SAN FRANCISCO BAY AREA PRECIPITATION IN A WARMER WORLD

Volume 1 State of the Science

Foreword by Brian Strong, Chief Resilience Officer:

Building a climate-resilient San Francisco requires us to understand and plan for current and future environmental hazards. Data and projections about the likely impacts of climate change can be used in the planning process to provide us with key information to establish policies for a climate-resilient city and to implement adaptative measures that can help protect our residents.

San Francisco's research into climate change impacts began in the early 2000's, as the City initially sought data on how a warming climate would affect our water supply. Since that time, we have been working on many different facets of climate change, including developing climate focused data sources to enable forward thinking decision making. As one example, we have already developed sufficient data to help us better understand how we can adapt to rising seas through the development of the 2014 Sea Level Rise Guidance for Capital Projects, 2016 Sea Level Rise Action Plan, and 2020 Sea Level Rise Vulnerability and Consequence Assessment.

Another priority has been to better understand the frequency and strength of precipitation events and how they may affect inland flooding. To do so, San Francisco undertook a unique, first of its kind in the nation climate modeling collaboration between a municipality, climate scientists at Lawrence Berkeley National Laboratory (LBNL), and climate consultants at Pathways Climate Institute to create a research team that focused on a better understanding of future precipitation events through climate modeling. Using supercomputing resources at LBNL's National Energy Research Scientific Computing Center (NERSC), the research team found that the effect of climate change on future storms is predicted to be significant, leading to more powerful events unleashing substantially more water. This initially resulted in a report published in April 2022. This two-volume report (*San Francisco Bay Area Precipitation In A Warmer World, Volume 1: State of the Science and Volume 2: Future Precipitation Intensity, Duration, and Frequency*) provides groundbreaking scientific data on precipitation events for use by the entire City as we develop planning tools and policies to adapt to a changing climate with increasingly extreme storms. These two volumes highlight that both large and small storms are increasing in intensity.

The City agencies that funded these studies include the San Francisco Public Utilities Commission, San Francisco Office of Resilience and Capital Planning, San Francisco International Airport, and the Port of San Francisco. They are joined by other City agencies that will be using this data into develop and improve resilience plans.

The results of Citywide climate change research projects illustrate how San Francisco must think holistically about how to manage increased rainfall, sea level rise, drought, extreme heat, and other climate induced events. Toward that end we created the ClimateSF program which brings together key City agencies whose services could be critically impacted by climate change. These agencies are taking collective action through planning, policy, and guidance, championing a coordinated vision on climate resilience that streamlines City responses and promotes an equitable, safe, and healthy city for generations to come. The precipitation information in these volumes is fundamental to our ability to create meaningful solutions.

While this Extreme Precipitation study analyzed future potential rainfall in San Francisco, it can be modified and used throughout the Bay Area to enhance the region's understanding of precipitation under a warming climate. The study's findings may not be relevant outside of the Bay Area, therefore use of the study's findings beyond the Bay Area is not recommended without independent scientific verification.

Brian Strong
Chief Resilience Officer
City and County of San Francisco

SAN FRANCISCO BAY AREA PRECIPITATION IN A WARMER WORLD

Volume 1: State of the Science

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Executive Summary

Background

For decades, climate scientists have warned of more intense storms that will occur more frequently. Recent scientific research highlights that today's extreme storms are a mere preview of what is to come as the climate continues to warm. The San Francisco Bay Area (Bay Area) has experienced damage and disruption from numerous extreme storms that delivered heavy precipitation and other severe storm conditions, such as strong winds and storm surge. These extreme precipitation events are expected to increase in intensity with climate change, increasing the likelihood of flooding, particularly when coupled with sea level rise.

For The City of San Francisco (City), understanding how large storms might change under a warming climate was identified as priority action for the City in the 2016 Sea Level Rise Action Plan[1]. The San Francisco Public Utilities Commission (SFPUC), the Port of San Francisco (Port), the San Francisco International Airport (SFO), and the City and County of San Francisco Office of Resilience and Capital Planning all have an interest in understanding how future storms could impact the City's residents, business activities, its critical infrastructure, and its natural resources. With funding from the four agencies, Pathways Climate Institute and Lawrence Berkeley National Laboratory (LBNL) completed this Extreme Precipitation Study to provide actionable information that San Francisco can use to prepare for future extreme precipitation.

The findings from this study are presented in two volumes to meet the needs of decision makers and practitioners. Developed for City decision makers, Volume 1 (this volume) provides an overview of the state of the science of extreme precipitation for San Francisco and the greater Bay Area region. Volume 2 presents a suite of updated Intensity-Duration-Frequency (IDF) curves that incorporate projected changes in future precipitation through the end of the century. The findings and IDF curves presented use the highest emissions scenario evaluated by the Intergovernmental Panel on Climate Change (IPCC), which is associated with 4 to 5 degrees Celsius of warming by 2100[2]. Volume 2 also provides a scaling mechanism whereby the results can be translated to any future warming scenario.

For the purposes of these Guidebooks, and as defined by the National Oceanic and Atmospheric Administration National Severe Storms Laboratory, flooding "is an overflowing of water onto land that is normally dry. Floods can happen during heavy rains, when ocean waves come on shore, when snow melts quickly, or when dams or levees break. Damaging flooding may happen with only a few inches of water, or it may cover a house to the rooftop. Floods can occur within minutes or over a long period, and may last days, weeks, or longer. Floods are the most common and widespread of all weather-related natural disasters."
Source: Severe Weather 101: Flood Basics (noaa.gov)

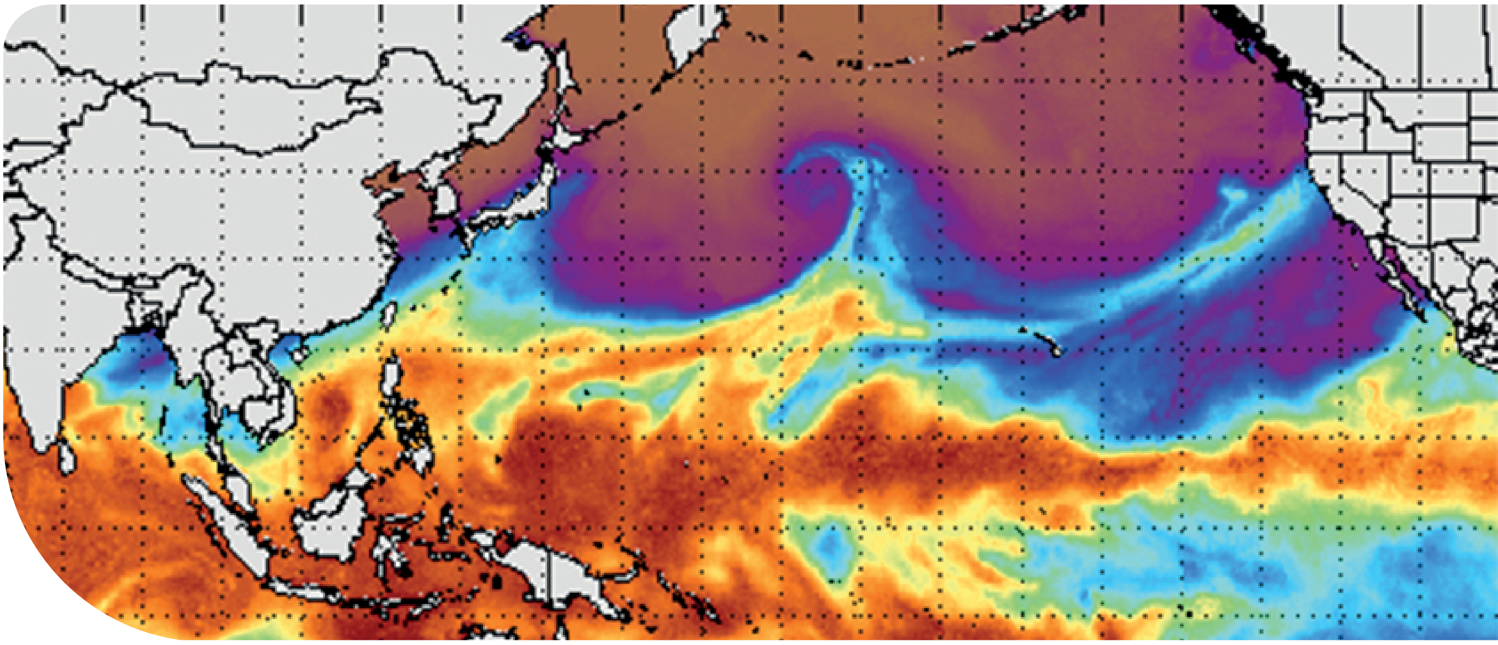
Bay Area Precipitation

The Bay Area has a Mediterranean climate, with about 75% of its annual average rainfall between November and March, and little to no rainfall occurring in summer. The Bay Area oscillates between extremes, with periods of below average annual rainfall (e.g., drought conditions) interspersed with years with above average annual rainfall. Two storm types bring rainfall to the Bay Area:

- **Extratropical cyclones (ETCs)** develop offshore and can bring cloudiness and mild showers to severe gales, thunderstorms, blizzards, and heavy rain.
- **Atmospheric rivers (ARs)** originate in the tropics and can bring light beneficial rain to torrential downpours and high winds.

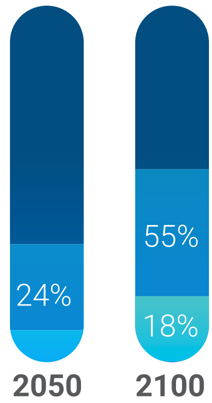
Each storm type can occur on its own or they can occur in combination. A single AR can also co-occur with a series of back-to-back ETCs. ARs and ETCs on the more hazardous end of the spectrum are associated with an increased risk of flooding in low-lying areas throughout the Bay Area.

The goal of the Extreme Precipitation Study was to understand how these storm types might change with a warming climate and how these changes impact future rainfall projections.

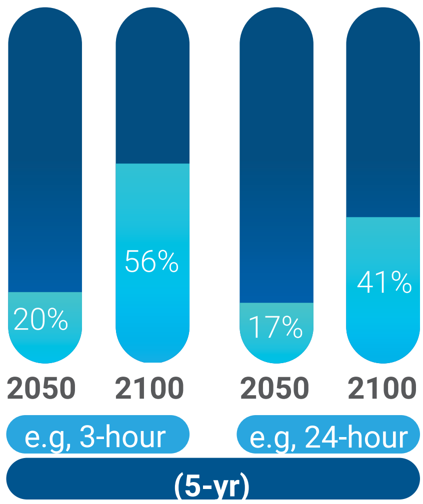


Study Findings

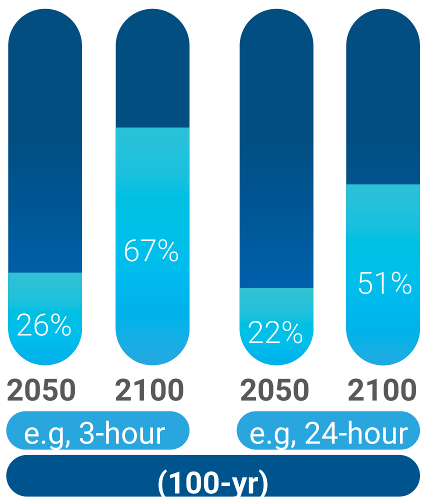
To model what today's AR and ETC storms could look like under a warmer climate, six historical storms were selected from a full climatological record of historic storms that have occurred since 1980. To support the region's various design storms and stormwater and wastewater management needs, the six storms each include different combinations of short-duration heavy precipitation, long-duration high precipitation totals, and high windspeeds. Across all storms, the models projected an increase in storm duration, ranging from 9 – 24% increase in duration by 2050 and from 18 – 55% increase in duration by the end of century, both relative to historic conditions. The greatest increase in intensity is projected for ETCs, and when ARs and ETCs occur together. The storm total precipitation could increase by up to 17% by 2050 and 37% by 2100[3]. When ARs occur on their own, the models projected a small increase (+5%) or a small decrease (-11%) in storm total precipitation[3].



