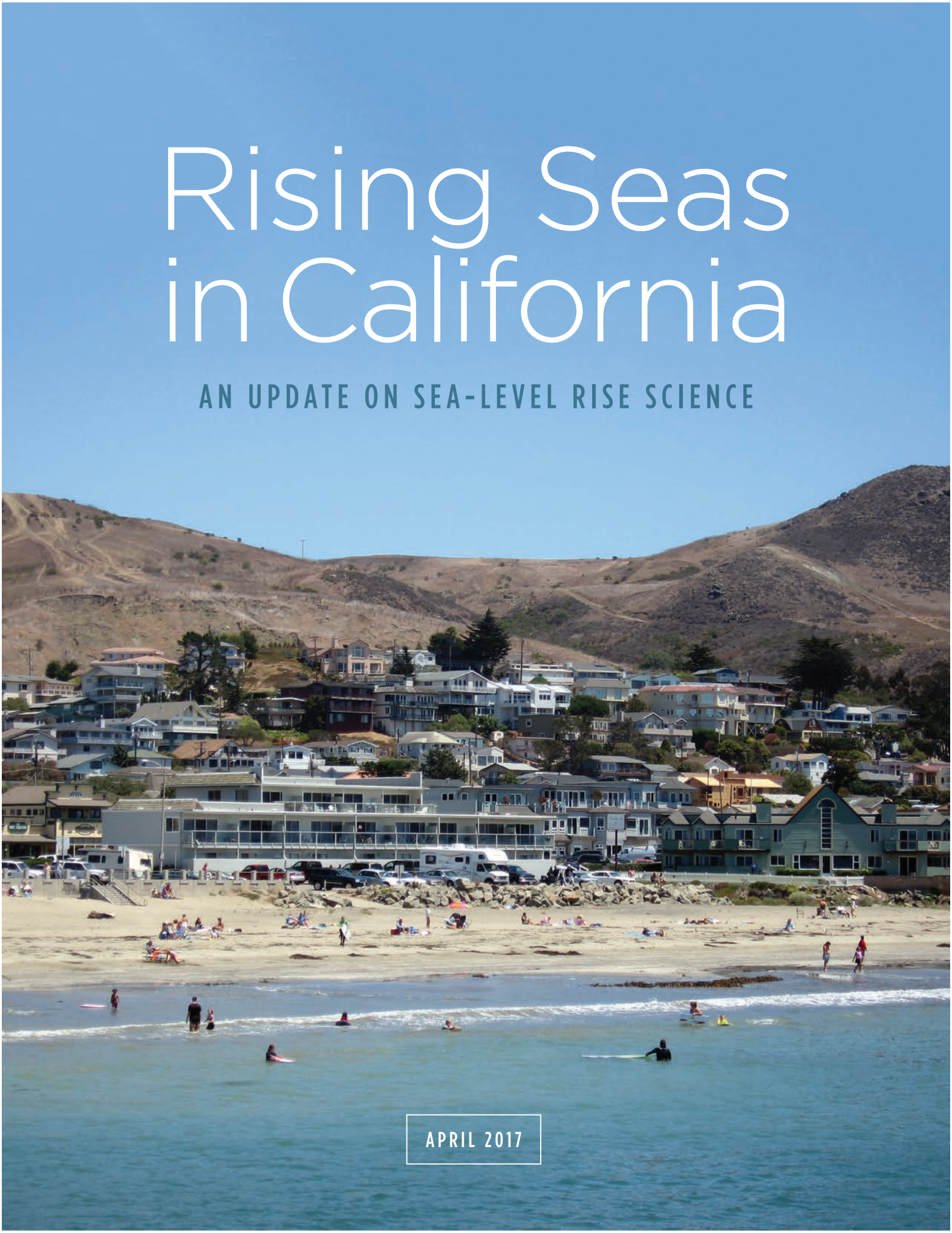
Rising Seas in California

AN UPDATE ON SEA-LEVEL RISE SCIENCE



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About This Document

This document was produced by a Working Group of the California Ocean Protection Council Science Advisory Team (OPC-SAT), supported and convened by the California Ocean Science Trust. *The State of California Sea-Level Rise Guidance Document,* initially adopted in 2010 and updated in 2013, provides guidance to state agencies for incorporating sea-level rise projections into planning, design, permitting, construction, investment and other decisions. Now, the California Ocean Protection Council and the California Natural Resources Agency, in collaboration with the Governor's Office of Planning and Research, the California Energy Commission, and the California Ocean Science Trust, are updating this statewide guidance to reflect recent advances in ice loss science and projections of sea-level rise. This document, requested by the California Ocean Protection Council and guided by a set of questions from the state Sea-Level Rise Policy Advisory Committee, provides a synthesis of the state of the science on sea-level rise. It provides the scientific foundation for the pending update to the guidance document.

CALIFORNIA OCEAN SCIENCE TRUST

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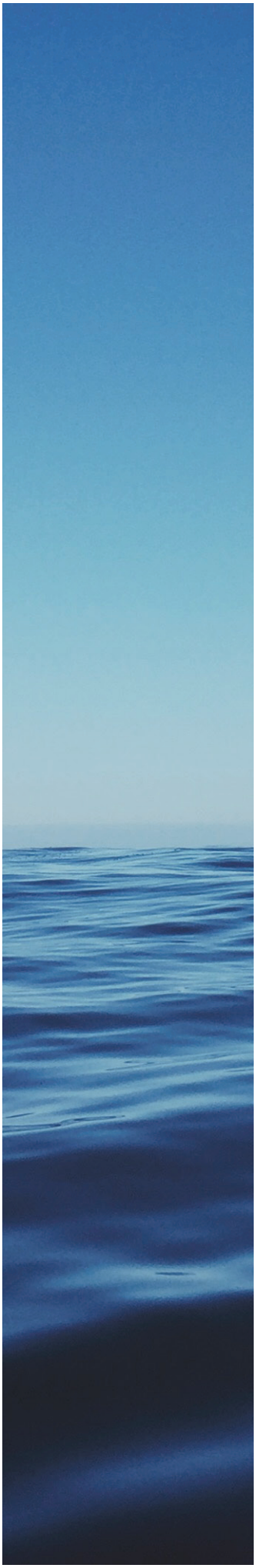


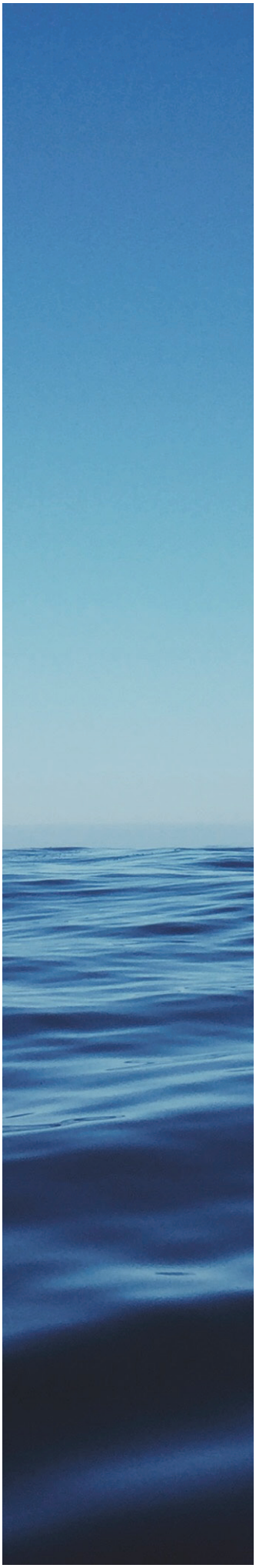
Key Findings

1 **Scientific understanding of sea-level rise is advancing at a rapid pace.** Projections of future sea-level rise, especially under high emissions scenarios, have increased substantially over the last few years, primarily due to new and improved understanding of mass loss from continental ice sheets. These sea-level rise projections will continue to change as scientific understanding increases and as the impacts of local, state, national and global policy choices become manifest. New processes that allow for rapid incorporation of new scientific data and results into policy will enable state and local agencies to proactively prepare.

2 **The direction of sea level change is clear.** Coastal California is already experiencing the early impacts of a rising sea level, including more extensive coastal flooding during storms, periodic tidal flooding, and increased coastal erosion.

3 **The rate of ice loss from the Greenland and Antarctic Ice Sheets is increasing.** These ice sheets will soon become the primary contributor to global sea-level rise, overtaking the contributions from ocean thermal expansion and melting mountain glaciers and ice caps. Ice loss from Antarctica, and especially from West Antarctica, causes higher sea-level rise in California than the global average: for example, if the loss of West Antarctic ice were to cause global sea-level to rise by 1 foot, the associated sea-level rise in California would be about 1.25 feet.

4 **New scientific evidence has highlighted the potential for extreme sea-level rise.** If greenhouse gas emissions continue unabated, key glaciological processes could cross thresholds that lead to rapidly accelerating and effectively irreversible ice loss. Aggressive reductions in greenhouse gas emissions may substantially reduce but do not eliminate the risk to California of extreme sea-level rise from Antarctic ice loss. Moreover, current observations of Antarctic melt rates cannot rule out the potential for extreme sea-level rise in the future, because the processes that could drive extreme Antarctic Ice Sheet retreat later in the century are different from the processes driving loss now.



5 **Probabilities of specific sea-level increases can inform decisions.** A probabilistic approach to sea-level rise projections, combined with a clear articulation of the implications of uncertainty and the decision-support needs of affected stakeholders, is the most appropriate approach for use in a policy setting. This report employs the framework of Kopp et al. (2014) to project sea-level rise for three representative tide gauge locations along the Pacific coastline: Crescent City in northern California, San Francisco in the Bay area, and La Jolla in southern California. These projections may underestimate the likelihood of extreme sea-level rise, particularly under high emissions scenarios, so this report also includes an extreme scenario called the H++ scenario. The probability of this scenario is currently unknown, but its consideration is important, particularly for high-stakes, long-term decisions.

6 **Current policy decisions are shaping our coastal future.** Before 2050, differences in sea-level rise projections under different emissions scenarios are minor but they diverge significantly past mid-century. After 2050, sea-level rise projections increasingly depend on the trajectory of greenhouse gas emissions. For example, under the extreme H++ scenario rapid ice sheet loss on Antarctica could drive rates of sea-level rise in California above 50 mm/year (2 inches/year) by the end of the century, leading to potential sea-level rise exceeding 10 feet. This rate of sea-level rise would be about 30-40 times faster than the sea-level rise experienced over the last century.

7 **Waiting for scientific certainty is neither a safe nor prudent option.** High confidence in projections of sea-level rise over the next three decades can inform preparedness efforts, adaptation actions and hazard mitigation undertaken today, and prevent much greater losses than will occur if action is not taken. Consideration of high and even extreme sea levels in decisions with implications past 2050 is needed to safeguard the people and resources of coastal California.

Report Outline

1. Introduction

Global sea-level rise is the most obvious manifestation of climate change in the ocean. It is an issue that will have far-reaching consequences for California, given its 1100-mile open coastline and many additional miles of estuarine shoreline, as well as high concentrations of people and development along the coast. Sea-level rise will continue to threaten coastal communities and infrastructure through more frequent flooding and inundation, as well as increased cliff, bluff, dune, and beach erosion.

Human development and pressures from a rising sea threaten the already diminished coastal wetlands along the California coast. Hundreds of miles of roads and railways, harbors and airports, power plants and wastewater treatment facilities, in addition to thousands of businesses and homes, are at risk from future flooding, inundation, and coastal retreat [1]. But the total potential impact of such coastal risks is significantly larger still: not only are economic assets and households in flood zones increasingly exposed, but also people's safety, lives, daily movement patterns, and sense of community and security could be disrupted.

California also has the nation's largest ocean economy, valued at over $44 billion/year [2], with the great majority of it connected to coastal recreation and tourism, as well as ports and shipping. Many of the facilities and much of the infrastructure that support this ocean economy, as well as the State's many miles of public beaches, lie within a few feet of present high tide.

1.1. Updating California's Statewide Guidance

The State of California Sea-Level Rise Guidance Document, initially released in 2010 and first updated in 2013, has provided guidance to state agencies for incorporating sea-level rise projections into planning, design, permitting, construction, investment, and other decisions. In 2010, the Governors of Oregon and Washington, along with 10 state and federal agencies, approached the National Research Council (NRC) with a request to provide estimates and projections of future sea-level rise. The NRC Committee built upon and updated the most recent Intergovernmental Panel on Climate Change report at the time [3]. The Committee's report, Sea-Level Rise for the Coasts of California, Oregon, and Washington - Past, Present and Future was completed in 2012 [4]. The future sea-level projections from this report have guided state agencies in their sea-level rise planning in the subsequent years. Five years have elapsed since the NRC study, during which time a new Intergovernmental Panel on Climate Change (IPCC) report was published containing updated sea-level rise projections based on new scenarios, model simulations, and scientific advances [5]. New research has also been published on some of the primary drivers of sea-level change, which includes important new work on ice sheet mass loss in Antarctica, as well as on new methods for producing probabilistic projections of local sea-level change [6,7].

Now, the California Ocean Protection Council and the California Natural Resources Agency, in collaboration with the Governor's Office of Planning and Research, the California Energy Commission, and the California Ocean Science Trust, are updating this statewide guidance for a second time to reflect recent advances in ice loss science and projections of sea-level rise. The updated guidance will focus on the needs of state agencies and local governments. It will help cities and counties as they comply with a new law that requires them to incorporate climate change into their planning efforts. The updated guidance document will also assist state agencies prepare for and adapt to climate change, as directed by Governor Brown's recent Executive Order B-30-15.

This document, a synthesis of the state of the science on sea-level rise, provides the scientific foundation for the update to the existing guidance document. Because effective planning for sea-level rise involves collaboration among various departments within coastal city and county governing bodies, special districts, state agencies, federal agencies, climate researchers, non-governmental organizations, business owners and other stakeholders, a robust public engagement process has been launched and will be implemented throughout 2017 to ensure that the new policy guidance is responsive to user needs. Public input will be integrated into the final guidance document update, which is scheduled for adoption by the California Ocean Protection Council in January 2018.

1.2. How this report was developed

This report was developed by a Working Group of the Ocean Protection Council Science Advisory Team, supported and convened by California Ocean Science Trust. The Working Group was convened from January - April 2017. Working Group members met regularly via videoconference during this period and convened for a two-day in-person meeting in February 2017. The scope and content of the report was informed by a set of questions from the state sea-level rise Policy Advisory Committee (Appendix 1). All Working Group members have contributed to the development of the report, and reviewed the final product. In addition the report has been peer reviewed by experts and revised to reflect the input received.

1.3. How to use this report

This report is intended to provide the scientific foundation for updating California's statewide sea-level rise policy guidance. It is also intended to be used alongside policy recommendations to support planning, permitting, investment, and other decisions at state and local scales. Planners, land managers, consultants, and government officials can draw directly on the scientific data, graphics, and text provided herein as it offers context, explanation, and scientific foundation for planning and decisions. Scientific information is one important input into the detailed and systematic process that decision-makers undertake to evaluate options to prepare for and respond to the emerging impacts of changing coastal hazards.

We have structured this report to provide scientific information that is useful for making decisions now. Although long-range (>40-50 year) sea-level rise futures are uncertain, we explain the sources of these uncertainties, and to the extent possible offer probabilistic sea-level rise projections that can be used in decisions today and in the near future. As the Earth system enters uncharted territory due to rapid changes in the Earth's climate, resulting in sea-level rise rates unprecedented at least in human experience, scientists are attempting to understand the processes contributing to sea-level rise as quickly as possible. An update of the science underlying sea-level rise is necessary because the effects of many decisions made today will persist for decades—e.g., 50, 70 and even 100 years into the future. Just as we are still living with decisions about houses, factories, roads, and power plants—made 50 years ago on the assumption of a stable environment and without foresight about possible changes to environmental conditions—the legacy of California's current decisions in the face of continued sea-level rise will persist. However, today, we have a much-advanced scientific understanding and know that the climate and the oceans are rapidly changing; thus more defensible decisions going forward are possible. This report offers an update on this understanding and provides the best available projections of future conditions.

1.4. How often should practitioners and policy makers reassess scientific data?

Our collective scientific understanding of sea-level rise is advancing at a very rapid pace. We anticipate that new observations, new models, refinement of existing models to capture newly described sea-level rise dynamics, and updated models that are validated with observational data, will continue to be published in the peer-reviewed literature over the coming years.

Moreover, it is not just scientific understanding that is evolving and improving. Sea-level rise projections will continue to change as the impacts of local, regional, national and global policy choices are manifest. Given this dynamic environment, we encourage the creation of science-policy processes that are flexible, iterative and adaptive. At minimum, we recommend that sea-level rise projections be updated every five years, aligned with existing climate change assessment cycles, or when new data become available that are judged to significantly modify existing projections. More fundamentally, we encourage California lawmakers and policy-makers to pursue institutional arrangements and processes for dynamic and rapid incorporation of the results of new science into policy. In this report we aim to provide a robust description of the considerations in selecting approaches to project sea-level rise, and justification of the current choices. Our goal is that this scientific information can begin to make the concept of adaptive policy tractable and actionable.

2. Understanding Sea-Level Rise

Sea level is expected to rise significantly over the next century due to a changing global climate. However, change in sea level is not a new phenomenon; sea level has been rising globally since the end of the last ice age about 18,000 years ago. Driven primarily by the melting of land ice, global mean sea level rose about 120-135 m (about 400-450 feet) during this period. Much of this took place between 18,000 and 8,000 years ago at average rates of about 11 mm/year (45 in/century) and then began to slow. Sea level rose very gradually (<1 mm/year) over the past 8,000 years.

With the onset of the Industrial Revolution and the expanded use of fossil fuels, the greenhouse gas content of the atmosphere began to increase and the Earth has gradually warmed in response, accompanied by thermal expansion of a warming ocean and melting of the Earth's land ice. Estimates of the average rate of sea-level rise between 1900 and 1990, derived from the global network of tide gauges have been made but are complicated by regional land motion and ocean dynamics as well as changes in the Earth's gravitational and rotational fields. These all cause local sea level changes measured by individual tide gauges to deviate from the rate of global mean sea-level rise. Several different approaches have been used to analyze the global tide gauge records in order to accommodate the spatial and temporal variations, and these efforts have yielded sea-level rise rates ranging from about 1.2 mm/year to 1.7 mm/year (about 0.5 to 0.7 inches/decade) for the 20th century, but since 1990 the rate has more than doubled, and the rise continues to accelerate [8–12]. Since the advent of satellite altimetry in 1993, measurements of

absolute sea level from space indicate an average global rate of sea-level rise of 3.4 mm/year or 1.3 inches/decade – more than twice the average rate over the 20th century and greater than any time over the past thousand years [13,14].

2.1. What contributes to current sea-level rise?

2.1.1.Contributors to global mean sea-level rise

Over the last century, ocean thermal expansion was the single greatest contributor to global mean sea-level rise, accounting for about 50% of the signal. The remaining 50% was contributed from land ice; a mix of melting mountain glaciers and ice caps, and the loss of ice from the great polar ice sheets covering Greenland and Antarctica [10]. However, the entire global inventory of mountain glaciers contains only enough ice to raise sea levels by about a half a meter (1.5 feet). In contrast, the Greenland and Antarctic Ice Sheets contain enough ice to raise global mean sea level by 7.4 m (24 feet) and 57 m (187 feet), respectively. While these ice sheets are not expected to melt completely, even on centennial or millennial timescales, the loss of even a small of fraction of either of these huge ice sheets could raise sea level significantly, with devastating consequences for global shorelines. This is particularly concerning because satellite observations clearly show that the rate of ice loss from both the Greenland and West Antarctic Ice Sheets is accelerating. If these trends continue, the contribution from the ice sheets will soon overtake that from mountain glaciers and ocean thermal expansion as the dominant source of sea-level rise (see Appendix 2 for a more detailed discussion of this topic).

Withdrawal of groundwater, and changes in water storage behind dams also impact sea level, although over most of the 20th century the filling of reservoirs had a small negative impact on sea-level rise (i.e., reduced the rate of sea-level rise [15]). In recent decades, increasing groundwater depletion has begun contributing positively to sea-level rise by about 0.4 mm/year (0.15 inches per decade; [10]), because about 80% of the groundwater that is withdrawn and then utilized for domestic, agricultural or industrial purposes ultimately flows to the ocean. However, ongoing contributions to global sea levels from this source will likely be small relative to other potential sources.

2.1.2. Contributors to regional and local relative sea-level rise

While global mean sea level is rising, it is relative sea level, the local difference in elevation between the height of the sea surface and the height of the land surface at any particular location, which directly impacts coastal communities and ecosystems at risk from coastal flooding. Changes in relative sea level arise from 1) vertical land motion, 2) changes in the height of the geoid (the gravitationally determined surface of the ocean in the absence of tides and ocean currents), and 3) changes in the height of the sea surface relative to the geoid. In sum, future changes in relative sea level will not be the same across the globe and will even vary along the length of the California coastline.

Vertical land motion can be caused by tectonics (see Box 2), sediment compaction, withdrawal of groundwater and hydrocarbons, and isostatic adjustments which describe the Earth's deformation associated with redistributions of ice and ocean mass [16,17]. For example, the Earth's surface, and relative sea level, is still adjusting to the retreat of the massive ice sheets that covered much of the Northern Hemisphere during the Last Glacial Maximum about 18,000 years ago. Locally, this post-glacial isostatic adjustment can either produce a long-term rise or fall of sea level, depending on the proximity to the past ice load. In the case of California, relatively far from the Last Glacial Maximum ice sheets, this effect is small [18]. Persistent changes in winds and ocean currents can also have local to regional scale impacts on relative sea level, although these effects are not projected to be as consequential for the U.S. West Coast as they are for the U.S. Northeast.

