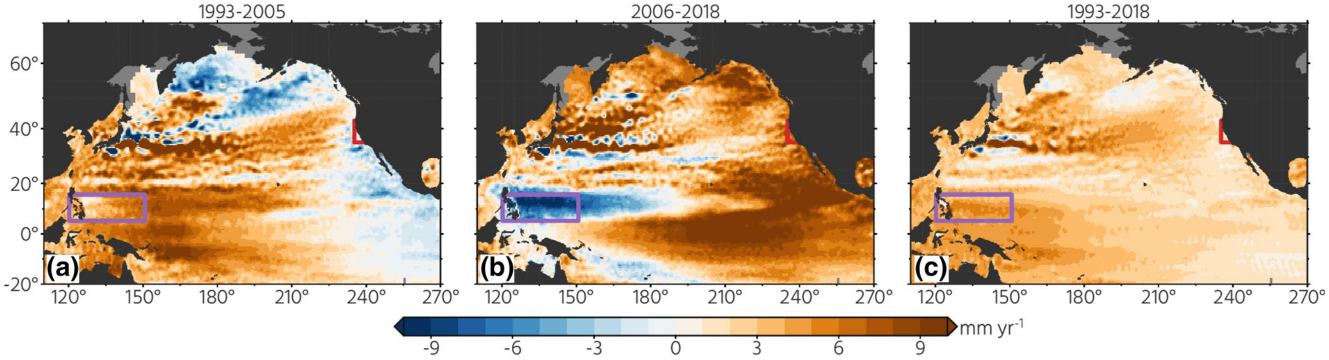

Figure 1. Regional linear trends in sea level as measured by satellite altimetry from (a) 1993 to 2005, (b) 2006–2018, and (c) 1993–2018. The red box shows the region denoted as US West Coast and the purple box shows the western tropical Pacific.

Peyser et al., 2016; Piecuch et al., 2019; Thompson et al., 2014), with higher than average sea-level rise in the western tropical Pacific, and lower than average sea-level rise in the eastern tropical and northeastern Pacific. This dipole pattern has been driven on shorter timescales by interannual variability associated with the El Nino-Southern Oscillation (ENSO, Becker et al., 2012; Moon et al., 2015; Zhang & Church, 2012), and on longer timescales by the substantial decadal variability in the Pacific Ocean (Bromirski et al., 2011; B. D. Hamlington et al., 2014, 2016; Merrifield & Maltrud, 2011; Merrifield, Thompson, & Lander, 2012; Meyssignac et al., 2012; Moon et al., 2015; Piecuch et al., 2019). This variability has been connected in some studies to the Pacific decadal oscillation (PDO, Mantua et al., 2002), although we note that this connection is primarily made through comparisons to a statistically defined index, which we leverage in the analysis to follow.

By separating the altimeter record into a first- (1993–2005) and second-half (2006–2018) and computing the regional linear trend pattern over each time period, a dramatic shift becomes apparent across the Pacific Ocean during the altimeter era (e.g., B. D. Hamlington et al., 2019). To motivate the study that follows and emphasize the role of interannual to decadal variability during the altimeter record, Figure 1a shows the trends computed during the first half of the altimeter record, with high rates of rise (~1 cm/yr) in the western tropical Pacific and negative trends in the eastern basin. During the second half of the altimeter record, this pattern reverses with elevated rates in the eastern tropical Pacific and along the western coasts of North and South America (Figure 1b). Over the full record, the magnitudes of the observed trends are reduced, though there are still regional variations that reflect a persistent east-west dipole pattern (Figure 1c). In particular, trends in the eastern Pacific are still below the global mean and trends in the western tropical Pacific are still elevated relative to the global mean.

The shifting trends in the region and the processes driving them have been heavily studied in recent years, and predominantly internal variability appears to drive these shifts (e.g., B. D. Hamlington et al., 2014, 2016, 2019; Merrifield, 2011; Moon et al., 2015; Peyser et al., 2016; Piecuch et al., 2019; Royston et al., 2018; Zhang & Church, 2012). The motivation for such studies extends beyond scientific curiosity; distinguishing between internal and low-frequency forced contributions to sea-level can be critical from an impact and planning perspective. Many of the low-lying areas in the western tropical Pacific have seen an increase in flooding during the satellite altimeter record (Nicholls et al., 2011). On the other hand, suppressed trends along the west coast of North America could lead to complacency in planning or the impression that future sea-level rise will be similarly suppressed despite evidence for an ongoing increase in sea-level (Bromirski et al., 2011; B. D. Hamlington et al., 2016; Piecuch et al., 2019). Understanding the extent to which the observed trends may persist into the future is critical for determining potential future impacts. Additionally, the interannual to decadal variability can lead to extended periods of elevated flood risk irrespective of the background trends, making an understanding of the processes driving this variability and associated magnitude important for making informed decisions going forward.

In this paper, we focus on two particular areas—the West Coast of the United States and the western tropical Pacific (see Figure 1)—and analyze past, present and future sea-level change using both observations and model-based estimates of sea-level. While these are two relatively small regions in the Pacific Ocean, we have chosen these areas as they are representative of the large spatial variability in the altimeter record (i.e., large departures from the global mean), have significant trend departures from the global mean, and are of high societal relevance. The specific areas were also chosen to capture long tide gauge records in the respective regions, as one of our goals is to provide context for the altimeter record. In particular, we seek to provide insight into the following questions, building off of previous studies in doing so:

1. To what extent will the sea-level trends estimated from the 26-year altimeter record vary as the record gets longer, and are these trends associated with a forced sea-level response?
2. How long will the positive rate of sea-level rise along the US West Coast and the negative rate in the western tropical Pacific observed over the last decade of the altimeter rate continue into the future?
3. Should we expect sea-level in the future to rise at different rates over the next century in the two regions considered here?

To provide answers to these questions, our approach is to first compute the degree to which trends in the two regions have varied since 1993 using the satellite altimeter record directly. Then, using other sources of data, we seek to determine the underlying processes contributing to the satellite altimeter-era trends. Next, we establish context for the trends observed during the satellite altimeter record using available tide gauge data and modeled sea-level. Finally, we use model projections of sea-level change to provide an indication of whether sea-level change in the two regions will continue to differ in the future and over what timescales. The overarching goal is to understand past, present and future sea-level variability in these two regions by relying on simple statistical analyses of available data, which should be informative and useful to both scientists and planners. By conducting an observation-focused investigation, this work also complements the studies conducted on the topic over the past decade and provides an update to the conclusions made therein.

2. Data

2.1. Satellite Altimetry

For the satellite altimeter record, we use the Jet Propulsion Laboratory MEaSUREs gridded sea surface height anomaly (SSHA) data set that is, part of the Integrated MultiMission Ocean Altimeter Data for Climate Research (Zlotnicki et al., 2019). These are gridded sea surface height anomalies (SSHA) measured by satellite altimeters over the time period from January 1993 through December 2018. While the satellite altimetry data used here is mapped onto a 1/6th degree grid every 5 days, the temporal resolution is reduced to monthly to ease computation time.

2.2. Tide Gauge Data

Monthly tide gauge records were retrieved from the Permanent Service for Mean Sea Level (Holgate et al., 2013). Only gauges that were in the two regions of interest—US West Coast and western tropical Pacific—and with records more than 80% complete during the time period from 1950 to 2019 were used. This led to eight gauges in the US West Coast and four gauges in the western tropical Pacific (information for these gauges in Table S1). Since these gauges measured relative sea-level and the goal of this study is to provide context to the satellite altimeter record, the impact of vertical land motion had to be removed from the records prior to use. Rather than correct directly for vertical land motion, we instead remove the rate and acceleration estimated from 1950 to 2019 using a second-order polynomial fit from the tide gauge records prior to use. Although this removes the background rate that may be associated with a forced response, it allows us to analyze the role of shorter-term variability in driving decadal trends and impact of this variability on the long-term trend (which is set to be zero in this case), while removing uncertainty associated with using an inadequate vertical land motion correction. Once the rate and acceleration were removed, the records for each gauge in the US West Coast and western tropical Pacific were averaged together to generate a single time series for each region.

