Changing impacts of Alaska-Aleutian subduction zone tsunamis in California under future sea-level rise

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The amplification of coastal hazards such as distant-source tsunamis under future relative sea-level rise (RSLR) is poorly constrained. In southern California, the Alaska-Aleutian subduction zone has been identified as an earthquake source region of particular concern for a worst-case scenario distant-source tsunami. Here, we explore how RSLR over the next century will influence future maximum nearshore tsunami heights (MNTH) at the Ports of Los Angeles and Long Beach. Earthquake and tsunami modeling combined with local probabilistic RSLR projections show the increased potential for more frequent, relatively low magnitude earthquakes to produce distant-source tsunamis that exceed historically observed MNTH. By 2100, under RSLR projections for a high-emissions representative concentration pathway (RCP8.5), the earthquake magnitude required to produce >1 m MNTH falls from ~Mw9.1 (required today) to Mw8.0, a magnitude that is ~6.7 times more frequent along the Alaska-Aleutian subduction zone.
To the more than one billion people worldwide living in the coastal zone below 10 m of elevation, the compound effects of relative sea-level rise (RSLR), tidal flooding, and storm surges are of increasing concern. Increasing tropical cyclone-driven flood heights due to changes in storm characteristics and RSLR over the past millennium and forecast increasing flood heights in the coming decades have been documented for specific locations such as New York City. Other research shows increased extreme sea levels during coastal storms due to RSLR along coasts in California as well as the contiguous United States. Still, other studies have investigated changes to extreme sea levels associated with coastal storms and RSLR in locations such as Australia and Europe and from a global perspective. However, the impacts of RSLR on coastal inundation during other potentially damaging events, such as tsunamis, need further research. Along coastlines affected by distant-source tsunamis, where potential tsunami amplitudes are generally on the order of or lower than projected twenty-first-century RSLR, rising baseline sea levels can significantly increase tsunami impacts.

The economic impacts of distant-source tsunamis in California have increased as coastal populations and infrastructure have grown. At the low-lying, densely populated, and economically important Ports of Los Angeles and Long Beach, recent maximum tsunami amplitudes (defined as the absolute value of the difference between a particular peak or trough of the tsunami and the undisturbed sea level at the time) recorded at tide gauge (TG1; Fig. 1c) are associated with distant-source tsunamis from earthquakes originating in Chile (1960; Mw9.5; maximum tsunami amplitude = 0.72 m), Alaska (1964; Mw9.2; maximum tsunami amplitude = 0.56 m), and Japan (2011; Mw9.0; maximum tsunami amplitude = 0.31 m). The 1960, 1964, and 2011 tsunamis coincided with differing stages of low tide at the ports; therefore, their maximum nearshore tsunami heights (MNTH; defined here as the maximum amplitude of the tsunami wave time series relative to mean sea level (MSL)) were dampened. Nevertheless, strong currents and inundation caused by MNTH of 0.27 m in 1960 and 0.41 m in 1964 caused ~$17 M and ~$149 M (amounts referenced in this paper are in 2019 in adjusted U.S. dollars) of damage in Los Angeles, respectively. Nevertheless, strong currents and inundation caused by MNTH; therefore, their maximum nearshore tsunami heights (MNTH; speculated to be in the billions of dollars for ports of the Pacific Rim, including the southern California coast. Over the past two centuries, at least 14 distant-source tsunamis have damaged the California coast, with 8 of the 14 occurring in the last ~70 years.

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In 2011, MNTH of 0.13 m created strong currents at the ports and disrupted operations, and higher MNTH (>1 m) along the northern California coast caused ~$115 M in damage.

Of the distant earthquake source regions posing a tsunami threat to the California coast, the Alaska-Aleutian subduction zone has the potential to produce the highest (1–2 m) tsunami amplitudes. The Semidi section of the Alaska-Aleutian subduction zone, defined as the portion of the subduction zone between western Kodiak Island and the Shumagin Islands, has been identified as a source area of particular concern because the continental slope azimuth there directs tsunamis towards southern California (Fig. 1a). However, historical and paleoseismic records show that earthquake ruptures in the region are not always confined to the Semidi section and that a rupture in 1788 (M8+), and probably older prehistoric ruptures, propagated east into the Kodiak section (Fig. 1a). Such evidence highlights the need for including multi-section (>9 M) as well as single-section ruptures along the Semidi and Kodiak sections in southern California and Pacific-wide tsunami hazard assessments.