Of particular relevance for California will be future redistributions of ice and water caused by the retreat of the polar ice sheets, especially on Antarctica. These mass redistributions affect the Earth's gravitational field and the orientation and rate of Earth's rotation, and deform the Earth's crust and mantle [16,19]. While the mantle responds on millennial timescales, the gravitational, rotational and crustal effects are essentially instantaneous. As a retreating ice sheet loses mass to the ocean, its gravitational pull on the surrounding ocean is reduced. Within about a thousand miles of a retreating ice sheet, the reduced gravitational pull on the ocean causes the sea-surface (and relative sea level) to drop, even though the ocean has gained volume overall. Further from the ice sheet (~4000 miles), the change in relative sea level is comparable to that expected from the increase in ocean volume contributed by the melting ice sheet. Beyond that distance, the change in

relative sea level is greater than expected from the extra water added to the ocean by the melting ice sheet. Consequently, Northern Hemisphere coastlines generally experience enhanced sea-level rise from the loss of Antarctic ice, while coastlines in the Southern Hemisphere experience enhanced sea-level rise from loss of Greenland ice. Changing distributions of ice and water also shift the Earth's pole of rotation (the physical North and South Poles) and rate of rotation, which modifies the main gravitational response.

Calculations of the spatial distribution of sea-level rise that take into account these gravitational and rotational effects, sometimes called sea level "fingerprints" (Figure 1, [16]), show that North America experiences more sea-level rise from a given meltwater contribution from Antarctica than from Greenland, and if the ice loss is from West Antarctica, the impacts are exaggerated even further. In fact, these calculations show that for California, there is no worse place for land ice to be lost than from the West Antarctic Ice Sheet. For every foot of global sea-level rise caused by the loss of ice on West Antarctica, sea-level will rise approximately 1.25 feet along the California coast, not including the additional local factors mentioned above. In addition, the West Antarctic Ice Sheet is considered the most vulnerable major ice sheet in a warming global climate, and serious irreversible changes are already underway (see discussion below and Appendix 2, [20–22]).

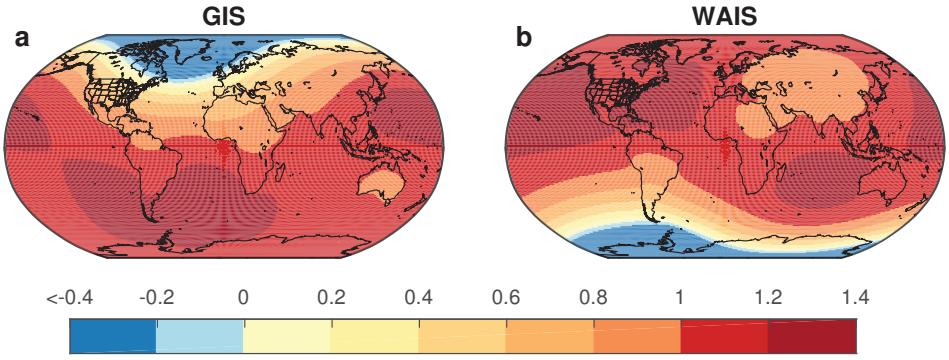


Figure 1. Sea-level 'fingerprints' resulting from the distribution of ice and water around the Earth and ensuing gravitational and rotational effects.

The maps depict the relative response of sea-level to the loss of ice mass from (a) Greenland Ice Sheet (GIS) and (b) West Antarctic Ice Sheet (WAIS). The color bar represents the fractional departure of relative sea level rise from that expected given the ice contribution to global mean sea level. For example, when ice is lost from the Greenland Ice Sheet the relative effect on the US West Coast is 75% of the sea-level rise expected from the water volume added to the ocean. By comparison, when ice is lost from the West Antarctic Ice Sheet the US West Coast experiences 125% of sea-level rise from that expected from the water volume added.

2.2. What are recent scientific advances in understanding sea-level rise?

2.2.1. New observations and understanding of climate changes

During the last five years, the atmospheric greenhouse gas concentration has continued to increase. Since late 2015, measurements of the atmospheric CO_2 concentration have consistently exceeded 400ppm.[i] Recent concentrations are approximately 45% higher than the pre-industrial level, and about 2.5% higher than in 2012. Increases in CO_2 and other greenhouse gases have resulted in the Earth's climate system absorbing more energy than it is emitting back to space, an imbalance estimated to be greater than 0.5 Watts/m^2. More than 90% of this excess heat is being captured by the global ocean [23]. Heat gain in the deep ocean has occurred unabated at least since 2006, with temperature increases extending from the surface to depths exceeding 1500m in all ocean basins [24].

The Earth's surface has also continued to warm. Sixteen of the 17 warmest years in the 136-year period of global temperature measurements have all occurred since 2001.[ii] 2016 was the warmest year on record, and it was the 3rd year in a row that the record was broken. Arctic sea ice at the peak of the summer melt season now typically covers 40% less area than it did in the early 1980s. Arctic sea ice extent in September, the seasonal low point in the annual cycle, has been declining at a rate of about 13% per decade.[iii]

2.2.2. Advances in observing and modeling sea-level rise

Of the major contributors to global sea-level rise, the loss of ice from the Greenland and Antarctic Ice Sheets has the greatest potential to increase sea levels. Contributions from ice sheet losses also present the greatest uncertainty in the rate and amount of sea-level rise at time horizons beyond the next few decades. In the past five years (since the existing State guidance document was developed), new models and observations have highlighted this possibility and advanced our understanding of the dynamics of ice loss, and the atmospheric and ocean conditions that can drive significant loss. A more comprehensive discussion of this topic is provided in Appendix 2.

Observational data from the GRACE (Gravity Recovery and Climate Experiment) satellites, which measure the Earth's gravitational field, have revealed increased loss of land ice from Greenland and West Antarctica [13], and confirmed previous observations. Satellite altimeter data show increased loss of grounded land ice from West Antarctica, and evidence of accelerated volume loss of ice shelves in West Antarctica, which buttress grounded ice [22].

[i] https://www.esrl.noaa.gov/gmd/ccgg/trends/monthly.html
[ii] https://www.nasa.gov/press-release/nasa-noaa-data-show-2016-warmest-year-on-record-globally
[iii] https://www.nasa.gov/feature/goddard/2017/sea-ice-extent-sinks-to-record-lows-at-both-poles

New radar sounding observations have also revealed that the very different climates and underlying bedrock topography of Greenland and Antarctica will result in markedly different contributions to global sea-level rise. The bedrock beneath the Greenland Ice Sheet is above sea level around most of its margin, and below sea level only in the interior, which limits its rate of outflow to the ocean [25]. By contrast, much of the West Antarctic Ice Sheet and parts of the East Antarctic Ice Sheet lie on bedrock that is below sea level and deepens toward the continental interior [26]. Model results indicate that, while low rates of loss are possible, much higher rates of ice loss and sea-level rise could occur if oceanic and atmospheric warming is great enough to erode the floating ice that buttresses grounded ice. Ice flow mechanics responding to a high warming scenario could result in an escalating, effectively irreversible discharge of ice into the ocean as the grounded ice front recedes inland. Importantly, the change in the Earth's gravitational field and rotation that would result from the loss of ice from West Antarctica would result in a higher sea-level rise along the coast of California than the overall global average, an amplification that becomes increasingly consequential as Antarctic ice loss grows larger (see above and Appendix 2).

New studies have also examined historical periods of high sea levels, and rapid rates of sea-level rise, to better understand the potential for specific levels of future sea-level rise [27]. Extremely high sea levels during the Last Interglacial Period (about 125,000 years ago) and Pliocene (about 3 million years ago) indicate that the polar ice sheets are sensitive to relatively modest climate warming. During the Last Interglacial Period, global mean temperatures were similar to today, but sea level was 20 - 30 feet (6 - 9 m) higher. Most of this sea-level rise is thought to have originated from Antarctic ice loss. The Pliocene was approximately 2°C - 3°C warmer than today, and sea levels may have been higher by 30 - 90 feet (10 - 30 m) than today, requiring a substantial contribution from East Antarctica in addition to Greenland and West Antarctica (Appendix 2). Using the reconstructed atmospheric and oceanic climate, new models have been applied to test mechanisms of ice loss (and resulting sea level rise) during those periods to better understand how those high sea levels could have occurred and also to inform future sea-level rise projections [27,28].

While there has been much progress in recent years in observing and modeling the Antarctic Ice Sheet, the precise magnitude and timing of when it will begin to contribute substantially to rising sea levels remains highly uncertain. This is partly due to insufficient knowledge of the physics of Antarctic ice loss processes, such that they cannot be faithfully represented in models. More importantly, however, we do not know what future greenhouse gas emissions

will be; so even if the physics were perfectly captured in the models, there would still be major uncertainty about which processes will become important as the ice sheet evolves. That said, the recent work does allow for some important new conclusions (see also Appendix 2):

- Previously underappreciated glaciological processes, examined in the research of the last five years, have the potential to greatly increase the probability of extreme global sea-level rise (6 feet or more) within this century if emissions continue unabated.

- The processes that could drive extreme Antarctic Ice Sheet retreat later in this century are different from those driving Antarctic Ice Sheet changes now, so the fact that the current rise in global sea level is not consistent with the most extreme projections does not rule out extreme behavior in the future.

- An aggressive reduction in greenhouse gas emissions substantially reduces but does not eliminate the risk of extreme global sea-level rise driven by Antarctic ice loss.

- Once marine-based ice is lost, the resulting global sea-level rise will last for thousands of years.

BOX 1

Short-term increases in sea level

Although long-term mean sea-level rise by itself will provoke increasing occurrences of nuisance flooding, over the next several decades it is highly likely that short-term increases in sea level will continue to be the driver of most of the strongest impacts to infrastructure and coastal development along the coast of California. Short-term processes, including Pacific Basin climate fluctuations (Pacific Decadal Oscillation, El Niño Southern Oscillation, and North Pacific Gyre Oscillation), King tides (perigean high tides), seasonal cycles, and winter storms, will produce significantly higher water levels than sea-level rise alone, and will present greater risks to coastal development.

El Niño associated flooding

Over the recorded era of the 20th and early 21st centuries, most of the significant storm damage to California's coastline has occurred during major El Niño events, when elevated sea levels coincided with storm waves and high tides [29]. The record from the San Francisco tide gauge, the longest continuously running gauge along California's coast, reveals several years when seasonal anomalies rose above the long-term trend of 1.9 mm/year (0.07 inches/year). The most prominent of those cases were major El Niño events, for example, 1940-41, 1982-83, and 1997-98, when sea levels were elevated 8-12 inches (20-30 cm) for several months at a time (Figure 2).

Adding these weather and short-period climate events to the more gradual, incremental global rise in mean sea level will present increasing risks for low-lying coastal infrastructure and development. The latest generation of climate model simulations suggests that North Pacific storminess will remain at about the same level of activity as seen in the 20th and early 21st century but that the frequency of extreme El Niño events may increase under a warmer climate [30]. Given the strong association between El Niño, large winter North Pacific storms, and anomalously high sea levels and storm surge [31], occasional large sea level events in future decades must be considered in future scenario planning.

King tides

High tides along the California coast occur twice daily, typically of uneven amplitude, and are caused predominantly by the gravitational attraction of the moon and the sun on the Earth's oceans. Extreme tides, called spring tides, occur in multi-day clusters twice monthly at times of the full and new moon. Additionally, even higher tides occur several times a year and are designated as perigean high tides, or more popularly "King tides". These events are now recognized as producing significant coastal flooding in some well-known areas such as the Embarcadero in San Francisco, where King tides are already washing onto the sidewalks. The Earth-moon-sun orbital cycles also amplify tidal ranges every 4.4 and 18.6 years, producing peaks in the monthly high tide that are about 6 inches (15 cm) and 3 inches (8 cm) respectively, higher than in the intervening years.

Storm surges

Storm surges, created when strong onshore winds combined with low barometric pressure force seawater onto the shoreline, also temporarily elevate sea levels. While storm surge along the coast of California is considerably less than that experienced during severe hurricanes and nor'easters along the Gulf and Atlantic Coasts of the United States, the storm surge during major winter storms here can reach as much as 3 feet above predicted sea levels.

Wave-driven water level increase

Large ocean waves can transport significant volumes of water up onto the shoreline as they break, causing temporary increases in sea level through two related processes. Wave run-up describes the process of an individual breaking wave washing up the beach face to an elevation as much as 6 feet above sea level. Wave set-up results from a set of large waves breaking in rapid succession, which can elevate the overall water level along the shoreline as much as 4 or 5 feet for a few minutes at a time. Because many beaches have shallow slopes, extremely high waves and resulting set-up and run-up events can have enormous impacts in causing erosion and damage to coastal infrastructure. Short-term elevated sea levels from any of these processes can not only cause flooding in low-lying coastal areas but can also exacerbate flooding along stream or river courses when runoff is temporarily obstructed by an elevated ocean or high tides, thereby leading to enhanced inland flooding.

Implications of short-term increases in sea level

The historic records and measurements (from tide gauges) of short-term elevated sea levels, whether due to El Niño events, King tides, storm surges, or a combination of these (as dramatically occurred during the 1982-83 El Niño), provide useful indicators for understanding future total water levels. These short-term elevated sea levels need to be added to projected future sea levels to obtain future total water levels.

3. Sea-Level Rise Projections

3.1. Approach, definitions, and limitations

3.1.1. Emissions scenarios

The Intergovernmental Panel on Climate Change (IPCC) adopted a set of emissions scenarios known as 'representative concentration pathways', or RCPs. These are a set of four future pathways, named for the associated radiative forcing (the globally averaged heat trapping capacity of the atmosphere measured in watts/square meter) level in 2100 relative to pre-industrial values: RCP 8.5, 6.0, 4.5 and 2.6 [32]. RCP 8.5 is consistent with a future in which there are no significant global efforts to limit or reduce emissions. RCP 2.6 is a stringent emissions reduction scenario and assumes that global greenhouse gas emissions will be significantly curtailed. Under this scenario, global CO_2 emissions decline by about 70% between 2015 and 2050, to zero by 2080, and below zero thereafter [33].

RCP 2.6 most closely corresponds to the aspirational goals of the United Nations Framework Convention on Climate Change's 2015 Paris Agreement, which calls for limiting global mean warming to less than 2°C and achieving net-zero greenhouse gas emissions in the second half of this century. This pathway will be very challenging to achieve, and most simulations of such stringent targets require widespread deployment of nascent carbon-negative technologies, such as sustainable bioenergy coupled to carbon capture and storage, or direct air capture of CO_2.

Three of these pathways are used here to project sea-level rise: RCP 8.5, RCP 4.5 and RCP 2.6. We do not include RCP 6.0 because it yields 21st century sea level projections that are nearly identical to those of RCP 4.5 [10], and few climate models have run RCP 6.0 beyond 2100.

3.1.2. Approach to projections

The scientific literature offers several distinct approaches to generating future sea-level rise projections. One set focuses on providing scenarios that span a range of possible futures, while making little or no attempt to assess the relative likelihood of different scenarios. Another set focuses on estimating the probability of different levels of future sea-level change, either by estimating a central projection with an associated range or by attempting to estimate a comprehensive probability distribution that also estimates the likelihood of extreme 'tail' outcomes. These approaches also differ in whether they explicitly represent the dependence of future sea-level change on specific greenhouse gas emission pathways (with the implied storyline about future economic and social development attached to them) or present results with no explicit connection to them, for example as a function of global average temperatures, independently of the emission pathways that would produce them, or as a set of low/medium/high projections with no explicit description of what would be driving them (see also Box 3).

For the Third National Climate Assessment, Parris et al. (2012) [34] constructed four discrete scenarios, spanning a range of global mean sea-level change in 2100 from 20 cm to 200 cm. They did not discuss the likelihood of these scenarios, nor did they tie them to specific emissions scenarios. They also did not make explicit geographic projections. However, the U.S. Army Corps of Engineers' sea-level rise calculator does combine these discrete scenarios with tide-gauge-based estimates of local background processes to produce partially localized sea-level rise projections.[iv]

The National Research Council effort in 2012 [4] produced a set of three scenarios (low, central, and high), with greater weight given to the central scenario. The dependence of ocean thermal expansion and ocean dynamics on emissions was explicitly considered in producing these projections, but the emissions dependence was combined with other sources of uncertainty in producing the low and high values. The IPCC's Fifth Assessment Report [5,10] did not produce local projections for California, but their global mean sea level projections served as a touchstone for all the work that has followed. They produced estimates of the 'likely' range of global sea-level rise under each of four RCPs, where 'likely' covers the central 66% of the probability distribution (i.e., the sea levels that fall within the range created by the value that is 17% likely to occur and the value that is 83% likely to occur). They did not, however, attempt to estimate sea-level rise outside these central 66% probability ranges.

[iv] http://www.corpsclimate.us/ccaceslcurves.cfm

Both the absence of local projections and the incompleteness of their estimated probabilities led Kopp et al. (2014) [6] to synthesize several lines of evidence to estimate comprehensive probability distributions for global mean sea level and local relative sea level changes under the four RCPs, with a focus on RCP 2.6, 4.5, and 8.5. In this approach, outputs from process-based models are combined with estimates of contribution from the polar ice sheets derived from an expert elicitation process [35]. The Kopp et al. (2014) framework has been employed by a range of risk analyses (e.g., [36,37]) and stakeholder groups, including the New Jersey Climate Adaptation Alliance [38], and regional groups in Washington State (e.g.,[39,40]).

Subsequent work found that the sea-level rise projections of Kopp et al. (2014) were consistent with the historical relationship between temperature and rate of global sea level change over the last two millennia [14]. Other probabilistic projections have yielded somewhat higher projections. For example, the Kopp et al., 2014 approach projects 1.2 m (almost 4 feet) global sea level rise for RCP 8.5 by 2100 (95th percentile), while Jevrejeva et al., (2014, 2016) project 1.8 m (almost 6 feet) for RCP 8.5 by 2100 (95th percentile) [41,42]. Importantly, while Kopp et al. (2014) provide comprehensive probability distributions conditional upon emissions scenarios, they emphasize the tentative nature of these distributions and highlight the 99.9th percentile of their RCP 8.5 projections (about 8 feet or 2.5 m) as being consistent with estimates of 'maximum physically plausible' global mean sea level estimates derived through other methods. An expert panel convened to provide guidance in New Jersey [38] included a narrative recommendation to give this outcome greater weight in decisions involving facilities or structures with a low tolerance for risk (e.g. international airports, large power plants or sewage treatment facilities).

Since 2014, new work on Antarctic Ice Sheet modeling (Appendix 2) has identified various modes of marine ice-sheet instability that could make extreme sea-level outcomes more likely than indicated by the IPCC Fifth Assessment Report or the Kopp et al. (2014) framework, particularly under high-emissions scenarios. To address this possibility, the City of Boston [43] and the Fourth California Climate Change Assessment [44] employed modified versions of the Kopp et al. (2014) framework, in which the Antarctic projections of Kopp et al. (2014) were replaced with ensembles of simulations from DeConto and Pollard (2016). This ad hoc approach highlights the sensitivity of global and local sea-level projections to Antarctic ice sheet instability. However, as Kopp et al. (in review) emphasize, DeConto and Pollard's (2016) ensembles of simulations were not intended to and do not constitute probability distributions of future Antarctic changes. DeConto and Pollard (2016) explored a discrete set of ice-sheet parameterizations consistent with the geological record, but did not undertake a comprehensive assessment of the probability of different parameterizations. Therefore, these ad hoc approaches cannot be viewed as yielding probability distributions of future changes in the same manner as Kopp et al. (2014).

For the Fourth National Climate Assessment, Sweet et al. (2017) [45] maintained the scenario-based approach of Parris et al. (2012), but drew upon the framework of Kopp et al. (2014) to localize their projections and to discuss the relative likelihood of different scenarios under different emissions pathways. Notably, in light of various assessments of the 'maximum physically plausible' global mean sea-level rise and new work such as that of DeConto and Pollard (2016), they added an extreme scenario reaching 8 feet (2.5 m) of global mean sea-level rise in 2100, a level that requires the invocation of the marine ice-sheet instability mechanisms discussed in Appendix 2. In this assessment, ice sheet mass changes were projected based on combining the IPCC expert assessment of likely ranges with information about the broader probability distribution from the expert elicitation of Bamber and Aspinall (2013).

After considering the comprehensive probabilistic approach of Kopp et al. (2014), the ad hoc modification of this approach in the California 4th Climate Change Assessment, and the scenario-based approach of the recent Fourth National Climate Assessment, the Working Group concluded that the comprehensive probabilistic approach was most appropriate for use in a policy setting in California. Probabilistic approaches can be used in a range of decision frameworks, including the sea-level rise allowance framework, which is focused on maintaining expected flood risk at a target level over the lifetime of a decision [46,47]. The scenarios-based approach in the Fourth National Climate Assessment does not provide as rich a source of information for risk management and does not highlight the dependence of future sea-level change on greenhouse gas emissions as clearly. The approach of the California 4th Climate Change Assessment depends heavily on a single recent modeling study in a rapidly developing field and does not provide truly probabilistic information. However,

recognizing that the Kopp et al. (2014) projections may underestimate the likelihood of extreme sea-level rise, particularly under high-emissions scenarios, the Working Group concluded that the extreme sea-level rise scenario in the Fourth National Climate Assessment (here called the H++ scenario) should be considered alongside the Kopp et al. (2014) probability distributions for RCPs 2.6, 4.5 and 8.5. At this point, it is scientifically premature to estimate the probability that the H++ scenario will come to pass, and, if so, when the world will move onto the H++ trajectory.

