

CALIFORNIA'S FIFTH
CLIMATE CHANGE
ASSESSMENT

San Diego Regional Report

A Regional Report for California's Fifth Climate Change Assessment

Coordinating Agency

CA Governor's Office of
Land Use and
Climate Innovation

About California's Fifth Climate Change Assessment

California's Climate Change Assessments are the state's scientific foundation for understanding future climate-related vulnerability across California's regions and systems. Senate Bill 1320 (Stern, 2020) requires the State to report the impacts and risks of climate change across California at least every five years, beginning with California's Fifth Climate Change Assessment (Fifth Assessment). Building on decades of climate research and previous Assessments, the Fifth Assessment presents new findings about California's climate future, with a dedicated focus on Tribal partnerships, public engagement, and communities most vulnerable to climate impacts.

The Fifth Assessment's research and tools are designed to fill knowledge gaps about California's climate future, inspire strategic climate actions, and shape planning, investments, and policies at the state, regional, and local scales. Guided by research priorities identified by state, Tribal, and local leaders, community representatives, and subject matter experts, its findings are designed to help illuminate potential climate futures, the challenges they may present, and the opportunities to build resilience through adaptation pathways.

For the full suite of Fifth Assessment research products, please visit: www.ClimateAssessment.ca.gov.

Purpose of the Regional Reports

The Fifth Assessment Regional Reports bring together the latest climate science, community input, and adaptation opportunities to meet the needs of communities across nine California regions. These reports can inform regional and local vulnerability assessments, adaptation planning, and community resilience efforts. The Regional Reports include analyses of climate projections and impacts to natural systems, built systems, and social systems. They uplift case studies of adaptation solutions and highlight developments that have emerged since the Fourth Assessment was released in 2018. While climate impacts are felt across regional boundaries, the Regional Reports deepen our understanding of how climate change interacts with the unique communities, histories, waters, and landscapes across California.

Climate Modeling, Scenarios, & Time Periods

The Fifth Assessment Regional Reports consider the following climate models, greenhouse gas (GHG) emissions scenarios, and time periods:

- **CMIP6** (Coupled Model Intercomparison Project Phase 6) is the most recent version of a global collaboration that standardizes and combines the most advanced climate models to project how Earth's systems will react to our changing atmosphere. With CMIP6, we can see the most likely climate trends and the less likely, but still possible, extremes.
- **Greenhouse Gas Emissions Scenarios:** Current international climate models integrate two kinds of scenarios: Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). The SSPs model how global society might evolve over the next century, including changes in population, policy, technology, and economic growth, while tracking the amount of heat trapped in the atmosphere. The RCPs correspond to GHG emissions and capture a quantifiable range of emissions and warming—how much do we expect the world will continue to emit, and the associated warming, throughout the century? Combined, these describe how global social conditions (e.g., population, technological, and economic growth) affect emission trajectories. This shift offers a more nuanced understanding of how our collective decisions today will shape the climate of tomorrow. The Fifth Assessment research primarily focuses on two RCP/SSP combinations:
- **SSP 2–4.5** (i.e., utilizing the second SSP narrative and RCP 4.5) describes an intermediate scenario indicating improvements toward meeting mitigation commitments. This scenario shows carbon dioxide equivalent (CO2e) emissions initially hover at current levels, then start to fall by mid-century.
- **SSP 3–7.0** articulates a high emissions scenario and less optimistic pathway, assuming current emission levels continue throughout the year 2100. This scenario shows CO2e emissions doubling by 2100.
- The Fifth Assessment also references a more aggressive emissions scenario (**SSP 5–8.5**), which describes a very high and unlikely emissions pathway that shows CO2e emissions tripling by 2075. The Assessment includes this scenario as a reference tool for a worst-case emissions outcome for informational and planning purposes rather than a plausible climate change future..
- **Global Warming Levels** (GWLs) ask "What happens to California once the world reaches a certain level of warming?" The focus is on adapting to a change in the expected climate, such as a 2°C (3.6°F) increase. While these models identify a range of years when these thresholds might be reached, the emphasis is on the intensity of the impact rather than the calendar date. This is a different and complementary approach to the previously used *date-based approach*.
- **Downscaling with Localized Constructed Analogues (LOCA) and Weather Research and Forecasting (WRF):** To make global climate models (GCMs) useful for local planning, scientists use a technique called downscaling. While global models provide a *big picture* view of the planet, the Fifth Assessment uses the LOCA2 statistical and WRF dynamical downscaling techniques and a hybridized version of these techniques, LOCA2-Hybrid, to focus on California's particular climate future.
- **Time Periods:** The Fifth Assessment uses a 30-year timeframe for analyses, as shown in the table below, alongside historical projections to draw comparisons between current and future time periods.

Descriptive Term	Time Range
Historical	1981–2010
Mid-Century	2041–2070
Late-Century	2071–2100

CALIFORNIA'S FIFTH
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ASSESSMENT



Map of California

Climate Change Assessment Regions

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Use of Artificial Intelligence (AI):

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Executive Summary

San Diego is California's southernmost coastal county, extending from the Pacific Coast across inland valleys and the Cuyamaca and Laguna Mountains to the desert edge of the Imperial Valley and encompassing a striking gradient of climatic and ecological zones. The county is home to 3.3 million people, and 17 federally recognized and one non-federally recognized Tribal governments. San Diego's key sectors include defense, healthcare, biotechnology, higher education, agriculture, tourism, and cross-border trade, creating a $260 billion economy. Climate change is already affecting these sectors and is projected to intensify in the decades ahead, driven by extreme heat, prolonged droughts punctuated by intense storms, growing wildfire risk, and rising seas. This report summarizes the latest science on San Diego's changing climate and highlights the region's efforts to reduce risks and strengthen resilience.

Climate Projections: San Diego's complex topography and coastal zone require global climate models to be translated to the local scale to capture the county's strong climate gradients. Climate models project with confidence that San Diego's temperatures will continue to rise, with temperatures projected to increase by approximately 4°F (2.2°C) by mid-century (2041–2070) compared to the historical period (1981–2010). The most pronounced warming is expected in spring and fall, effectively extending the summer season and increasing the number of days with extreme heat. Interior regions are likely to warm by at least 1 ºF (0.56ºC) more than the coastal zone by mid-century.

Unlike temperature, future precipitation in San Diego remains uncertain. While many climate models project modest declines of approximately 5–20% across the region, others indicate little change or small increases. However, the models consistently indicate that rainfall will occur less frequently but with greater intensity. Atmospheric rivers (ARs), the dominant drivers of heavy precipitation in San Diego, will become more intense, raising the likelihood of floods like those during the winters of 1980 and 2017. Conversely, projected warming will raise evaporative demand, making one- to three-year extreme droughts roughly four to five times more likely, even in the absence of major changes in average annual precipitation.

Drought conditions combined with Santa Ana wind events have historically contributed to the region's biggest fall and winter wildfires. Santa Ana winds, which begin in the fall and peak in winter, are a defining feature of San Diego's climate. Projections suggest an overall decline in the number of Santa Ana wind events across Southern California, largely due to reductions in moderate and weak occurrences. At the same time, a drying landscape is increasing wildfire danger, and continued population growth in the wildland–urban interface is placing more people and homes in harm's way, even if Santa Ana wind events do not change in frequency.

Sea Level Rise and Coastal Impacts: San Diego's tide gauges record a sea level rise of 0.67 feet (0.20 m) over the past century, consistent with the global average. Looking ahead, sea level is expected to rise by 1.0–1.6 feet (0.32–0.49 m) by 2075, in line with projections for much of the California coast. Sea level rise and beach erosion threaten San Diego's beaches and shorelines and all the benefits they provide, including beach recreation, which is central to the region. The South Bay and Imperial Beach are among the most vulnerable regions. Estuaries in San Diego have limited capacity to migrate inland, constraining their ability to adapt. Enhanced monitoring

and warning systems, as well as nature-based solutions (e.g., living shorelines, dune restoration, and beach nourishment) are emerging as key strategies, but require sustained coordination and investment.

Ecosystems and Biodiversity: San Diego is a national biodiversity hotspot, but climate change threatens native species and habitats. Climate-driven stressors act as a threat-multiplier, compounding existing pressures from development, habitat fragmentation, and invasive species. Adaptation efforts include restoring habitat connectivity, multi-species conservation planning, and implementing nature-based solutions through diverse partnerships and Indigenous stewardship.

Agriculture and Food Systems: San Diego County agriculture production was $1.67 billion in 2024, and the county hosts more small farms than any other in the nation. A recent survey of farmers in San Diego County found that 50% of agricultural producers were concerned about extreme heat, while 59% cited drought as a major issue. Adaptation strategies include regenerative practices, agroforestry, soil conservation, and micro-irrigation. Urban agriculture, school gardens, food forests, and marine aquaculture also support climate resilience, food security, and equity.

Energy: While San Diego's energy use is low due to the mild climate, the region's energy system is nonetheless facing growing threats from extreme heat, wildfire, and shifting demand. Rising temperatures increase electricity use for cooling while reducing grid efficiency and stressing infrastructure. Wildfire risk due to downed powerlines has led to more public safety power shutoffs (PSPS), especially in inland and mountain areas. As the region transitions to renewable energy and electrification, utility providers and Tribes are investing in microgrids, battery storage, distributed solar, and undergrounding.

Transportation: San Diego's transportation network is increasingly disrupted by extreme heat that degrades pavement and warps rails, wildfires that close corridors and degrade air quality, and more intense storms that overwhelm drainage systems. Coastal erosion and sea level rise threaten key infrastructure. Adaptation strategies include drainage retrofits, shaded transit stops, asset elevation or relocation, and coastal rail realignment. Long-term resilience depends on coordinated planning among federal, state, regional and Tribal partners.

Water Resources: The San Diego region faces growing challenges in managing its water supply, delivery infrastructure, and water quality in the context of climate variability and regional growth. Stormwater and wastewater infrastructure remain particularly vulnerable to extreme flooding events. San Diego's water supply has changed over the past several decades, with per capita use decreasing and reliance on local sources increasing. Adaptation measures include water conservation and projects that deliver co-benefits, like green stormwater infrastructure.

Public Health: Climate change threatens public health through extreme heat, wildfire smoke, flooding, and the spread of vector- and waterborne diseases. Older adults, children, outdoor workers, unhoused individuals, and people with pre-existing conditions face greater health risks from climate hazards. The county's public health agency and Tribal governments are strengthening heat response, disease surveillance, and air quality monitoring and alert systems, often in partnership with community-based organizations who provide bottom-up leadership and place-based expertise.

Governance: San Diego's climate governance is remarkably cohesive with a unified council of governments (SANDAG), enabling rare alignment across jurisdictions. The San Diego Regional Climate Collaborative fosters cross-sector knowledge sharing and capacity-building. Still, coordination remains uneven. More integrated regional data systems, shared indicators, and clearer cross-agency project tracking could unlock greater impact and reduce duplication. Promising efforts, such as multi-jurisdictional hazard mitigation planning and climate equity networks highlight the value of early engagement, Tribal leadership, and sustained community partnership.

Economy: Climate change is already imposing economic costs across San Diego County, from heat-related productivity losses and rising insurance premiums to wildfire damages and coastal asset risks. Key sectors such as agriculture, tourism, and cross-border trade are exposed to acute shocks from extreme weather events and to longer-term pressures from climate change. Yet climate adaptation presents a generational opportunity to modernize infrastructure, protect communities, and grow the economy. Building regional prosperity will require integrating climate risk into planning and investment decisions and directing adaptation efforts to benefit all communities.

Cross-Border Considerations: San Diego's future is inextricably linked with Baja California. The region shares watersheds, an airshed, a coastline, and interconnected ecosystems. The Kumeyaay Nation spans the international border. Shared challenges such as wastewater pollution, aging infrastructure, wildfire smoke, and vector-borne disease demand binational coordination. Building resilience across the plurinational Cali–Baja region will require integrated monitoring, cross-border investment, and deep collaboration among governments, scientists, and communities on both sides of the border.

San Diego's adaptation progress is significant, but climate risks are accelerating and unevenly distributed. From the growing recognition of Indigenous knowledge systems to the use of artificial intelligence in climate science, the region is drawing on a wide range of approaches to better understand and respond to climate risks. With continued investment and collaboration, San Diego has all the elements needed to enhance climate adaptation, allowing the region to thrive under changing climate conditions.

Table of Contents

Executive Summary 10

Table of Contents 13

Chapter 1. Introduction 15

Chapter 2. Climate Science: Historical & Projected Trends 20

Key Messages 21

2.1 San Diego Climate 21

2.2 Downscaling Global Climate Models to the San Diego Region 22

2.3 Temperature and Heat Waves 23

2.4 Wildfire Risk and Santa Ana Winds 28

2.5 Precipitation and Flood Risk 30

2.6 Drought 35

2.7 Sheltering Marine Layer Clouds 36

2.8 Compound Extremes 38

Chapter 3. Natural and Working Lands & Waters 40

3.1 San Diego Coasts 41

Key Messages 41

3.1.1 Sea Level Rise and Extreme Sea Level 41

3.1.2 Current and Projected Impacts on San Diego from Sea Level Rise 47

3.1.3 Beaches, Dunes, and Cliffs 49

3.1.4 Coastal Estuaries 51

3.1.5 San Diego Marine Ecosystems 53

3.2 San Diego's Terrestrial Ecosystems 54

Key Messages 54

3.2.1 Introduction 55

3.2.2 Ecological Impacts Across Ecosystems 56

3.2.3 Collaborative Climate Adaptive Strategies for San Diego's Ecosystems 61

3.3 Agriculture and Food Systems 63

Key Messages 63

3.3.1 Introduction 63

3.3.2 Impacts of Climate Change on Agriculture and Food Systems 64

3.3.3 Adaptation in Agricultural Systems 65

3.3.4 Indigenous Food Systems in San Diego County 66

3.3.5 Urban Food Systems 67

3.3.6 Aquatic Food Systems 68

Chapter 4. Built Systems 70

4.1 Energy 71

Key Messages 71

4.1.1 Introduction 71

4.1.2 Climate Vulnerabilities 73

4.1.3 Climate Adaptation for the Energy Sector 74

4.1.4 Energy Policy Impact on the Future Energy System ..... ?

4.1.5 Climate Adaptations ..... ?

4.2 Water 77

Key Messages 77

4.2.1 Introduction 78

4.2.2 Water Supply and Infrastructure 78

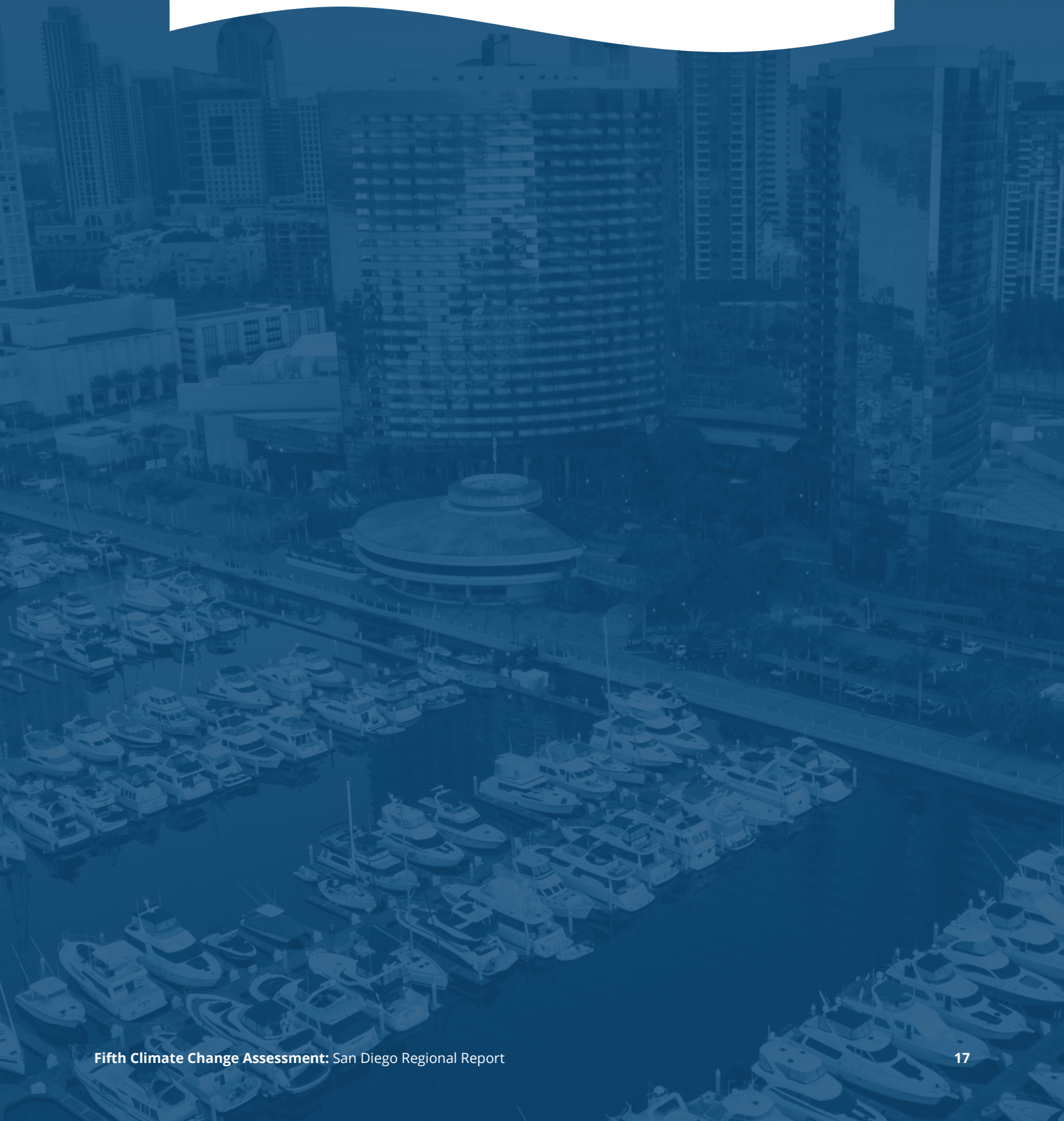


4.2.3 Groundwater-Dependent Communities 79
4.2.4 Stormwater and Wastewater Infrastructure 80
4.2.5 Water Quality 81
4.2.6 Water Affordability and Equity 81
4.2.7 Climate Adaptation Strategies 82
4.3 Transportation 83
Key Messages 83
4.3.1 Introduction 84
4.3.2 Current and Future San Diego Transportation 84
4.3.3 Historic and Projected Transportation Climate Vulnerabilities 85
4.3.4 Transportation Climate Resilience and Adaptation 87
Chapter 5. Social Systems 89
5.1 Public Health 90
Key Messages 90
5.1.1 Climate Change and Public Health in San Diego County 90
5.1.2 Extreme Heat and Public Health Risks 91
5.1.3 Air Pollution and Wildfire Events 92
5.1.4 Waterborne Diseases 93
5.1.5 Infectious and Vector-Borne Diseases 93
5.1.6 Climate Adaptation for Healthier Communities 93
5.2 Governance 95
Key Messages 95
5.2.1 Regional Roles and Partnerships in Climate Resilience 95
5.2.2 Adaptation Planning: Guidance, Capacity, and Collaboration 98
5.2.3 Tribal Priorities and Intergovernmental Collaborations 99
5.3 Economy & Climate 100
Key Messages 100
5.3.1 Climate Change and the San Diego Economy 100
5.3.2 Economic Disruption from Climate Change 101
5.3.3 Economic Drivers and Adaptation 103
5.4 San Diego and Baja California Cross-Border Resilience 104
Key Messages 104
5.4.1 Introduction 105
5.4.2 Climate Vulnerabilities and Adaptation 106
5.4.3 Addressing Financial Barriers 108
5.4.4 Climate Adaptation Focused Collaboration 109
Chapter 6. Conclusion: Looking Forward 110
Summary of Findings 111
6.1 Climate Science, Historical and Projected Trends 111
6.2 Natural Systems 111
6.3 Built Systems 112
6.4 Social Systems 112
6.5 Gaps and Opportunities 113
References 117
Acronyms 145



Chapter 1.

Introduction



San Diego is California's southernmost coastal county and one of nine regions highlighted in California's Fifth Climate Change Assessment (**Figure 1.1**). Located near the equatorward edge of the midlatitudes and on the eastern flank of the North Pacific High, a semi-permanent high-pressure system that shapes seasonal weather patterns, San Diego experiences a Mediterranean climate, with warm, mostly dry and sunny summers and mild, occasionally rainy winters. But this climate is far from uniform or predictable. The region has some of the highest year-to-year variability in precipitation in the United States, and dramatic contrasts unfold over short distances, from the cool, marine-influenced coast across inland mountains to the arid expanse of the Anza-Borrego Desert. Recent climate and weather extremes (including prolonged drought, record-setting heat, wildfires, and powerful winter storms known as atmospheric rivers) continue to shape present conditions and offer signals of how the region's climate may evolve in the coming decades.

These climatic ingredients, driven largely by topography and distance from the Pacific Ocean, create distinct climate zones and contribute to San Diego County being one of the most biodiverse counties in the nation (Stein et al., 2020). The Tribal Nations of the San Diego region—the Cahuilla, Kumeyaay (Diegueño), Kuupangaxwichem (Cupeño), and Payómkawichum (Luiseño)—have supported and maintained the region's biodiversity through generations of stewardship rooted in ancestral and Traditional Ecological Knowledges (TEK) (Harrison et al., 2024). Their longstanding experience spans climatic conditions well beyond the instrumental record and reflects exposure to a wider range of droughts, wet periods, and environmental variability than has been directly measured. Their stewardship shaped the ecological foundations of the region long before the establishment of San Diego County and continues today as an important contribution to climate resilience in the region.

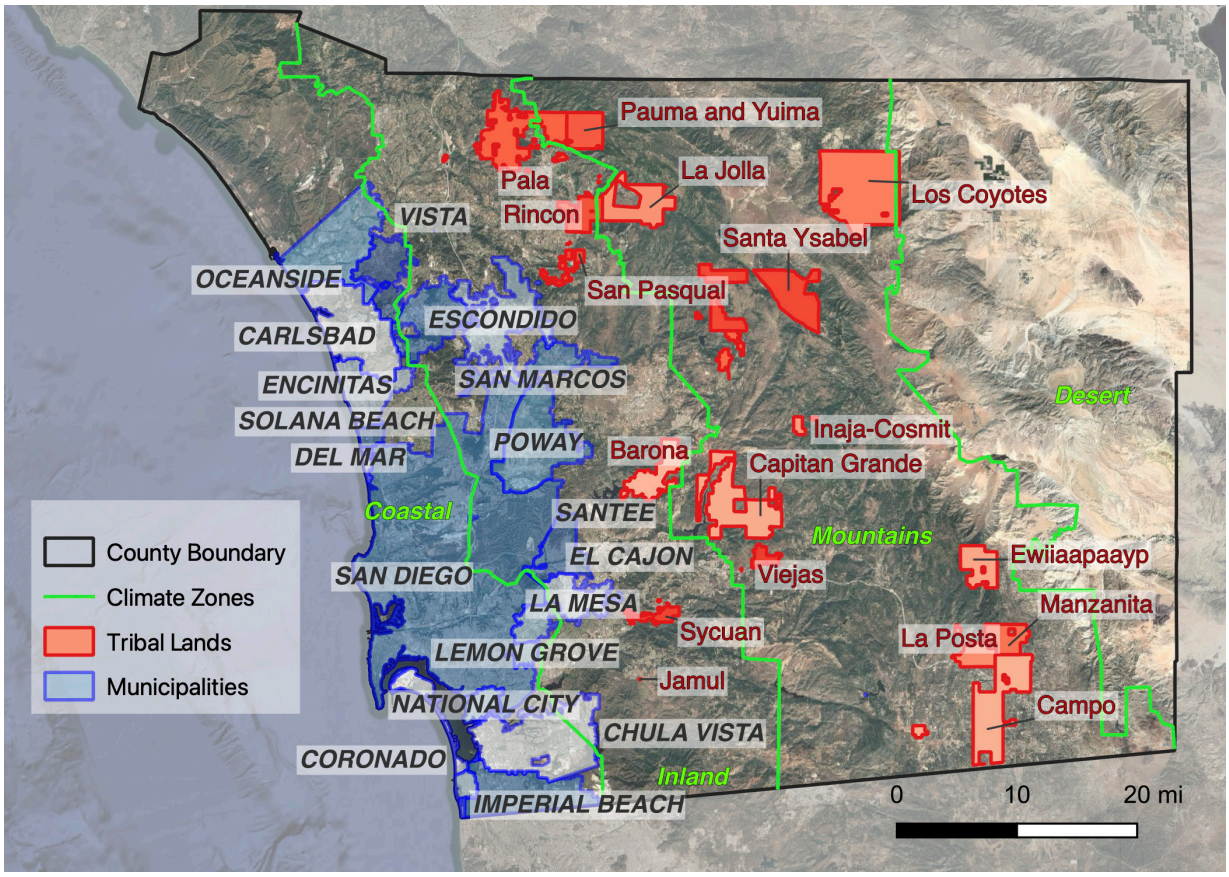


Figure 1.1: *Relief map of San Diego County showing the geographic boundaries used in this report. The black line outlines the county. Red boundaries indicate federally recognized Tribal Lands, blue boundaries indicate municipalities, and green lines separate the four climate regions used in this report: coastal, inland, mountains, and desert. Provided by Tom Corringham, Scripps Institution of Oceanography, UC San Diego.*

Today, San Diego County spans 4,530 square miles (nearly 3 million acres or 12,000 square km), with about half of its land (1.3 million acres; 5,300 square km) under some form of environmental protection (Kalansky et al., 2018). In addition to the 17 federally recognized and one non-federally recognized Tribal governments, the region includes 18 incorporated cities and the unincorporated county coordinated in regional planning by the area's metropolitan planning organization or Council of Governments, the San Diego Association of Governments (SANDAG). Nearly 3.3 million residents live in the county, with most concentrated in the western coastal region. San Diego is the second most populous county in California, after Los Angeles County (State of California Department of Finance, 2025), and about one-third of its residents identify as Hispanic or Latino (United States Census Bureau, 2020).

San Diegans show a high level of concern about climate change. A 2022 poll found that more than 70% of residents were either alarmed, concerned, or cautious about climate change (Deitrick, et al., 2022). This widespread concern reflects the region's experience of unusually warm years over the past two decades, consistent with record-breaking global temperatures during the same

period. Several of these warm years have also been extremely dry (**Figure 1.2**). As detailed in this report, this warming and drying trend is expected to continue, punctuated by occasional but increasingly intense wet extremes.

Climate models project that climate change impacts will vary across San Diego's diverse climate zones. Coastal communities face increasing coastal flooding from sea level rise, while inland communities are disproportionately exposed to rising heat and wildfire risk, particularly during Santa Ana wind events. Low-lying areas and riparian corridors are most vulnerable to flooding from atmospheric river storms. Socially vulnerable populations often experience the most severe impacts from these extremes (Benevolenza & DeRigne, 2019). Within the county, such populations are concentrated near San Diego Bay, in parts of Imperial Beach, Chula Vista, and National City, as well as inland in El Cajon and Escondido. Rural communities in the eastern part of the county also face elevated risks compared with more urbanized western cities (Centers for Disease Control, 2022).

San Diego's economy has a significant stake in both climate adaptation (preparing for and responding to climate impacts) and mitigation (reducing greenhouse gas emissions to limit future change). The county's Gross Domestic Product (GDP) reached $261.7 billion in 2024, making it the fourth-largest economy by county in California (US Bureau of Economic Analysis, 2024). Much of this economic and population growth has occurred since 1940, spurred by World War II military expansion, followed by a postwar boom in the 1950s and 1960s, driven by aerospace and San Diego's appealing climate. Since the 1970s, the economy has diversified into services, research and development, manufacturing, agriculture, and tourism. While agriculture accounts for a small share of regional GDP, San Diego has more small farms than any county in the United States. The region also maintains strong social and economic ties with Mexico as part of the Cali–Baja region, which includes the busiest land-border crossing in the US.

