# Chapter 3

## Sea Level Rise Science

This chapter provides information on sea level rise science and covers the following subjects:

- The best available science on sea level rise
- Using scenario-based analysis in response to sea level rise projection ranges
- The physical impacts of sea level rise
- Storms, extreme events, and abrupt change

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 (MSL) has increased by 7 to 8 in (17 to 21 cm; IPCC 2013). It is extremely likely (>95% probability of occurrence) that human influence has been the dominant cause of the observed warming of the atmosphere and the ocean since the mid-20th century (IPCC 2013).

There are a number of methods for projecting future changes in global sea level, including using extrapolations from historical trends and observations, estimations from physical models, and combinations of observations and modeling, known as semi-empirical methods. For a detailed description of these techniques, see Appendix A.

Scientists also measure sea level change at a variety of scales, from the global down to the local level. For example, the sea level rise projections in Intergovernmental Panel on Climate Change (IPCC) reports are based on large scale models that give global projections. But sea level does not change uniformly around the globe, so modifications for local conditions are necessary for adaptation planning.

In particular, global average sea level rise is driven by the expansion of ocean waters as they warm, the addition of freshwater to the ocean from melting land-based 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 result in 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 2018 OPC SLR Guidance, described below, provides sea level rise projections that have been refined for 12 tide gauges throughout California. More detailed refinement of sea level rise projections is not considered necessary at this time, as variations from the nearby tide gauges will often be quite small, and may be insignificant compared to other sources of uncertainty[14]. It is important to note, though, that while the sea level rise projections are fairly similar throughout the state, the physical impacts may be quite different,

[14] Although the Commission believes that the OPC Guidance projections can be used without modification, it recognizes that other studies exist with localized data, for example those completed in the Humboldt Bay region, which may also be appropriate for use.

and locally-specific analysis of impacts will be very important. Detail on physical impacts and how to assess them is provided in Section C of this chapter and in Appendix B.

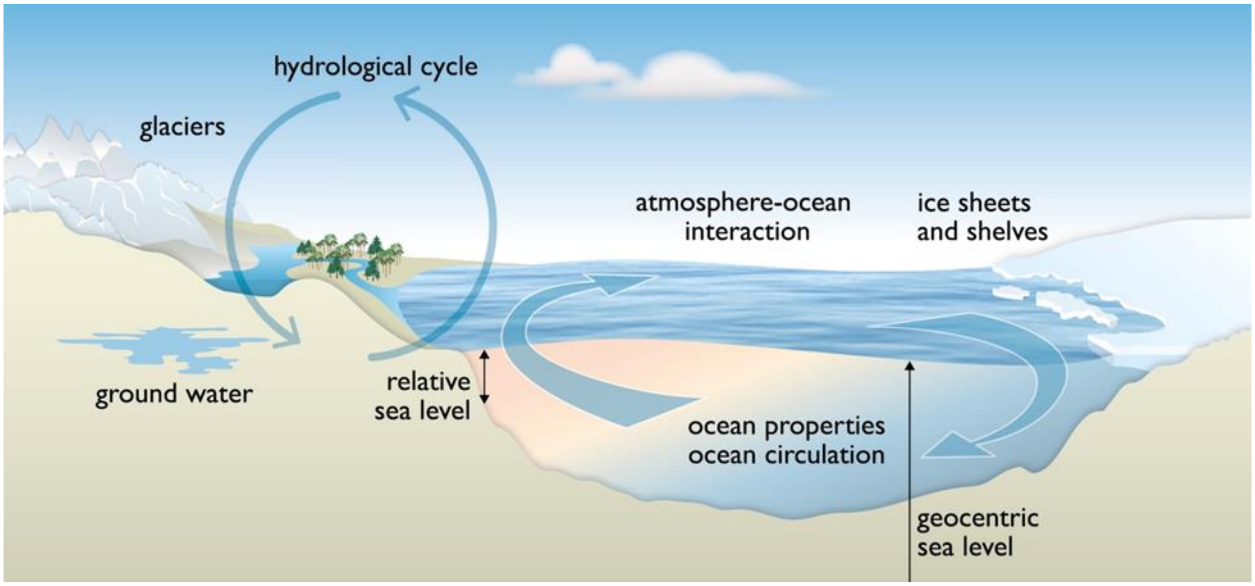


Figure 3. Climate-sensitive processes and components that can influence global and regional sea level. Changes in any one of the components or processes shown will result in a sea level change. The term "ocean properties" refers to aspects such as temperature, salinity, and density, which influence and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