One important point that is underscored by the ad hoc approaches is that the mechanisms driving Antarctic ice mass loss today are different than those that may drive future ice sheet collapse. Although sea-level rise is not following the H++ scenario at this moment, this scenario cannot be excluded for the second half of this century on these grounds.

3.1.3. Timeframes and planning horizons

The projections of sea-level rise provided here are averages across an interval of 19 contiguous years, centered on 2030, 2050, 2100 and 2150. Although the planning horizons of most infrastructure decisions fall within the near-term end of this range, we believe that it is essential to place all decisions within a longer-term context to foster choices that - to the extent possible - do not eliminate or reduce future options.

3.1.4. Starting in 2000

The baseline for the projections in this report is the year 2000, or more specifically, average relative sea level over 1991-2009. Due to a combination of atmosphere and ocean dynamics, the decadal average sea level in San Francisco can change up to 2 inches around the mean, which is equivalent to about 15 years of present-day global sea-level rise.

3.1.5. California tide gauges

There are 12 active NOAA tide gauges along the outer coast of California[v], which range in their periods of record from 39 years (Point Arena) to 162 years (San Francisco). Considerable local variability is evident in rates of sea-level rise recorded across these tide gauges, simply because they are all anchored on some land mass or structure that may be experiencing long-term uplift or subsidence (Box 2).

We selected three of these gauges to use as the basis for sea-level rise projections: Crescent City, San Francisco Golden Gate, and La Jolla. Although there is considerable local variation that they do not represent, these gauges span the broad scale geographic extent of the California coastline taking into account the changing tectonic context along the coastline, the gradient of storm and wave climate from north to south, and in consideration of centers of human population and development.

[v] http://www.corpsclimate.us/ccaceslcurves.cfm

BOX 2

Local sea-level rise rates along the coastline of California

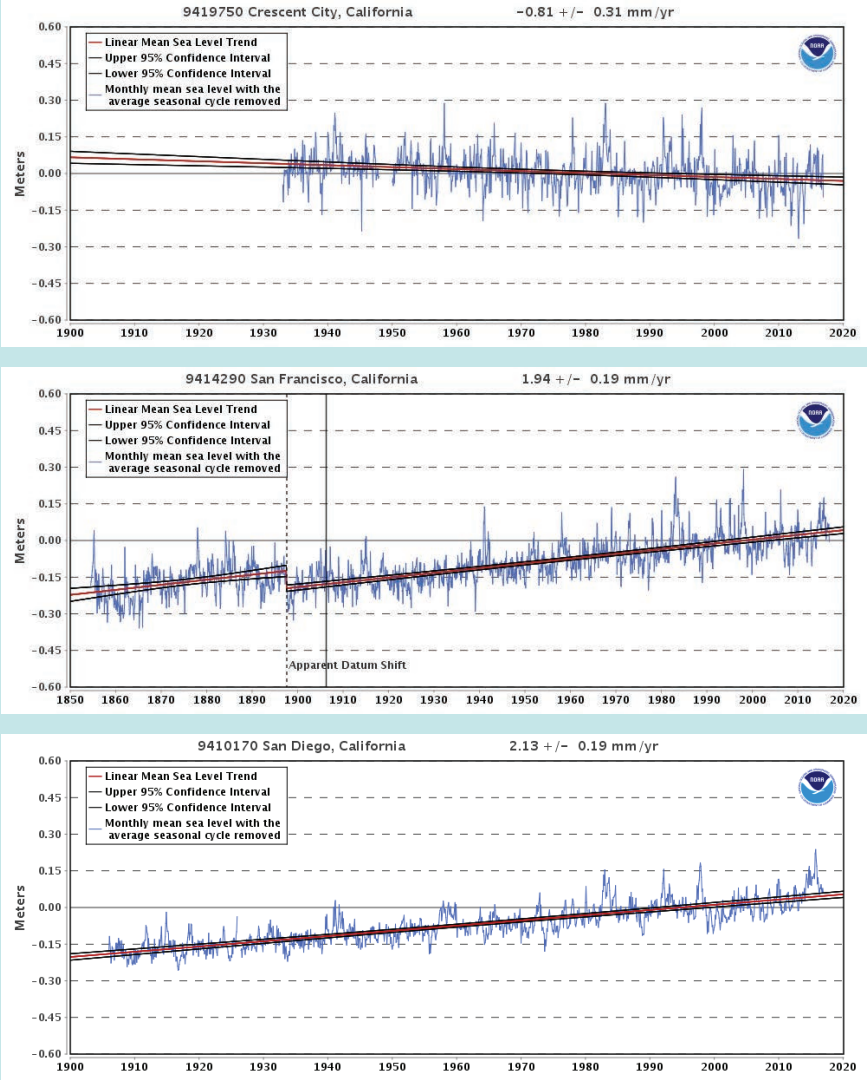
For the shoreline of Southern and Central California (San Diego to Point Reyes) sea-level rise rates recorded at NOAA tide gauges range from just under 1 mm/year to just over 2 mm/year (a little less than 4 inches to just over 8 inches/century). By comparison, the state's three northernmost tide gages lie in tectonic environments that modify global sea-level rise rates. Point Arena, which lies virtually on the San Andreas Fault, has recorded 0.4 mm/year of relative sea-level rise for the past 39 years. At Cape Mendocino, one hundred miles to the north, a major tectonic boundary occurs as the strike slip or transform boundary marked by the San Andreas Fault transitions to the Cascadia Subduction Zone, which continues northward to Vancouver Island. From Cape Mendocino north for the next 120 miles to the Oregon border, the shoreline is being arched upward due to the collision and subduction of the Gorda Plate beneath northern California, although there are local settings, for example Humboldt Spit, where subsidence is occurring. The general pattern of uplift is evidenced by the Crescent City tide gauge, which has recorded relative sea-level change averaging -0.8 mm/year over the past 84 years, or a drop in sea level relative to the coast, illustrating that the coastline here is rising faster than sea level (Figure 2, [4]).

The pattern of coastal uplift north of Point Arena is subject to major periodic interruptions. A wide range of evidence indicates that the Cascadia Subduction Zone periodically generates great earthquakes of magnitude 8 to over 9 that cause sudden shifts and reset rates of vertical motion. Fieldwork along the coasts of northern California, Oregon and Washington indicates that these great earthquakes are accompanied by shoreline subsidence on the order of three feet or more, as well as major tsunami flooding. The last great earthquake occurred in January 1700 and caused a large segment of coastline to subside and be suddenly inundated. The geologic evidence revealing a long series of these events, which occur every 300 to 500 years on average, strongly suggests that the present regime of relatively quiescent sea-level rise along the California coast north of Cape Mendocino will change virtually instantaneously when the next great earthquake occurs.

While the timing of such an event is impossible to predict, the fact that this phenomena has repeatedly occurred over thousands of years means that it must be taken as a serious threat.

Figure 2. NOAA tide gauge records for Crescent City, San Francisco, and La Jolla stations.

Long-term change is listed on top of each record in mm/year. Short-term increases in sea level (such as 1982-93 and 1997-98 El Niños) are clear in the records for all three stations.



3.2. How much sea-level rise will California experience?

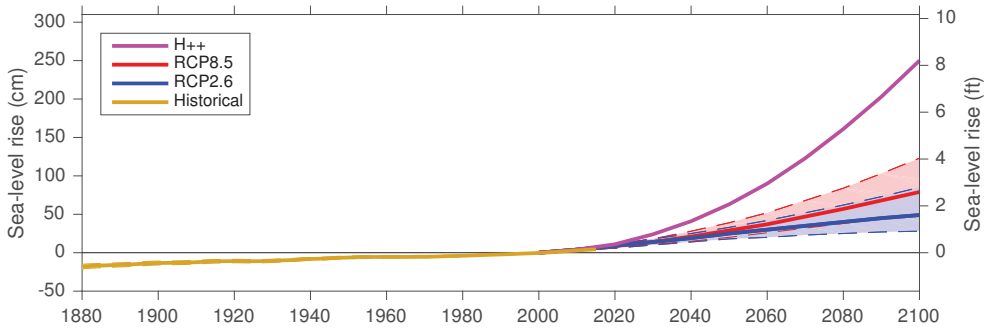
Using the methodology of Kopp et al. (2014), we provide projections of sea-level rise that are based on the data from tide gauges in Crescent City, San Francisco and La Jolla (Figure 3, Table 1). As described above (Section 3.1.1), these projections may underestimate the probability of extreme Antarctic ice loss, an outcome that is highly uncertain but, given recent observations and model results, cannot be ignored. Accordingly, we have also included an extreme sea-level rise scenario, which we call the H++ scenario. This is an unknown probability, high consequence scenario such as would occur if high rates of Antarctic ice loss were to develop in the last half of this century. When decisions involve consequential infrastructure, facilities or assets, we advise that extra consideration be given to this upper end of potential sea-level rise outcomes.

We note that the differences in projections under different emissions scenarios before 2050 are minor. By comparison, after 2050, projections increasingly depend on greenhouse gas emissions. Accordingly, we present only projections for RCP 8.5 through 2050, and distinguish between emissions pathways for 2100 and 2150.

Figure 3: Projections of: (a) Global mean sea level, and; (b) Relative sea level in San Francisco, California.

Sea-level rise projections for RCP 8.5 and RCP 2.6 are calculated using the methodology of Kopp et al., 2014. The shaded areas bounded by the dashed lines denote the 5th and 95th percentiles. The H++ scenario corresponds to the Extreme scenario of Sweet et al. (2017) and represents a world consistent with rapid Antarctic ice sheet mass loss. Note that the behavior of the Antarctic ice sheet early in this century is governed by different processes than those which would drive rapid mass loss; although the world is not presently following the H++ scenario, this does not exclude the possibility of getting onto this path later in the century. The historical global mean sea level curve in (a) is from Hay et al. (2015).

(a) Global mean sea level



(b) Relative sea level in San Francisco, California

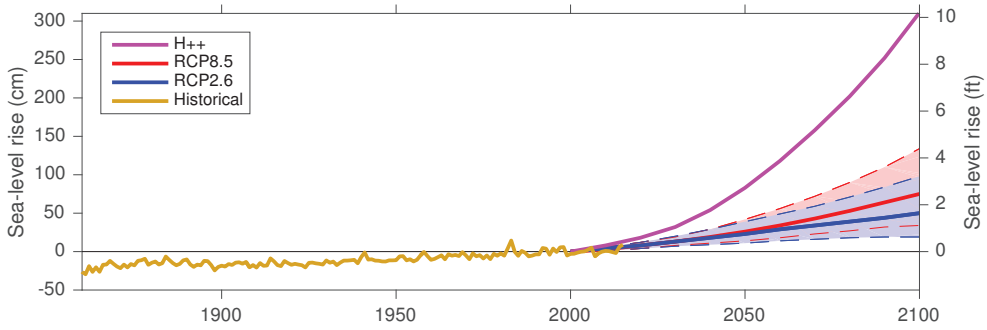


Table 1. Projected sea-level rise (measured in feet) for three tide gauge locations in California: (a) Crescent City (b) San Francisco, Golden Gate, and (c) La Jolla.

Projections are based on the methodology of Kopp et al., 2014 with the exception of the H++ scenario. The 'likely range' is consistent with the terms used by the IPCC meaning that it has about a 2-in-3 chance of containing the correct value. All values are with respect to a 1991-2009 baseline. The H++ scenario is a single scenario, not a probabilistic projection, and does not have an associated distribution in the same sense as the other projections; it is presented in the same column for ease of comparison.

(a) Crescent City

Feet above 1991-2009 mean	MEDIAN	LIKELY RANGE	1-IN-20 CHANCE	1-IN-200 CHANCE
Year / Percentile	*50% probability SLR meets or exceeds...*	*67% probability SLR is between...*	*5% probability SLR meets or exceeds...*	*0.5% probability SLR meets or exceeds...*
2030	0.1	0.0 — 0.3	0.4	0.5
2050	0.4	0.2 — 0.7	0.9	1.5
2100 (RCP 2.6)	0.7	0.1 — 1.5	2.3	4.8
2100 (RCP 4.5)	1.0	0.3 — 1.8	2.6	5.0
2100 (RCP 8.5)	1.5	0.7 — 2.5	3.4	5.9
2100 (H++)	9.3			
2150 (RCP 2.6)	1.0	0.0 — 2.4	4.2	9.6
2150 (RCP 4.5)	1.6	0.3 — 3.2	5.0	10.4
2150 (RCP 8.5)	2.6	1.3 — 4.4	6.2	11.6
2150 (H++)	21			

(b) San Francisco, Golden Gate

Feet above 1991-2009 mean	MEDIAN	LIKELY RANGE	1-IN-20 CHANCE	1-IN-200 CHANCE
Year / Percentile	*50% probability SLR meets or exceeds...*	*67% probability SLR is between...*	*5% probability SLR meets or exceeds...*	*0.5% probability SLR meets or exceeds...*
2030	0.4	0.3 — 0.5	0.6	0.8
2050	0.9	0.6 — 1.1	1.4	1.9
2100 (RCP 2.6)	1.6	1.0 — 2.4	3.2	5.7
2100 (RCP 4.5)	1.9	1.2 — 2.7	3.5	5.9
2100 (RCP 8.5)	2.5	1.6 — 3.4	4.4	6.9
2100 (H++)	10			
2150 (RCP 2.6)	2.4	1.3 — 3.8	5.5	11.0
2150 (RCP 4.5)	3.0	1.7 — 4.6	6.4	11.7
2150 (RCP 8.5)	4.1	2.8 — 5.8	7.7	13.0
2150 (H++)	22			

(c) La Jolla

Feet above 1991-2009 mean	MEDIAN	LIKELY RANGE	1-IN-20 CHANCE	1-IN-200 CHANCE
Year / Percentile	*50% probability SLR meets or exceeds...*	*67% probability SLR is between...*	*5% probability SLR meets or exceeds...*	*0.5% probability SLR meets or exceeds...*
2030	0.5	0.4 — 0.6	0.7	0.9
2050	0.9	0.7 — 1.2	1.4	2.0
2100 (RCP 2.6)	1.7	1.1 — 2.5	3.3	5.8
2100 (RCP 4.5)	2.0	1.3 — 2.8	3.6	6.0
2100 (RCP 8.5)	2.6	1.8 — 3.6	4.6	7.1
2100 (H++)	10			
2150 (RCP 2.6)	2.5	1.5 — 3.9	5.7	11.1
2150 (RCP 4.5)	3.1	1.9 — 4.8	6.5	11.8
2150 (RCP 8.5)	4.3	3.0 — 6.1	7.9	13.3
2150 (H++)	22			

3.3. How fast will sea levels rise?

We recognize that planning decisions are often informed by estimates of rates of sea-level rise and estimates of when a particular level of sea-level rise is projected to occur. Rates of sea-level rise provide important context for the time needed to plan and implement adaptation options. They are also an important consideration in evaluating when and where natural infrastructure is a feasible and prudent choice for helping to mitigate the effects of sea-level rise. In some locations, rates of sea-level rise may exceed the rate at which habitats (e.g., seagrass beds, coastal marshes) can migrate and adapt. It is also important to keep in mind that while these natural habitats may provide some buffer to future sea-level rise in estuarine environments (San Francisco Bay, for example), on the exposed, high-energy, open coast, there are very few locations where biological buffers or habitats exist to provide any significant reduction to the impacts of coastal flooding and erosion from future sea-level rise.

Employing the methodology of Kopp et al. (2014), and consistent with the projections above, we provide probabilistic estimates of the rates of sea-level rise at each of the three selected tide gauges: Crescent City, San Francisco and La Jolla (Table 2). We also provide tables of probabilities that sea-level rise will meet or exceed a given height for RCP 8.5 and RCP 2.6 at each of the three tide gauges (Tables 3, 4 and 5). Under the H++ scenario, with rapid ice-sheet loss in the Antarctic, average rates of sea-level rise in California would exceed 50 mm/year (2 inches/year) by the end of the century.

Table 2. Projected average rates (mm/year) of sea-level rise in: (a) Crescent City (b) San Francisco, and (c) La Jolla.

Projections are based on the methodology of Kopp et al., 2014 with the exception of the H++ scenario. For example, there is a 50% probability that sea-level rise rates in San Francisco between 2030-2050 will be at least 3.8 mm/year. The 'likely-range' is consistent with the terms used by the IPCC meaning that it has about a 2-in-3 chance of containing the correct value. The H++ scenario is a single scenario, not a probabilistic projection, and does not have an associated distribution in the same sense as the other projections; it is presented in the same column for ease of comparison.

(a) Crescent City

mm / yr	MEDIAN	LIKELY RANGE	1-IN-20 CHANCE	1-IN-200 CHANCE
Year / Percentile	*50% probability SLR meets or exceeds...*	*67% probability SLR is between...*	*5% probability SLR meets or exceeds...*	*0.5% probability SLR meets or exceeds...*
2010-2030	1.9	1.0 — 2.9	3.8	5.7
2030-2050 (RCP 2.6)	2.4	0.4 — 4.7	6.8	12
2030-2050 (RCP 4.5)	3.1	1.3 — 5.1	6.9	12
2030-2050 (RCP 8.5)	3.8	1.6 — 6.4	9	14
2030-2050 (H++)	23			
2080-2100 (RCP 2.6)	2.6	-0.2 — 6.4	11	25
2080-2100 (RCP 4.5)	3.9	0.7 — 8	12	26
2080-2100 (RCP 8.5)	8	3.4 — 13	19	34
2080-2100 (H++)	51			

(b) San Francisco, Golden Gate

mm / yr	MEDIAN	LIKELY RANGE	1-IN-20 CHANCE	1-IN-200 CHANCE
Year / Percentile	*50% probability SLR meets or exceeds...*	*67% probability SLR is between...*	*5% probability SLR meets or exceeds...*	*0.5% probability SLR meets or exceeds...*
2010-2030	4.7	3.8 — 5.7	6.5	8.4
2030-2050 (RCP 2.6)	5.1	3.1 — 7.4	9.6	15
2030-2050 (RCP 4.5)	5.8	4.2 — 7.7	9.5	14
2030-2050 (RCP 8.5)	6.7	4.5 — 9.3	12	17
2030-2050 (H++)	26			
2080-2100 (RCP 2.6)	5.2	2.3 — 9.1	14	28
2080-2100 (RCP 4.5)	6.5	3.1 — 11	15	29
2080-2100 (RCP 8.5)	11	6.0 — 16	22	37
2080-2100 (H++)	55			

(c) La Jolla

mm / yr	MEDIAN	LIKELY RANGE	1-IN-20 CHANCE	1-IN-200 CHANCE
Year / Percentile	*50% probability SLR meets or exceeds...*	*67% probability SLR is between...*	*5% probability SLR meets or exceeds...*	*0.5% probability SLR meets or exceeds...*
2010-2030	5.1	4.1 — 6.2	7.1	9.1
2030-2050 (RCP 2.6)	5.4	3.6 — 7.6	9.7	16
2030-2050 (RCP 4.5)	6.2	4.5 — 8.3	10.2	15
2030-2050 (RCP 8.5)	7.2	5.1 — 9.6	12	18
2030-2050 (H++)	26			
2080-2100 (RCP 2.6)	5.3	2.4 — 9.2	14	28
2080-2100 (RCP 4.5)	6.7	3.3 — 11	16	29
2080-2100 (RCP 8.5)	11	6.5 — 17	22	38
2080-2100 (H++)	54			

Table 3. Probability that sea-level rise at Crescent City will meet or exceed a particular height (feet) in a given year under: (a) RCP 8.5, and (b) RCP 2.6.

Estimates are based on Kopp et al., 2014. All heights are with respect to a 1991-2009 baseline; values refer to a 19-year average centered on the specified year. Grey shaded areas have less than a 0.1% probability of occurrence.

(a) RCP 8.5

	1 FT.	2 FT.	3 FT.	4 FT.	5 FT.	6 FT.	7 FT.	8 FT.	9 FT.	10 FT.
2020										
2030										
2040	0.3%									
2050	3%	0.1%								
2060	13%	1%	0.1%							
2070	31%	2%	0.4%	0.1%	0.1%					
2080	49%	8%	1%	0.4%	0.2%	0.1%				
2090	63%	17%	4%	1%	0.4%	0.2%	0.1%	0.1%		
2100	72%	30%	9%	3%	1%	1%	0.3%	0.2%	0.1%	0.1%
2150	90%	67%	40%	21%	11%	6%	3%	2%	1%	1%
2200	92%	81%	67%	51%	37%	26%	18%	13%	9%	6%

(b) RCP 2.6

	1 FT.	2 FT.	3 FT.	4 FT.	5 FT.	6 FT.	7 FT.	8 FT.	9 FT.	10 FT.
2020										
2030										
2040	0.3%									
2050	2%	0.1%								
2060	6%	0.3%	0.1%							
2070	13%	1%	0.2%	0.1%						
2080	20%	2%	1%	0.2%	0.1%	0.1%				
2090	28%	5%	1%	0.4%	0.2%	0.1%	0.1%			
2100	36%	8%	2%	1%	0.4%	0.2%	0.1%	0.1%	0.1%	
2150	52%	23%	11%	6%	3%	2%	1%	1%	1%	1%
2200	58%	39%	24%	16%	11%	7%	5%	4%	3%	2%

Table 4. Probability that sea-level rise at San Francisco, Golden Gate, will meet or exceed a particular height (feet) in a given year under: (a) RCP 8.5, and (b) RCP 2.6.

