Chapter 3. Sea Level Rise Science

This chapter covers the following subjects:

- The best available science on sea level rise
- Guidance on the application of best available science for activities subject to Coastal Act review
- Using scenario-based analysis and adaptation pathways in response to the uncertainty regarding anticipated amounts of sea level rise
- The physical impacts of sea level rise
- Storms and extreme events

Sea level rise science continues to evolve, and the discussion below reflects the best available science at the time this document was published.

BEST AVAILABLE SCIENCE ON SEA LEVEL RISE

Scientists widely agree that the climate is changing and that it has led to global increases in temperature and sea level. In the past century, global mean sea level (GMSL) has increased by nearly 8 inches (20 cm; Fox-Kemper *et al*., 2021). The Intergovernmental Panel on Climate Change's (IPCC) most recent report, the *Sixth Assessment Report* (AR6), states that human activities have unequivocally caused global warming, with global surface temperatures in 2011–2020 reaching 1.1°C above temperatures observed in 1850–1900. It also states that human influence was very likely the main driver of sea level rise since at least 1971, and that GMSL has risen faster since 1900 than over any preceding century in at least the last 3000 years (IPCC 2021).

Observations of sea level rise rates have also shown that global sea level rise has been accelerating in recent decades. While tide gauge measurements show roughly 5 inches of global mean 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).

Scientists measure and project sea level change at a variety of scales, from the global down to the local level. The global sea level rise projections in IPCC reports are based on large-scale models as well as scientific understanding of the historical climate and best available information regarding climate sensitivity (IPCC 2021). Global average sea level rise is driven by the expansion of ocean waters as they warm (thermal expansion), the addition of freshwater to the ocean from melting ice sheets and glaciers, and from extractions in groundwater (Figure 3).

However, regional and local factors such as tectonics and ocean and atmospheric circulation patterns can cause different parts of the globe to experience relative sea level rise rates that may be higher or lower than the global average. As such, global-scale models are often "downscaled" through a variety of methods to provide locally relevant data.

For California, the Ocean Protection Council's 2024 State of California Sea Level Rise Guidance, described below (with additional detail in Appendix A), provides both statewide average sea level rise scenarios as well as scenarios that have been refined for 14 tide gauges throughout California.[21] While these tide gauge-specific sea level rise scenarios are fairly similar throughout the state, the physical impacts experienced in each location may be quite different, and locally-specific analysis of impacts will be very important. Detail on physical impacts and how to assess them is provided in this chapter and in Appendix B.

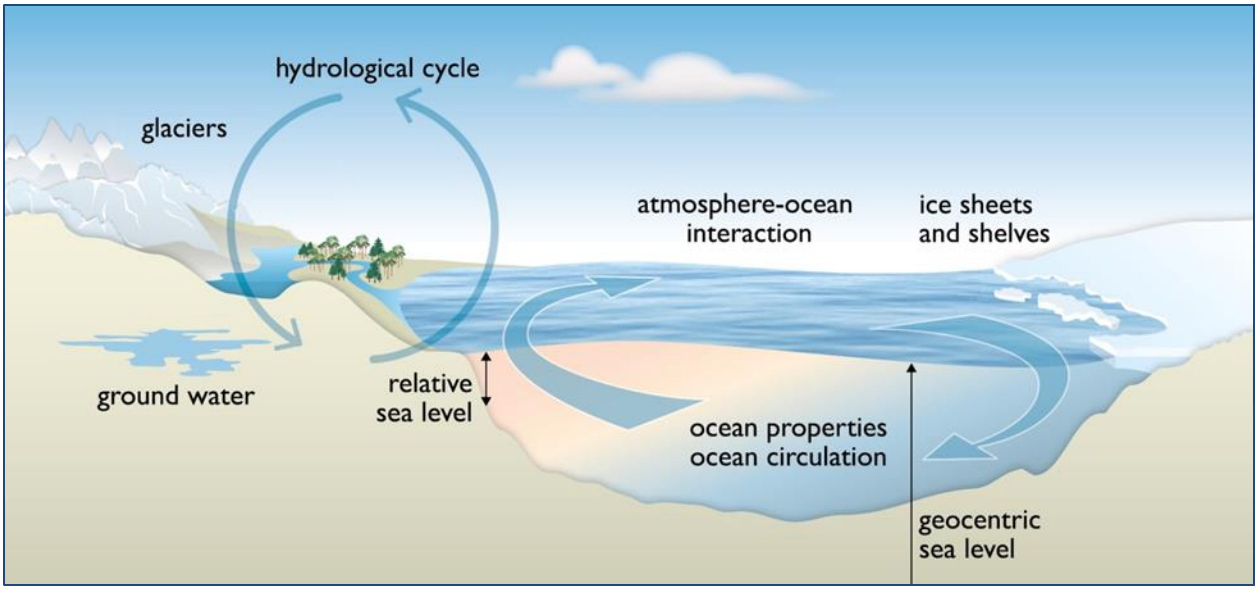

Figure 3. Climate-sensitive processes and components that can influence global and regional sea level. Changes in any one of the components or processes shown will result in a sea level change. The term "ocean properties" refers to aspects such as temperature, salinity, and density, which influence and are dependent on ocean circulation. (*Source*: IPCC 2013, Figure 13.1)

Global Sea Level Rise Projections

The IPCC Sixth Assessment Report, Climate Change 2021: the Physical Science Basis (AR6) was released in 2021 (IPCC 2021). AR6 describes both a *plausible range* of potential future sea level rise, as well as a more narrow *likely range*. IPCC's full *plausible range* of future sea level rise reflects how sea level rise would vary under the IPCC's range of conceivable global development, emissions, and warming futures (which are called Shared Socioeconomic Pathways, or SSPs[22]) as well as the possibility of rapid ice sheet disintegration. Below is a graph

[21] For any given analysis, sea level rise scenarios for the closest of the 14 tide gauges can be used, or where very localized GPS data is available allowing more resolved estimates of vertical land motion, these can be added to the statewide average scenario values provided in this chapter and in Appendix G.

[22] 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 would each result in various amounts of radiative

generated by NASA and the IPCC's Sea Level Projection Tool that depicts all of AR6's global mean sea level rise projections (Figure 4).

