Appendix A. Sea Level Rise Science and Scenarios of Future Change

DRIVERS OF SEA LEVEL RISE

The main mechanisms driving increases in *global* sea level are: 1) expansion of sea water as it gets warmer (thermal expansion) and, 2) increases in the amount of water in the ocean from melting of land-based ice sheets and glaciers. Less significant contributors include human-induced changes in water storage and groundwater pumping.[113]

Sea level at the *regional and local levels* often differs from the average global sea level.[114] Regional variability in sea level results from large-scale tectonics and ocean and atmospheric circulation patterns. The primary factors influencing local sea level include tides, waves, atmospheric pressure, winds, vertical land motion and short duration changes from seismic events, storms, and tsunamis. Other determinants of local sea level include changes in the ocean floor (Smith and Sandwell 1997), confluence of fresh and saltwater, and proximity to major ice sheets (Clark *et al.* 1978; Perette *et al.* 2013; Fox-Kemper *et al*., 2021). Table 9.7 in the IPCC Sixth Assessment Report summarizes all global, regional, and local processes driving sea level rise. In California, long tide gauge records together with recent observations suggest that the long term sea level rise trend in California will track the global average (Hamlington *et al*., 2021).

Several other factors can influence local water levels in California, and these influences should be analyzed along with local sea level rise when examining local hazard conditions. For example, California's water levels are influenced by large-scale oceanographic phenomena such as the El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO), which can increase or decrease coastal water levels for extended periods of time. For example, strong El Niño events can temporarily elevate local sea levels by six to twelve inches over several months, while more sustained changes in ocean temperature and atmospheric circulation patterns can affect sea level on the order of decades. Over the past 30 years, for example, sea level rise was essentially absent during the first 15 years and then substantially accelerated during the second half due to the combined effects of ENSO and PDO (Hamlington *et al*., 2021) Please see Appendix B for more detail on how to incorporate both sea level rise and seasonal and temporary influences on water levels into local hazards analyses.

APPROACHES FOR PROJECTING FUTURE GLOBAL SEA LEVEL RISE

As summarized above, there are several different drivers of sea level rise, and scientists are using a variety of methods to research each one and project their future contributions to sea level rise (see box below). For some, like thermal expansion, there is thorough research and fairly high agreement about how it may respond to different levels of warming and contribute

[113] Large movements of the tectonic plates have been a third major mechanism for changes in global sea level. The time periods for plate movements to significantly influence global sea level are beyond the time horizons used for even the most far-reaching land-use decisions. Plate dynamics will not be included in these discussions of changes to future sea level.

to global sea level rise in the future; whereas others, like certain ice sheet melt processes, are areas of developing research where more work is needed.

Many reports, including the IPCC Assessment Reports, build global mean sea level rise projections by totaling the contributions of each major driver of sea level rise under certain assumptions about what the global climate will look like in the future. Because each driver has its own degree of scientific uncertainty,[115] total sea level rise reflects the various uncertainties associated with each contributor. Total sea level rise projections are then presented as means (or averages) with uncertainty bands around them, and users often look at the mean, the likely range (i.e., the middle 66% of the uncertainty range, or 17th to 83rd percentiles), and the very likely range (i.e., the middle 90% of the uncertainty range, or the 5th to 95th percentiles) to understand how much sea level rise could potentially occur under the given assumptions about emissions and warming. Estimates of sea level rise produced in this manner are known as "probabilistic projections." In addition to the IPCC Assessment Reports, other studies that produced projections include Kopp *et al*., 2014, the Fourth California Climate Assessment, and *Rising Seas in California* (Griggs *et al*., 2017). Each produced projections for various Representative Concentration Pathways (RCPs), the emissions scenarios defined by the IPCC.

Besides probabilistic projections, another way that researchers often present potential future sea level rise is in the form of "scenarios." Unlike projections, which are based on pre-defined assumptions about future greenhouse gas emissions and global warming, scenarios are instead hypothetical futures that span the range of what is considered plausible sea level rise according to the best available science. They often span several sets of projections that cover multiple potential emissions futures, and they can be compared to probabilistic projections to describe their likelihoods under various emissions futures. Examples of reports that provide scenarios include Parris *et al*., 2012, Hall *et al*., 2016, Sweet *et al*., 2017, Sweet *et al*., 2022, and the State Sea Level Rise Guidance (OPC 2024).

[115] To describe the varying statuses of scientific research on different research topics, the IPCC established a common approach for evaluating and communicating the degree of certainty in findings. It defined a range of "confidence levels" to describe the level of evidence and degree of agreement in the body of scientific literature on a particular subject (very low, low, medium, high, and very high). Table 9.7 in the IPCC Sixth Assessment report summarizes the methods used to generate the projections of SLR resulting from each physical driver of SLR as well as the degree of confidence in each.

Categories of methods for projecting future change

Scientists have employed a variety of techniques to model the various mechanisms that contribute to sea level rise, including:

1. **Physical Models**. Physical climate models use mathematical equations that integrate the basic laws of physics, thermodynamics, and fluid dynamics with chemical reactions to represent physical processes such as atmospheric circulation, transfers of heat (thermodynamics), development of precipitation patterns, ocean warming, and other aspects of climate. Some models represent only a few processes, such as the dynamics of ice sheets. Other models represent larger scale atmospheric or oceanic circulation, and some of the more complex General Climate Models (GCMs) include atmospheric and oceanic interactions. AR6 sea level rise projections drew from the sixth Coupled Model Intercomparison Project (CMIP6) climate models, particularly to inform sea level rise contributions based on medium confidence processes (i.e., processes of sea level rise for which the AR6 scientists had medium or higher confidence) from thermal expansion and ice sheets.
2. **Empirical or semi-empirical methods**. The semi-empirical method for projecting sea level rise is based on developing a relationship between sea level and some factor (a proxy) – often atmospheric temperature or radiative forcing – and using this relationship to project changes to sea level. An important aspect for the proxy is that there is fairly high confidence in models of its future changes; a key assumption that is made by this method is that the historical relationship between sea level and the proxy will continue into the future. For example, Rahmstorf 2007 projected future sea levels based on the historical relationship between global temperature changes and sea level changes.
3. **Expert elicitations**. Expert elicitation is a formalized use of experts in climate science and sea level change to help either narrow uncertainty for sea level projections, or to help with specifying extremes of a range. For example, Bamber and Aspinall (2013) used a statistical analysis of a large number of expert estimates to develop their projected range of future sea level, projecting sea level rise by 2100 ranging from 1–4.3 ft (0.33–1.32 m). Bamber *et al*., 2019 used structured expert judgement to quantify contributions to total sea level rise from Greenland and Antarctica ice sheets, and these estimates were incorporated into AR6 sea level rise projections.
4. **Extrapolations of historical trends**. Using extrapolation of historical trends in sea level to project future changes in sea level assumes that there will be no abrupt changes in the processes that drive the long-term trend, and that the driving forces will not change, which is not the case. An alternative approach is to estimate rates of sea level rise during the peak of the last interglacial (LIG) period (~125,000 years before present, when some drivers of sea level rise were similar to those today)[116] and use these as proxy records to project sea level rise rates to the 21st Century. For example, Kopp *et al.* (2009) used sea level rise rates inferred from the LIG to estimate a range of sea level rise for Year 2100 between 1-3 ft (0.3-1 m).