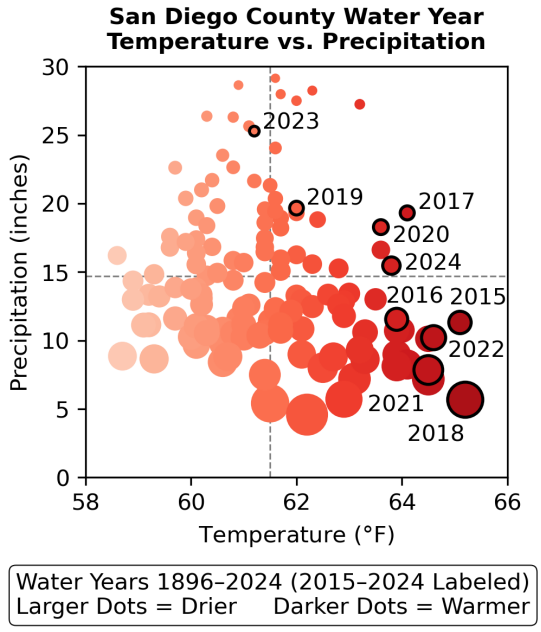


Figure 1.2: *San Diego County water-year precipitation totals and annual average temperatures 1896–2024. Dashed lines show average over the period of record. Larger dots indicate drier years, darker dots indicate warmer years. The most recent decade (2015–2024, labeled), includes five of the hottest and driest years on record. Data: Western Regional Climate Center. Provided by Peter Yao, Scripps Institution of Oceanography, UC San Diego.*

California leads the nation in developing legally enforceable strategies, regulations, and funding programs to identify climate vulnerabilities and address climate change impacts at state, regional, and local levels. San Diego has emerged as a leader in climate adaptation, given its diverse landscapes and history of resilience planning. Nearly all jurisdictions in the county have integrated climate adaptation into their general plans or developed standalone adaptation strategies. Many coastal cities have also created Local

Coastal Programs that include climate adaptation measures. Strong research institutions and a culture of innovation have ensured that science and information continue to guide resilience planning. This report supports ongoing planning by describing San Diego's historical and projected climate, examining sectoral impacts and vulnerabilities, and highlighting selected efforts to build resilience. It concludes with a summary of emerging needs and opportunities to strengthen adaptation in the decades ahead.

Chapter 2.

Climate Science: Historical & Projected Trends



Key Messages

- *San Diego's future weather and climate will continue to be shaped by midlatitude and subtropical climate systems and their interactions. The region's Mediterranean climate, along with shorter term events that include atmospheric rivers (ARs), Santa Ana winds, heat waves, and marine layer cloud cover remain as defining features.*
- *Average annual daily minimum and maximum temperatures are projected to rise about 4ºF (2.2°C) by mid-century (2041–2070) relative to the 1981–2010 historical period. Heat waves are projected to become hotter, more frequent and longer-lasting.*
- *Strong local variation is projected to continue, including precipitation contrasts across the county and a warming gradient in which interior regions are likely to warm by at least 1ºF (0.6°C) more than the coastal zone by mid-century.*
- *Major wildfire risk will likely remain linked to autumn and early winter Santa Ana wind events, though Santa Ana wind event frequency is projected to decrease. Risk typically declines after the first significant cool-season precipitation event, whose timing is variable and projected to remain so.*
- *Annual precipitation totals are projected to change only incrementally. Wet days are projected to become less frequent generally but more intense during occasional heavy storm events. This shift is driven by increased AR precipitation in winter and decreased non-AR precipitation, particularly in the fall and spring.*
- *Droughts will continue to occur irregularly, similar to those in historical dry spells. However, the precipitation deficit that drives future drought will be exacerbated by warming, which causes increased evaporative demand to the point that the frequency of 12- and 36-month drought may see a fivefold increase throughout much of San Diego County.*
- *Marine layer clouds will continue to affect San Diego's climate between May–September with strong variation year-to-year. No* long-term trends are observed to date.

2.1 San Diego Climate

The San Diego region's dry, warm summers and wet, temperate winters are characteristic of a Mediterranean climate. San Diego's climate zones lie on the flank of a large oceanic high pressure center that resides between the subtropics and midlatitudes; the North Pacific High varies in strength and location as the seasons change and weather patterns fluctuate. In summer, high-pressure systems associated with subtropical atmospheric dynamics suppress precipitation and produce warm, dry weather. In winter, the North Pacific High may recede, so that midlatitude storms can deliver rain and, on rare occasions, mountain snow. San Diego's Mediterranean climate is distinguished by the interplay of several iconic weather systems, including marine layer clouds, atmospheric rivers, and Santa Ana winds, and is punctuated by extreme events such as heat waves, droughts, floods, fire weather conditions, and coastal sea level anomalies. The sequence of high impact climate and weather in the San Diego region's historical record, along with projections of extreme events in future decades, provides a foundation for identifying vulnerabilities and developing adaptation strategies.

2.2 Downscaling Global Climate Models to the San Diego Region

The Earth's climate is changing as heat-trapping greenhouse gases (GHGs) accumulate in the atmosphere. Increasing concentrations of GHGs are causing increases in temperature, shifts in the timing and amount of precipitation, and rising sea levels, among other changes (IPCC, 2023). Some of the best tools available for estimating future climatic changes are global climate models (GCMs), which represent the relevant physical, biological and chemical processes. GCMs can model different future scenarios by modifying inputs such as levels of GHGs, land use changes, and the release of aerosols from air pollutants. Under the most recent generation of GCMs, these scenarios are termed Shared Socioeconomic Pathways (SSPs). Future conditions represented by SSPs range from relatively modest changes, where stringent policies limit GHG emissions and future warming, to high-change scenarios where unconstrained fossil fuel-use deposits high levels of GHGs in the atmosphere, resulting in large temperature increases. We focus on SSP3–7.0 (Hausfather, 2018; Rogelj et al., 2018), a medium-high GHG emission and societal scenario that is in line with current projected emissions. The SSP framework combines a socioeconomic storyline or pathway (denoted by the first number) with a radiative forcing level in 2100 (denoted by the second number, in watts per square meter). Radiative forcing is the change in how much energy is entering versus leaving the atmosphere due to GHGs relative to pre-industrial levels (prior to 1850). SSP3–7.0 represents a world characterized by regional rivalry, limited international cooperation, and relatively high population growth (SSP3), experiencing a radiative forcing of approximately 7.0 W/m^2 over pre-industrial levels by 2100.

Climate projections typically run through the end of the 21st century, but in this report, we emphasize mid-21st century (2041–2070) changes relative to the recent historical period, 1981–2010. Although not used here, some practitioners merge different SSPs and time periods by analyzing "warming levels," which combine results from all SSPs and periods that have achieved the desired warming target, such as 2°C (3.6°F) relative to historical averages. We use climate change projections produced by 15 GCM results found suitable for California (Krantz et al., 2021) from institutions around the world, collected in the Coupled Model Intercomparison Project version 6 (CMIP6) archive. However, while these GCM simulations provide important descriptions of broad scale changes, they are not directly usable in San Diego applications because the 50-mile or greater spatial resolution that is typical of the GCMs is too coarse to resolve key aspects of the region's environment. Accordingly, the GCM projections were downscaled to a higher resolution (3 km; 1.9 miles), allowing important features of San Diego's varied topography to be better represented. For California's Fifth Climate Change Assessment (Fifth Assessment), 15 GCMs were included in order to factor in the considerable range of differences across model projections. The results from these GCMs have been downscaled with the hybrid statistical-dynamical methodology called Localized Constructed Analogs version 2 Hybrid (LOCA2-Hybrid) (Pierce et al., 2023, 2025).

Most results shown here are aggregated across the 15 selected GCMs, either as an average or a range of modeled projections, since multi-model results may provide better estimates of future climate than any individual GCM. Individual models differ from the model averages and other aggregates due to differences in the methods they use to represent climate processes, along with the inherent natural climate variability from phenomena such as the El Niño-Southern Oscillation, which is not synchronized across model runs. Owing to this model variability, weather and short period climate fluctuations simulated by each of the models will differ from past and

future observed weather and climate. However, the overall statistical tendencies of the model projections, which represent both natural and human-caused climatic effects, are nonetheless useful in understanding possible impacts and for planning purposes.

2.3 Temperature and Heat Waves

Annual mean temperature in San Diego County increased more than 2.5ºF (1.4°C) from 1950–2024, based on estimates from station observations and gridded climate datasets (**Figure 2.1**). The record shows that most years before the late 1970s were cooler than the 1981–2010 average, and that temperatures rose steadily beginning in the late 20th century, with frequent positive anomalies after 1990 and the strongest warm anomalies occurring since about 2010. Daily minimum temperature (Tmin; usually occurring just after dawn) increased at a faster rate than daily maximum (Tmax; usually early to late afternoon) over the same period. Temperatures increased in all regions since 1950 (**Figure 2.3; Table 2.1**). The downscaled climate models suggest that future annual mean daily minimum and maximum temperatures will increase much faster than has been observed, to about 4ºF (2.2°C) above 1981–2010 levels by mid-century and to between 5–9ºF (2.8–5.0°C) above 1981–2010 levels by the end-of-century depending on the scenario (**Figure 2.2**). Somewhat lesser warming is expected along the coast than that in other San Diego regions, where rates are higher and quite similar across regions. Interestingly, the model projections suggest that daily maximum temperatures (Tmax) will warm more than daily minimum temperatures (Tmin) in all regions except the coast (**Figure 2.3, Table 2.1**).

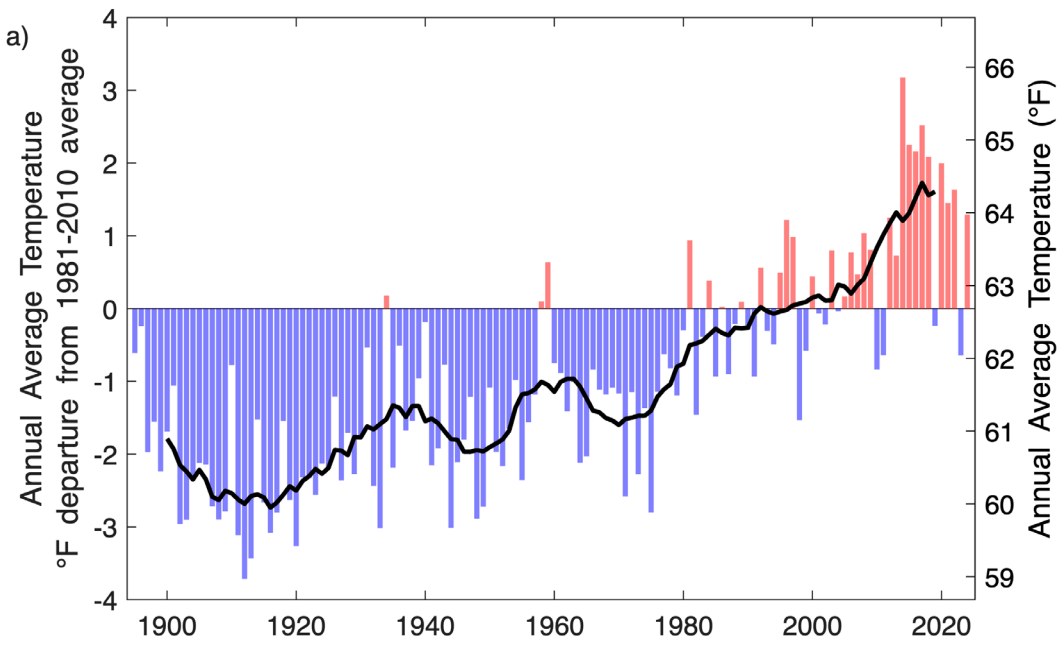


Figure 2.1: *Observed average annual temperature for San Diego County, shown as departures (°F) from the 1981–2010 average. Blue bars indicate cooler-than-average years; red bars indicate warmer-than-average years. The black line is the 11-year moving average. Data: NOAA nClimGrid. Provided by John Abatzoglou, UC Merced.*

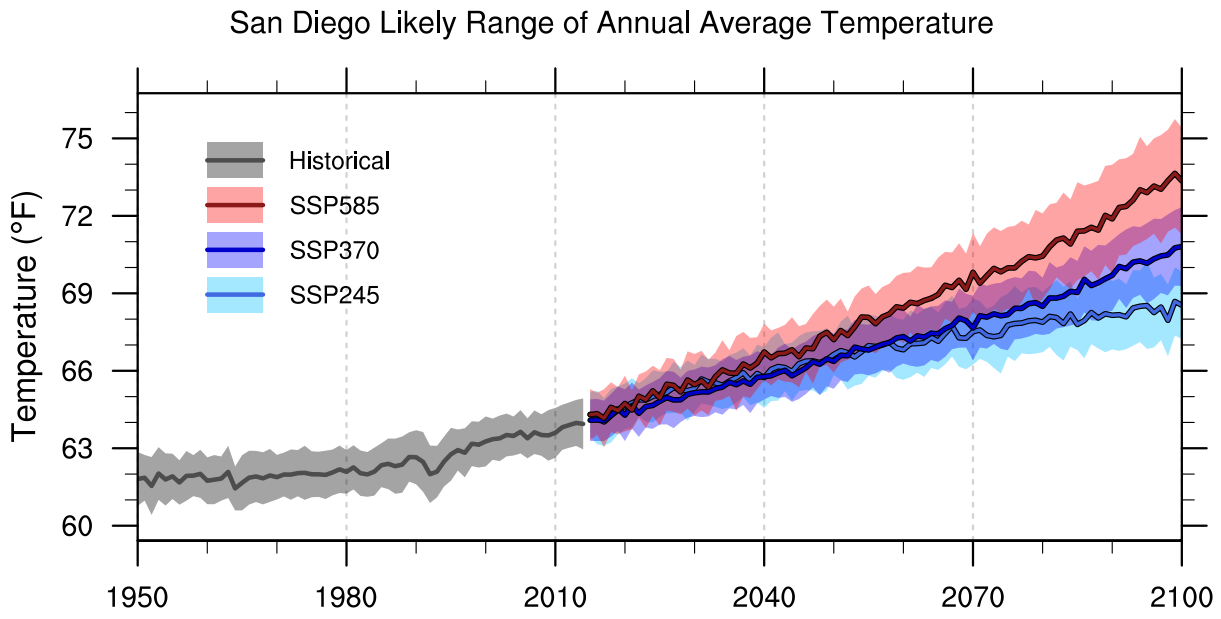


Figure 2.2: *Projected annual average temperature for San Diego County under three future scenarios: SSP2–4.5 (cyan), SSP3–7.0 (blue), and SSP5–8.5 (red), with shading showing ± one standard deviation across models. Historical period (1950–2014) in gray. Projections diverge around mid-century. Based on multiple CMIP6 models downscaled using LOCA2. Provided by Paul Ullrich, UC Davis.*

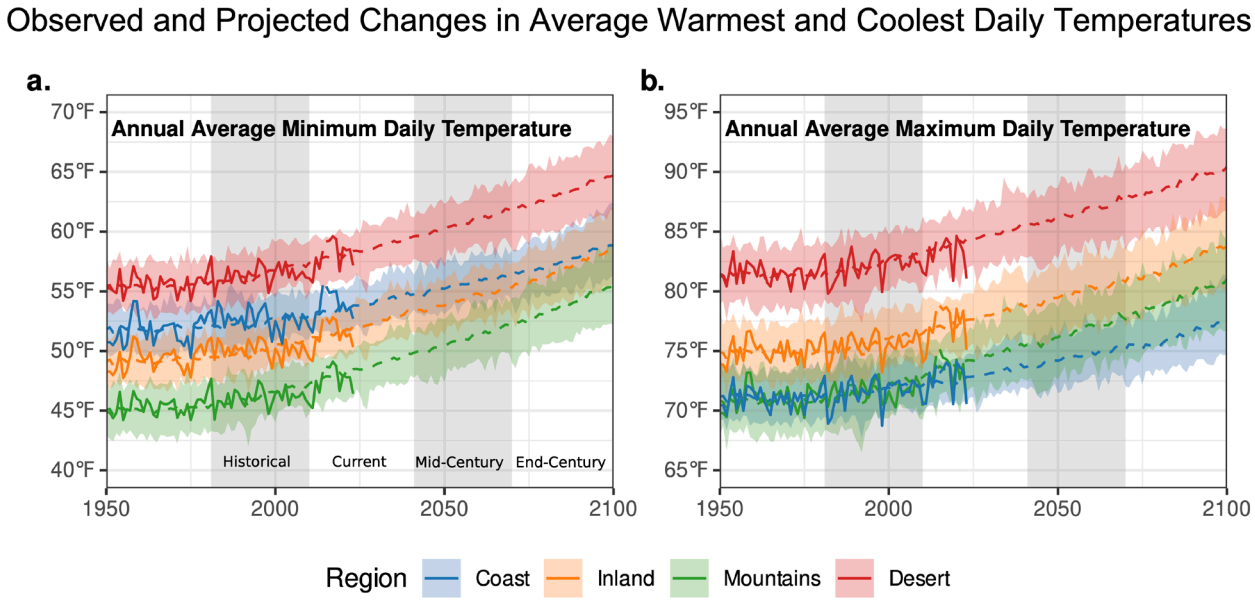


Figure 2.3: *Annual average daily minimum (a) and maximum (b) temperatures for four San Diego County regions (Coast, Inland, Mountains, Desert). Solid lines show observations; dashed lines show projections (mean of 15 downscaled models, SSP3–7.0) with shaded model range. Gray background shading marks the historical (1981–2010) and mid-century (2041–2070) periods. Regional divisions follow California Energy Commission (CEC) climate zones. Provided by Alexander Weyant, Scripps Institution of Oceanography, UC San Diego.*

Table 2.1: *Projected warming (°F) of daily maximum and daily minimum temperatures by region relative to the historical period (1981–2010). Values show the mean of 15 equally weighted downscaled models (SSP3–7.0); parentheses show the full model range. Provided by Alexander Weyant, SIO, UC San Diego.*

Region	Metric	Mid-Century (2041–2070) Projected Warming Relative to Historical (°F)	Near-Term (2011–2040) Projected Warming Relative to Historical (°F)	Additional Warming from Current to Mid-Century (°F)
Coast	Tmax	2.9 (1.7 to 4.0)	1.2 (0.2 to 2.2)	1.6 (0.8 to 2.3)
Coast	Tmin	3.2 (2.1 to 4.7)	1.3 (0.2 to 2.5)	1.7 (0.7 to 2.4)
Inland	Tmax	4.3 (2.4 to 5.7)	2.0 (0.7 to 3.2)	2.2 (1.2 to 3.0)
Inland	Tmin	4.2 (3.0 to 5.5)	1.9 (0.6 to 3.1)	2.2 (1.1 to 2.9)
Mountains	Tmax	4.9 (2.6 to 6.5)	2.4 (1.0 to 4.2)	2.4 (1.3 to 3.3)
Mountains	Tmin	4.8 (3.3 to 6.2)	2.2 (0.9 to 3.4)	2.4 (1.4 to 3.2)
Desert	Tmax	4.4 (2.3 to 6.1)	2.1 (1.0 to 3.8)	2.1 (0.9 to 3.0)
Desert	Tmin	4.3 (2.9 to 5.7)	1.9 (0.8 to 3.1)	2.3 (1.3 to 3.0)

Among the many consequences of a changing climate, heat waves carry some of the most severe impacts. The physics of heat waves and their effects on people, ecosystems, and infrastructure vary across San Diego due to its diverse landscapes and communities (**Figure 2.4**). Along the coast, marine cloud cover moderates temperatures, leading to smaller day-to-night and summer-to-winter variations compared with inland areas (**Figure 2.5**). San Diego experiences impactful heat waves throughout the year; while the highest absolute temperatures typically occur in summer or fall, winter heat waves can also have significant health consequences (McElroy et al., 2020). In fall, winter, and spring, coastal heat waves are often associated with hot, dry Santa Ana winds which are becoming more frequent from January–March (Gershunov et al., 2021). In summer, heat waves may either be dry or humid, with humid heat waves typically resulting in limited nighttime cooling. Notable examples include the widely studied July 2006 heat wave, which has been linked to hundreds of deaths in California (Gershunov et al., 2009; Knowlton et al., 2009; Ostro et al., 2009); the deadly event of August 31–September 9, 2022; and several excessive heat events in 2024 where temperatures reached up to 118°F (48°C) in the San Diego deserts. A common driver of San Diego's heat waves is an atmospheric high-pressure ridge that settles over the region, causing heat to build near the surface. Recent research suggests that these ridge patterns are increasing in frequency, which, if trends continue, will add to global climate warming by making heat waves in the County and throughout California more likely in the future (Guirguis et al., 2023).

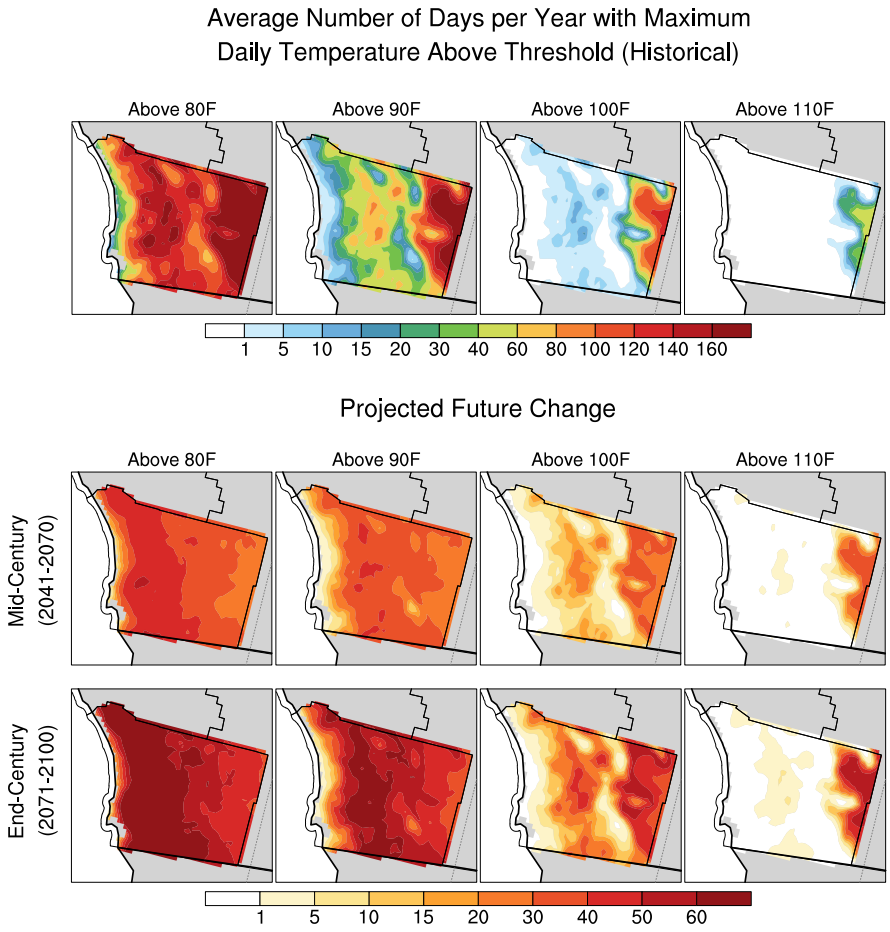


Figure 2.4: *Average (above) and projected change (below) in the average number of days per year exceeding 80°F, 90°F, 100°F, and 110°F, relative to 1980–2010, for mid-century (2041–2070) and end-of-century (2071–2100) periods. Based on climate model simulations under the SSP3–7.0 scenario. Provided by Paul Ullrich, UC Davis.*

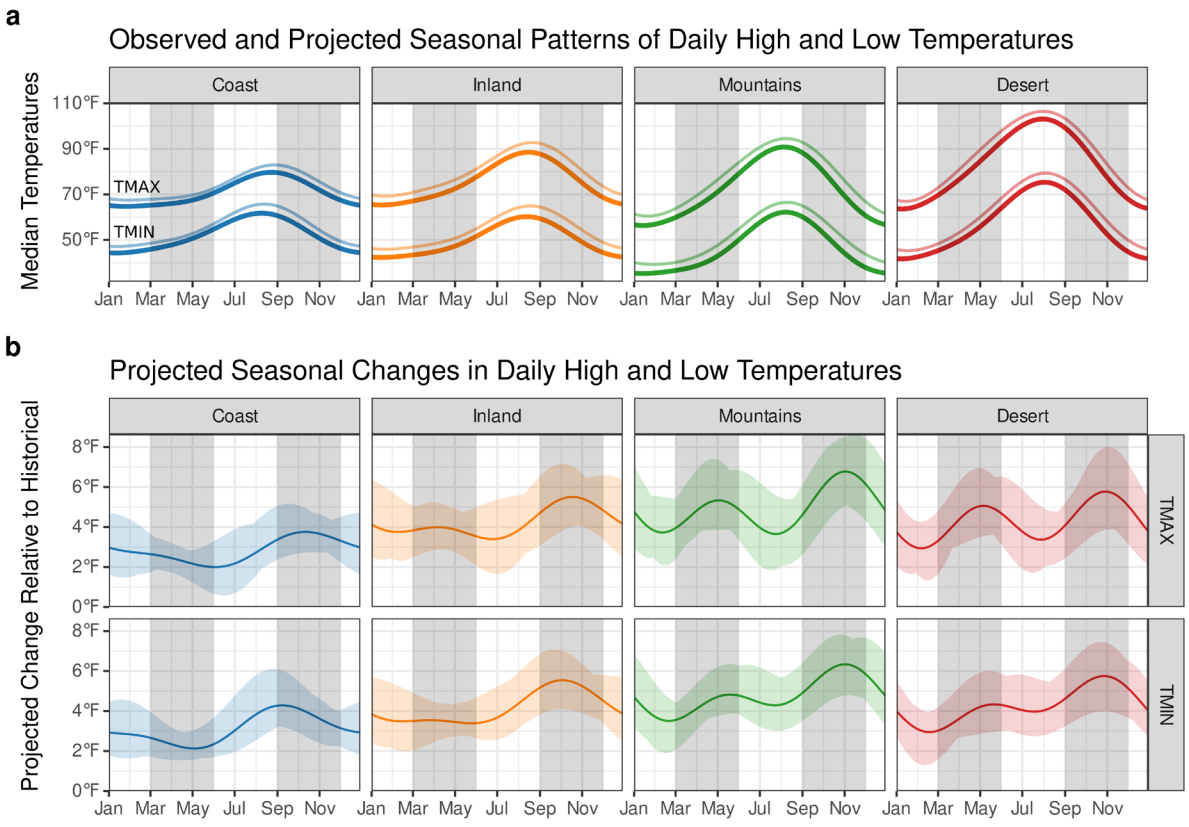


Figure 2.5: *(a) Historical (1981–2010, bold) and projected mid-century (2041–2070, faint) seasonal cycles of daily maximum and minimum temperatures for four county regions (multimodel median). (b) Projected change (mid-century minus historical); solid lines show multimodel averages; shading shows full model range. Based on 15 downscaled models, SSP3–7.0. Provided by Alexander Weyant, Scripps Institution of Oceanography, UC San Diego.*

Beyond annual average temperatures, more detailed seasonal information is especially important for health and infrastructure planning. For instance, a trend in winter daytime temperatures has very different practical implications than rising nighttime temperatures in summer. Temperature climatologies highlight the differences among regions: the coast shows a smaller seasonal range and narrower spread between Tmax and Tmin, the mountains exhibit a wider annual range, and the desert experiences the highest overall temperatures (**Figure 2.5**). Future projections indicate that warming generally intensifies farther inland. The coast and inland climate zones share a similar seasonal pattern, with the strongest warming projected from late summer into autumn. In the mountains and desert, both spring and autumn warm considerably, effectively extending the summer season in both directions. Along the coast and inland, the season for warm nights greatly lengthens (**Figure 2.5**). By mid-century, the median nighttime temperature is expected to remain above the historical August peak median from early July–mid-September. Thus, by mid-century, July 1 and September 15 will resemble the historical early-August peak, with the intervening two and a half months generally warmer than any season experienced in the past. These rising temperatures heighten the occurrence of heat waves. One definition of heat waves is a stretch of days that exceed the historical 98th percentile temperature. Such days are projected to occur far more

frequently by mid-century (2041–2070), extending heat wave durations. For example, in the inland and desert regions, the longest heat wave duration is expected to increase by 4–6 days by mid-century.

2.4 Wildfire Risk and Santa Ana Winds

Santa Ana winds (SAWs) are a distinctive feature of San Diego's weather, beginning in the fall, peaking in early winter, and declining into the spring (Guzman-Morales et al., 2016). They are strong, dry offshore winds that typically blow from the northeast toward the southwest, in contrast to the more common onshore wind patterns in coastal Southern California that originate from the west, southwest, or northwest. Originating in the elevated Great Basin as cold, dry air masses, the southwestward flow of SAWs is driven by a large-scale atmospheric pressure gradient (Abel & Hall, 2010) and can present in San Diego as either cool or warm events. Cool events are associated with transient midlatitude cyclones and are often preceded by rain and mountain snow. Climatologically, cool SAW events start out as very cold air masses settling into the Great Basin after the passage of the cold front. They tend to produce the strongest winds, while hot SAW events start out warmer and tend to blow longer (Gershunov et al., 2021). During all Santa Ana events, winds descend from the elevated high desert toward the coast, warming adiabatically (i.e., by compression) and accelerating down the lee (southwest-facing) slopes of the coastal topography, further lowering humidity and creating the hot, dry conditions most closely associated with Santa Ana winds. Importantly, warm SAW events are most typically linked to the spread of large wildfires.