In this work, we explore the effect of RSLR on low-probability, high-impact distant-source tsunami events at the Ports of Los Angeles and Long Beach. We combine single and multi-section earthquake and tsunami modeling along the Alaska-Aleutian subduction zone with probabilistic local RSLR projections for the ports to estimate potential MNTH for the ports during the twenty-first century.

Results

Distant-source tsunami simulations for the ports of Los Angeles and Long Beach. We use a time-independent, deterministic earthquake modeling approach to generate a dataset of possible tsunamiigenic earthquake sources ranging from Mw8.0 to Mw9.4 (15 magnitude steps) along the Semidi and Kodiak sections of the Alaska-Aleutian subduction zone. To account for source variability, we use 50 randomized earthquake areas (composed of adjacent NOAA unit sources) and hypocenter locations (assumed to be in the center of the earthquake area) for each step in earthquake magnitude (Fig. 1b and “Methods” section). Slip is uniform across unit sources for each earthquake, however, the area (i.e., number of unit sources) over which the slip is distributed for each earthquake magnitude varies (see “Methods” section). Our approach differs from probabilistic tsunami hazard assessments in that we use the same source region, suite of earthquake magnitudes, and slip variations for every year from 2000 to 2100, without considering the probability of each earthquake magnitude. This approach allows us to consider the changing impact of the same suite of significant earthquakes and tsunamis during twenty-first-century RSLR.

Our earthquake modeling (15 earthquake magnitudes × 50 earthquakes per magnitude step) generates 750 deformation fields that are input into GeoClaw for the simulation of tsunami wave propagation (Fig. 1b, Supplementary Table S1 and “Methods” section). We report the resultant distribution of MNTH at the Ports of Los Angeles and Long Beach from our tsunami simulations as the maximum tsunami amplitude at our synthetic tide gauge 2 (TG2; located in the outer harbor at 17 m water depth) relative to MSL (Fig. 1c, d).

We performed a parameter study to see how the MNTH produced by our method of varying the number of unit sources over which slip is distributed for each earthquake magnitude compared to a uniform and non-uniform slip approach for the same earthquake magnitudes (Supplementary Fig. S3). The parameter study supports the conclusion that uniform slip (using a constant number of unit sources and slip for each magnitude while only varying the earthquake location) results in a significant underestimation of MNTH. Our method produces a broader range of MNTH similar to a non-uniform slip approach, although there may be an underestimation of the higher extremes of possible MNTH (Supplementary Fig. S3). Therefore, the MNTH described in this paper provide a conservative estimate of possible tsunami impacts at the ports. We also performed a parameter study to evaluate how many earthquake areas per magnitude were necessary to produce a consistent and reproducible distribution of MNTH at the ports. Simulating a consistent distribution of MNTH is critical to ensuring that source variability is not the driving factor in changing MNTH. We show that 50 random earthquake areas and hypocenter locations per magnitude step are sufficient to produce a robust statistical representation (i.e., consistent and reproducible) distribution of MNTH at the ports (Supplementary Fig. S4 and “Methods” section).

Note that we do not analyze inundation or currents, nor do we explore the nonlinear interaction of tides with tsunamis. These processes are complex in a port setting and are computationally prohibitive due to the high-resolution topography and bathymetry needed to obtain reliable results (see “Methods” section). Instead, we use TG2 as a reference point to
compare how MNTH distributions are influenced by RSLR over time. We acknowledge that strong and erratic currents may be induced by distant-source tsunamis at the ports (e.g., refs. 22,36) and that the interaction of tidal currents with distant-source tsunamis may amplify MNTH38. Not including these processes in our modeling may underestimate the possible effects of distant-source tsunamis at the ports.

Although not included in our modeling or calculations, we analyzed the earthquake catalog along the entire Alaska-Aleutian subduction zone (see “Methods” section) in order to put the relative frequency of our chosen earthquake magnitudes into context. We used a declustered earthquake catalog \( (b-value = 0.75) \) to calculate the relative rate of earthquake magnitudes along the Alaska-Aleutian subduction zone (Supplementary Table S2)39,40. This approach may underestimate larger magnitude events14,42; however, because the catalog at the Alaska-Aleutian subduction zone spans M5-9.2, we believe this is the most conservative approach for calculating relative earthquake rates.