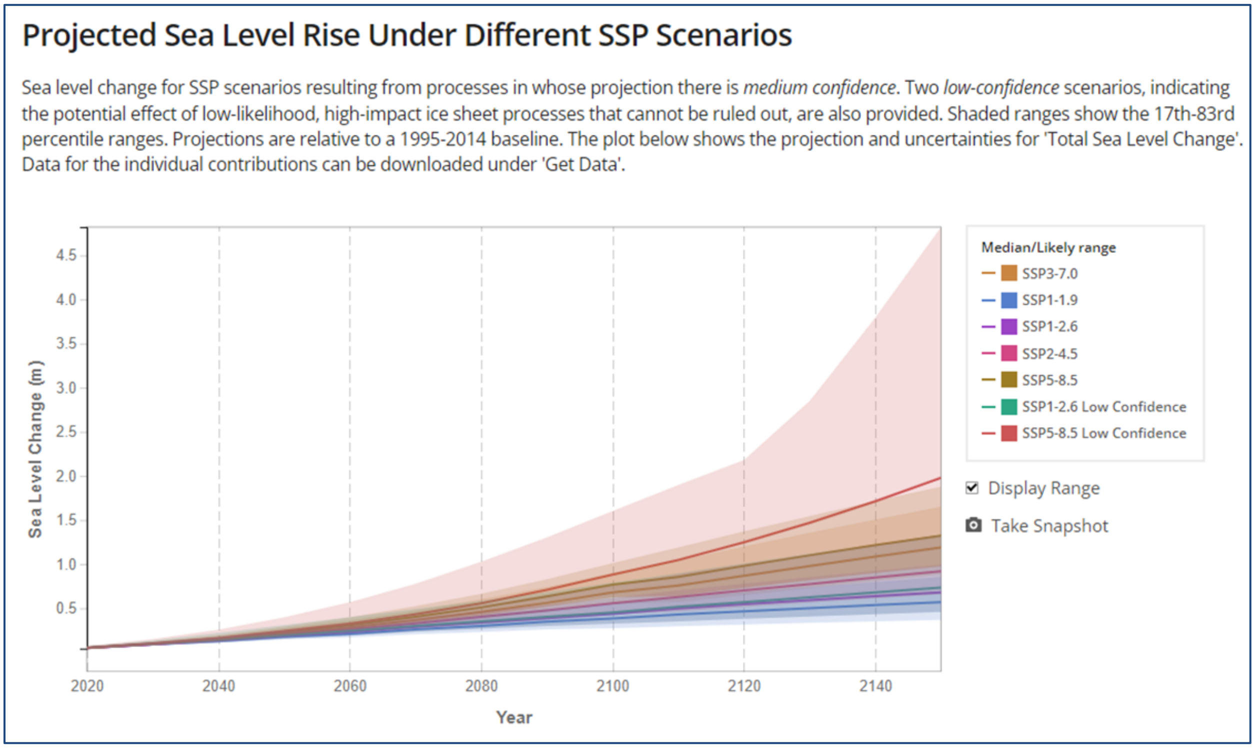

Figure 4. IPCC AR6 plausible range of future sea level rise. A graph generated by NASA and the IPCC's Sea Level Projection Tool that depicts the global mean sea level rise projections under all five SSPs, plus the two additional projections that incorporate additional low confidence ice sheet processes.

In addition to the full plausible range of sea level rise, AR6 identifies a narrower *likely range* of future sea level rise. It distinguishes the projections that are based on processes in which the authors have at least medium confidence (e.g., thermal expansion of seawater and some ice sheet and glacier melt processes) from those in which they have "low confidence" due to a present lack of sufficient research (i.e., processes that would lead to rapid ice sheet disintegration). IPCC therefore describes the shaded regions of Figure 5 below as the likely range of sea level rise by 2100 and the dashed line as a low-likelihood, high impact scenario that includes ice sheet instability processes and cannot be ruled out due to deep uncertainty in those processes.

forcing (a measure of warming), 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.

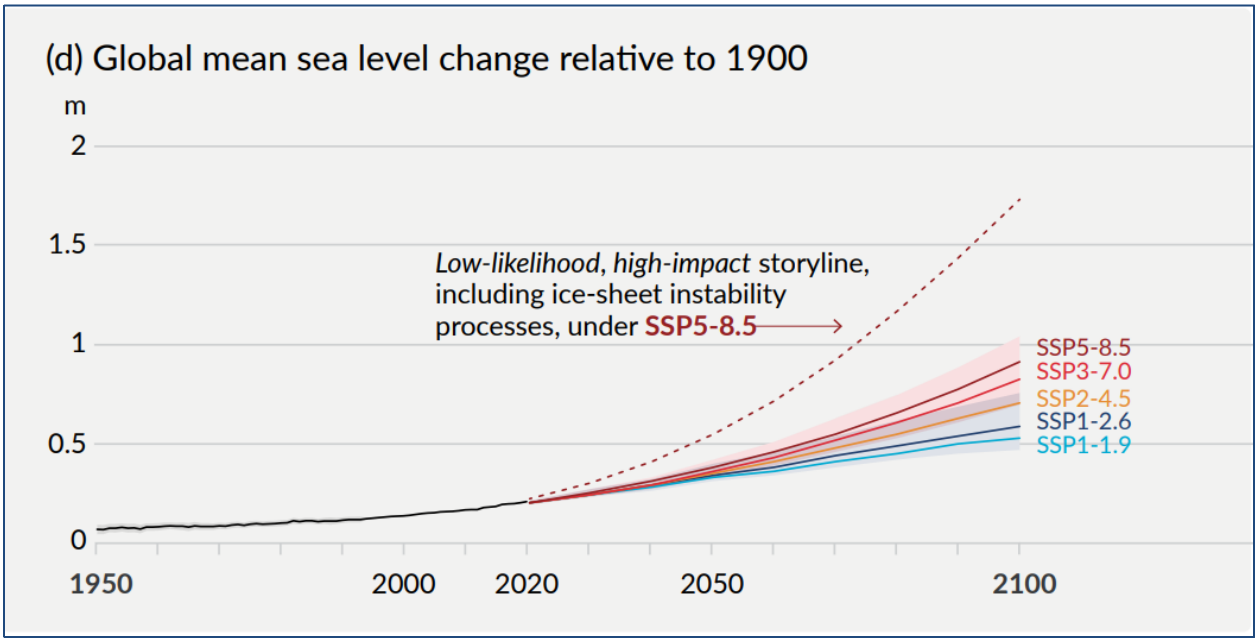

Figure 5. IPCC AR6 SLR projections by 2100. This figure is figure SPM.8(d) in AR6 Summary for Policymakers, and its caption reads, in part, "Only likely ranges are assessed for sea level changes due to difficulties in estimating the distribution of deeply uncertain processes. The dashed curve indicates the potential impact of these deeply uncertain processes. It shows the 83rd percentile of SSP5-8.5 projections that include low-likelihood, high-impact ice-sheet processes that cannot be ruled out; because of low confidence in projections of these processes, this curve does not constitute part of a likely range."