Fire risk is particularly high during strong wind events in the dry period before the first significant autumn or early winter rainfall (Cayan et al., 2022; Syphard, Keeley, et al., 2022). San Diegans experienced this combination of drought and extreme winds during December 2024–January 2025, which brought several public safety power shutoffs (PSPS) and the Border 2 Fire. An analysis of large fires in Southern California from 1948–2018 showed that burned area declined substantially after the first significant rainfall of the cool season exceeding one-third of an inch (8.5 mm). Moreover, large wildfires after this seasonal onset were rare unless Santa Ana winds were present (Cayan et al., 2022). In San Diego County, all major winter wildfires and more than 80% of November wildfires have been associated with Santa Ana wind events (**Figure 2.6**), underscoring their central role in driving wildfire activity. These extreme Santa Ana events have trended toward greater intensity (Guzman-Morales et al., 2016) and atmospheric circulation regimes that promote hot Santa Ana winds in winter are becoming more frequent (Guirguis, et al., 2023). Nonetheless, Santa Ana winds are expected to decline in frequency, not in intensity, in the fall and spring due to the warming of the Great Basin, resulting in a smaller temperature difference between the Great basin and the coasts (Guzman-Morales & Gershunov, 2019).

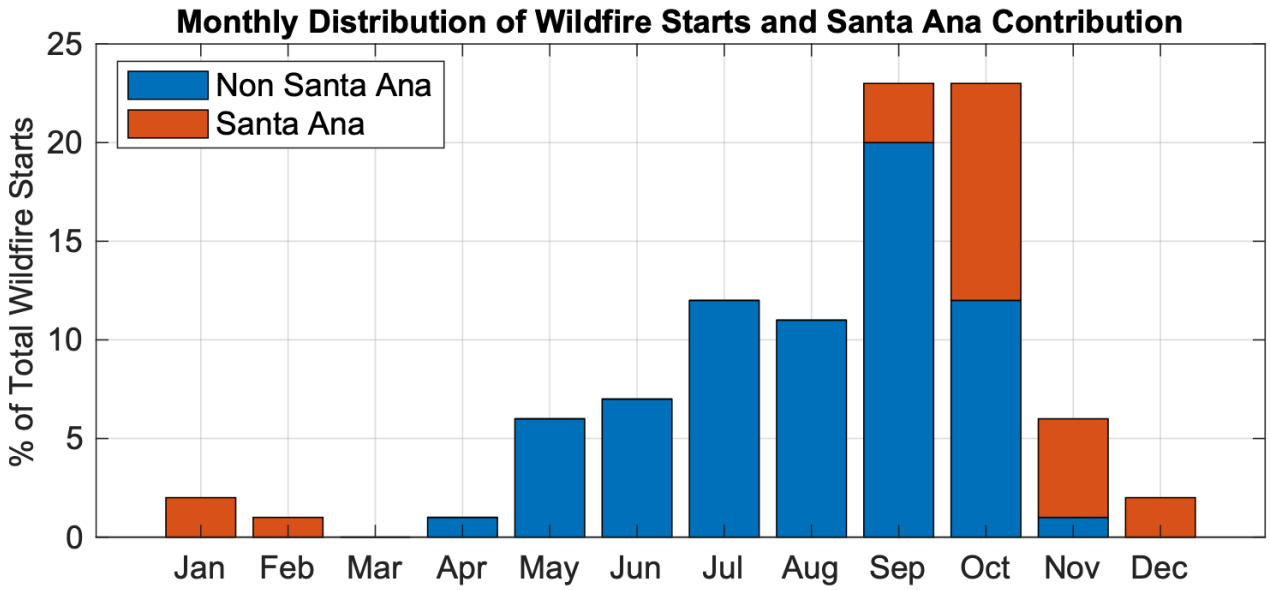


Figure 2.6: *Percentage of large wildfire starts (>1,500 acres) by month in San Diego County, 1950–2017 (n=95), with the portion starting during Santa Ana wind (SAW) conditions highlighted. Large fires peak in late summer and fall, while SAW-associated fires concentrate in late fall and winter. Although fewer fires started during SAW events, they account for the most destructive fires and greatest area burned. Data: CAL FIRE FRAP. Provided by Kristen Guirguis, Scripps Institution of Oceanography, UC San Diego.*

To investigate future conditions associated with high fire risk, the occurrence of Santa Ana wind (SAW) events and the onset of significant autumn precipitation in the San Diego region were analyzed using a 38-member ensemble of LOCA2 statistically downscaled CMIP6 SSP3–7.0 models (Pierce et al., 2023). Consistent with prior studies, the CMIP6-derived projections show a steady decline in the number of SAW events over the 21st century. This decrease is largely due to reductions in moderate and weak SAW events, while the rare, strong SAW events exhibit little change. Ground-moistening precipitation that minimizes wildfire risk, defined as a 1/3 inch (8.5 mm) in area-averaged precipitation accumulated over a 3-day period (Cayan et al., 2022), shows little projected change. As in the historical record, the CMIP6 precipitation onset occurs, on average, near the beginning of November, with only a slight shift to later in the season (delayed by about four days in 2100 relative to the 1950s). However, as observed historically, onset timing varies substantially from year to year, often by several weeks. Notably, when SAW events are tallied, most of the SAW decline occurs after the precipitation onset. In contrast, SAW events during the critically dry period before the precipitation onset show very little projected change, underscoring the continued need for vigilance to prevent and prepare for dangerous wildfires as this risk continues.

While weather conditions create high fire risk, human actions strongly influence ignition, spread, and recovery. In San Diego County, most wildfires are caused by human ignitions such as powerlines, equipment use, and arson (J. E. Keeley & Syphard, 2018; Syphard et al., 2007). Structure density is also a key factor, with medium- to low-density housing most at-risk (Syphard et al., 2012). Strategies to reduce ignitions and mitigate impacts include adapting land-use planning practices, using fire-resistant construction materials, and maintaining defensible space

(Syphard et al., 2017). Further, traditional Tribal burning practices by the Kumeyaay, Luiseño, Cupeño, and Cahuilla reduce fuel loads, revitalize plant communities, and support food and material resources. These practices recognize fire as a vital ecological and cultural process. For more information, see the Fifth Assessment's "Tribal and Indigenous Communities Statewide Topical Report." Pairing Indigenous fire stewardship with Western science reduces wildfire risk, strengthens ecosystem resilience, and honors sovereignty-based approaches to land management.

2.5 Precipitation and Flood Risk

The wet season in the San Diego region is narrow, typically spanning from November–April and sporting between 5–15 intermittent storms that arrive primarily during December through February. San Diego experiences an exceedingly large variation of total precipitation from one year to the next—some of the largest year-to-year volatility in the United States (**Figure 2.7**; Dettinger et al., 2011). The record is characterized by strong year-to-year and multi-year variability, including occasional extremely wet years (over twice as wet as average) and very dry years (60% or more below average), but does not exhibit a consistent long-term increase or decrease in total precipitation. Between 1896–2024, the annual average precipitation throughout San Diego ranged between a low of 4 inches (102 mm) in 2002 to a high of over 28 inches (711 mm) in 1941, with an average of 13.8 inches (348 mm), but it is somewhat unusual for any specific place within the region to receive average precipitation. For example, during the 21st century so far, only four years have been within 20% of this long-term average (NCEI, n.d.). Climate change is projected to increase this degree of natural volatility even further (Gershunov et al., 2019).

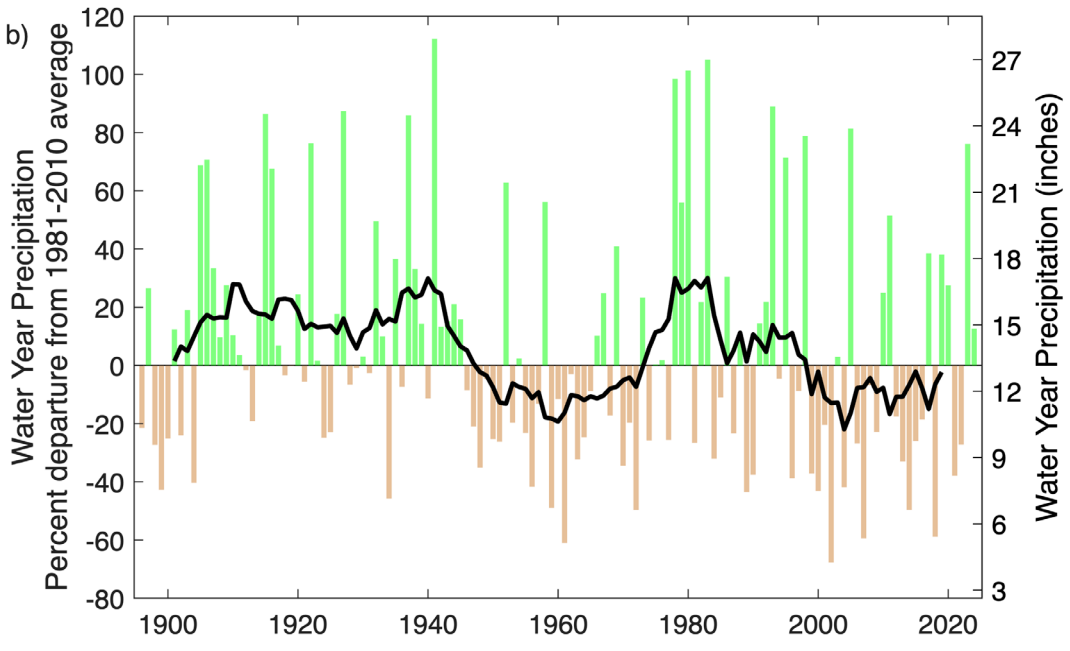


Figure 2.7: *Observed water year (October–September) precipitation for San Diego County, shown as percent departures from the 1981–2010 average. Green bars indicate wetter-than-average years; brown bars indicate drier-than-average years. Black line: 11-year moving average. Data: NOAA nClimGrid. Provided by John Abatzoglou, UC Merced.*

A few different storm types provide most of the precipitation delivered to the San Diego region. The high year-to-year variability of precipitation in San Diego is mainly driven by the presence or absence of a few big storms in cool season months each year. Closed lows—low pressure systems that separate from the atmospheric flow, which can cause them to stall or move slowly—can deliver large amounts of rain (Oakley & Redmond, 2014). But the greatest drivers of high interannual variability in San Diego are landfalling atmospheric rivers (ARs), ephemeral jets of concentrated water vapor originating over the Pacific Ocean that transport moisture and sometimes cause extreme precipitation. ARs are particularly productive when they encounter coastal topography. To illustrate the importance of ARs to extreme precipitation in San Diego—from 1980–2011, all 95th and 99th percentile precipitation events, as well as the vast majority of flood damages (Corringham et al., 2019), were associated with ARs (analysis not shown). In addition, ARs can often act as disruptors to the seasonal prediction of wet or dry winters associated with El Niño and La Niña respectively (Luna-Niño et al., 2025). Transitioning to summer and early fall, days are mostly dry, although occasional precipitation can be heavy, usually in the form of convective rains from monsoonal moisture or remnants of tropical storms.

Notably, there is a great deal of natural variation in San Diego regional precipitation, making it difficult to identify slowly developing changes in the precipitation regime due to climate change. A study of observed precipitation over California and the broader western United States was unable to find evidence of anthropogenic (human-influenced) climate change driving more intense winter storms in the region (Williams et al., 2024). Given the high interannual variability, when trends become statistically significant, enhanced precipitation from storms will likely already be impacting the region, suggesting that relying solely on statistical significance of long-term trends may not be the most effective tool to assess emerging impacts of climate change on precipitation extremes (Gershunov et al., 2025).

As has been discussed in previous assessments, annual precipitation in the San Diego region is projected to change only incrementally under all scenarios (**Figure 2.8**). In San Diego, projected changes in precipitation by mid- and late 21st century (**Figure 2.10a**) are fractional declines of -5% to -20% over most of the region with the largest decreases in the southern and eastern desert portions of San Diego County, though there is little agreement between models (**Figure 2.8**). However, the models generally agree that the precipitation regime will shift, wherein precipitation will occur less often but become more intense when it does occur (Gershunov et al., 2019). The frequency of days with measurable precipitation is projected to decrease throughout the entire San Diego region by 5–15% (**Figure 2.9b**). Counteracting the decline in wet days, daily precipitation intensity is projected to increase by 5–15% compared to historical amounts (**Figure 2.9c**). Evaluation of the storm systems that deliver the region's precipitation reveals that the increased intensity is projected to be driven by increases in AR precipitation, while the diminished frequency likely arises from a decline in non-AR sources of precipitation.

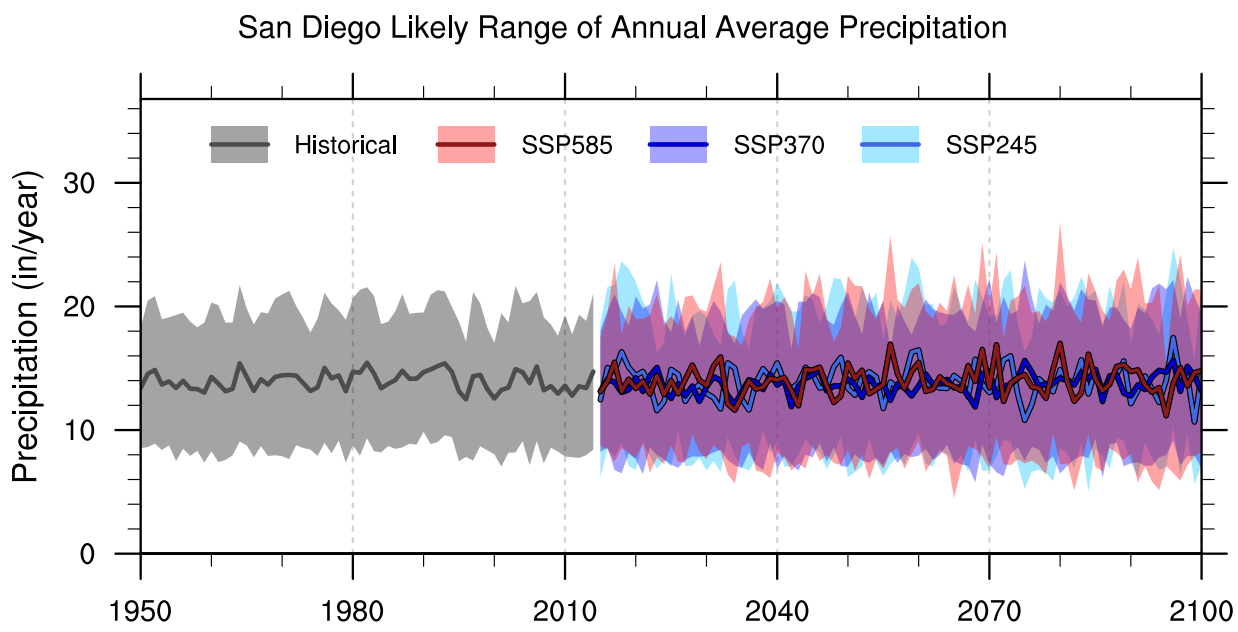


Figure 2.8: *Projected annual precipitation for San Diego County under three emissions scenarios: SSP2–4.5 (cyan), SSP3–7.0 (blue), and SSP5–8.5 (red), with shading showing ± one standard deviation. Historical period in gray. Unlike temperature (**Figure 2.2**), annual precipitation shows no significant projected trend under any scenario, though year-to-year variability remains large. Based on LOCA2-downscaled CMIP6 models. Provided by Paul Ullrich, UC Davis.*

Sequences, or back-to-back precipitation events, are an important ingredient of San Diego's regional precipitation climatology that factor into the threat from floods. Historically, this has been noted in the massive California flood during the winter of 1861–1862. A more recent example occurred between the second week of January and the third week of February 1980, when a series of moisture-laden AR storms pounded California. The Cuyamaca rain gauge (4,640 feet/1,410 m) in the Laguna Mountains, upstream of the San Diego River drainage, recorded more than 46 inches (117 cm) of rainfall, with individual daily amounts exceeding 4 inches (10 cm) in January and exceeding 5 inches (12 cm) in February. The February storms saturated the already wet terrain that was primed by the January storms, resulting in widespread floods that continued for several days (Wahl et al., 1980). More than 30 deaths and millions of dollars of damage were reported in San Diego County. The Tijuana River in northern Baja California (Mexico) and southern San Diego County flooded many square miles of lowlands. Discharge on the Tijuana River gauge at Nester reached an estimated peak of 34,000 cubic feet per second (936 cubic meters per second) on February 21. Most reservoirs in San Diego County spilled, several for the first time since their completion.

Storm sequences may grow more important as the climate warms and the atmosphere gains more moisture. Ongoing research examining changes in AR sequences in an ensemble of CMIP6 projections finds that the number of AR sequences per year affecting San Diego County between water years 1981–2010 and the mid-21st century water years (2041–2070) increases by 27% under the SSP2–4.5 scenario, and increases by 35% under the SSP3–7.0 scenario (Castellano, n.d.).

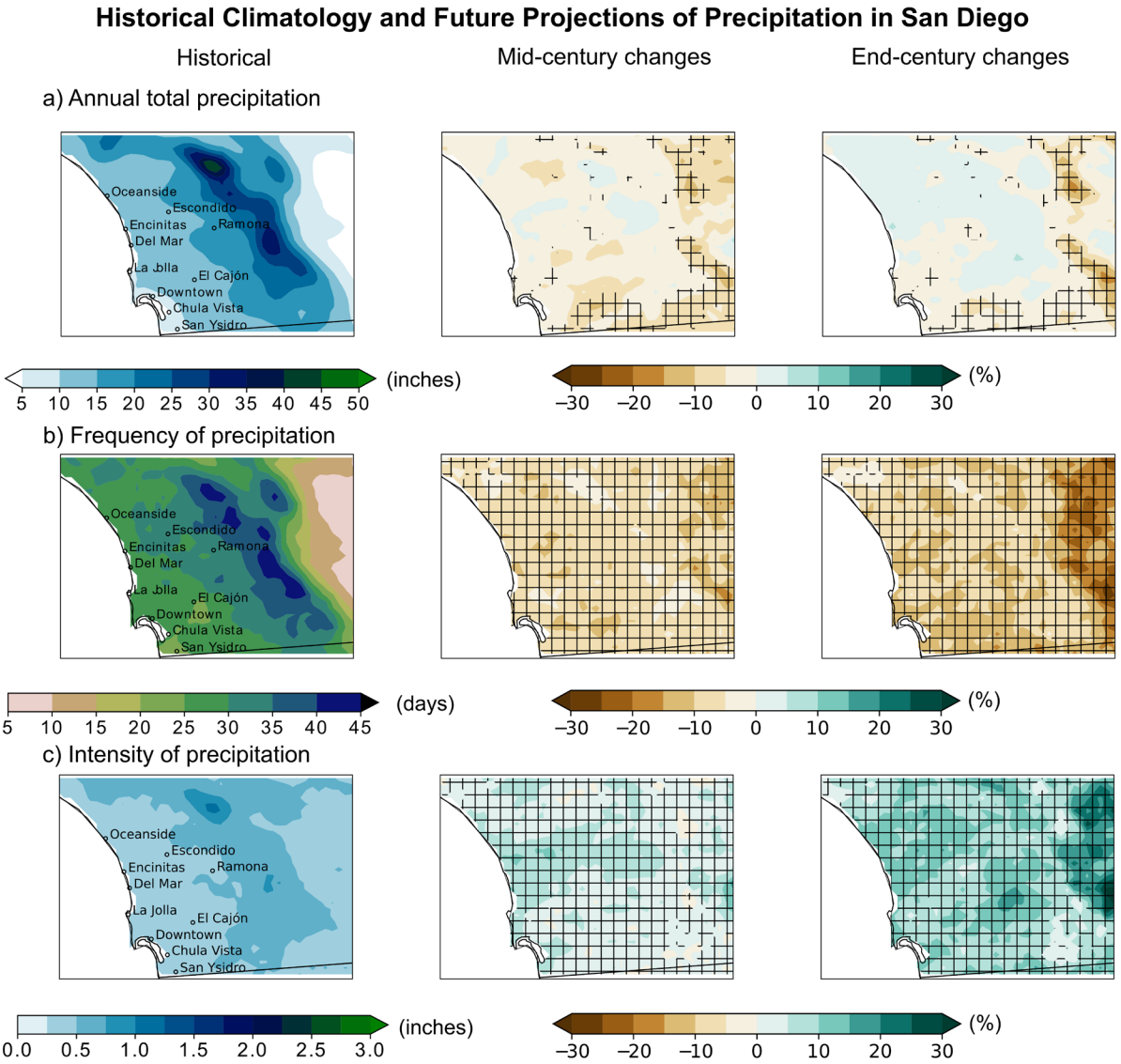


Figure 2.9: *Historical (1981–2010) and projected changes in (a) annual total precipitation, (b) wet-day frequency, and (c) precipitation intensity (average per wet day) across San Diego County. Middle and right columns show mid-century (2041–2070) and end-century (2071–2100) changes under SSP3–7.0. Cross-hatching indicates where at least two-thirds of models agree on the direction of change. Provided by Rosa Luna-Niño, Scripps Institution of Oceanography, UC San Diego.*

Box 2.1: *January 22, 2024: San Diego Flooding Event*

On January 22, 2024, San Diego experienced a high intensity precipitation event that generated flooding in southeast San Diego, in the communities along Chollas Creek, and in the City of Coronado. This storm produced 2.73 inches (6.9 cm) of precipitation in 24 hours at Lindbergh Field, breaking the previous January 22 record of 1.57 inches (4 cm), becoming the fourth all-time highest rainfall since 1850. An amount of 2.13 inches (5.4 cm) fell in just three hours, overwhelming drainage systems and rapidly generating extreme floods. As of April 2024, FEMA had provided $22.2 million in disaster recovery relief (FEMA, 2024). The atmospheric processes that created this high intensity rain event occurred on much smaller scales than is represented by global or even some regional climate models. With new dynamical downscaling approaches, it is becoming possible to assess these fine scale phenomena in the future climate. Global studies suggest that high intensity rain, especially in urban landscape, may increase more than lower intensity events (Fowler et al., 2021; Torelló-Sentelles et al., 2024) Dynamical models project increases in annual hourly maximum precipitation by 5–20% in mid-century and greater amounts at end-of-century, particularly across inland and mountain areas (**Figure 2.10**).

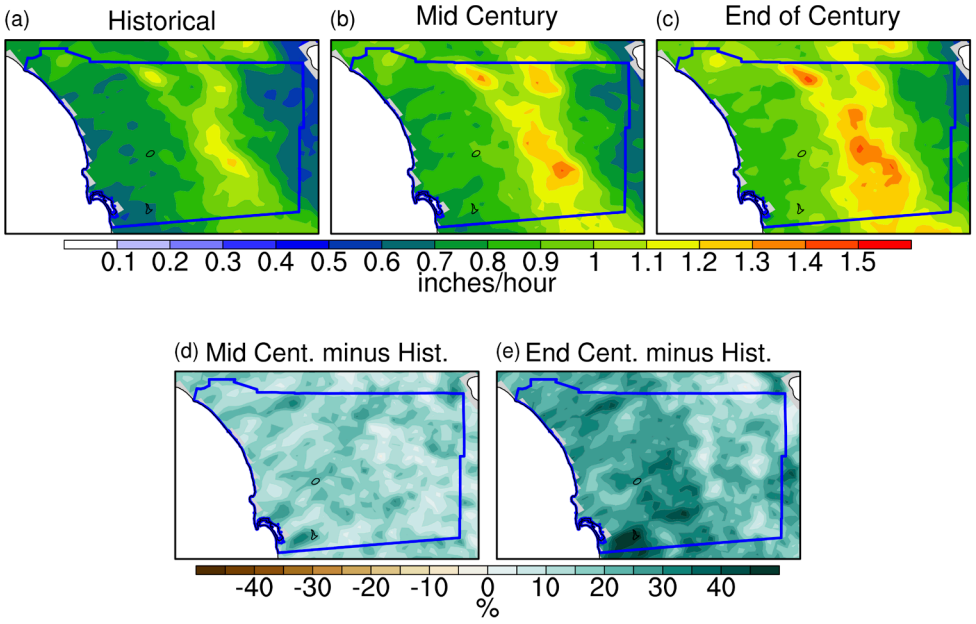


Figure 2.10: *Annual precipitation during the rainiest hour of the year for historical conditions (1981–2010), mid-century (2041–2070), and end-of-century (2071–2100) climates (top row), and projected fractional changes from historical to mid-century and historical to end-century (bottom row). Results are averaged across four dynamically downscaled models (MIROC6, TaiESM, EC-Earth3, and MPI-ESM1-2-HR) under SSP3–7.0. Provided by Jesse Norris, University of California, Los Angeles.*

In recently burned landscapes, short duration, high intensity rainfall events (similar to, but less severe than, the January 2024 Chollas Creek flood) can trigger post-fire debris flows. Increases in rainfall intensity, specifically sub-hourly rainfall intensity, could lead to increases in debris flow likelihood and volume (Gartner et al., 2014; Staley et al., 2017). A projected increase of 18% in rainfall intensity across Southern California, driven by increased temperatures under RCP4.5 (a middle-of-the-road warming scenario from the previous generation of climate models), is estimated to increase the probability of major debris flows by 110% (Kean & Staley, 2021).

A majority of global climate models project a decline in the number of wet days in future years, resulting from the widening of the Hadley circulation, poleward displacement of the jet stream, and subtropical subsidence (Johanson & Fu, 2008; Lau & Kim, 2015). From past work (Pierce et al., 2023; Pierce et al., 2018; Swain, 2021), the seasonal cycle of precipitation is also projected to sharpen, with a shorter and more intense wet season and longer and drier dry season. The recent projections show similar results (**Figure 2.11**). Examining how the average projected annual precipitation cycle of San Diego County changes from the historical (1981–2010) period to mid-century (2041–2070) across the multi-model ensemble reveals increased precipitation in February—and to a lesser extent January and March—but decreases in the spring (April and May) and autumn (November). The changes continue to amplify through the end of the century (**Figure 2.11**, panels on the right), with the largest absolute increases seen in January and February and the largest relative declines seen in May and June. The models also suggest some tendency toward an increase in monsoonal moisture in July–September, although the actual amount of precipitation is quite small; the large percent increases are due to the low precipitation totals in these months.