[116] During the last interglacial, global mean temperature was 1-2ºC warmer than the pre-industrial era (Levermann *et al.* 2013), while global mean sea level was likely 16.4-29.5 ft (5-9 m) above present mean sea level (Kopp *et al.* 2009; Dutton and Lambeck 2012; Levermann *et al.* 2013).

The State Sea Level Rise Guidance (OPC 2024) drew from the sea level rise scenarios in a federal report, *Global and Regional Sea Level Rise Scenarios for the United States* (Sweet *et al*., 2022). This report updated a set of global mean sea level rise scenarios that had been included in the previous iteration of the report which was published in 2017. These 2017 scenarios included 0.3, 0.5, 1.0, 1.5, 2.0, and 2.5 meters in 2100, also called Low, Intermediate-Low, Intermediate, Intermediate-High, High, and Extreme. The 2.5-meter-in-2100 scenario was included in this 2017 set of scenarios to capture the amount of sea level rise that could occur due to possible extreme Antarctic ice sheet and ice cliff instability as described in the then-recently released 2016 report by DeConto & Pollard.

However, a subsequent report, DeConto *et al*., 2021, looked at updated regional climate model forcing and found that air temperatures are not expected to rise as quickly in Antarctica as presumed in DeConto & Pollard 2016; rather, warming may take about 25 years longer to rise enough to potentially trigger the mechanisms of rapid retreat of the Antarctic Ice Sheet[117] that were described in DeConto & Pollard 2016 – i.e., by about the year 2125. Due to this change, Sweet *et al*., 2022 did not include the 2.5-meters-in-2100 (or Extreme) sea level rise scenario, leaving 0.3, 0.5, 1.0, 1.5, and 2.0 meter-in-2100 scenarios, which were called the Low, Intermediate-Low, Intermediate, Intermediate-High and High scenarios.

In effect, this action backtracked on the reasoning that led to the inclusion of 2.5 meters-in-2100 (which was regionalized to 10.2 feet-in-2100 in California) in Sweet et al., 2017, Rising Seas in California, and the 2018 version of the State Sea Level Rise Guidance. This change caused Sweet et al., 2022 to state, "the 'Extreme' scenario from the 2017 report (2.5 m global mean sea level rise by 2100) is now viewed as less plausible and has been removed." In other words, while 2.5 meters of sea level rise could occur a few decades after the year 2100 in the worst-case scenario, updated research has generally concluded that there is little to no possibility of that amount of sea level rise occurring as early as the year 2100 (DeConto *et al*., 2021).

Similar to Sweet *et al*., 2017, which overlaid its sea level rise scenarios with probabilistic sea level rise projections based on a group of papers, Sweet *et al*., 2022 overlaid its scenarios with the probabilistic projections from AR6. An associated FAQ describing the methods used in Sweet *et al*., 2022 states,

> "To generate the scenarios used in this report, the ensemble – or set – of projections in the AR6 that are tied to specific shared societal pathways (SSPs) are filtered to identify subsets of pathways that are consistent with the scenario target values in 2100 (i.e., 0.3 m, 0.5 m, 1 m, 1.5 m and 2 m). As in the AR6, these scenarios are regionalized and then

[117] DeConto *et al*., 2021 states, "With more extreme RCP8.5 warming, thinning and hydrofracturing of buttressing ice shelves becomes widespread, triggering marine ice instabilities in both West and East Antarctica. The RCP8.5 median contribution to GMSL is 34 cm by 2100. This is substantially less than reported by ref. 8 [DeConto & Pollard 2016] (64–105 cm), owing to a combination of improved model physics and revised atmospheric forcing (Methods) that delays the onset of surface melt by about 25 years. Nonetheless, the median contribution to GMSL reaches 1 m by 2125 and rates exceed 6 cm yr−1 by 2150 (Extended Data Figs. 6, 7). By 2300, Antarctica contributes 9.6 m of GMSL rise under RCP8.5, almost 10 times more than simulations limiting warming to +1.5 °C."

provided at individual tide gauge locations. The median, 17th and 83rd percentile values are provided for each scenario at each region and location."

In other words, a subset of sea level rise curves from the sets of AR6 projections that go through 0.3, 0.5, 1.0, 1.5 and 2.0 meters in the year 2100 were identified, thus informing each Sweet *et al*., 2022 scenario. This exercise was also summarized in Chapter 2 of the State Sea Level Rise Guidance (2024).

The information pulled through from AR6 also yielded a "storyline" for each scenario, which is summarized in Figure 4 of the report and copied below. For example, the Intermediate, Intermediate-High and High scenarios correspond to projections in AR6 that assume high emissions and warming and various levels of contribution from low confidence ice sheet processes (see below). The information from AR6 also allowed Sweet *et al*., 2022 to provide exceedance probabilities for various sea level rise amounts at various times in the future and under different amounts of global warming.

BEST AVAILABLE SCIENCE ON SEA LEVEL RISE

In the past century, global mean sea level (GMSL) has increased by nearly 8 inches (20 cm; Fox-Kemper *et al*., 2021). Observations of sea level rise rates have also shown that sea level rise has been accelerating in recent decades. While tide gauge measurements show roughly 5 inches of sea level rise during the entirety of the 20th century (Frederikse *et al*., 2020), satellite altimeters have measured an additional 4 inches of sea level rise since 1993, a period of only 30 years (Willis, Hamlington, Fournier, 2023). The current rate of GMSL rise (1.7 inches/decade) is triple the 20th century rate (Dangendorf *et al*., 2019; Nerem *et al*., 2018). The best available science on projected future sea level rise is summarized here and in the Ocean Protection Council's State Sea Level Rise Guidance (OPC 2024).

Global Projections of Sea Level Rise

IPCC AR6: The best available science on global sea level rise projections is currently the IPCC Sixth Assessment Report: Climate Change 2013 (AR6) released in 2021 (IPCC, 2021). AR6 projects slightly more rapid sea level rise compared to the Fifth Assessment (AR5) released in 2013. By Year 2100, the AR6 projects likely global sea level rise in the year 2100 to be 0.63–1.01 m whereas AR5 projected 0.49–0.95 m (AR5) when comparing similar, high emission scenarios.

Like AR5, AR6 produced projections of sea level rise by compiling the latest research on the various drivers of sea level rise, including thermal expansion of seawater, melting of land-based ice in Antarctica and Greenland, and other processes. Some drivers of sea level rise were well studied and there was strong agreement about their potential future contributions to sea level rise, whereas others were less studied and not as well understood. The AR6 authors distinguished between drivers of sea level rise in which there was at least medium confidence and drivers in which there was low confidence. Projections based on medium-confidence processes were computed for the emissions and global development futures called SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5[118]. For two of these five emissions scenarios, SSP1-2.6 and SSP5-8.5, additional work was done to also incorporate low confidence processes of extreme ice melt in Antarctica, including those described in DeConto *et al*., 2021[119], creating two additional sets of projections for a total of seven different sets of sea level rise projections. Figure A-1 is a graph generated by NASA and the IPCC's Sea Level Projection Tool that depicts the global mean sea level rise projections under all seven SSPs. Together, these seven sets of projections describe the IPCC's full plausible range of future sea level rise, reflecting how sea level rise would vary under the IPCC's range of conceivable global development, emissions, and warming futures as well as the possibility of rapid ice sheet disintegration.