Moreover, modeling of future rain accumulations indicates that rainfall intensity and frequency, and subsequent rainfall accumulations, will increase for both short (e.g., 3-hour) and long (e.g., 24-hour) durations, for both more frequent (e.g., 5-year) and less-frequent (e.g., 100-year) recurrence intervals. For the more frequent 5-year recurrence interval, the rainfall depth for the 3-hour duration is projected to increase by ~20% by 2050 and by ~56% by 2100; and the rainfall depth for the 24-hour duration will increase by ~17% by 2050 and ~41% by 2100. In other words, today's 5-year, 3-hour event could be about a 2-year, 3-hour event by 2050, and a 1-year, 3-hour event by 2100. Today's 5-year, 24-hour event could be about a 3-year, 24-hour storm by 2050, and a 1.5-year, 24-hour storm by 2100.



Similarly, for the less frequent 100-year recurrence interval, the 3-hour duration is projected to increase by 26% by 2050 and 67% by 2100; and the 24-hour duration could increase by 22% by 2050 and 51% by 2100. In other words, today's 100-year, 3-hour event could become a 30-year, 3-hour event by 2050, and an 8-year, 3-hour event by 2100. Today's 100-year, 24-hour rainfall event could become a 40-year, 24-hour event by 2050, and a 20-year, 24-hour event by 2100.



Setting the Stage

Climate's Imprint on Storms and Disasters

For decades, climate scientists have warned of more intense storms that will occur more frequently[2,4-8]. Today's global headlines reflect how this new reality is leading to catastrophic flooding the world over. Flooding in Pakistan in June 2022 captured the hearts and minds of the world as one-third of Pakistan's population (some 33 million people) were impacted by record monsoon flooding, displacing most (and many remain displaced), and killing 1,500 people. Heavy rain led to destructive and dangerous flooding in many corners of the world, from Malaysia, Mozambique, and the Philippines, to Germany, and the United States (U.S.); all these floods disrupted society, damaged infrastructure, and claimed lives.

The number of weather-related natural disasters with damages exceeding one billion dollars increases every year (Figure 1), with 18 extreme weather- and climate-related disasters occurring in 2022[9]. ARs and ETCs led to severe flood events in central and northern California and the Bay Area between December 26, 2022 and January 16, 2023; the damage costs of this event likely exceed the one billion dollar threshold and may be attributed to 2022, 2023, or both depending on the final calculations.

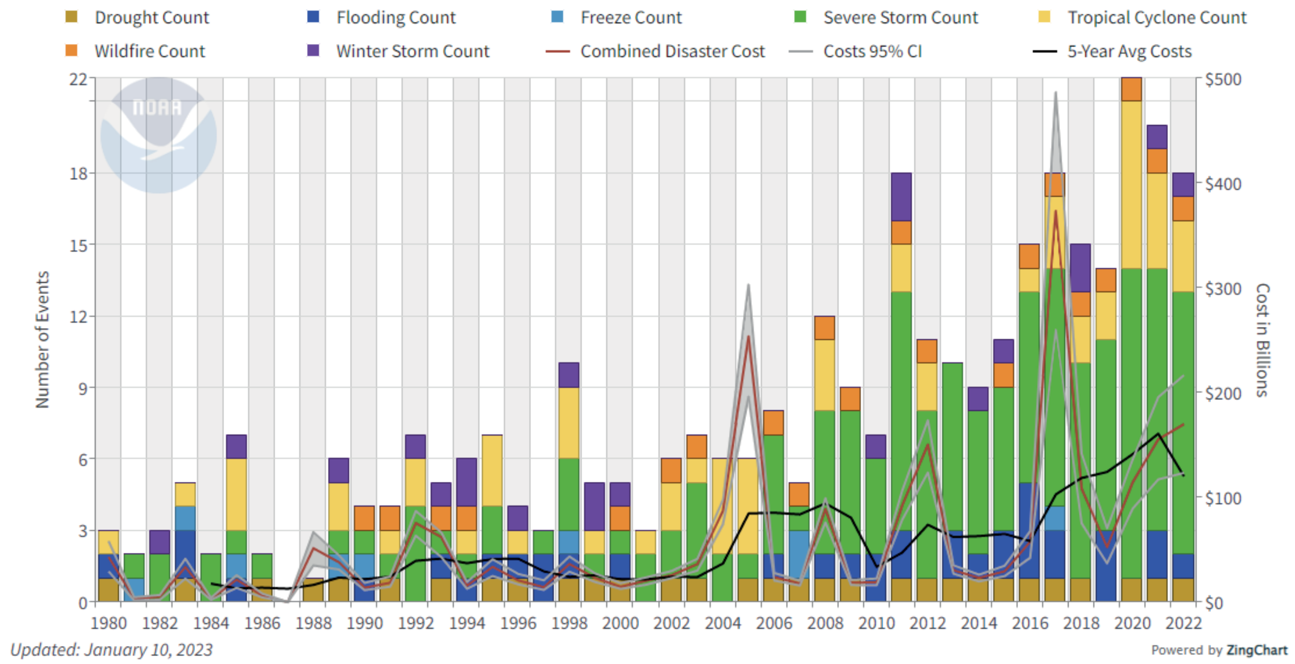


Figure 1. United States Billion-Dollar Disaster Events 1980 – 2022 (CPI-Adjusted)
Source: NOAA's National Centers for Environmental Information (Accessed 3/18/2023)

Recent scientific research highlights that today's flood events are a mere preview of what is to come as the climate continues to warm, with an increased likelihood of potential future California megafloods[10], increased Bay Area storm total precipitation[3], increased precipitation intensity across short-duration events[11], increased frequency of high-intensity extreme precipitation events[12,13], and the cascading effects of compound and consecutive events[14–16].

Scientists at Scripps University analyzed potential intensity increases for ARs under a warming climate and estimated the average annual damages that could occur along the West Coast. Using historical ARs between 1950 and 1990 and linking them to flood insurance data from the National Flood Insurance Program (NFIP), they projected that annual AR-related flood damages in the western U.S. could triple from about one billion in 1990 to 3.2 billion in 2090[17]. The actual increases in AR-related flood damages over time are likely to be much higher, as NFIP insured losses underestimate the full cost of storm-related damage and disruption.

The Components of a Storm

Whether or not a precipitation event is beneficial or hazardous is a function of its intrinsic properties and the overall capacity of the community's infrastructure (e.g., sewers, roadways, open space, green infrastructure) to manage those properties.

Storms are often described by three intrinsic properties: **intensity**, **frequency**, and **duration**.

- **Intensity** describes the amount of rainfall per unit of time (often expressed as centimeters or inches per hour).
- **Duration** describes the amount of time over which the rain falls (usually measured in minutes, hours, or days)
- **Frequency** describes the probability of an event (e.g., intensity and duration) occuring with a given year or years (often expressed by return intervals).

As described in a recent study commissioned by the Water Utility Climate Alliance, many utilities rely on intensity, duration, and frequency information from NOAA Atlas 14, which is derived from historical observations[18]. However, storms occurring today already bear the hallmarks of climate change and are increasing in intensity and severity when compared with historical observations. As storms continue to change with the warming climate, estimates of intensity, duration, and frequency that are based on historical events are no longer reasonable projections of future storms. This increased volatility is challenging for communities.

Developing a coordinated monitoring and tracking system for storm events (e.g., precipitation -based and coastal flooding) was listed as a priority action item in the 2016 Sea Level Rise Action Plan[1]. Today, San Francisco's 311 system provides a simple method for residents to report non-emergency matters, including street and property-based flooding. Residents can upload photos and descriptions of flooding, and these photos help inform where and how flooding is occurring. All 311 data and photos are accessible and in the public domain, and a sample of these photos are provided in Volume 1 and Volume 2. Most photos were submitted on December 31, 2022, which received record-breaking rainfall.

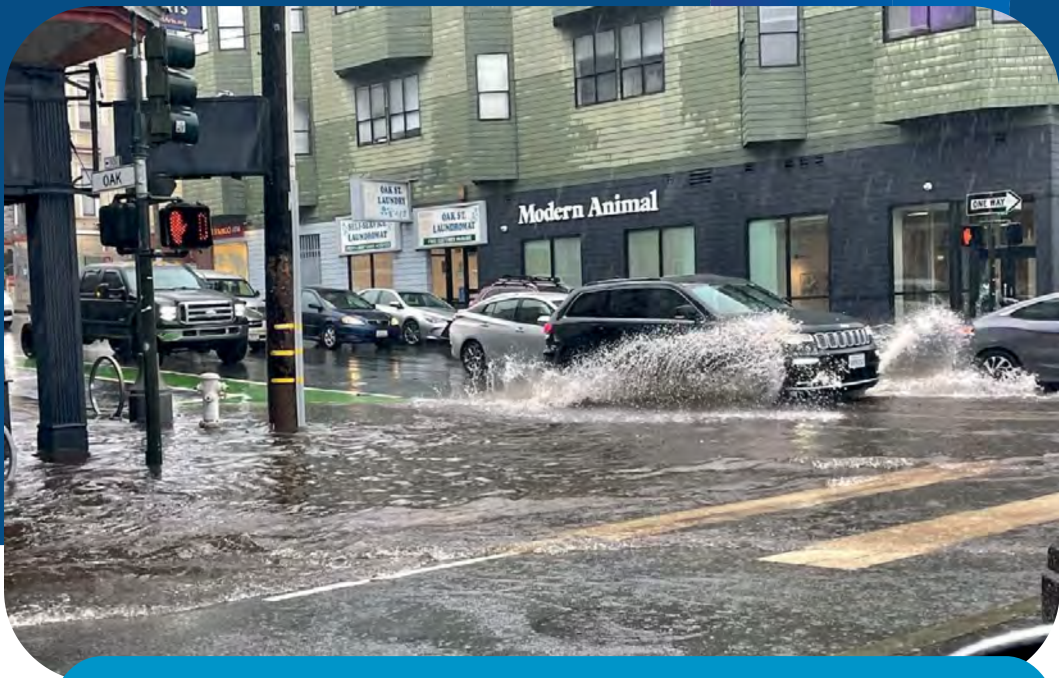


Photo: Intersection of Divisadero and Oak Street in San Francisco on December 31, 2022 (Photo Credit: 311 data and photo submitted by a San Francisco resident).

About the Guidebooks

The findings from this study are presented in two volumes to meet the needs of decision makers and practitioners. Volume 1 provides an overview of the state of the science of extreme precipitation for San Francisco and the greater Bay Area region. It describes known historic storms and highlights how they may change in a warmer climate. Volume 2 presents a suite of updated Intensity-Duration-Frequency (IDF) curves that incorporate projected changes in future precipitation through the end of the century (or 4 to 5 degrees C of warming). Volume 2 also describes other stakeholder-requested data products including a summary of other storm evolution trends, such as potential changes to windspeeds and storm surge.

This Guidebook can also serve as a resource for other infrastructure managers in the Bay Area, as well as other municipalities. Though Volume 2's IDF curves are specifically relevant for San Francisco and SFO, the methods, data, and change factors provided by the Extreme Precipitation Study can be used to create updated IDF curves throughout the Bay Area. As all infrastructure lifelines are interdependent, the discussions in this guidebook can also inform other infrastructure managers interested in understanding changing storm patterns and how to incorporate the latest climate science within their own infrastructure management plans.

Climate Change and the San Francisco Bay Area

From Global to Local

The climate science and adaptation practitioner communities rely on global climate models, or GCMs, to help understand and prepare for our future under a warming planet. Although the current generation of GCMs are excellent at developing projections of future regional and global temperatures, developing location-specific precipitation projections (and in particular precipitation within extreme storms) is very challenging using only global scale models[19].