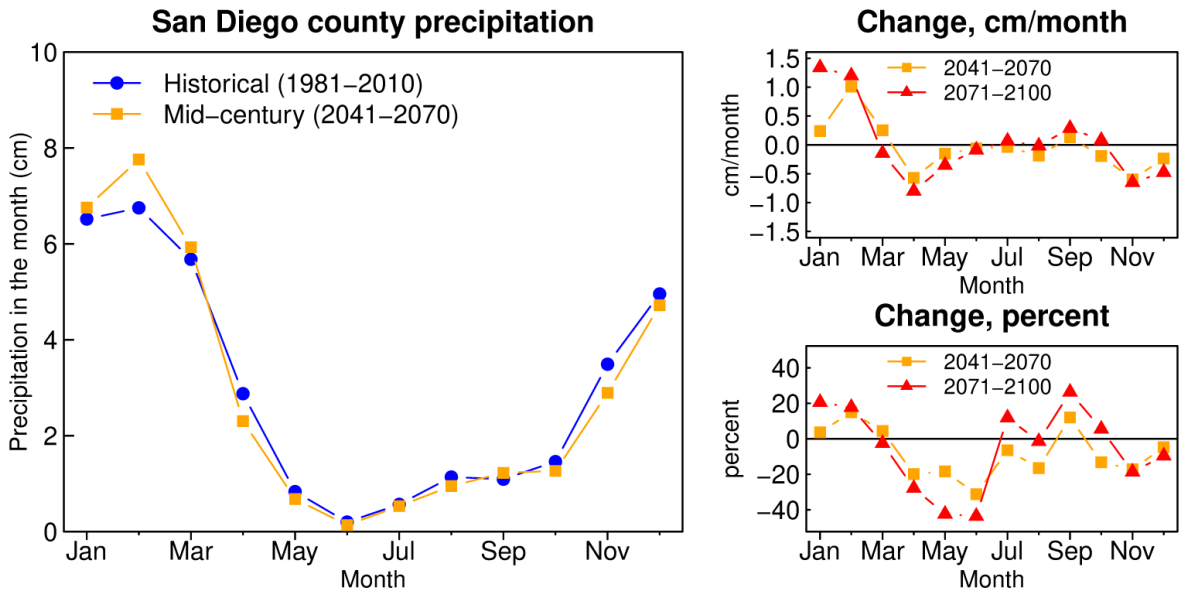


Figure 2.11: *Left: observed monthly precipitation climatology for historical (1981–2010; blue) and projected mid-century (2041–2070; orange) (SSP3-7.0). Right panels: (top) projected change by month in absolute (cm/month) and (bottom) relative (percent) terms for mid-century (2041–2070; orange) and end-of-century (2071–2100; red). Provided by David Pierce, Scripps Institution of Oceanography, UC San Diego.*

2.6 Drought

Drought is not uncommon and occurs in many forms. For example, San Diego almost always undergoes a seasonal drought with a warm and dry extended summer. Depending on Pacific storm activity and storm tracks, some years fall into an extended dry period, leading to year-long and possibly multi-year droughts. These extended dry episodes are particularly impactful on water

supply, agriculture, and ecosystems. The intensity of extended dry periods, calculated by annual (water year) precipitation totals, varies across the CMIP6 GCMs, but in general the magnitude of the most extreme droughts in the projected future is consistent with those that San Diego has experienced during the historical period covered by instrumental records (analysis not shown). For example, San Diego's driest single dry year, 2002, fell below 35% of the long-term historical mean, and the driest 5-year sequence, 2000–2004, was approximately 63% of the historical mean. Drought based on the absence of precipitation is projected to become up to half a year longer in the mid-21st century.

A precipitation-only perspective provides an incomplete assessment of drought frequency and intensity. Evaporative demand (which drives landscape drying) is influenced by temperature, humidity, solar radiation, and wind speed. Over the past 40 years, evaporative demand has increased primarily due to rising temperatures (Albano et al., 2022). By mid-century, evaporative demand is projected to increase throughout San Diego County, with the greatest increases occurring in the eastern part of the county (**Figure 2.12a**). Using a drought index that incorporates evaporative demand, the likelihood of a 12-month extreme drought occurring is projected to increase by four to five times in inland areas and up to five times in desert regions. A 36-month extreme drought has an even higher likelihood. By mid-century, it is five times more likely for an extreme drought to occur throughout most of the county, except along the coast and to a lesser extent, in the mountains (**Figure 2.12b,c**).

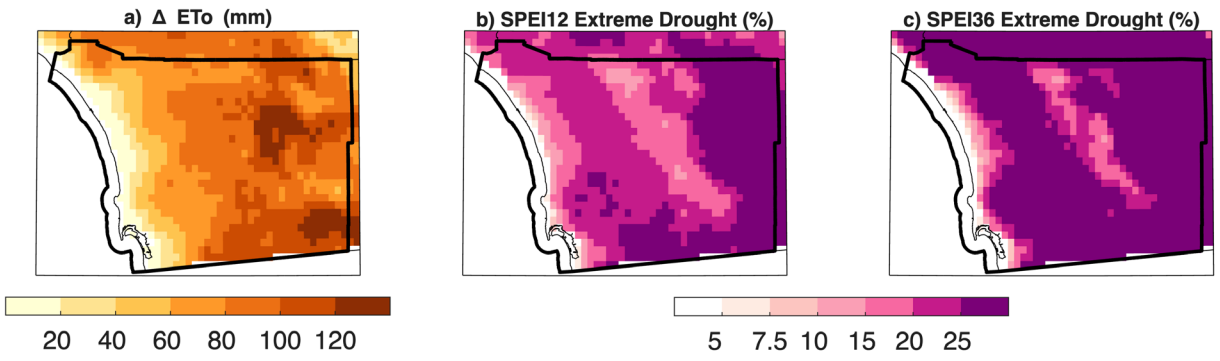


Figure 2.12: *Projected mid-century (2041–2070) changes under SSP2–4.5: (a) annual evaporative demand (ETo), (b) percentage of time in extreme 12-month drought, and (c) percentage of time in extreme 36-month drought. Values represent the future frequency of conditions that historically occurred only 5% of the time; for example, 25% indicates a fivefold increase. ETo calculated using Penman-Monteith with CO_2 effects on stomatal closure; multi-model mean of seven CMIP6 models. Provided by John Abatzoglou, UC Merced.*

2.7 Sheltering Marine Layer Clouds

The North Pacific marine layer clouds, which are common in May and June but can extend into September, shelter the region from sun and heat. When present, these low-altitude, coastal stratiform (blanket-like) clouds reduce incoming solar radiation. When low enough that the cloud base intercepts the terrain, these clouds become fog and add incremental moisture to the landscape during a typically rain-free time of year.

As San Diego residents know, these coastal low clouds are highly variable across the region, with strong gradients from the cloudier coast to cloud-free inland (**Figure 2.13**). The inland reach of the cloud deck is strongly determined by topographic barriers, but on a daily basis cloudiness is typically greatest in the early morning and early in the season (i.e., in May). Passing weather systems drive day-to-day variability and often modulate the normal daily clearing pattern, sometimes even leading to reverse clearing or little-to-no clearing over much of the county. Seasonally, coastal cloudiness in Southern California and northern Baja reaches its apex during "May Gray" and "June Gloom" months, during which the immediate coast is overcast more than 50% of the time (**Figure 2.13**). Records of low cloud observations extending back 75 years contain no long-term trend in low cloud cover along the San Diego County coast (**Figure 2.14**). Because of the complex interaction from large to small scales that govern the dynamics of coastal low-level clouds, GCMs have trouble reproducing this climate feature. Identifying projected changes from climate models remains an active area of research given the many factors that influence coastal low-level clouds.

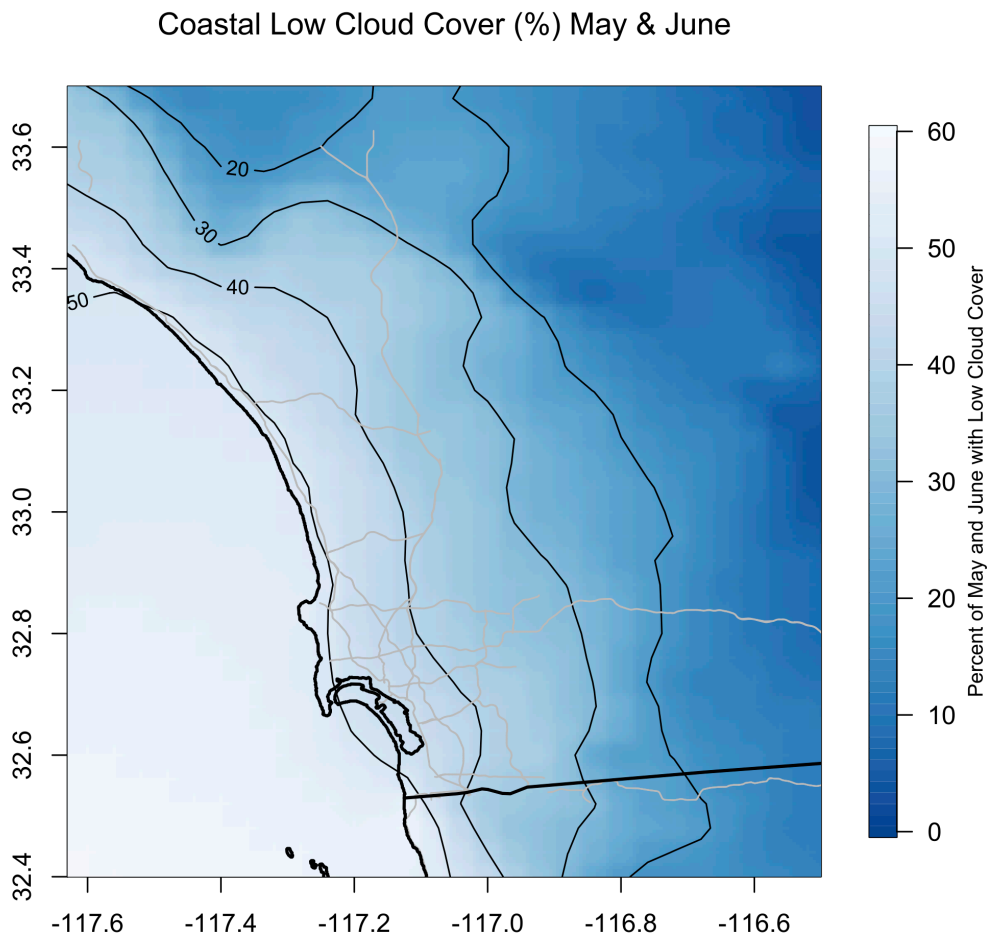


Figure 2.13: *Average May–June low cloud cover (%) over San Diego County, showing the pronounced marine-layer-driven coastal-to-inland gradient, characteristic of the "May Gray/June Gloom" pattern. Overcast conditions exceed 50% along the immediate coast. Based on the GOES-WEST satellite low-cloud product (Clemesha et al., 2016) updated through 2024. Contour interval: 10%. Gray lines denote major highways. Provided by Rachel Clemesha, Scripps Institution of Oceanography, UC San Diego.*

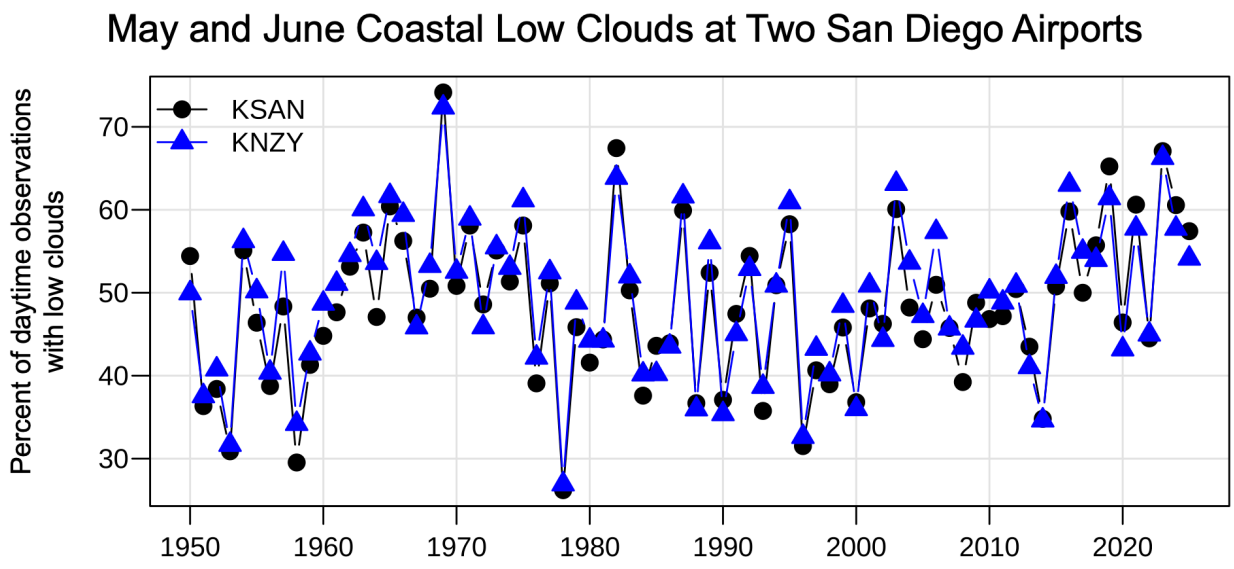


Figure 2.14: *May–June daytime low cloud frequency at San Diego International Airport (KSAN; black) and Naval Air Station North Island (KNZY; blue), 1950–2025. Low clouds are defined as cloud bases below 2,000 m. The two independent stations agree closely (r = 0.96). Cloud frequency ranges from roughly 25–75%, with strong year-to-year variability but no long-term trend. Provided by Rachel Clemesha, Scripps Institution of Oceanography, UC San Diego.*

2.8 Compound Extremes

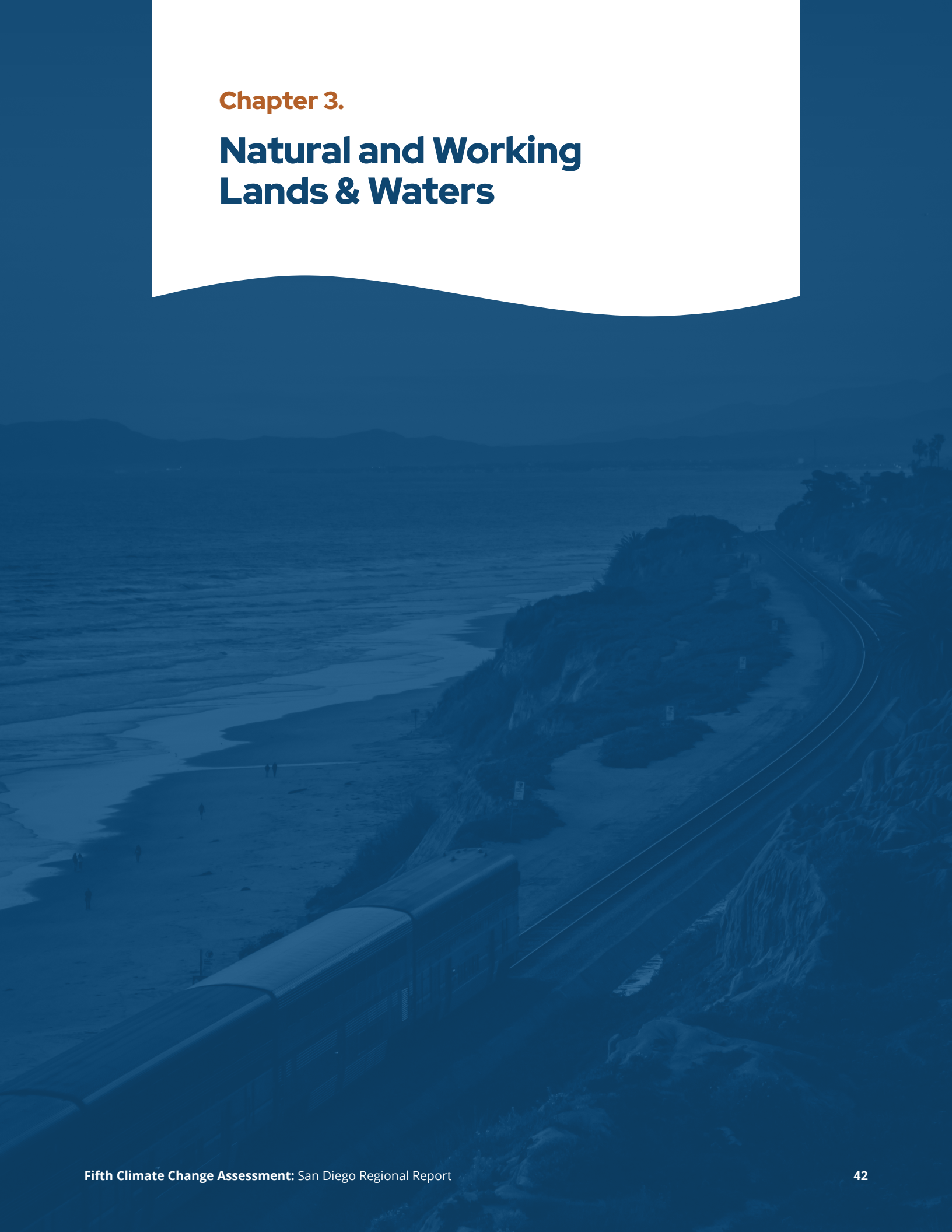
Two or more weather (or anomalous short period climate) events that either co-occur or occur in a certain sequence, exacerbating the impacts of any one event occurring in isolation, are called compounding weather events. Compounded impacts from weather events occur in San Diego County in various forms, for example:

- Rainfall supporting vegetation on the west- and southwest-ward-facing slopes of the coastal topography that later experience strong SAWs (this AR-SAW sequential compounding determines the geography, severity, and timing of wildfire risk)
- Wildfire scarring followed by high intensity precipitation (often associated with ARs) is conducive to damaging debris flows.
- A series of rainstorms can produce persistent average-intensity rainfall that saturates the soil, while localized convection often embedded in ARs can create short but intense downpours that cause flash flooding, coastal erosion, and even landslides. January 22, 2024 and April 10, 2022 are recent examples of such localized damaging floods, and multiple landslides, respectively.
- Coastal heat waves are often caused by SAWs and public health impacts from heat can be compounded by wildfire smoke transported by the same SAWs from the back-country where most of the fires burn down to the densely populated coast.
- Coastal flooding and erosion due to high tides and big waves can be compounded by a landfalling AR and associated strong winds and rainfall runoff into the coastal zone.

Weather events can compound with longer-term climate conditions to amplify impacts. For example, delayed onset of the winter wet season can extend dry fuels into the late fall and early winter, coinciding with Santa Ana winds that are common during this period and drive devastating wildfires. This type of compounding helped enable unusually late-season fires such as the Thomas Fire (December 2017) and the January 2025 Los Angeles fires. Another example involves sea level inflated by El Niño compounding the impact of storm waves. When coinciding with astronomically high tides, as occurred during Winter 1983, this climate-weather compounding led to the destruction of many installations along the California coast, including the original wooden Scripps Pier. In addition, weather events can also compound with other types of events, sometimes including climate-related decisions, leading to compounded impacts. For example, during strong SAWs in dry vegetation, public safety power shutoffs (PSPS) can lower the risk of fire ignition but compound the health risks from SAW-caused heat waves. Understanding compounding weather and climate events is critical for disaster preparedness and risk management, as compound events can create complex challenges that cannot be addressed by considering single weather hazards in isolation.

Chapter 3.

Natural and Working Lands & Waters



3.1 San Diego Coasts

KEY MESSAGES

- *Sea level has risen by 0.67 feet (0.2 m) over the last 100 years and is projected to rise by an additional 1.0–1.6 feet (0.3–0.5 m) by 2075. In the near term, the most impactful coastal flooding will result from the combination of high tides and storm events.*
- *The South Bay and Imperial Beach are projected to experience the greatest coastal flooding impacts and are among the region's most vulnerable areas to sea level rise.*
- *Sea level rise and erosion threaten San Diego's beaches and shorelines, which are central to the region's identity and economy. Adaptation projects, including major beach nourishment projects, are underway along the San Diego coast to mitigate these impacts.*
- *Coastal cliff erosion poses significant risks to public safety, property, and infrastructure. New monitoring and warning systems can improve risk assessment and hazard mitigation.*
- *Many coastal dunes have been lost over the last century, but restoration projects are expanding to restore habitat and reduce the impacts of coastal flooding.*
- *Estuaries that would naturally migrate inland with sea level rise are limited by urban development. Adaptive management approaches are being tested to support the resilience of these natural flood barriers and important ecosystems.*

3.1.1 Sea Level Rise and Extreme Sea Level

Over the past century (1924–2024), mean sea level at the La Jolla tide gauge has risen by 0.67 feet (0.2 m) (**Figure 3.1, Table 3.1**). With respect to future projections of sea level rise (SLR), multiple scenarios were developed to account for uncertainty in future greenhouse gas emissions and the incomplete understanding and difficulty in modeling processes that control sea level (e.g., the rate at which polar ice sheets may melt or destabilize) (California Ocean Protection Council & California Ocean Science Trust, 2024; Sweet et al., 2022). California's recent sea level trajectory appears to align most closely with the mid-range intermediate scenario (California Ocean Protection Council, 2024). Under the intermediate scenario, sea levels from the year 2000 are projected to rise 0.79 feet (0.24 m) by 2050, slightly more SLR than occurred during the entire 20th century. By 2080, the intermediate scenario has sea level accelerating to approximately 1.84 feet (0.56 m) (Sweet et al., 2022). Primary factors of the projected SLR involve enhanced thermal expansion, as ocean waters warm, and an increasing contribution of freshwater volume, as glaciers and the world's great ice sheets on Greenland and Antarctica melt. Vertical land motion, including land subsidence, accounted for approximately 16% of this rise over the last century (NOAA, 2024; Sweet et al., 2022) but estimates indicate that this component will contribute less than 1% to future SLR.

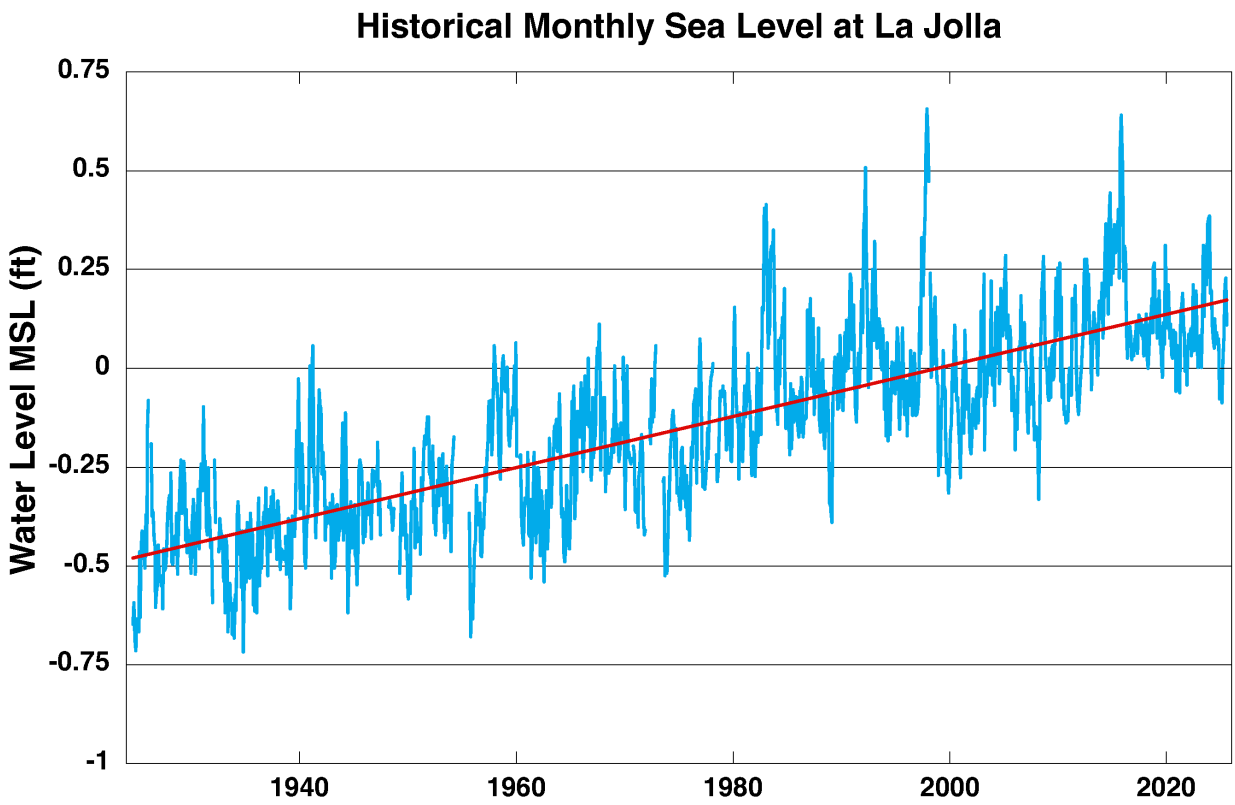


Figure 3.1: *Monthly sea level at the La Jolla tide gauge (Scripps Pier), 1924–2025. This record illustrates the medley of monthly, interannual, and decadal variability, superimposed on a long-term rise of approximately 0.8 inches/decade (2 cm/decade), shown by the red line. Provided by Sam Iacobellis, Scripps Institution of Oceanography, UC San Diego.*

Table 3.1 *Historically observed and projected sea level rise (SLR) in San Diego at the La Jolla tide gauge. Projected SLR in San Diego based on the intermediate scenario and the range is the 17th to 83rd percentiles. The SLR is reported as the reference minus the mean sea level at year 2000. Data are from (Sweet et al., 2022).*

Period	Observed and Projected Sea Level Rise	Likely Range	Takeaways
Historical: 1924–2024 (100 years)	0.67 ft (0.20 m) *~ 0.8 in (2 cm) / decade*	—	Accounting for vertical land motion, the observed rise in La Jolla is comparable to global SLR over the last 100 years.
Projected: 2025–2049 (25 years)	0.46 ft (0.14 m) *~ 2.2 in (5.6 cm) / decade*	0.38–0.60 ft (0.12–0.18 m)	Projected SLR over the next 25 years amounts to about 65% of the total rise observed from 1924–2024. Uncertainty is dominated by interannual to decadal variability. Impacts: Chronic nuisance flooding is expected to begin.
Projected: 2025–2074 (50 years)	1.25 ft (0.38 m) *~ 3.0 in (7.6 cm) / decade*	1.04–1.60 ft (0.32–0.49 m)	Average rise over the next 50 years reaches two times the observed SLR over 100 years. Impacts: Widespread nuisance flooding as sea level exceeds many original design thresholds for infrastructure.
Projected: 2025–2099 (75 years)	2.74 ft (0.84 m) *~ 4.4 in (11.2 cm) / decade*	2.18–3.03 ft (0.66–0.91 m)	Large ice sheet contribution drives accelerated SLR during the latter half of the 21st century. More than four times observed SLR over 100 years. Impacts: Redesign and relocation of coastal infrastructure become necessary.

On top of the global components of SLR, short period extremes are expected to deliver some of the most severe coastal hazards during the next several decades. These high-water events are

driven by tides and storms. Of the 10 highest sea level events recorded at La Jolla since 1950, seven have occurred since 2000, mostly during winter months. The previous record high water level of 5.05 feet (1.54 m) above mean sea level occurred on November 25, 2015 (NOAA, 2024; NOAA Tides and Currents, 2024). The La Jolla tide gauge at Scripps Pier recorded a new maximum water height in November 2025 of 5.1 ft (1.6 m) above the 1983–2001 mean sea level. Under the intermediate scenario and the SSP3–7.0 emission trajectory, water levels reaching this height are projected to occur about 12 days per year around 2060 and as frequently as 51 days per year between 2070–2080 (**Figure 3.2**). Coastal storms coinciding with high tides and heavy rainfall are also expected to increase the frequency and severity of compound flooding events. These impacts may be further amplified by elevated groundwater levels and increased surface runoff. The frequency of such compound events is projected to rise notably by 2040, reaching approximately 10–20 events per year, and further increase to 40–80 events annually by 2070 (**Figure 3.3**). Although a rare hazard, tsunami impact increases with SLR and has been examined in Patton et al. (2026). In the San Diego region, under 1.6 ft (0.5 m) of SLR, a tsunami with a 100-year return period will increase onshore inundation by 157% compared to the same event under no SLR (Patton et al., 2026).