2.3. Sterodynamic Sea-Level

Sterodynamic sea-level encompasses both global-mean steric changes and regional changes associated with ocean dynamics (see Gregory et al., 2019) for extended definition. To estimate coastal sterodynamic effects, we use the ECCO state estimate Version 4 Release 4 (Forget et al., 2015, Fukumori et al. 2020). ECCO is an ocean state estimate, which combines an ocean model with a wide range of observations to compute a physically consistent best estimate of the state of the ocean, and provides sea-level changes on an approximately 1-degree resolution grid. We use the dynamic sea surface height, which is the sea-surface height corrected for the inverse barometer effect. To include the global-mean thermosteric sea-level changes, we first removed the global-mean evolution of dynamic sea surface height, and replaced it with the global thermosteric changes as estimated by Cheng et al. (2017).

2.4. Ocean Mass Change

Exchange of water mass between land and ocean, such as melting of glaciers and ice sheets or changes to the hydrological cycle, results in sea-level changes that vary from place to place. Loss of terrestrial water mass to the ocean influences regional sea-level via the Earth's gravitational, rotational, and deformational (GRD) responses to mass redistribution, which dictate the spatial distribution of water across the global ocean (Farrell & Clark, 1976; Milne & Mitrovica, 1998; Mitrovica et al., 2001). Computing the GRD effects from global ocean mass redistribution requires two steps: quantification of the mass redistribution and computing the resulting GRD patterns. We quantify the mass redistribution over 1993–2018 by combining in situ estimates from 1993 to 2003 with GRACE and GRACE Follow-On observations over 2003–present. We use the in situ mass redistribution estimate from Frederikse et al. (2020), which incorporates the effects from ice sheets, glaciers, and land hydrology from groundwater depletion, dam retention, and natural variability from 1993 to 2003. For 2003–2018, we use the JPL RL06 GRACE mascon solution (Watkins et al., 2015; Wiese et al., 2016), corrected for glacial isostatic adjustment (GIA) using the estimates from Caron et al. (2018), as described in Frederikse et al. (2020). From the aggregate mass redistribution estimates, we compute the GRD effects following Frederikse et al. (2019). Both the in situ and GRACE mass estimates come with an estimate of the uncertainties, based on the individual in situ mass estimate uncertainties and the uncertainties in GRACE processing and GIA, which we propagate into GRD uncertainties. See Frederikse et al. (2019, 2020) for more details of the computation of these uncertainties.

2.5. Earth System Models

We use the Coupled Model Intercomparison Project Phase 6 (CMIP6) model ensemble to compute the historical and projected sea-level changes due to changes in global steric sea-level and local ocean dynamics (sterodynamic sea-level). The CMIP6 models we have included are listed in Table S2. From each model, we combine the historical run with four Shared Socio-economic Pathway (SSP) scenarios, sorted from low-end to high-end greenhouse gas forcing: SSP1 2.6, SSP2 4.5, SSP3 7.0, and SSP4 8.5. We add the global-mean thermosteric sea-level rise (variable "zostoga") to spatial ocean dynamic sea-level variability fields (variable "zos") to obtain local sterodynamic sea-level changes. We have removed model drifts in both "zos" and "zostoga" from the combined historic and scenario runs by removing the linear trend inferred from the preindustrial control ("piControl") run. We then extract global-mean thermosteric sea-level change and the sterodynamic sea-level changes over the western tropical Pacific and the US West Coast. We use the model mean and intermodel standard deviation to obtain the mean and uncertainties of the annual-mean projected sea-level changes. We also processed the natural-only historical runs for some of the models. These runs are the same as the historical runs, except for that no anthropogenic forcing is applied to the runs. Note that all these projections only describe the evolution of sterodynamic sea-level. Other large contributors to projected sea-level changes, such as mass loss from glaciers and ice sheets are not included.

3. Results

In the investigation into the observed sea-level trends and variability for the US West Coast and western tropical Pacific, we focus on two metrics: (1) variability in 10-year trends and (2) the evolution of the full-record trend as the record lengthens over time. The first metric allows us to assess the degree to which trends can vary on decadal timescales leading to extended periods of elevated or depressed rates of sea-level rise. In other words, changes in 10-year trends are largely reflective of shifts in natural forcing and variability as such short-term reversals are unlikely to be driven by the long-term, steadily increasing human-driven forcing of the climate. The second metric provides a basic measurement of the relative influence of natural variability on the trend as the record lengthens. By comparing this metric computed for the altimeter record to the metric computed from other longer records provided by tide gauges or models, a determination can be made of the potential emergence of a background, long-term forced increase in sea-level as the record lengthens and the relative influence of interannual to decadal variability should decrease. As an example, the rate of sea-level rise off the US West Coast from 1993 to 2019 is still lower than the global mean despite the high rates seen during the second half of the altimeter record. The evolution of the trend provides an indication of whether the trend is stabilizing and now representative of a forced rate of rise, or if further changes in this rate are likely to occur as the altimeter record continues. We do note that the forced response in sea-level is not fully represented by a trend, and the linear trends discussed here should be viewed as smoothed representations of the forced response. All linear trends were estimated over different time periods using least squares. Also, to adequately account for serial correlation of the residuals in the trend estimates, we follow the procedure from Haigh et al. (2014) and reduce the degrees of freedom to compute the uncertainty associated with the trend estimates (see supplementary material for more information). We have elected not to show uncertainties on the 10-year trends as the main driver of the uncertainty is the interannual to decadal variability we are interested in. In other words, it is assumed these trends are heavily influenced by shorter-term variability and are subsequently not interpreted as representative of a long-term trend.

Taken together, these two metrics allow us to infer how sea-level variability occurring on different timescales is evolving and represented in records of differing lengths. We separate our results into three different time periods: (1) the satellite altimetry era: 1993–present, (2) the prealtimetry era: 1850–present, and (3) the future: present–2100.

3.1. Satellite Altimetry Era: 1993–Present

During the satellite altimeter era, both the US West Coast and western tropical Pacific have seen decadal variability and significant departures from the decadal trends in GMSL (Figure 2a; for clarity, the first data point shown represents the trend from 1993 to 2002). For the first half of the altimeter record, the 10-year trends off the US West Coast were lower than the global mean, with extended periods of decreasing sea-level. Conversely, the western tropical Pacific experienced substantially elevated rates toward the end of the first half of the record, exceeding 2 cm/yr for the 10-year period centered in 2007. In the second half of the record, however, a dramatic shift occurred, illustrated in part by the trend patterns in Figure 1. For the 10-year period centered in 2010, the decadal trends in US West Coast, western tropical Pacific, and GMSL were approximately equal, but were then followed by elevated rates in the US West Coast (∼1 cm/yr) and depressed rates in the western tropical Pacific (~ -1.5 cm/yr). As these rates have continued for the most recent 10-year period centered on 2014, we can evaluate the impact they have had on the full-record trends estimated during the altimeter era (Figure 2b; for clarity, the first data point represents the trend from 1993 to 2005). Starting in 2005 when the 10-year rates were diverging for the US West Coast and western tropical Pacific, the full-record trends estimated since the starting point in 1993 have evolved in very different ways. The trend off the US West Coast has steadily increased since 2006, with the largest increase between 2014 and 2016, likely associated with the 2015/2016 El Nino event. Since 2016, the US West Coast rate has been relatively stable at −1 mm/yr lower than the rate in GMSL. On the other hand, the trend in the western tropical Pacific has been consistently higher than the rate in GMSL since 2006. As the record has approached 26 years, however, the full-record trend in the western tropical Pacific has decreased significantly with the trend from 1993 to 2019 only 1.5 mm/yr higher than the trend in GMSL.