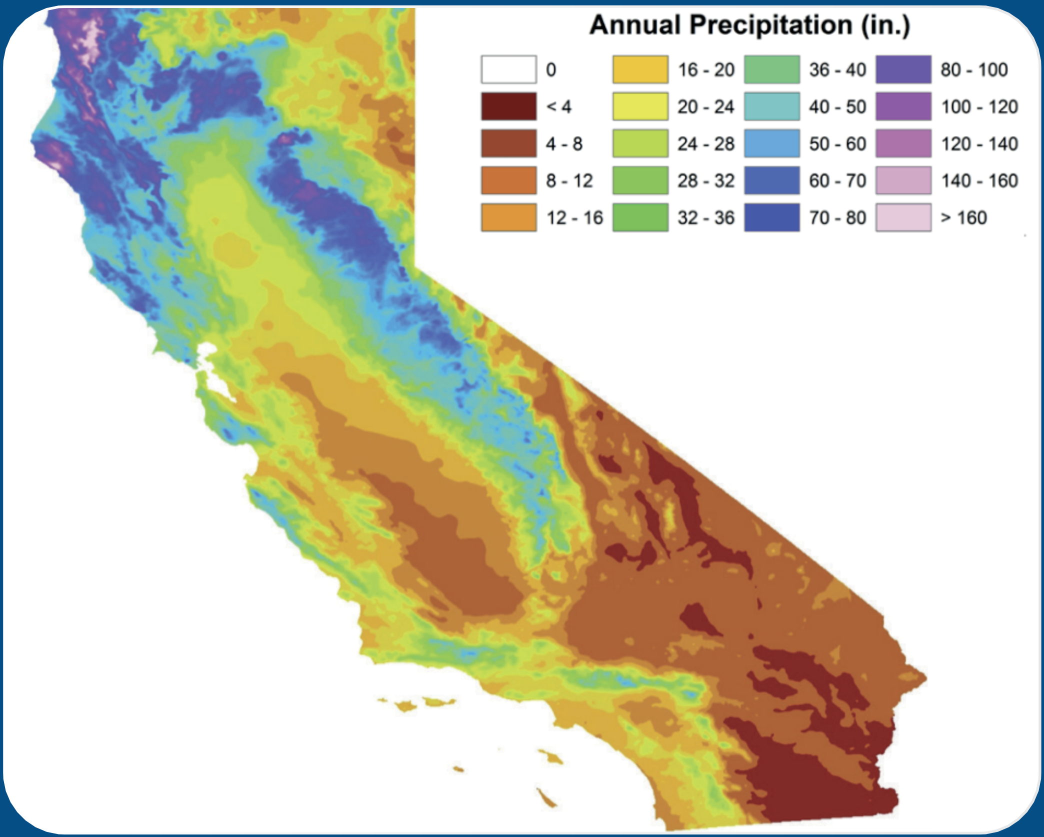
Moreover, in the Bay Area, where the highly variable and complex topography (i.e., combinations of low-lying areas surrounded by steep hills) influences both temporal and spatial differences in local precipitation, GCMs fall short. The grid resolution in some GCMs is on the order of 150 to 500 km – with just one model grid representing the entire Bay Area. The current state-of-the-art climate models are approaching resolutions of 25 km, which can broadly represent west coast atmospheric rivers. However, even at 25 km, the models cannot adequately capture the complex topographic differences across the Bay Area that lead to highly variable precipitation rates.

Climate scientists and modelers can "downscale" the GCMs to provide more granular projections for a smaller geographically-defined area. There are numerous downscaled data sets available, and these data sets vary with respect to the downscaling method used, number of downscaled GCMs available, emissions scenarios or greenhouse gas trajectories selected, and horizontal resolution[20].

For California's Fourth Climate Change Assessment released in 2018, scientists used the Localized Constructed Analogs (LOCA)[21–23] downscaled data to assess future climate patterns. Called statistical downscaling, LOCA relies on observations and data time series to develop statistical projections of climate at a smaller regional scale and provides projections down to a 6 km (or 2.3 mile) square resolution, instead of the 150 to 500 km resolution of the GCMs. Scientists compiled current annual precipitation totals for the entire state (Figure 2) and developed projections for the end of century (2070 - 2100, relative to 1950-2005), for two different climate futures (Figure 3)[24]. Figure 3 (left panel) shows projections under a future climate in which humans limit their greenhouse gas emissions (known as RCP4.5) and Figure 3 (right panel) shows projections for a "business-as-usual" scenario (RCP8.5), in which humanity continues on its same emissions trajectory path for the foreseeable future.

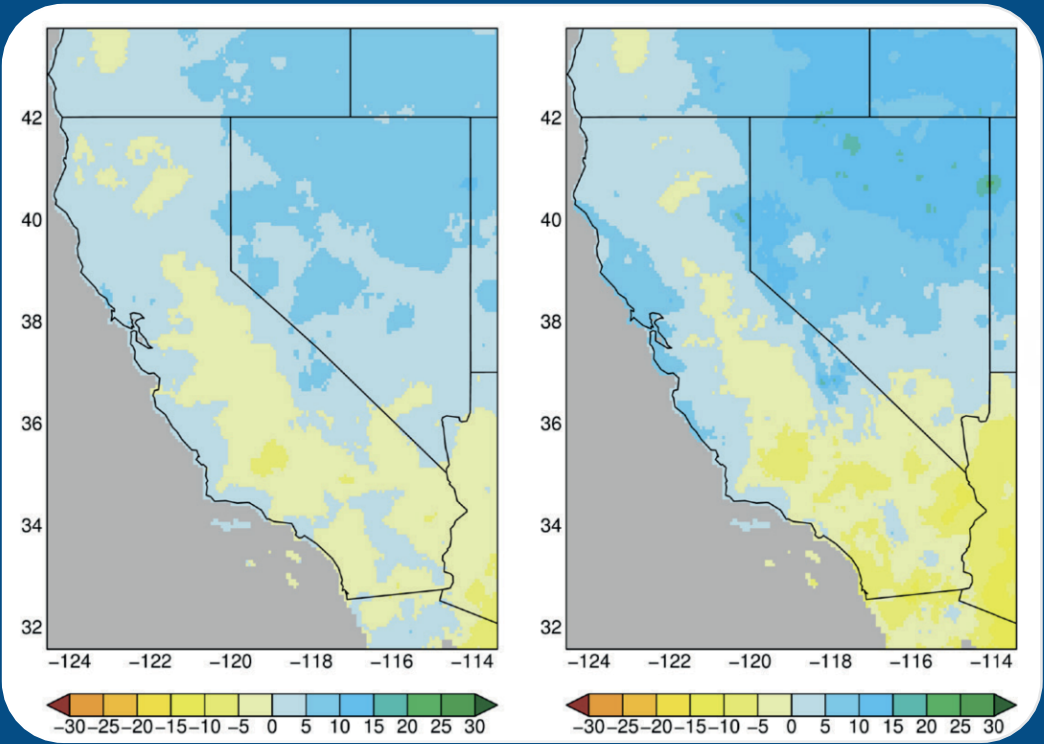
For both RCP4.5 and RCP8.5, average annual precipitation for the Bay Area is not anticipated to change significantly under a warming climate. Some global climate models predict an increase in average annual precipitation, while others predict a decrease in average annual precipitation, partially due to the challenges of resolving the climate variables in this area with coarse resolution GCMs.

A key limitation in statistical downscaling is that it requires long-term, high-quality observations to establish statistical relationships between the large-scale variables from the global climate models and local observations. Also, once downscaled, the best temporal resolution is generally limited to daily outputs - a data gap for informing the change in short duration, high intensity events in a warming climate[25]. These limitations provided the impetus for this extreme precipitation study.



Source: Bedworth et al. (2018)

Figure 2. Historical Annual Average Precipitation in California



Source: Bedsworth et al. (2018)

Figure 3. Projected Percent Changes (2070 – 2100 relative to 1950 – 2005) in Annual Average Precipitation for RCP4.5 (left) and RCP8.5 (right).

A Brief History of Climate Science: What's in a Name?

Infrastructure managers and practitioners often cite the climate science community's technical and inaccessible jargon as a barrier to incorporating climate science in planning, design, and implementation[18]. With every new climate report, a new suite of terms are defined. All fields have their own nomenclature and terms, yet the constantly updated terminology around climate scenarios and projections can be particularly intimidating or off-putting to practitioners who are not steeped in climate science literature.

Yet, the global climate modeling community and their GCMs hold important pieces of the puzzle that can help practitioners prepare appropriately for the future. To build a bridge between high level GCM outputs and applied information for on-the-ground decision-making, it is important that both sides learn to speak the others' language or use a trusted translator.

The role carbon dioxide plays in warming the earth was initially postulated as far back as 1856 by Eunice Foote and published in the Journal of Science and Arts[26]. In the early 1900s, scientists began developing models that could provide projections of future weather and climate conditions. However, Syukuro Manabe and Richard Wetherald's 1967 article published in the *Journal of Atmospheric Sciences* provided key advancements in climate modeling that quantified the global-warming effects of carbon dioxide and laid the foundation for the current generation of GCMs and climate research that continues today[27].

The most well-recognized international body addressing climate change, the Intergovernmental Panel on Climate Change (IPCC), was first established in 1988. Comprised of scientists from all over the world, the IPCC is tasked with providing objective, scientific information on climate change and the potential impacts and risks, and mitigation and adaptation options. The IPCC achieves this mission by holding discussions and meetings among leading climate scientists and modelers, and increasingly social scientists and climate mitigation and adaptation practitioners, culminating in regularly updated IPCC Assessment Reports. The first IPCC Assessment Report was released in 1990 and served as the basis of the United Nations Convention on Climate Change. Since then, the IPCC releases Climate Assessment Reports and updated climate modeling projections (referred to as Coupled Modeled Intercomparison Project, or CMIP) of our future climate on a regular basis.

The recently released IPCC 6th Assessment Report (AR6) and CMIP6 adopted a new set of climate scenarios and new associated nomenclature[2]. AR6 includes five possible socioeconomic pathways in which potential changes in society, economy, and demographics will affect global changes in greenhouse gas emissions, resulting in global warming ranging from 3.1 to 5.1 degrees C by 2100. Named Shared Socioeconomic Pathways (SSPs), the SSPs allow for broader exploration of socioeconomic futures including baselines of business as usual without climate policies. The SSPs were designed to be complementary to the more widely used Relative Concentration Pathways (or RCPs) adopted by the IPCC 5th Assessment Report (and CMIP5) and reflect how each RCP scenario would be achieved:

SSP1 - a world of sustainability-focused growth and equality, with less emphasis on economic growth

SSP2 - "middle of the road" scenario where the state of global development continues on its current path

SSP3 - a fragmented world of regional rivalries and conflict overshadowing global issues

SSP4 - increasing inequality across societies, with some regional success in environmental policies but not globally

SSP5 - continued fossil fuel dependence and rapid and unconstrained growth in economic output and energy use. Innovations and progress in technologies continue to globalize economies, with success in mitigation but adaptation in lower income societies is still challenged.

While the naming convention changes require adjustment by practitioners (and the climate science community as well) each time a new Assessment Report or CMIP is released, the goal is to provide refined physical science modeling outputs that also model human-behavior complexity. As is demonstrated by Figure 4, CMIP5 (thin grey line and grey shading) and CMIP6 (thin blue line and blue shading), both mirror historic observational trends through 2020 (thin black line). This should provide confidence that even if the names change, the fundamental science underpinning this modeling is robust and builds on past knowledge, testing, and validation.