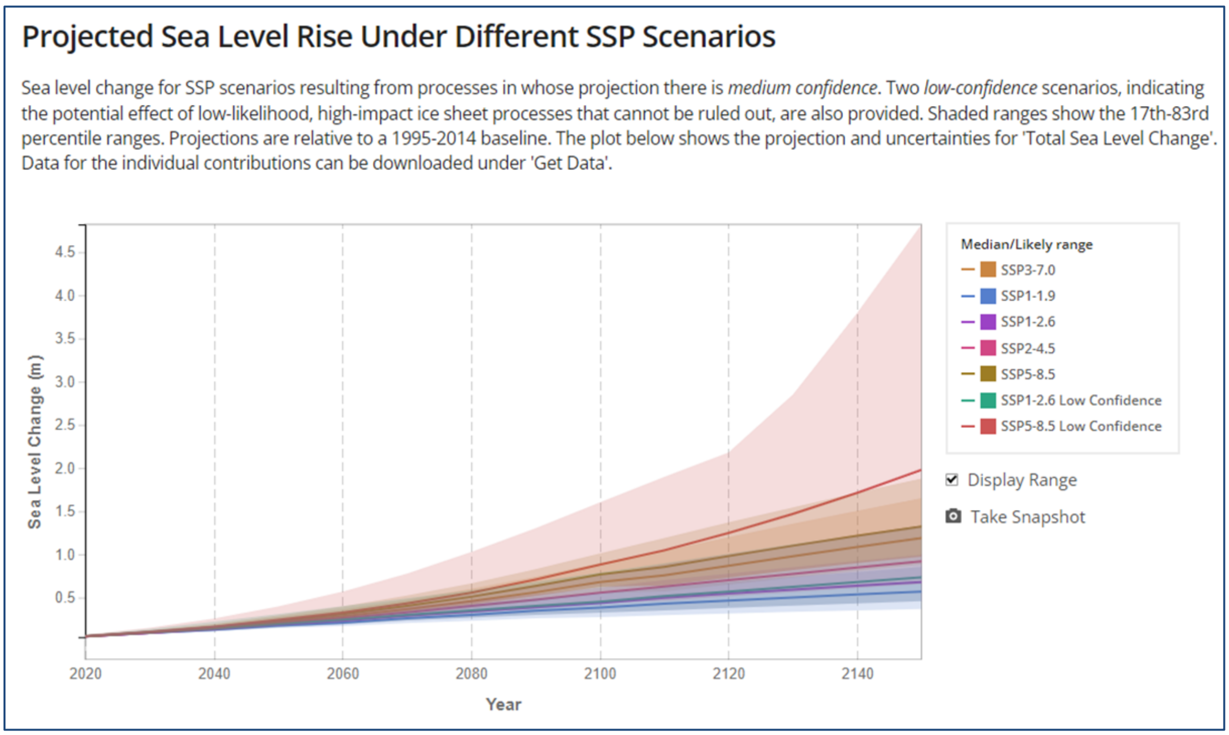

Figure A-1. IPCC AR6 plausible range of future SLR. A graph generated by NASA and the IPCC's Sea Level Projection Tool that depicts the global mean SLR projections under all five SSPs, plus the two additional scenarios that incorporate additional low confidence ice sheet processes.

[118] The Scenario Model Intercomparison Project (ScenarioMIP) for the Coupled Model Intercomparison Project Phase 6 (CMIP6) developed five different Shared Socioeconomic Pathways (SSP1 through SSP5) (O'Neill *et al*., 2016). These SSPs capture different ways the world could evolve in terms of population, economic growth, education, urbanization, and technological development, which, without additional new efforts to curb climate change. Each would result in various amounts of radiative forcing, which is expressed in the second half of the SSP name. For example, SSP3-7.0 comes from SSP3 and results in 7.0 Watts/m^2 of radiative forcing.

[119] Low confidence processes include earlier-than-projected disintegration of marine ice shelves and the abrupt, widespread onset of Marine Ice Sheet Instability (MISI) and Marine Ice Cliff Instability (MICI) around Antarctica, as well as faster-than-projected changes in the surface mass balance and dynamical ice loss from Greenland. AR6's low confidence SLR projections stemmed from a structured expert-judgement study (Bamber *et al*., 2019) and a single Antarctic ice-sheet modeling study (DeConto *et al*., 2021). See §9.6.3.2, §9.6.3.3, and Box 9.4 of Fox-Kemper *et al*., 2021, for further discussion. Box 9.4 of AR6's Chapter 9, in particular, discusses AR6's separation of medium-confidence sea level rise SLR projections from low-confidence sea level rise projections.

NOAA technical report: In 2017, NOAA released a report entitled Global and Regional Sea Level Rise Scenarios for the United States (Sweet et al., 2017) which provided global sea level rise scenarios and projections[120]. It provided scenarios of 0.3, 0.5, 1.0, 1.5, 2.0, and 2.5 meters in 2100 (also called Low, Intermediate-Low, Intermediate, Intermediate-High, High, and Extreme), and overlaid them with emissions-based, probabilistic sea level rise projections compiled from Church *et al*., 2013a (which is IPCC's Fifth Assessment Report, or AR5), Miller *et al*., 2013; Kopp *et al*., 2014, 2016a; Slangen *et al*., 2014; and Mengel *et al*., 2016, which produced probabilistic projections under assumed climate trajectories of RCPs 2.6, 4.5, and 8.5.

When discussing how to apply the scenarios, Sweet *et al* 2017 suggested a potential strategy as follows: "Define a scientifically plausible upper-bound (which might be thought of as a worst-case or extreme scenario) as the amount of sea level rise that, while low probability, cannot be ruled out over the time horizon being considered. Use this upper-bound scenario as a guide for overall system risk and long-term adaptation strategies. Define a central estimate or mid-range scenario (given assumptions about greenhouse gas emissions and other major drivers). Use this scenario as baseline for shorter-term planning, such as setting initial adaptation plans for the next two decades."

In 2022, an update to Sweet et al., 2017 titled, Global and Regional Sea Level Rise Scenarios for the United States (Sweet et al., 2022) was released, which incorporated new research that occurred between 2017 and 2022. Of the many papers published in that time period was DeConto et al., 2021, which built on the DeConto & Pollard 2016 paper that was key in justifying the inclusion of 2.5 meters-in-2100 as a sea level rise scenario in Sweet et al., 2017. DeConto et al., 2021 looked at updated regional climate model forcing and found that air temperatures are not expected to rise as quickly in Antarctica as presumed in DeConto & Pollard 2016; rather, warming may take about 25 years longer to rise enough to potentially trigger the mechanisms of rapid retreat of the Antarctic Ice Sheet[121] that were described in DeConto & Pollard 2016 – i.e., by about the year 2125. Due to this change, Sweet et al., 2022 removed 2.5-meters-in-2100 (or Extreme) sea level rise scenario, leaving 0.3, 0.5, 1.0, 1.5, and 2.0 meter-in-2100 global mean scenarios, which were called the Low, Intermediate-Low, Intermediate, Intermediate-High and High scenarios. Figure A-2 is a graph generated by NASA Interagency Sea Level Rise Scenario Tool that depicts Sweet *et al*., 2022's five sea level rise scenarios.