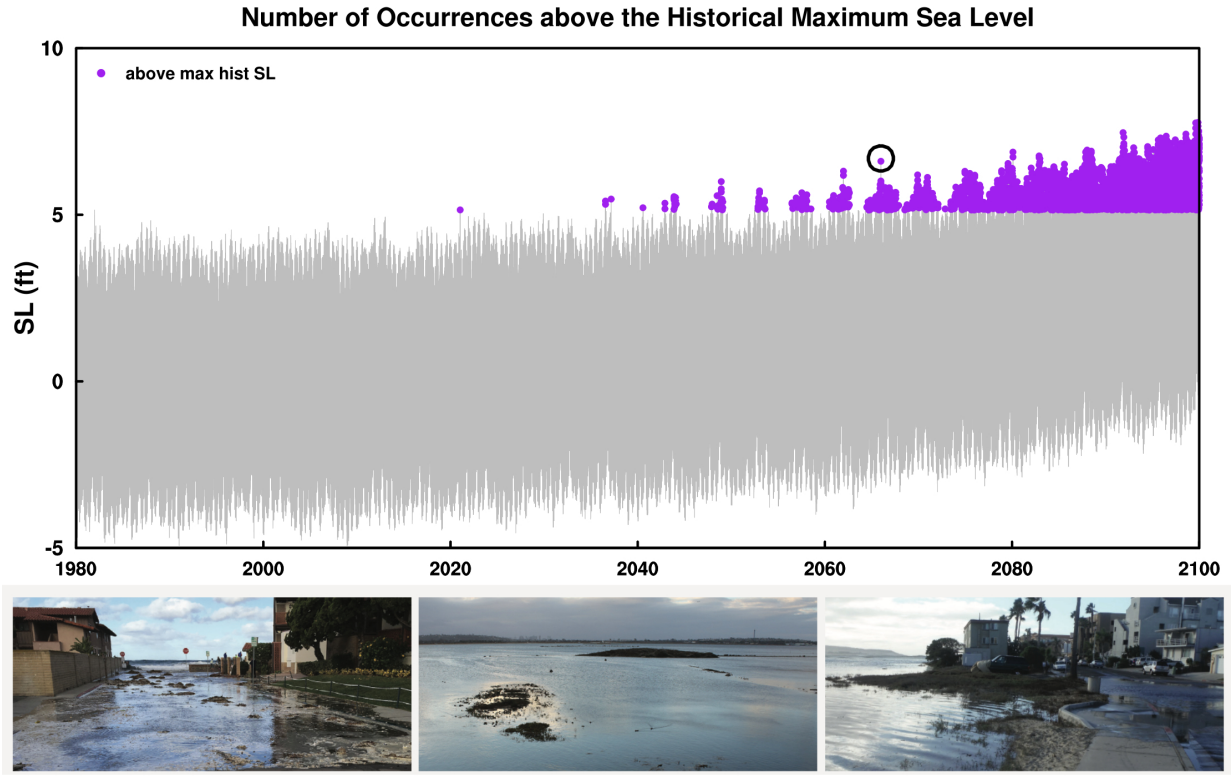


Figure 3.2: *Projected hourly sea levels at the La Jolla tide gauge (gray) with hours exceeding the historical maximum highlighted in purple. Exceedances become frequent after mid-century and nearly continuous by late-century. Black circle: modeled 100-year extreme. Based on an intermediate SLR scenario with SSP3–7.0 forcing (MIROC6). Photos show high-water impacts: loss of beach access in La Jolla (left), marsh submergence in Mission Bay (center), and street flooding in Imperial Beach (right). Provided by Sam Iacobellis, Scripps Institution of Oceanography, UC San Diego.*

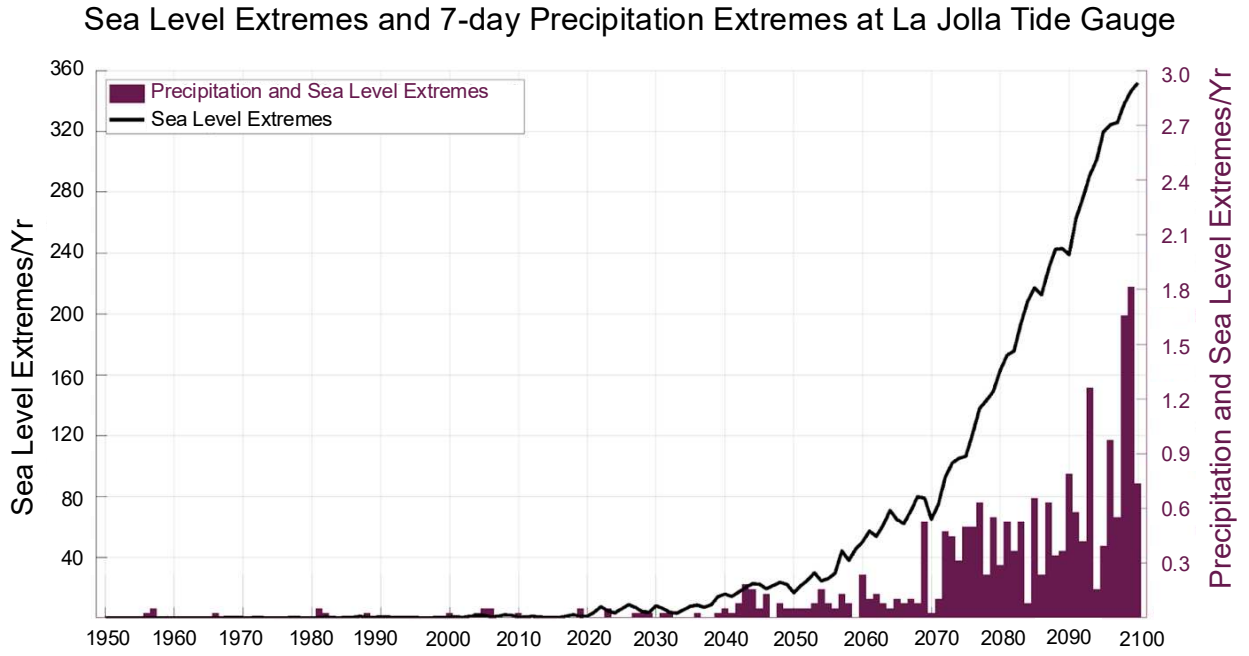


Figure 3.3: *Projected extreme sea level events (black line; hours exceeding the historical 99.99th percentile) and compound events where extreme sea levels co-occur with heavy seven-day precipitation (purple bars; 99.8th percentile). Both increase sharply after mid-century, indicating growing risk of simultaneous coastal and fluvial flooding. Based on 38 SSP3–7.0 simulations from 10 CMIP6 models. Provided by Dan Cayan and Josh Mumford, Scripps Institution of Oceanography, UC San Diego.*

The influence of waves, particularly during coastal storms, also plays a critical role in driving coastal flooding, beach erosion, and cliff retreat throughout San Diego County. This was experienced in January 2023 when a large atmospheric river brought larger waves and coastal flooding to the boardwalk in Mission Beach and street flooding around houses in Imperial Beach. Large coastal storm events can occur sequentially within a single winter season, often in association with El Niño conditions. However, the severity of wave impacts depends on wave direction and timing relative to tides. During the 2015–2016 El Niño, Southern California beaches were less affected than other parts of the West Coast, owing to sheltering from dominant northerly waves and favorable timing (Young et al., 2018). To support preparedness and response efforts, Scripps Institution of Oceanography at UC San Diego developed a short-term coastal flood forecast system, initially implemented in Imperial Beach. Following successful refinement, the system has been expanded to other sites across San Diego County, including Torrey Pines, Cardiff State Beach, and Naval Base Coronado.

Often less visible are the impacts of SLR and sea level extremes on coastal groundwater systems, which interact directly with the ocean and are highly sensitive to rising sea levels. In unconfined surface aquifers, the boundary between freshwater and saline water shifts inland with SLR, elevating the groundwater table and pushing fully saturated soils closer to the ground surface, a process known as groundwater shoaling (Jiao & Post, 2019). Early impacts may include infrastructure corrosion, compromised roads, contaminant mobilization toward the surface, and flooding as groundwater tables rise (Bjerklie et al., 2012; Habel et al., 2024; Hill et al., 2023; Knott et al., 2017; McKenzie et al., 2021). In San Diego specifically, areas with deeper water tables

today are expected to transition to shallow, or even emergent conditions, over time (**Figure 3.4**). At Camp Pendleton there is concern about sea water intrusion into the Base wells due to SLR (Chadwick et al., 2015). Sweetwater Authority (publicly-owned water agency in San Diego County) is currently conducting well studies to minimize potential sea water intrusion.

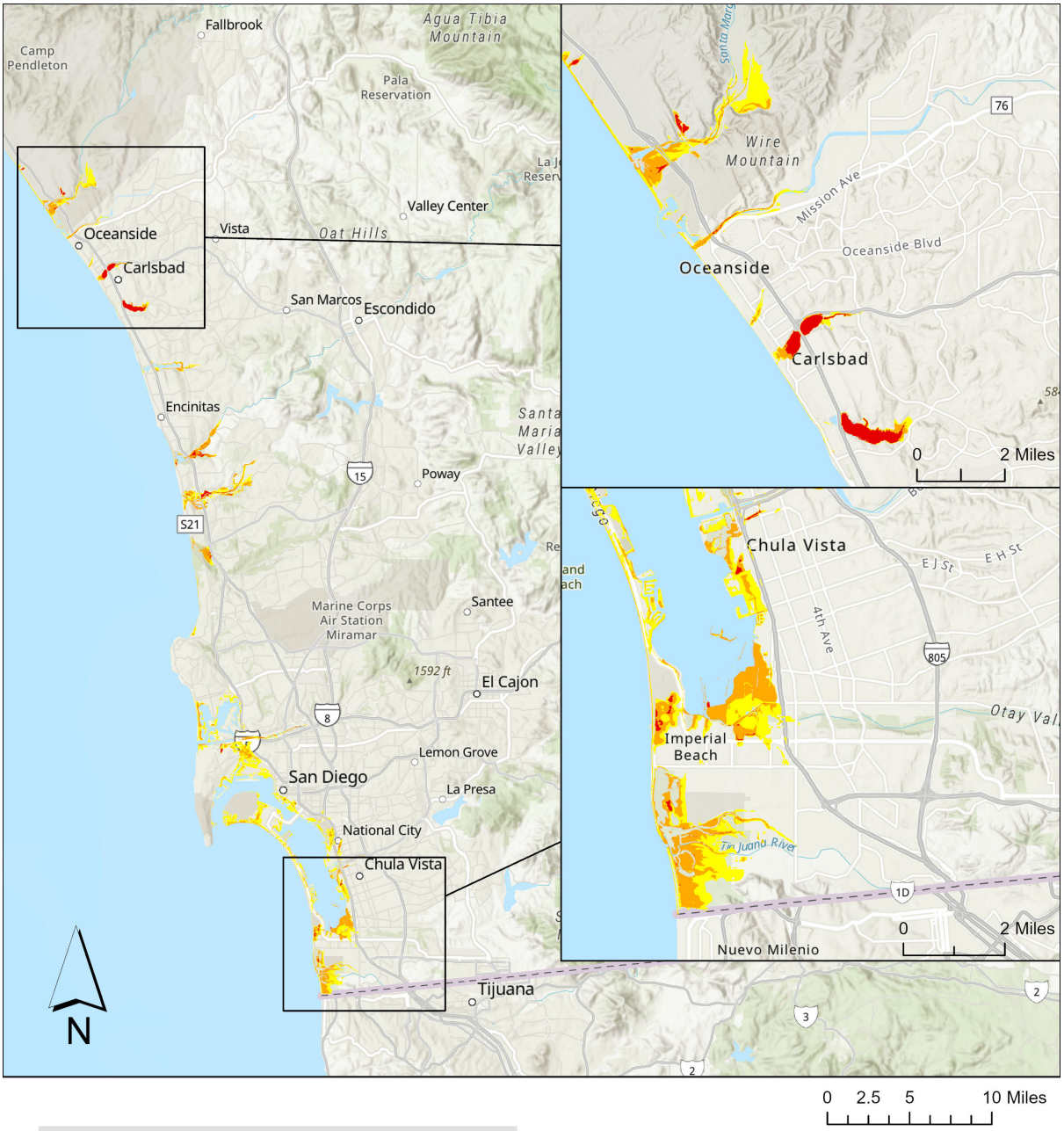


Figure 3.4: *Projected groundwater table depth along coastal San Diego under 0.8 ft (25 cm) of sea level rise. Colors indicate depth to the water table: yellow (3.3–6.6 ft/1.1–2.0m, shallow), orange (0.3–3.3ft/0.1–1.0m, very shallow), and red (emergent groundwater at or above the surface, contributing to flooding). Insets show detail from Carlsbad and Chula Vista/Imperial Beach areas. Data: USGS CoSMoS-Groundwater (Befus et al., 2020). Provided by Hanna Bliska, California Governor's Office of Land Use and Climate Innovation.*

Box 3.1: *Imperial Beach as a Case Study for SLR and Groundwater Impacts*

Situated at the southernmost point of California's coastline, Imperial Beach (IB) is highly vulnerable to compound flooding due to its low elevation and proximity to multiple water bodies (Gallien, 2016; Merrifield et al., 2021). Regional studies incorporating direct groundwater observations have modeled the impacts of SLR and precipitation on IB's stormwater drainage (Sangsefidi, Barnes, et al., 2023) and sewage infrastructure (Sangsefidi, Bagheri, et al., 2023). While projections indicate that direct marine inundation will be limited, groundwater infiltration into compromised infrastructure could lead to significant increases in storm drain and sewage system failures. Analyses of groundwater levels in IB show that static models (Befus et al., 2020; Sangsefidi, Bagheri, et al., 2023) do not capture the tidal variability of the coastal aquifer or how it varies with local geology across the city (Barnes et al., 2025). More comprehensive regional studies that incorporate local geology, dynamic aquifer behavior, and direct groundwater measurements will be critical for accurately assessing vulnerabilities and developing effective SLR adaptation strategies.

3.1.2 Current and Projected Impacts on San Diego from Sea Level Rise

As of January 2025, 11 locally-focused SLR vulnerability assessments had been completed across the San Diego region, as documented in the San Diego Regional Plan Tracker (SDRCC, 2025). Several studies and reports examine the impacts of different SLR scenarios in San Diego. Many rely on the US Geological Survey's Coastal Storm Modeling System (CoSMoS), which includes multiple SLR scenarios combined with additional extreme coastal flooding events. Analyses using CoSMoS indicate that areas throughout San Diego Bay, Imperial Beach, Coronado and regions surrounding coastal lagoons are most vulnerable to SLR. Imperial Beach and portions of the southern San Diego Bay area are also among the most socio-economically vulnerable communities in the region (**Figure 3.5**), often facing barriers to funding and mitigation measures that can compound risks and reduce community capacity to recover from coastal impacts (SDRCC et al., 2023). A more detailed examination of the compounding and intersecting impacts of SLR on San Diego's communities is presented in *Tools for Accelerating Coastal Resilience: The Cost of Coastal Inaction in the San Diego Region* (SDRCC, 2024). CoSMoS does not assign specific time horizons to its SLR scenarios; however, when these scenarios are combined with projections of sea level extremes, they can be used to estimate the frequency at which a given SLR condition may occur (**Figure 3.2**).

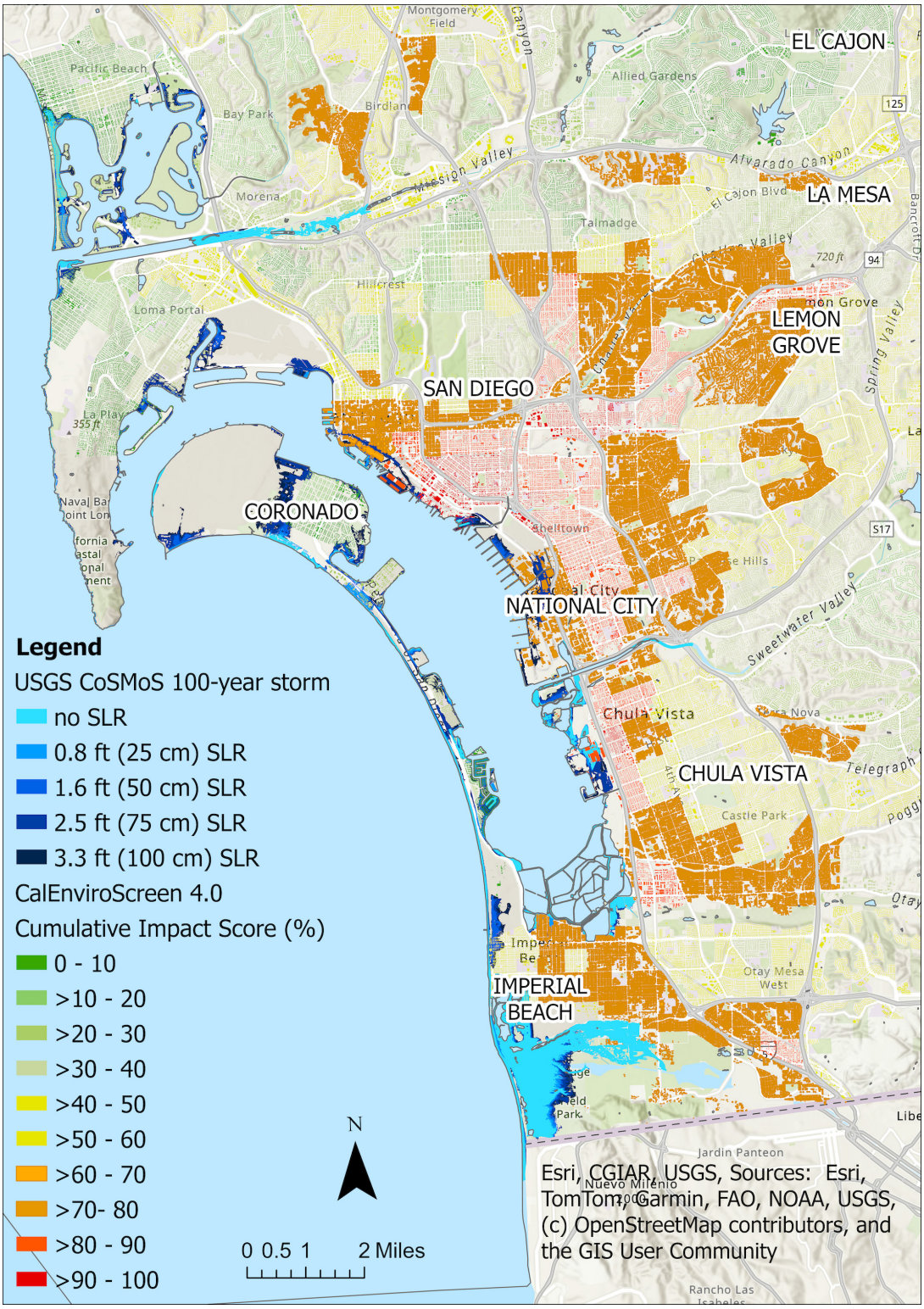


Figure 3.5: *Projected 100-year coastal storm flood extent in south San Diego County under present-day sea level and with 0.8–3.3 ft (25–100 cm) of sea-level rise (blue shading; see legend for increments). Buildings are colored by CalEnviroScreen 4.0 cumulative impact score, with darker orange and red indicating higher social and environmental vulnerability. Flood zones expand substantially inland around San Diego Bay. Provided by Denali Pinto, Scripps Institution of Oceanography, UC San Diego.*

Impacts from SLR vary widely across infrastructure, recreation, and the economy—what is reported below represents only a snapshot of these impacts. In San Diego, SLR is expected to progressively affect coastal access points, amenities, and parking areas. Approximately 15.9% of coastal access points in San Diego County would be lost with 1.6 feet (50 cm) of SLR and 26.5% lost with 3.3 feet (1 m) SLR (Patsch & Reineman, 2024). Under a scenario of 3.3 feet (1 m) of SLR combined with storms expected to occur annually, 230 commercial establishments, 7,600 jobs, $0.95 billion in sales, and $1.1 billion in GDP become vulnerable (SDRCC & Middlebury Center for Blue Economy, 2018). Water-related infrastructure impacts may include damage to stormwater outfalls, sewer pipelines, and pumping stations (Sangsefidi, Barnes, et al., 2023; Stephens, 2023). Under 2.5 feet (0.8 m) of SLR, flooding is projected along low-lying segments of State Route 75 (SR-75), particularly along Silver Strand, portions of the downtown Trolley Green Line, and several bridges and railroads near lagoons (SANDAG, 2020).

Tribal access and cultural resources are also at risk from SLR. Historical land dispossession along the Southern California coast has resulted in many Tribes in the San Diego region losing jurisdiction over their ancestral coastal homelands, with lasting consequences for cultural practice, food sovereignty, and stewardship (Lightfoot, 2006; Middleton, 2011). As a result, most federally recognized Tribes in San Diego County lack coastal trust lands and face legal and regulatory barriers to accessing shorelines for traditional gathering of marine foods, plants, and other cultural resources (Ocean Protection Council, 2023). California's Ocean Protection Council's (OPC) SB 1 (2021) Tribal Cultural Resources Funding Program provides funding for Tribes to assess and plan for the impacts of SLR on their ancestral lands and cultural resources (SDRCC et al., 2023). Furthermore, OPC's Tribal Engagement Strategy provides a framework to ensure meaningful and consistent, government-to-government consultation and collaboration with California Native American Tribes on ocean and coastal issues.

3.1.3 Beaches, Dunes, and Cliffs

Beaches are naturally fluctuating landscapes. Historical analyses of beach width provide valuable insights into how San Diego County beaches have responded to and recovered from severe storm and regional nourishment efforts. The period from 2016–2023 marked the most recent El Niño–Southern Oscillation (ENSO) recovery phase. Most North County beaches experienced a net loss over this seven-year period, owed to two winters with frequent atmospheric rivers (2017 and 2023) and an extreme wave event in January 2021. Nearly all San Diego County State Beaches recorded negative trends in annual beach width between 2021–2023, ranging from -3 to -9 feet (-0.9 to -2.7 m) per year (SIO, 2023). Fortunately, the 2024 El Niño impacts were mild compared to those of 2010 and 2016, allowing most beaches to experience slight gains or only minor losses in width during 2024. Notable anomalies include a sudden increase in width of 65 feet (19 m) at Moonlight State Beach from a beach nourishment project and a loss of 30 feet (9m) at Silver Strand during the 2024 El Niño year, despite a positive long-term trend of +3 feet (0.9 m) per year from 2016 to 2023 (SIO, 2024).

Beach nourishment, the practice of adding sand to the shoreline to offset erosion, has been widely used in the San Diego region to mitigate coastal erosion and maintain beach width. Beach loss, if significant enough and combined with rising sea level, can lead to a loss of recreational activities—beach nourishment helps counter this. Notably, SANDAG has a monitoring program

studying sand transport since 1996 and has implemented two large-scale nourishment projects, placing a total of 3.6 million cubic yards (2.7 million m^3) of sand on regional beaches in 2001 and 2012 at a combined cost of $44 million. Following the 2001 Regional Beach Sand Project (RBSP I), which placed sand on 12 badly eroded local beaches, SANDAG developed a Coastal Regional Sediment Plan to facilitate sand management on a regional basis (SANDAG & California Coastal Sediment Management Workgroup, 2009). SANDAG carried out the 2012 Regional Beach Sand Project (RBSP II) which placed sand on eight beaches. Monitoring results showed that beaches that were nourished by RBSP II were on average 33 feet (10 m) wider and 3–6 feet (0.9–1.8 m) higher in 2015–2016 than in 2009–2010 (SANDAG, 2020).

Beach nourishment varies in effectiveness and impact. Coastal monitoring has shown that outcomes depend on factors such as sand grain size, placement methods, and local wave dynamics. For example, projects using coarse-grained sand have demonstrated greater longevity and resistance to erosion compared to those using finer sediments, which are more easily transported offshore during high-energy storm events (Ludka et al., 2023). While beach nourishment offers important benefits (enhanced recreational opportunities, protection of low-lying areas from wave overtopping, and support for local economies), it also involves trade-offs. Potential negative impacts include elevated groundwater levels, as observed in Imperial Beach, and ecological disruptions, such as smothering intertidal habitats or altering estuarine mouth dynamics. For instance, the Tijuana River Estuary experienced closure following an adjacent beach nourishment project (Ludka et al., 2023).

Box 3.2: *Beach Adaptation Projects*

SANDAG is leading the planning for ***Regional Beach Sand Project III*** which proposes placing up to 4.8 million cubic yards (3.7 million cubic meters) of sand on 15 sites in San Diego County from Oceanside to Imperial Beach, and up to 1.6 million cubic yards (1.2 million cubic meters) of sand on three sites in southern Orange County (SANDAG, 2025b).

The City of Oceanside is working on design and permitting for a pilot project called ***Re:BEACH Oceanside***, which will construct an offshore reef between 2026–2027 to slow wave energy complemented by two artificial headlands in the nearshore to stabilize sand on the beach along Oceanside's south coast.

San Diego Port Authority is leading the ***Living Shorelines*** project, an adaptive strategy designed to mitigate the effects of SLR and protect natural resources in San Diego Bay. The project includes creating habitats, such as native oyster reefs and coastal vegetation areas, to stabilize sediments and protect the shoreline in south San Diego Bay (Quandt et al., 2022).

Coastal dunes are an integral feature along San Diego's beaches, providing natural protection against storm surges and coastal erosion. San Diego's coastline from the Mexican border to the top of San Diego Bay (Zuniga Point) contained approximately 642 acres (2.6 km^2) of coastal dunes in the late 1880s, but by 2016, 62% of this habitat had been lost (Baxter et al., 2025). In response to increasing shoreline erosion and the growing threat of SLR, dune restoration experiments are underway at several sites in the region, including Border Field State Park, Cardiff State Beach, and South Ponto Beach. The City of San Diego's Draft Coastal Resilience Master Plan (2024) identifies additional beaches for potential dune restoration, while the City of Oceanside and the US Department of Fish & Wildlife are exploring restoration concepts for areas near Oceanside Harbor. Some of San Diego's dunes are currently being monitored which helps to evaluate effectiveness in mitigating storm damage and responding to coastal hazards (Marraffini et al., 2024). Preliminary research on the Cardiff dune-berm structure has shown that it significantly reduced backshore

and coastal highway flood vulnerability. However, adaptive maintenance was required to address rainfall runoff erosion, and more maintenance may be needed if more frequent energetic wave events erode the foredune (Winters et al., 2020).

Cliff erosion in San Diego County threatens coastal infrastructure, public parks, beach access locations, residential structures, highways, railways, and more. Cliff erosion rates vary widely depending on climatic forces, geologic conditions, cliff and shore geometry, and broader coastal setting. A three-year study of weekly cliff erosion in Del Mar found that erosion at the cliff toe was correlated with wave impact height and duration, while rainfall was more strongly correlated with erosion of the upper cliff (Young et al., 2021). Further, weak cliff faces retreat at twice the rate of cliffs with medium or high material hardness. San Diego County cliffs have relatively low hardness compared to other coastal cliffs in California, making them more susceptible to erosion (Swirad & Young, 2022). Between 2010 and 2016, Sunset Cliffs experienced the most significant erosion in the county, with both the cliff top and face retreating at mean rates of 1.47 feet (0.45 m) per year and 1.41 feet (0.43 m) per year, respectively. Cliffs in Carlsbad exhibited the second and third highest erosion rates between 2010 and 2016. The southern portion of the reach eroded at a mean rate of 0.75 feet (0.23 m) per year along the cliff face, while the Cannon Road reach in Carlsbad experienced an average rate of 0.45 feet (0.14 m) per year (SIO, 2024; Swirad & Young, 2021, 2022; Young, 2018). Coastal cliff erosion can expose Tribal cultural sites and artifacts (Gallegos, 2017), placing them at risk of disturbance, theft, or loss. In extreme cases, cliff erosion can be lethal; in 2019, a coastal cliff collapse in Encinitas killed three people.

The response of cliff erosion to future SLR is complex and varies with shoreline geometry and SLR scenarios, suggesting that future cliff erosion rates will also be variable (Matsumoto et al., 2024). To help mitigate erosion impacts, researchers at Scripps Institution of Oceanography are conducting research to inform the development of a coastal cliff alert warning system (Cook et al., 2024). Current study sites include Beacons, San Elijo State Beach, and Del Mar. These issues highlight the importance of continued coastal hazard monitoring and coastal risk assessment, coupled with efforts to address erosion risks.

3.1.4 Coastal Estuaries

San Diego County wetlands are already undergoing significant changes driven by rising sea levels. While increased precipitation can produce positive effects such as freshwater input and sediment delivery, large stream discharge events can lead to prolonged inundation and the delivery of pollutants and excess nutrients, negatively affecting marsh vegetation. Wetlands with greater wave exposure, such as those near open inlets, tend to experience greater loss of vegetated habitat. For example, the San Luis Rey Estuary has seen vegetation declines linked to rising temperatures, above approximately 63°F (17°C), particularly among salt marsh species sensitive to high vapor pressure deficits (Doughty et al., 2024).

During the 2015–2016 El Niño, large wave events caused substantial sand accretion at the mouths of intermittently closed estuaries. The Tijuana River Estuary experienced its first inlet closure since 1983, primarily due to wave-driven sediment deposition and low precipitation. At Los Peñasquitos Lagoon, closures lasted up to 36 days and required mechanical breaching to mitigate flooding risks. Prolonged closures exacerbated water quality issues, leading to hypoxia and fish kills. Southern estuaries such as the Tijuana River Estuary, which are more exposed to large waves

due to the geometry of the Southern California Bight, experienced higher estuary mouth closure frequencies compared to northern sites (Harvey et al., 2020).

Tailored management strategies offer opportunities to maintain wetland resilience. Sediment augmentation in transition zones can help large, low-elevation wetlands maintain surface elevation and avoid drowning (Doughty et al., 2024). Creating wide transition zones (up to 500 yards or 450 m) facilitates vertical vegetation migration in response to SLR, enhancing ecosystem resilience (SCWRP, 2018). Planting species such as saltmarsh cordgrass (*Spartina foliosa*) can stabilize sediments and promote organic carbon accumulation (He et al., 2025) in the upper marsh. Although not tested in San Diego, an additional marsh restoration effort includes the use of dredged sediment to elevate wetland surfaces, promoting vertical accretion at rates exceeding 0.23 inches (6 mm) per year, sufficient to keep pace with projected SLR (SCWRP, 2018; Harvey, 2020).