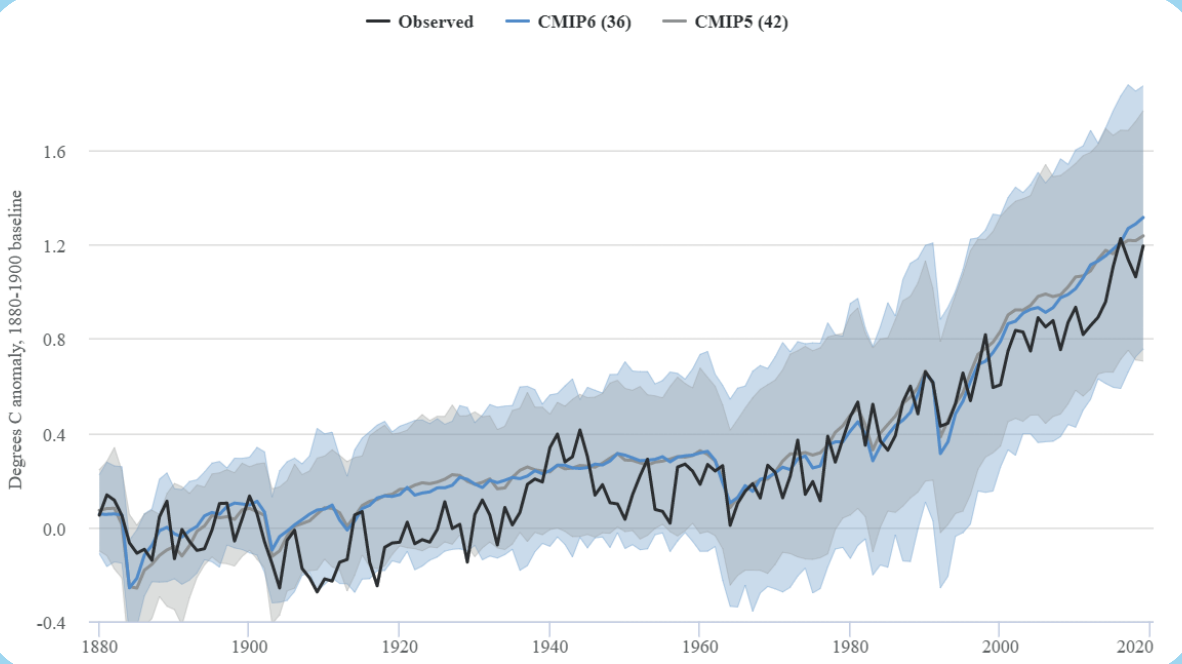


Figure 4. CMIP5 (42 models) and CMIP6 (36 models) Historical Trends for the 1880-2019 and 1970-2019 Periods

Future global climate is based entirely on if, and then how quickly, humanity chooses to reduce emissions at the global scale. Warming has already reached between 1.1 to 1.3 degrees C compared to the pre-industrial age[28,29]. The goal of the Paris Accord was to limit warming to 1.5 degrees C by the end of century, the tipping point at which scientists project irreversible recovery from many dire climate impacts[8]. The global community may be on track to limit warming to about 2.5 degrees C by 2100 based on current trends, policies, and global commitments to reduce greenhouse gas emissions and support developing countries[30]. However, global commitments have often fallen short, and climate progress is also impacted by global-scale events, such as the COVID-19 pandemic, Russian-Ukraine War, and other as yet unknown future global disruptions[31]. If climate-related progress continues, particularly over the next two decades, there is still time to keep future warming under 2.5 degrees C (as opposed to the business-as-usual scenario that would propel the world towards 4 to 5 degrees C of warming) by end of century.

Bay Area Storms

The Bay Area has a Mediterranean climate, with about 75% of its annual average rainfall between November and March, and little to no rainfall occurring in the summer. The Bay Area oscillates between extremes, with periods of below average annual rainfall (e.g., drought conditions) interspersed with years with above average annual rainfall. Two storm types bring rainfall to the Bay Area:

- **Extratropical cyclones (ETCs)** develop offshore and can bring cloudiness and mild showers to severe gales, thunderstorms, blizzards, and heavy rain;
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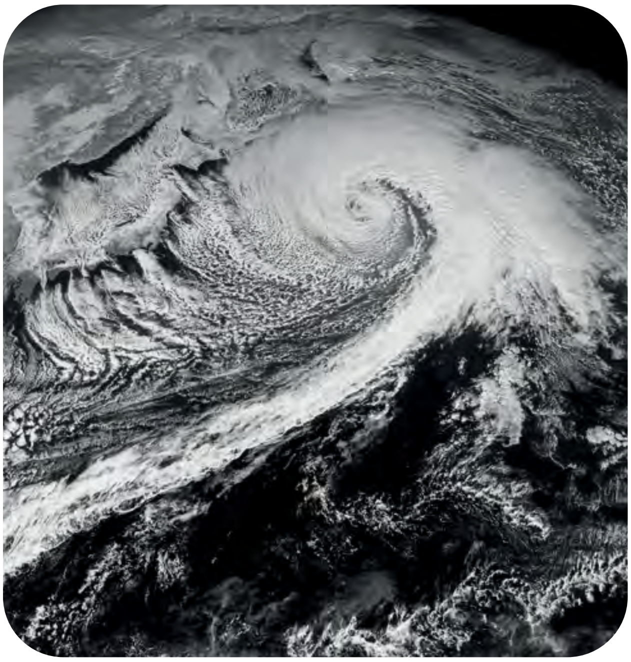


Source: NOAA

Figure 7. Northwest Pacific Extratropical Cyclone and Atmospheric River, January 15, 2013

Source: NOAA

Figure 5. Atmospheric River Satellite Image on January 28, 2021

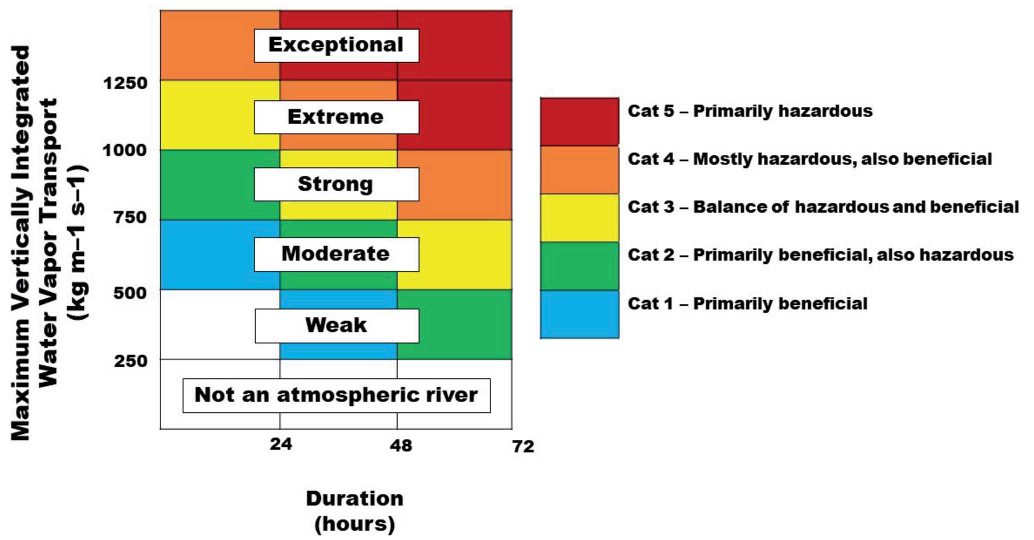
Atmospheric Rivers

First coined by Newell and Zhu in the 1990s, ARs have captured considerable media attention over the last decade[32,33]. ARs are often described as long and narrow atmospheric conveyor belts that, on average, span ~500 miles wide and thousands of miles long (Figure 5). They are found in the lower atmosphere (within 2 – 9 km, or 1.2 – 5.6 miles, high) and transport water vapor moisture from the tropics to the subtropics.

The most recognizable AR, named the "Pineapple Express," brings warm, moist air from Hawaii to the west coast of the U.S. and Canada. ARs can deliver heavy precipitation when they make landfall as they are forced up over mountainous regions or stall in a valley or along a floodplain. When ARs carrying water vapor from the tropics make landfall along the California coast, precipitation can be sustained over a span of hours to days with varying intensity[34–37].

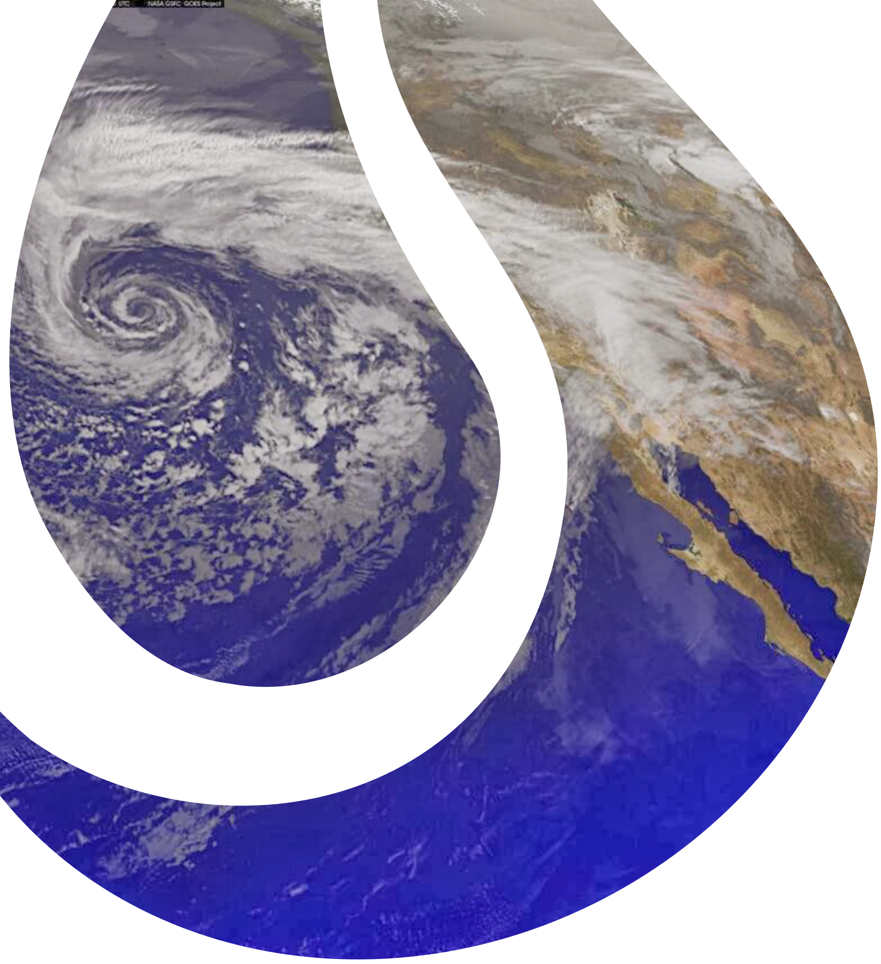
As noted in the Fourth National Climate Assessment (NCA4) report, released by the U.S. Global Change Research Program[38], landfalling ARs account for 30%–50% of precipitation and snowpack along the western US[36,39] and are associated with severe flooding events in California and other western states[4,35,36,39–41].

Historically, forecasts of ARs did not capture their wide-ranging characteristics, nor their co-occurrence with ETCs. Only recently was an AR category rating system (Figure 6) developed as an analog to the long-standing hurricane classification scale[42]. The rating system categorizes ARs from one (1) - primarily beneficial (bringing much needed rain and freshwater to regions) - to five (5) – primarily hazardous (causing flooding, mudslides, or other harmful impacts from too much rain, that falls too quickly and/or for too long). The AR categories are assigned based on the strength and duration of the storm. Each category is achieved as integrated vapor transport (IVT, or the amount of water vapor being transported horizontally in the atmosphere measured in kilograms per meter per second - kg/m/sec) exceeds set thresholds for up to 72 hours. For instance, an AR is given a Category 4 rating at any location where an IVT of at least 1,000 kg/m/sec lasts for 24 to 48 hours. While this AR rating system does not provide predictions of rainfall intensity, duration, or frequency, it does provide an important early warning mechanism so communities can use their best judgement to prepare for potential extreme rain events.