After the publication of sea level rise projections in AR6 in 2021, NOAA's Global and Regional Sea Level Rise Scenarios for the United States (Sweet *et al*., 2022) provided a set of five global mean sea level rise scenarios – hypothetical trajectories of future sea level rise spanning the scientifically plausible range defined by the IPCC[23]. These five scenarios were benchmarked to 0.3, 0.5, 1.0, 1.5, and 2.0 meters-in-2100 and were called the Low, Intermediate-Low, Intermediate, Intermediate-High and High, respectively. Below is a graph generated by NASA Interagency Sea Level Rise Scenario Tool that depicts these five sea level rise scenarios (Figure 6).

NOAA deemed the High scenario, which includes 2.0 meters of sea level rise in the year 2100, to be a reasonable high-end sea level rise scenario for the year 2100 due to updated research on potential mechanisms of rapid ice sheet disintegration. Namely, DeConto *et al*., 2021 used updated regional climate model forcing to find that air temperatures may trigger mechanisms of rapid retreat of the Antarctic Ice Sheet[24] by about the year 2125 – and the associated extreme sea level rise trajectory could reach approximately 2.0 meters in 2100.

[23] For an explanation of the difference between sea level rise projections and sea level rise scenarios, please see Appendix A.

[24] DeConto *et al*., 2021 updated DeConto *et al*., 2016, which provided the basis for the H++ sea level rise scenario included in the past iteration of the OPC *State Sea Level Rise Guidance* and the past iteration of this policy guidance document. DeConto *et al*., 2021 found that, when considering updated climate models, the processes of

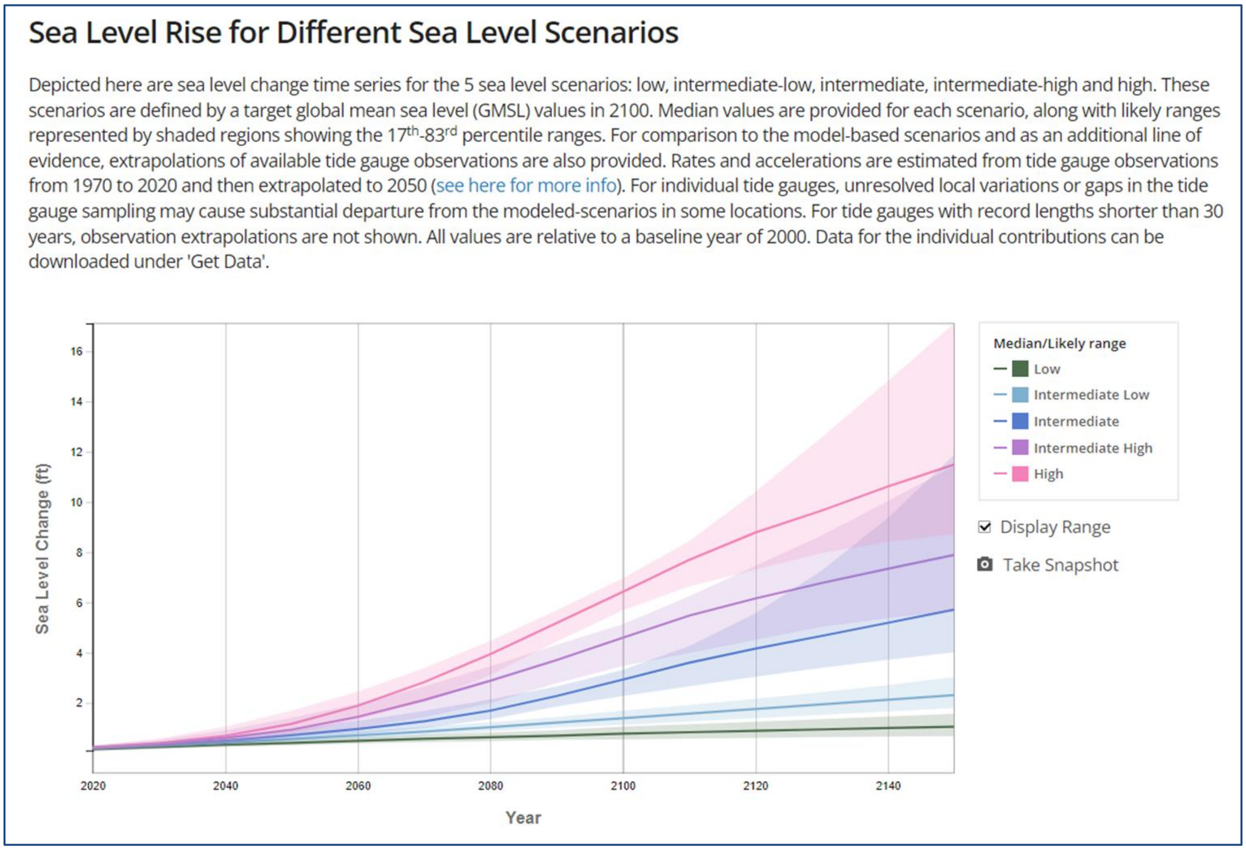

Figure 6. Global Sea Level Rise Scenarios from Sweet *et al*., 2022. This graph was generated by NASA Interagency Sea Level Rise Scenario Tool and depicts Sweet *et al*., 2022's five global mean sea level rise scenarios.

National Sea Level Rise Projections

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 its five global scenarios. These regionalized scenarios reflect 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 (GRD) changes (i.e., ice sheet fingerprinting). In general, sea level rise scenarios for the United States are similar to or higher than global mean sea level rise due to effects from these regional influences on sea level (Sweet *et al*., 2022). Below 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 7).

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rapid ice sheet disintegration would be delayed about 25 years relative to DeConto et al 2016. (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.")