### Global Sea Level Rise Projections

The IPCC 5th Assessment Report (AR5), which was released in September 2013, is the most recent global scale assessment of sea level rise. The report projects a rise in *global* average sea level by 10-39 in (26 to 98 cm) by the year 2100 (relative to mean sea level from 1985 to 2005) depending on the emissions scenario[15] (Figure 4). These projections are about 50% higher than the projections from the IPCC 4th Assessment Report (AR4, released in 2007). This is because the IPCC changed the climate model inputs between AR4 and AR5. In particular, much of the increase in the amount of sea level rise projected in the AR5 is due to the inclusion of sea level rise resulting from the loss of ice sheets. Ice sheet dynamics were not included in the AR4, but enhancements in physical models that account for such ice sheet dynamics have allowed for a better understanding and greater confidence in this input, and as such were included in the AR5[16]. The IPCC also released a special report in October 2018 that discusses the impacts associated with limiting global warming to 1.5°C as compared to 2°C. This report found that sea level rise would be about 10cm less with only 1.5°C, enabling greater opportunities for adaptation in both human and ecological systems (IPCC 2018).

[15] See Appendix A for more detail on emissions scenarios and the IPCC reports.

[16] Many of the other reports and studies cited in this Guidance used the AR4 as a reference (and for this reason detail on the AR4 is included in Appendix A). It is important to note, though, that while these other reports relied on the AR4 scenarios and model outputs for some climatic changes, many (*e.g.*, the *National Climate Assessment* (Melillo *et al*. 2014) and the NRC (2012) reports highlighted below) accounted for the loss of ice sheets through the use of semi-empirical models or other methods, further honing their results.

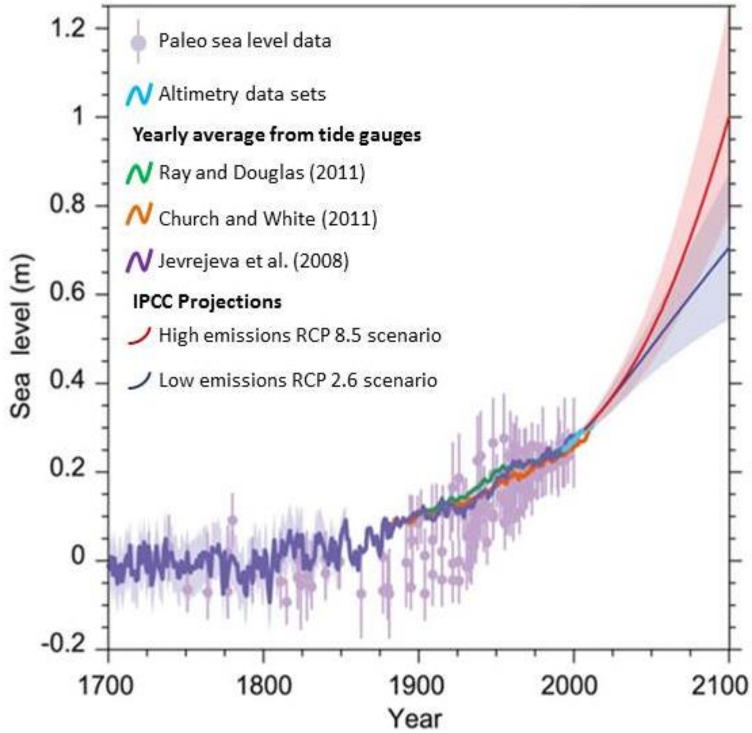


Figure 4. Past and projected future sea level trends (IPCC). Compilation of paleo sea level data, tide gauge data, altimeter data, and central estimates and likely ranges for projections of global mean sea level rise for low emissions RCP2.6 (blue) and high emissions RCP8.5 (red) scenarios, all relative to pre-industrial values. (*Source*: IPCC 2013, Figure 13.27)