Estimates are based on Kopp et al., 2014. All heights are with respect to a 1991-2009 baseline; values refer to a 19-year average centered on the specified year. Grey shaded areas have less than a 0.1% probability of occurrence.

(a) RCP 8.5

	1 FT.	2 FT.	3 FT.	4 FT.	5 FT.	6 FT.	7 FT.	8 FT.	9 FT.	10 FT.
2020										
2030	0.1%									
2040	3.3%									
2050	31%	0.4%								
2060	65%	3%	0.2%	0.1%						
2070	84%	13%	1.2%	0.2%	0.1%					
2080	93%	34%	5%	0.9%	0.3%	0.1%	0.1%			
2090	96%	55%	14%	3%	0.9%	0.3%	0.2%	0.1%	0.1%	
2100	96%	70%	28%	8%	3%	1%	0.5%	0.3%	0.2%	0.1%
2150	100%	96%	79%	52%	28%	15%	8%	4%	3%	2%
2200	100%	97%	91%	80%	65%	50%	36%	25%	18%	13%

(b) RCP 2.6

	1 FT.	2 FT.	3 FT.	4 FT.	5 FT.	6 FT.	7 FT.	8 FT.	9 FT.	10 FT.
2020										
2030										
2040	3.1%									
2050	19%	0.3%								
2060	43%	1.4%	0.2%							
2070	62%	4%	0.6%	0.2%						
2080	74%	11%	2%	0.4%	0.2%	0.1%				
2090	80%	20%	3%	1.0%	0.4%	0.2%	0.1%	0.1%		
2100	84%	31%	7%	2%	0.8%	0.4%	0.2%	0.1%	0.1%	
2150	93%	62%	31%	14%	7%	4%	2%	2%	1%	1%
2200	93%	68%	42%	22%	12%	7%	5%	3%	2%	1%

Table 5. Probability that sea-level rise at La Jolla will meet or exceed a particular height (feet) in a given year under: (a) RCP 8.5, and (b) RCP 2.6.

Estimates are based on Kopp et al., 2014. All heights are with respect to a 1991-2009 baseline; values refer to a 19-year average centered on the specified year. Grey shaded areas have less than a 0.1% probability of occurrence.

(a) RCP 8.5

	1 FT.	2 FT.	3 FT.	4 FT.	5 FT.	6 FT.	7 FT.	8 FT.	9 FT.	10 FT.
2020										
2030	0.1%									
2040	5.5%									
2050	40%	0.5%								
2060	74%	4%	0.3%	0.1%						
2070	89%	17%	1.5%	0.3%	0.1%					
2080	95%	41%	6%	1.1%	0.3%	0.1%	0.1%			
2090	97%	62%	17%	4%	1.0%	0.4%	0.2%	0.1%	0.1%	
2100	98%	75%	33%	10%	3%	1%	0.5%	0.3%	0.2%	0.1%
2150	100%	97%	83%	58%	33%	17%	9%	5%	3%	2%
2200	100%	98%	93%	83%	70%	55%	40%	28%	20%	14%

(b) RCP 2.6

	1 FT.	2 FT.	3 FT.	4 FT.	5 FT.	6 FT.	7 FT.	8 FT.	9 FT.	10 FT.
2020										
2030										
2040	4.4%									
2050	25%	0.3%								
2060	52%	1.7%	0.2%							
2070	70%	6%	0.7%	0.2%						
2080	80%	14%	2%	0.4%	0.2%	0.1%				
2090	85%	24%	4%	1.1%	0.4%	0.2%	0.1%	0.1%		
2100	88%	36%	8%	2%	0.9%	0.4%	0.2%	0.1%	0.1%	
2150	96%	68%	35%	16%	8%	4%	3%	2%	1%	1%
2200	96%	72%	47%	26%	14%	8%	5%	3%	2%	2%

BOX 3

Sources of, and approach to, uncertainties

Depending on the time horizon being considered, different sources of uncertainty play smaller or larger roles in projections of sea-level rise [48]. For long-term changes (second half of this century and beyond), the choice of model and scenario of anthropogenic greenhouse gas emissions significantly affect the outcome. By comparison, for short- to mid-term projections (within the next two or three decades), variability in the Earth's climate system, which would exist even in the absence of human-driven changes, is the predominant source of uncertainty.

Emissions scenarios

Emissions of the last decade position us along the highest scenario considered by the last IPCC report, RCP 8.5, and greenhouse gas emissions will continue through this century. However, exactly how large emissions will be depends on policy and societal choices, as well as technological progress, at local to global scales. Greenhouse gas emissions scenarios, which serve as inputs into climate models, are not predictions but rather the outcomes of a set of internally consistent assumptions about the evolution of population, GDP, technology, and, in some cases, mitigation policies. As such, the scientific community that develops and uses them has generally resisted attaching relative likelihoods to different scenarios, and future climate change projections are usually provided specific to - and conditional upon - a given scenario, as is the case in this report.

Model uncertainty

The uncertainty in model projections stems from the unavoidable approximations involved in the modeling of complex and interacting processes of the Earth system: any type of process model needs to adopt a grid resolution, and choose which processes to either represent explicitly, approximate through parameter selection, or not include at all [49]. These choices introduce unavoidable imprecision in the representation of the real world by any model, and differences among any ensemble of models. The diversity of existing models, each of which relies on a defensible set of parameter choices and computational approaches, translates into differences and uncertainties in sea-level rise projections.

In this report we adopt an approach (that of Kopp et al., 2014) in which model uncertainties are quantified for thermal expansion of seawater, ocean dynamics, and glaciers. These are the model components that are derived (directly for thermal expansion and ocean dynamics, and indirectly via a surface mass-balance model for glaciers) from climate model simulations. For these types of models, a large multi-model ensemble is available [50] that is used to calibrate the probability distributions in the model. By comparison, there is not yet an equivalent model ensemble that would enable us to develop probabilities of other sources of sea-level rise, including ice loss from ice sheets. As a result, we are forced to make approximations or use single-model estimates. In the case of the Antarctic or Greenland Ice Sheets, recent scientific advances reveal deep uncertainties, with different modeling approaches changing our understanding and projections (see also Appendix 2). Even with additional observations, it will not be straightforward to characterize model structural dependencies, limitations, and uncertainties, hence the need for a special treatment of the ice-sheet component in sea-level rise projections (see further below).

Variability in the Earth system

Natural variability in the Earth's climate system occurs alongside variability caused by anthropogenic influences. Variability in the Earth's system occurs on daily to centennial timescales and affects both mean water levels and the amplitude of extreme

BOX 3

storm surges. Long-term tide gauge records give us observational data to use in validating models of sea-level rise.

Statistical models of decadal amplitude changes (driven by natural modes of variability in the ocean, like ENSO or other oscillations) and of storm surges (driven by short-term weather phenomena, like storms) can be estimated on the basis of observed or modeled records, thus isolating these components from mean sea level changes and - when needed - superimposing them on projected mean sea-level rise [51]. The underlying assumption here is that the interplay of the two sources of variability is additive rather than non-linear. We note that locations may be identified where changes in mean sea level can indeed affect the size of surges, in which case ad-hoc process models of storm surges driven by scenarios of sea-level rise can be deployed.

As for climate system drivers at large (e.g., ENSO, storms), the question boils down to assessing possible future changes and their statistical characteristics. At the moment, uncertainties in modeling outcomes are large and there is not robust evidence that the internal variability of these phenomena will change significantly under future scenarios [52]. As mentioned, the interplay of these different sources of uncertainty is not unique as we move from short- to mid- to long-term horizons for our projections. Estimated probabilities of particular outcomes are increasingly less robust -- in the sense of comprehensively covering the range of expected outcomes and firmly quantifying their relative probability -- as we lengthen those horizons, and we move into climate scenarios of unprecedented nature as far as anthropogenic forcing is concerned.

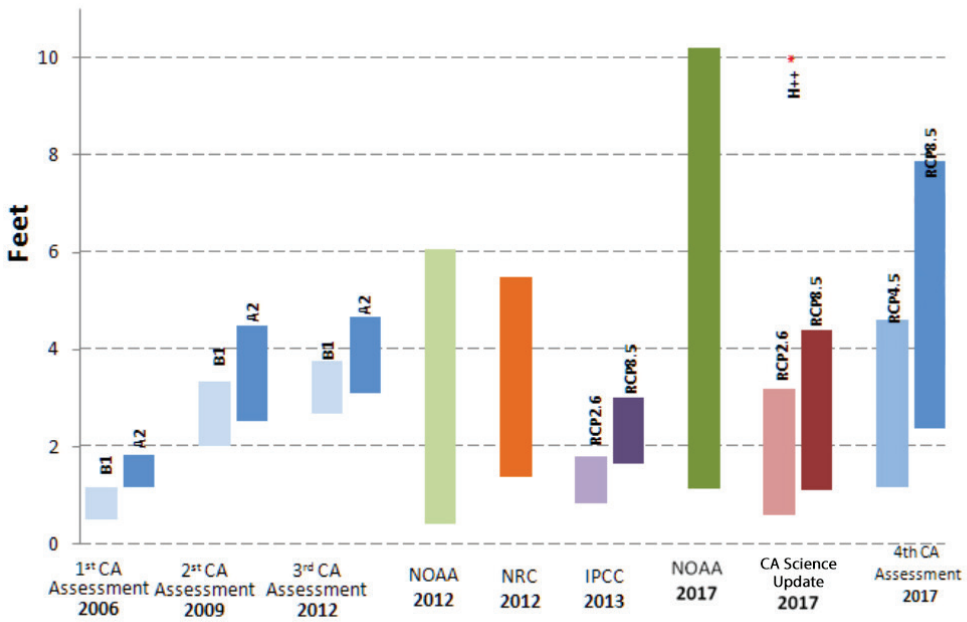
Accounting for uncertainty

For projections over the next few decades, we do not expect the role of models and scenarios to be as crucial to pin down. However, as we move into the more distant future, our ability to guess what society will do diminishes, different models will be more or less dependable, and the processes generating our extreme scenario will unfold. As a result, our ability to quantify uncertainty through formal probability distributions decreases. We therefore include a qualitatively different scenario (H++) whose likelihood we cannot characterize at this time, and note that quantified probabilistic projections need to be taken as an evolving representation of our understanding, open to updates and modifications especially in the tails of probability distributions. In this context of likely continued and unquantifiable uncertainties, incorporating long-range planning for sea-level rise in decisions is increasingly urgent.

3.4. How do these projections compare with other regional and national projections?

Figure 4. Projections of sea level rise in California and U.S. national reports and assessments of the last decade.

Projections are provided for 2100 according to the approach described in each report. The different approaches reflect the evolution of modeling techniques to project sea-level rise including new approaches to provide greater geographic resolution in projections and probabilistic projections, as well as the different intended purposes of the assessments (i.e., state and national). In brief, the figure depicts: CA 1st, 2nd, 3rd Assessments: range of projections for South Cape Mendocino, NOAA 2012 – range of projections of global mean sea level rise, NRC 2012 – range of projections for South Cape Mendocino, IPCC 2013 – projections of global mean sea-level rise under RCP2.6 and RCP 8.5, NOAA 2017 – range projections for U.S. sea level rise, California 4th Assessment – 5th-95th percentile probabilistic projections for San Francisco under RCP 4.5 and RCP 8.5, California Science Update (this report) – 5th -95th percentile for San Francisco using the Kopp et al., 2014 framework and H++ scenario from NOAA 2017.



Over the last decade, projections of sea-level change in California have evolved considerably (Figure 4).

The common threads across these evolving projections are the recognition that the magnitude and timing of future sea-level rise is uncertain, and that emissions in the near- and mid-term 21st century will have long-lasting consequences that will become increasingly clear in the decades after 2050.

In particular, the magnitudes of estimated sea-level rise have grown, especially at the upper, low probability "tail" of ranges that have been estimated. For example, sea-level rise projections for 2100 in the California 1st Climate Change Assessment (conducted in 2006) ranged from 6 - 22 inches (15 - 56 cm) above a year 2000 starting point. By comparison, the recently released estimates of the California 4th Climate Change Assessment (California 4th Assessment) range from 14 - 94 inches (36 cm - 239 cm) with an additional very low probability worst-case estimate that exceeds 9 feet (274 m).

The sea-level scenarios presented in the California 4th Assessment present a range of scenarios whose mid-to-upper level is higher than that provided in the 2012 National Research Council Report, and much higher than that published in the 4th IPCC Report. At the same time, the high end of the California 4th Assessment range is approximately comparable to that recently provided by the 2017 USGCRP Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force led by NOAA, as well as the 99.9th percentile of Kopp et al. (2014)'s projections.

The strongest driver of this shift toward higher distributions of possible future sea levels is the possibility of high rates of ice loss from the West Antarctic Ice Sheet under scenarios of continued increases in greenhouse gas emissions. The California 4th Assessment includes recent estimates by DeConto and Pollard (2016) of Antarctic Ice Sheet losses from a model that introduces new physical processes that invoke high rates of ice discharge into the Antarctic Ocean. The Working Group's assessment for the purposes of developing updated sea-level rise projections for California was that the DeConto and Pollard (2016) results are compelling enough to include an extreme SLR scenario (called the H++ scenario), based on the highest scenario developed by Sweet et al. (2017). However, since these results are very fresh, and the processes are not yet actually observed in Antarctica, they await further modeling and observational evidence. Consequently, we rely upon the earlier model presented in Kopp et al. (2014) for the emissions scenario-dependent probabilistic projections presented in this report.

BOX 4

Integrating Sea-Level Rise with Coastal Storm and Wave Impacts

There are several different sea-level rise visualization tools available; the NOAA Sea Level Rise Viewer and Climate Central's Surging Seas are the two most commonly used examples. These allow a user to develop an inundation map for virtually any coastal area in California that will project a range of future sea levels onto the specific area of concern or interest. These viewers have been referred to as a "bathtub approach" simply because, while they use accurate elevation and tide data, inundation is determined by uniformly raising water levels by various selected future sea level values in combination with the average daily high tide. This passive approach is a reasonable approximation of the future everyday impacts of sea-level rise. However, it does not consider potential flooding driven by the dynamic processes that affect coastal water levels daily (e.g., tidal variability, waves), seasonally (e.g., elevated water levels during El Niño events) or during storm events (e.g., storm surge, wave run-up, and river discharge) and the hydrodynamic complexity associated with bathymetry, built structures and the natural coastline configuration.

The Coastal Storm Modeling System (CoSMoS)[vi] is a dynamic modeling approach that has been developed by the United States Geological Survey in order to allow more detailed predictions of coastal flooding due to both future sea-level rise and storms integrated with long-term coastal evolution (i.e., beach changes and cliff/bluff retreat) over large geographic areas. This model simulates a reasonable range of plausible 21st century sea-level rise and storm scenarios to provide coastal planners and decision makers with more accurate information than sea-level rise alone in order to predict areas of coastal flooding and impacts. The model incorporates wave projections, tides and regional atmospheric forcing to generate sea and surge levels that can then be dynamically downscaled to depict local changes. CoSMoS has now been applied to most of the urbanized California coast (e.g., Southern California and the San Francisco Bay Area) and will soon cover the state's shoreline. Considerable opportunity exists to align the methodology for deriving sea-level rise projections in this science summary with the underlying model in CoSMoS. Doing so will not only return the greatest value on existing investments but also set the stage for efficiently incorporating updated projections into decisions as scientific understanding increases and as sea levels change.

[vi] https://walrus.wr.usgs.gov/coastal_processes/cosmos/index.html

4. Conclusions

4.1. Rapidly evolving scientific understanding

Increasing the reliability of future sea-level projections will be important in decision-making for both existing and proposed development and infrastructure. This is a tractable problem, but it will require concerted action on two fronts. First, it will require improved scientific understanding of mass-loss processes from the vast polar ice sheets across all the relevant spatial and temporal scales. This can only be achieved through continued and new observations from satellites and the field (both on the ice and in the surrounding atmosphere and ocean), combined with modeling to investigate key processes such as ice-ocean interactions, surface melting, and fracture mechanics of ice. This will require substantial international and interagency investment to support collaborations across the disciplines of glaciology, meteorology, oceanography, and computational science. Second, it will require tighter integration between the scientific and decision-making communities such that feedbacks from the latter can inform, via recursive process of scientific analysis and stakeholder deliberations [53,54], future sea-level rise studies and projections.

Advances in our understanding of global, regional, and local sea-level rise are already occurring and substantial advances are expected within the next decade. In the meantime, research currently underway and expected in the next one to five years includes improved understanding of the warming thresholds capable of driving substantial retreat in the West Antarctic Ice Sheet. Given these expected rapid developments, the approach taken here allows for relatively frequent updates of location-specific sea-level rise projections. Updating of the science underpinning California's statewide guidance will be important as our understanding of these ice-

sheet contributions to sea-level rise increases, and/or the range of likely future emissions scenarios begins to narrow. In addition, the explicit consideration of an extreme H++ scenario of indeterminate probability flags for decision-makers the potential for extreme outcomes. Based on some modeling studies the possibility of such extreme sea-level rise is now supported and may come to be viewed as either more or less likely as scientific understanding evolves.

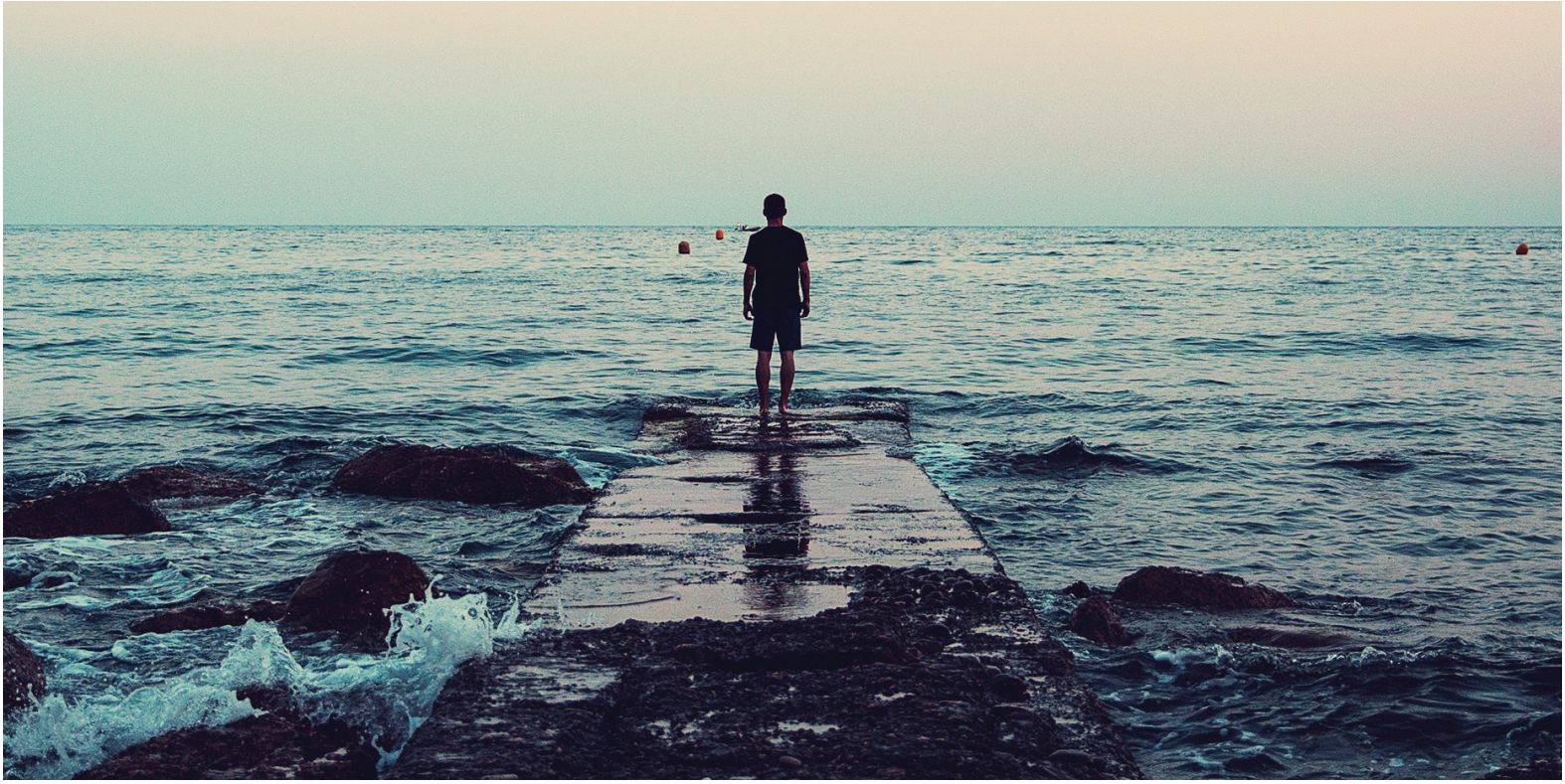
4.2. Informing near-term decisions

These projections of future sea level and changing coastal hazards can and should be used along with a comprehensive assessment of what is at risk (i.e., exposed to future coastal hazards) and what is at stake (i.e., the monetized and non-monetary values attached to what is exposed) to weigh the different types of costs, and potential losses and benefits of taking action now to prevent future harm against the wide-ranging risks of inaction [55].