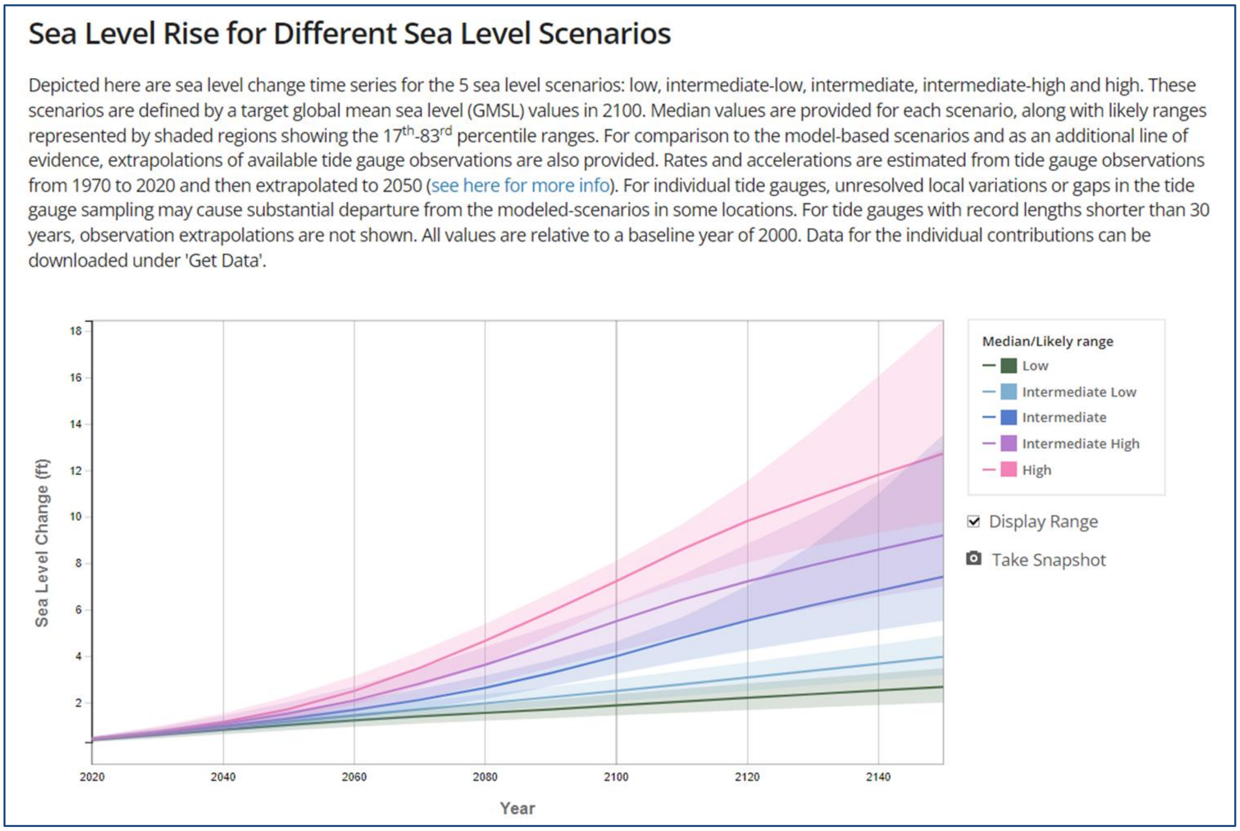

Figure 7. Sea level rise scenarios for the contiguous United States from Sweet *et al*., 2022. This graph was generated by NASA Interagency Sea Level Rise Scenario Tool and depicts Sweet *et al*., 2022's five sea level rise scenarios for the contiguous United States.

Sea Level Rise Projections for California

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 California Coastal Commission has historically aligned its *Sea Level Rise Policy Guidance* with the best available science provided in each iteration of the *California State Sea Level Rise Guidance*, as has been done here.

The 2024 State Sea Level Rise Guidance (OPC 2024) provides the same five sea level rise scenarios as Sweet *et al*., 2022[25] with further downscaling to reflect regional and local influences on sea level rise in California. Scenarios are provided for California as a whole, reflecting statewide average vertical land motion, as well as for each of the 14 tide gauge locations in the state to reflect local vertical land motion. The median statewide values are shown below in Table 3. The tide gauge-specific scenarios are provided in Appendix 2 of the State Sea Level Rise Guidance (2024) and in Appendix F of this document.

Table 3. Sea Level Rise Scenarios for California [26]

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

[25] 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.

[26] 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.

To describe the likelihood of each scenario occurring in the future, the State Sea Level Rise Guidance (OPC 2024) compares each scenario to AR6 to derive information about what would have to happen in the future climate for each one to come to pass. The State Guidance presents these "storylines" 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 feet), 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 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."

The State Sea Level Rise Guidance also provides information about how likely each scenario is to occur in the year 2100 under various amounts of plausible future warming (the first five columns of Table 4). Likelihoods were also provided assuming rapid ice sheet disintegration processes come into play in the 2100s (the last two columns of Table 4). These likelihoods were derived from AR6, and they provide valuable information to inform our understanding of the likelihood that each scenario as well as the risk that the higher or lower scenarios may occur.

As explained in the State Guidance, this table can be 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 4. Exceedance probabilities for the sea level scenarios based on IPCC warming level-based global mean sea level projections[27]

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%

As highlighted in Table 3, the State Sea Level Rise Guidance identifies the Intermediate, Intermediate-High, and the High scenarios as the most appropriate scenarios to use in technical analyses of future sea levels, consistent with its precautionary approach. The following section and Chapters 5 and 6 provide additional detail on how to use these sea level rise scenarios to guide SLR planning in the context of the California Coastal Act.

[27] The 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."

Comparing the 2024 Best Available Science to the 2018 Science

The previous iteration of this CCC guidance was published in 2018, and this document replaces and supersedes that one. Likewise, the previous iteration of the OPC's California State Sea Level Rise Guidance was published in 2018 and has since been replaced by a revised document published in 2024. Each document synthesized the best available science on sea level rise that was available at the time. The 2024 updates to both documents reflect additional research conducted since 2018.

Both 2018 guidance documents provided SLR projections based on the Rising Seas in California report (Griggs et al., 2017). Like the IPCC Assessment Reports, it provided probabilistic projections of sea level rise tied to high and low Representative Concentration Pathways (RCPs, or the IPCC's scenarios of future emissions levels) (RCP 8.5 and 4.5, respectively), which defined possible future amounts of global warming. In addition, both 2018 documents provided a standalone, extreme SLR scenario called H++, which illustrated the rate of SLR that could occur if the mechanisms of extreme ice sheet collapse occurred as described in the then-recently released paper, DeConto & Pollard, 2016 in a high emissions future (RCP 8.5). The guidance documents went on to define low, medium-high, and extreme (H++) risk aversion scenarios to use in various contexts that depended on the project and planning context.