According to our simulations, for the year 2000, without considering RSLR or tidal variability, the 95% central range (CR) of MNTH at the Ports of Los Angeles and Long Beach generated by tsunamis from \( M_w8.0, M_w8.5, \) and \( M_w9.1 \) earthquakes is 0.06–0.26 m, 0.12–0.45 m, and 0.33–1.44 m (Supplementary Fig. S1), respectively. For our full suite of earthquakes (\( M_w8.0-9.4 \)), the 95% CR of MNTH is 0.19–1.78 m (median MNTH = 0.54 m; Fig. 1d).

The tidal stage during which a tsunami strikes the coast can be very important in determining the highest water levels reached during the event43–45. To account for the influence that tidal stage has on MNTH at the Ports of Los Angeles and Long Beach, we linearly combine our MNTH with tidal stages derived from a distribution composed of ~30 years of tidal data from TG120. For our full suite of earthquakes (\( M_w8.0-9.4 \)), the 95% CR of MNTH at the ports is 0.19–1.78 m (median MNTH = 0.54 m; Fig. 1d). Incorporating tidal variability in the calculation of MNTH at the ports results in a 95% CR of MNTH, generated by our full suite of earthquakes (\( M_w8.0-9.4 \)), of −0.45–2.03 m (median MNTH = 0.62 m; Fig. 1d).

**Fig. 1 Alaska-Aleutian subduction zone tectonic setting and distant-source tsunami modeling.** a Plate tectonic setting of Alaska showing the locked and creeping sections of the Alaska-Aleutian subduction zone, earthquake section boundaries, and approximate historical earthquake extents. Red circles show sites with paleoseismic evidence supporting multi-section earthquake ruptures. Ch Chirikof Island, Si Sitkinak Island, St Stikladak Island. b Light gray shaded area shows the approximate extent of slip used in the U.S. Geological Survey (USGS) Science Application for Risk Reduction (SAFRR) scenario magnitude 9.1 Semidi section earthquake underlain by a grid of the NOAA unit sources used in this paper. c Map of the Ports of Los Angeles and Long Beach showing the location of the long-term tide gauge (est. 1923) measuring water levels at the ports (TG167) and the synthetic tide gauge (TG2) where maximum nearshore tsunami heights (MNTH) were measured in this study. d Plot showing the probability density function (PDF) of the MNTH from our suite of modeled earthquake magnitudes in the year 2000 with no tidal variability included (blue histogram), the PDF of the tidal variability at TG1 (green histogram), and the combined MNTH and tidal variability PDF (red histogram). The dashed line shows the 1-m amplitude SAFRR scenario tsunami striking at high tide (MHW)36, resulting in a MNTH of 1.5 m at the ports.
Relative sea-level rise at the ports of Los Angeles and Long Beach. Changes in relative sea level during the twenty-first century vary by location as a result of processes such as atmospheric-ocean dynamics, the gravitational, rotational, and dynamic effects of ocean/cryosphere/hydrosphere mass redistribution, glacioisostatic adjustment, sediment compaction, and tectonic uplift or subsidence. In southern California, gravitational effects are augmented by large contributions from the West Antarctic Ice Sheet (WAIS), considered to be the most vulnerable ice sheet in a warming climate, causing the coast to be exceptionally sensitive to RSLR.

To estimate the contribution of RSLR to future MNTH at the Ports of Los Angeles and Long Beach, we use probabilistic projections of local RSLR (see “Methods” section). We examine low and high greenhouse-gas emissions pathways (Representative Concentration Pathways [RCPs] 2.6 and 8.5, respectively). RCP2.6 represents a low-emissions future with mitigation measures most consistent with the Paris Climate Agreement, while RCP8.5 represents a high-emissions future with no mitigation targets. We consider each pathway under two different treatments of Antarctic Ice Sheet uncertainty (denoted K14 and DP16) (Fig. 2 and Table 1). The K14 projections are consistent with projections from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report. The DP16 projections use outputs from a continental-scale model incorporating marine ice-sheet and ice-cliff instability mechanisms and are highly sensitive to atmospheric warming. Using the year 2000 as a baseline, we generate projections of local RSLR at the Ports of Los Angeles and Long Beach for the two emissions pathways during each decade of the twenty-first century.