However, doing so will require the development of decision-support systems that help California decision-makers and stakeholders to decompose what will be complex, uncertain, and inter-temporal decisions into more manageable parts. Various approaches are available for decision analysis and decision-making under uncertainty that aim to go beyond economic efficiency in determining the best possible way forward in the face of multiple objectives and criteria for making difficult choices [55,56]. At their core, these approaches help stakeholders and decision-makers to identify, define, and bound management problems and opportunities; they help these same groups to identify, characterize, and operationalize a shared set of objectives to guide management choices; these approaches emphasize the importance of characterizing the anticipated consequences, based on scientific assessments, of a broad array of different development and management alternatives; and they support the need for tradeoffs when objectives across alternatives inevitably conflict [57–59].

These decision-support approaches, together with numerous studies on the cost of inaction, generally suggest that uncertainty about the exact amount of future sea-level rise should not be a deterrent to taking action now [60–62]. Adaptation and hazard mitigation decisions and investments in the near-term can prevent much greater losses (many times the initial cost) than would incur if such action were not taken (e.g., [63,64]).

The forthcoming, updated sea-level rise policy guidance will thus provide a decision-centric approach to using sea-level rise projections that is informed by a clear understanding of the decision-makers and the decision contexts. It will guide decision-makers through a systematic and defensible process that assists them in framing and structuring the decisions at hand, explicitly laying out objectives and decision criteria, laying out distinct solution options and assessing them in the context of sea-level rise projections and key uncertainties, directly confronting trade-offs, and setting up an adaptive management process going forward [56,65]. In addition, providing recommendations for how to effectively communicate sea-level rise risks and meaningfully engage stakeholders in these challenging planning and decision processes can make the use of uncertain sea-level rise projections in decision making easier and ultimately lead to decisions that reflect decision-makers' risk tolerances and desired outcomes.



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Appendix 1

Questions from the Policy Advisory Committee to the OPC-SAT Working Group

The questions below were developed by the State Sea-Level Rise Policy Advisory Committee. The intention of the questions is to elicit information about the current estimates of sea level rise for the California coast and how to understand the scientific context around those estimates, including the state of the science (e.g., areas of uncertainty, emerging science), the importance of each contributor to sea level rise, and sensitivity of the estimates to policy actions.

Following each question we provide a reference to the associated section of the document where the question is addressed and answered.

Estimates of Sea-level Rise

1. What is the current range of estimates of sea level rise for the California coast? *(Section 3)*

- **a.** What probabilities can be assigned to those estimates given the current state of science? *(Section 3.1)*
- **b.** Should more weight be given to certain parts of the range, and if so, why? *(Section 3.2)*

2. Across the physically plausible range of sea-level rise projections, is it possible to say which scenario(s) are more likely than others? *(Section 3.1.2)*

- **a.** What progress has been made since the existing State Sea-level Rise Guidance Document was published in 2013 on assigning probabilities to different emissions, warming and sea-level rise scenarios? *(Section 3.1.2)*
- **b.** Which contributors to sea-level rise (e.g., thermal expansion, ice loss) are currently included in developing probabilistic sea-level rise scenarios? *(Section 3.1.2)*
- **c.** What is the OPC-SAT Working Group's recommendation on how to estimate the likelihood of certain amounts of sea-level rise occurring at future dates for a given global emissions scenario? *(Section 3.1.2)*
- **d.** What other approaches is the OPC-SAT Working Group aware of, or could the Working Group recommend, for presenting uncertain sea-level rise projections? *(Section 3.1.2)*
- **e.** Is it possible to identify and characterize the degree of uncertainty in different contributors to sea-level rise? Where do the biggest uncertainties lie and what causes these uncertainties? *(Box 3)*

State of the Science

These questions are designed to elicit information on the state of sea-level rise science, including emerging issues and the treatment of ice loss in Antarctica.

3. What are the significant and notable emerging insights in sea-level rise science since the current State Sea-Level Rise Policy Guidance was issued? Why do they warrant attention? *(Section 2.2)*

- **a.** Have there been any notable changes in understanding how thermal expansion of ocean water contributes to sea-level rise? *(Section 2.1.1 and Section 2.2)*
- **b.** Have there been any notable changes in understanding of the role of ice loss from inland glaciers and major ice sheets? *(Section 2.1 and 2.2)*

c. Have there been any notable changes in understanding of steric or dynamic ocean current changes that affect regional sea-level rise projections? *(Section 3.1.2)*

d. Have there been any notable changes in understanding of local or regional land movement that could affect projections of relative sea level change? *(Section 2.2)*

4. Does the OPC-SAT Working Group consider the emerging science important and significant enough to warrant consideration in the current update to the State Sea-level Rise Guidance Document? If yes, why? If no, why? Please comment on the current confidence in new scientific insights or advances. *(Section 2.2, Section 3.1.1, Appendix 2)*

5. Existing models, including Kopp et al. (2014) and Cayan et al. (2016), project very different sea-level rise estimates under different emissions scenarios. However, some scientists suggest that sea levels in 2100 are determined by events in Antarctica, regardless of future GHG emission levels and trajectories. What is your scientific opinion about this issue? *(Section 2.1, Section 3.2)*

6. What are the scientific advances in best approaches to project sea-level rise since the publication of the existing State Sea-level Rise Guidance Document (2013)? What makes some modeling approaches better than others; in what way? *(Section 3.1)*

a. What are the strengths and weaknesses of the different approaches for projecting global sea-level rise? *(Section 3.1)*

b. Which approach or combination of approaches would the OPC-SAT Working Group recommend for estimating future global sea levels? *(Section 3.1.2)*

7. What are the best/most reliable approaches for translating global projections into regional projections? *(Section 3.1.2)*

8. What are the factors that cause sea-level rise projections to differ among locations? *(Section 2.1.2, Box 2)*

9. How are these factors considered in regional projections? *(Section 3.1.2)*

10. Is the OPC-SAT Working Group aware of additional research/modeling efforts, etc., presently underway that should inform the update to the State Sea-level Rise Guidance Document? *(Section 4.1)*

a. How soon does the OPC-SAT Working Group expect major breakthroughs in understanding of sea-level changes? What would constitute a major breakthrough? How might these breakthroughs affect sea-level rise projections? Given current uncertainties in scientific understanding, and the anticipated rate of accumulation of new knowledge or observations, can the Working Group provide a recommended frequency for reviewing the latest available science to update guidance for state and local decision-makers? *(Section 1.4, Section 4.1, Appendix 2)*

b. Similarly, can the Working Group provide recommendations, from a scientific perspective, on how this science could be considered in a policy setting (e.g., establishing an appropriate frequency for policy updates, establishing a scientific body to provide regular updates)? *(Section 1.4)*

Understanding the Contributors to Local Sea-Level Rise

11. In addition to projecting future sea levels, other factors may also be important.

a. What is the state of science on identifying future (a) tidal amplitude and/or phase, and (b) frequency and intensity of extreme events (e.g., high water due to storm surges, ENSO events)? *(Box 1)*

b. What are the pros and cons of different approaches of arriving at total water level? *(Box 4)*

c. What is the OPC-SAT Working Group's recommendation on how to integrate (global or regional) sea-level rise projections with expected changes in tidal and extreme events? *(Box 4)*

d. What is the OPC-SAT Working Group's assessment of the adequacy of superimposing historical extreme event departures from mean onto projected mean sea levels to estimate future values? *(Box 4)*

Policy Sensitivity of Sea-Level Rise Projections

12. How "policy dependent" are the different contributors to sea-level rise? *(Section 2.3)*

a. Are the different contributors to sea-level rise equally sensitive to changes in global emissions/temperature? *(Section 2.1)*

b. How much sea-level rise can be avoided or how much can it be slowed down by significant emission reductions (e.g., achieving the global commitments made at COP21 in Paris or 80% GHG emissions reductions by 2050)? *(Section 2.1, Section 3.2, and Section 3.3)*

c. What new implications for planning and decision making, if any, are introduced by including ice loss scenarios in sea-level rise projections (e.g., magnitude, timing, non-linear rates, nature of the impact)? *(Section 3.1.2. Appendix 2)*

13. Sea-level rise projections typically use emissions scenarios (e.g., IPCC emissions scenarios/ Representative Concentration Pathways (RCPs)) as inputs into general circulation/sea-level rise models. The RCP 2.6 scenario (lowest IPCC emission scenario) appears out of reach, given current greenhouse gas emission trends, and the unlikely development of more ambitious emission reduction targets in the near future. Is there any physically plausible scenario under which it remains sensible to retain such low-end scenarios in the range of projections? If not, what is the lowest plausible sea-level rise scenario? *(Section 3.1.1)*

Sea-Level Rise Exposure vs. Risk-based Assessment

14. Risk (often defined as probability multiplied by consequence) is a critical input to planning and decision-making.?

a. What is the OPC-SAT Working Group's recommendation on whether and, if so, how to incorporate consideration of risk as part of the State Sea-level Rise Guidance Document to state and local decision-makers? *(Section 1.3, Section 4.2)*

b. How would this approach take account of the uncertainties in sea-level rise projections? *(Section 4.2, Box 3)*

15. What other questions should we be asking that we haven't asked? What other considerations should be brought to bear on this topic?

Appendix 2

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Role of Polar Ice Sheets in Future Sea-Level Rise:
IMPLICATIONS FOR CALIFORNIA

ABOUT THIS REPORT

This document was developed in response to a request from the California Ocean Science Trust to synthesize current scientific understanding of ice loss from the polar ice sheets, with particular focus on West Antarctica, and to discuss the implications for projections of sea-level rise in California. It was developed to inform an update to the science foundation of California's statewide policy guidance on sea-level rise, and an associated update in sea-level rise projections for California.

Abstract

Global mean sea level (GMSL) has risen by about 18 cm (7 inches) since 1900. Most of this rise is attributed to a combination of the thermal expansion of a warming global ocean and the loss of land ice (made up of mountain glaciers and small ice caps, and the great polar ice sheets covering Greenland and Antarctica). During the 20th-century, sea-level rise was dominated by ocean thermal expansion, but recently land-ice loss has taken over as the primary contributor. While mountain glaciers and ice caps are currently contributing more meltwater to the ocean than the ice sheets, the rate of ice loss from both Greenland and Antarctica is accelerating, and ice sheets will likely soon become the dominant component of the land-ice contribution. This is particularly concerning because the ice sheets contain enough ice to raise GMSL by about 65 meters (213 feet) if they melted completely. This report reviews emerging science that suggests ice loss from the Antarctic Ice Sheet poses the greatest potential risk to California coastlines over the next 100 years.

Sea Level is Rising, the Rate is Accelerating, and Land Ice has become the Primary Contributor.

Between ~1900 and 1990, the average rate of global mean sea level (GMSL) rise was ~1.2 ± 0.2 mm/yr (0.5 inches per decade), but the rate has risen sharply since 1990 to ~3 mm per year (1.2 inches per decade) and it continues to accelerate (Hay et al., 2015). The primary contributors to rising GMSL are ocean thermal expansion (a warmer ocean has lower density and takes up more space), increased groundwater withdrawal and diminished rates of land-water storage behind dams, shrinking mountain glaciers, and net changes in the mass of the polar ice sheets covering Greenland and Antarctica (Church et al., 2013).

Over the last century, the rise in GMSL was dominated by ocean thermal expansion, which accounted for about 50% of the increase. Land ice, collectively from mountain glaciers, ice caps, and the polar ice sheets, accounted

1 Contributions to GMSL from groundwater and land water storage were small or slightly negative over most of the 20th century. These contributions are now positive (mainly due to groundwater depletion) but are smaller than contributions from land ice or ocean thermal expansion. Together, groundwater and land water storage contributions to GMSL were 0.38 ± 0.12 mm per year (0.15 ± 0.05 inches per decade) between 1993 and 2010 (Church et al., 2013).

for most of the remaining increase, with mountain glaciers and ice caps contributing roughly 25%[1] and ice sheets the remaining 25%. However, there are vast differences in the sizes of the land ice reservoirs; losing the entire global inventory of mountain glaciers and ice caps would raise GMSL by only ~0.5 m (1.6 feet; Church et al., 2013), whereas complete loss of the Greenland and Antarctic ice sheets would raise GMSL by ~7.4m (24 feet) and ~57m (187 feet), respectively (Bamber et al., 2013; Fretwell et al., 2013). These massive ice sheets represent the greatest potential threat to the long-term sustainability of coastal populations and infrastructure.

Recently, the loss of land ice has surpassed ocean thermal expansion as the largest contributor to sea-level rise (Figure 1). Land ice contributions come from mountain glaciers and small ice caps and the polar ice sheets (Antarctica and Greenland). While glaciers and ice caps continue to contribute substantial meltwater to the oceans (Meier et al., 2009; Marzeion et al., 2012), satellite observations (Figure 2) indicate that the rate of mass loss from Greenland and Antarctica is accelerating (Harig and Simons, 2015; Rignot et al., 2011; Velicogna et al., 2014). The ice sheets have recently taken over as the dominant source of land-ice sea-level rise, with the potential to raise GMSL by several meters in future centuries (Clark et al., 2016; DeConto and Pollard, 2016; Golledge et al., 2015; Huybrechts et al., 2011; Robinson et al., 2012; Winkelmann et al., 2015).

The Greenland Ice Sheet (GIS) is currently losing mass at a faster rate than the Antarctic Ice Sheet (AIS; Figure 1), via a roughly equal combination of surface melt and dynamic thinning of its marginal outlet glaciers (Csatho et al., 2014; Moon et al., 2012). As surface melt increases, particularly around its lower elevation ice margins, the GIS will continue to lose mass at an increasing rate (Huybrechts et al., 2011; van den Broeke et al., 2009). In contrast, Antarctica's recent increase in mass loss is not through surface melt, but is instead mostly related to the increasing flow and retreat of outlet glaciers in the Amundsen Sea region of West Antarctica (Mouginot et al., 2014; Pritchard et al., 2012; Rignot et al., 2014). As discussed below, warming ocean temperatures in this region are thinning ice shelves (the floating, seaward extensions of the glaciers) triggering a dynamic response of the grounded ice upstream (Pritchard et al., 2012; Paolo et al., 2015).

NASA's Ice, Cloud and land Elevation (ICESat) mission revealed major mass loss from Antarctica's ice shelves (Pritchard et al., 2012) and grounded ice sheet (Shepherd et al., 2012) for the period 2003-2009 by estimating the change in ice height with time and converting that to mass. This Ice Sheet Mass Balance Exercise (IMBIE; Shepherd et al., 2012) also included estimates of height change from satellite radar altimetry, and results from two other mass balance techniques (gravity and mass flux) for the period 1992 to 2011. The synthesis of all three techniques showed that the grounded ice changed in mass over this period by: (1) Greenland: –142 ± 49 Gt per year, (2) East Antarctica: +14 ± 43 Gt per year, (3) West Antarctica –65 ± 26 Gt per year, and (4) Antarctic Peninsula: –20 ± 14 Gt per year. Together this contributed 0.59 ± 0.20 mm/year to GMSL (0.23 ± 0.08 inches per decade).

2 Gt (gigatonne) is a billion metric tonnes of ice, and 360 Gt of ice lost to the ocean represents about 1 mm of GMSL rise.

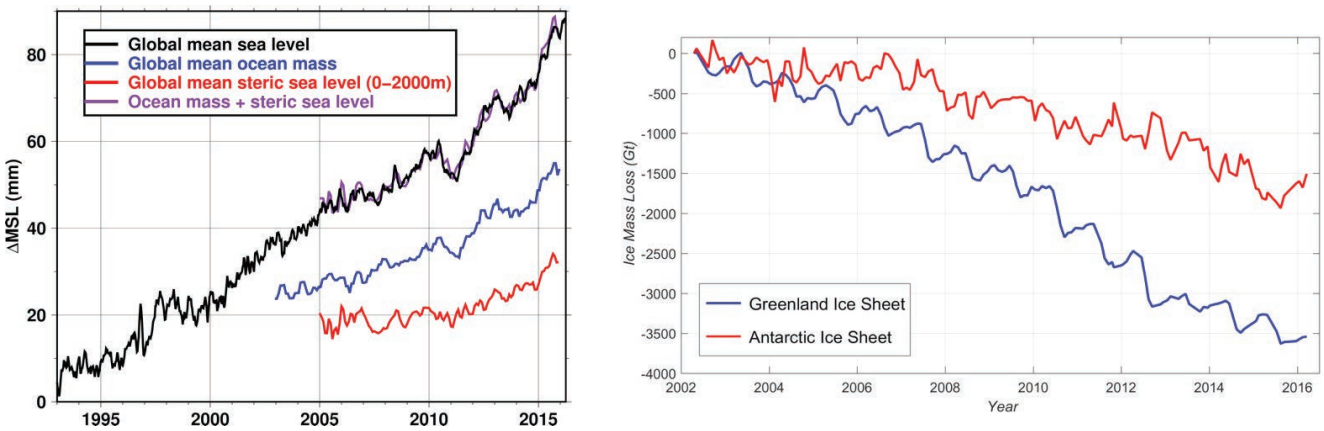

Figure 1. Left: Observations of global mean sea-level rise from satellite radar altimetry (Leuliette and Scharroo, 2010) since 1992 (black line) relative to contributions from 1) the total change in ocean mass contributed by land ice (mountain glaciers, ice caps and the polar ice sheets), and smaller contributions from groundwater and land water storage (Johnson and Chambers, 2013) (blue), and 2) the contribution from thermal (thermo-steric) expansion of the upper ocean (red) from Argo floats (Roemmich and Gilson, 2009). Note that increasing ocean mass, mostly from melting land ice, is now the dominant source of sea-level rise (Figure source: Leuliette and Nerem, 2016). Right. Estimates of ice mass loss on Greenland (blue) and Antarctica (red) from gravity measurements made by the GRACE satellites. Combined, Greenland and Antarctica have been losing an average of ~400 Gt per year since 2002 and the rate is accelerating. The ~5000 Gt of ice lost by the ice sheets since 2002 (right panel) represents a GMSL contribution of about 14 mm, more than 50% of the rise attributed to increasing ocean mass over this period (left panel). Data Source: NASA.

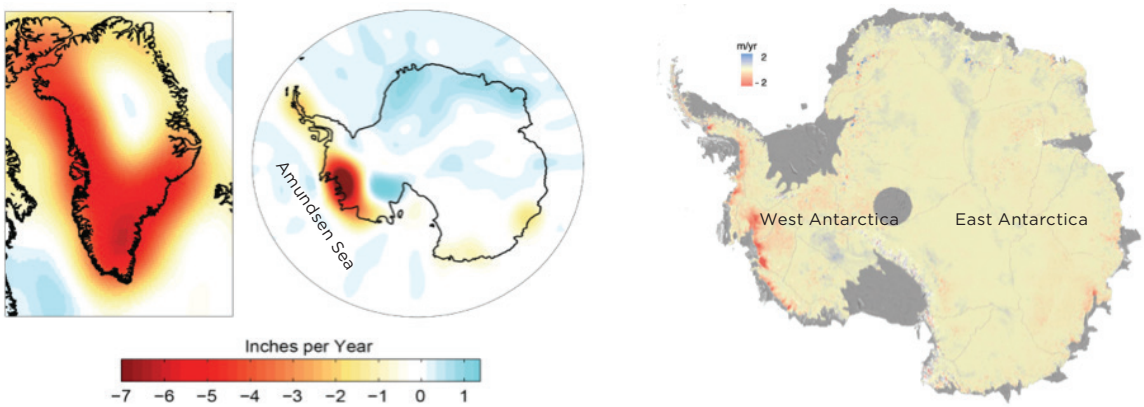

Figure 2. Spatial patterns of ice mass loss (inches of water equivalent lost per year between 2003 and 2012) over Greenland and Antarctica (left), inferred from the GRACE (Gravity Recovery and Climate Experiment) satellites' measurements of Earth's gravitational field (Velicogna et al., 2014; Velicogna and Wahr, 2013). Note the widely distributed ice loss around much of the Greenland Ice Sheet margin. In contrast, Antarctica's ice mass loss is concentrated in the Amundsen Sea sector of West Antarctica, where warming sub-surface ocean temperatures are in direct contact with the underside of ice shelves (figure source: NASA Jet Propulsion Laboratory). The image at right shows the rate of change in the surface elevation of the Antarctic ice sheet between 2010 and 2013, measured by satellite altimetry. Note the coherence between gravity and altimetry measurements, and the concentrated thinning of Amundsen Sea outlet glaciers (from McMillan et al., 2015).

Greenland's Contribution to Future Sea Level

While Greenland is currently a greater contributor to sea-level rise than Antarctica, ice sheet modeling studies spanning a range of future warming scenarios and timescales (Goelzer et al., 2012; Huybrechts et al., 2011; Seddik et al., 2012), show that the potential for the Greenland Ice Sheet (GIS) to contribute truly catastrophic sea-level rise is limited. Most projections of Greenland's contribution to GMSL by the year 2100 are below 25 cm (10 inches), even in high-end greenhouse-gas emissions scenarios (Church et al., 2013). While the balance between the rate of accumulating snowfall and the rate of meltwater and iceberg discharged to the ocean is sensitive to relatively modest warming (>2° C above 19th century temperatures), modeling studies show that the near-complete loss of the GIS will be measured in millennia (Figure 3), not decades or centuries (Robinson et al., 2012).