[120] Note that The Fourth National Climate Assessment (USGCRP, 2018) points to the scenarios of Sweet et al., 2017 and includes a discussion of other studies that provide sea level rise estimates as well as a discussion of overall uncertainty (see pages 106-109).

[121] DeConto et al., 2021 states, "With more extreme RCP8.5 warming, thinning and hydrofracturing of buttressing ice shelves becomes widespread, triggering marine ice instabilities in both West and East Antarctica. The RCP8.5 median contribution to GMSL is 34 cm by 2100. This is substantially less than reported by ref. 8 [DeConto & Pollard 2016] (64–105 cm), owing to a combination of improved model physics and revised atmospheric forcing (Methods) that delays the onset of surface melt by about 25 years. Nonetheless, the median contribution to GMSL reaches 1 m by 2125 and rates exceed 6 cm yr−1 by 2150 (Extended Data Figs. 6, 7). By 2300, Antarctica contributes 9.6 m of GMSL rise under RCP8.5, almost 10 times more than simulations limiting warming to +1.5 °C."

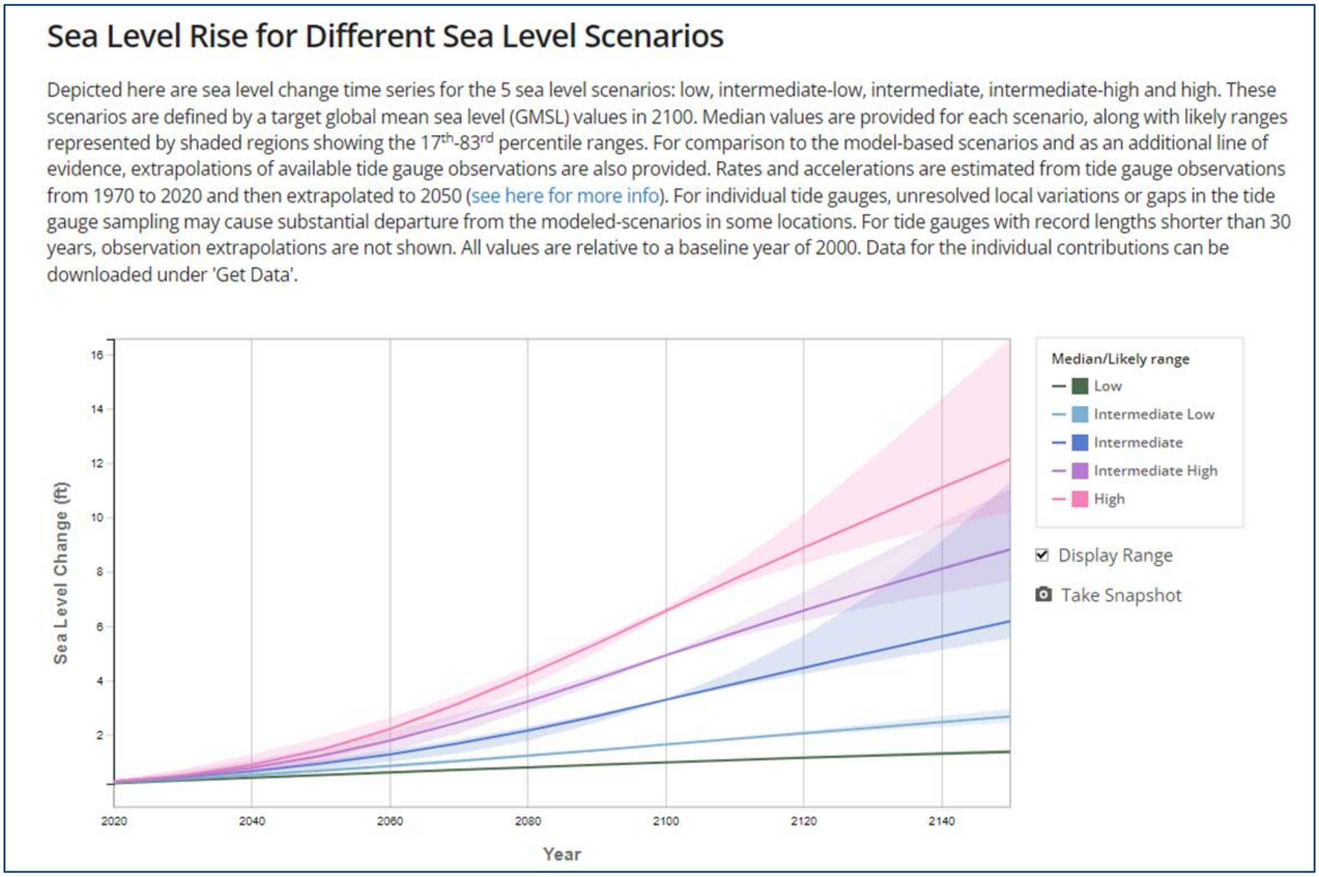

Figure A-2. Global SLR Scenarios from Sweet *et al*., 2022. This graph was generated by NASA Interagency Sea Level Rise Scenario Tool and depicts Sweet *et al*., 2022's five global mean sea level rise scenarios.

National Projections of Sea Level Rise

NOAA technical report: In addition to providing global mean sea level rise scenarios, Global and Regional Sea Level Rise Scenarios for the United States (Sweet *et al*., 2022) provided scenarios for the contiguous United States by regionalizing the global scenarios. This process reflects how sea level rise around the United States may differ from the global average due to ocean dynamics (i.e., changes to the ocean's currents and density due to climate change), large scale vertical land motion (i.e., glacial isostatic adjustment (GIA), tectonics, sediment compaction, and/or groundwater and fossil fuel withdrawals), and the impacts of gravitational, rotational, and deformational changes (i.e., GRD, or ice sheet fingerprinting). In general, sea level rise scenarios for the United States are at or higher than global mean sea level rise due to effects from vertical land motion, GRD, and ocean circulation changes (Sweet *et al*., 2022). Figure A-3 is a graph generated by NASA Interagency Sea Level Rise Scenario Tool that depicts the five sea level rise scenarios regionalized for the contiguous United States.