Future maximum nearshore Tsunami heights. To study the influence of future RSLR on MNTH at the Ports of Los Angeles and Long Beach over the twenty-first century, we linearly combined a subsample of local probabilistic RSLR projections (RCP2.6 K14 and DP16, RCP8.5 K14 and DP16) spanning the low and high-end values of RSLR for each decade with our MNTH distribution including tidal variability. Our approach of linearly combining MNTH with RSLR projections resulted in a difference of ~7% to +15% in MNTH compared to an approach that accounts for changing bathymetry due to RSLR for each tsunami simulation (see “Methods” section). Previous tsunami and storm surge studies also highlight the potential nonlinear effect of RSLR on flood heights over time, but the effect is small for RSLR of < 2 m.

At the ports, RSLR causes tsunamis from our full suite of earthquakes to have higher median MNTH in 2050, 2070, and 2100 than today (Fig. 3 and Supplementary Table S3). The median of the MNTH distribution with tidal variability in 2000 is 0.62 m, reflecting the median of distant-source tsunamis generated by all earthquakes (Mw 8.0 to Mw 9.4) with no RSLR included. By 2050, median MNTH distributions range from 0.74 m (RCP2.6 DP16) to 0.84 m (RCP8.5 K14). By 2070, the median of MNTH distributions ranges from 0.83 m for RCP2.6 DP16 to 1.08 m for RCP8.5 DP16. The medians of the MNTH distributions in 2100 reflect the wide range in emissions pathways and sea-level projections, ranging from 0.95 m for RCP2.6 DP16 to 1.86 m for RCP8.5 DP16.

To explore the temporal relationship between earthquake magnitude and MNTH, we calculated the earthquake magnitude that generates tsunamis that have a 50% chance of exceeding a defined MNTH as a function of time (Fig. 4 and Table 2). We examined three MNTH: 0.5 m (measured multiple times during the historical period), 1.0 m (2 times larger than any historical event), and 1.5 m (similar to a previous tsunami scenario conducted at the ports and the highest storm-driven extreme sea level recorded at the ports).

For all RSLR projections considered (RCP2.6 K14 and DP16, RCP8.5 K14 and DP16), the earthquake magnitude required to exceed MNTH of 0.5 m drops to the lowest considered magnitude between 2040 and 2060. Today, a ~Mw 8.7 earthquake generates tsunamis that have a 50% chance of exceeding MNTH of 0.5 m.

| Year | RCP 2.6 K14 | RCP 2.6 DP16 | RCP 8.5 K14 | RCP 8.5 DP16 |
|------|-------------|-------------|-------------|-------------|
| 2050 | 0.07–0.33   | 0.10–0.54   | 0.12–0.95   | 0.01–0.28   |
| 2070 | 0.10–0.37   | 0.18–0.67   | 0.28–1.29   | 0.04–0.37   |
| 2100 | 0.12–0.95   | 0.37–1.57   | 0.57–2.4    | 0.01–0.28   |

RSLR projections are 95% credible intervals for the RCP2.6 and RCP8.5 emissions pathways under two treatments of Antarctic Ice Sheet uncertainty (K14 and DP16).
By 2040 (RCP2.6 K14 and RCP8.5 K14), 2050 (RCP8.5 DP16), and 2060 (RCP2.6 DP16), a Mw8.0 or lower earthquake generates tsunamis that have the same probability of exceeding MNTH of 0.5 m (Fig. 4a). Along the Alaska-Aleutian subduction zone, a Mw8.0 earthquake is ~3.4 times more likely to occur than a ~Mw8.7 (see "Methods" section).

The influence of different RSLR projections becomes more apparent for higher MNTH. For RCP2.6 K14 and DP16, there is a small decrease in the earthquake magnitude required to exceed MNTH of 1.0 m by 2100; today, a ~Mw9.1 earthquake generates tsunamis that have a 50% chance of exceeding MNTH of 1.0 m. By 2100, an earthquake of Mw8.9 (RCP2.6 DP16) or Mw8.8 (RCP8.5 DP16) can generate tsunamis with MNTH of 1.5 m.