## National Sea Level Rise Projections

The third National Climate Assessment (NCA; Melillo *et al*.) was released in May 2014, and includes the current best-available science on climate change and sea level rise at the *national* scale[17]. The sea level rise projections in the NCA were informed by the 2012 NOAA report titled *Global Sea Level Rise Scenarios for the United States National Climate Assessment* (Parris *et al*. 2012). This report provides a set of four global sea level rise scenarios ranging from 8 in to 7 ft (0.2 to 2.0 m) by the year 2100 (using mean sea level in 1992 as a baseline) reflecting different amounts of future greenhouse gas emissions, ocean warming and ice sheet loss (Figure 5). The low and intermediate-low scenarios assume very significant reductions in greenhouse gas emissions, and limited changes in ocean warming and ice sheet loss. The intermediate-high scenario is based on the average of the high projections from semi-empirical models, which are based on the highest IPCC 4th Assessment Report (AR4; 2007) emissions scenario (A1FI).[18] The highest scenario (2.0 m) combines the IPCC AR4 projections with the maximum possible ice

[17] Note that the 4th National Climate Assessment is due to be released in late 2018. https://www.globalchange.gov/nca4

[18] The IPCC emissions scenarios make assumptions about future changes in population growth, future economic growth and the introduction of clean and efficient technology. The A1FI scenario assumes continued intensive use of fossil fuels, high economic growth, and low population growth that peaks mid-century. The B1 scenario assumes significant reduction in fossil fuel use, an increase in clean technologies, and the same low population growth that peaks mid-century. The A1F1 yields the highest $CO_2$ emissions by 2100 and the B1 scenario yields the lowest.

sheet melt that could occur by 2100. Given the recent studies that suggest that glacier and ice sheet loss could contribute significantly to rising sea levels (*e.g.*, Rahmstorf 2007; Vermeer and Rahmstorf 2009; IPCC 2013; McMillan *et al*. 2014; Morlighem *et al*. 2014) and evidence that current greenhouse gas emissions are tracking with intermediate IPCC AR4 scenarios (Rahmstorf *et al*. 2012), the low and intermediate-low scenarios likely underrepresent future sea level rise unless demonstrable reductions in global greenhouse gas emissions occur soon.