Improving estuary mouth dynamics is also critical. Adaptive methods, such as restoring natural tidal flows, periodic strategic dredging, and deploying mobile barriers, can reduce inlet closures by up to 30% in bar-built systems like Los Peñasquitos Lagoon (Biggs et al., 2022). Additional strategies include periodic dredging combined with permeable structures to stabilize flows and prevent sediment blockages (Shipley et al., 2023). San Elijo Lagoon saw significant increases in wetland area following restoration efforts that enhanced tidal circulation and reduced eutrophication.

In estuarine systems such as the Tijuana Basin, excess organic matter can lead to hypoxia (i.e., reducing dissolved oxygen levels below 2 mg/L). These low oxygen conditions critically affect fish and mollusk populations (Biggs et al., 2022; SCWRP, 2018). Increasing water flow through restored tidal inlets and channels has been shown to improve oxygen levels by up to 15% within three months (Harvey et al., 2020). Despite these efforts, urbanized regions have seen a 25% decline in key marsh species such as California killifish (*Fundulus parvipinnis*), although local restoration initiatives have helped stabilize some populations (He et al., 2025). While highly variable between salt marshes, SLR may reduce plant diversity in salt marshes due to increased competitive pressures. However, native species occupying higher elevations may gain a relative advantage over non-native species, which often have lower salt tolerance (Uyeda et al., 2013).

Box 3.3: *Estuary Adaptation Projects*

The ***Otay River Restoration Project***, located in South San Diego County's Lower Otay River Watershed, aims to rehabilitate over 300 acres of river, floodplain, and upland habitats. Efforts include re-establishing natural hydrology, removing invasive species, and enhancing upland buffers.

The ***De Anza Natural Plan*** was adopted by the City of San Diego in May 2024 and is pending certification by the California Coastal Commission. The long-term development plan aims to enhance and revitalize De Anza Cove for continued recreation, low-cost visitor accommodations, and wetland restoration. In the plan, over 225 acres of wetlands will provide habitat and improved water quality, and 48.5 acres will provide for low-cost visitor accommodation including camping, boating, and other recreational activities.

WILDCOAST's Blue Carbon: Restoring Coastal Wetlands in Southern California project focuses on restoring iconic wetlands such as the San Dieguito Lagoon and Batiquitos Lagoon. By removing invasive species and planting native vegetation, the project enhances the capacity of these wetlands to store carbon while providing protection against climate change impacts. Additional wetland restoration and adaptive management initiatives are also underway in the Chollas Creek watershed and Los Peñasquitos Lagoon. Lower Otay, Mission Bay, and Chollas Creek have reached out for consultation with Kumeyaay resource advisors for their expertise, Traditional Knowledges, and guidance for the project.

3.1.5 San Diego Marine Ecosystems

San Diego's nearshore and offshore waters are part of the larger California Current Ecosystem (CCE). Understanding climate-driven changes in San Diego's marine environment often requires consideration of broader oceanographic trends in the CCE and the Southern California Bight. The region's 11 Marine Protected Areas (MPAs)—including three no-take zones, five State Marine Conservation Areas, and three State Marine Reserves—also serve as valuable reference sites for tracking habitat change, species shifts, and coastal water quality. The primary climate-related stressors affecting San Diego's marine ecosystems are increasing temperatures, ocean acidification, and hypoxia.

Long-term records show significant warming of both surface and bottom waters. Sea surface temperature (SST) at Scripps Pier in La Jolla has increased by approximately 2.23°F (1.24°C) per century, with seafloor temperatures rising by about 3°F (1.67°C) (Rasmussen et al., 2020). When confined to data since 1950, the SST warming trend strengthens to 4.6°F (2.56°C) per century, consistent with observations of a 4.5°F (2.5°C) warming trend offshore Southern California between 1949 and 2020 (Lund, 2024). Temperature changes have been associated with species shifts in marine ecosystems between Baja and Monterey (Lonhart et al., 2019). SST warming is accompanied by more frequent and intense marine heat waves (Fumo et al., 2020). The North Pacific's third-largest marine heat wave in 2022 caused SST anomalies of approximately 3.6°F (2 °C) in the southern CCE (Thompson et al., 2024). Recent model projections suggest SSTs in the California Current System will continue warming by approximately 0.54°F (0.3°C) per decade through 2050 (Alexander et al., 2018; Varela et al., 2023).

The southern California Current is especially vulnerable to ocean acidification because of its proximity to upwelling zones, which bring CO_2-rich waters to the surface. Over the past 37 years, regional pH has declined at a rate of 0.0015 ± 0.0001 per year (Wolfe et al., 2023). This acidification trend, combined with a slight decrease in phosphate, reflects broader changes in the region's carbonate chemistry. These shifts threaten organisms such as snails and bivalves that rely on

calcium carbonate for shell and skeleton formation and may contribute to degradation of intertidal habitats and biodiversity loss (Wolfe et al., 2023).

The southern CCE has experienced a long-term decline in subsurface dissolved oxygen (DO), causing the hypoxic boundary (the depth at which oxygen becomes critically low) to rise closer to the surface. This DO decline is more severe in coastal areas, including those near San Diego, than in the open ocean (Shi et al., 2023). By the end of the century, models suggest that hypoxic conditions could persist for up to 65% of the summer period in the southern CCE (Shi et al., 2023).

Box 3.4: *Harmful Algal Bloom Forecast*

Harmful algal blooms (HABs) illustrate the combined effects of rising temperatures, acidification, and hypoxia, which alter nutrient availability. Certain diatoms are uniquely adapted to survive in nutrient-deprived environments. This adaptation promotes the production of domoic acid, a potent neurotoxin responsible for HAB toxicity. HABs can lead to substantial economic losses in fisheries and aquaculture, mass mortality events among marine mammals, and significant human health risks (Brunson et al., 2024). In summer 2023, a major domoic acid-related HAB event affected the southern CCE. In San Diego County, numerous animals displayed erratic behavior, including more than 30 reported attacks on beachgoers (SCCOOS, 2023). Additional domoic acid events occurred in late 2024 and 2025 with public health warnings to avoid certain seafood.

Efforts to monitor and understand HABs are supported by several initiatives. The monthly ***California HAB Bulletin***, led by the Southern California Coastal Ocean Observing System (SCCOOS), integrates model outputs, near real-time observations, and public health alerts to provide comprehensive regional HAB updates. Since 2019, a real-time HAB tracking and early warning system funded by the Ocean Protection Council (OPC) has further enhanced monitoring. South of the US-Mexico border, a similar HAB monitoring system, the ***Sistema de Alerta Temprana de Florecimientos Algales Nocivos (SiAT-FAN)***, was launched with the collaboration of academic institutions, fishery and aquaculture producers, civil society organizations, and government agencies.

3.2 San Diego's Terrestrial Ecosystems

KEY MESSAGES

- *Chaparral and coastal sage scrub systems are increasingly threatened by shortened fire-return intervals that limit native plant recovery, leading to conversion to invasive grasses that intensify fire frequency, presenting a risk to biodiversity.*
- *Since the 1980s, San Diego's forests have experienced some of the highest rates of tree loss in California, with drought stress, rising temperatures, and insect outbreaks driving widespread mortality and limiting regeneration.*
- *Riparian and aquatic ecosystems are facing more extreme droughts and floods which interact with non-climate stressors such as altered hydrology, pollution, and invasive species, like giant reed, degrading water quality and habitat.*
- *Although habitat loss remains the primary threat, collaborative efforts are increasingly integrating climate adaptation strategies into conservation and management to build regional resilience.*
- *Successful climate-adaptive conservation relies on filling data gaps, translating science into practical strategies, and implementing nature-based solutions through multi-stakeholder partnerships and Indigenous stewardship.*

3.2.1 Introduction

San Diego County is a biodiversity hotspot with a diverse variety of native flora and fauna, many of which are endemic to the region. This biodiversity evolved from the region's unique combination of topography, geology, climate, fire ecology, and human interaction, creating a range of ecosystems, including shrublands, oak woodland and montane coniferous forests, riparian and aquatic systems, grasslands, and deserts (**Figure 3.6**). San Diego County hosts more plant, bird, and mammal species than any other county in the contiguous United States. However, many species are habitat specialists, have narrow geographic ranges, and/or are sensitive to disturbance, putting them at risk of extirpation or extinction.

The region's ecosystems have evolved in relationship with Tribal peoples of San Diego County. For countless generations, Indigenous communities have tended these lands through practices that sustained biodiversity and ecological balance. This relationship has been substantially altered over the last 250 years. Development and land-use change in San Diego County have led to extensive habitat loss and fragmentation, making continued development the most immediate threat to native species and ecosystems, especially at wildland-urban interface.

Nearly 30 years of collaborative conservation planning and implementation efforts in San Diego County have resulted in a network of conserved lands designed to protect the region's imperiled species and their habitats. Today, over 55% of San Diego County's landscape now receives some degree of protection from development (Kalansky et al., 2018). However, these areas are increasingly facing threats of changing climatic conditions, particularly for species that are already imperiled. The vulnerabilities to and impacts from climate change and external stressors are unique to each ecosystem's processes and inhabitants.

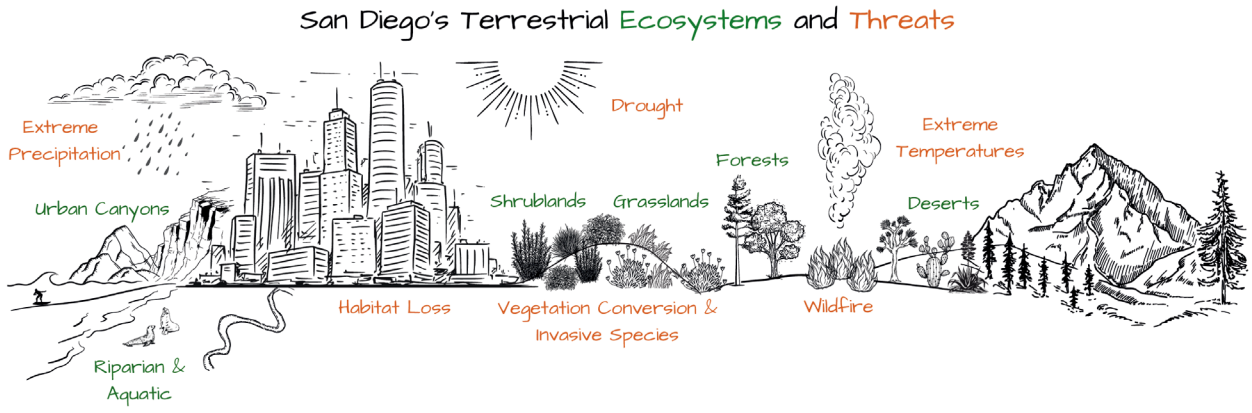


Figure 3.6: *Major terrestrial ecosystems across the San Diego region (labeled in green) and the primary climate- and human-driven threats they face (labeled in orange). Graphic provided by Elly Gay, San Diego State University.*

3.2.2 Ecological Impacts Across Ecosystems

SHRUBLANDS

San Diego County is dominated by biologically diverse chaparral and sage scrub shrublands that are often intermixed with grasslands, oak woodlands, and conifer forests at higher elevations. Chaparral is generally resilient to San Diego's semi-arid climate with extended summer drought and variable interannual precipitation. Direct habitat loss and fragmentation are the primary threats to these shrublands (Syphard et al., 2018) and the species that inhabit them, like the coastal sage scrub specialist conservation flagship species, the California gnatcatcher (*Polioptila californica californica*). But shrublands and associated species are also affected by shorter intervals between wildfires (Kus et al., 2024; Pratt, 2022; Syphard et al., 2019).

Given the profound impact of vegetation type conversion from woody shrubs to invasive grass, the primary climate threat facilitating this conversion in shrublands has been fire. With population growth and urban expansion, human-caused wildfires have increased fire frequency well beyond the 10–30 years many shrubs need to regenerate and re-establish dormant, fire-cued seed banks (Grupenhoff & Safford, 2024). If fire recurs within this window, recovering species can be replaced by invasive grasses (Park & Jenerette, 2019; Pratt, 2022; Syphard, Brennan, et al., 2022). These grasses are highly flammable and facilitate a grass-fire cycle that increases fire risk to people and threatens biodiversity (Fusco et al., 2022; Lee West et al., 2025).

Unlike other ecosystems, climate change has not had a significant direct influence on wildfire activity in San Diego because climatically extreme wildfire conditions are present every year (Grupenhoff & Safford, 2024). However, precipitation extremes can affect both wildfire conditions and post-fire recovery. High precipitation can promote prolific growth of annual grasses, increasing fire activity in the following year (Hernández Ayala et al., 2021; Keeley & Syphard, 2025), particularly when followed by an anomalously dry autumn (Cayan et al., 2022) and strong Santa Ana winds. In contrast, drought can promote dieback in chaparral through direct mortality (Aguirre et al., 2024; Jacobsen & Pratt, 2018) or a reduced resistance to pathogens (Drake-Schultheis et al., 2020). Furthermore, drought-fire interactions in shrublands can facilitate faster spread in wind-driven fires (Keeley et al., 2022; Keeley & Zedler, 2009) and create a feedback cycle, with drought inhibiting chaparral establishment and recovery after a fire (Dewees et al., 2022; Jacobsen & Pratt, 2018; Syphard et al., 2022; Syphard et al., 2019). Drought can also lower fire severity in shrubland ecosystems, which create conditions that favor the persistence and expansion of invasive grasses (Kimball et al., 2024).

Climate, wildfire, and vegetation change can interact to affect shrublands via additional invasive species. Two in particular have been expanding in San Diego County shrublands: fountain grass (*Pennisetum setaceum*) and stinknet (*Oncosiphon pilulifer*). Both are highly flammable and can subsequently colonize disturbed landscapes. In the absence of wildfire, there is high likelihood for climatically driven range shifts for many plant species (Molinari et al., 2018), further affecting fuel volume, arrangement, and moisture, and in turn, wildfire (Syphard et al., 2019). Fuel breaks and other treated areas can facilitate dispersal and establishment of invasive grasses (Brennan & Keeley, 2017; Grupenhoff & Molinari, 2021; Merriam et al., 2006). While strategically located fuel breaks are important for firefighter access (Gannon et al., 2023; Syphard et al., 2011), their placement and maintenance should be weighed against their ecological costs.

In 2021, a statewide analysis found that Southern California has lost a higher proportion of conifer forest and oak woodland cover since 1985 than any other region of the state (Wang et al., 2022). In San Diego County, two prominent areas of forest loss emerged after the Cedar Fire in 2003 and the Chariot Fire in 2007, in the vicinities of Cuyamaca Peak and Garnet Peak (Franklin et al., 2006; Franklin & Bergman, 2011; Goforth & Minnich, 2008; Safford & Vallejo, 2019). On the ground, forest loss is a dynamic process that develops over years, often through severe wildfire and subsequent failure of forest regeneration. Regional climatic shifts have contributed to both increases in severe fire effects and regeneration failure with cascading impacts for plants, wildlife, and people.

Drought is a major driver of tree mortality in forested systems (Allen et al., 2015), caused by a combination of periods of low precipitation and high evaporative demand from warming air temperatures (Diffenbaugh et al., 2015). Increasing temperatures will also intensify drought stress in forests (Naumann et al., 2018), decreasing soil moisture and resulting in higher baseline forest mortality (van Mantgem et al., 2009). Drought stress also limits natural regeneration because seedlings and saplings rely on multi-year wet periods thereby decreasing the likelihood of successful recovery during droughts (Safford & Stevens, 2017). At montane elevations, changes in the amount and timing of snowfall also affect forest health. San Diego's mountains have already experienced a reduction in the number of freezing months per year. For example, the freezing season on Mt. Palomar is a month shorter now compared to 75 years ago (Molinari et al., 2018).

Drought-stressed conifer trees are often more susceptible to insect attack because they produce fewer secondary defense compounds and maintain lower energy reserves to protect themselves (Anderegg et al., 2015; Raffa et al., 2008). Bark beetles are among the most impactful insects in conifer forests. A 1999–2003 drought triggered a western pine beetle outbreak across Southern California that killed millions of trees (Fettig, 2019; Kolb et al., 2016; Minnich, 2007; Minnich et al., 2016). There is past evidence of upslope shifts in conifer distribution resulting from stress at lower elevations during drought (Freeman et al., 2017). In contrast, the gold-spotted oak borer (GSOB) is driving mortality of mature oaks, but drought stress does not appear to increase the risk of infestation (Coleman et al., 2011). Old growth oaks are more susceptible to GSOB mortality, even though their deep root systems minimize their drought exposure compared to adjacent, smaller oaks (Coleman et al., 2011). In northern San Diego County, the La Jolla Band of Luiseño Indians has documented severe cultural and economic impacts from GSOB and is advancing forest-management research and adaptation planning in response to climate change and GSOB, supported by California Department of Conservation and US Bureau of Indian Affairs funding (UCANR, n.d.).

A contributing factor to forest stress from climatic changes is the history of fire suppression over the last century, which produced overly dense forests and accumulations of fuels (Hagmann et al., 2021). In addition, the outlawing of Indigenous land management practices, including traditional cultural burning, disrupted long-standing stewardship that had previously maintained forest resilience (Anderson, 2005; Lake & Long, 2014). These altered fire regimes are now interacting with the warming and drying climate and insect outbreaks resulting in more severe wildfire impacts (Hessburg et al., 2021). Drought and insect-induced mortality create additional fuel, contributing to increases in high-severity burn area detected across the western US and

in Southern California's wildlands (Stephens et al., 2018; Parks & Abatzoglou, 2020; Nigro & Molinari, 2019). Forest habitat species, such as the California spotted owl (*Strix occidentalis occidentalis*), have been affected by the decline in forest conditions as evidenced by reductions in territory occupancy and reproductive output in Southern California associated with forest disturbance (Tempel et al., 2022).

RIPARIAN & AQUATIC SYSTEMS

San Diego County's riparian and aquatic ecosystems support some of the region's most vulnerable species and provide valuable ecosystem services. Many species in these habitats are unique to the area, so their survival depends on the resilience of the ecosystem. For example, riparian and bottomland forests provide crucial habitat for endangered species like the least Bell's vireo (*Vireo bellii pusillus*) (US Fish & Wildlife Service, n.d.). These forests improve water quality and help buffer against flooding (California Coastal Commission, n.d.; Gay et al., 2023) as well as fire. Additionally, these habitats are where tule is found, a wetland sedge (*Schoenoplectus acutus*) also known as bulrush that was widely used by San Diego's Indigenous communities to make thatch dwellings and boats. However, stream health in Southern California is a growing concern as the region has the lowest percentage of streams in healthy conditions compared to other parts of the state (Rehn, 2021). Similarly, vernal pools, which fill during the wet season and completely dry during the summer, support species adapted to these temporary ponds (Bai & Cotrufo, 2022; Bailey et al., 2019; Keeley et al., 2023; Luong, 2022). However, climate change threatens the ability of these riparian and aquatic habitats to support vulnerable species and provide ecosystem services.

The primary climate threat to San Diego County's riparian and aquatic ecosystems is the intensification of precipitation and temperature extremes, which exacerbate events like severe drought and extreme flooding. Historically, these ecosystems have adapted to the region's seasonal variability (**Figure 2.11**). However, recent studies indicate that anthropogenic warming will amplify these events, increasing the intensity of wet and dry extremes (**Figures 2.9, 2.12**). This will result in higher peak flows and lower low flows (Mallakpour et al., 2018), leading to ecosystem degradation such as riparian woodland mortality (Kibler et al., 2021).

Wildfire is also an increasing threat to riparian and aquatic systems. Post-fire landscapes experience reduced infiltration, limiting recharge and increasing runoff, which can degrade stream water quality, affecting biodiversity and drinking water quality. When wildfires remove the riparian canopy, the resulting light exposure in aquatic systems has been shown to increase algal biomass by five to 20 times (Klose et al., 2015).

Non-climate stressors interact with climate changes to exacerbate water quantity and quality issues in aquatic and riparian ecosystems. The hydrologic landscape of the region has been significantly altered to mitigate flooding and meet human water demands. Historically, the San Diego River flowed uninterrupted from its headwaters in the Cuyamaca Mountains of the Cleveland National Forest to its delta at the Pacific Ocean. Today, the river is confined by hardened channels and dams (City of San Diego, 2005). These modifications have removed the river's natural meanders, which provided vital habitat and slowed water flow. During storms, untreated wastewater becomes the primary source of pollution in the watershed, often due to leaking infrastructure (Mladenov et al., 2020).

Invasive species are another major stressor to these ecosystems, outcompeting native plants and animals, altering river geomorphology, and exacerbating flooding. A troubling example is giant reed (*Arundo donax*), which obstructs wildlife corridors and nesting habitats in riparian areas and alters channel geomorphology with its dense growth, negatively impacting fish and amphibian species (California Invasive Plant Council, 2011). As of 2011, more than $70 million had been spent controlling giant reed between the Monterey and San Diego area. This region is one of only two areas in the US where giant reed infestation is considered severe.

GRASSLANDS

Grasslands were once a prominent component of California's ecosystems, but today, only about 1% of the state's native grasslands remain intact. In San Diego County, approximately 140 acres of grasslands persist (US Fish and Wildlife Service, n.d.). Grasslands fall into two main vegetation types: 1) native perennial grass and forblands, which comprise a smaller fraction of what remains and are characterized by species like purple needlegrass and blue-eyed grass, alongside a diverse array of forbs that contribute to their rich biodiversity; and 2) non-native grasslands, dominated by annual invasive grasses (Minnich, 2008). The dense structure, earlier phenology, and decreased diversity of annual grasslands reduces the overall level of ecosystem services provided, but with active management, can provide habitat for native species (McCullough Hennessy et al., 2016). Grasslands are experiencing fluctuations in climate drivers such as rising temperatures and changes in precipitation patterns, along with non-climate factors such as habitat fragmentation, overgrazing, and the spread of invasive species.

Annual grasslands are strongly controlled by climatic factors where year-to-year composition and productivity are driven by precipitation and temperature rather than activities such as grazing (Jackson & Bartolome, 2007). Warming trends have become a primary climate driver in San Diego grasslands, which are at risk of becoming more arid and warmer in the face of climate change (Mayer & Silver, 2022), placing growing stress on native species. Prolonged droughts can reduce grassland primary productivity by as much as 38%, threatening ecosystem stability and functionality (Smith et al., 2024). Declining soil moisture reduces biomass production and weakens root structures, increasing erosion risk (Chavez Rodriguez et al., 2024), while high temperatures amplify evapotranspiration, further stressing water-limited vegetation (Nelson et al., 2023). Nitrogen from anthropogenic sources can further compound grasslands' sensitivity to drought (Fenn et al., 2010; Bharath et al., 2020; Suding et al., 2024). These interacting climate drivers influence grassland composition, leading to a decline in native biodiversity.

Invasive species have transformed many perennial grasslands into non-native annual grasslands (Minnich, 2008), highlighting the need to protect the grasslands where native species persist (Catford & Jones, 2019; Harrison et al., 2024). While invasives often outcompete native species, extreme drought conditions may weaken invasive grass seed banks, and native annual forbs demonstrate resilience through increased seed bank presence, indicating potential for recovery and adaptation (LaForgia et al., 2018). In particular, managed grazing and beneficial fire, including prescribed and cultural burning, can be used to enhance native grassland resilience, though overgrazing risks type conversion and inadequate follow-up can lead to woody species encroachment (Bai & Cotrufo, 2022; Bailey et al., 2019; Keeley et al., 2023; Luong, 2022).

DESERTS

San Diego features expansive desert ecosystems with diverse vegetation communities, including desert scrub, dunes, playas, and badlands. These ecosystems host an array of flora and fauna, including iconic species like the Peninsular bighorn sheep (*Ovis canadensis nelsoni*) and numerous plants and animals adapted to endure the region's harsh conditions. Climate change is driving more frequent and severe extreme heat events, particularly in arid and transition-zone ecosystems. While desert species are adapted to extreme climate conditions, some taxa (including shallow-rooted desert shrubs, annual plants, reptiles, and certain desert mammals) may already live at their physiological limits, necessitating behavioral and morphological adaptations or shifts in their distributional ranges to survive in changing environments (Weiskopf et al., 2020). Extreme temperatures can inhibit germination and have led to significant loss of vegetation, with key species such as brittlebush (*Encelia farinosa*) experiencing high mortality rates (Potter, 2019).

The interaction of extreme temperatures and prolonged drought can disrupt desert ecosystems by increasing wildfire susceptibility through plant mortality (Keeley et al., 2022). Increasing aridity and drought events, particularly after fire, create opportunities for invasive species to establish (Overpeck & Udall, 2020; McDermott, 2024). These combined stresses alter plant communities and phenology, with earlier germination and delayed blooming disrupting ecological interactions, such as pollinator-plant relationships and dependent species (Heller & Zavaleta, 2009; Johnson et al., 2023).

Agriculture, urban development, and recreation have historically led to habitat loss in the desert ecosystem. In the past two decades, energy development has intensified, leading to extensive vegetation removal across California (Dunlap et al., 2025; Smith et al., 2023). These stressors can lead to homogenization of soils and topography, changes in microclimate, and establishment of invasive species (Karban et al., 2024), reducing climate resilience and disrupting local carbon sequestration and increasing soil erosion (Smith et al., 2023).

URBAN CANYONS

There are over 150 urban canyons in San Diego (USD et al., 2024) that are islands of undeveloped land among a sea of urbanization. The region's system of coastal canyons provides important natural landscapes within the urban matrix (Crooks, 2002) and is host to 85 rare species of plants and animals (USD et al., 2024). Given the urban landscape in which these canyons are situated, most are readily accessible and provide important recreational opportunities for local communities. While their location within the urban landscape of a major metropolitan area provides important remnant habitat and connectivity among preserved lands, these areas are also exposed to a host of threats due to their proximity to developed areas. Although climate is not the primary threat in these canyons, it plays a role in urban ecosystem dynamics and species persistence. Heat from surrounding urban landscapes poses the primary climate threat to canyon-dwelling species, though topography may provide some relief through shading and cold-air pooling. Extreme heat is likely to stress plants and animals, particularly if events exceed thermal tolerance levels. The interacting threats of land use change, human activity, fire, and spread of invasives coupled with climatic change put the region's canyons at even greater risk of habitat and biodiversity loss. Without connectivity across the network of urban canyons, canyon-dwelling species are likely to be hemmed in, making them particularly vulnerable and limiting their ability

to adapt to changing climatic conditions. For example, urban canyons are already altered by urban inflows or urban "drool," which creates habitat for persistence of nonnative plants and animals such as crayfish, bullfrogs, giant reed, and fan palm that might otherwise not be able to compete with native species in these landscapes.

3.2.3 Collaborative Climate Adaptive Strategies for San Diego's Ecosystems

Habitat loss and fragmentation have long been the primary threat to San Diego's ecosystems with climate change exacerbating the stressors on these systems. At the 2024 San Diego Biodiversity Conservation Summit, 261 stakeholders identified regional conservation priorities. Climate, collaboration, connectivity, and change were four cross-cutting themes that emerged. The input from workshop participants emphasized that systemic changes are needed to increase regional resilience through system-level planning that includes transboundary management, Indigenous stewardship perspectives and practices through partnerships with Tribes, land-water connections, and applications of nature-based solutions to achieve multiple benefits.

To implement such changes and strategically plan at a system level, collaboration is essential. Collaborative efforts have underpinned San Diego's conservation history and ongoing activities are working to conserve habitats and species by managing a suite of threats, including the impacts of climate change. To support the integration of climate adaptation science into these conservation and land management efforts, the formation of communities of practice and science-management partnerships have been essential. These collaborations have helped build capacity to advance climate adaptation planning and implementation to address conservation and climate challenges.

In western San Diego County, collaborative management across the Multiple Species Conservation Plan preserves has been coordinated by the San Diego Management and Monitoring Program (SDMMP, n.d.). A recent evaluation of the preserve system, which included 19 indicators, determined that the preserve was in a state of "concern" (Preston et al., 2022). Although a separate climate vulnerability assessment has not been undertaken, many indicators, including rare species and key vegetation communities that are regularly monitored, highlighted climate impacts such as prolonged droughts affecting riparian and aquatic species and drought-fire interactions threatening chaparral and coastal sage scrub systems. To guide management, climate-informed habitat modeling and genetic analyses for several target species have been completed (Brehme et al., 2023; Hitchcock et al., 2022; Vandergast et al., 2022). Landscape scale assessments to map areas of refugia and connectivity have already been developed and more studies and monitoring are underway to identify strategies to protect at-risk species and systems.