The 2024 guidance documents provide updated sets of sea level rise amounts. Instead of probabilistic projections and a single H++ scenario, the 2024 updates include five SLR scenarios that span the plausible range of sea level rise included in IPCC's Sixth Assessment Report. These scenarios are slightly lower than the sea level rise amounts provided in the 2018 guidance documents. One main reason for this change is that additional research was conducted on possible extreme ice sheet melt (DeConto et al., 2021). This research incorporated updated climate models which found that the atmospheric warming needed to potentially trigger the processes of rapid ice sheet disintegration were delayed about 25 years relative to the earlier research (DeConto et al., 2016). Thus, the high amounts of SLR associated with the 2018 H++ scenario could occur if the ice sheet disintegration mechanisms begin (which is still an area of developing research), but they appear more likely to occur about 25-30 years later than previously thought. Thus, while H++ included 10 feet of SLR in the year 2100, the High scenario in the 2024 Guidance documents includes 10 feet in the year 2130.

Similar to how the low, medium-high, and extreme risk aversion scenarios were recommended for use in different contexts in the 2018 guidance, the 2024 guidance recommends using the Intermediate, Intermediate-High, and High scenarios. More information on choosing appropriate SLR amounts is included in the next section and Chapters 5 and 6.

The Coastal Commission considers the State of California Sea Level Rise Guidance (OPC 2024) to be the best available science on sea level rise in California, and recommends using the Intermediate, Intermediate-High, and High scenarios in relevant Coastal Commission planning and permitting decisions. More information on which scenarios to use in certain circumstances can be found in the following section as well as Chapters 5 and 6. The Commission will continue to periodically re-examine and update sea level rise projections as they evolve with the release of new scientific reports and information on local and regional sea level trends. Additionally, as sea level rise science continues to evolve, equivalent resources may be used by local governments and applicants provided the sources are peer-reviewed, widely accepted within the scientific community, and locally relevant.

The Coastal Commission will be using and recommends that local governments and applicants use best available science, currently identified as the scenarios provided in the 2024 OPC California State Sea Level Rise Guidance (Table 3; Appendix F), in all relevant local coastal planning and coastal development permitting decisions.

Guidance for Application of Best Available Science

This section offers key pieces of guidance for both the analysis of sea level rise as well as the development of project designs, adaptation strategies, and/or adaptation pathways to be included in Coastal Development Permits (CDPs), adaptation plans, or Local Coastal Programs (LCPs).

Sea level rise analyses

There is a diversity of planning exercises, studies, and development projects that take place in the Coastal Zone, and their associated technical analyses on sea level rise can also vary in terms of level of detail and complexity. This guidance generally recommends analyzing several sea level rise scenarios including a relatively high, precautionary scenario relevant to the planning/project context, as described in the general framework listed below. However, a variety of site- and situation-specific factors may warrant analysis of a different set of sea level rise amounts or a particular number of scenarios.

The overall goal of technical analyses should be to provide sufficient detail on how coastal hazard conditions may develop over time, considering sea level rise, to inform appropriate land use policies and zoning, project siting and design, implementation of adaptation strategies or adaptation pathways, and so on for the subject project, site, or planning area. Considering higher end amounts of sea level rise is important for understanding what types of planning and adaptation options may be necessary if worst case scenarios come to pass, or to inform decisions for new development with long lifetimes that would be hard to relocate, remove, or otherwise adapt to higher amounts of sea level rise in the future. Conversely, analysis of lower sea level rise amounts may assist in identification of tipping points – i.e., amounts of sea level rise or other combinations of hazard conditions that could lead to significant impacts and warrant adaptive responses. Similarly, understanding lower or nearer-term sea level rise amounts may be important for guiding design of restoration projects, or other types of projects that are meant to be within or immediately adjacent to the ocean or intertidal areas.

It is also important to note that it may not always be necessary to evaluate different sea level rise amounts in the same level of detail. In some cases, it may be sufficient to use screening tools such as CoSMoS to analyze high- or low-end scenarios to build a general understanding of the implications of sea level rise amounts, while more detailed analysis may be appropriate for scenarios that constitute important tipping points or on which detailed decision points depend. The following section further discusses the benefits of scenario-based analysis in the context of both LCPs and CDPs, and Chapters 5 and 6 discuss steps for conducting analyses of SLR and incorporating the results into LCPs and CDPs, respectively.

While the above context and caveats will always be important, this guidance offers the following framework to generally guide the selection of sea level rise scenarios to include in technical *analyses* over the life of the proposed development or planning horizon[28], including at the project level and in broader vulnerability assessments:

1. *Intermediate Scenario*: The Intermediate scenario should be included in technical analyses for development with low risk aversion, i.e., development that would have limited consequences or a higher ability to adapt, such as some ancillary development or public access amenities.
2. *Intermediate-High Scenario*: The Intermediate-High scenario should be included in technical analyses for development with medium-high risk aversion, i.e., development that would experience greater consequences and/or have a lower ability to adapt, such as most residential and commercial structures.
3. *High Scenario*: The High scenario should be included in technical analyses for development with extreme risk aversion, i.e., development with little to no adaptive capacity that would be irreversibly destroyed or significantly costly to repair, and/or would have considerable public health, public safety, or environmental impacts should that level of sea level rise occur, such as most critical infrastructure.[29]

Project design and selection of adaptation strategies or pathways

In practice, the Coastal Commission has found that there is an important distinction between selecting sea level rise scenarios to *analyze* (as described above) and selecting scenarios to

[28] Chapters 5 and 6, respectively, discuss appropriate planning horizons for LCP analyses and anticipated project lifetimes in greater detail. In general, LCP analyses should account for long-term planning horizons (75-100 years). For proposed development, temporary structures or ancillary development often have shorter lifetimes (~25 years); residential structures have 75-100 year lifetimes; and critical infrastructure has a 100-year (or greater) lifetime.

[29] For more information on sea level rise planning for critical infrastructure, see also the Coastal Commission's Critical Infrastructure at Risk planning guidance.

inform on-the-ground *siting and design*, including individual project designs and adaptation strategies for sites or regions. Technical analyses should describe the hazards the site might experience from a range of possible sea level rise scenarios, including a likely amount of sea level rise that could occur over the planning horizon at hand as well as sea level rise amounts that are higher and less likely to occur, though still possible, as identified above. This information should inform alternatives analyses, adaptation pathways (or phased adaptation), monitoring programs, and public awareness of the full range of possible risks. In contrast, decisions regarding immediate on-the-ground development – including project siting and design, land use designations, and adaptation projects – may, in some cases, reflect a different amount of sea level rise than the highest amount included in technical analyses.