### Table 2: The earthquake magnitude that has a 50% chance of generating a tsunami that exceeds flood heights of 0.5, 1.0, and 1.5 m today (2020) and in the year 2040*, 2050**, or 2060*** (for 0.5 m flood heights) or 2100 (for 1.0 m MNTH and 1.5 m MNTH) under the four RSLR projections considered.

| MNTH (m) | Today | 2040-60 | 2050 | 2060 | 2100 |
|----------|-------|---------|------|------|------|
| 0.5 m    | Mw8.7 | Mw8.0*  | Mw9.1| Mw8.8| Mw9.4|
| 1.0 m    | Mw8.7 | Mw8.0** | Mw9.1| Mw8.9| Mw9.4|
| 1.5 m    | Mw8.7 | Mw8.0***| Mw9.1| Mw8.0| Mw9.4|

The influence of different RSLR projections becomes more apparent for higher MNTH. For RCP2.6 K14 and DP16, there is a small decrease in the earthquake magnitude required to exceed MNTH of 1.0 m by 2100; today, a ~Mw9.1 earthquake generates tsunamis that have a 50% chance of exceeding MNTH of 1.0 m. By 2100, an earthquake of Mw8.9 (RCP2.6 DP16) or Mw8.8 (RCP8.5 DP16) can generate tsunamis with MNTH of 1.5 m.
(RCP2.6 K14) generates tsunamis that have the same probability of exceeding \(M_{\text{NTH}}\) of 1.0 m (Fig. 4b). A \(M_{\text{NTH}}=8.8\) earthquake is \(\sim 1.7\) times more likely to occur than a \(M_{\text{NTH}}=9.1\) along the Alaska-Aleutian subduction zone. For RCP8.5, we see a significant decrease in the earthquake magnitude—\(M_{\text{NTH}}=8.0\)—that has a 50% chance of exceeding \(M_{\text{NTH}}\) of 1.0 m by 2080 (DP16) and 2100 (K14). A \(M_{\text{NTH}}=8.0\) earthquake is \(\sim 6.7\) times more likely to occur than a \(M_{\text{NTH}}=9.1\) along the Alaska-Aleutian subduction zone.

The wide range of RSLR projections strongly influences future \(M_{\text{NTH}}\) of 1.5 m or higher (Fig. 4c). For RCP2.6 K14 and DP16, we see a small decrease in the earthquake magnitude required to exceed \(M_{\text{NTH}}\) of 1.5 m by 2100; today, a \(M_{\text{NTH}}=9.4\) or larger earthquake generates tsunamis that have a 50% chance of exceeding \(M_{\text{NTH}}\) of 1.5 m. By 2100, under RCP2.6 RSLR, an earthquake of approximately \(M_{\text{NTH}}=9.2\) generates tsunamis that have the same probability of exceeding \(M_{\text{NTH}}\) of 1.5 m. For RCP8.5, \(M_{\text{NTH}}=9.0\) earthquake generates tsunamis that have a 50% chance of exceeding \(M_{\text{NTH}}\) of 1.5 m by 2100. A \(M_{\text{NTH}}=9.0\) earthquake is \(\sim 2.0\) times more likely to occur than a \(M_{\text{NTH}}=9.4\) along the Alaska-Aleutian subduction zone. For RCP8.5 DP16, we see a more rapid and substantial drop in the earthquake magnitude required to produce \(M_{\text{NTH}}\) of 1.5 m: by 2100, a \(M_{\text{NTH}}=8.4\) earthquake generates tsunamis that have a 50% chance of exceeding \(M_{\text{NTH}}\) of 1.5 m. A \(M_{\text{NTH}}=8.4\) earthquake is \(\sim 5.6\) times more likely to occur than a \(M_{\text{NTH}}=9.4\) along the Alaska-Aleutian subduction zone (see “Methods” section).