Refugia are areas that are buffered from the impacts of climate and other stressors, which can provide opportunities for conservation of locations that can adapt at a slower pace than the surrounding landscape (Morelli et al., 2020). Recently, an assessment of refugia for shrublands across Southern California was developed to support nature-based climate adaptation (Rojas et al. 2022). Across the region, two of the three largest contiguous blocks of areas buffered from multiple stressors were in the valleys and foothills of the central part of San Diego County (Rojas et al., 2022). In contrast, a similar assessment for montane forest systems of Southern California revealed that San Diego's mountains were less buffered than the mountains to the north (Jennings et al., 2025). The results of these analyses highlighted shrubland areas to conserve and areas where the risk of forest loss could be mitigated by reducing vulnerabilities in zones of refugia.

In addition to refugia, connectivity conservation is an adaptation strategy used to enhance the resilience of populations, species, and ecological systems to climate change (Hilty et al., 2019). Although San Diego County has large tracts of undeveloped land, fragmentation threatens the region's biodiversity and its ability to adapt to changing climatic conditions. In 2019, SDSU completed development of a Climate Resilient Connectivity plan for the ecoregion (Jennings et al., 2020). This regional modeling and mapping considered future climate dynamics (Zeller et al., 2020) to identify linkages to support persistence of biodiversity based on a suite of focal species and important landscape features for wildlife movement. The outputs from this research are actively in use, guiding both conservation acquisitions and management of conserved lands.

Connecting fragmented landscapes can also benefit local community resilience. The climate connectivity plan was also used as the foundation for identifying nature-based solutions to link natural resource management and community resilience through collaborative coordination among conservation planners, local jurisdictions, and Tribal communities. That effort, the *Connecting Wildlands and Communities* project, produced an interactive map portal with climate projections, data on the impacts of shifting fire regimes, metrics of water quantity and quality, as well as case studies and adaptation menus to guide multi-benefit planning ("Connecting Wildlands & Communities", n.d.). This cross-sectoral, transdisciplinary collaboration has supported conservation, wildfire resilience planning, drought preparedness, watershed protection in natural and built environments as well as ecocultural resilience for Tribal communities.

Box 3.5: *Case Study: Addressing Invasive Species for Multiple Benefits*

One of San Diego's most invasive species is the highly flammable ***Arundo donax***, giant reed, which outcompetes native plants (Kinoshita et al., 2022), alters habitat use by carnivores (Hardesty-Moore et al., 2020), and reduces biodiversity. This species spreads through watersheds and has a limited removal window for chemical treatment due to nesting birds. To enhance connectivity while reducing the risk of fire spread through corridors, focused removal of giant reed can improve habitat, facilitate wildlife movement, and address fire risk. Removal is achieved with a combination of mulching and herbicide but requires diverse participation to manage the spread (M. Liu et al., 2020).

Advancing ecocultural resilience has specifically been a priority of the Climate Science Alliance's Tribal Working Group, a community of practice including representatives of multiple Tribes across Southern California as well as non-Tribal partners. Through a partnership with researchers from the University of California, Riverside, and San Diego State University on the Resilient Restoration Project ("Resilient Restoration", n.d.), models of projected habitat (Rose et al., 2023, 2024) and population shifts (Backus et al., 2023) under climate change were developed for culturally important plant species identified by the working group. Traditional uses of these plants include harvesting of willow and juncus for basketry; cattails (bulrushes), duck weed, and water cress (*Nasturtium officinale*) for food; and other species for craft, arrows, teas, and medicine. Traditional harvesting can also be used to manage the landscape under climate variability such as harvesting in wetlands to thin out riparian species, increasing water availability, though current regulations can inhibit this. The results from the modeling effort were designed to complement Traditional Ecological Knowledges, informing stewardship strategies and capacity-building training. Continued work to track the outcomes of these strategies and share information to guide adaptive management are critical for restoration success.

While advancing climate adaptation efforts is essential to the resilience of San Diego's ecosystems, the protection of land remains a conservation priority and key ecosystem resilience strategy. Under Governor Newsom's Nature-Based Solutions Executive Order (N-82-20), and the Pathways to 30x30 Strategy and the Natural and Working Lands Climate Smart Strategy, the Tribal Nature-Based Solutions (TNBS) Program awarded funding to the Rincon Band of Luiseño Indians and the Iipay Nation of Santa Ysabel for land acquisition. The Tribes each purchased several hundred acres of land for conservation, increasing protected lands and ecosystems in San Diego County, advancing stewardship of Tribal homelands, and reducing barriers for Tribes (Governor of California, 2020), affirming the role of Indigenous leadership in restoring ecosystems, strengthening cultural relationships to place, and advancing climate resilience (Governor of California, 2020).

Taken together, the advancements in conservation and climate adaptation in San Diego over the last decade demonstrate the region's capacity for addressing the challenges ahead. With collaboration and coordination guiding the preservation of the region's diverse terrestrial systems under climate change, ecosystems and communities will be more resilient.

3.3 Agriculture and Food Systems

KEY MESSAGES

- *San Diego's unique climate and geography, spanning urban, rural, and coastal food systems, along with diversified crop production that includes many small, organic farms and a focus on perennial and nursery crops, presents both challenges and opportunities in the face of climate impacts.*
- *Extreme heat, water scarcity, and high cost of land, water, and labor constrain adaptation.*
- *Only a handful of studies have examined the impacts of and adaptation to climate change within San Diego's agriculture and food systems, representing a major gap in knowledge. Research to date has focused on high-value crops including avocados and wine grapes.*
- *Efforts to adapt urban agriculture and food systems include a growing network of community-based organizations, community and school gardens, urban forestry initiatives, and sustainable shellfish and seaweed aquaculture.*

3.3.1 Introduction

San Diego County's diverse climate, geography, and crop production make its agriculture and food systems unique, presenting both challenges and opportunities in the face of climate change. The county is home to 4,031 farms, 68% of which are between 1 and 9 acres (County of San Diego, 2023a). It has more small farms than any other county in the US (San Diego County Farm Bureau, 2025), ranks first in the number of organic farms, and ranks second in farms operated primarily by women. Indigenous agricultural and food sovereignty in San Diego is actively being revitalized through Tribal-led efforts to reclaim traditional foods, land stewardship practices, and cultural knowledges. In 2023, agricultural production totaled approximately $1.7 billion across 210,732 acres (County of San Diego, 2023a). The region's highly diversified agricultural output includes nursery and cut flowers, avocados, lemons, vegetables, oranges, other subtropical fruits, as well as livestock and eggs (**Figure 3.7**).

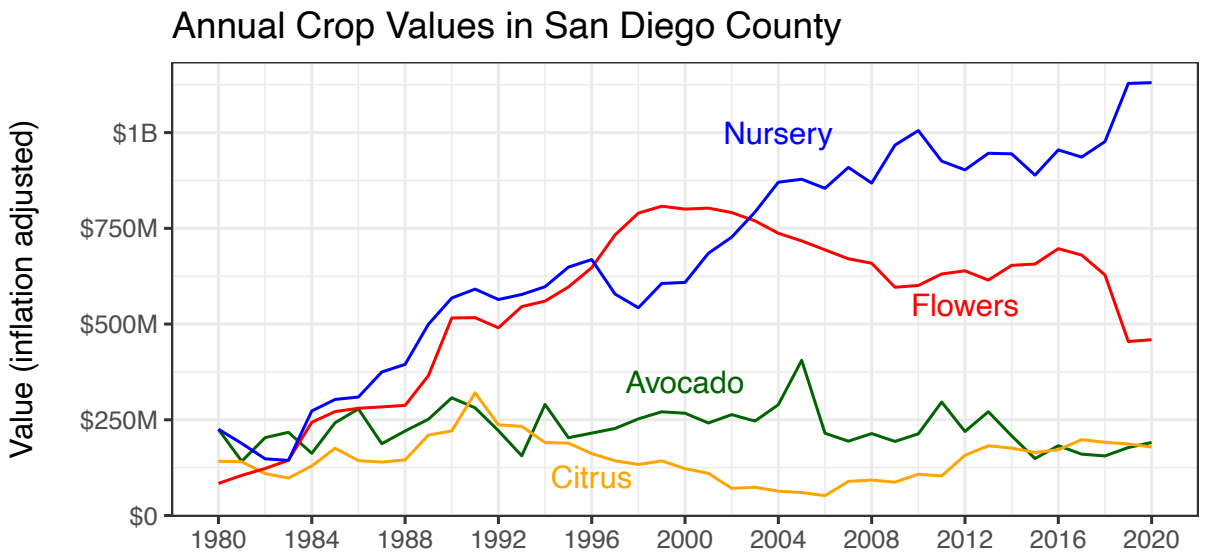


Figure 3.7: *Inflation-adjusted annual crop values in San Diego County for major agricultural commodities from 1980–2020. Nursery crops (blue) show strong long-term growth, exceeding $1 billion by 2020. Cut flowers (red) rose rapidly through the 1990s and early 2000s before declining slightly in recent years. Avocados (green) and citrus (orange) represent a smaller share of total crop value. Data from USDA National Agricultural Statistics Service (NASS) Agriculture Commissioner reports. Figure provided by Tom Corringham, Scripps Institution of Oceanography, UC San Diego.*

Despite its agricultural success, San Diego County also has the highest number of part-time farmers in the US, meaning that many rely on additional sources of income (San Diego County Farm Bureau, 2025). Over the past 15 years, the total acreage dedicated to agriculture has declined by more than 25% (County of San Diego, 2023a). Key challenges for the region's farmers are water scarcity and high water costs, issues that are expected to intensify with climate change. Over the past decade, water costs have risen by an average of 8% annually (Smith et al., 2022). By 2021, agricultural users were paying up to $1,800 per acre-foot of water (Smith et al., 2022), while water purchased from public utilities operated by the City of San Diego was even more expensive, reaching approximately $3,000 per acre-foot (City of San Diego, 2022b).

San Diego County has a thriving urban agriculture movement, including community and school gardens, community-supported agriculture programs in urban areas, and innovative production methods such as hydroponics and aquaponics. The county also has a significant fishing industry, harvesting over 60 species with an annual value exceeding $10 million (County of San Diego, 2019b). Despite this activity, food insecurity remains a pressing issue, with one in four San Diegans experiencing nutrition insecurity (County of San Diego, 2019b).

3.3.2 Impacts of Climate Change on Agriculture and Food Systems

A recent survey of farmers in San Diego County found that 50% of agricultural producers were concerned about extreme heat, while 59% cited drought as a major issue (Bross, 2024; **Figure 3.8**). The frequency, intensity, and duration of extreme heat events are expected to increase in the future, though not all crops will be affected equally (Bross, 2024; Nabors et al., 2022). Notably, 67% of avocado producers in the survey expressed "high concern" about extreme heat, as excessive

temperatures can cause sunburn damage and fruit drop in avocados (Bross, 2024). Precipitation variability is also a key concern among farmers in the county (Bross, 2024; Nabors et al., 2022). Drought can exacerbate plant stress and increase irrigation demands, raising overall farming costs. Meanwhile, flooding poses a recurring threat to low-lying areas, particularly farms in the Tijuana River Valley (Bross, 2024).

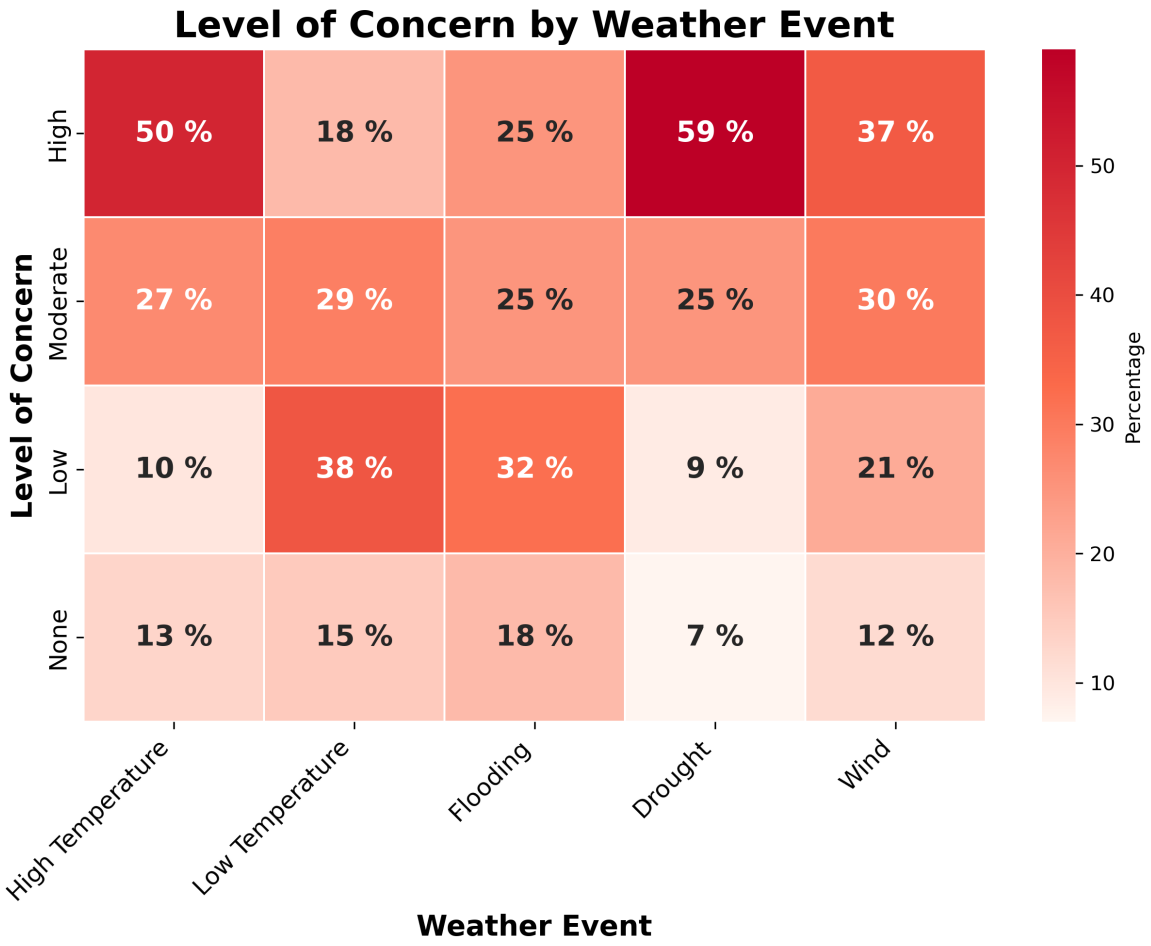


Figure 3.8: *Distribution of farmer concern levels for five extreme weather events in San Diego County (Bross, 2024). Drought and high temperatures elicit the highest levels of concern, with 59% and 50% of respondents reporting high concern, respectively. Figure provided by Judith Bross, San Diego State University.*

Wine grapes face increasing threats from rising temperatures and decreasing precipitation, with growers reporting fewer rain events (73%), more frequent heat (63%), and earlier harvest dates (41%) (Monteverde & De Sales, 2020; Zuniga et al., 2024). Moving forward, further research is needed to better understand how climate change impacts will affect agriculture and food systems in San Diego County, as studies on the region remain limited.

3.3.3 Adaptation in Agricultural Systems

Only a handful of studies have directly explored how agricultural systems in San Diego County are adapting to climate change. Farmers across the county identified key adaptation strategies, including upgrading irrigation systems (64% of respondents), improving soil management to maintain soil health and moisture (47%), and diversifying crops or transitioning to more resilient varieties (46%) (Bross, 2024).

Box 3.6: *Case Study: Agroforestry for Climate Change Adaptation*

Since much of San Diego County's agricultural land is used for perennial crops, incorporating trees and other long-lived plants into farming systems could help farmers adapt to climate change. Agroforestry, the practice of combining trees and shrubs with crops and/or livestock, is one such strategy (Bross, 2024; Quandt et al., 2023). 82% of farmers in the region already implement agroforestry, utilizing practices such as alley cropping, forest farming, riparian forest buffers, silvopasture, pollinator hedgerows, and windbreaks. Agroforestry can help create microclimates with lower mean air temperatures (Gomes et al., 2020), reduce crop transpiration, protect crops from storms with windbreaks (Philpott et al., 2008), and increase soil nitrogen and carbon levels (Haskett et al., 2019). Farmers in San Diego County cited additional advantages such as shade provision, soil moisture retention, habitat for beneficial insects and pollinators, reduced input costs, and cultural and aesthetic value (Bross, 2024). Notably, 62% of surveyed farmers agreed that agroforestry is an effective strategy for adapting to extreme weather in the region (Bross, 2024).

Increasing irrigation efficiency is critical for mitigating the impacts of extreme heat and drought while also reducing water use and costs. This includes adopting micro-irrigation systems such as drip lines, bubblers, and micro-sprinklers, which deliver water directly to plant roots, minimizing evaporation (Nabors et al., 2022). Some farmers are experimenting with innovative techniques such as high-density tree planting to promote soil moisture retention and sensor-based irrigation monitoring (Bross, 2024; Nabors et al., 2022). In recent years, there has been a significant effort to promote and enhance soil management practices, including carbon farming and compost application (San Diego Food System Alliance, 2018). Carbon farming techniques can include applying compost or mulch, cover cropping, and adopting no-till or reduced-till practices to improve soil health and water retention (Batra, 2018; Nabors et al., 2022; San Diego Food System Alliance, 2025).

3.3.4 Indigenous Food Systems in San Diego County

San Diego County has a long history of Indigenous and cross-border agriculture. Before European contact, the Kumeyaay Tribes in the region practiced plant husbandry (cultivation and management of plants), rotational agriculture, and forest farming, including cultural burning, coppicing, and selective harvesting (Nabors et al., 2022; Shipek, 1981). Tribes in the region developed complex, place-based food systems adapted to the diverse microclimates of Southern California. Acorns from coast live oak and black oak were especially important; the Kumeyaay are sometimes described as an Acorn Culture, with sophisticated knowledge systems surrounding acorn processing, storage, and land management (Manzanita Band of the Kumeyaay Nation, 2020; Standiford & Purcell, 2015).

Many Tribal communities continue to engage in agriculture both on and off reservation lands. However, jurisdictional boundaries or lack of access often constrain Tribal peoples' ability to maintain reciprocal relationships with plant communities. The interruption of practices such as seed gathering, cultural burning, thinning, and coppicing contributes to reduced plant population health, distribution, and resilience. Additional pressures, such as illegal poaching of protected plants, such as white sage (*Salvia apiana*), exacerbate climate impacts on Tribal foods and medicines.

To combat these threats, Indigenous food systems in San Diego County are being actively revitalized through Indigenous-led agriculture, education, and cultural knowledge-sharing, reconnecting land stewardship, food sovereignty, and climate resilience. Community scholarship and public education, including the published cookbook of Heather Ponchetti Daly (Iipay Nation of Santa Ysabel), document Kumeyaay relationships to marine foods and advance intergenerational knowledge of harvesting, preparation, and respect for coastal ecosystems (Museum of Us, n.d.; Sepuka, 2024; Talley et al., 2025).

On Tribal lands in North County, Pauma Tribal Farms (Pauma Band of Luiseño Indians) and Golden Eagle Farm (Mesa Grande Band of Mission Indians) demonstrate how Tribal agriculture can support community food access, local economies, and climate-resilient land management through diversified production and conservation-oriented practices (Golden Eagle Farm, n.d.; Intertribal Agriculture Council, 2025; Pauma Band of Luiseño Indians, n.d.; San Diego Food System Alliance, 2021). These place-based efforts are reinforced by regional initiatives such as Indigenous Regeneration (San Diego Foundation, 2024) and countywide planning led by the San Diego Food System Alliance that recognizes Indigenous leadership as foundational to a resilient food system (San Diego Food System Alliance, 2021). The Manzanita Band's Tribal Resilience Project emphasizes food sovereignty, climate adaptation, and Traditional Ecological Knowledges rooted in acorn-based subsistence practices (Manzanita Band of the Kumeyaay Nation, 2020). Together, these initiatives illustrate how Indigenous food systems in San Diego County function as adaptive strategies that support cultural continuity, ecosystem stewardship, and climate resilience.

3.3.5 Urban Food Systems

Urban food systems in San Diego County are evolving to enhance food security and climate resilience through innovative projects that integrate green infrastructure and climate adaptation strategies. For example, Ocean View Growing Grounds, a community garden, food forest, and neighborhood-scale research-to-action learning hub, was a vacant lot transformed by the Advocating Green Infrastructure for Learning and Equity (AGILE) project at the University of California San Diego (UC San Diego Bioregional Center, 2025). Expanding on these efforts, Project New Village is advancing the concept of a "Good Food District", which integrates food production and food waste utilization with environmental restoration (Project New Village, 2025). This initiative provides multiple benefits, including increased access to fresh produce in underserved communities, urban heat mitigation, improved stormwater management, and enhanced soil and ecosystem health. At a regional scale, the San Diego Food System Alliance is developing strategies and policies to support local, integrated, and climate-friendly food systems (San Diego Food System Alliance, 2025). These efforts align with the San Diego Regional Decarbonization

Framework developed by the County, which emphasizes food systems as a key strategy for achieving equitable climate action and carbon neutrality (McCord et al., 2022).

Community gardens play a crucial role in San Diego's urban agriculture, contributing to a more resilient, sustainable, and equitable food system. They help reduce food miles (distance food travels from production to consumption), enhance local food security, stimulate urban biodiversity, mitigate heat island effects, reduce waste, promote circular economies, and foster climate awareness. Additionally, there are approximately 842 school gardens across the county (Joassart-Marcelli et al., 2025; Master Gardener Association of San Diego County, 2025), with at least 78 active community gardens identified in urbanized areas of San Diego County with an annual yield of 2,858 pounds (1,296 kg). However, not all growers have the same capacity to adapt or even participate. Significant disparities exist in access to clean land, healthy soil, financial resources, volunteers, and technical assistance, reinforcing the racial and economic inequities that characterize San Diego's urban food landscape (Joassart-Marcelli, 2024; San Diego Food System Alliance, 2022). These structural barriers shape the ability of urban agriculture to contribute to environmental sustainability and food security (Community Alliance with Family Farmers, 2024).

Trees and urban greening can also contribute to healthy urban environments, and increasing tree canopy is a common goal in climate action plans across the San Diego region. The City of San Diego's Climate Action Plan aims to achieve 35% tree coverage citywide by 2035 to sequester carbon, provide shade during extreme heat events, reduce flooding, and offer local sources of fruit and nuts (City of San Diego, 2022b). However, expanding and maintaining tree canopy presents challenges, including losses from development and drought, and historical inequities in urban greening have resulted in uneven tree cover across neighborhoods.

3.3.6 Aquatic Food Systems

Climate stressors also impact ocean-based food systems (Cheung et al., 2010; Palacios-Abrantes et al., 2022). Some stressors, such as extreme weather events, are localized and short-lived, while others, like species range shifts, extend across multiple jurisdictions and present long-term challenges (Pinsky & Mantua, 2015). Key climate-related challenges for Pacific fisheries include marine heat waves, shifting species distributions, harmful algal blooms, ocean acidification, and increasingly severe storms (Vogel et al., n.d.). Fishers' ability to adapt depends on factors including income, mobility, and permit access, with regulatory constraints identified as greater barriers than individual limitations (Powell et al., 2022). These findings highlight the role of flexible fishery management strategies in supporting fishers' adaptation to climate stressors while maintaining sustainable fisheries (Golden et al., 2024; Mason et al., 2023).

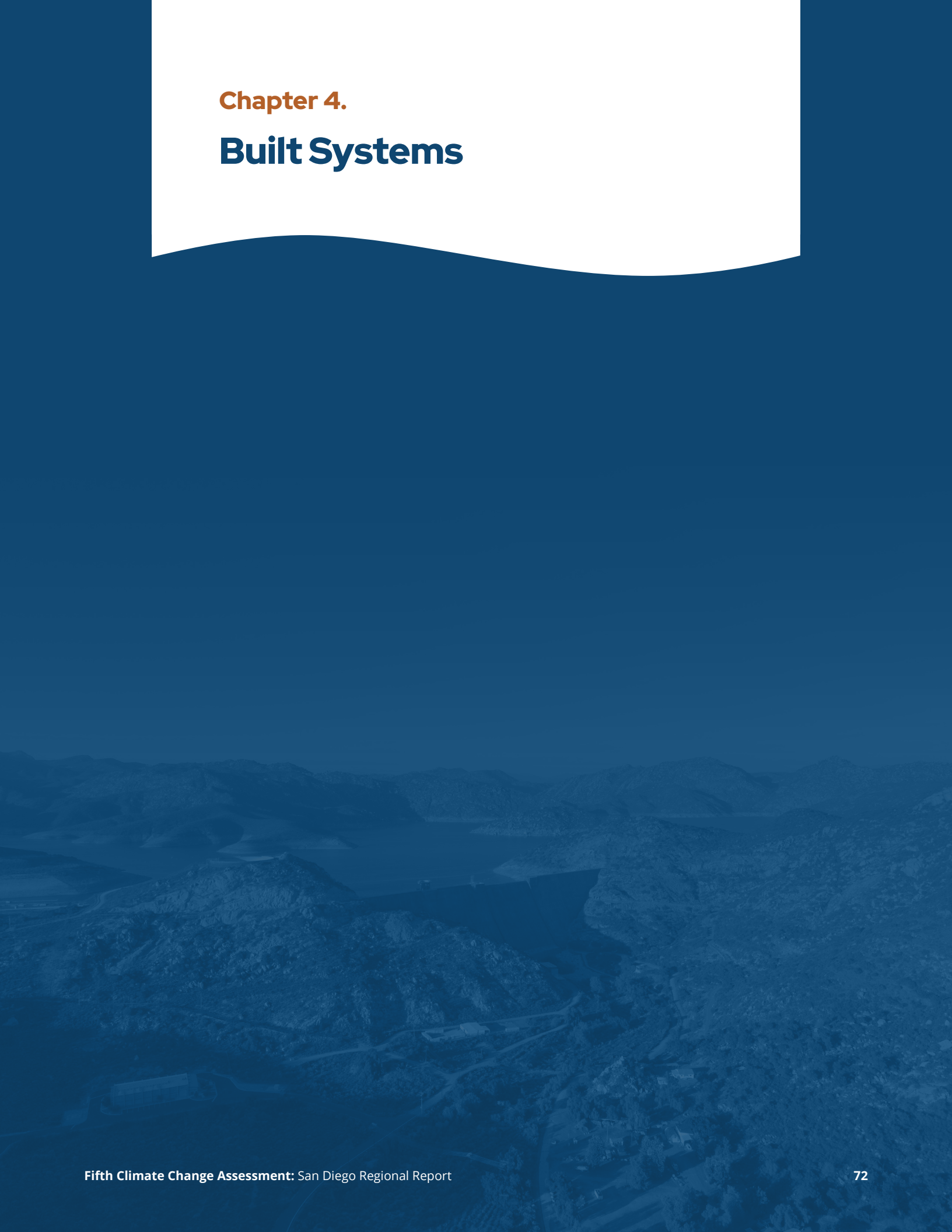
Mariculture is similarly threatened by changing ocean conditions, along with a myriad of other non-environmental stressors. The California mariculture industry is primarily oyster aquaculture, which is valued at $270 million across California, Oregon, and Washington (NOAA Fisheries, 2024). Research documenting these stressors indicates that California shellfish growers are particularly concerned about shifting carbonate chemistry, marine diseases, and warming waters, among other factors, each of which may worsen under future ocean conditions (Ward et al., 2022).