The shifts in the 10-year trends in Figure 2a highlights the substantial influence of interannual to decadal variability on sea-level in the western tropical Pacific and US West Coast. Additionally, the evolution of the full-record trend in Figure 2b demonstrates that this variability still has an impact on the trends estimated with the 26-year altimeter record. To provide a better assessment of how sea-level may change in the coming decades in these regions, it is necessary to understand the processes driving these changes. Satellite

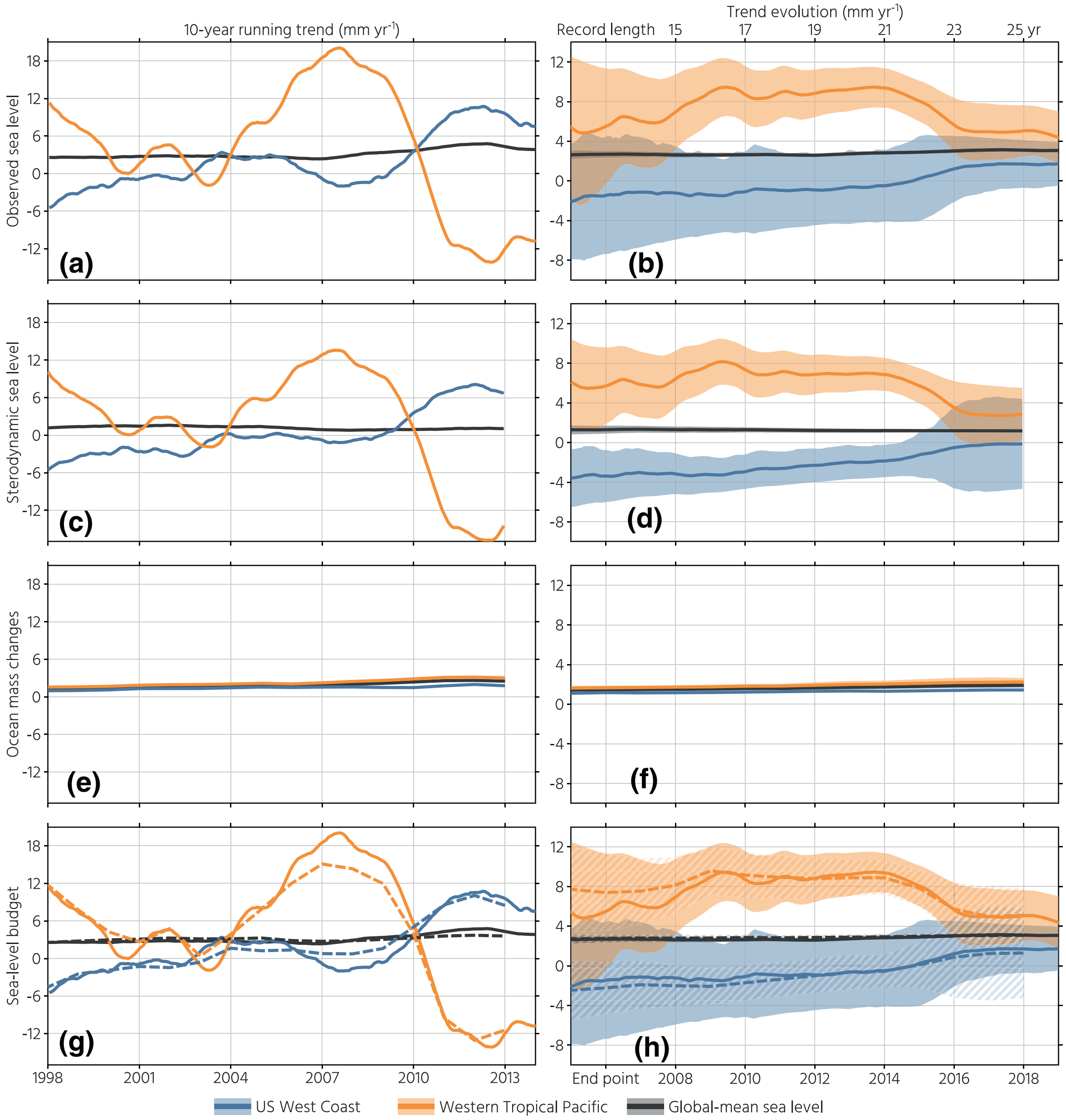

Figure 2. For the time period from 1993 to 2019, 10-year trends and trend evolution for total sea level from (a and b) satellite altimetry, (c and d) sterodynamic sea level, and (e and f) ocean mass change. The sum of the sterodynamic and ocean mass change (dashed lines) is also compared to (g and h) total sea level (solid lines). Shading indicates 95% confidence interval for trend estimates.

altimeters provide measurements of total sea-level change which includes the contributions of sterodynamic and ocean mass change-induced sea-level variability. Sterodynamic sea-level encompasses both global-mean steric changes and regional patterns associated with ocean dynamics (Gregory et al., 2019). The sea-level variability due to ocean mass change comes from the redistribution of water from GRD changes associated with the transport of water between land and ocean (Gregory et al., 2019). This transport is associated with melting of land ice and changes in terrestrial water storage. Using a combination of in situ, satellite and model data, we can separately quantify the sterodynamic and ocean mass change contributions to the trends observed during the satellite altimeter era. As seen in Figures 2c and 2d, the variability in the 10-year trends and the evolution of the full-record trend seen in both the western tropical Pacific and US West Coast in total sea-level (Figures 2a and 2b) arises predominantly from the sterodynamic variability. The ocean mass change contributions to the sea-level trends in both regions increase throughout the altimeter record (Figures 2e and 2f), consistent with the accelerating ice mass loss over the same time period (e.g., B. D. Hamlington et al., 2020). The sea-level contribution from ocean mass change is higher in the western tropical Pacific than the US West Coast, again consistent with the expectation from the GRD response to ice mass loss during the altimeter era (e.g., Adhikari et al., 2016; B. D. Hamlington et al., 2020), but much lower in magnitude compared to the contribution from sterodynamic variability. We also find that the combined trend contributions from sterodynamic variability and ocean mass change explain the observed changes from the satellite altimetry (Figure 2g and 2h), which has been shown for GMSL (Cazenave et al., 2018) but not for the specific regions of the western tropical Pacific and US West Coast.

Based on this analysis, there are two intermediate conclusions to draw: (1) the interannual to decadal variability in the western tropical Pacific and US West Coast is associated with sterodynamic variability and (2) the lower rates over the full altimeter record in the US West Coast compared to the western tropical Pacific are driven primarily by sterodynamic variability although with an additional contribution from the redistribution of mass in the ocean (Figures 2c and 2e). The analysis completed thus far, however, does not inform us about the relative contributions of natural and forced sea-level variability, which impacts our ability to extend the conclusions above to make a statement about future sea-level in these two regions. In other words, it is possible that the lower rate in the US West Coast results from the influence of ongoing natural variability and is not representative of the forced sea-level change that will persist into the future.

To estimate and then separate the natural variability in the Pacific Ocean, we rely on the method of Zhang and Church (2012) and Royston et al. (2018) that used two climate indices derived from the Mutlivariate ENSO Index (Wolter & Timlin, 2011) and PDO Index (Mantua et al., 2002). The first is representative of the interannual variability of ENSO and is obtained by high-pass filtering the MEI. The other is representative of variability occurring on decadal timescales in the Pacific Ocean and is obtained by low-pass filtering the PDO index. By regressing these two indices onto the satellite altimetry, we can provide an indication of the influence of this interannual to decadal variability and estimate the underlying trends once it is removed. There are other methods for estimating the contribution from large-scale climate variability (e.g., B. D. Hamlington et al., 2019), but we rely on the regression of climate indices due to ease of understanding. Our goal is simply to provide an approximation of the potential contribution of large-scale climate variability during the record. There are also other drivers of decadal variability within the altimeter record (e.g., Fasullo et al., 2016) that are not separately accounted for, although these signals could be aliased into the contribution obtained from the regression analysis here.

The 10-year trends associated with the regression of these two indices are shown in Figure 3a and the influence of this variability on the full-record trends is shown in Figure 3b. The majority of the variability in both metrics seen in total sea-level (Figures 2a and 2b) and sterodynamic sea-level (Figures 2c and 2d) is explainable by ENSO and decadal variability in the Pacific. This is further emphasized once the estimated large-scale climate variability contribution is removed from the satellite altimeter data (Figures 3c and 3d). The variability in the 10-year trends is significantly reduced in both the US West Coast and western tropical Pacific. The evolution of the full-record trends during the altimeter record is also now similar for both regions, with an increasing trend estimated as the altimeter record lengthens. This increase in the trend is consistent with—although larger in magnitude—the increasing trend associated with ocean mass change (Figure 2f). Finally, the difference between the trends in western tropical Pacific and US West Coast is reduced once the natural variability is removed, suggesting that ENSO and decadal variability are still playing a role in the spatial trend pattern observed in the 26-year altimeter record.