Source: Ralph et al. (2019)

Figure 6. Atmospheric River Rating System



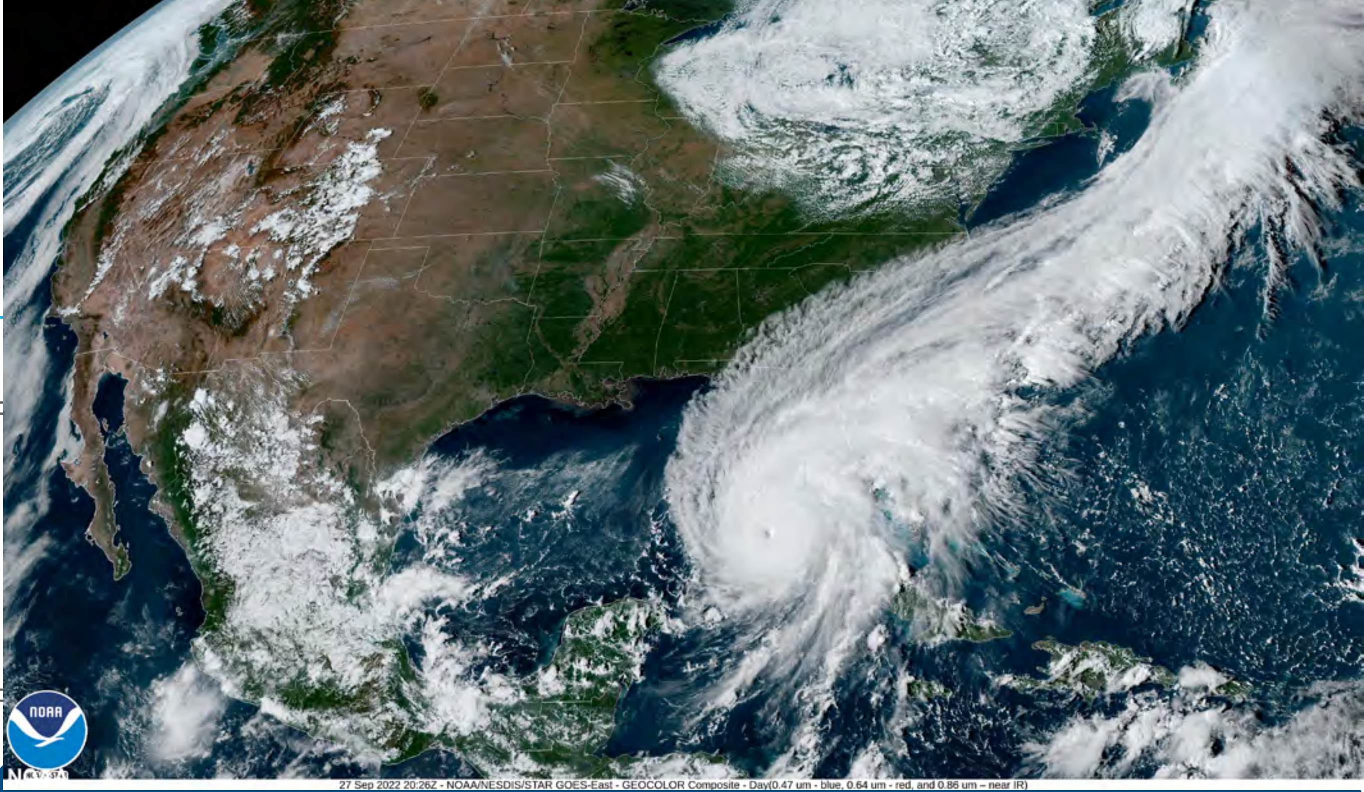
Extratropical Cyclones

Within the Earth's middle latitudes, cyclones are called mid-latitude cyclones or ETCs and can impact both the Pacific and Atlantic coasts[43–45]. ETCs are frequent winter weather systems that generally travel from west to east, vary in size and strength, with a low-pressure core and high rotating windspeeds that can resemble a hurricane when viewed via satellite imagery (Figure 7)[46]. However, hurricanes and ETCs have many differentiating features, including their frequency of occurrence, duration, vertical wind and temperature profile, and their direction of movement.

ETCs can produce mild cloudy days with light showers to a myriad of extreme weather conditions including heavy precipitation, thunderstorms, coastal storm surge, high winds, and tornadoes. These cyclones form along weather fronts, producing rapid changes in temperature and dew point. Multiple ETCs may pass over the same area in sequence within a short period of time (e.g., days to weeks)[47].

The most damaging storms for the Bay Area that have occurred between 1980 and today have resulted from the co-occurrence of a large and rapidly intensifying ETC and an AR off the California coastline[48]. ETCs can intensify ARs with stronger winds, and ARs with strong water vapor transport can provide favorable conditions for rapid ETC intensification (i.e., explosive cyclogenesis)[49]. Explosive cyclogenesis occurs when the central pressure within the ETC drops rapidly – by at least 24 millibars in 24 hours – creating a condition referred to as a "bomb" cyclone with extreme rainfall and high winds[33,50]. In addition, ARs can feed off the warm water vapor or moisture from the ETCs, which can help to lift the ARs higher in the atmosphere and result in increased rain[49].

From an analysis of storms from 1979 to 2010, Zhang et al. (2019) found that in California, 9% of storms were AR only, 41% of storms were AR+ETC, and 50% of storms were ETC only.



Source: NOAA, Satellite Image of Hurricane Ian on September 27, 2022, just before making landfall on Florida.

East Coast Storms vs. West Coast Storms: Wave-Driven Coastal Flooding and Storm Surge

During hurricane season, California watches as communities along the east coast of the U.S. repeatedly prepare for, respond to, and recover from tropical storms and hurricanes. A common question in California generally follows an east coast storm: *Does California need to prepare for the often 6+ feet of storm surge and resultant flooding that many east coast towns experience during a hurricane?*

Because extratropical cyclones over the Pacific Ocean remain in deep ocean water until they are very near the shoreline due to the narrow continental shelf along the Pacific coast, the rotating winds within extratropical cyclones cannot create a mound of water, or storm surge, comparable to hurricanes.

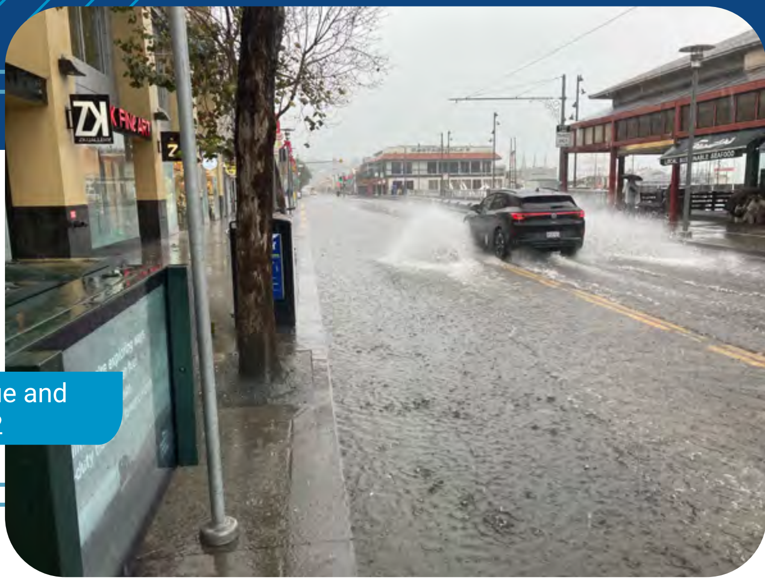
Instead, the storm surge is limited to the increase in water level driven by the decrease in barometric pressure within the storm system. Most large, historic extratropical cyclones that have impacted the Bay Area and the San Francisco shoreline have had barometric pressure drops on the order of 20 to 30 millibars, corresponding to a storm surge height of 8 to 12 inches. When coupled with El Niño effects and other ocean and atmospheric processes that influence water levels, a large rise in ocean water level on the Pacific coast is generally in the range of 3 to 3.5 feet.

In October 2021, a large AR (the Pineapple Express) collided with a series of ETCs and brought heavy rainfall, flooding, and damaging storm conditions from the central California coast and up into Canada. The first and third ETCs in the series underwent explosive cyclogenesis and became bomb cyclones. While this storm was not modeled as part of this study, it serves as a recent memory for the Bay Area and provides a good example of what can happen when ARs and ETCs converge and unleash extreme weather impacts.

As categorized by the Center for Western Weather and Water Extremes (CW3E), the first ETC to collide with the Pineapple Express produced AR 4 conditions in southwestern Oregon and AR 2 to AR 3 conditions were observed elsewhere along the coast from the Bay Area to the Olympic Peninsula[51]. The third ETC to collide with the Pineapple express reached AR 5 conditions over California, near Point Reyes, due to the combination of maximum IVT values (> 1000 kg/m/sec) and AR duration (> 48 hours)[42]. This was the strongest October storm system to make landfall in the Bay Area in the previous 40 years, and the most powerful bomb cyclone recorded in the northeastern Pacific. Intense rainfall on October 24th caused flooding in the Bay Area and triggered multiple landslides in Northern California. Portions of Northern California received more than 15 inches of total precipitation from the consecutive storms.

Explosive cyclones, or "bomb" cyclones, are associated with extreme and rapid pressure drops (i.e., explosive cyclogenesis), and bomb cyclones can cause signi icant looding and damage due to heavy precipitation, large storm surge, and strong winds[46].

Winter 2023-2022 Consecutive and Compounding ARs and ETCs



(Photo Credit: Port of San Francisco.)

Photo: Jefferson Street near Taylor Avenue and Fisherman's Wharf on December 31, 2022

Early weather predictions for the 2022-2023 wet winter season suggested California would experience low precipitation accumulations relative to average conditions, consistent with La Niña conditions. However, the 2022-2023 winter season started out as one of the wettest winters on record, breaking a 152-year-old record for the second wettest 10-day period since 1871. The wettest 10-days on record occurred in 1862.

Between December 26, 2022 and January 16, 2023, the Bay Area was hit with nine consecutive ARs, some that co-occurred with ETCs, and one that became a powerful bomb cyclone on January 5, 2023. In San Francisco, 18 inches of rain fell over the 21 days, representing 75% of the total average annual rainfall. The Bay Area experienced widespread flooding, power outages, mudslides, downed trees, and disruption to daily life.

In parallel to these historic rain events along the coast, concomitant record-breaking snowfall was recorded across the state's mountain ranges, even down to the Southern California mountains east of Los Angeles and San Diego.

Although the October 2021 storms led to widespread flooding, damage and disruption, the shorter duration of the events did little to provide relief for California's extreme drought conditions. However, the back-to-back series of storms in winter 2022/2023, and the continued rainfall and snowfall that occurred through March 2023 replenished most reservoirs and provided some reprieve from the prolonged drought.

Future Storms Modeling

To model what today's storms could look like under a warmer climate (up to 4 to 5 degrees C), historical storms were selected from a full climatological record of historic storms that have occurred since 1980. The study team analyzed the following variables at both the NOAA San Francisco Downtown Station and the NOAA SFO Station to identify storm candidates that represented a range of heavy precipitation and high windspeed conditions across both San Francisco and SFO:

- Storm duration (i.e., storm start and end dates)
- Storm total precipitation
- 1-hour, 3-hour, 12-hour, and 24-hour maximum precipitation
- Maximum hourly wind speed and direction
- Minimum barometric pressure
- Maximum wind gust
- Strength of El Niño/La Niña using Oceanic Niño Index
- Storm type (e.g., AR, ETC, AR + ETC)

Through review of the available data and desktop research related to storm impacts around the region, the majority were found to be combined AR + ETC events[48]. The study team identified an initial list of 15 extreme storms. From these, six storms were selected (the first storm consisted of two separate back-to-back storms that were modeled separately), as this was the greatest number of storms that could be simulated with the available supercomputing resources, while meeting simulation design requirements (3 km resolution over the Bay Area and a multi-model member ensemble).

The six storms include a balance of short-duration heavy precipitation, long-duration high precipitation totals, and high windspeeds. Evaluating storms with this variety in overall climatology provides valuable insights to stakeholders on how the storms will respond and change over the coming century. Additional details on the storms and storm selection process are available in May et al. (2019).

Storm Modeling, Planning Horizon, and Climate Scenario

To model how these six events could look in the future, study leads selected the SSP5-8.5/RCP8.5 future climate scenario as it represents the highest emission scenario evaluated by IPCC, representing a future with continued fossil-fuel development and dependency, and the adoption of resource and energy intensive lifestyles around the world, including within developing countries. The selection of SSP5-8.5/RCP8.5 will also better support the translation of the future modeled conditions to more optimistic greenhouse gas emissions scenarios that produce lesser warming, since the selection of the highest emissions scenario provides the upper bound temperature increase for 2100, while historical conditions represent the lower bound.

Two planning horizons were selected for this study:

Mid-Century: 2050 (or 2035-2064): evaluates a mid-century time horizon aligns with the end of the functional lifespan of many existing facilities (20 to 30 years from today) and can also support longer-term capital planning decisions for new facilities.

Late-Century: 2100 (or 2070-2099): supports evaluation of long-term planning and resilience efforts, including large capital projects intended to have long functional lifespans. Consideration of 2100 conditions or beyond in the planning of large-scale projects can help provide future generations with more infrastructure.

Findings

Change in AR Category

While the AR category scale developed by Ralph et. al (2019) was intended as a real-time forecasting and communication tool, it can also support visualizations of how ARs may evolve in a warmer climate. In all six selected storms, the AR categories increased in a warmer future. In the historical condition, only two of the six storms (Storm 1b – Dec 2014 and Storm 5 – Dec 1995) exceeded a Category 4 after landfall; in a warmer future five out of the six storms reach a Category 5 over land. Three of the six modeled storms exceed a Category 6 by the end of century time horizons, and one storm (Storm 5 – Dec 1995) exceeds a Category 8 (Table 1).