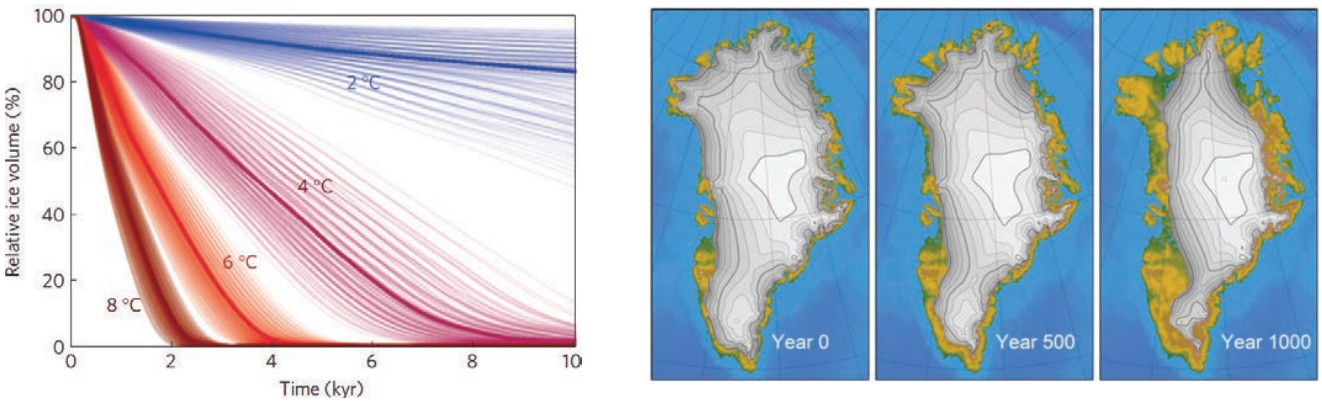

Figure 3. Future projections of the Greenland Ice Sheet. The percentage of Greenland ice volume lost in model simulations (left) using a range of melt-rate parameterizations and increasing summer temperature anomalies from 2 to 8°C (Robinson et al., 2012), whereby 100% loss is equivalent to a 7.4 m rise in global mean sea level. Note the jump in ice-sheet loss with summer temperature anomalies >2°C. Climate-ice sheet simulations (right) assuming a 4-fold increase in CO_2 concentrations over the next 200 years and maintained into the future (Huybrechts, et al., 2011). In both examples, substantial loss of the ice sheet takes centuries to millennia.

Ice Loss from Antarctica will Impact California More than an Equivalent Ice Loss from Greenland

GMSL is clearly rising (Figure 1), but it is relative sea level (RSL), the local difference in elevation between the height of the sea-surface and the height of the solid-Earth surface, that directly impacts coastal communities and ecosystems at risk from coastal flooding.[3] The rise in RSL from shrinking glaciers and ice sheets is not uniformly distributed around the Earth. Changes in the distribution of ice and water over the Earth's surface affects its gravitational field, the orientation and rate Earth's rotation, and the deformation of the Earth's crust and mantle (Mitrovica et al., 2011; Peltier, 2004). While the crust and mantle respond on long (millennial) timescales, the gravitational/rotational effects are essentially instantaneous (annual timescales) and have particular relevance for California.

[3] Changes in RSL arise from 1) vertical land motion, 2) changes in the height of the geoid (the gravitationally determined surface of the ocean in the absence of tides and ocean currents), and 3) changes in the height of the sea surface relative to the geoid. Vertical land motion can be caused by tectonics (California is tectonically active), sediment compaction, or withdrawal of groundwater and hydrocarbons, and the Earth deformation associated with redistributions of ice and ocean mass. This deformation can be separated into 1) glacial isostatic adjustment (GIA), which is the ongoing viscoelastic response of the Earth to past changes in ice volume, and 2) the elastic (gravitational/rotational) response to recent changes in land ice. Both past and current changes in ice volume also affect Earth's gravitional field and rotation, and thus the height of the geoid (Peltier, 2004; Mitrovica et al., 2011). Only the elastic, gravitational, and rotational (fast) components are shown in Figure 4.

As a retreating ice sheet loses mass to the ocean, its gravitational pull on the surrounding ocean is reduced. Within a few thousand kilometers of a retreating ice sheet, the reduced gravitational pull on the ocean causes the sea-surface and thus RSL to drop, even though the ocean has gained volume overall. At some distance further away from the ice sheet (~7000 km), the change in RSL is comparable to that expected from the increase in ocean volume contributed by the melting ice sheet. Beyond that distance, the change in RSL is greater than expected from the extra water added to the ocean by the melting ice sheet. Consequently, Northern Hemisphere coastlines generally experience enhanced relative sea-level rise from the loss of Antarctic ice, while coastlines in the Southern Hemisphere experience enhanced sea-level rise from loss of ice on Greenland. Changing distributions of ice and water also shift the Earth's pole of rotation (the physical North and South Poles) and rate of rotation, which slightly modifies the main gravitational response. The Earth's crust also flexes in response to the change in loading, affecting the height of the land; and given enough time, the Earth's viscous mantle also responds, but these are slower processes generally measured in thousands of years (Peltier, 2004).[4]

Calculations of the gravitational and rotational effects (Figure 4), sometimes called sea level "fingerprints" (Mitrovica et al., 2011), show that North America experiences more sea-level rise from a given meltwater contribution from Antarctica than Greenland, and if the ice loss is from the West Antarctic Ice Sheet (WAIS), the impacts are exaggerated even further. In fact, for California, there is no worse place for land ice to be lost than from West Antarctica (Figure 4). In the near-term, the WAIS is widely considered the most vulnerable major ice sheet to a warming ocean and atmosphere, and serious changes there are already underway, particularly in the Amundsen Sea region (Joughin et al., 2014; Mouginot et al., 2014; Paolo et al., 2015). Consequently, this report focuses on emerging science regarding the vulnerability of the polar ice sheets with a special emphasis on West Antarctica.

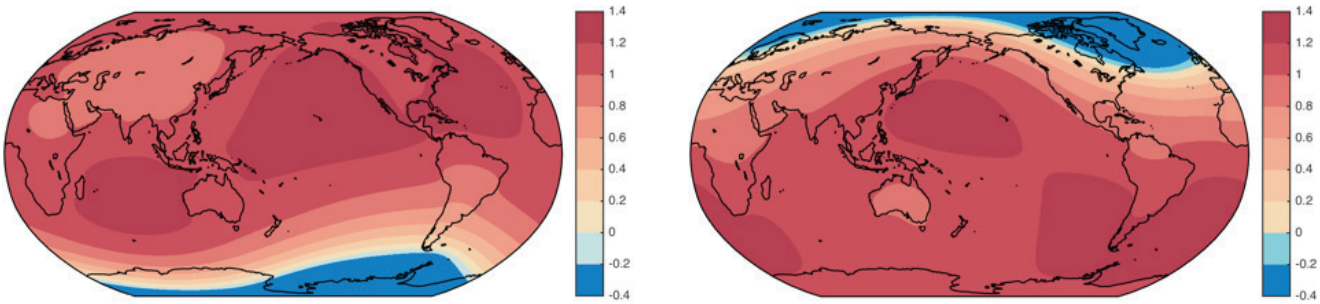

Figure 4. Sea-level "fingerprints" (Mitrovica, et al., 2011; Hay et al., 2017). The map at left shows the rapid (gravitational and rotational) response of sea level to an arbitrary unit of equivalent GMSL contributed by the Greenland Ice Sheet (GIS). The map at right shows the response from an equivalent mass loss from the the West Antarctic Ice Sheet (WAIS). The units are the fractional departure of RSL relative to a given change in GMSL. Note that the U.S. West Coast only experiences about 75% of the GMSL rise contributed by Greenland (left), but the rise in RSL is about 25% greater than expected if meltwater is added to the ocean from West Antarctica (Figure, compliments of Carling Hay).

[4] The Earth's surface is still adjusting to the retreat of the massive ice sheets that covered the Northern Hemisphere during the Last Glacial Maximum (LGM) about 18 thousand years ago. Locally, this post-glacial isostatic adjustment (GIA) can either produce a long-term rise or fall of RSL, depending on the proximity to the past ice load. In the case of California, relatively far from the LGM ice sheets, this effect is relatively small and generally on the order of <1 mm per year (Stella et al., 2007).

Greenland and Antarctic Ice Sheets are Fundamentally Different

The ice sheets covering Greenland and Antarctica behave differently, in part because of the different climate regimes they occupy (relatively warm with massive snowfall on Greenland, versus cold and dry on Antarctica), but more fundamentally, because their subglacial topographies are so different. The bedrock beneath the GIS is above sea level around most of its margin, and below sea-level only in the interior (Figure 5). As a result, much of the ice in the GIS margin is terrestrial, with fast-flowing tidewater glaciers reaching the ocean in deep fjords (Moon et al., 2012). The GIS outlet glaciers lose mass via approximately equal proportions of iceberg calving and melting at their termini.

The AIS, in contrast, contains more than seven times more grounded ice above sea level than the GIS.[5] Moreover, nearly half of the AIS sits on bedrock that is hundreds of meters (or more) below sea level (Fretwell et al., 2013). In many places around the Antarctic margin, grounded ice flows into the ocean and lifts off the bedrock to form large ice shelves; platforms of floating ice that extend over the ocean to form deep sub ice-shelf cavities. The location where the grounded, seaward flowing ice first loses contact with the bedrock to become an ice shelf is called the "grounding line" (Figure 6). Rather than surface melt, almost all of Antarctica's mass loss processes occur in the ice shelves: oceanic basal melting in the sub-ice cavities and iceberg calving from the ice fronts (Rignot et al., 2013; Paolo et al. 2015). Importantly, the ice shelves exert a back stress on the grounded ice, inhibiting its seaward flow, a process commonly called "buttressing" (Weertman, 1974; Thomas et al., 2004; Schoof, 2007). Thinning or loss of these ice-shelves reduces or eliminates this buttressing effect, allowing the grounded ice to flow faster toward the ocean (Rignot et al., 2004; Scambos et al.; 2004; Pritchard et al., 2012; Harig and Simmons, 2015, Paolo et al., 2015).

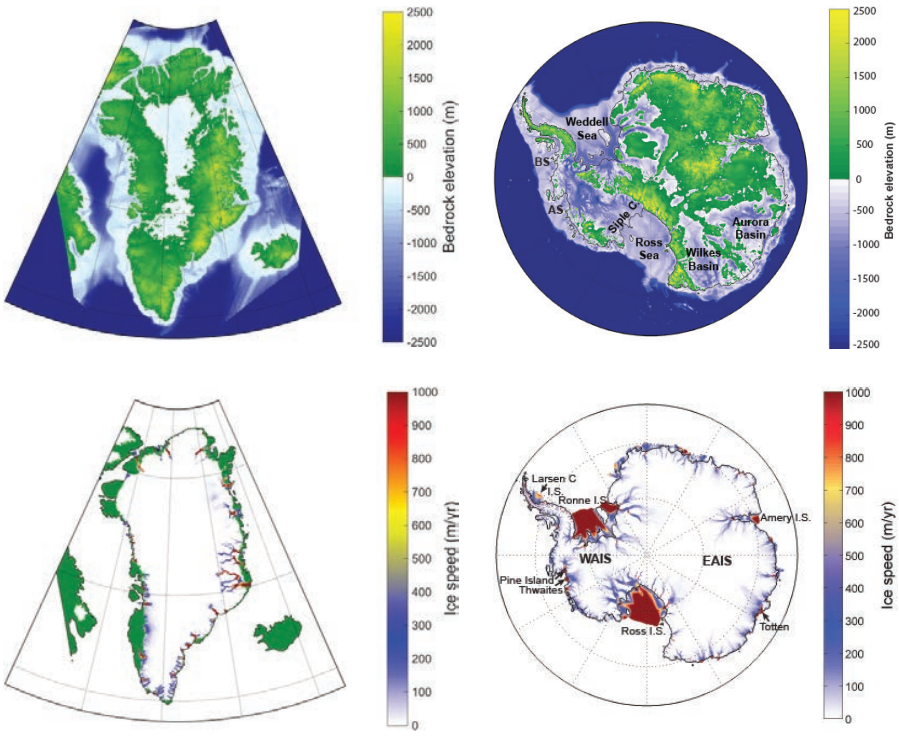

Figure 5. Greenland bedrock elevation (top left; Morlighem, et al., 2015), Antarctic bedrock elevation (top right; Fretwell, et al., 2013), and ice surface speeds from a numerical ice-sheet model (bottom; DeConto and Pollard; 2016). Most of the Greenland bedrock margin is above sea level (top left). Note the opposite configuration of Antarctica (top right), with deep sub-glacial basins adjacent to the open ocean. As a result, much of the GIS margin terminates on land, with the exception of fast flowing outlet glaciers. In contrast, almost all of the thick AIS terminates in the ocean. The location of features mentioned in the text include AS (Amundsen Sea), BS (Bellingshausen Sea), and Siple Coast. Fast ice speeds (red) show the location of major ice streams, outlet glaciers, and floating ice shelves. Major Antarctic ice shelves are labeled, as are the retreating Pine Island and Thwaites glaciers in the Amundsen Sea region.

[5] The loss of floating ice and ice below sea level have only a small direct effect on sea level.

In many places in Antarctica, especially in West Antarctica, deep troughs beneath the ice extend inland from the grounding lines, and slope downward toward the interior of the continent, eventually leading to submarine basins that can be more than 1 km deep. For example, Thwaites Glacier (Figure 5) rests on a reverse-sloped bed, leading to the deep WAIS interior (see Figures 6 and 7) where there is enough ice above floatation to raise GMSL by ~3 m (9.8 feet).[6] Vast areas of the much larger East Antarctic Ice Sheet (EAIS) also rest in deep sub-marine basins and these East Antarctic basins contain enough ice to raise GMSL by ~19 m (62 feet) if the ice they contain were lost to the ocean. With a few exceptions (e.g., Totten Glacier), the majority of the EAIS ice shelves and outlet glaciers are currently stable (Rignot et al. 2013; Paolo et al., 2015), but that situation could change with increased ocean and atmospheric warming.

Key Processes at Play in Antarctica (Marine-Based Ice)

The climate in Antarctica is colder than in Greenland, but because most of the ice sheet margin terminates in the deep ocean, its outlet glaciers, grounding lines, and the underside of buttressing ice shelves are vulnerable to even modest amounts of ocean warming. In part, this is because the melting point of ice becomes lower with increasing water depth (Holland et al., 2008; Jacobs et al., 2011; Paolo et al., 2015; Shepherd, 2004). In the Amundsen Sea sector, seasonally stronger westerly winds have driven a change in ocean circulation, favoring intrusions of warm salty deep water (upper Circumpolar Deep Water, or CDW) across the continental shelf break into the sub-ice cavities and towards the grounding zones of major ice outlets such as Thwaites Glacier, enhancing ice shelf basal melting (Pritchard et al., 2012; Steig et al., 2012). Currently, the Southern Ocean is taking up more heat and warming faster than other parts of the global ocean (Levitus et al., 2012; Masahiro et al., 2013), especially at intermediate depths (Schmidtko, et al., 2014) where CDW has the potential to flow into sub ice-shelf cavities,.

Many marine-based Antarctic outlet glaciers rest on bedrock hundreds of meters to more than 1 km below sea level (Figure 5), and many of these have reverse-sloped beds. In places with this reverse-sloped geometry, including much of WAIS and deep EAIS subglacial basins (Fricker, et al., 2015), the ice sheet is susceptible to a Marine Ice Sheet Instability (MISI; Figure 6), whereby a reduction in ice-shelf buttressing causes an initial grounding-line retreat onto a reverse-sloped bed, which triggers a non-linear acceleration of ice loss and ongoing retreat of the ice margin, because the seaward flow of ice is strongly dependent on the grounding line's thickness (Pollard and DeConto, 2009; Schoof, 2007; Weertman, 1974) which thickens upstream.

[6] Bedrock is 'reverse-sloped' if it deepens toward the continental interior. This is the reverse of the situation off the coast of most continents, including North America, where the continental shelf deepens away from the interior.

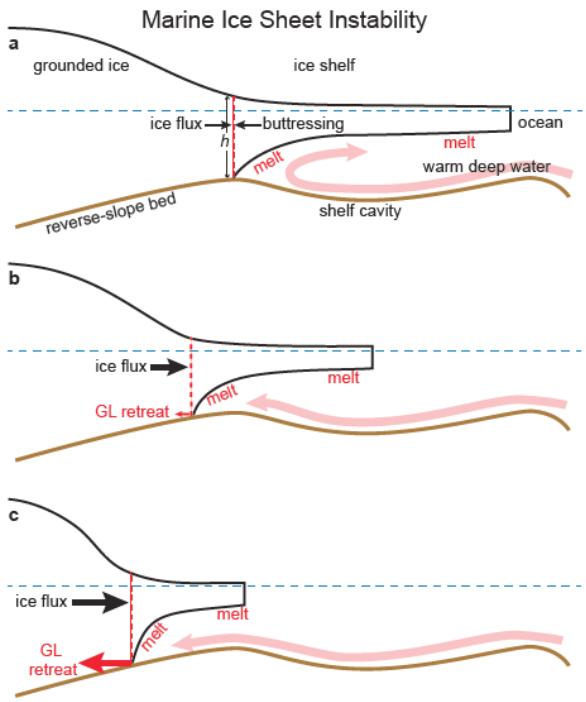

Figure 6. A time-evolving schematic sequence illustrating marine ice sheet instability (a-c), whereby a ~1-km deep, marine terminating ice-sheet margin with reverse-sloped bed is undergoing ice-shelf thinning due to oceanic warming. Note the sequentially thickening grounding lines (red dashed lines) from top to bottom and enhanced seaward ice flux as the ice margin retreats landward into a deepening basin. Once set in motion, even if the ocean forcing is removed, the retreat will continue until the grounding line meets upward sloping bedrock or a topographic bump, or if a confined ice shelf can reform to provide some buttressing against the seaward ice flow.

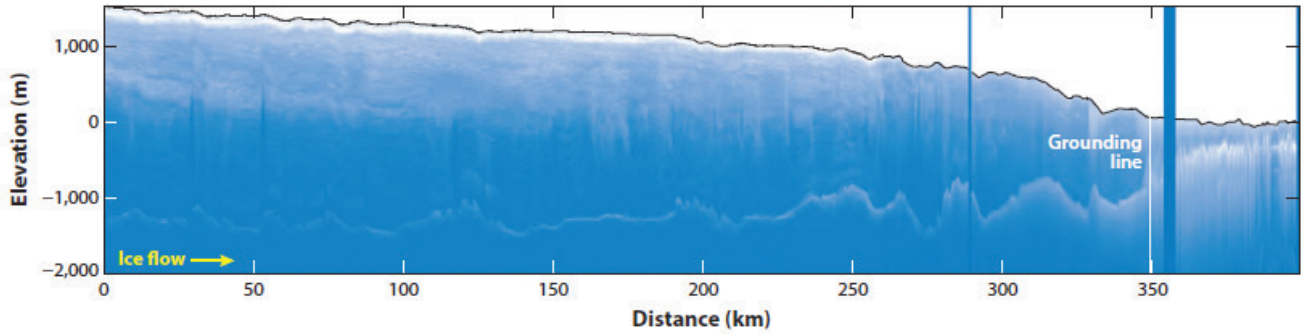

Figure 7. An ice-penetrating radar image (vertical cross section) along a flowline of Thwaites Glacier in the Amundsen Sea sector of WAIS (see Figure 5 for location). The underlying bed is clearly visible. The glacier is ~120 km wide where it reaches the ocean (right) and reaches back into a deep, ice-filled basin almost 2 km below sea level (left) under the heart of the WAIS. The grounding line (vertical white line) is currently retreating on a reverse-sloped bed and undergoing MISI at an estimated rate of ~1 km per year (Rignot, et al., 2014). Its current grounding line thickness is too thin (~600m) to trigger widespread ice-cliff instability (see below), but that situation could change if its current retreat continues (figure source: Alley et al., 2015).

The key glaciological processes associated with MISI have been known for decades, and studied with theoretical, analytical, and numerical models along flowlines or in limited-area domains (Cornford et al., 2015; Favier et al., 2014; Joughin et al., 2014; Schoof, 2007; Weertman, 1974). However, predicting what these processes mean in terms of sea-level rise requires their representation in continental-scale ice sheet models. Only recently have such models become capable of accounting for the linked dynamics of the grounded and floating ice components required to represent MISI.

There are various and well established approaches to independently model the grounded (e.g., Oerlemans, 1982; Huybrechts, 1994; Pattyn et al., 2003; Le Meur et al., 2004) and floating components of marine ice sheets (Morland, 1986; MacAyeal, 1989). However, coupling the grounded component (where vertical shear dominates ice flow) and the floating part (where horizontal stretching dominates) is a challenge, and requires either high spatial resolution at the transition between the grounded and floating ice (Goldberg et al., 2009; Cornford, et al., 2015) or a parameterization of the ice flow across the grounding zone (Schoof, 2007; Pollard and DeConto, 2012). Regardless of the approach, simplifications must be made to allow the computational efficiency needed to run a marine ice sheet model for an entire ice sheet for long time periods.