3.2. Prealtimetry Era: 1850–Present

From the analysis conducted above, it is clear that there is substantial decadal variability in the altimeter record and this decadal variability has heavily impacted sea-level in recent years. The high rates of sea-level rise in the northeastern Pacific in the last decade have led to an increase in the full-record trend off the US West Coast, while the negative rates in the western tropical Pacific have served to decrease full-record trends. The altimeter record alone, however, cannot tell us whether we should expect further changes and of what magnitude in the future as the record continues to lengthen. To provide context for the satellite altimeter record, we can first use available in situ observations from tide gauges on the US West Coast (eight total gauges) and in western tropical Pacific (four total gauges) (see Table S1 for details). Although some

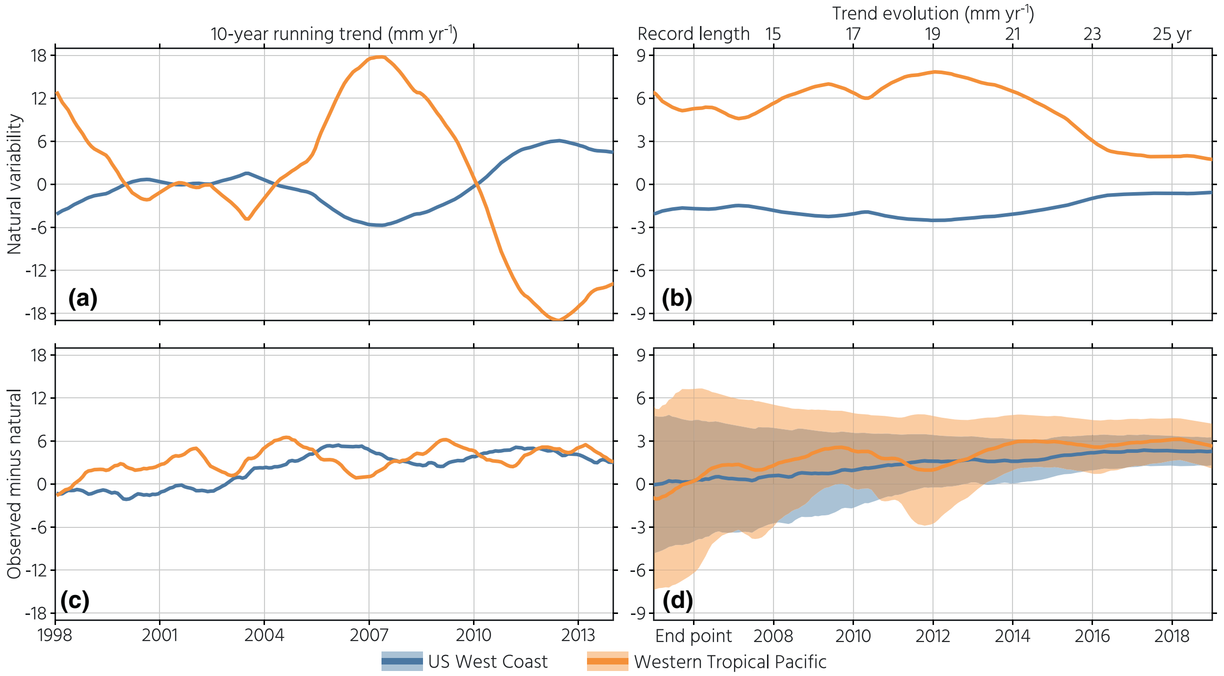

Figure 3. For the time period from 1993 to 2019, 10-year trends and trend evolution for total sea level from the estimate of natural variability arising from El Nino-Southern Oscillation and the Pacific decadal oscillation. The residual after removing this variability from total sea level (Figures 2a and 2b) is also shown (c and d).

tide gauge records extend back to the start of the 20th century and beyond, we limit our study to the time period from 1950 to present for completeness of the tide gauge records and for consistency between the US West Coast and western tropical Pacific regions. Since tide gauges measure relative sea-level (the movement of the ocean relative to land) and without adequate corrections for vertical land motion, we remove the full-record rate and acceleration from each record. While this restricts our ability to determine the impact on long-term rates, we are still able to analyze the variability in 10-year trends and determine the degree to which the full-record trend varies as the record length changes. There are also possible shorter-term variations in vertical land motion that we do not account for, but are likely smaller in magnitude relative to the other signals driving sea-level change in the region.

With the longer record provided by the tide gauges, the seesaw relationship between the 10-year trends for the US West Coast and western tropical Pacific is evident (Figure 4a). The correlation between the 10-year

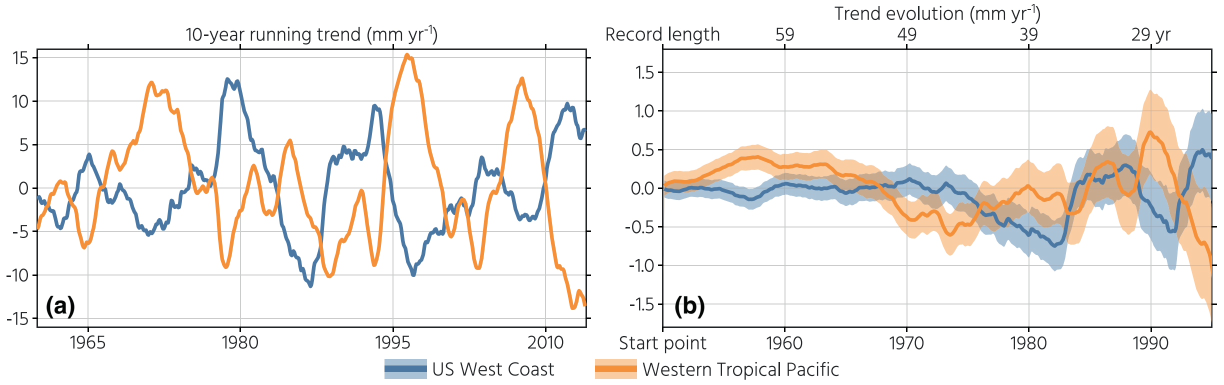

Figure 4. For the time period from 1950 to 2019, (a) 10-year trends and (b) trend evolution as estimated from available tide gauge data. For this figure, the end-date for the trend evolution computation is 2019, and *x*-axis indicates start-date for trend estimate. The last data point is therefore the trend from 1993 to 2019 and first data point is the trend from 1950 to 2019. Full-record trend and acceleration have been removed prior to computing 10-year trends and trend evolution.

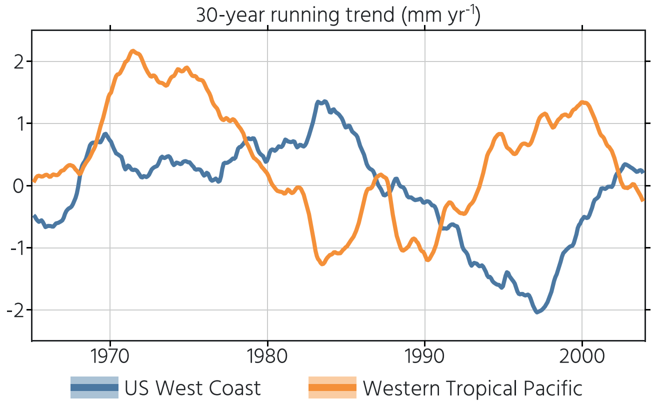

Figure 5. For the time period from 1950 to 2019, 30-year trends estimated from available tide gauge data. The years on the *x*-axis indicate the center point for the trend estimate. The last data point corresponds to the time period from 1989 to 2019. Full-record trend and acceleration have been removed prior to computing 30-year trends.

trends in the US West Coast and western tropical Pacific from 1950 to present is −0.67, showing that when rates are elevated in the US West Coast the 10-year trend in the western tropical Pacific is negative (and vice versa). In terms of magnitude, the 10-year trends in the tide gauges are consistent with those seen in the altimeter record, with rates exceeding ±10 mm/yr at several times during the longer tide gauge record. Using the 70-year record from the tide gauges, we can provide context to the evolution of the trend in the western tropical Pacific and US West Coast shown in Figure 2b. In a change from the computation done for the altimeter record, here we fix the end-date to be 2019 and extend the starting point back to 1950 (Figure 4b). This means that the last point in the time series is the trend from 1993 to 2019, while the first point in the time series is the trend from 1950 to 2019. For comparison, the same analysis conducted with a start-date of 1950 and extending forward it shown in the supplementary material (Figure S1). In this case, the long-term rate is also set to be zero as the rate and acceleration have been removed from the tide gauge records prior to performing the analysis. It should be noted that this ties the phasing of the decadal variability to an end date of 2019, and a different end date would necessarily shift the resulting lines up or down. Our goal here is to simply determine the extent to which the full-record trend can change with the addition of years to the record. With the record length of the altimetry, departures from the background rate can be on the order of ±1 mm/yr. As the record length approaches 40–50 years, departures from the background rate on the order of ±0.5 mm/yr are seen in both the US West Coast and western tropical Pacific. As the record lengthens to 60 years, departures from the long-term rate are reduced and on the order of ±0.2 mm/yr. Although this result does not use the altimeter data directly and makes no prediction about the phasing or magnitude of future variability, it does provide an envelope for future changes in the full-record trend in the altimeter record. In other words, based on the available tide gauge data, changes in the trends measured in the western tropical Pacific and US West Coast since 1993 could still deviate from the global average trend ±1 mm/yr in the coming years and on the order of ±0.5 mm/yr in the coming decades as a result of decadal variability.