AR Category				
Storm Number	Event Dates	Historical	2050	2100
Storm 1a	Dec 2-6, 2014	3	3	3
Storm 1b	Dec 11-12, 2014	4	5	5
Storm 2	Jan 3-5, 1982	3	3	4
Storm 3	Nov 4-7, 1994	3	4	5
Storm 4	Jan 31-Feb 8, 1998	4	5	6
Storm 5	Dec 10-13, 1995	5	7	8

Table 1. Historical and Future AR Category

Change in Rainfall Duration

Initial modeling demonstrates that ARs, in combination with ETCs, are likely to get more intense and severe as the climate warms. Across all storms, the models projected an increase in duration, ranging from 9 – 24% increase in duration by 2050 and from 18 – 55% increase in duration by the end of century, both relative to historic conditions.

Change in Rainfall over Long and Short Durations

Understanding how the long and short duration intensities within the storms may change is important for long-term planning. Most studies of extreme precipitation have focused on daily rain totals, often due to the lack of subdaily information in climate modeling. A key finding from this study is that the shorter durations are increasing at a faster rate than the longer durations and storm totals.

Change in Long Durations

Modeling results for the 24-hour duration for both the 5-year and 100-year recurrence interval demonstrates that rainfall accumulations, as defined by rainfall depth in inches, is expected to increase by both 2050 and 2100 (Table 2). By 2050, accumulated rainfall for the 5-year recurrence interval is expected to increase by 17% (with a 90% confidence interval of 7 – 24%); by 2100, rainfall accumulation is expected to increase by 41% (with a 90% confidence interval of 26 – 57%). For the 100-year recurrence interval, similar increases are projected with an increase of 22% (90% confidence interval of 12 – 32%) by 2050 and 51% (90% confidence interval of 35 – 67%) by 2100.

Stated differently, and in the measure that is often reported in the media after a storm, the Bay Area can expect an increase from 3.1 inches of rain for the 5-year, 24-hour event under historical conditions to 3.6 inches by 2050 and 4.3 inches by 2100 (Figure 8). The 100-year, 24-hour event could increase from 5.8 inches under historical conditions, to 7.1 inches by 2050 and 8.8 inches by 2100.

		5-year, 24-hour	100-year, 24-hour
Historical		0%	%+0
		- 10 to +13%	-17 to +23%
2050		+17%	+22%
	CI 90%	+7 to +27%	+12 to +32%
2100		+41%	+51%
	CI 90%	+26 to +57%	+35 to +67%

Table 2. Historical and Future Return Frequency for 24-hour Duration with 90% Confidence Interval

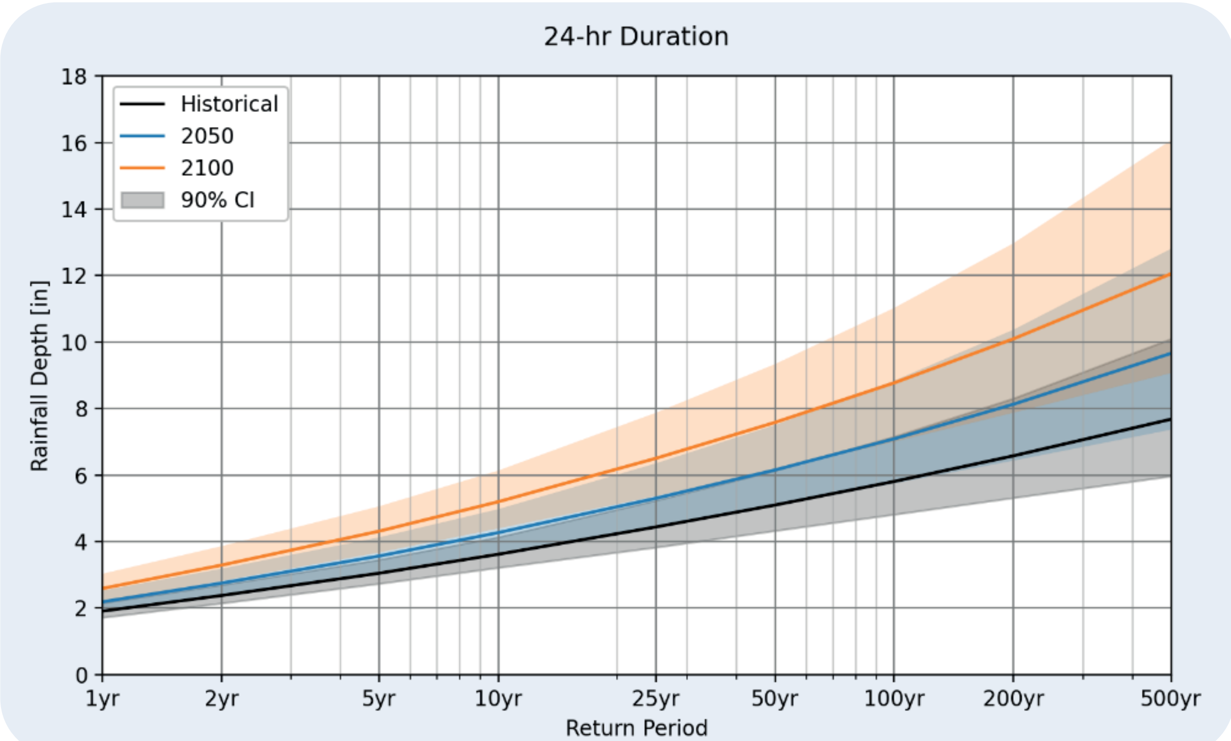


Figure 8. Historical and Future Return Period Verses Rainfall Depth for 24-hour Duration

Change in Short Durations

Short durations are projected to increase at a faster rate than the long durations, consistent with recent findings in other geographies[11]. For example, the 5-year, 3-hour event is projected to increase by ~20% by 2050, and 56% by 2100; and the 100-year, 3-hour event is projected to increase by 26% by 2050 and 67% by 2100 (Table 3). These percentage increases translate to changes in total accumulation for the 5-year, 3-hour event of 1.3 inches for the historical event, to 1.5 inches by 2050, and 2 inches by 2100. For the 100-year, 3-hour event, this results in an increase from 2.3 inches for the historical event, to 2.8 inches by 2050, and to 3.8 inches by 2100. Durations shorter than the 3-hour increase at an even faster rate and are explored in Volume 2. These increased percentages and inches translate into more rain falling in shorter periods of time, increasing the potential for urban flooding and flash floods[11].

These changes can also be viewed in terms of changing frequency (Figure 9). For example, rainfall accumulations associated with a historical 5-year, 3-hour event will become a 2-year, 3-hour event by 2050, and a 1-year, 3- hour event by 2100. Similarly, the rainfall accumulation for the historical 100-year, 3-hour event will become the 40-year, 3-hour event by 2050, and the 8-year, 3-hour event by 2100.

Moreover, it is increasingly likely that the region will see storms occurring in rapid succession, such as occurred during early winter 2022-2023, during which nine successive atmospheric rivers inundated the California coast leading to widespread flooding. (These successive 2022-2023 storms and their impact on the Bay Area are discussed in more detail Volume 2.)

		5-year, 3-hour	100-year, 3-hour
Historical		+0%	+0%
		-11 to +14%	-20 to +27%
2050		+20%	+26%
	CI 90%	+12 to +30%	+16 to +35%
2100		+56%	+67%
	CI 90%	+38 to +75%	+47 to +87%

Table 3. Historical and Future Return Frequency for 3-hour Duration with 90% Confidence Interval

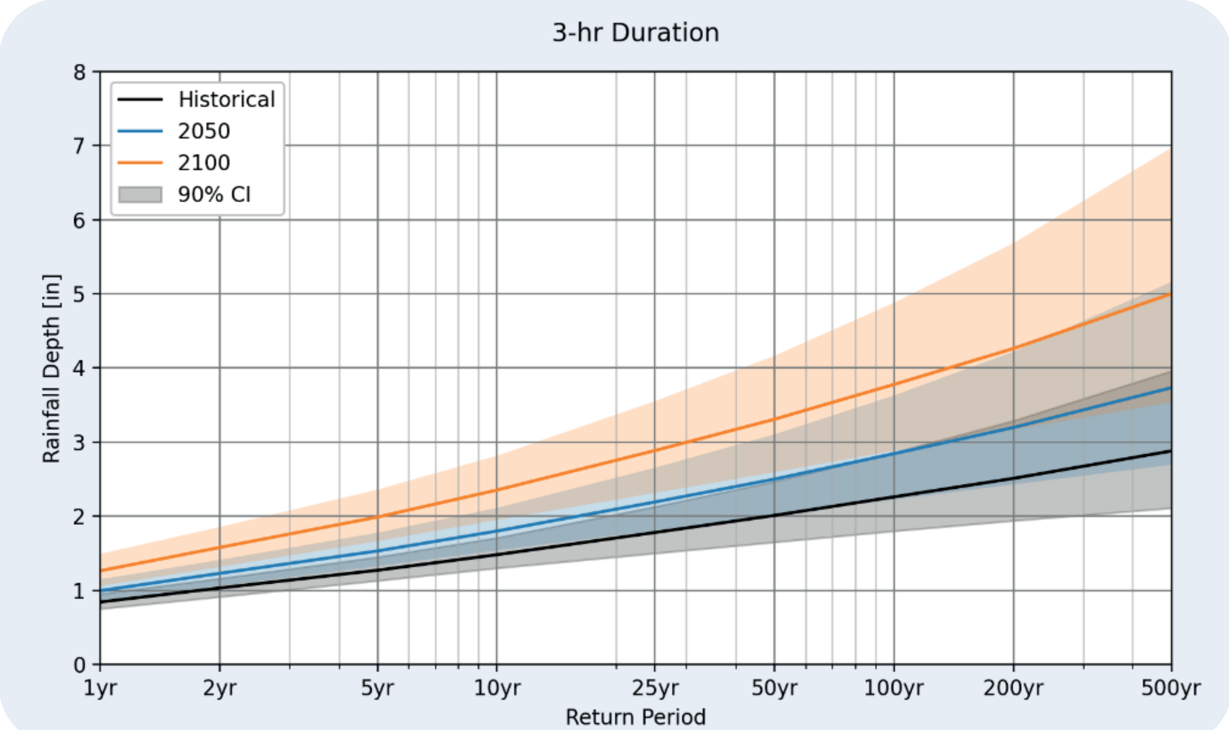


Figure 9. Historical and Future Return Period versus Rainfall Depth for 3-hour Duration

Does an increase in extreme precipitation mean a decrease in drought?

Given California's history of drought, an increase in extreme precipitation may seem like it could help stave off dry soils, vegetation, and alleviate California's challenges with water shortages. Unfortunately, observations of changing rain patterns and climate models show that this is likely not the case.

While it is not clear whether average annual precipitation will change in the future[52,53], climate models do show strong support for a significant change in precipitation patterns. Long-term climate projections show a shortening of the precipitation season[54–56] an increase in whiplash likelihood[57] (e.g., an extreme dry year followed by a wet year, or vice versa), a decrease in snowpack[24,58–63], and an increase in rain on snow events[57].

Moreover, studies show that these are already underway. For example, observations of precipitation data show that precipitation has decreased in the early fall months, with the average onset of the rainy season delayed by about 27 days since 1960[64]. Precipitation also decreased by about 0.5 inches (12 mm) per decade statewide during autumn months[66]. Temperature records show that over the past century, warming has occurred during all 12 months, with most warming occurring in late summer and early autumn, leading to an increase in the likelihood and magnitude of hydrologic drought[67] and in the drying of vegetation and forest mortality[68].

These changes could have serious implications for California's water supply, ecosystem health, and wildfire risk.

- **Increase in water spillage due to full reservoirs:** With more water projected to come in concentrated, intense rain events, and as rain rather than snow, it is more likely that California's current water management system will not have the capacity to store water during flooding and runoff events, leading to a loss of water and less water available during dry summer months[57].

- **Decrease in absorption during rain events:** With less rain in the spring and fall, soils will be drier, leading to more runoff rather than absorption during rain events. In addition, less rain in the fall means soils and vegetation are drier during the fire-inducing offshore winds that occur in the fall. Even a small amount of rain during this time can help reduce the flammability of vegetation[54].