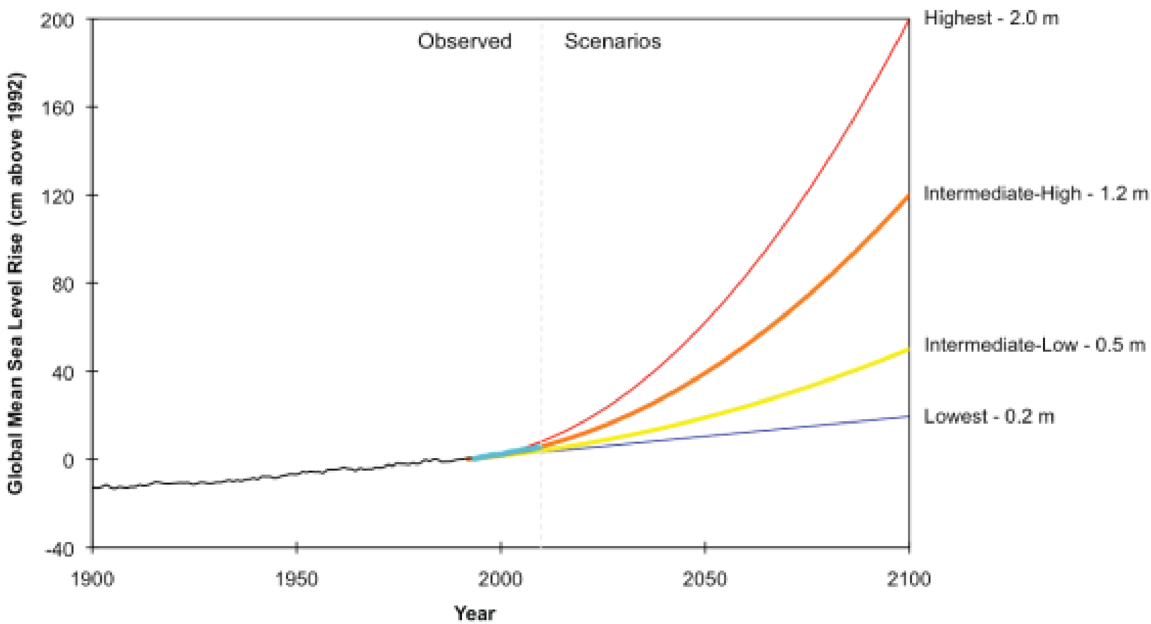


Figure 5. Observed and projected future sea level rise scenarios (Melillo *et al.* 2014). Global mean sea level rise scenarios used in the *US National Climate Assessment*. The Intermediate High Scenario is an average of the high end of ranges of global mean SLR reported by several studies using semi-empirical approaches. The Intermediate Low Scenario is the global mean SLR projection from the IPCC AR4 at 95% confidence interval. (*Source: Global Sea Level Rise Scenarios for the United States National Climate Assessment (*Parris *et al*. 2012))

## Sea Level Rise Projections for California

Tide gauges and satellite observations show that in the past century, mean sea level in California has risen 8 in (20 cm), keeping pace with global rise. For the early portion of the 21st century (through approximately 2011), mean sea level in California remained relatively constant, and may have been suppressed due to factors such as offshore winds and other oceanographic complexities. Bromirski *et al*. (2011, 2012) postulated that persistent alongshore winds have caused an extended period of offshore upwelling that has both drawn coastal waters offshore and replaced warm surface waters with cooler deep ocean water. Both of these factors could offset the global sea level rise trend in this region. However, localized sea level suppression will not continue indefinitely. As the Pacific Decadal Oscillation, wind, and other conditions shift, California sea level will continue rising (NRC 2012; Bromirski *et al.* 2011, 2012). Indeed, satellite altimetry data shows that sea level along the west coast of the United Sates has increased over the past five years, and studies suggest that the shift in sea level in the Pacific Ocean will likely persist in the coming years, leading to substantially higher sea level off the west coast of the United States and lower sea level in the western tropical Pacific (Hamlington *et al.*, 2016).

The State of California has undertaken significant research to understand how much sea level rise to expect over the coming decades and the likely impacts of such sea level rise. In 2013, the Ocean Protection Council (OPC) recognized the National Research Council (NRC) report, *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past Present and Future*, as best available science for the State of California, and recommended in its 2013 State Sea-Level Rise Guidance that state agencies and others use these projections in their planning processes. Likewise, when the Coastal Commission initially adopted this Sea Level Rise Policy Guidance in 2015, it recommended using the NRC report as best available science.

The NRC Report presents sea level rise projections in ranges due to several sources of uncertainty. One significant source of uncertainty is over future greenhouse gas emissions: researchers cannot know the amount or rate of greenhouse gas emissions that will be generated over the coming decades. Large-scale curtailment of greenhouse gas emissions would keep sea level rise towards the lower end of the projections, while business as usual emissions scenarios would result in the higher end of the projections. Because the rate of future greenhouse gas emissions is dependent on global policy decisions, researchers use various climate models that account for different emissions scenarios (business as usual, with little reduction in the current rate of greenhouse gas emissions; large-scale emissions reductions that begin in the near future; and various intermediate scenarios).

A second significant source of uncertainty is related to the dynamics of ice sheet loss. This topic has continued to be extensively researched since the NRC report was published, and recent studies have since informed updated statewide guidance. In April 2017, a Working Group of the Ocean Protection Council's Science Advisory Team released a report synthesizing current sea level rise science. The report, titled *Rising Seas in California: An Update on Sea-Level Rise Science*, presents advances in sea level rise modeling, notably including improved understanding of the processes that could drive extreme global sea level rise from ice loss from the Greenland and Antarctic ice sheets. A significant finding from this report is that Antarctic ice sheet loss could have an outsized impact on sea level rise in California compared to the global average due to ocean circulation dynamics. Further, the report states that rapid ice sheet loss could result in upwards of 10 feet of sea level rise along the California coast by 2100 (this scenario is referred as an "extreme scenario" or "H++ scenario" throughout the OPC Science Report and this Guidance).