As one final test using the longer tide gauge record, running 30-year trends—roughly corresponding to the length of the altimeter record—are estimated for the time period from 1950 to 2019 (Figure 5). We find that trends estimated over 30 years in each region can deviate from the long-term trend by magnitudes exceeding 1 mm/yr and approaching 2 mm/yr for some time periods. It is notable that for the window closest to the altimeter time period (1989–2019), the trends in both the western tropical Pacific and West Coast of the United States are near the long-term trend estimated from 1950 to 2019. It is thus possible that the phasing of natural variability is such that the current altimeter rates are relatively unimpacted by interannual to decadal variability, supporting the findings of recent studies (Fasullo & Nerem, 2018; B. D. Hamlington et al., 2019). Without investigating this longer-term trend, however, we only state that the 30-year trend evolution shown in Figure 5 supports the conclusion that a 30-year trend can only be determined to be within 1–2 mm/yr of a long term trend likely associated with the forced response.

To further test these conclusions over a longer time period, historical model runs from CMIP6 from 1850 to 2020 can be used (see Table S2 for information on models). Unlike the records available from observations, these models provide separate runs for full forcing (forced response plus natural variability), and natural variability only. This allows for directly testing the influence of natural variability on the estimated trends without having to rely on the regression technique used previously. Note, we make no evaluation of accuracy of the sea-level representation within any of these models, and instead simply seek to provide an indication of future trend variations. A more thorough investigation into the variability contained in the models on regional scales would require additional vetting and scrutiny. The similar trend evolution computation as shown in Figure 4 is done for both the full historical runs (Figures 6a–6c) and natural-only runs (Figures 6d–6f) for five different CMIP6 models. In this case, the end-date is fixed at 2020 and the record is extended into the past for the trend computation. With an end date of 2020, the first time shown in the figure corresponds to a trend computed over the time period from 1850 to 2020 and the last time is the

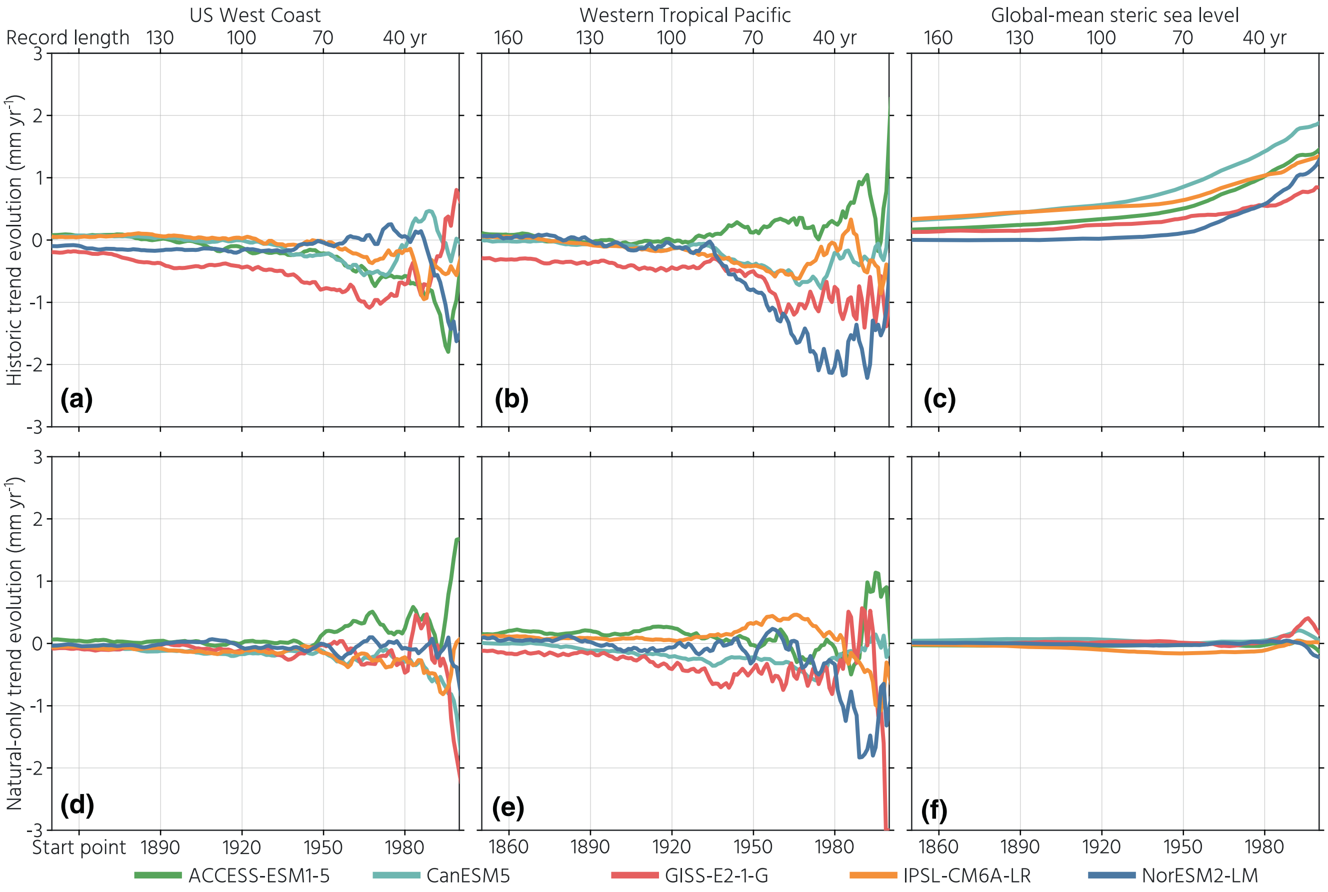

Figure 6. The evolution of the trend computed from the starting point on the *x*-axis to an ending point of 2019 for available CMIP6 models. As with Figure 4, the end-date for the trend evolution computation is 2019, and *x*-axis indicates start-date for trend estimate. The last data point is therefore the trend from 1993 to 2019 and first data point is the trend from 1850 to 2019. Historical runs driven by both natural and anthropogenic forcing are shown in panels a–c, while the runs only driven by natural forcing are shown in d–f. The US West Coast and western tropical Pacific estimates do not include global-mean sea level (e.g., the trends show the deviation from the global mean).

trend from 1993 to 2020. For both the US West Coast and western tropical Pacific, the trends in both the full and natural-only runs deviate from the long-term trend (set to be zero in this case) outside of the range of ±0.5 mm/yr for record lengths on the order of 50 years, which is consistent with the result obtained from the tide gauges (Figure 4). As the record continues to lengthen, however, the influence of natural variability decreases more rapidly along the US West Coast than in the western tropical Pacific, narrowing into a range of ±0.3 mm/yr for record lengths greater than 70 years, again roughly consistent with the results shown in Figure 4. With the benefit of being able to separate the fully forced sea-level signal from the sea-level signal associated with natural variability, we can also determine that although trends can deviate from the long-term trend for short record lengths, this is a result of natural variability and not associated with the forced response captured by the models. Finally, it should be noted that we are not making a quantitative determination of the emergence of the forced response over time. Instead this test is intended to give an indication of the influence of natural variability in record lengths similar to that of the satellite altimetry and longer.