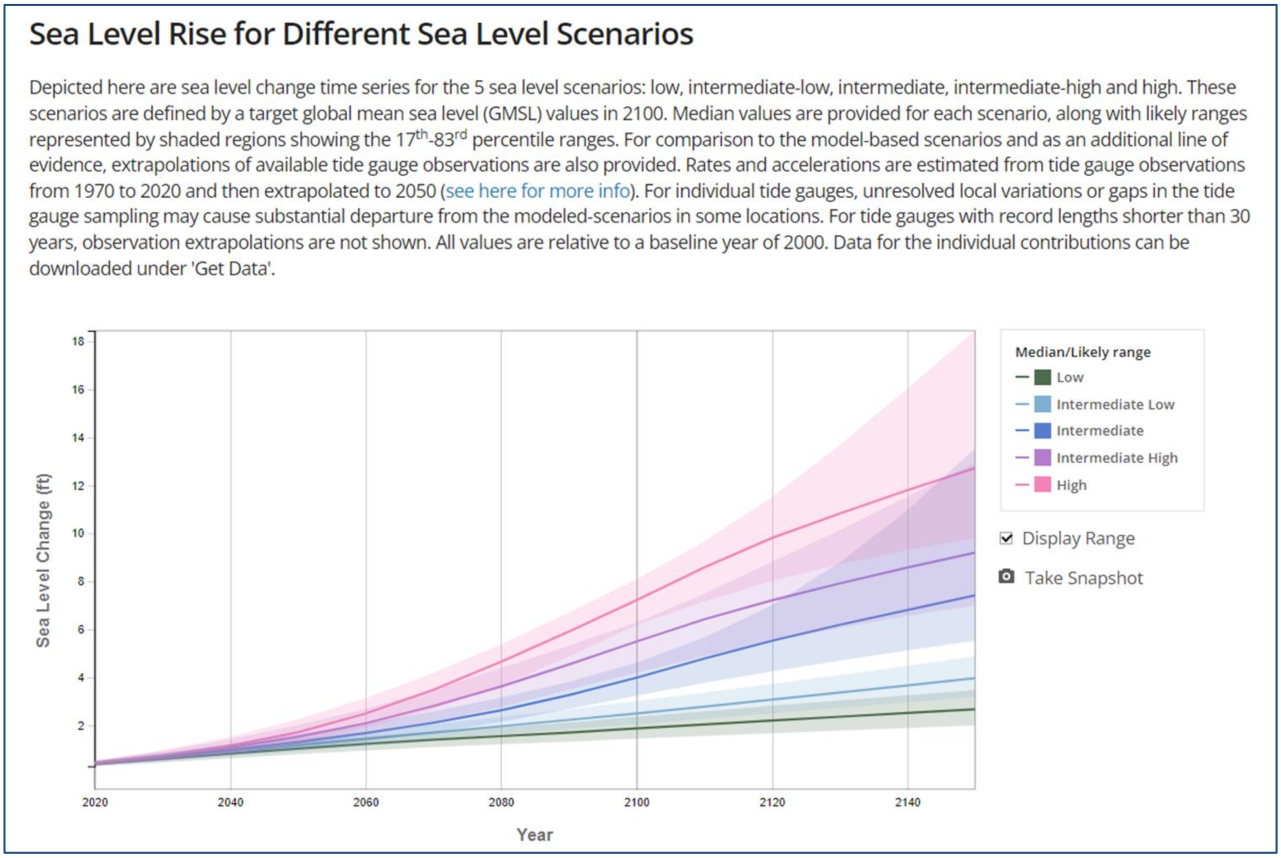

Figure A-3. SLR Scenarios for the contiguous United States from Sweet *et al*., 2022. This graph was generated by NASA Interagency Sea Level Rise Scenario Tool and depicts Sweet *et al*., 2022's five sea level rise scenarios for the contiguous United States.

California-Specific Sea Level Rise Scenarios and Best Available Science

The State of California has long supported the development of scientific information on climate change and sea level rise to help guide planning and decision-making. Several iterations of the *State Sea Level Rise Guidance* have been informed by key research that, at the time, provided the best available science on sea level rise projections:

- The 2013 State Sea-Level Rise Guidance (OPC 2013) was informed by the 2012 National Research Council (NRC) report, Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future.
- The 2018 State Sea Level Rise Guidance (OPC 2018) was informed by Rising Seas in California: An Update on Sea-Level Rise Science (Griggs et al., 2017).
- The 2024 State Sea Level Rise Guidance (OPC 2024) was informed by Global and Regional Sea Level Rise Scenarios for the United States (Sweet et al., 2022).

The 2024 State Sea Level Rise Guidance provides sea level rise scenarios based on Sweet et al., 2022.[122] Like Sweet et al., 2022, the State Guidance establishes the plausible range of global mean sea level rise in 2100 to be between 0.3 and 2.0 m and identifies roughly even increments of sea level rise to span that range: 0.3-, 0.5-, 1.0-, 1.5-, and 2.0 m-in-2100. These five scenarios are named Low, Intermediate-Low, Intermediate, Intermediate-High, and High.

Next, these sea level rise amounts were compared to the thousands of sea level rise projections within the seven sea level rise projections the provided in AR6. A +/- 2 cm "gate" around each scenario was created (i.e., 0.3m +/- 2cm in 2100, 0.5m +/- 2cm in 2100, 1.0m +/- 2cm in 2100, etc.) and the samples of AR6 projections that go through each gate were extracted, creating five sample sets, as shown in Figure A-4.

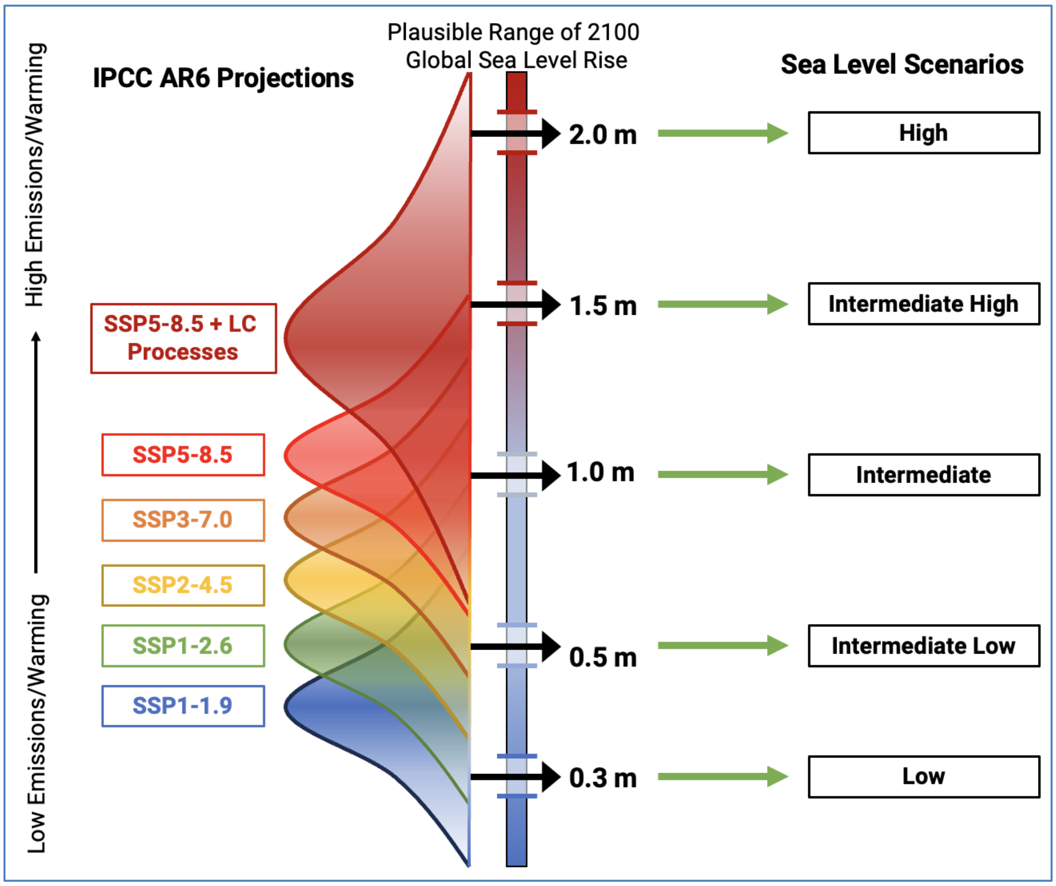

Figure A-4. Schematic showing that the construction of the sea level scenarios is based on SSPs, which inform a range of plausible future sea level rise. Provided as Figure 2.2 in the *California State Sea Level Rise Guidance* (OPC 2024)