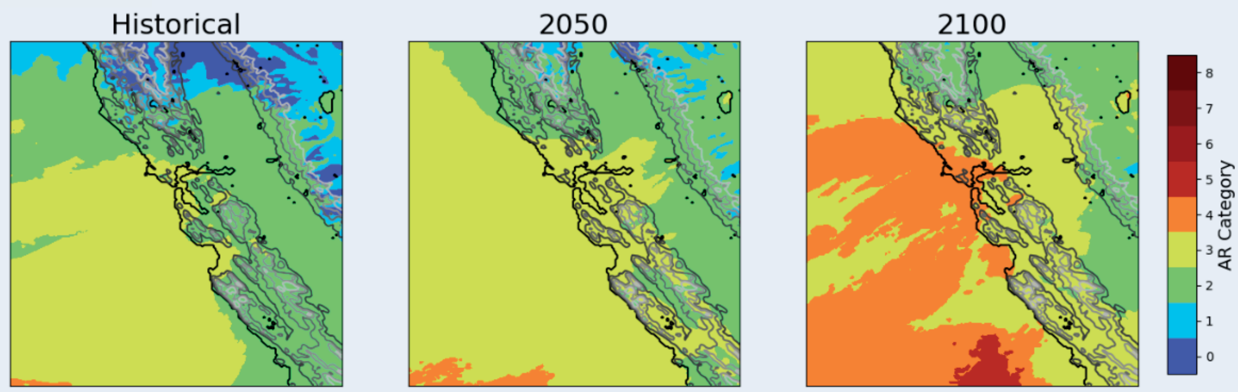
- **Increase in wildfire risk and debris flows from whiplash events:** Climate models show an increase in frequency of both wet years and dry years, with an increase in the frequency of alternating extreme wet and extreme dry years – e.g., a very wet year followed by a very dry year or vice versa[57]. Rain after wildfire events leads to mudslides, debris flows, and flash flooding due to the loss of vegetation and change in soil properties in wildfire scar areas. Dry periods after rainy winters leads to increases in wildfires due to an increase in growth of grasses and brush, which then dry out and are highly flammable.

A Closer Look at Storms 2 and 5

A closer look at the January 1982 (AR only storm) and December 1995 (AR in combination with ETC storm) illustrates how these two storm types could worsen in a warmer future. For both storms, the following four visualizations describe how intensity, duration, and frequency of the ARs, and associated rainfall, will change for both 2050 and 2100 under SSP5-8.5:

Storm 2: January 3 – 5, 1982

The January 1982 winter storm was short duration but strong in magnitude, delivering heavy rainfall over the Bay Area concurrently with extraordinarily high tides resulting in widespread flooding. In San Francisco, 4.7 inches of rainfall was recorded across the storm's duration, and SFO recorded about 5.6 inches of rainfall. This storm was an AR occurring on its own. AR only events exhibit less change in overall precipitation as the climate warms, although the changes in the short durations are greater than the long durations and the storm totals. Only 9% of storms impacting the west coast are AR only events[49].



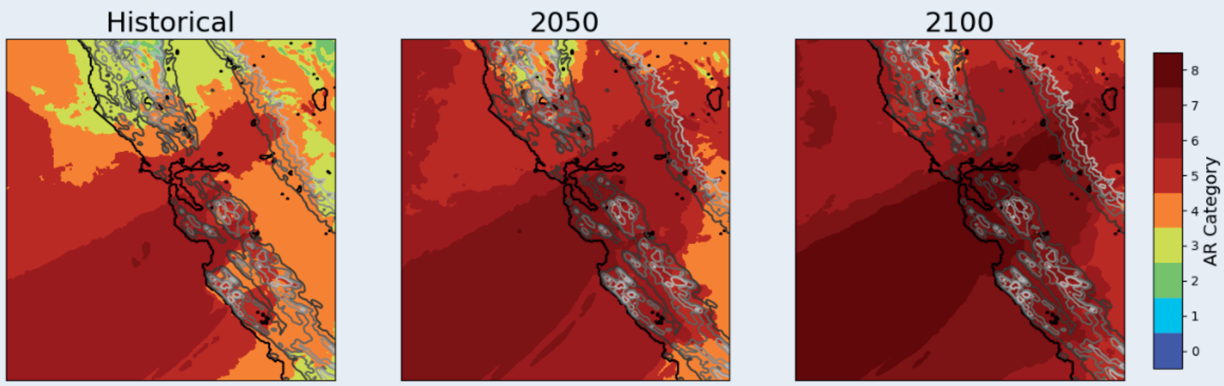
AR Categorization

- This historic storm was a Category 3
- By 2050, this storm would still be Category 3
- By 2100, this storm could reach a Category 4 along the coast

- **AR Categorization:** change in AR category rating under a warmer climate.
- **AR Duration:** change in the total duration (hours) of the AR event exceeding its historical category.
- **Rainfall Intensity:** Increase in the maximum 1-hour intensity of precipitation during the entire storm event.
- **Rainfall Total:** The increase in storm total precipitation for the full event.

Storm 5: December 10 – 15, 1995

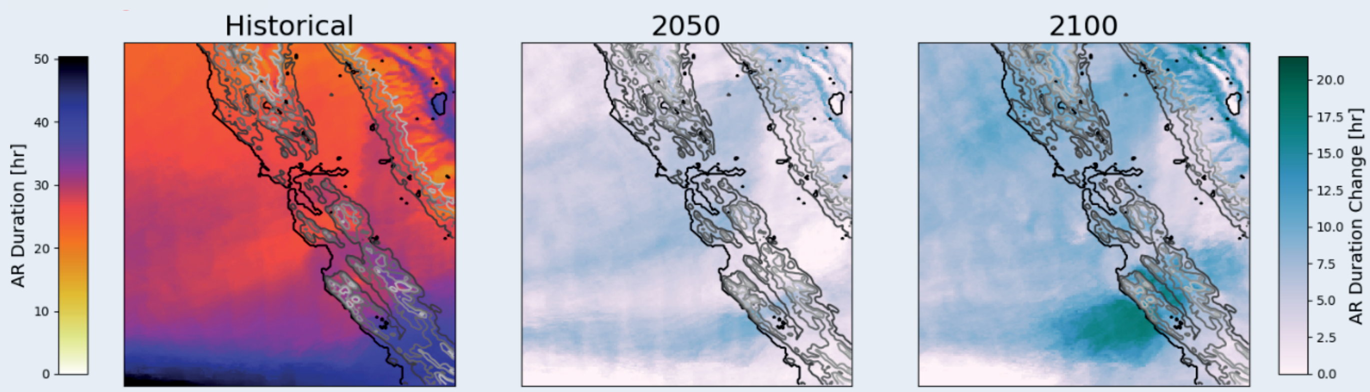
This storm was considered the strongest winter storm of the previous 70 years of record, with heavy rainfall and peak winds of 80 miles per hours observed at several sites in the Bay Area. The heavy winds downed both power lines and trees, including 1,000 trees in Golden Gate Park. Between December 11 and 12th, the ETC had an extreme and rapid pressure drop and became a bomb cyclone off the California coast. This storm included an ETC and AR. Both ETCs on their own, and ETC and AR combinations, are expected to increase in intensity and total precipitation as the climate warms. 90% of the storms that impact the West Coast fall into this category[49].

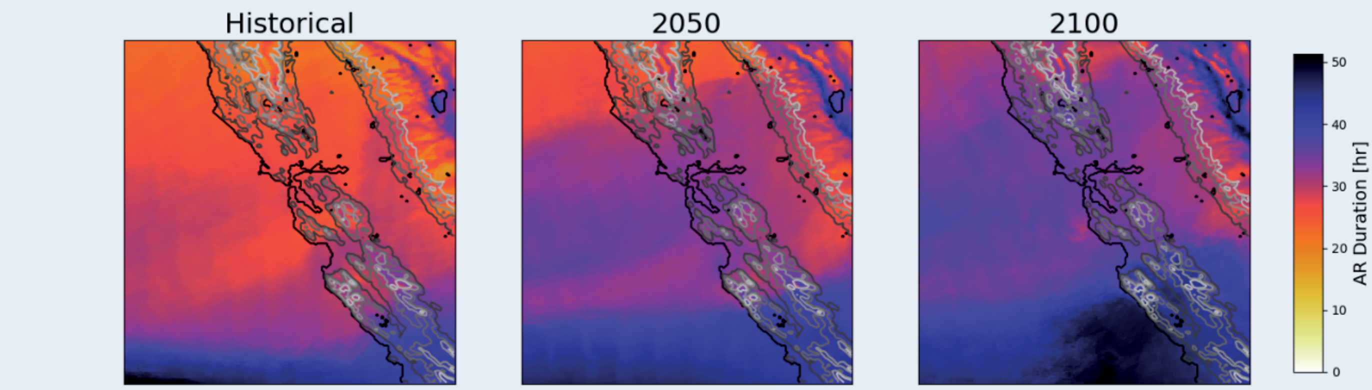


AR Categorization

- The historic storm was already categorized at the top of the rating scale, receiving a Category 5.
- By 2050 and 2100 if this storm were to occur again it could exceed the current AR rating scale, reaching a Category 7 by 2050 and a Category 8 by 2100 across San Francisco and the surrounding Bay Area.

Storm 2: January 3 – 5, 1982

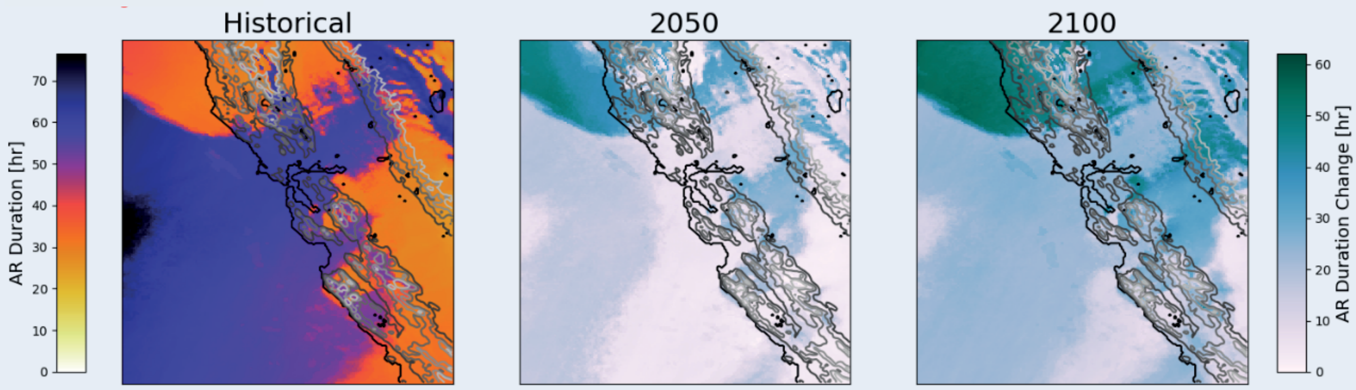


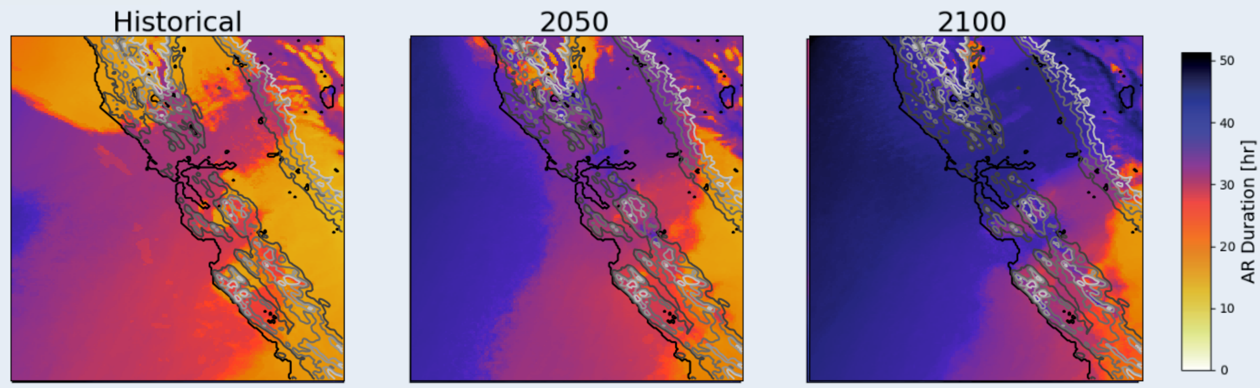


AR Duration

- Historically, the AR lasted roughly 27 hours over the Bay Area but persisted longer south of the Bay, up to a duration of 44 hours.
- This AR is expected to last over the Bay Area roughly 5 hours longer by 2050 and 8 hours longer by 2100.