3.3. Future Sea-Level Change: Present–2100

As a final step in our assessment of sea-level change in the US West Coast and western tropical Pacific, we use modeled projections of future sea-level in the region. We first focus on the projections of sterodynamic sea-level in the two regions and how these projections compare to the global mean. Figure 7 shows the projections of sterodynamic sea-level for four different scenarios from available CMIP6 models. For the three scenarios with the strongest forcing, the projection for GMSL is marginally higher than the projection

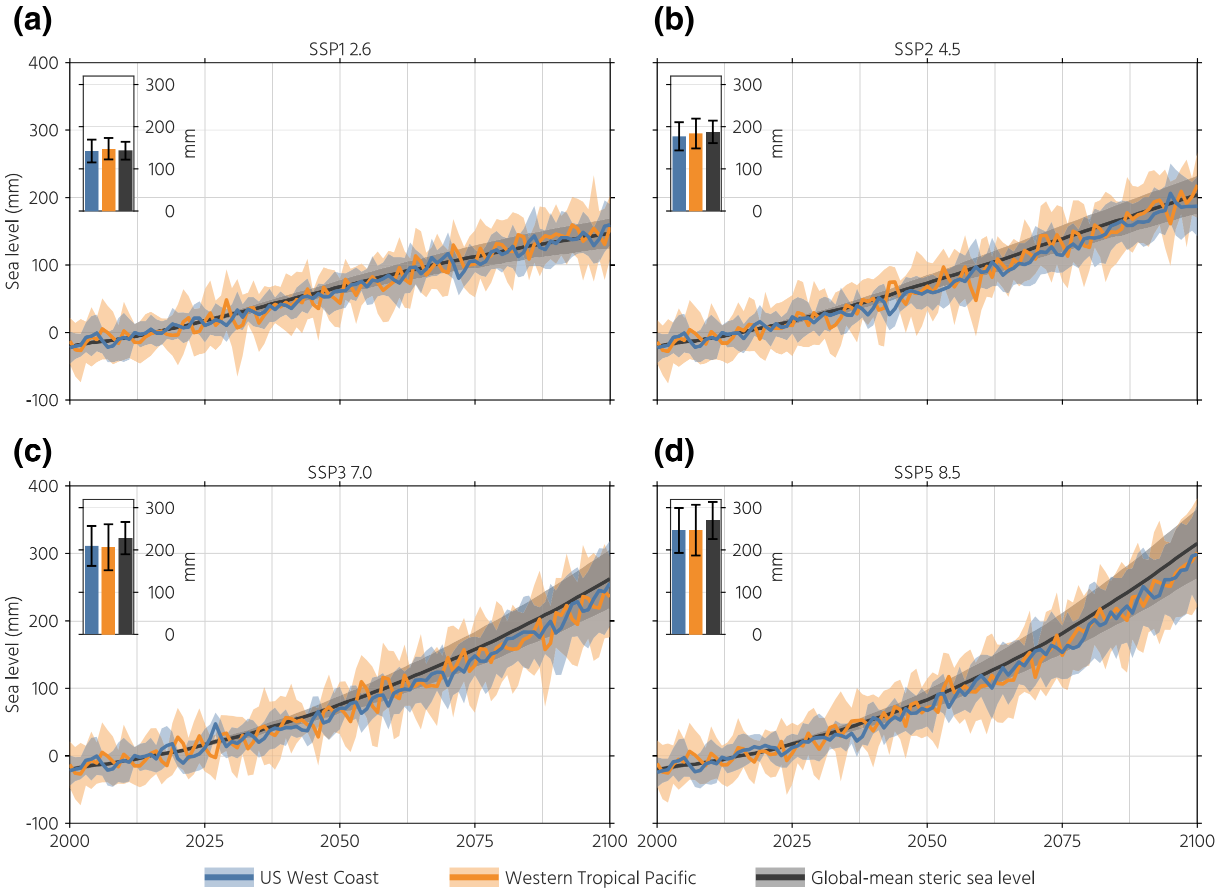

Figure 7. Projected sterodynamic sea-level changes under four scenarios. The bar graph depicts the sterodynamic sea-level rise between 2000–2019 and 2081–2100. The shading and error bars correspond to one standard deviation of the intermodel spread. Note that these projections only show sterodynamic sea level, and projected sea-level changes due to other processes, such as glacial isostatic adjustment, mass loss from glaciers and ice sheets, and local subsidence are not included in these projections.

for both the western tropical Pacific and US West Coast. This is consistent with the findings of Fasullo et al. (2020), although the projections for the three regions are not statistically different at the 95% confidence level for any of the four scenarios considered here. The uncertainty here is mainly a result of model uncertainty and not driven by natural variability as has been assumed in the observational analysis. As a result, caution must be taken not to over interpret this result. A simple comparison can be made to the total sea-level (Figure 2b) and sterodynamic estimates during the altimeter record (Figure 2d). With the 26-year record, the rates in the US West Coast and western tropical Pacific differ from each other and deviate from the global mean. Once natural variability is removed (Figure 3d), the trends from 1993 to 2019 in the two regions are similar, reflecting the similarity in future sterodynamic sea-level shown in the modeled projections (Figure 7). Regarding the contributions from ocean mass change, we do not make a projection of future contributions from ice mass loss, but we can infer differences between the US West Coast and western tropical Pacific by examining GRD patterns. As seen in Figure 8, the sea-level in the US West Coast will increase at less than the global mean with ice mass loss from glaciers and the Greenland ice sheets, while the contribution from the Antarctic ice sheet will be substantially greater than the global mean. For the western tropical Pacific, sea-level increase resulting from ice mass loss in each location will be greater than the global mean. With the contribution from glaciers and both ice sheets continuing into the future, both the US West Coast and western tropical Pacific will be subject to increasing sea-level. Furthermore, projections show a large but uncertain contribution from the Antarctic ice sheet in the 21st century (Seroussi et al., 2020), which could lead to sea-level rise in the US West Coast greater than the global average. Further investigation is required into both the representativeness of regional sea-level in the different models

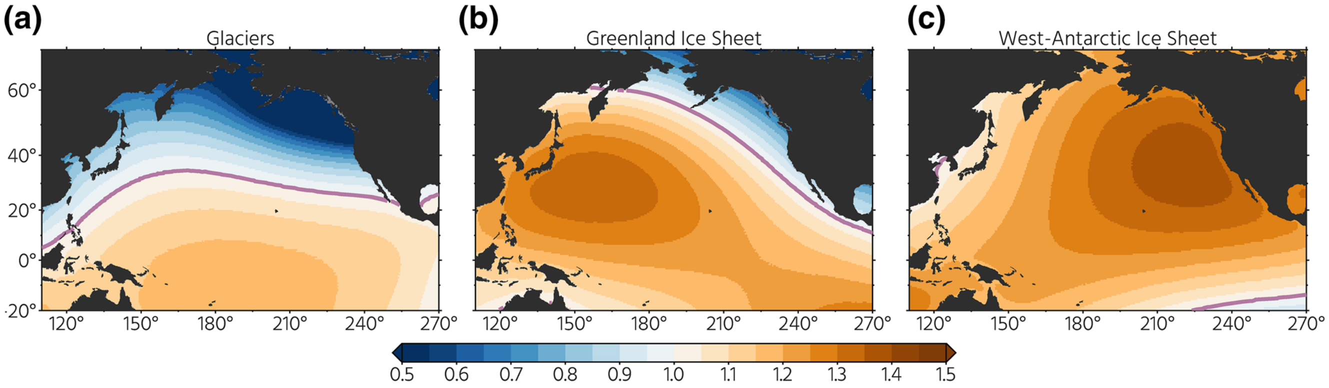

Figure 8. Normalized sea-level fingerprints due to glacier and ice-sheet mass loss. The numbers in each panel denote local sea-level changes relative to a global mean of 1. The purple line shows the contour where local sea-level rise is equal to the global-mean rise.

included in Figure 7 and the impact of uncertainties in future ice mass loss to provide a more definitive assessment of future sea-level in the western tropical Pacific and off the US West Coast.