The composition of these sample sets informed both the trajectory of each sea level rise scenario over time and a "storyline" for each scenario. In other words, the sample set for each scenario was used to describe the climate conditions under which each may occur. The State

[122] Please see Chapter 2 of the 2024 State Sea Level Rise Guidance to read the report's full summary of how the sea level rise scenarios were generated.

Sea Level Rise Guidance provides these storylines in Section 2.4 and summarizes them in its Executive Summary as follows:

- **"Low Scenario**: The target of 1 foot of increase in global sea level rise by 2100 is set under the assumption of the current rate of sea level rise continuing on into the future. This assumption is inconsistent with current observations of an acceleration in sea level rise, but could still be considered plausible under the most aggressive emission reduction scenarios. As a result, the Low Scenario provides the lower bound for plausible sea level rise in 2100 and sits below the median value for all AR6 scenarios at all times between 2020 to 2150. The likelihood of exceeding this Sea Level Scenario is greater than 90% at all warming levels.
    - SUMMARY: Aggressive emissions reductions leading to very low future emissions; the scenario is on the lower bounding edge of plausibility given current warming and sea level trajectories, and current societal and policy momentum.

- **Intermediate-Low Scenario:** This scenario arises under a range of both future warming levels and possible SSPs, spanning low, intermediate and high emissions pathways, and integrates many of the AR6 SSP pathways as a result (see Figure 2.2) This scenario is consistent with the median projected sea level rise in a 2°C world, which means there is a 50% probability of exceeding this scenario with 2°C of additional warming by 2100. At a warming level of 3°C in 2100, the probability of exceeding this scenario is 82%. Given the extrapolation of GMSL to 2100 (approximately 2.2 feet36), the current projection of future warming of 3°C, and the range of sea level rise across the IPCC AR6 scenarios (Figure 2.4), the Intermediate Low Scenario provides a reasonable lower bound for the most likely range of sea level rise by 2100. Since the low confidence processes are not important to this scenario, the range of possible sea level rise after 2100 does not expand significantly.
    - SUMMARY: A range of future emissions pathways; a reasonable estimate of the lower bound of most likely sea level rise in 2100 based on support from sea level observations and current estimates of future warming.

- **Intermediate Scenario**: The Intermediate Scenario is driven dominantly by high emissions scenarios, and thus higher warming levels. For the first time in the scenarios, the low confidence projections from the IPCC AR6 contribute significantly and provide about 25% of the pathways for reaching the Intermediate Scenario target by 2100. Given the extrapolation of GMSL to 2100 and the range of sea level rise across the IPCC AR6 scenarios (Figure 2.4), the Intermediate Scenario provides a reasonable upper bound for the most likely range of sea level rise by 2100. At a warming level of 3°C in 2100, the probability of exceeding this scenario is 5%. In a very-high emissions future with low confidence processes, there is about a 50% chance of exceeding the Intermediate scenario in 2100.

- SUMMARY: A range of future emissions pathways; could include contribution from low confidence processes. Based on sea level observations and current estimates of future warming, a reasonable estimate of the upper bound of most likely sea level rise in 2100.

- **Intermediate-High Scenario**: Pathways combining both higher emissions and low confidence processes become the majority, with over 50% of the samples used to construct this scenario coming from the SSP5-8.5 scenario. At all times from 2020 to 2150, the Intermediate High Scenario exceeds the median value of the AR6 scenarios. This scenario is similar to the high-end estimate from van de Wal et al. (2022) under the assumption of high levels of warming in 2100. At a warming level of 3°C in 2100, the probability of exceeding this scenario is 0.1% when not considering the low confidence processes, emphasizing the degree to which these processes are needed to get to this scenario. With the low confidence processes, the probability of exceeding this scenario is approximately 20% for very high warming levels.
  - SUMMARY: Intermediate-to-high future emissions and high warming; this scenario is heavily reflective of a world where rapid ice sheet loss processes are contributing to sea level rise.

- **High Scenario:** Pathways combining both high emissions and low confidence processes are dominant, providing over 80% of the samples to construct the scenario. Low emissions pathways are not plausible under this scenario, and intermediate emissions pathways require a significant contribution from rapid ice sheet loss processes. Before 2100, the High Scenario is significantly above the range of SSP AR6 scenarios, although the range of plausible sea level expands beyond 2150. The probability of exceeding the High Scenario in 2100 is less than 0.1% for all warming levels without considering low confidence processes. With very high emissions and warming and contributions from the low confidence processes, this probability increases to 8%.
  - SUMMARY: High future emissions and high warming with large potential contributions from rapid ice-sheet loss processes; given the reliance on sea level contributions for processes in which there is currently low confidence in their understanding, a statement on the likelihood of reaching this scenario is not possible."

These five trajectories of sea level rise were then regionalized to California, and the California State Sea Level Rise Guidance presented a single set of scenarios representing the median sea level rise scenarios for California that reflect an average statewide value of vertical land motion, which is a negligible rate of 0.1 mm (0.0003 ft) per year uplift. These median statewide values are presented below in Table A-1.

Table A-1. Sea Level Rise Scenarios for California [123]

Projected SLR Amounts (in feet)					
	Low	Intermediate-Low	Intermediate	Intermediate-High	High
2030	0.3	0.4	0.4	0.4	0.4
2040	0.4	0.5	0.6	0.7	0.8
2050	0.5	0.6	0.8	1.0	1.2
2060	0.6	0.8	1.1	1.5	2.0
2070	0.7	1.0	1.4	2.2	3.0
2080	0.8	1.2	1.8	3.0	4.1
2090	0.9	1.4	2.4	3.9	5.4
2100	1.0	1.6	3.1	4.9	6.6
2110	1.1	1.8	3.8	5.7	8.0
2120	1.1	2.0	4.5	6.4	9.1
2130	1.2	2.2	5.0	7.1	10.0
2140	1.3	2.4	5.6	7.7	11.0
2150	1.3	2.6	6.1	8.3	11.9

These average statewide scenarios were also further regionalized to reflect the observed rates of vertical land motion at each of California's 14 coastal tide gauges. These tide gauge-specific scenarios are provided in in Appendix 2 of the State Sea Level Rise Guidance (OPC 2024) and in Appendix G of this document.