The Science Report also includes new "probabilistic projections" which associate a likelihood of occurrence with the sea level rise amounts and rates. These probabilistic projections are based on the probabilities that the ensemble of climate models used to estimate contributions of sea level rise (from thermal expansion, ice sheet loss, oceanographic conditions, and other relevant factors) will predict a certain amount of sea level rise. A critical caveat is that these probabilistic projections did not account for the most recent science regarding the potential for rapid ice sheet loss, and therefore may underestimate the probability of higher sea level rise scenarios. It is understood that as inputs to climate models change (based on evolving science for example), so too will the probabilities associated with different projections.[19]

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[19] The 4th California Climate Assessment developed projections that present a broader range of SLR estimates than the Rising Seas science report and the 2018 OPC SLR Guidance. Both programs' projections are based on estimates of contributions to SLR from primary sources using different methods, including model projections and expert input. However, the 4th Assessment

OPC incorporated these findings into updates to their 2013 State Sea-Level Rise Guidance. The new *State of California Sea-Level Rise Guidance: 2018 Update* (2018 OPC SLR Guidance) contains projections for 12 tide gauges throughout California (to account for localized variations in vertical land motion and other factors) for each decade from 2030 to 2150. The projection table for the San Francisco tide gauge is provided below in Table 3, and the projection tables for the other tide gauges can be found in Appendix G. The tables are adapted from the 2018 OPC SLR Guidance, and present the three scenarios that OPC recommends for use in planning, permitting, investment, and other decisions. These scenarios include:

1. *Low risk aversion scenario:* the upper value for the "likely range" (which has approximately a 17% chance of being exceeded); may be used for projects that would have limited consequences or a higher ability to adapt.
2. *Medium-high risk aversion scenario:* the 1-in-200 chance (or 0.5% probability of exceedance); should be used for projects with greater consequences and/or a lower ability to adapt.
3. *Extreme risk aversion (H++):* accounts for the extreme ice loss scenario (which does not have an associated probability at this time); should be used for projects 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.

In accordance with this statewide guidance, the Coastal Commission considers the 2018 OPC Sea-Level Rise Guidance (and the related 2017 Rising Seas science report) as the best available science on sea level rise in California, and recommends using the above scenarios in relevant Coastal Commission planning and permitting decisions.[20] More information on which scenarios to use in certain circumstances can be found in 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 projections provided in the 2018 OPC Sea-Level Rise Guidance (Table 3; Appendix G), in all relevant local coastal planning and coastal development permitting decisions.***

incorporates the findings from the recent studies regarding the potential for rapid loss of Antarctic ice sheets (which results in the H++ scenario of about 10ft. of SLR by 2100) into its probabilistic projections whereas the OPC reports do NOT include this possibility in the probabilistic projections, as explained above.

[20] Note that while the Coastal Commission now recognizes the 2018 OPC SLR Guidance as best available science on sea level rise projections, the 2012 NRC Report and other related studies still contain valuable information, and references to these documents and studies throughout this guidance remain relevant and applicable.

Table 3. Sea Level Rise Projections for the San Francisco Tide Gauge[21] (OPC 2018)

| Projected Sea Level Rise (in feet): *San Francisco* | | | |
|---|---|---|---|
| | Probabilistic Projections (in feet) (based on Kopp et al. 2014) | | H++ Scenario (Sweet et al. 2017) |
| | **Low Risk Aversion** | **Medium-High Risk Aversion** | **Extreme Risk Aversion** |
| | *Upper limit of "likely range" (~17% probability SLR exceeds...)* | *1-in-200 chance (0.5% probability SLR exceeds...)* | *Single scenario (no associated probability)* |
| 2030 | 0.5 | 0.8 | 1.0 |
| 2040 | 0.8 | 1.3 | 1.8 |
| 2050 | 1.1 | 1.9 | 2.7 |
| 2060 | 1.5 | 2.6 | 3.9 |
| 2070 | 1.9 | 3.5 | 5.2 |
| 2080 | 2.4 | 4.5 | 6.6 |
| 2090 | 2.9 | 5.6 | 8.3 |
| 2100 | 3.4 | 6.9 | 10.2 |
| 2110* | 3.5 | 7.3 | 11.9 |
| 2120 | 4.1 | 8.6 | 14.2 |
| 2130 | 4.6 | 10.0 | 16.6 |
| 2140 | 5.2 | 11.4 | 19.1 |
| 2150 | 5.8 | 13.0 | 21.9 |

**Most of the available climate model experiments do not extend beyond 2100. The resulting reduction in model availability causes a small dip in projections between 2100 and 2110, as well as a shift in uncertainty estimates (see Kopp et al., 2014). Use of 2110 projections should be done with caution and acknowledgement of increased uncertainty around these projections.*

[21] Probabilistic projections for the height of sea level rise and the H++ scenario are presented. The H++ projection is a single scenario and does not have an associated likelihood of occurrence. Projections are with respect to a baseline year of 2000 (or more specifically, the average relative sea level over 1991-2009). Table is adapted from the 2018 OPC SLR Guidance to present only the three scenarios OPC recommends evaluating. Additionally, while the OPC tables include low emissions scenarios, only high emissions scenarios, which represent RCP 8.5, are included here because global greenhouse gas emissions are currently tracking along this trajectory. The Coastal Commission will continue to update best available science as necessary, including if emissions trajectories change.