4. Discussion

Sea-level in the Pacific Ocean can perhaps best be understood by separating processes by the timescales on which they vary. The long-term change associated with ice mass loss and thermal expansion, and the significant interannual to decadal variability associated with large scale climate signals like ENSO and the PDO play important roles in driving sea-level change in the region. When providing an assessment of past, present or future sea-level, it is important to consider how these processes contribute individually to sea-level rise, either in observational records or model simulations. Several studies have made attempts to remove interannual to decadal variability to provide an improved representation of the underlying trend (e.g., B. D. Hamlington et al., 2014, 2019; Palasinamy et al., 2015; Royston et al., 2018; Zhang & Church, 2012). Such studies, however, do not diminish the significant contribution from natural variability and the degree to which it can and will impact coastal flooding in the future.

Based on the analysis performed here, we draw the following conclusions:

1. The satellite altimeter trends in the US West Coast and western tropical Pacific from 1993 to 2019 are still influenced—and will continue to be—by interannual to decadal variability associated with ENSO and decadal variability, potentially contributing more than ±1 mm/yr to the trends over this period
2. Over a given 10-year window, sea-level trends in the US West Coast and western tropical Pacific can be substantially more than 10 mm/yr, which is almost entirely the result of sterodynamic variability related to modes of coupled atmospheric and oceanic variability
3. Differences in the trends in the US West Coast and western tropical Pacific are partially a result of ocean mass change (associated with ice mass loss) and those trends have increased during the satellite altimeter era
4. Based on this statistical analysis, the current altimeter trends in the two regions are likely within ±1 mm/yr of the forced trend over the same period
5. Based on climate model projections considered here, for the remainder of this century, sea-level change due to forced sterodynamic changes are not statistically different for the western tropical Pacific and US West Coast when compared to GMSL, although large uncertainty driven primarily by differences in the available models inhibits a more comprehensive assessment of future sterodynamic sea-level in the two regions
6. Based on the past observational record, sea-level in both the western tropical Pacific and US West Coast will continue its long-term increase in the coming years, and will be significantly elevated and suppressed due to interannual and decadal variability at different time periods in the future
7. While no attempt is made to predict decadal variability in the coming years, based on comparisons to similar periods in the past record the 10-year running sea-level trend in the US West Coast will likely

remain elevated for the next 5 years while the 10-year sea-level trend in the western tropical Pacific will continue to be suppressed by a similar amount as a result of the phasing of decadal variability in the region

With regards to the last two items in the list above, it is critical for stakeholders to account for the full range of substantial natural variability that is, present in both the US West Coast and western tropical Pacific when undertaking planning efforts. Based on this analysis and historical comparisons, the decadal variability of focus here could contribute an additional 5 cm of sea-level rise over the next 5 years. Additionally, while we do not know during what year an El Nino event (as an example) may occur in the future, based on the past record, we do know that for a given decade there will almost certainly be an El Nino event. With a higher underlying sea-level, the coastal impacts that occur during these times of elevated sea-level will be exacerbated. This has been true for the western tropical Pacific for much of the satellite altimeter era, and will likely be true for the coming decade along the US West Coast given the sea-level rise of approximately 10 cm that has occurred between 2010 and 2019, and with an elevated rate of rise that still persists today.

Competing Interests

The authors declare no competing interests.

Materials and Correspondence

All materials and correspondence requests can be directed to B. D. Hamlington at Benjamin.D.Hamlington@jpl.nasa.gov

Data Availability Statement

Tide gauge data is available from the Permanent Service for Mean Sea Level. GPS data is available from University of Nevada Reno Geodetic Laboratory (http://geodesy.unr.edu/). The steric sea-level data set is available athttps://doi.org/10.6084/m9.figshare.11971860.v1. The ECCO central estimate (Version 4 Release 4) is available from https://ecco.jpl.nasa.gov/drive/files. Gridded Surface Height Anomalies Ver. 1812 available from NASA JPL PO.DAAC, CA, USA at https://doi.org/10.5067/SLREF-CDRV2. Model data is available using the links provided in Table S2.

Acknowledgments
The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

Adhikari, S., Ivins, E. R., & Larour, E. (2016). ISSM-SESAW v1.0: mesh-based computation of gravitationally consistent sea-level and geodetic signatures caused by cryosphere and climate driven mass change. *Geoscientific Model Development*, *9*(3), 1087–1109. https://doi.org/10.5194/gmd-9-1087-2016

Becker, M., Meyssignac, B., Letetrel, C., Llovel, W., Cazenave, A., & Delcroix, T. (2012). Sea level variations at tropical Pacific islands since 1950. *Global and Planetary Change*, *80-81*, 85–98. https://doi.org/10.1016/j.gloplacha.2011.09.004

Bromirski, P. D., Miller, A. J., Flick, R. E., & Auad, G. (2011). Dynamical suppression of sea level rise along the Pacific coast of North America: Indications for imminent acceleration. *Journal of Geophysical Research*, *116*(C7). https://doi.org/10.1029/2010jc006759

Caron, L., Ivins, E. R., Larour, E., Adhikari, S., Nilsson, J., & Blewitt, G. (2018). GIA Model Statistics for GRACE Hydrology, Cryosphere, and Ocean Science. *Geophysical Research Letters*, *45*(5), 2203–2212. https://doi.org/10.1002/2017gl076644

Cheng, L., Trenberth, K. E., Fasullo, J., Boyer, T., Abraham, J., & Zhu, J. (2017). Improved estimates of ocean heat content from 1960 to 2015. *Science Advances*, *3*(3), e1601545. https://doi.org/10.1126/sciadv.1601545

ECCO Consortium; Fukumori, I., Wang, O., Fenty, I., Forget, G., Heimbach, P., & Ponte, R. M. (2020). *Synopsis of the ECCO central production global ocean and sea-ice state estimate (version 4 release 4)*. Retrieved from http://doi.org/10.5281/zenodo.3765929

Farrell, W. E., & Clark, J. A. (2007). On Postglacial Sea Level. *Geophysical Journal of the Royal Astronomical Society*, *46*(3), 647–667. https://doi.org/10.1111/j.1365-246x.1976.tb01252.x

Fasullo, J. T., Gent, P. R., & Nerem, R. S. (2020). Forced Patterns of Sea Level Rise in the Community Earth System Model Large Ensemble From 1920 to 2100. *Journal of Geophysical Research: Oceans*, *125*(6). https://doi.org/10.1029/2019jc016030

Fasullo, J. T., & Nerem, R. S. (2018). Altimeter-era emergence of the patterns of forced sea-level rise in climate models and implications for the future. *Proceedings of the National Academy of Sciences*, *115*(51), 12944–12949. https://doi.org/10.1073/pnas.1813233115

Fasullo, J. T., Nerem, R. S., & Hamlington, B. (2016). Is the detection of accelerated sea level rise imminent? *Scientific Reports*, *6*(1). https://doi.org/10.1038/srep31245

Forget, G., Campin, J.-M., Heimbach, P., Hill, C. N., Ponte, R. M., & Wunsch, C. (2015). ECCO version 4: an integrated framework for non-linear inverse modeling and global ocean state estimation. *Geoscientific Model Development*, *8*(10), 3071–3104. https://doi.org/10.5194/gmd-8-3071-2015

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V. W., et al. (2020). The causes of sea-level rise since 1900. *Nature*, *584*(7821), 393–397. https://doi.org/10.1038/s41586-020-2591-3

Frederikse, T., Jevrejeva, S., Riva, R. E. M., & Dangendorf, S. (2018). A Consistent Sea-Level Reconstruction and Its Budget on Basin and Global Scales over 1958–2014. *Journal of Climate*, *31*(3), 1267–1280. https://doi.org/10.1175/jcli-d-17-0502.1

Frederikse, T., Landerer, F. W., & Caron, L. (2019). The imprints of contemporary mass redistribution on local sea level and vertical land motion observations. *Solid Earth*, *10*(6), 1971–1987. https://doi.org/10.5194/se-10-1971-2019

Gregory, J. M., Griffies, S. M., Hughes, C. W., Lowe, J. A., Church, J. A., Fukimori, I., et al. (2019). Concepts and Terminology for Sea Level: Mean, Variability and Change, Both Local and Global. *Surveys in Geophysics*, *40*(6), 1251–1289. https://doi.org/10.1007/s10712-019-09525-z