Model inter-comparisons (Pattyn et al., 2012) have tested and compared the ability of independently developed models representing a wide range of complexities and numerical approaches to capture migrating marine grounding lines (Figure 6) and the fundamental dynamics associated with MISI. These comparisons have increased our overall confidence in models' ability to capture the dynamics of retreating grounding lines on reverse-sloped bedrock, but other processes, not previously included in ice sheet models, could also be critical to Antarctica's future.

Emerging Science and Previously Underappreciated Glaciological Processes

Recently, another glaciological process: *Marine Ice Cliff Instability (MICI)*; Figure 8), not previously considered at the continental ice-sheet scale, was shown to have a profound effect on ice sheet simulations in climates warmer than today (DeConto and Pollard, 2016; Pollard et al., 2015). With summer warming sufficient to produce extensive meltwater ponding around the Antarctic margin, as expected to occur within decades if greenhouse gas emissions continue at their present rates (Trusel et al., 2015), it is possible that water-filled crevasses may 'hydrofracture' ice shelves (Banwell et al., 2013). This was witnessed during the breakup of the Larsen B ice shelf on the Antarctic Peninsula in 2002 (Scambos et al., 2000). If this were to happen to ice shelves that currently protect thick grounding lines where the bedrock has a reverse slope, this could not only trigger MISI, but could also result in tall ice cliffs, as observed at the termini of the few, ~1km thick outlet glaciers in Greenland that have recently lost their ice shelves. Such tall cliffs would be inherently unstable and fail structurally under their own weight (Bassis and Walker, 2012). Because of Antarctica's bedrock geometry and thick, marine-terminating grounding lines, if protective ice shelves were suddenly lost to hydrofracturing or a combination of hydrofracturing and ocean melt from below, then many places around the Antarctic margin would have structurally unstable ice cliffs.

Including MICI dynamics in an ice sheet model is challenging, in part because the numerical representation of fracture mechanics at an ice front is highly complex. Calving is controlled by many interacting processes. These include the stress regime at the ice front, water depth, ice thickness, flow speed, conditions at the bed of the ice, the penetration depth and spacing of crevasses, the presence of lateral shear (along the walls of a fjord for example), undercutting of the calving front by warm water, tides,

and importantly, the presence of mélange (a mix of previously calved, broken icebergs and sea ice) that can provide some support (buttressing) to the cliff face. Many of these processes are not resolved in continental-scale ice-sheet models, so the approach taken to date has been to "parameterize" (simplify) the representation of cliff-failure, to a point where retreat rates can be related to some of the basic prognostic variables (outputs) that ice sheet models can provide-like water depth at the ice terminus, ice flow speed, cliff height, buttressing, and crevassing.

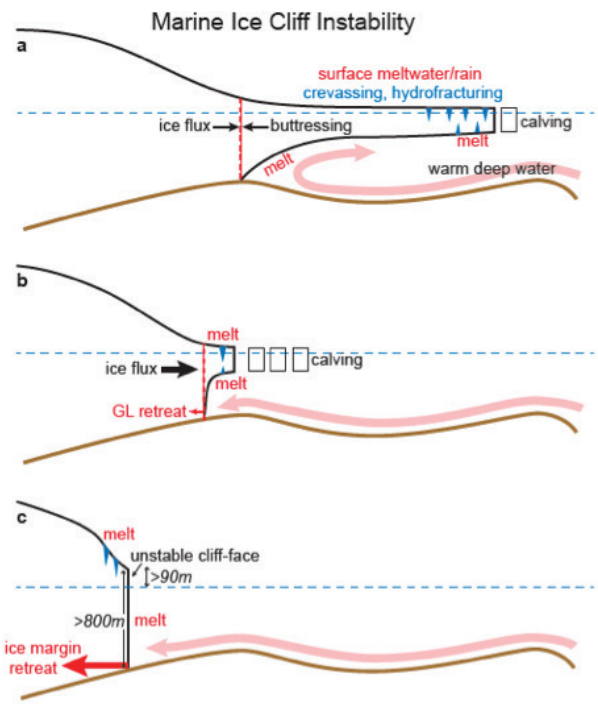

Figure 8. A similar ice sheet margin as shown in Figure 6, but feeling the effects of both sub ice-shelf oceanic warming and atmospheric warming. Meltwater and rainwater accumulating on the ice-shelf surface can fill crevasses (a), which deepens the crevasses, potentially leading to hydrofracturing (b). If the newly exposed grounding line is thick enough to have a tall subaerial ice cliff (c), the terminus would fail structurally. If the rate of structural failure outpaces the seaward flow of ice, the ice margin would back into the deep basin (after Pollard et al., 2015; DeConto and Pollard, 2016), resulting in a massive loss of ice.

The parameterization of complex processes in models usually relies on real-world observations. In the case of ice-cliff retreat, one major limitation is that marine-terminating grounding lines that are 1) thick enough to generate ~100m tall ice cliffs, and 2) have completely lost their ice shelves (like the Helheim and Jakobsavn Glaciers in Greenland; Figure 9) are few and far between today. While widespread MICI has not yet been observed in Antarctica, observations on the Antarctic Peninsula (Rignot et al, 2004; Scambos et al., 2004) and in Greenland (Joughin et al., 2008) have shown that brief episodes of ice-cliff instability lead to accelerated retreat.

Today, most places in Antarctica where ice >800m thick reaches the ocean, floating ice shelves provide buttressing and preclude exposed, tall cliffs at the 'tidewater' grounding line. In the future, given enough atmospheric and ocean warming, it is possible that wide stretches of the marine-terminating Antarctic margin, where thick ice meets the ocean, could lose their protective ice shelves and ice tongues. In that case, cliffs could begin to appear in places like the throat of the Thwaites Glacier. Thwaites Glacier is >10 times wider than the few outlet glaciers in Greenland undergoing MICI today and it is only minimally buttressed. Its grounding line is retreating on reverse-sloped bedrock via MISI (Joughin et al., 2014), but most of the grounding zone is currently resting on bedrock too shallow (Millan et al., 2017) to form a cliff face tall enough to induce MICI (Bassis and Walker, 2012). If grounding line retreat continues into the deep basin upstream, MICI could be initiated, exacerbating the rate of ice mass loss in West Antarctica.

Figure 9. The terminus of Helheim glacier in Southeast Greenland. The heavily crevassed glacier has no ice shelf and is thick enough at the calving front to produce a ~100m tall subaerial ice cliff. The cliff is failing structurally, with the calving front retreating at a rate roughly equivalent to the seaward flow of the glacier (~10 km year), despite the dense mélange trapped within the narrow, 5-km wide fjord. In Antarctica, taller and vastly wider ice cliffs could emerge if ice shelves are lost to warming ocean and atmospheric temperatures (photo: Knut Christianson).

Implications of MISI and MICI for California's Future

Accounting for MICI in an ice sheet can model dramatically increase future sea level projections, and because the epicenter of change will most likely be in WAIS, California would be especially impacted (Figure 2). After including MISI and MICI in their ice sheet model, DeConto and Pollard (2016) tested the performance of the model against the only reasonable analogue for future sea-level: times in the geologic past when GMSL was higher than today and Antarctic temperatures were known to be warmer. The benchmarks they used were the Last Interglacial (LIG, about 125 thousand years ago) and the middle Pliocene (about 3 million years ago). During the Last Interglacial, global mean temperatures were similar to today (Capron et al., 2014; Hoffman et al., 2017), but GMSL was about 6 to 9 meters (20-30 feet) higher (Dutton et al., 2015). Most of the sea-level rise is now thought to have come from Antarctica, because Greenland is believed to have remained partially to mostly intact at that time (Dahl-Jensen et al., 2013; Stone et al., 2013), although the precise magnitude of Greenland retreat continues to be re-evaluated (e.g. Yau et al., 2016). Nonetheless, Last Interglacial sea levels provide a powerful message that the polar ice sheets are sensitive to modest warming.

Global average temperatures during the middle Pliocene were warmer than the LIG, 2°-3° warmer than today. GMSL, while uncertain, is thought to have been in the range of 10-30m (30 to 90 feet) higher than present (Miller et al., 2012; Rovere et al., 2014), requiring a substantial contribution from East Antarctica in addition to Greenland and West Antarctica. Pliocene atmospheric CO_2 concentrations were comparable to today (~400 ppmv; Pagani et al., 2009), although cyclic changes in Earth's orbit (which control the seasonal distribution of solar radiation) likely contributed to periods within the Pliocene when Antarctic temperatures were amplified. It is important to note that Pollard and DeConto's models with MISI physics alone, could not come close to matching Pliocene and Last Interglacial sea level targets, even including the effects of orbital changes. (Pollard and DeConto, 2009). Only after accounting for the effects of hydrofracturing and ice-cliff failure were they able to simulate Pliocene and Last Interglacial sea levels (DeConto and Pollard, 2016), although other factors yet to be considered could have also played a contributing role.

The Pliocene and LIG sea level targets were used to explore a range of model parameters controlling 1) the sensitivity of ice-shelf melt to warming ocean temperatures, 2) the sensitivity of ice shelf hydrofracturing to surface meltwater and rain, and 3) the maximum rates of ice-cliff collapse, regardless of the height or width of the cliff face. They found 29 combinations of these model parameters capable of achieving Pliocene and LIG sea levels. Versions of the model that produced higher or lower sea levels than justified by the geological records were discarded. Hence, only the 'validated' versions of the ice model were used in future simulations, driven by a range of greenhouse gas forcing scenarios. Evolving future atmospheric conditions and ocean temperatures provided by climate model simulations were applied to the ice model, allowing the model to respond to the combined effects of both a warming ocean and a warming atmosphere.

Depending on their assumptions about the magnitude of Pliocene sea levels, which affect the choice of model physical parameters (Pliocene sea-level estimates are more uncertain than LIG estimates), DeConto and Pollard (2016) found that Antarctica has the potential to contribute between 64 ± 0.49 cm and 105 ± 0.30 cm (25 ± 0.19 inches and 41 ± 12 inches) of sea-level rise by the year 2100 in the warmest future greenhouse gas scenario (Figure 10). Another important implication of the study was the recognition that by 2100, the rate of Antarctica's contribution to sea-level rise could be in the range of 2 cm (almost an inch) per year. This finding is fundamentally different than the assessment of the IPCC AR5 (Church et al., 2013), which concluded that Antarctica would contribute little if any GMSL rise by the year 2100, even in the highest greenhouse gas forcing scenario, Representative Concentration Pathway (RCP) 8.5 (van Vuuren et al., 2011). While at the high end, the results point to the potential for much higher sea levels than previously considered, but they also demonstrate a much reduced risk of future sea-level rise from Antarctica if the lowest greenhouse gas emissions pathway (RCP2.6) is followed.[7]

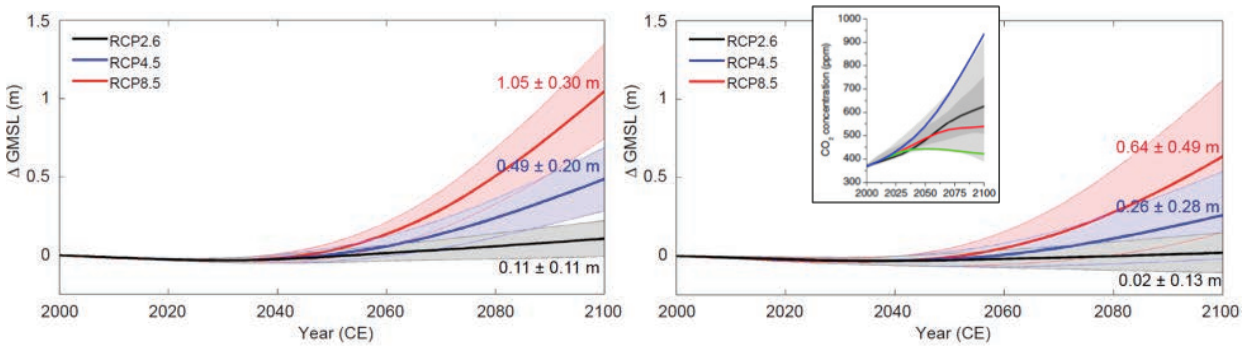

Figure 10. Ensembles of Antarctic's future contribution to sea level, using paleo-calibrated ice-model physics, high-resolution atmospheric climatologies from a regional atmospheric model, and time-evolving ocean model temperatures (from DeConto and Pollard, 2016). The inset at right shows time-evolving CO_2 concentrations (RCPs) used to force the ice sheet simulations (from van Vuuren et al., 2011). Note that different colors are used to represent the RCPs and ice sheet ensembles. The difference between the ensembles at left versus right lies in the assumptions used in the model calibration (based on geological sea-level reconstructions). These differences demonstrate the large uncertainty remaining in current projections. The timing when Antarctica begins major retreat in RCP4.5 and 8.5 (after ~2060) also remains uncertain. In addition to greenhouse-gas forcing, the onset of major retreat will be dependent on the trajectory of Antarctic warming in response to a complex combination of factors including recovery of the ozone hole, linkages with tropical dynamics, and feedbacks between the ice-sheet, solid-Earth, ocean, and sea-ice which are not accounted for here. Addressing these shortcomings and uncertainties will be the focus of future work.

[7] The RCP's refer to the extra radiative forcing (in Watts per square meter, Wm-2) added by the greenhouse gases in each scenario at the year 2100. RCP2.6 is roughly consistent with the aspirational goal of the United Nations' Framework Convention on Climate Change 2015 Paris Agreement to limit the rise in global temperature to less than 2°C. RCP8.5 is consistent with a fossil-fuel-intensive "business as usual" scenario and RCP4.5 is an intermediate scenario, closer to RCP2.6 than RCP8.5.

The Loss of Marine-Based Ice is a Multi-Millennial Commitment.

Another underappreciated consequence of the loss of marine-based ice (as in WAIS) is that it can only re-advance (regrow) if confined ice shelves can be reestablished. The shelves are required to buttress the grounding line, allowing it to migrate seaward on its reverse-sloped bed. Because ice-shelf melt rates are so sensitive to a warm ocean (Holland et al., 2008; Shepherd, 2004), the ocean will have to cool down before the ice shelves can reform. Because of the large thermal "inertia" of the ocean, this could take centuries to several thousands of years, after greenhouse gas concentrations return to their preindustrial levels (Winkelmann et al., 2015). The net result is that sea-level rise driven by the loss of marine-based ice (like WAIS) will remain elevated for thousands of years (DeConto and Pollard, 2016).

Reducing Risk of a Serious Sea Level Contribution from Antarctica

The RCP2.6 ensemble averages in Figure 10 suggest Antarctica will make only a small contribution to 21st-century sea-level rise if future greenhouse gas emissions are strictly limited. However, some of the individual RCP2.6 simulations do involve serious WAIS retreat (Figure 11), with the two highest (of 58) ensemble members exceeding a 50 cm (20 inches) contribution to GMSL by 2100. This implies that the risk of threatening sea-level rise, while much reduced, is not completely eliminated in the scenario with the lowest emissions. This finding is in general agreement with other recent modeling studies and observations of the Amundsen Sea outlet glaciers (Thwaites in particular), suggesting that MISI has commenced in that location and retreat into the heart of the WAIS could be irreversible (e.g., Rignot et al., 2014; Joughin et al., 2014). More observational and modeling work will be required, before a precise climatic threshold for unstoppable WAIS retreat can be defined. In preliminary studies, a combined atmospheric and oceanic warming in the Amundsen Sea region of 2- 3°C is found to be enough to trigger major retreat of the WAIS (Scambos et al., in press), but the timing when that much regional warming will appear in the Amundsen Sea remains difficult to predict.

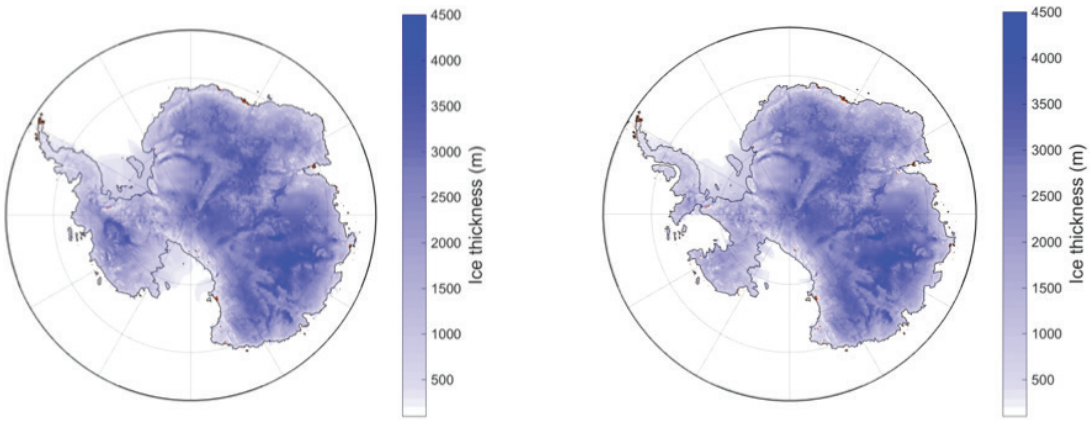

Figure 11. Two individual members of the RCP2.6 ice sheet ensembles (Figure 10) using identical future climate forcing (ocean and atmospheric temperatures), but slightly different model parameters controlling oceanic sub-ice melt rates, sensitivity of hydrofracturing to surface meltwater, and the maximum rate of ice-cliff failure. In this case, both versions of the model are equally capable of simulating realistic modern and ancient ice sheets, so both results can be considered possible future outcomes. As in most RCP2.6 simulations, the model on the left produces almost no contribution to future sea-level rise. In contrast, the model on the right undergoes dramatic retreat of Thwaites Glacier and near compete loss of the WAIS within 500 years. Despite the limited warming in the RCP2.6 scenario, the model on the right produces ~57 cm (22 inches) of GMSL rise by 2100. Reducing the range of uncertainty in future ice sheet simulations should be a top priority.

How Much Confidence Should be Placed in the New Projections?

The obvious question is: how confident can we be in the recent model projections? First, it should be emphasized that the model ensembles (Figure 10) hinge on the performance of a single ice-sheet model and a single climate model. Furthermore, the ensembles do not explore the full range of parameters in the ice sheet model. Thus, the ensembles do not provide a true probabilistic assessment of Antarctica's possible future. While much progress observing and modeling the ice sheet has been made in recent years, the precise magnitude and timing when Antarctic might begin to contribute substantial sea level should still be considered deeply uncertain. Regardless of uncertainty in model physics, one of the greatest sources of uncertainty lies in which future greenhouse gas scenario will be followed; so even if the physical model were perfect in its representation of the natural world, there would still be major uncertainty in the Antarctic ice sheet's future. With that said, the recent work does provide important, new information that should be considered at the policy level (Kopp et al., in review):

- Previously underappreciated glaciological processes have the potential to greatly increase the probability of extreme GMSL rise (2 meters or more) within this century if emissions continue unabated.
- An aggressive reduction in greenhouse gas emissions substantially reduces but does not completely eliminate the risk of extreme GMSL rise from Antarctica.
- Once marine-based ice is lost, the resulting GMSL rise will last for thousands of years.
- The processes (atmospheric dominated) that could drive extreme AIS retreat later in this century are different from those driving AIS changes now (ocean dominated), so the fact that the current rise in GMSL rise is not consistent with the most extreme projections does not rule out extreme behavior in the future.

What are the Major Model Limitations?

The model developed and used by DeConto and Pollard has a number of fundamental limitations that could lead to either an underestimate or overestimate of future ice sheet retreat. These limitations also apply to other recent studies using continental-scale ice sheet models. Perhaps the most fundamental limitation is the lack of observations in the key regions of the ice sheet, for example we do not know the ocean temperature, the ice thickness, or the bathymetry for the sub ice shelf cavities surrounding the entire Antarctic perimeter (see below). Another limitation is the interaction between the retreating ice sheet and the surrounding ocean. Massive volumes of fresh meltwater and ice volumes flowing into the Southern Ocean as the ice sheet retreats could enhance sea ice production, which might ameliorate the pace of atmospheric warming (Bintanja et al., 2013). At the same time, the resulting ocean stratification could enhance heat buildup in the subsurface, increasing ocean melt rates (Hansen et al., 2016). Interactively coupling ice and ocean models is a major challenge and accounting for these interactions at the continental scale is currently a priority of the international ice sheet modeling community.

Another missing feedback is that between the retreating ice sheet and relative sea level at the grounding line. The reduced gravitational pull on the surrounding ocean as the ice sheet retreats leads to a local relative sea level drop at the grounding line. This can have a stabilizing effect on some retreating groundling lines, particularly in places where the onset of MISI is close to a threshold (Gomez et al., 2015). While this negative feedback reduces the total amount of modeled ice sheet retreat on millennial timescales, it has only a small influence in the near-term and is not likely to substantially reduce sea level rise risk on decadal to century timescales.

In DeConto and Pollard (2016) and other recent Antarctic modeling studies (e.g., Cornford et al., 2015; Golledge et al., 2015), ice sheet retreat early in the

21st century is largely driven by sub-surface ocean warming and MISI as illustrated in Figure 6. Ocean models are well known to do a poor job simulating recent sub-surface warming trends around Antarctica (Little and Urban, 2016), making the location and magnitude of future ocean warming an important source of uncertainty, especially in the near term.