The Coastal Act sets forth a series of requirements for development in the coastal zone, including that development assure stability and structural integrity (Section 30253(b)). In some cases, the most appropriate way to comply with this requirement may be to completely avoid hazards, including those related to higher end amounts of sea level rise, over the full anticipated lifetime of the development. For some projects or adaptation plans, decision-makers may find that doing so would achieve the best outcomes for coastal resources and pose no significant tradeoffs, costs, or feasibility implications. However, there are a variety of interrelated factors that affect decisions regarding project design (and/or LCP policies that direct project design) that may support or necessitate initially designing for lower sea level rise amounts and incorporating requirements to adapt in some manner if higher, but less likely, sea level rise scenarios come to pass. These factors may directly relate to Coastal Act issues, such as potential coastal resource impacts, while others relate to broader planning considerations such as costs and engineering feasibility. Such factors may include:

- **Coastal resource impacts**: Designing to be safe from the highest scenario included in the technical analysis could present tradeoffs for coastal resources or cause two coastal resource interests to conflict. For example, building higher or longer bridges to account for the highest amounts of potential sea level rise may result in greater fill or other impacts to wetlands or estuarine habitat from more substantial bridge supports. Similarly, setting portions of Coastal Trail further back may avoid the need for future realignments, but doing so may mean the trail is no longer in sight of the ocean in the short and medium-term. Understanding the scope and scale of such resource impacts and weighing them against project design and phasing alternatives will be important.
- **Community impacts**: Similarly, designing to be safe from the highest scenario included in the technical analysis could present tradeoffs for communities, including environmental justice communities that may experience unequal burdens or impacts. For example, redesigning or relocating parking lots or other public access amenities to completely avoid impacts from high-end sea level rise may limit opportunities for visiting the coast, disproportionately impacting those who live further away. And relocating transportation infrastructure farther inland without assessing the communities who live nearby or use the current and alternative routes may result in a pollution or displacement burden to these inland communities. Any adverse impacts such as loss of wages or a disruption in day-to-day routines will have an even greater

impact on low-income workers or individuals who often have less capacity to adapt to these changes.

- **Site Considerations**: Site constraints, such as parcel size, presence of coastal resources, surrounding patterns of development, or property ownership may limit the range of feasible adaptation alternatives. For example, parcel sizes may be too small to allow for setbacks for new houses that account for the highest amounts of sea level rise. Similarly, the presence of ESHA or wetland habitat in a portion of the site may affect where or how development could be sited and designed.
- **Interconnected Systems**: A project or plan's relationship to a networked system of development or infrastructure could limit the range of feasible alternatives due to the necessity of providing connections to the rest of the network. For example, a single pump station may need to be redesigned to account for continued coastal hazards-related damage. Over the long-term, the entire system of wastewater infrastructure may need to be redesigned to account for higher amounts of sea level rise, something that would require significant and complex planning, but in the immediate term, the single pump station will need to adapt in ways that continue to carry out the functions of the connected system, likely only accounting for lesser amounts of sea level rise while a longer term plan is developed.
- **Feasibility and Costs**: Engineering and cost constraints can also affect the analysis of feasible alternatives. In some cases, "over"-designing to account for the highest sea level rise amounts could result in significant cost increases that may jeopardize feasibility and result in a project that cannot be funded and undertaken. "Over"-design could also result in over-engineered projects that result in greater coastal resource impacts. As described above, a bridge designed to account for the highest amount of sea level rise could result in greater wetland fill. Similarly, over-designing development or shoreline protective devices to account for worst-case sea level rise could make such structures more difficult to remove without significant coastal resource impacts in the future. Conversely, "under" designing could result in higher total costs and impacts if the project has no adaptive capacity and has to be completely rebuilt sooner than expected. Cost analyses can compare the marginal cost of designing for higher sea level rise amounts at the outset versus the cost of implementing additional adaptation phases in the future.
- **Adaptation pathway alternatives**: In some cases, it may be possible to design for higher-end sea level rise amounts at the outset, even considering some of the above factors that result in various trade-offs. In other cases, it may be necessary to consider adaptive responses to address higher amounts of sea level rise. Rather than initially designing a project or plan to address the full range of sea level rise included in the technical analysis, adaptation pathways based on monitoring and triggers can allow for stepwise adaptation that maximizes coastal resource benefits over time, avoids overdesigning or overengineering projects, and is cost effective. Depending on the specific hazards, vulnerabilities, coastal resource trade-offs, costs, and so on, adaptation pathways can be fairly basic – such as requiring removal of a structure if and when it

becomes threatened by sea level rise – or more detailed – such as identifying multiple steps for redesigning a City's water infrastructure over time. It also may be prudent to harmonize an adaptation pathway approach with any geographically broader or regional adaptation planning efforts that aim to balance benefits and burdens of adaptation across communities, geographically, and/or across coastal resource types.

The importance of these factors has been borne out by many projects and plans approved by the Coastal Commission in the past. For example, in the Cardiff living shoreline project designed to protect a low-lying stretch of Highway 101 in Encinitas, the dunes of the living shoreline could not be built high enough to fully protect the highway from a full range of sea level rise without blocking views of the ocean from the highway – an adverse scenic and visual impact inconsistent with the Coastal Act. Because it was possible to adaptively manage the height of the dunes, the Commission approved a design with lower dune heights in order to preserve the visual resource.

Similarly, the Gleason Beach Highway 1 Realignment project in Sonoma County was designed to account for sea level rise but had to consider a variety of the above factors, including the presence of agricultural lands, ESHA, wetlands, private property, and public access. The final design sets most of the segment of highway back far enough to be safe from most potential sea level rise impacts over the project's planning horizon except for the parts on either end of the project area that connect with the adjoining highway. To account for possible impacts to these connector points, the project requires monitoring and establishes triggers to initiate future planning if and when they are threatened. At the same time, the project was able to minimize impacts to and actually realize the enhancement of habitat restoration including salmon stream restoration.

Using scenario-based analysis and adaptation pathways in response to uncertainty in sea level rise scenarios

As described in the sections above, sea level rise scenarios, including those in the State Sea Level Rise Guidance (OPC 2024) (Table 3; Appendix G) and other state, national, and global reports, are typically presented in ranges due to several sources of significant uncertainty.

The two primary sources of uncertainty in global sea level projections include:

1) Uncertainty about future greenhouse gas emissions and concentrations of sulfate aerosols, which will depend on future human behavior and decision making, and
2) Uncertainty about future rates of land ice loss (Fox-Kemper *et al*., 2021; Sweet *et al*., 2022).