Haigh, I. D., Wahl, T., Rohling, E. J., Price, R. M., Pattiaratchi, C. B., Calafat, F. M., & Dangendorf, S. (2014). Timescales for detecting a significant acceleration in sea level rise. *Nature Communications*, *5*(1), 3635. https://doi.org/10.1038/ncomms4635

Hamlington, B. D., Cheon, S. H., Thompson, P. R., Merrifield, M. A., Nerem, R. S., Leben, R. R., & Kim, K.-Y. (2016). An ongoing shift in Pacific Ocean sea level. *Journal of Geophysical Research: Oceans*, *121*(7), 5084–5097. https://doi.org/10.1002/2016jc011815

Hamlington, B. D., Fasullo, J. T., Nerem, R. S., Kim, K.-Y., & Landerer, F. W. (2019). Uncovering the Pattern of Forced Sea Level Rise in the Satellite Altimeter Record. *Geophysical Research Letters*, *46*(9), 4844–4853. https://doi.org/10.1029/2018gl081386

Hamlington, B. D., Gardner, A. S., Ivins, E., Lenaerts, J. T., Reager, J. T., Trossman, D. S., et al. (2020). Understanding of contemporary regional sea-level change and the implications for the future. *Reviews of Geophysics*, *58*(3), e2019RG000672. https://doi.org/10.1029/2019rg000672

Hamlington, B. D., Strassburg, M. W., Leben, R. R., Han, W., Nerem, R. S., & Kim, K.-Y. (2014). Uncovering an anthropogenic sea-level rise signal in the Pacific Ocean. *Nature Climate Change*, *4*(9), 782–785. https://doi.org/10.1038/nclimate2307

Holgate, S. J., Matthews, A., Woodworth, P. L., Rickards, L. J., Tamisiea, M. E., Bradshaw, E., et al. (2013). New data systems and products at the permanent service for mean sea level. *Journal of Coastal Research*, *29*(3), 493–504. https://doi.org/10.2112/JCOASTRES-D-12-00175.1

Mantua, N. J., & Hare, S. R. (2002). *Journal of Oceanography*, *58*(1), 35–44. https://doi.org/10.1023/a:1015820616384

Merrifield, M. A. (2011). A Shift in Western Tropical Pacific Sea Level Trends during the 1990s. *Journal of Climate*, *24*(15), 4126–4138. https://doi.org/10.1175/2011jcli3932.1

Merrifield, M. A., & Maltrud, M. E. (2011). Regional sea level trends due to a Pacific trade wind intensification. *Geophysical Research Letters*, *38*(21). https://doi.org/10.1029/2011gl049576

Merrifield, M. A., Thompson, P. R., & Lander, M. (2012). Multidecadal sea level anomalies and trends in the western tropical Pacific. *Geophysical Research Letters*, *39*(13). https://doi.org/10.1029/2012gl052032

Meyssignac, B., Salas y Melia, D., Becker, M., Llovel, W., & Cazenave, A. (2012). Tropical Pacific spatial trend patterns in observed sea level: internal variability and/or anthropogenic signature? *Climate of the Past*, *8*(2), 787–802. https://doi.org/10.5194/cp-8-787-2012

Milne, G. A., & Mitrovica, J. X. (1998). Postglacial sea-level change on a rotating Earth. *Geophysical Journal International*, *133*(1), 1–19. https://doi.org/10.1046/j.1365-246x.1998.1331455.x

Mitrovica, J. X., Tamisiea, M. E., Davis, J. L., & Milne, G. A. (2001). Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. *Nature*, *409*(6823), 1026–1029. https://doi.org/10.1038/35059054

Moon, J.-H., Song, Y. T., & Lee, H. (2015). PDO and ENSO modulations intensified decadal sea level variability in the tropical Pacific. *Journal of Geophysical Research: Oceans*, *120*(12), 8229–8237. https://doi.org/10.1002/2015jc011139

Nerem, R. S., Beckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., & Mitchum, G. T. (2018). Climate-change–driven accelerated sea-level rise detected in the altimeter era. *Proceedings of the National Academy of Sciences*, *115*(9), 2022–2025. https://doi.org/10.1073/pnas.1717312115

Nicholls, R. (2011). Planning for the Impacts of Sea Level Rise. *Oceanography*, *24*(2), 144–157. https://doi.org/10.5670/oceanog.2011.34

Palanisamy, H., Cazenave, A., Delcroix, T., & Meyssignac, B. (2015). Spatial trend patterns in the Pacific Ocean sea level during the altimetry era: the contribution of thermocline depth change and internal climate variability. *Ocean Dynamics*, *65*(3), 341–356. https://doi.org/10.1007/s10236-014-0805-7

Peyser, J. E., Yin, J., Landerer, F. W., & Cole, J. E. (2016). Pacific sea level rise patterns and global surface temperature variability. *Geophysical Research Letters*, *43*(16), 8662–8669. https://doi.org/10.1002/2016gl069401

Piecuch, C. G., Thompson, P. R., Ponte, R. M., Merrifield, M. A., & Hamlington, B. D. (2019). What Caused Recent Shifts in Tropical Pacific Decadal Sea-Level Trends? *Journal of Geophysical Research: Oceans*, *124*(11), 7575–7590. https://doi.org/10.1029/2019jc015339

Richter, K., Meyssignac, B., Slangen, A. B. A., Melet, A., Church, J. A., Fettweis, X., et al. (2020). Detecting a forced signal in satellite-era sea-level change. *Environmental Research Letters*, *15*(9), 094079. https://doi.org/10.1088/1748-9326/ab986e

Royston, S., Watson, C. S., Legrésy, B., King, M. A., Church, J. A., & Bos, M. S. (2018). Sea-Level Trend Uncertainty With Pacific Climatic Variability and Temporally-Correlated Noise. *Journal of Geophysical Research: Oceans*, *123*(3), 1978–1993. https://doi.org/10.1002/2017jc013655

Seroussi, H., Nowicki, S., Payne, A. J., Goelzer, H., Lipscomb, W. H., Abe-Ouchi, A., et al. (2020). ISMIP6 Antarctica: A multi-model ensemble of the Antarctic ice sheet evolution over the 21st century. *The Cryosphere*, *14*(9), 3033–3070. https://doi.org/10.5194/tc-14-3033-2020

Stammer, D., Cazenave, A., Ponte, R. M., & Tamisiea, M. E. (2013). Causes for Contemporary Regional Sea Level Changes. *Annual Review of Marine Science*, *5*(1), 21–46. https://doi.org/10.1146/annurev-marine-121211-172406

Thompson, P. R., Merrifield, M. A., Wells, J. R., & Chang, C. M. (2014). Wind-Driven Coastal Sea Level Variability in the Northeast Pacific. *Journal of Climate*, *27*(12), 4733–4751. https://doi.org/10.1175/jcli-d-13-00225.1

Watkins, M. M., Wiese, D. N., Yuan, D.-N., Boening, C., & Landerer, F. W. (2015). Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons. *Journal of Geophysical Research: Solid Earth*, *120*(4), 2648–2671. https://doi.org/10.1002/2014jb011547

WCRP Global Sea Level Budget Group. (2018). Global sea-level budget 1993-present. *Earth System Science Data*, *10*, 1551–1590. https://doi.org/10.5194/essd-10-1551-2018

Wiese, D. N., Landerer, F. W., & Watkins, M. M. (2016). Quantifying and reducing leakage errors in the JPL RL05M GRACE mascon solution. *Water Resources Research*, *52*(9), 7490–7502. https://doi.org/10.1002/2016wr019344

Wolter, K., & Timlin, M. S. (2011). El Niño/Southern Oscillation behaviour since 1871 as diagnosed in an extended multivariate ENSO index (MEI.ext). *International Journal of Climatology*, *31*(7), 1074–1087. https://doi.org/10.1002/joc.2336

Zhang, X., & Church, J. A. (2012). Sea level trends, interannual and decadal variability in the Pacific Ocean. *Geophysical Research Letters*, *39*(21). https://doi.org/10.1029/2012gl053240

Zlotnicki, V., Qu, Z., & Willis, J. (2019). *SEA_SURFACE_HEIGHT_ALT_GRIDS_L4_2SATS_5DAY_6THDEG_V_JPL1609. Ver. 1812*. CA, USA: PO.DAAC. Retrieved from https://doi.org/10.5067/SLREF-CDRV2