Discussion

The U.S. Geological Survey (USGS) Science Application for Risk Reduction (SAFR) project modeled a \(M_{\text{NTH}}=9.1\) earthquake and its tsunami sourced along the Semidi section of the Alaska-Aleutian subduction zone (Fig. 1b). The SAFRR tsunami scenario found that such an earthquake could produce a distant-source tsunami with an amplitude of \(\sim 1\) m at the Ports of Los Angeles and Long Beach. In the scenario, the tsunami struck the coast during mean high water (MHW), producing \(M_{\text{NTH}}\) of 1.59 m, and causing losses of up to \(\sim 4.2\) billion (Fig. 1d). However, the SAFRR tsunami scenario did not consider the amplification of \(M_{\text{NTH}}\) under RSLR over the next century. In addition, the scenario did not consider multi-section, higher magnitude earthquake ruptures creating higher tsunami amplitudes or the varying tidal stages during which a tsunami may strike. Both may dampen or amplify \(M_{\text{NTH}}\).

By including future RSLR, multi-section ruptures, and tidal variability in our tsunami modeling, we provide a more complete picture of potential future \(M_{\text{NTH}}\) at the Ports of Los Angeles and Long Beach. We show that under rising sea levels, the possibility of economically and socially disruptive distant-source tsunami events like the one simulated in the SAFRR scenario\(^{18}\) will increase as the earthquake magnitude required to exceed \(M_{\text{NTH}}\) of \(>1.0\) m drops dramatically (from \(M_{\text{NTH}}=9.1\) to a \(M_{\text{NTH}}=8.0\)). A similar increase in flood frequencies under future RSLR in southern California has been predicted in storm surge and tidal flooding studies\(^{6, 11}\).

Our results highlight the need to consider RSLR when assessing possible future \(M_{\text{NTH}}\) and planning for RSLR at the Ports of Los Angeles and Long Beach. Finally, given that changing sea levels threaten coastal communities around the globe, these results suggest that RSLR should also be considered as part of the planning and decision-making process at other distant- and near-source tsunami-prone coasts worldwide\(^{17}\).

Methods

Probabilistic sea-level rise projections. In the coming centuries, global mean sea level (GMSL) will continue to rise due to the warming climate, generating hazards for coastal populations, economies, infrastructure, and ecosystems around the world\(^{38}\). For a low-emissions future with mitigation measures most consistent with the Paris Climate Agreement [Representative Concentration Pathway (RCP) 6.0], the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) projected a “likely” (>66% probability) GMSL rise of 0.28–0.61 m by 2100 relative to 1986–2015\(^{35}\). For a high-emissions “business as usual” future with no particular mitigation targets (RCP 8.5), IPCC AR5 projected a “likely” GMSL rise of 0.52–0.98 m by 2100 relative to 1986–2015\(^{35}\). However, recent studies suggest the IPCC AR5 GMSL rise estimates may be too low. For example, a physical ice-sheet model that includes important mechanisms such as ice-shelf hydrofracturing and the structural collapse of marine-terminating ice-cliffs shows the Antarctic Ice Sheet (AIS) could contribute far greater amounts to RSLR than previously estimated by 2100 under RCP8.5\(^{39}\). The possibility of higher-end projections being realized or even exceeded has many stakeholders preparing for sea-level rise in excess of 1 m by 2100\(^{41}\), and under extreme scenarios 2+ m of sea-level rise by 2100\(^{40}\).

The early impacts of higher sea levels are already being felt in southern California, where coastal flooding during storms, periodic tidal flooding, and increased coastal erosion are becoming more frequent and extensive\(^{35, 36}\). Higher sea levels will also leave southern California coastlines even more vulnerable to distant-source tsunamis, which have repeatedly impacted the coast in the last few centuries\(^{66}\).