Additionally, the further into the future sea level rise is projected, the greater the uncertainty (and therefore the range in projections) becomes. This occurs because the longer the projection period, the greater the likelihood that models will deviate from the actual impacts of climate change and the more dependent projections become on the trajectory of greenhouse gas emissions (California State Sea Level Rise Guidance, 2024). According to the 2024 OPC Guidance, near-term sea level rise has been locked in by past greenhouse gas emissions whereas sea level rise over the longer-term will become increasingly dependent on efforts to curtail greenhouse gas emissions.

This Guidance recommends using scenario-based analysis to address the uncertainty in sea level projections. Scenario-based analysis (or planning) refers to the idea of identifying multiple scenarios from which to analyze vulnerabilities, generate new ideas and adaptation options, and/or test strategies. In the context of this Guidance, scenario-based analysis includes choosing several possible sea level rise amounts as a starting point to evaluate impacts to coastal resources and potential risks to development over time. This type of scenario-based approach is useful because it reveals the full range of possible consequences of sea level rise that can be reasonably expected for particular regions or sites according to the best available science. Additionally, a scenario-based analysis helps to reveal the tipping points indicating if or when sea level rise will become a serious issue in a particular location. In many cases, using multiple sea level rise scenarios will help to hone in on the types of hazards for which to prepare.

In general, the Coastal Commission recommends using best available science (currently the 2024 State Sea Level Rise Guidance (OPC 2024)) to identify a range of sea level rise scenarios up to and including an appropriately high, precautionary scenario relevant for the planning or project context at hand. In practice, the process for choosing scenarios and performing scenario-based analysis will be slightly different for LCP planning and CDP applications due to the different planning goals and levels of technical detail required for each.

For a Local Coastal Program (LCP), the general goal is to assess the potential impacts from sea level rise over the entire planning area and over a range of time horizons so that both short and long term adaptation strategies can be identified and implemented. Another important facet of LCP planning is identifying locations and communities that are particularly vulnerable so that additional, more detailed studies can be performed if necessary, and adaptation options and actions can be prioritized. Scenario-based analysis in the context of LCP planning includes choosing a range of sea level rise scenarios to analyze so as to understand the best and worst case scenarios and to identify amounts of sea level rise and related conditions that would trigger severe impacts and the associated time period for when such impacts might occur. This information can lead to the development of adaptation pathways, or series of adaptation measures to deploy when certain triggers or thresholds are crossed. LCP updates can then be developed to reflect the first stage of the adaptation pathway (e.g., land use designations or development standards that carry out the initial adaptation steps), as appropriate, along with policies outlining and establishing the goals for the next stages of the adaptation pathways. Choosing sea level rise scenarios in the context of LCP planning is described in greater detail in Chapter 5.

In the context of a Coastal Development Permit (CDP) application, the goal is to understand how sea level rise will impact a specific site and a specific project over its expected lifetime so as to ensure that the proposed development is safe from hazards and avoids impacts to coastal resources. Thus, in the context of a CDP, it is important to identify the amounts of sea level rise that could result in effects to a particular site as well as the time period(s) over which those effects could occur so that the proposed development can be safely sited and designed to avoid resource and development impacts, or so that adaptation pathways can be developed to address the impacts of sea level rise as they unfold. Some sites will be completely safe from sea level rise under even the highest projection scenarios, while others will depend on the timing and magnitude of sea level rise to determine safety. Therefore, scenario-based planning analysis can be used as a screening process to identify if and when sea level rise might become a problem. Identifying sea level rise scenarios in the context of CDPs is described in greater detail in Chapter 6.

Overall, scenario-based planning should help planners make reasonable and informed decisions about whether their projects or plans are compatible with the local hazards influenced by sea level rise, and identify the types of adaptation measures or pathways that might be appropriate given the local circumstances and requirements of the Coastal Act. By exploring the range of future scenarios based on the best available science, users of this document can make decisions based on full understanding of possible future hazards, ultimately achieve outcomes that are safer for development, coastal resources, and communities, and avoid costly damages to projects.

For more information on scenario-based planning and development of adaptation pathways in the context of LCPs and CDPs see Chapters 5 and 6, respectively.

PHYSICAL EFFECTS OF SEA LEVEL RISE

Accelerating sea level rise has and will continue to have widespread adverse consequences for California's coastal resources (see summary in Figure 10). The main physical effects of sea level rise include increased flooding, inundation, groundwater rise, wave impacts, coastal erosion, changes in sediment dynamics, and saltwater intrusion. These impacts are interrelated and often occur together. Absent any preparatory action, an increase in sea level may have serious implications for coastal resources, development, and communities, as described in Chapter 4. In addition, these physical effects could have disproportionate impacts on environmental justice and tribal communities that have a high social vulnerability due to several factors, which can result in their increased exposure and sensitivity to adverse climate impacts as well as a lower ability to adapt.

Physical effects from sea level rise to the coastal zone include the following[30]:

- **Flooding and inundation:** Low lying coastal areas may experience more frequent flooding (temporary wetting) or inundation (permanent wetting), and the inland extents of 100-year floods may increase. Rising sea levels can accelerate flood risk; for example,

[30] Please see Chapter 4 of the State Sea Level Rise Guidance (2024) for additional discussion of the physical impacts of sea level rise.

only a 10 cm rise in sea level could double the flooding potential along the west coast in locations such as San Francisco and Los Angeles (Vitousek *et al*. 2017). Sea level rise will also increase the frequency of what we today consider to be high-tide flooding, especially starting in the 2030s. For example, the frequency of minor high-tide flooding is projected to increase by a factor of three to four from 2030 to 2050 under the Intermediate sea level rise scenario (Thompson *et al*., 2021; NASA Flood Analysis Tool). Riverine and coastal waters come together at river mouths, coastal lagoons, and estuaries, and higher water levels at the coast may cause water to back up and increase upstream flooding (Heberger *et al*. 2009). Drainage systems that discharge close to sea level could have similar problems, and inland areas may become flooded if outfall pipes back up with salt water. In addition, other climate change impacts such as increases in the amount of precipitation falling as rain rather than snow will add to river flooding in some areas.