### USING SCENARIO-BASED ANALYSIS IN RESPONSE TO SEA LEVEL RISE PROJECTION RANGES

Despite the recent advances in sea level rise science, sea level rise projections, including those in the 2018 OPC SLR Guidance (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 (NRC 2012; McMillan *et al*. 2014; Morlighem *et al*. 2014; Griggs *et al.* 2017; OPC 2018).

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 (NRC 2012) and the more dependent projections become on the trajectory of greenhouse gas emissions (OPC 2018). This is reflected in the projections included in the 2018 OPC SLR Guidance, which includes single values for the years 2030, 2040, and 2050, but projections for both low and high emissions scenarios in 2060 and beyond. According to the 2018 OPC SLR 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 developing 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 2018 OPC SLR Guidance) to identify a range of sea level rise scenarios, including the low, medium-high, and, as appropriate, extreme risk aversion scenario[22]. In practice, the process for choosing scenarios and performing scenario-based analysis will be slightly different for LCP planning and

[22] Similar to the recommendation in the OPC's 2011 *State Sea-Level Rise Resolution*, as well as the 2018 OPC SLR Guidance, the Commission does not recommend using projections solely from the lower end of the ranges, as this does not give a full picture of the risks. Looking instead at a range of projections allows users to build an understanding of the overall risk sea level rise poses to the region or site.

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 that are particularly vulnerable so that additional, more detailed studies can be performed if necessary, and adaption options and actions can be prioritized. Scenario-based analysis in the context of LCP planning includes choosing a range of sea level rise projections 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. 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. However, 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 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 both development and coastal resources, and avoid costly damages to projects.

For more information on scenario-based planning in the context of LCPs and CDPs see Chapters 5 and 6, respectively. A number of additional resources related to scenario-based planning are available, including a handbook from the National Park Service (2013) and guidance from Point Blue Conservation Science and the California Coastal Conservancy (Moore *et al*. 2013). See Appendix C for these and other resources related to scenario-based analysis and adaptation planning.

## PHYSICAL EFFECTS OF SEA LEVEL RISE

Continued and accelerated sea level rise will have widespread adverse consequences for California's coastal resources (See summary in Figure 8). The main physical effects of sea level rise include increased flooding, inundation, 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 and development, as described in Chapter 4. In addition, these physical effects could have disproportionate impacts on vulnerable communities that have lower capacity to adapt.

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

- **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. 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). 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.
- **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).
- **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 (NRC 2012). 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, and 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 land loss of 62 – 135 feet by 2100 (Limber *et al.* 2018 (in press). 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 6. 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; 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).
- **Saltwater intrusion and rising groundwater:** An increase in sea level could cause saltwater to enter 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 coastal agricultural lands may also be susceptible to saltwater intrusion. Sea level rise can also result in higher groundwater, presenting another source of flood rise (Hoover *et al.* 2016).

## STORMS, EXTREME EVENTS, AND ABRUPT CHANGE

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.

Climate change will likely modify or change much more than just sea level. One potential climate change-related impact that will interact most directly with sea level rise hazards is a change in frequency or intensity of coastal storms (storminess) and extreme events. The extremes associated with high-intensity events may be particularly devastating since they have the potential to cause broad-scale damage, as seen from recent events such as Hurricanes Katrina and Rita, Superstorm Sandy, and the Tohoku tsunami. Abrupt change in sea levels is another potential impact of climate change. Both potential impacts are described below.