We consider probabilistic sea-level rise projections from the Los Angeles tide gauge (33° 43.2′ N, 118° 16.4′ W\(^{35}\)) in Fig. 1c under two methodological approaches for the Antarctic ice sheet (K14 and DP16) and two different emissions pathways (RCP2.6 and RCP 8.5)\(^{35, 36}\). RSL projections are determined from 10,000 Monte Carlo samples of SLR projected at the Los Angeles Tide Gauge using the approach outlined in Kopp et al.\(^ {66}\). Both K14 and DP16 projections combine semi-empirical thermal expansion estimates of ocean dynamics from CMIP5 global climate model simulations, glacier melt from CMIP5-forced surface-mass balance modeling, global land water storage changes from semi-empirical modeling, long-term non-climatic relative sea-level change based on spatio-temporal statistical modeling of tide-gauge data, and gravitational, rotational, and deformational effects of glacial melting. Both sets also use Greenland ice sheet projections based on a combination of AR5 expert assessment regarding likely changes and tail-risk information from the structured expert judgment exercise of Bamber and Aspinall\(^ {66}\). The K14 projections use the same approach for Antarctica as for Greenland (and are thus generally consistent with the projections of AR5)\(^ {53, 68}\), while the DP16 projections replaced the K14 Antarctic projection with projections from the continental-scale ice-sheet/ice-shelf model of DeConto and Pollard\(^ {59}\). The DP16 projections were the first continental-scale RCP-driven projections to account for marine ice-cliff instability associated with the combined effects of ice-shelf hydrofracturing and gravitational instability\(^ {98, 99}\). The two sets of projections taken together provide a reasonable approach to bracketing the range of plausible probability distributions of future rise\(^ {47}\).

Earthquake realizations. To study the influence of future relative sea-level rise (RSLR) on tsunami impacts in the Ports of Los Angeles and Long Beach, we consider the same suite of earthquakes between \(M_{\text{NTH}}=8.0\) and \(M_{\text{NTH}}=9.4\) (with 15 magnitude steps) in each year. We do not take the occurrence probability of each earthquake magnitude into account in order to focus on the tsunami impact that each magnitude step would have under different sea-level rise projections. For our model, we generate robust distributions of maximum nearshore tsunami heights (\(M_{\text{NTH}}\)) that are based on 50 spatially varying earthquakes in each magnitude step to address uncertainties in epicenter locations (see more details on this approach in the paragraph below). We also considered another possible source of uncertainty in the \(M_{\text{NTH}}\) generated by our earthquake realizations: uniform vs. non-uniform slip. Traditionally, it was assumed that the tsunami dynamic filters and averages the slip differences across the rupture area as the tsunami propagates away from the source area. However, Li et al. and Melgar et al.\(^ {15, 34, 71}\) demonstrated that tsunami amplitudes are underestimated in earthquakes with uniform slip across the earthquake area, even in the far-field. Indeed, slip inversion studies of historical events show that slip distribution varies greatly across the rupture area and interface, and if this is not considered in earthquake realizations, \(M_{\text{NTH}}\) will be underestimated\(^ {35}\). To avoid underestimating tsunami amplitude in the Ports of Los Angeles and Long Beach, we devised the method of varying the number of unit sources over which slip is distributed for each earthquake magnitude (described below). Our approach is similar to the variable-area-uniform-slip (VAUS) applied by Davies\(^ {35}\).

We employ the empirical equations from Strasser\(^ {72}\) to estimate the average earthquake area that characterizes each magnitude step (15 magnitude steps between \(M_{\text{NTH}}=8.0\) and \(M_{\text{NTH}}=9.4\)). Because the earthquake area varies in each magnitude step, we multiply the calculated earthquake area by a random factor varying between 0.5 and 1.5 to produce 50 randomized earthquake areas (15 magnitude steps \(\times 50\) earthquake areas per magnitude \(= 750\) simulations). We use the 50 earthquake areas per magnitude step to determine how many adjacent NOAA unit sources (100 km \(\times 50\) km)\(^ {30}\) per earthquake have to be used to cover those earthquake areas (Fig. 1b). At the same time, to vary the hypocentral depth over each magnitude step, we place the unit sources associated with each earthquake randomly within the unit source grid of the Semidi and Kodiak sections (Fig. 1b).
Unit sources are not superposed. It should be noted that the arrangement of the unit sources is loosely constrained by the length of the computed earthquake area to avoid unrealistically long and thin earthquake areas. To determine the slip (D; in this study, slip is uniform across unit sources) for each of the 50 randomized earthquake areas and hypocenter locations per magnitude step, we use the following equation, derived from the moment magnitude and the seismic moment:

\[ D = 10^{(M_w + 10) / 3} \mu A \]

For example, a M\(_{w}\)8.1 can be composed of one, two, or three-unit sources, translating into slips of D = 8 m (one unit source), D = 4 m (two unit sources), or D = 2.7 m (three unit sources). Thus, for each earthquake magnitude, slip can be concentrated over a variable amount of unit sources to account for slip variability within each magnitude step. The minimum, average, and maximum slip and resultant deformation for each magnitude step are reported in Supplementary Table S1.