- **Rising groundwater:** An increase in sea level could cause saltwater to push further into coastal groundwater aquifers, causing groundwater tables to rise (Befus *et al*., 2020; May *et al*., 2020). In general, coastal groundwater tables are expected to rise proportionally with sea level rise at a ratio that depends on the composition of the substrate. With enough sea level rise, groundwater tables could become shallow enough to compromise subsurface infrastructure. Additionally, groundwater could rise high enough to emerge at the surface, causing flooding even in places where overland flooding is curtailed by seawalls or other shoreline protective devices. Rising groundwater may also affect contaminated sites across the state, mobilizing contaminants in shallow soils that were previously above the water table (Cushing *et al*., 2023; Hill *et al*., 2023).
- **Saltwater intrusion:** An increase in sea level could cause saltwater to intrude into groundwater resources, or aquifers. Existing research suggests that rising sea level is likely to degrade fresh groundwater resources in certain areas, but the degree of impact will vary greatly due to local hydrogeological conditions. Generally, the most vulnerable hydrogeological systems are unconfined aquifers along low-lying coasts, or aquifers that have already experienced overdraft and saline intrusion. In California, saline intrusion into groundwater resources is a problem in multiple areas, including but not limited to the Pajaro Valley (Hanson 2003), Salinas Valley (Hanson *et al*. 2002a; MCWRA 2012), Oxnard Plain (Izbicki 1996; Hanson *et al*. 2002b), and the heavily urbanized coastal plains of Los Angeles and Orange Counties (Edwards and Evans 2002; Ponti *et al*. 2007; Nishikawa *et al*. 2009; Barlow and Reichard 2010). Groundwater sources for other coastal agricultural lands may also be susceptible to saltwater intrusion.
- **Wave impacts:** Wave impacts can cause some of the more long-lasting consequences of coastal storms, resulting in high amounts of erosion and damage or destruction of structures. The increase in the extent and elevation of flood waters from sea level rise will also increase wave impacts and move the wave impacts farther inland. Erosion rates of coastal cliffs, beaches, and dunes will increase with rising sea level and are likely to further increase if waves become larger or more frequent (NRC 2012). In addition,

recent research has suggested that winter wave heights and winter storm intensity in the North Pacific have, on average, increased over the last 50 years in parallel with climate change, sending larger and more powerful waves to the California shoreline. Some studies suggest that wave heights could continue to increase in the future, generally extending the reach of wave run up and further exacerbating the erosion that is already expected to increase due to rising sea levels, though this is a subject of ongoing research (Bromirski *et al*., 2023).

- **Erosion:** Large sections of the California coast consist of oceanfront bluffs that are often highly susceptible to erosion. With higher sea levels, the amount of time that bluffs are pounded by waves would increase, causing greater erosion. This erosion could lead to landslides and loss of structural and geologic stability of bluff top development such as homes, infrastructure, the California Coastal Trail, Highway 1, and other roads and public utilities. The Pacific Institute (Heberger *et al*. 2009) estimated that 41 square miles (106 square km) of coastal land from the California-Oregon border through Santa Barbara County could be lost due to increased erosion with 4.6 ft (1.4 m) of sea level rise by the year 2100. Approximately 14,000 people now live in those vulnerable areas. Increased erosion will not occur uniformly throughout the state. Dunes in Humboldt County could erode a distance of approximately 2000 ft (nearly 600 m) by the year 2100 (Heberger *et al*. 2009; Revell *et al*. 2011). In southern California, higher sea level rise could result in a two-fold increase in bluff retreat rates over historic rates, causing a total retreat of 75 feet on average by 2100 (Limber *et al.* 2018). Man-made structures like dikes and levees may also be impacted by erosion, increasing flooding risk of the areas protected by those structures, such as low-lying agricultural land. Over the long term, rising sea levels will also cause landward migration of beaches due to the combined effects inundation and loss of sediment due to erosion (NRC 2012).

Figure 8. Photo of Esplanade Apartments threatened by cliff erosion in 2013 in Pacifica, CA. (Source: California Coastal Records Project)

- **Changes in beaches, sediment supply and movement:** Sediment is important to coastal systems in, for example, forming beaches and mudflats and as the substrate for wetlands. Sea level rise will result in changes to sediment availability. Higher water levels and changing precipitation patterns could change erosion and deposition patterns. Loss of sediment could worsen beach erosion and possibly increase the need for beach nourishment projects (adding sand to a beach or other coastal area), as well as decrease the effectiveness and long-term viability of beach nourishment if sand is quickly washed away after being placed on a beach (Griggs 2010). Shoreline change models predict that by 2100, without changes in coastal management, 30 to 67% of Southern California beaches may be completely lost due to rising sea level (Vitousek *et al.* 2017; 2021; 2023; Bedsworth *et al.* 2018). Sediment supplies in wetland areas will also be important for long-term marsh survival. Higher water levels due to sea level rise, however, may outpace the ability of wetlands to trap sediment and grow vertically (Titus 1988; Ranasinghe *et al*. 2012; Van Dyke 2012).

STORMS AND EXTREME EVENTS

Much of the California coast is currently vulnerable to flooding and wave damage during large storm events, and even more of the coast is vulnerable to storm impacts when they occur during times of heightened water levels, such as high tides, El Niño events, a warm phase of the Pacific Decadal Oscillation, or a combination of these factors. Sea level rise will increase vulnerability to storms even more because rising water levels will result in more areas being impacted. Furthermore, climate change could impact the frequency and intensity of storms.

As summarized above, Bromirski *et al*., 2021 suggested that winter wave heights and winter storm intensity in the North Pacific have, on average, increased over the last 50 years in parallel with climate change, and studies suggest that wave heights could continue to increase in the future, further exacerbating the erosion that is already expected to increase due to rising sea levels. Previous research had shown conflicting evidence on whether storminess and wave size will change in the North Pacific Ocean (Cayan *et al*. 2009; Lowe *et al*. 2010; Dettinger 2011).

Extreme events are of particular concern to the examination of coastal vulnerability and damage because they tend to cause the greatest community upheaval and can result in irreversible changes to the coastal landscape. In the El Niño winter of 1982-1983, for example, a series of storms, several of which coincided with high tide, caused more than $200 million in damage (in 2010 dollars) to coastal California (OPC 2013). Similarly, the 2015/16 El Niño was one of the strongest on record, resulting in significant changes to the shoreline. California also experienced significant damage over a series of storms in January 2023 and January 2024.

Sea level rise will compound the impacts of storms. The 4^{th} California Climate Assessment found that a 100-year coastal flood would almost double the damages associated with just 20 inches of sea level rise alone (Bedsworth *et al.* 2018). Barnard *et al*., 2019 found that approximately 700,000 California residents and $250 billion in property could be exposed to flooding by 2100 under the high scenario and a 100-year storm. These impacts result because a rise in sea level will mean that flooding and damage will likely reach further inland. For these reasons, it is important to include these factors in the analysis of sea level rise hazards. Further discussion of the physical effects of sea level rise and methodologies for these analyses are included in Appendix B.