### Extreme Events and Storms

There are several ways to describe extreme events, and most definitions tend to frame these events in terms of consequences or past observations. Kruk *et al*. 2013 define extreme events as "the floods that displace us from our homes, the high waves that wash out coastal roads, or the toppling of trees and power poles from a passing storm." The IPCC defines climate extremes as "the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variables" (IPCC 2012, p. 5). In general, extreme events, by their very nature, are those beyond the normal events that are considered in most shoreline studies. For example, for storm waves and flood conditions, an extreme event will normally be anything worse than the 100-year event.

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. The 2012 NRC report notes that "waves riding on these higher water levels will cause increased coastal damage and erosion—more than that expected by sea level rise alone" (NRC 2012, p.107), and the 4th 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). These impacts result because a rise in sea level will mean that flooding and damage will likely reach further inland. The IPCC *Fifth Assessment Report* (2013) states that it is very likely[23] that there will be a significant increase in the occurrence of future sea level extremes primarily as a result of an increase in mean sea level, with the frequency of a particular sea level extreme increasing by an order of magnitude or more in some regions by the end of the 21st century.

[23] The IPCC has assigned quantitative levels to various terms of confidence and likelihood. High confidence means there is about an 8 out of 10 chance of being correct. Very likely has a greater than 90% probability of occurrence. Other terms that will be used later in this discussion are likely (> 66% probability of occurrence), medium confidence (about a 5 out of 10 chance), low confidence (about a 2 out of 10 chance). *Source of terms*: http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note_ar4.pdf

According to the 2012 NRC report, if the frequency or intensity of storms changes, then so will the frequency and intensity of extreme sea level events. However, the evidence that storminess will change in the North Pacific Ocean is conflicting and inconclusive (Cayan *et al*. 2009; Lowe *et al*. 2010; Dettinger 2011). Still, even if storminess does not change, sea level rise will exacerbate storm surge and high waves, magnifying their impact on the coastline. For this reason, it is important to include these factors in the analysis of sea level rise hazards. Methodologies for these analyses are included in Appendix B.

### Abrupt change

Currently, the best available science is inconclusive as to whether sea level could change abruptly. Thermal expansion and direct melting of land ice is expected to be gradual, leading to slow and steady sea level rise. However, rapid collapse of land-based ice sheets could lead to sudden acceleration of sea level rise, as discussed in the 2017 Rising Seas science report and the 2018 OPC SLR Guidance. Specifically, the science report explains that if greenhouse gas emissions are not curtailed, "glaciological processes could cross thresholds that lead to rapidly accelerating and effectively irreversible ice loss." Recent ice sheet observations and model simulations that consider positive feedback loops associated with ice sheet melting and related non-linear acceleration of sea level rise have attempted to estimate the maximum physically plausible amount of sea level rise. These studies informed the extreme/H++ scenario included in the OPC science report and 2018 SLR OPC Guidance (of approximately 10 feet by 2100). Importantly, it will be difficult to determine if the world is on track for extreme and irreversible ice loss for some time because the processes that drive extreme ice loss in the later part of the century or beyond are different than those that are driving ice loss now. Thus, the likelihood of extreme sea level rise is uncertain and remains an area in need of future research (NRC 2012; Griggs *et al.* 2017; OPC 2018).

Rapid change in land elevation during an earthquake is another potential cause of an abrupt sea level change in a localized area. A large earthquake in the Cascadia Subduction Zone could cause land in northern California, Oregon, and Washington to suddenly subside relative to sea level, causing a sudden rise in relative sea level by 3-6.5 ft (NRC 2012). Large earthquakes in this zone are expected to occur about every several hundred to one thousand years, and the most recent such earthquake occurred in 1700. The sudden rise or drop in land elevation would occur in a matter of minutes. If the land were to subside, the relative rise in sea level would be rapid and it would add to sea level rise already occurring from climate-related forcing.

There is also potential for oceanographic conditions to lead to a relatively rapid rate of sea level rise in California. Examination of the tidal gauge records indicate that there was no significant interannual rise in California's sea level from 1983 to 2011, despite a rise in global sea level over the same time period. One explanation, presented by Bromirski *et al*. (2011, 2012), links this suppression of sea level rise with persistent alongshore winds and an extended period of offshore upwelling that has both drawn coastal waters offshore and replaced warm surface waters with cooler deep ocean water. However, this suppression will not continue indefinitely and as the Pacific Decadal Oscillation, wind, and other conditions shift, California sea level will continue rising, likely at an accelerated rate (NRC 2012; Bromirski *et al.* 2011, 2012).