Storm 5: December 10 – 15, 1995

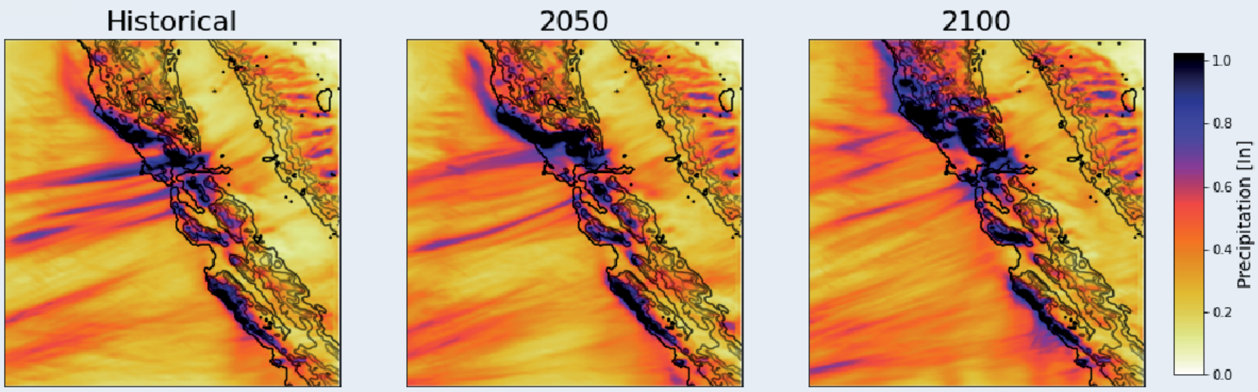




AR Duration

- This AR lasted roughly 53 hours over the Bay Area, putting it above the 48-hour benchmark used for long ARs in the AR category system.
- This duration increased even further in the future simulations, lasting about 10 hours longer by 2050 and 25 hours longer by 2100.

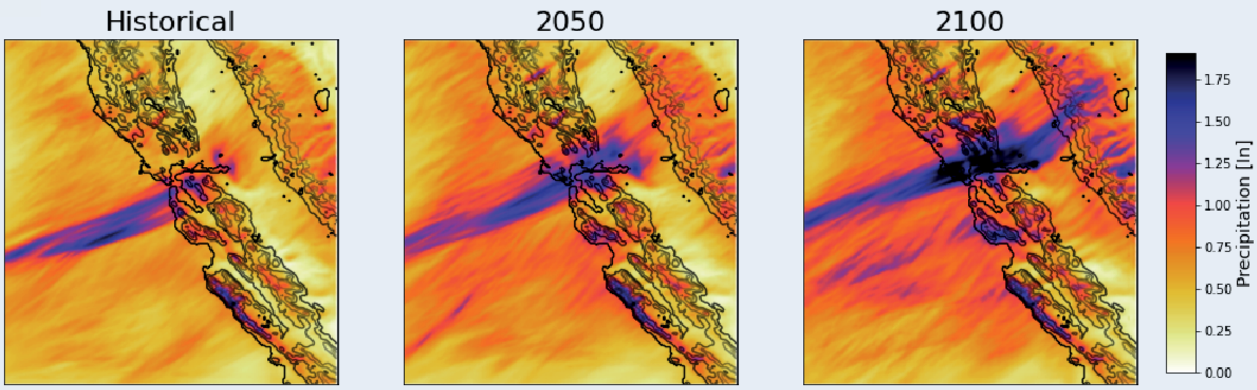
Storm 2: January 3 – 5, 1982



Peak Hourly Rainfall

- This AR-only event had negligible increases in mean precipitation across the Bay Area by 2050 and 2100.
- Slight increases were observed in the peak hourly precipitation, increasing from 1.5 inches under historic conditions, to 1.6 inches by 2050 and 1.7 inches by 2100.

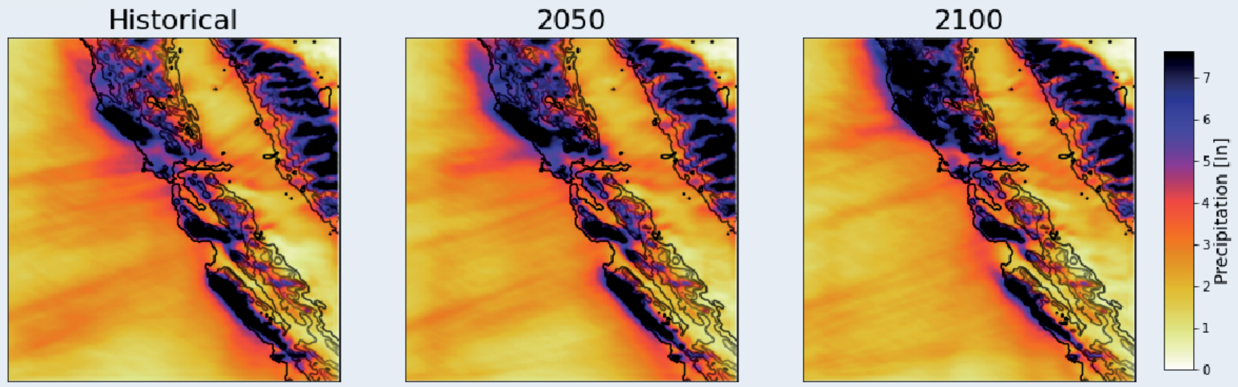
Storm 5: December 10 – 15, 1995



Peak Hourly Rainfall

- Under historical conditions, the peak hourly precipitation over the Bay Area was 2.0 inches.
- By 2050 and 2100, the peak hourly precipitation increased to 2.4 inches and 2.9 inches, respectively.
- While the bull's eye of this AR tracks northerly in these simulations, this is not evidence that San Francisco would be spared from extreme future storms. If the initial storm had tracked south of San Francisco, the bull's eye could have landed squarely over San Francisco as the climate warmed.

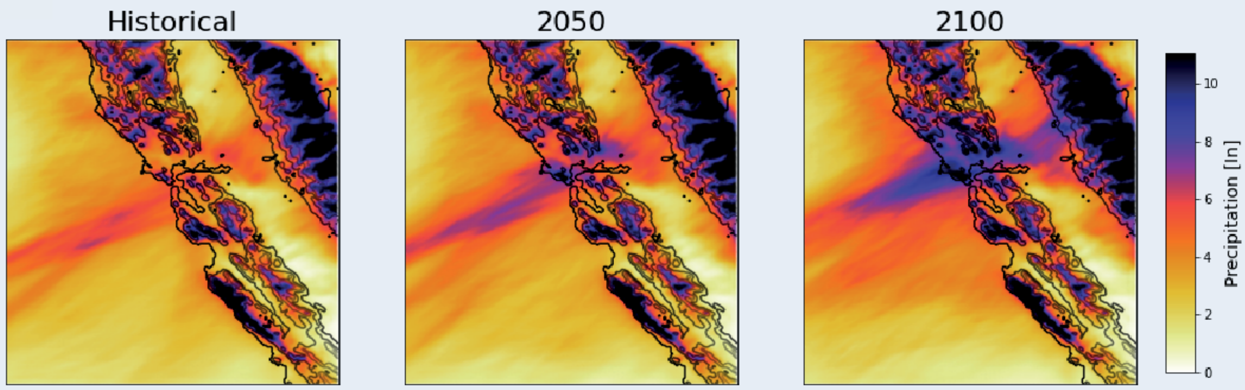
Storm 2: January 3 – 5, 1982



Rainfall Total

- The rainfall total over the duration of the entire storm is projected to have negligible changes by 2050 and 2100.
- Historical storm totals increased from 9.0 inches historically, to 9.9 inches by 2050 and 11.4 inches by 2100, but this increase is much weaker than observed in storms with ARs combined with an ETC (such as Storm 5).
- The most notable increase in future precipitation occurred in high elevation areas where the slopes could wring out the extra moisture from the AR without the needed the presence of an ETC.

Storm 5: December 10 – 15, 1995



Rainfall Total

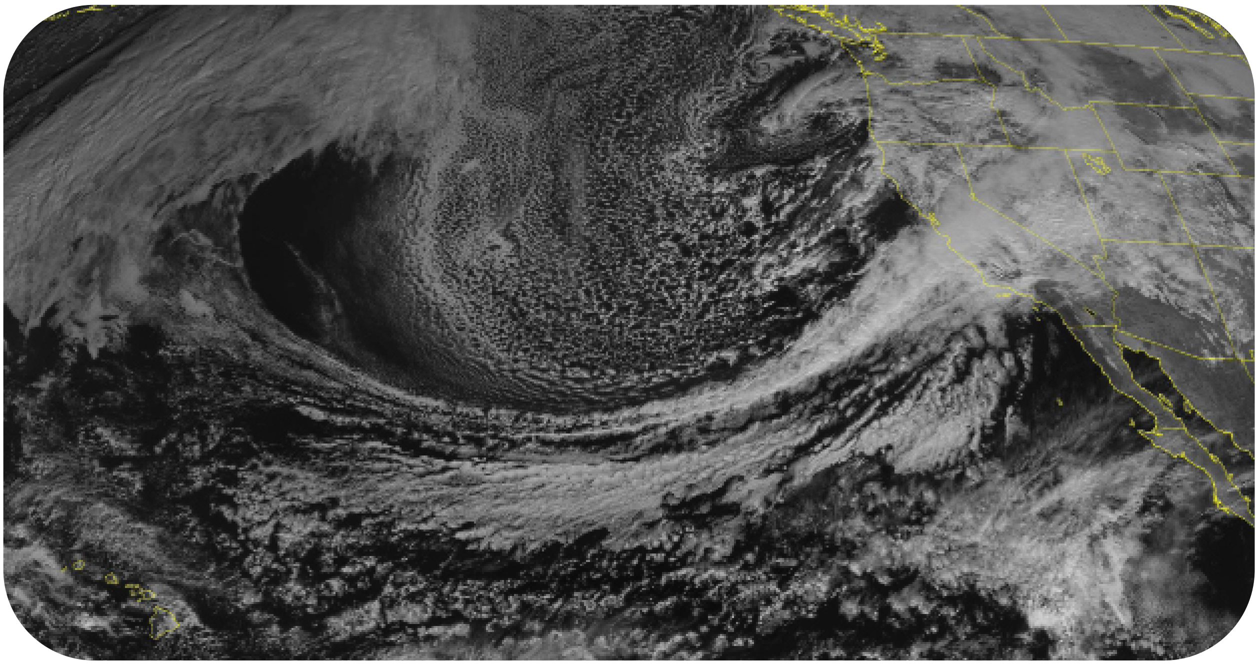
- In 1995, this storm delivered a rainfall total of 7.8 inches over the Bay Area, with roughly 5.5 inches recorded at the San Francisco Downtown Station.
- The rainfall totals increased by 38% to 10.8 inches by 2050 and by 66% to 13.1 inches by 2100.
- Dramatic increases across the entire Bay Area drove similar increases in the mean precipitation.

Closing Thoughts

The Bay Area has experienced damage and disruption from numerous extreme storms that delivered heavy precipitation and other severe storm conditions (e.g., high winds and storm surge). However, San Francisco has not experienced devastating or catastrophic flooding and the associated consequences that have impacted so many other cities around the U.S. and the world. As our climate continues to warm, sea levels rise, and extreme storms become more intense, San Francisco could begin to see more flooding across the city.

Pathways and LBNL completed this Extreme Precipitation Study to help San Francisco prepare for future extreme precipitation. Understanding how extreme precipitation will change in a warming climate was identified as priority action for the City[1]. This information gap has been filled by state-of-the-art and defensible science. Although no historical storm will ever occur again exactly as it did in the past, an analysis of real storms that impacted the region helps provide the best estimate of a reasonable range of extreme storm conditions that could exist in the future. A warmer climate is projected to fuel the increasing intensity of the most common extreme storm types that make landfall in the Bay Area, just like the October 2021 Bomb Cyclone and the 2022-2023 winter consecutive ARs and ETCs, that all led to severe flooding, mudslides, downed trees, power outages, and overtopping of rivers due to exceeded flood stages.

The findings from this Extreme Precipitation Study provide the foundation for how extreme storms may change. Volume 2 of the Guidebook translates these findings into actionable science that practitioners, modelers, and engineers can use to prepare for future extreme precipitation.



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