**Tsunami simulations.** To generate the initial conditions for the tsunami simulations from the aforementioned suite of earthquakes, we employ the Okada deterministic method\(^{20}\) to generate the maximum vertical ocean-surface deformation that is responsible for tsunami generation (Supplementary Table S1). Okada’s method requires the surface area of the earthquake, its depth, rake, strike, and dip. We utilize the NOAA tsunami unit sources to provide the required information (depth: 5−40 km, rake: 90°, strike: see unit source orientation on Fig. 1b, dip: 15°)\(^{32}\).

We use GeoClaw to carry out the tsunami simulations. GeoClaw is a widely used modeling tool for geophysical flows and is part of ClawPack software\(^{23}\). GeoClaw has been validated and verified\(^{24}\) and applied to a variety of different past tsunamis, such as the 2013 Chile\(^{25}\) and 2011 Japan\(^{26–27}\) events. One of the main advantages of GeoClaw is the Adaptive Mesh Refinement (AMR) that is implemented and available for tsunami simulations. AMR automatically refines the computational grid in areas where a finer resolution of the employed grid helps to find a more accurate numerical solution. For tsunami simulations, this area coincides with the traveling tsunami wave train. It is possible to force the refinement level in certain areas (e.g., southern California), which is a powerful method, for example, if all is needed at once, when many model runs are needed such as in our case. Supplementary Fig. S2 depicts the refinement areas we used in our simulations. As mentioned earlier, GeoClaw employs AMR to make the computations more efficient. In the open Pacific Ocean (Supplementary Fig. S2A, Box A), GeoClaw uses resolutions between 1° and 20′. For the tsunami evolution from the source to the continental shelf, for example, when many model runs are needed such as in our case. Supplementary Fig. S2 depicts the refinement areas we used in our simulations. As mentioned earlier, GeoClaw employs AMR to make the computations more efficient. In the open Pacific Ocean (Supplementary Fig. S2A, Box A), GeoClaw uses resolutions between 1° and 20′. For the tsunami evolution from the source to the continental shelf, for example, when many model runs are needed such as in our case. Supplementary Fig. S2 depicts the refinement areas we used in our simulations. As mentioned earlier, GeoClaw employs AMR to make the computations more efficient. In the open Pacific Ocean (Supplementary Fig. S2A, Box A), GeoClaw uses resolutions between 1° and 20′. 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Acknowledgements
This work was supported by funding from National Science Foundation awards to T.D. (EAR-1624795), T.D. and B.P.H. (EAR-1624533), R.W. (DGE-1735139 and GLD-1630099), A.J.G. (EAR-1625150), and R.E.K. (ICER-1663807), and from the National Aeronautics and Space Administration to R.E.K. (80NSSC17K0609). B.P.H. is also supported by the Singapore Ministry of Education Academic Research Fund MOE2019-T3-1-004 and MOE2018-T2-1-030, the National Research Foundation Singapore, and the Singapore Ministry of Education, under the Research Centers of Excellence initiative. R.C.W., R.W.B., C.S.M., and A.R.N. are supported by the Earthquake Hazard Program of the U.S. Geological Survey. This work is a contribution to PALSEA2 (Palaeo-Constraints on Sea-Level Rise) and the International Geoscience Programme (IGCP) Project 639 and 725. This work is Earth Observatory of Singapore contribution 417. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Author contributions
T.D., A.J.G., R.W., and B.P.H. led the writing of the main text, with contributions from other authors. T.D., R.W., and A.J.G. prepared the figures and tables. R.W. ran and analyzed the earthquake and tsunami simulations. A.J.G. and R.E.K. produced the local probabilistic sea-level rise projections. C.S.M. constructed the earthquake catalog. S.E.E., R.C.W., R.W.B, and A.R.N. contributed to the earthquake modeling and preparation of the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41467-021-27445-8.

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Peer review information Nature Communications thanks Jörn Behrens, Debi Kilb, and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Peer reviewer reports are available.

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