The State Sea Level Rise Guidance also provided information about how likely each scenario is to occur in the year 2100 under various amounts of plausible future warming (Table A-2). Likelihoods were also provided assuming rapid ice sheet disintegration processes come into play in the 2100s. These likelihoods were derived from the sample sets of projections from AR6 on which each scenario was based, and they provide valuable information to shape our understanding of the likelihood that each scenario will or will not come to pass, and the risks the higher or lower scenarios may occur. As explained in the State Guidance, this table can be

[123] This table provides median values for sea level scenarios for California, in feet, relative to a year 2000 baseline. These statewide values all incorporate an average statewide value of vertical land motion – a negligible rate of 0.1 mm (0.0003 ft) per year uplift (OPC 2024). The red box highlights the three scenarios that the *State Sea Level Rise Guidance* and this guidance recommend for use in various planning and project contexts.

read as saying, "assuming 3°C of warming in 2100 and no influence from low-confidence ice sheet processes, there is a 5% chance of exceeding the Intermediate scenario in 2100" or "assuming high levels of warming in 2100 and contributions from the low confidence processes, there is a 49% chance of exceeding the Intermediate Scenario in 2100" and so on. The State Guidance also explains that global surface temperatures are currently on track to reach 3.0°C above pre-industrial levels by 2100, assuming current rates of emissions-driven warming.

Table A-2. Exceedance probabilities for the sea level scenarios based on IPCC warming level–based global mean sea level projections[124]

Global Mean Surface Air Temperature 2081-2100	1.5°C	2.0°C	3.0°C	4.0°C	5.0°C	Low Confidence Processes, Low Warming	Low Confidence Processes, High Warming
Low Scenario	92%	98%	99.5%	99.9%	>99.9%	90%	99.5%
Intermediate-Low Scenario	37%	50%	82%	97%	99.5%	49%	96%
Intermediate Scenario	0.5%	2%	5%	10%	23%	7%	49%
Intermediate-High Scenario	0.1%	0.1%	0.1%	1%	2%	1%	20%
High Scenario	<0.1%	<0.1%	<0.1%	<0.1%	0.1%	<0.1%	8%

The State Sea Level Rise Guidance (OPC 2024) offers the following Key Takeaways about the best available science on sea level rise:

- **"The California Sea Level Scenarios show greater certainty in the amount of sea level rise expected in the next 30 years** than previous reports and demonstrate a narrow range across all possible emissions scenarios. Statewide, sea levels are most likely to rise 0.8 ft (Intermediate Scenario) by 2050.

- **In the mid-term (2050-2100), the range of possible sea level rise expands** due to more uncertainty in projected future warming from different emissions pathways and certain physical processes (i.e. rapid ice sheet melt). By 2100, statewide averaged sea levels are expected to rise between 1.6 ft and 3.1 ft (Intermediate-Low to Intermediate Scenarios), although higher amounts are possible.

[124] The *California State Sea Level Rise Guidance* provides the following explanatory information for this table: "Global mean surface air temperature anomalies are projected for years 2081–2100 relative to the 1850–1900 climatology. Global surface temperatures are currently on track to reach 3.0°C above pre-industrial levels by 2100, assuming current rates of emissions-driven warming…The probabilities shown here are imprecise probabilities, representing a consensus among all projection methods applied by the IPCC AR6."

- **Over the long-term (towards 2100 and beyond), the range of sea level rise becomes increasingly large** due to uncertainties associated with physical processes, such as earlier-than-expected ice sheet loss and resulting future sea level rise. Sea levels may rise from 2.6 ft to 11.9 ft (Intermediate-Low to High Scenarios) by 2150, and even higher amounts cannot be ruled out.

- **Vertical land motion is the primary driver of local variations in sea level rise across the state**, driven by a combination of tectonics, sediment compaction, and groundwater and hydrocarbon withdrawal. Vertical land motion is incorporated into the sea level scenarios for each National Oceanic and Atmospheric Administration (NOAA) tide gauge and illuminates locations experiencing subsidence or uplift. The pathway associated with the extreme sea level rise scenario (i.e. H++) from Rising Seas 2017 is higher than the best available science now supports. The key lines of evidence that resulted in the extreme sea level rise scenario (i.e. H++) from Rising Seas 2017 have been updated and are now reflected in the Intermediate-High and High Scenarios.

- **Today's coastal storms provide a glimpse into our future** in which storm events will become more damaging and dangerous as climate change and sea level rise continue. Coastal storms under future sea level scenarios will cause accelerated cliff and bluff erosion, coastal flooding and beach loss, and mobilization of subsurface contaminants. Sea level rise will increase the exposure of communities, assets, services and culturally important areas to significant impacts from coastal storms.

- **Sea level rise will increase the frequency of coastal flooding events**, which occur when sea level rise amplifies short-term elevated water levels associated with higher tides, large storms, El Niño events, or when large waves coincide with high tides. California communities need to be aware of and prepared for a likely rapid increase in the frequency of coastal flooding in the 2030s, even beyond the increases in coastal flood frequency already occurring as a result of extreme storms.

- **Groundwater rise poses a threat to below-ground infrastructure and freshwater aquifers under future Sea Level Scenarios**. In areas with shallow unconfined groundwater, the water table will generally rise with sea level, depending on local geomorphology. Rising groundwater may mobilize subsurface contaminants in soils, expose underground infrastructure to corrosive saltwater, and put freshwater aquifers at risk of saltwater intrusion. The low-lying Sacramento-San Joaquin Delta, which supplies fresh water to two-thirds of the state's population and millions of acres of farmland, is particularly vulnerable to saltwater intrusion into freshwater aquifers."

The table of median sea level rise scenarios for California is provided above (Table A-1), and tables for each California tide gauges are presented in Appendix F. The State Sea Level Rise Guidance (OPC 2024) is currently considered best available science on sea level rise for the State of California.

REFERENCES: APPENDIX A

Bamber JL, WP Aspinall. 2013. An expert judgment assessment of future sea level rise from the ice sheets. *Nature Climate Change* 3: 424-427. doi:10.1038/nclimate1778.

Bamber, J.L., M. Oppenheimer, R.E. Kopp, W.P. Aspinall, and R.M. Cooke, 2019: Ice sheet contributions to future sea-level rise from structured expert judgment. Proceedings of the National Academy of Sciences of the United States of America, 116 (23), 11195–11200. https://doi.org/10.1073/pnas.1817205116

California Sea Level Rise Guidance: 2024 Science and Policy Update. 2024. California Sea Level Rise Science Task Force, California Ocean Protection Council, California Ocean Science Trust.

Clark JA, WE Farrell, WR Peltier. 1978. Global changes in postglacial sea level: a numerical calculation. *Quaternary Research* 9(3): 265-287. doi:10.1016/0033-5894(78)90033-9.

Dangendorf, S., Hay, C., Calafat, F. M., Marcos, M., Piecuch, C. G., Berk, K., & Jensen, J. (2019). Persistent acceleration in global sea level rise since the 1960s. *Nature* Climate Change, 9(9), 705–710. https://doi.org/10.1038/s41558-019-0531-8

DeConto RM, Pollard D. 2016. Contribution of Antarctica to past and future sea-level rise. Nature 531: 591-7

DeConto, R.M., Pollard, D., Alley, R.B. et al. The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature* **593**, 83–89 (2021). https://doi.org/10.1038/s41586-021-03427-0

Dutton A, K Lambeck. 2012. Ice volume and sea level during the last interglacial. *Science* 337(6091): 216–219. doi: 10.1126/science.1205749.