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By the second half of this century, around 2060, DeConto and Pollard (2016) show that the atmosphere will likely take over as the primary driver of ice retreat, mainly though the influence of surface meltwater on hydrofracturing. This is an important new twist on our understanding of Antarctica's possible future behavior. The inclusion of hydrofracturing physics more directly links ice sheet dynamics with atmospheric conditions; the onset of major retreat is largely determined by the appearance of extensive summer meltwater and rainwater on ice shelves. Thus, the projected timing when massive sea-level rise might commence is strongly dependent on the atmospheric model forcing the ice sheet from above. Climate models currently do a poor job resolving recent changes in coastal Antarctic climate, particularly in some of the most sensitive regions of the ice sheet, like the Amundsen Sea region of West Antarctica (Bracegirdle, 2012) adding uncertainty in the predicted timing of retreat. Furthermore, in the future, the trajectory of Antarctic climate and ocean temperatures will be strongly influenced by important teleconnections to the tropical Pacific (Steig et al., 2012; Dutrieux et al., 2014) and the depletion of the Antarctic stratospheric ozone hole (Marshall et al., 2014; Turner et al., 2016), both of which remain uncertain and poorly represented in climate models.

Due to existing computational limitations, continental-scale ice sheet models, like those discussed here, need to make approximations in the mathematical representations of ice dynamics. Ice sheet models with more complete and rigorous dynamical treatments are beginning to appear, but are still too computationally expensive for the long-term, continental-scale, and parameter-exploring experiments that are required. This will likely change within the decade as greater computer power becomes available. It remains to be seen (and is an open and debated question) whether the simplifications used in the current generation of models matter to the results, and if so, by how much. This is an important issue, because key processes related to MISI are concentrated in the grounding zones, which are effectively important boundary layers between different modes of flow (grounded/shearing versus floating/stretching) that are best represented at high spatial resolution and without simplifications of the underlying physics.

A further possible complication is related to firn, old snow that is transitioning to ice and forms a layer below the newer snow. In a warming world, more snow is anticipated to fall over the EAIS, and hence the firn layer will thicken, at least in the short term. As summer air temperatures begin to exceed the freezing point, meltwater will be absorbed by the underlying firn, as long as there is remaining poor space between snow grains to allow refreezing (Figure 12). Eventually, ice lenses will begin to form, the firn will compact, and it will no longer have the ability to absorb summer melt water. At that point, meltwater will have the potential to flow into underlying crevasses where it can cause hydrofracturing. Presently, the meltwater-buffering capacity of firn is poorly represented in most ice-sheet models. Because of this limitation, the timing when hydrofracturing begins to impact ice shelves in the models could be occurring sooner (by years to a few decades) than it will in reality. With that said, in the warmest (RCP8.5) scenario, so much meltwater would begin to appear over the ice shelves by the second half of the 21st century, the firn layer would be quickly overcome regardless of its thickness or the details of the firn model. However, in more moderate warming scenarios closer to a meltwater/hydrofracturing threshold, the buffering capacity of the firn layer could be a determining factor of the timing when hydrofracturing might begin.

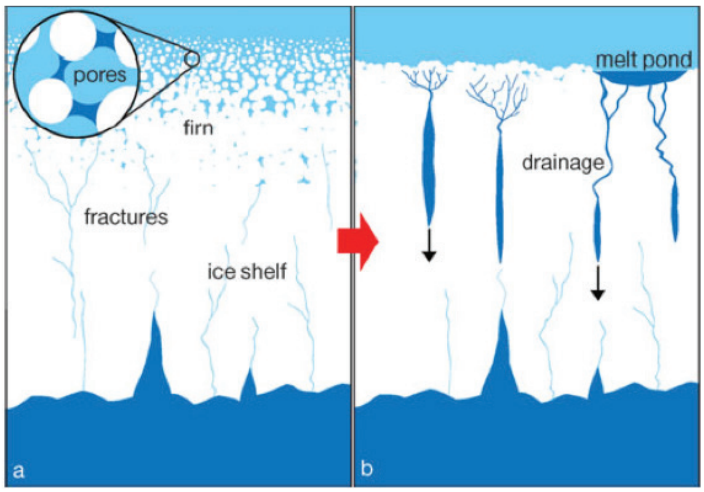

Figure 12. Porous firn (a, left) can absorb seasonal meltwater and delay water flow into underlying crevasses (b, right), delaying hydrofacturing and ice-shelf breakup. Better treatments of these processes in ice sheet models will be critical for predicting the precise timing of the ice sheet's response to a warming climate (figure source: Munneke, et al., 2014).

Could Future Sea-Level Rise be Even Worse than the new Projections?

The future ice sheet projections in DeConto and Pollard (2016) imply the potential for substantially more sea-level rise (2 m or more by 2100) than any previous model results. This is largely due to the explicit treatment of the hydrofracturing and ice-cliff physics described above. While the results remain uncertain for the reasons described here, it should be stressed that the ensemble averages in Figure 10, do not represent the model's maximum possible rates of Antarctica's contribution to sea-level rise.

In the model cliff-collapse (the horizontal rate of ice-loss at the marine "tidewater" calving terminus) only occurs where ice cliffs are tall enough to generate stresses that exceed the strength of the ice. The rate of cliff retreat ranges from near zero where this stress-strength threshold is just exceeded, to some maximum allowable rate, regardless of the cliff height. This "speed limit" imposed on the model's representation of ice-cliff retreat is meant to represent 1) the average size and frequency of individual calving events, which involve brittle fracture mechanics and modes of ice failure whose controlling factors are not well understood, and 2) the buttressing effects of mélange (icebergs and fragments of icebergs locked together by sea ice) at the ice terminus. Faster cliff collapse should generate more mélange, providing a negative feedback that dampens the rate of retreat.

In the future ice-sheet ensembles shown in Figure 10, a range of maximum cliff-failure rates are used, ranging between one and five km per year. At the tallest vertical ice cliffs observed today (e.g., Helheim and Jakobsavn glaciers in Greenland), the horizontal rate of cliff retreat is as high as 10-14km per year (Joughin et al., 2010; 2012). This is quite remarkable, considering these outlet glaciers rest in narrow fjords 5 to 12 km wide, choked with dense mélange as seen in Figure 9.

In Antarctica, the cliff faces that could appear in the future will be much taller and wider than those in Greenland, where mélange can clog seaways. For example, Thwaites Glacier is >120 km wide and its terminus ends in open ocean rather than a narrow fjord, so it might be reasonable to assume cliff collapse in open settings like Thwaites could approach the rates observed in narrow Greenland fjord settings where mélange is presumably providing some back pressure at the grounding line. Increasing the model's maximum cliff retreat values closer to those observed in Greenland (~10 km per year) increases Antarctica's simulated contribution to GMSL to more than 2m by 2100 in the RCP8.5 scenario (DeConto et al., in preparation).

Considering the implications of multiple meters of sea-level rise on century timescales, additional study of these processes and more explicit model treatments of the buttressing mélange in front of retreating ice fonts should be a priority. In reality, rates of cliff retreat depend on the details of fracture mechanics in addition to back-pressure from mélange and other processes not explicitly represented in the current generation of models. Nonetheless, observed behavior of the few tidewater glaciers thick enough to undergo this type of structural failure hints at the possibility that current ice sheet projections, including those in DeConto and Pollard (2016), could be conservative and that 2.5 m or more of total GMSL rise by 2100 cannot be ruled out.

Other Recent Antarctic Modeling

In the last year, several other modeling studies of the AIS' future were published in high profile journals (e.g., Clark et al., 2016, Golledge et al., 2015, Ritz et al., 2015, and Winkelmann et al., 2015). Among these, Ritz et al., (2015) and Golledge et al., (2015) are the most directly comparable to DeConto and Pollard (2016), because they explicitly discuss the possible state of the ice sheet in 2100.

Ritz et al. (2015) used a hybrid physical-statistical modeling approach, whereby the physical processes triggering the onset of MISI (Figure 6), which DeConto and Pollard attempt to model directly, are determined statistically rather than physically. They estimated probabilities of MISI onset in eleven different sectors around the ice-sheet margin, based on observations of places undergoing retreat today (mainly in the Amundsen Sea) and expected future climate change following the A1B emissions scenario used in IPCC AR4 (Solomon et al., 2007).[8] In places where they project MISI to begin, the persistence and rate of grounding-line retreat is parameterized as a function of the local bedrock topography (slope), grounding line thickness (Schoof et al., 2007), basal slipperiness, and one of three different model treatments of basal friction which is shown to provide considerable uncertainty.

The advantage of the approach used by Ritz et al., (2016) is that the relative simplicity of the ice sheet model allows thousands of model iterations in each of the eleven Antarctic sectors, allowing a probabilistic assessment of the results based on each ensemble member's performance relative to modern, observed retreat rates in the Amundsen Sea. While their A1B future climate scenario is not directly comparable to the RCPs used by DeConto and Pollard (2016), they concluded that Antarctica could contribute up to 30 cm (12 inches) GMSL by 2100 (95% quantile), similar to the RCP4.5 results of DeConto and Pollard (2016) but considerably less than RCP8.5 (Figure 10).

The Ritz et al., (2015) study represents a careful and statistically rigorous approach, but their conclusions may be hampered by their reliance on modern, observed rates of retreat in the Amundsen Sea to calibrate their results. Today, retreat in the Amundsen Sea is being driven by oceanic sub-ice melt. In the future, atmospheric warming may become an increasingly dominant driver of ice-sheet retreat via hydrofracturing and cliff failure, processes that recent observations in the region do not inform. Furthermore, their maximum retreat rates consider only those processes associated with MISI, and do not consider the additional potential contributions from the physical processes associated with MICI.

Golledge et al. (2015), used the PISM ice sheet model (Winkelmann et al., 2011) which is similar in its formulation to the ice-sheet model used by DeConto and Pollard (2016), but without hydrofracturing and ice-cliff physics, to simulate the future response of the AIS to simplified RCP emissions scenarios. The PISM model captures MISI dynamics, but not MICI, so again, the bulk of simulated ice-sheet retreat is driven by oceanic warming and sub-ice melt, rather than atmospheric warming. PISM's treatment of sub-ice melt in response to warming ocean temperatures (Feldmann and Levermann et al., 2015) makes PISM more sensitive to ocean warming than DeConto and Pollard's model. As a result, Golledge et al., (2015) find they can produce 39 cm (10 inches) of GMSL by 2100 from Antarctic in RCP8.5 (mainly through MISI),

[8] Greenhouse gas emissions scenario A1B is roughly intermediate between RCP4.5 and RCP8.5.

without the MICI physics used by DeConto and Pollard, (2016). Using a more conservative oceanic melt-rate parameterization in their simulations, the GMSL contribution drops from 39 to 10 cm by 2100, highlighting the ongoing uncertainty in heavily parameterized continental-scale ice sheet models, particularly with regard to their sensitivity to a warming ocean.

While Ritz et al. (2015) and Golledge et al. (2015) both simulate less ice sheet retreat by 2100 than DeConto and Pollard (2016), these studies still represent a considerable departure from IPCC AR5 (Church et al., 2013), which assessed little to no contribution to future sea level from Antarctica by 2100, even under the high-emissions RCP8.5 scenario. Furthermore, despite the enhanced sensitivity of the PISM model to a warming ocean, Golledge et al. (2015) also find that a low emissions scenario like RCP2.6 essentially eliminates the risk of a substantial future sea-level contribution from Antarctica. This important conclusion is in agreement with the findings of DeConto and Pollard (2016).

Outlook: The Science is Moving Quickly

Recent advances in monitoring and modeling the Greenland and Antarctic ice sheets are leading to steady improvements in our understanding of the underlying processes driving ice-sheet retreat, but the multifaceted complexity of the coupled ice-atmosphere-ocean-Earth system continues to hamper predictions of the ice sheet's future. A number of coordinated, international programs are either just getting underway, or are planned in the near future with the goal of reducing uncertainty in future sea-level rise. Among others, these include, the NRC ESAS 2007 Decadal Survey, which identified the following as a major science question for satellite observations of Earth over the next decade: "Will there be catastrophic collapse of the major ice sheets, including those of Greenland and West Antarctica and, if so, how rapidly will this occur? What will be the time patterns of sea-level rise as a result?" It recommended three key Earth-observation missions for ice-sheet monitoring: (i) DESDynI (now NiSAR, a synthetic aperture radar (SAR) to estimate surface deformation); (ii) Ice, Cloud and land Elevation Satellite-2 (ICESat-2) (laser altimeter to estimate ice sheet height) and (iii) a follow on to the current GRACE satellite. NISAR will launch in 2020, and the other two missions are due for launch within the next 2 years. Operation IceBridge is an airborne mission carrying instruments such as an laser altimeter and a sounding radar to bridge the gap between ICESat (ended 2009) and ICESat-2 (to be launched 2018). Internationally, there are several missions collecting relevant data: the European Space Agency has operated CryoSat-2 since 2010 to monitor the ice sheets with radar altimetry, another element in its continuous record since 1992 (ERS-1, ERS-2 and Envisat), and there are plans for a CryoSat-3. Other relevant SAR data also come from Sentinel-1a (ESA), ALOS (Japan) and TerraSAR-X (Germany). Continued availability of these types of observations will be critical for understanding processes and monitoring when and where the ice is thinning and retreating.

One of the key limitations in understanding processes driving ice sheet mass loss is the lack of observations near the ice margins and the surrounding oceans. This is challenging, as the areas are often ice covered, and are logistically difficult to reach, and so much of the region remains unmapped. A NASA Earth Ventures mission, Oceans Melting Greenland (OMG), was launched in 2015 for $30M. This mission is acquiring, via aircraft and ship, vital measurements in the ocean off Greenland's outlet glaciers to understand how the ocean conditions are changing. The same needs to be done in Antarctica. In 2016 six ALAMO floats were deployed in the Ross Sea off the Ross Ice Shelf. Observations like these are needed all around Antarctica and especially in the vulnerable Amundsen Sea region.

Constraining how much and how fast the WAIS will change in the coming decades has recently been identified as a

top priority in Antarctic research (National Academies, 2015). The U.S. National Science Foundation and the U.K. National Environmental Research Council recently announced a joint, $23M solicitation for collaborative US-UK science proposals to understand the Thwaites Glacier, how it behaved in the past, and how it might retreat in the future. This level of international coordination is required to surmount the expense and logistical challenges of doing science in the Antarctic.

While observational programs are advancing our understanding of ice-sheet processes and interactions between ice, ocean, atmosphere, and the underlying Earth, numerical models must keep pace, as it is models that will ultimately provide improved projections. While ice sheet modeling advances have been steady in recent years, some of the key limitations described above will need to be resolved before uncertainties in projections can be reduced and the possible thresholds and tipping points can be more robustly identified. Part of the challenge in modeling the ice sheets is illustrated by the number of interacting processes (Figure 13) at an ice sheet margin, or even in a single outlet glacier like Thwaites. Many of these interacting processes operate on different timescales, adding to the modeling challenge.

While detailed and highly resolved models of individual processes or local regions are being developed, the lessons learned from such detailed modeling must be 'scaled up' to the continental scale. This often requires parameterizations of the processes that cannot be resolved at the spatial resolution (5-40 km) of typical continental ice sheet models. Furthermore, the decadal to century timescales most relevant for policy decisions, are short for a whole ice sheet. The fast, dynamic behavior of individual outlet glaciers, surging or sticking ice streams, and growing or collapsing ice shelves can be thought of as the 'weather' of the ice sheet. The continental ice-sheet models now being tasked with providing useful future projections on decadal-to-century timescales are analogous to climate models, best suited to modeling long-term changes rather than short-term forecasts of the ice sheet 'weather'. Furthermore, the predictive skill of any model is not only determined by the validity of the physics represented in the model, but also the initial conditions applied at the beginning of a simulation. For an ice sheet model, this means that the bedrock topography, conditions at the bed of the ice, internal ice temperatures, ice rheology, speed of the ice, underlying ocean conditions, overlying atmospheric conditions, etc., need to be known at the spatial resolution of the model. Such details remain unresolved in parts of Greenland and Antarctica and will have to be improved before model confidence can be substantially increased at the continental ice-sheet scale.

Key continental-scale modeling challenges that must be overcome in the short term include 1) two-way ice sheet-ocean-atmosphere coupling, 2) more explicit modeling of grounding line and ice cliff physics, including the effects of mélange, and 3) firn models coupled to both the atmosphere and underlying ice physics. Advances in all of these areas are occurring steadily, and substantial advances are expected within the next decade. In the meantime, work currently underway and expected in the next one to five years includes improved understanding on the ocean and warming thresholds capable of driving substantial WAIS retreat. Furthermore, a more complete exploration of the upper-end (maximum) estimates of what is possible in terms of future sea-level rise from Antarctica (and Greenland) will be particularly valuable for California policy and planning purposes. Based on the emerging science, this extreme upper bound is likely to be higher than in the current literature or published national or international climate assessments.

It is worth emphasizing that the threat of massive sea-level rise from Antarctica is not only supported by the recent ice-sheet modeling literature, but also from basic observations and fundamental physical principles. First, lessons from the geological record show that the polar ice sheets and the AIS in particular are sensitive to modest amounts of warming (Dutton et al., 2015). Second, the amount of warming over Antarctica in high-emissions future greenhouse gas emissions scenario will produce massive amounts of meltwater on Antarctic ice shelves before the end of the century (DeConto and

Pollard, 2016; Trusel et al., 2015) and meltwater has been observed to drive ice-shelf breakup in the recent past. This includes the sudden collapse of the Larsen B ice shelf in 2002 that resulted in the speed-up of upstream glaciers, previously buttressed by the ice shelf, by a factor of eight in some instances (Rignot et a;, 2004; Scambos et al., 2004). Third, loss of Antarctic ice shelves and the associated loss of buttressing will trigger MISI on reverse-sloped bedrock as is occurring in the Amundsen Sea today. Fourth, in some locations in Antarctica, marine-terminating ice cliffs greater than 100 meters tall will emerge in some places and these cliffs will fail structurally under their own weight as observed in Greenland today. Fifth, much of the Antarctic Ice Sheet rests in deep sub-marine basins, exposing the ice-sheet margin to a warming ocean, and dynamical instabilities induced by reverse-sloped bedrock.

In summary, the current pace of global sea-level rise (1.2 inches per decade) is already impacting California 's coastline. New ice-sheet projections suggest the rate of rise could accelerate sharply later in this century, with the potential for two meters (6.5 feet) or more of total sea-level rise by 2100. While the uncertainty in these projections remains high, the risk is not negligible given the stakes to future society, development, and infrastructure. Given the level of uncertainty but also the potential impacts, significant investment in any major new coastal development with long lifespans needs to be carefully assessed. Similarly, responses to both long-term sea-level rise and short-term elevated sea levels for existing infrastructure and development also need to consider economic, social, and environmental impacts and costs as well as the lifespan of any approach. Increasing the reliability of future sea-level projections will be important in decision making for both existing and proposed development and infrastructure. This is a tractable problem, but it will require improved scientific understanding of mass-loss processes from the vast polar ice sheets across all the relevant spatial and temporal scales. This can only be achieved through continued and new observations from satellites and the field (both on the ice and in the surrounding atmosphere and ocean), combined with modeling to investigate key processes such as ice-ocean interactions, surface melting, and fracture mechanics of ice. This will require substantial international and inter-agency investment to support collaborations across the disciplines of glaciology, meteorology, oceanography, and computational science.

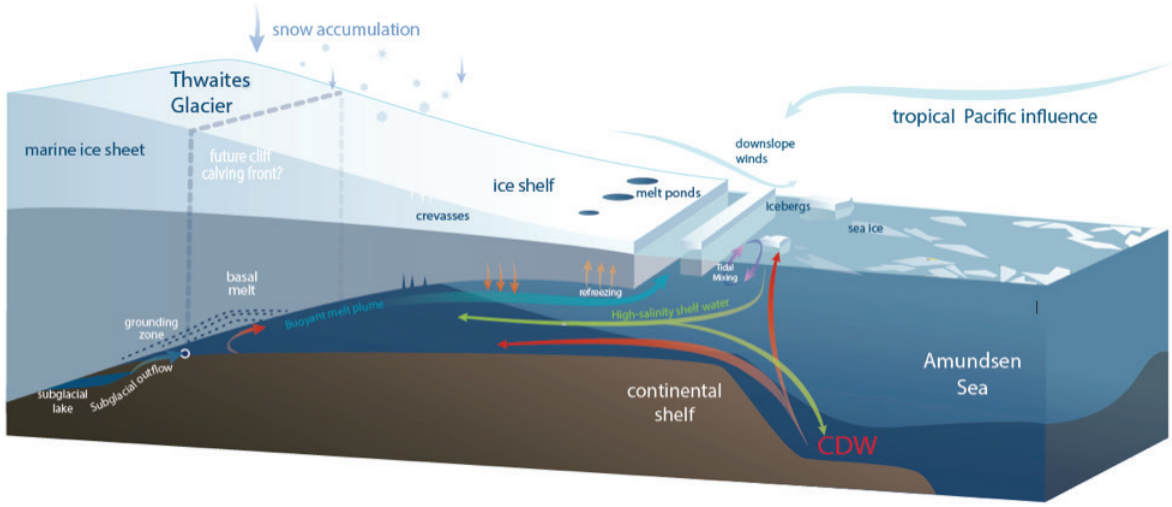

Figure 13. A schematic representation of the primary, interconnected processes operating at a marine-terminating outlet glacier like the Thwaites Glacier. Both the individual processes and their coupled interactions must be understood to be properly modeled, illustrating the grand challenge faced when trying to predict how a system like this will behave in the future. Some processes shown, like cliff collapse and extensive meltwater ponding, have not begun in the region, but could if grounding line retreat and warming continues.

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