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V. W., Dangendorf, S., Hogarth, P., Zanna, L., Cheng, L., & Wu, Y.-H. (2020). The causes of sea level rise since 1900. Nature, 584(7821), 393–397. https://doi.org/10.1038/s41586-020-2591-3

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, doi:10.1017/9781009157896.011.
https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter09.pdf

Griggs, G, Árvai, J, Cayan, D, DeConto, R, Fox, J, Fricker, HA, Kopp, RE, Tebaldi, C, Whiteman, EA

(California Ocean Protection Council Science Advisory Team Working Group). Rising Seas in California: An Update on Sea-Level Rise Science. California Ocean Science Trust, April 2017.

Hall, J.A., S. Gill, J. Obeysekera, W. Sweet, K. Knuuti, and J. Marburger, 2016: Regional Sea Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide. U.S. Department of Defense, Strategic Environmental Research and Development Program, Alexandria, VA, 224 pp. https://climateandsecurity.files.wordpress.com/2014/01/regional-sea-level-scenarios-for-coastal-risk-management_managing-uncertainty-of-future-sea-level-change-and-extreme-water-levels-fordepartment-of-defense.pdf

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, 9(4), e2020EF001839. https://doi.org/10.1029/2020EF001839

Intergovernmental Panel on Climate Change (IPCC). 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change.* [TF Stocker, D Qin, G Plattner, MMB Tignor, SK Allen, J Boschung, A Nauels, Y Xia, V Bex, PM Midgley (eds.)], Cambridge University Press: Cambridge, UK and New York, NY, USA. 1535pp. https://www.ipcc.ch/report/ar5/.

Intergovernmental Panel on Climate Change (IPCC). 2022. Annex II: Glossary [Möller, V., R. van Diemen, J.B.R. Matthews, C. Méndez, S. Semenov, J.S. Fuglestvedt, A. Reisinger (eds.)]. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. *Cambridge University Press*, Cambridge, UK and New York, NY, USA, pp. 2897–2930, doi:10.1017/9781009325844.029.

Intergovernmental Panel on Climate Change (IPCC). 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. doi:10.1017/9781009157896.

Kopp RE, RM Horton, CM Little, JX Mitrovica, M Oppenheimer, DJ Rassussen, BH Strauss, C Tebaldi. 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future* 2(8): 383-406. doi:10.1002/2014EF000239.

Kopp R, F Simons, J Mitrovica, A Maloof, M Oppenheimer. 2009. Probabilistic assessment of sea level during the last interglacial stage. *Nature* 462: 863-867. doi:10.1038/nature08686.

Levermann A, P Clark, B Marzeion, G Milne, D Pollard, V Radic, A Robinson. 2013. The multimillennial sea-level commitment of global warming. *Proceedings of the National Academy of Sciences* 110(34): 13745-13750. doi: 10.1073/pnas.1219414110.

Mengel M, Levermann A, Frieler K, Robinson A, Marzeion B, Winkelmann R. 2016. Future sea level rise constrained by observations and long-term commitment. *PNAS* 113(10): 2597-2602. doi.org/10.1073/pnas.1500515113

Miller, K. G., R. E. Kopp, B. P. Horton, J. V. Browning, and A. C. Kemp (2013), A geological perspective on sea-level rise and its impacts along the U.S. mid-Atlantic coast, Earth's Future, doi:10.1002/2013EF000135.

National Research Council (NRC). 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Report by the Committee on Sea Level Rise in California, Oregon, and Washington. National Academies Press, Washington, DC. 250 pp. http://www.nap.edu/catalog/13389/sea-level-rise-for-the-coasts-of-california-oregon-and-washington.

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

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., and Sanderson, B. M.: The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6, Geosci. Model Dev., 9, 3461–3482, https://doi.org/10.5194/gmd-9-3461-2016, 2016. https://gmd.copernicus.org/articles/9/3461/2016/

Perrette M, F Landerer, R Riva, K Frieler, M Meinshausen. 2013. A scaling approach to project regional sea level rise and its uncertainties. *Earth System Dynamics* 4(1): 11-29. doi:10.5194/esd-4-11-2013.

Rahmstorf S. 2007. A semi-empirical approach to projecting future sea-level rise. *Science* 315(5810): 368-370. doi:10.1126/science.1135456.

Slangen, A.B.A., Carson, M., Katsman, C.A. *et al.* Projecting twenty-first century regional sea-level changes. *Climatic Change* **124**, 317–332 (2014). https://doi.org/10.1007/s10584-014-1080-9

Slangen, A., Palmer, M., Camargo, C., Church, J., Edwards, T., Hermans, T. Hewitt, G., Gregory, J., Kopp, R., Santos, V., Van de Wal, R. (2023). The evolution of 21st century sea-level projections from IPCC AR5 to AR6 and beyond. *Cambridge Prisms: Coastal Futures, 1*, E7. doi:10.1017/cft.2022.8

Smith WH, DT Sandwell. 1997. Global sea floor topography from satellite altimetry and ship depth soundings. *Science* 277(5334): 1956-1962. doi: 10.1126/science.277.5334.1956.

Smith, W.H. and Sandwell, D.T. (1997) Global Sea Floor Topography from Satellite Altimetry and Ship Depth Soundings. Science, 277, 1956-1962. http://dx.doi.org/10.1126/science.277.5334.1956

Sweet, W.V., R.E. Kopp, C.P. Weaver, J. Obeysekera, R.M. Horton, E.R. Thieler and CZ. Global and Regional Sea Level Rise Scenarios for the United States. 2017.

Sweet, W.V., B.D. Hamlington, R.E. Kopp, C.P. Weaver, P.L. Barnard, D. Bekaert, W. Brooks, M. Craghan, G. Dusek, T. Frederikse, G. Garner, A.S. Genz, J.P. Krasting, E. Larour, D. Marcy, J.J. Marra, J. Obeysekera, M. Osler, M. Pendleton, D. Roman, L. Schmied, W. Veatch, K.D. White, and C. Zuzak, 2022: Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines. NOAA Technical Report NOS 01. National Oceanic and Atmospheric Administration, National Ocean Service, Silver Spring, MD, 111 pp. https://aambpublicoceanservice.blob.core.windows.net/oceanserviceprod/hazards/sealevelrise/noaa-nos-techrpt01-global-regional-SLR-scenarios-US.pdf

USGCRP, 2018: Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II: [Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart (eds.)]. U.S. Global Change Research Program, Washington, DC, USA, 1515 pp. doi: 10.7930/NCA4.2018. https://nca2018.globalchange.gov/downloads/NCA4_2018_FullReport.pdf

Willis, J., Hamlington, B., & Fournier, S. (2023). Global Mean Sea Level, Trajectory and Extrapolation (Version 101) [dataset]. Zenodo. https://doi.org/10.5281/zenodo.7702315