Box 3.7: *Case Study: Aquaculture and Seaweed*

Aquaculture, the farming of aquatic plants and animals, is one of the fastest-growing sectors in the US (USDA, 2025). ***Ola Farms***, an ocean restoration company, collaborates with research institutions, the Port of San Diego, and private enterprises to explore these issues while growing seaweed and shellfish using regenerative practices (Ola Farms, 2025). Bioremediation, use of organisms to mitigate pollution, through aquaculture has the potential to address these vulnerabilities by supporting carbon sequestration (Froehlich et al., 2019), erosion and storm protection, habitat and biodiversity conservation (California Sea Grant, 2025), and nitrogen absorption (Ramli et al., 2020). Efforts to expand regenerative aquaculture, including projects like those at Ola Farms, must navigate permitting requirements that vary across jurisdictions. Along similar principles, the Port of San Diego's ***Shellfish and Seaweed Aquaculture Program*** (SSAP) aims to mitigate climate change impacts by fostering sustainable aquaculture. The program focuses on shellfish, such as mussels and oysters, and seaweed, including kelp and red and green seaweeds, species that are native or naturalized to the region and selected for their ability to grow efficiently in local waters. The native species are also important cultural foods to the Kumeyaay (Cuero & Connolly Shipek, 1991; Lee, 1949). Shellfish, as filter feeders, can improve water quality by removing excess nutrients like nitrogen, while seaweeds absorb carbon dioxide and store it in their biomass. The program's emphasis on ecosystem services highlights its dual role in restoring marine health and reducing GHG emissions while supporting local economies and creating new market opportunities for sustainable aquaculture products.

Chapter 4.

Built Systems



4.1 Energy

KEY MESSAGES

- *San Diego has relatively low building energy use due to its milder year-round climate compared with other counties in California.*
- *While San Diego Gas & Electric continues to deliver electricity to homes and businesses, San Diego Community Power and Clean Energy Alliance, two new Community Choice Aggregation programs formed by local jurisdictions in 2021, now purchase electricity and serve roughly 80% of the customers in San Diego County.*
- *San Diego's electrical infrastructure faces increasing exposure to extreme heat, wildfire, inland flooding, and localized coastal flooding in low-lying coastal areas. Gas infrastructure vulnerability to inland flooding and landslides is projected to gradually increase through 2070.*
- *Local jurisdictions and agencies have adopted ambitious climate and clean energy targets that will increase demand for renewable or zero-carbon electricity. Meeting this demand will require upgrades to electric distribution and transmission infrastructure with additional climate adaptation planning.*

4.1.1 Introduction

San Diego's energy system, which includes electricity and gas in the residential, commercial, and industrial sectors, has experienced significant transitions in the last decade with the increase in solar production, Community Choice Aggregation (CCA) programs, and the 2024 approval of the San Diego Regional Energy Network (SDREN) by the California Public Utilities Commission (CPUC).

In 2022, the San Diego region used 522 million therms of natural gas (159 therms per capita) and 20,243 gigawatt-hours (GWh) (6,177 kilowatt-hour [kWh] per capita) of electricity (CEC, 2025). Residential electricity use has been relatively consistent since 1990 with seasonal household electricity use spiking in late summer, due to air conditioning needs, with a smaller peak in December and January (The Nonprofit Institute, USD, n.d.). When compared with other counties in California, the San Diego region has low energy use due to the area's milder year-round climate.

The San Diego region has seen a significant change in the number of electricity providers and in the energy portfolio in the last few years. San Diego Gas & Electric (SDG&E), an investor-owned utility (IOU), owns the electricity transmission and distribution system in the San Diego region, and is responsible for delivering electricity to end-use residential and non-residential customers. Before 2021, SDG&E served as the primary utility in the region that purchased electricity on behalf of customers, with other electric service providers (ESPs), non-utility entities, purchasing a small portion of the electricity within the SDG&E service territory (Direct Access program). In 2021, San Diego Community Power (Community Power) and Clean Energy Alliance (CEA), two CCA programs, began serving residential and non-residential customers in the region.

Currently, 11 cities and the unincorporated communities of San Diego County are members of CCAs. In alignment with Assembly Bill (AB) 117 (Migden, 2002), CCAs are public, not-for-profit locally governed entities that have been formed by cities and counties throughout California in the past 20 years to purchase electricity for their communities. For Community Power and CEA customers, SDG&E still delivers the electricity and continues to provide billing and line

maintenance, but Community Power and CEA purchase the electricity, set the electric generation portion of electricity rates, and engage in regulatory proceedings based on their priorities. The San Diego Regional Energy Network (SDREN), approved by California Public Utilities Commission (CPUC) in 2024, will fund energy efficiency and electrification programs in the San Diego region, in addition to the IOU's customer programs (SDREN, 2024). The portfolio of programs is included in the SDREN Strategic Business Plan, which will be updated every four years to reflect changing local needs and address programming gaps.

The use of a CCA was proposed as a GHG mitigation strategy in the City of San Diego's 2015 Climate Action Plan as an alternative to help the city purchase cleaner electricity sooner for its citizens (City of San Diego, 2015). The City of Solana Beach was the first city in the region to establish a CCA program. In 2018, it formed Solana Energy Alliance to provide a cost-competitive and locally controlled alternative for its citizens. Solana Beach later joined other cities to form CEA. As of 2024, Community Power and CEA serve more than 80% of the customers within the SDG&E service area (SDG&E, 2024b).

Several Tribal communities in San Diego have incorporated renewable energy into their systems. Some Tribes are using large scale arrays to offset casino operations' usage and to supplement electric car charging stations. A 50-megawatt (MW) wind turbine project by the Campo Band of Kumeyaay Indians generates significant energy that is sold under a power purchase agreement to SDG&E, and an additional 1.5 MW wind turbine offsets a large portion of the Tribe's casino usage. The Viejas Band of Kumeyaay Indians has developed a Tribal microgrid that includes the largest non-lithium-ion battery storage system in California, enhancing both community resilience and regional grid stability. Additionally, many of the reservations have incorporated roof-top solar and battery storage into their governmental and residential systems, often with funding assistance coming from programs like Disadvantaged Communities Single-family Homes program, administered by the nonprofit GRID Alternatives (GRID Alternatives, 2025). Efforts have been made for homes to utilize programs that reduce energy waste through insulation and double-paned window installations. Many reservations are also incorporating EVs into their government vehicle fleets. The Rincon Band of Luiseño Indians has been working on joining the "hydrogen highway" of fueling stations in the state.

Unlike electricity, SDG&E is the only utility in the region that transports natural gas to all customers through its gas system. Natural gas is mainly used for water heating, space heating, clothes drying, and cooking (County of San Diego RDF, 2022). Residential natural gas end-use has been declining since 1990, especially since 2013, likely due to California's warmer winters, and appliance and building energy efficiency standards. Non-residential natural gas end-use has been relatively stable since 1990, with a dip in 2020, likely due to the COVID pandemic. In 2023, the CPUC voted to phase out incentives for natural gas measures with the intent of promoting the adoption of more energy-efficient alternatives (Kao, 2023).

4.1.2 Climate Vulnerabilities

As the owner and operator of the transmission and distribution system in the region, SDG&E's Climate Adaptation and Vulnerability Assessment (CAVA) summarizes the impact of climate change on the energy sector (SDG&E, 2025a). The assessment identifies extreme heat, wildfire, and inland flooding as the most impactful climate hazards to the electrical infrastructure. Extreme heat drives peak energy demand due to increased cooling needs, while also reducing system efficiency and, in severe cases, causing equipment failures.

Wildfire is projected to increase in inland and mountain regions, especially by mid- and late-century. **Figure 4.1** provides an example of how wildfire vulnerability of overhead conductors (power lines suspended above ground) is projected to evolve through 2070, offering insight into how increases in vulnerability may vary spatially. Inland flooding exposure is growing, particularly in the inland and mountain regions, with peak precipitation near Palomar Mountain. While SDG&E's electrical assets are primarily subject to increasing exposure to extreme heat, wildfire, and inland flooding, coastal flooding in low-lying areas may impact electrical assets in specific locations. Unlike the electrical infrastructure, the gas infrastructure within the San Diego region is largely not vulnerable to extreme heat and wildfire due to most of the system being underground. The gas infrastructure vulnerability to inland flooding and landslides is expected to gradually increase through 2070. In addition to the infrastructure assessment, the CAVA community engagement surveys found that wildfire was the climate hazard of most concern among disadvantaged vulnerable communities' populations. However, regional variation in climate concerns in these surveys and interviews indicates the need for localized adaptation responses (SDG&E, 2025b).

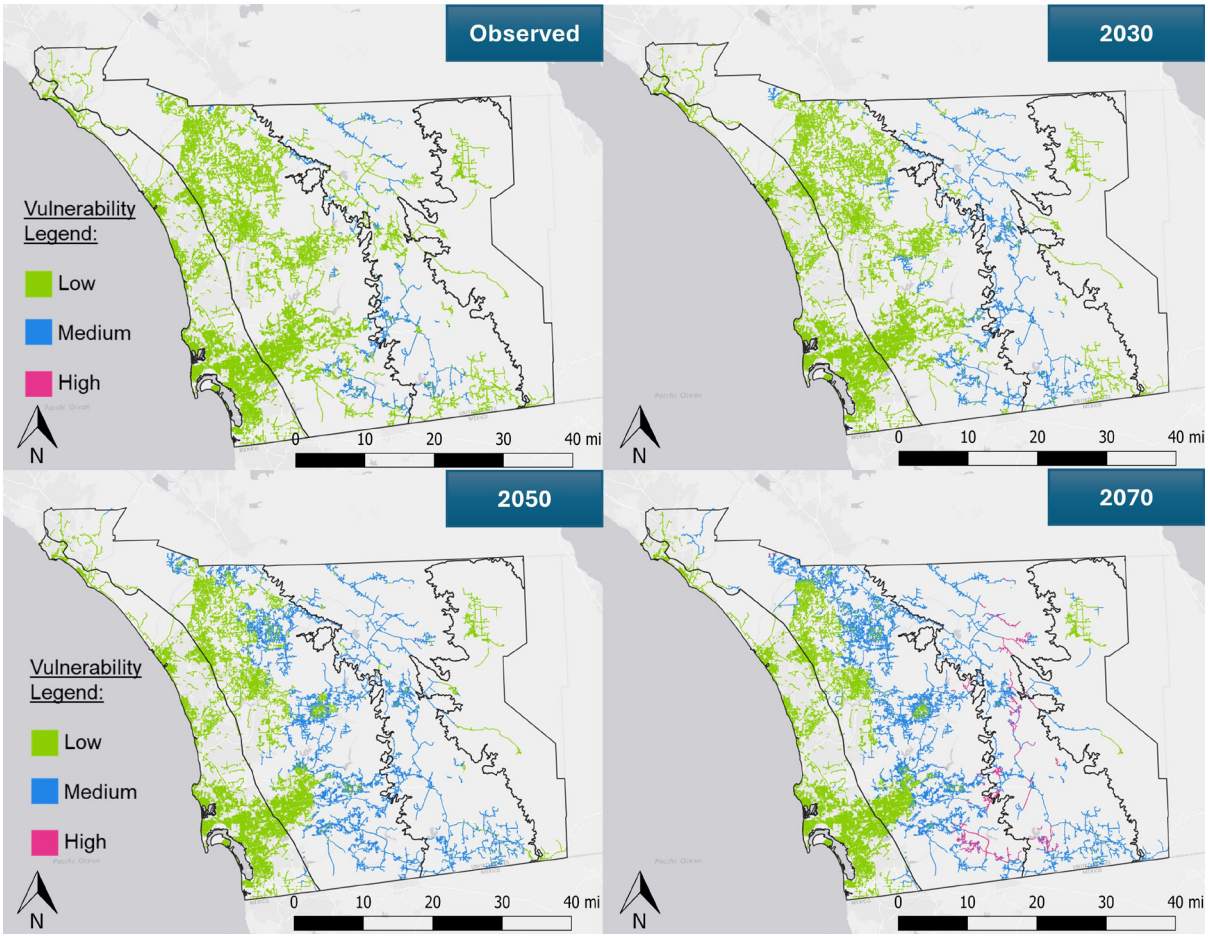


Figure 4.1: *Observed and projected wildfire vulnerability of overhead electrical conductors in the San Diego Gas & Electric electricity service territory for a historical baseline (1995–2014) and future periods centered on 2030, 2050, and 2070 under the SSP3–7.0 emissions scenario. Maps show low (green), medium (blue), and high (pink) vulnerability, with wildfire risk expanding and intensifying over time. Projections are based on a median-model, median-year (model-P50, time-P50) estimate (SDG&E, 2025b). Figure provided by SDG&E for information purposes only.*

4.1.3 Climate Adaptation for the Energy Sector

ENERGY POLICY IMPACT ON THE FUTURE ENERGY SYSTEM

While this report focuses on adaptation rather than mitigation (i.e., the reduction of GHGs), the future of the energy system is shaped by policies that are designed to mitigate future GHG emissions. California has the ambitious target of reducing statewide anthropogenic GHG emissions to 40% below 1990 levels by 2030, 85% below 1990 levels by 2045 and to achieve carbon neutrality with carbon capture and storage through natural and working lands and mechanical approaches. California Air Resources Board (CARB), the leading agency in California for climate change and air pollution control programs, developed a Scoping Plan that laid out a sector-by-sector roadmap to reduce fossil fuel use. The plan includes strategies such as moving

to a zero-emission transportation sector by electrifying cars, buses, trains, and trucks; phasing out natural gas for heating homes and buildings; and continuing to build renewable energy to displace fossil-fuel fired electricity generation (CARB, 2022). This transformative change will increase demand for renewable or zero-carbon electricity in future years. The increase in demand and clean energy production is increasing the need for electric distribution and transmission infrastructure.

SDG&E, Community Power, CEA, and other providers serving the region are required to meet California's Renewables Portfolio Standard (RPS) targets. The current RPS targets are from SB 100 (De León, 2018), setting the 2030 target to 60% and requiring all the state's electricity to come from either RPS-eligible renewable resources or zero-carbon resources by 2045. In 2023, all suppliers in the region offer service options exceeding California's statewide renewable average of 36.9%, with options ranging from approximately 41% to 100% renewable (CEA, 2020; San Diego Community Power, n.d.; SDG&E, n.d.).

Meeting the estimated 5,700 MW of capacity needed in the San Diego region by 2050 with renewable resources will require roughly two newly operational 100 MW clean power plants coming online every year between now and 2050 (McCord et al., 2022). Close coordination with state agencies, such as the California Independent System Operator (CAISO) and CPUC, can help accelerate the deployment of clean energy infrastructure, including transmission systems. Community Power and CEA have accelerated renewable energy targets (San Diego Community Power, 2023), and have power purchase agreements with multiple renewable energy and storage projects in the San Diego or broader Southern California region for local reliability purposes. SDG&E also adopted a Sustainability Strategy to achieve net zero GHG emissions by 2045. Even though SDG&E, Community Power, and CEA all have acted to procure longer-term contracts to build new local, utility-scale renewable projects in the region, the region is constrained by both transmission and land availability, which limit the approval of new large-scale generation resources (California Independent System Operator, 2024).

Increased behind-the-meter (i.e., customer side) solar with energy storage could reduce the needs for utility-scale renewable development and decrease peak load. The San Diego region has seen a significant increase in behind-the-meter battery storage systems in recent years. In fact, with over 2 GW connected at the end of 2024 and total behind-the-meter battery capacity at 300 MW (**Figure 4.2**), it now has the highest total behind-the-meter solar capacity among California counties. Residential battery storage systems represent over 95% of the Self-Generation Incentive Program (SGIP) application (The Nonprofit Institute, USD, n.d.).

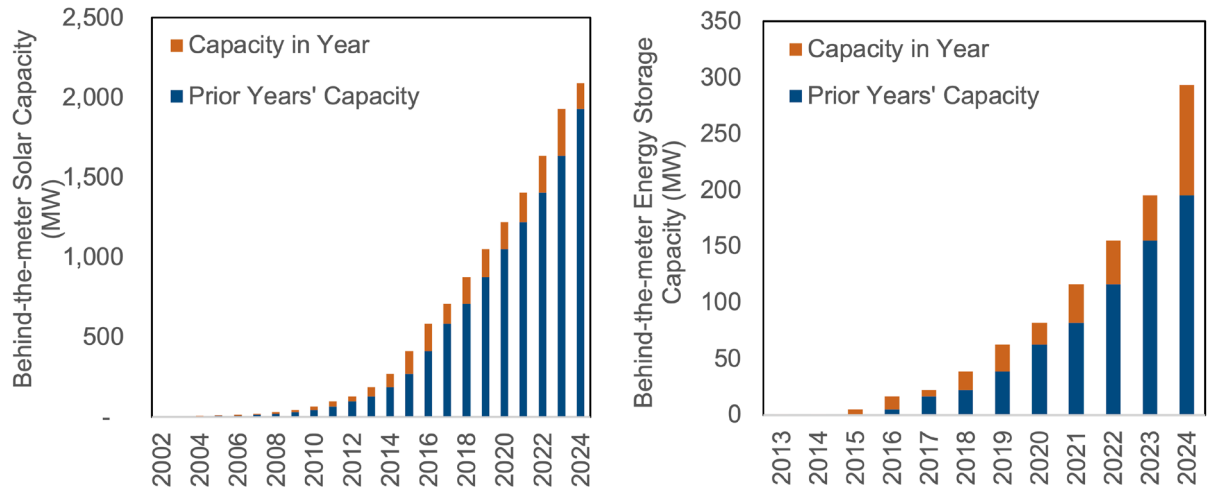


Figure 4.2: *Behind-the-meter solar capacity (left) and energy storage capacity (right) in the San Diego region (2002–2024). Bars show cumulative installed capacity from prior years (blue) and new capacity added each year (orange), indicating acceleration of rooftop solar and on-site battery storage after 2015. Source: California Distributed Generation Statistics, n.d.*

CLIMATE ADAPTATIONS

Climate change will stress the electrical grid while the region is also requiring more electricity to reduce reliance on carbon-based fuels. Given these multiple stressors, new adaptive technologies are needed to support key resilience objectives that SDG&E laid out in the CAVA. These four objectives include:

- Strengthen assets and operations to withstand climate extremes
- Increase the ability to anticipate extremes
- Bolster the system's ability to respond
- Recover from an extreme, and advance and adapt the system to changing threats from climate change and other factors.

Meeting these objectives requires integrating climate projections into grid planning and operations, a process that is still evolving as climate models and sales forecast models are adapted to accommodate changing future conditions (Wieland, 2025). New methodologies for climate data integration are being explored to better consider climate change in operations and grid planning.

In addition to new data methods, SDG&E is using new modeling and data to mitigate wildfire risks and reduce the impacts of public safety power shutoffs. SDG&E continues efforts to harden and underground electrical infrastructure. Decisions about undergrounding infrastructure versus other mitigation approaches, like covered conductors, are informed by the Wildfire Next Generation System (WiNGS) model. The WiNGS model can be run in an operational mode and, using weather and other relevant data, it helps guide risk-based de-energization decisions during extreme fire weather conditions (SDG&E, 2024a).

Microgrids are a grid resilience strategy mitigating disruption caused by public safety power shutoffs and other disruptions that have been part of the energy system for over a decade and are increasing in prevalence in San Diego. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode. UC San Diego has a microgrid with a 55 MW peak load and supplies 92% of the campus energy needs. In 2024 the Port of San Diego installed a microgrid at the Tenth Avenue Marine Terminal, reducing GHG emissions and enabling operation for four hours in the case of an outage. SDG&E currently has nine microgrids throughout the region. The Pala Tribe's Community Microgrids Project provides independent control over energy generation, storage, and use, protecting critical facilities during wildfires, public safety power shutoffs, and other disruptions. The project offsets 102% of electricity use at three key facilities, is expected to save $6.4 million over 25 years, and combines 1,073.2 kW of solar photovoltaic with battery energy storage (Pala Band of Mission Indians & US Department of Energy, 2021).

Box 4.1: *Strengthening Grid Resilience with Digital Twin Technology*

SDG&E is harnessing digital twin technology to transform climate vulnerability assessments into actionable strategies. A digital twin—a dynamic, data-driven replica of the grid—allows teams to model scenarios, assess vulnerabilities, and optimize local resilience measures. Through the Climate Intelligence Platform, SDG&E integrates the best-available climate exposure information, infrastructure vulnerability, and community vulnerabilities into a high-resolution geospatial model. Using a fine-grained hexagonal grid, the Climate Intelligence Platform refines vulnerability assessments beyond traditional methods, pinpointing areas where infrastructure and communities are most exposed. Developed in collaboration with an interdisciplinary team, this systems approach equips operators and planners with the insights needed to strengthen grid reliability and drive proactive climate adaptation. Beyond identifying vulnerabilities, this digital twin capability helps assess the intersection of electrification scenarios and their impact on grid reliability. By simulating future energy demands, SDG&E can strategically plan system adaptations, outreach, and engagement that support clean energy transitions while bolstering local climate resilience.

4.2 Water

KEY MESSAGES

- *San Diego's water supply has changed significantly over the past several decades, with declining per capita use and increasing reliance on local sources. Together, these shifts have made the region's water supply more resilient to drought.*
- *Stormwater and wastewater infrastructure remains particularly vulnerable to extreme flooding. Across San Diego, adaptation efforts are underway to prepare for extreme precipitation, with co-benefits that include reducing flood impacts, improving water quality, and supporting ecosystems.*
- *Tribal Nations are collaborating to develop new mechanisms that ensure water quality standards and environmental protections reflect Tribal values and lifeways while safeguarding the natural and cultural resources that are vital to Tribal communities.*

4.2.1 Introduction

The San Diego region faces growing challenges in managing its water supply, delivery infrastructure, and water quality in the context of climate variability, regional growth, and evolving state, federal, and international policies and agreements. With a population of over 3.3 million residents, aging infrastructure, and a diverse landscape, spanning from densely urbanized coastal communities to rural, inland valleys, the region must rely on its interdependent system of imported and local water sources and adaptive planning strategies. Regional dynamics are shaped by factors such as reliance on imported water from the Colorado River and Northern California, and emerging threats, including extreme weather events and prolonged droughts. As the region's wholesale supplier, the San Diego County Water Authority (SDCWA) plays a central role in coordinating water imports, local production, storage, and conservation programs. Smaller agencies and unincorporated communities outside of the SDCWA's service area face their own water security challenges, particularly concerning groundwater supply reliability and limited infrastructure.

4.2.2 Water Supply and Infrastructure

The SDCWA supplies between 75%–95% of the region's water needs depending on weather and supply source conditions (Hazen and Sawyer, 2021; San Diego County Water Authority, 2021). Its service area includes both urban and rural regions, extending eastward from the coast to the Laguna and Cuyamaca mountain ranges. In 2025, the SDCWA's water supply was distributed across residential (64%), commercial and industrial (22%), agriculture (6%), and public uses (8%) (San Diego County Water Authority, 2025). In 2025, approximately 64% of the SDCWA's water was imported (**Figure 4.3**). The MWD water comes from the Colorado River via the Colorado River Aqueduct, and Northern California rivers via the State Water Project (SWP). The California Department of Water Resources (DWR) projects that by 2043 the reliability of SWP deliveries to Southern California could be reduced by 13% (with 5% probability to reach 23%), relative to 2023 baseline levels (California Department of Water Resources, 2024b). During 2000–2022, the Colorado River experienced the driest period in over a century, and possibly the driest in 1,200 years (Williams et al., 2022), a reminder of San Diego's vulnerability to weather fluctuations and climate trends in the Colorado River basin. The United States Bureau of Reclamation is leading a process to determine post-2026 operations of the Colorado River which may have implications for future water supply in San Diego. Approximately 36% of the regional water supply comes from local water sources such as sea water desalination (from the Carlsbad desalination plant, completed in 2015), groundwater, surface water, and recycled water (**Figure 4.3**). Groundwater, while just 5% of the total SDCWA supply, plays a larger role in areas like Lakeside, Camp Pendleton, Pauma Valley, and the San Luis Rey River area.

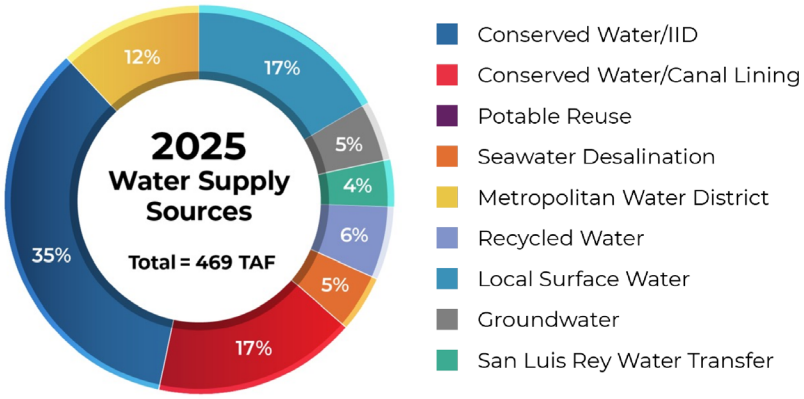


Figure 4.3: *Water sources and their percent contributions to the San Diego County Water Authority's 2025 supplies. Water sources include Metropolitan Water District (MWD) deliveries, Colorado River water via the Imperial Irrigation District (IID), and conserved water from the lining of the All-American and Coachella Canals. Local water sources include surface water, sea water desalination, groundwater, and recycled water. Data from the San Diego County Water Authority.*

The region has 21 reservoirs with a combined capacity of 719,000 acre-feet (887,000,000 cubic m) (*Water Storage Overview*, 2025), expanded by the 2014 San Vicente Dam Raise. Local surface water storage has grown from 194,000 acre-feet (239,000,000 cubic m) in 2004 to about 498,000 acre-feet (614,000,000 cubic m) in 2024, roughly 69% of total capacity (San Diego County Water Authority, 2024). However, five of the regional dams are restricted in the amount of water they can hold due to safety concerns (California Department of Water Resources, 2024a).

Despite population growth, the per-capita potable water use fell dramatically from 235 gallons (890 L) per day in 1990 to 119 gallons (450 L) per day in 2025 (SDCWA, 2025). The decline in water use can be attributed to conservation efforts and increased water use efficiency as responses to historic supply shortages. In 2025, the total annual water demand in SDCWA's service area was 469,000 acre-feet (578,502,000 cubic m), about 5% lower than in 2022. Further, a recent analysis found that projected water supply is sufficient to meet future water demand in San Diego, even under a high housing growth scenario (Miro et al., 2026).

4.2.3 Groundwater-Dependent Communities

Eastern San Diego County, and other areas outside of SDCWA's service area, rely heavily on groundwater from local wells owned and operated by small agencies, private users, or Tribal authorities. These communities are often rural, unincorporated, and lack the robust infrastructure for water, sewer, or stormwater collection. Specifically, there are 36 groundwater basins in the region, and three—Upper San Luis Rey Valley, San Pasqual Valley, and Borrego Springs basins—were designated by DWR as either medium or high priority, making them subject to management in accordance with the Sustainable Groundwater Management Act (SGMA) through adopted Sustainability Plans (California Department of Water Resources, 2021). The other basins were designated as low or very low priority and are therefore not subject to management in accordance with SGMA. In addition to the 36 groundwater basins, much of the region's unincorporated area relies on wells in fractured rock, where water availability can be highly variable and especially

sensitive to prolonged drought. A continued challenge for groundwater use and aquifer conditions is the limited data availability. Naturally occurring contaminants in groundwater, such as radionuclides and heavy metals, result in high treatment costs. Long-term aquifer depletion, exacerbated by drought and overuse, increases concentrations of these contaminants. Non-point source pollution from highways, livestock, and septic systems further degrades groundwater quality (San Diego Regional Water Management Group, 2019).

Tribal Nations in Southern California are disproportionately reliant on groundwater due to historic exclusion from surface-water rights settlements, delayed implementation of federally reserved water rights, and long-standing underinvestment in Tribal water infrastructure, which together have constrained access to rivers, reservoirs, and imported supplies (US Bureau of Reclamation, 2003; US Government Accountability Office, 2018). Even where Tribes have secured legal entitlements to imported Colorado River water, such as member Tribes of the San Luis Rey Indian Water Authority, limited conveyance, storage, and treatment infrastructure has restricted actual use, perpetuating dependence on local groundwater supplies (San Luis Rey Indian Water Authority, n.d.). This reliance heightens vulnerability because many Tribal aquifers are shared with off-reservation agricultural and municipal users, exposing Tribes to overdraft, declining water tables, and contamination they do not control (California Department of Water Resources, 2014; State Water Resources Control Board, 2022). Climate change compounds these risks by reducing recharge and intensifying drought, underscoring the need for integrated planning and sustained investment to secure Tribal water sovereignty (National Congress of American Indians, 2013).

4.2.4 Stormwater and Wastewater Infrastructure

Stormwater systems across the region consist of drains, pipes, and channels that convey stormwater and non-stormwater flows into local water bodies. As runoff moves over urban surfaces, it picks up pollutants such as oil, metals, and bacteria, which enter the county's waterways untreated (San Diego Regional Water Board, 2025a). Nature-based stormwater solutions, such as bioretention basins and tree wells, are increasingly used to filter runoff in situ while providing co-benefits like carbon sequestration and urban cooling. However, the January 22, 2024, record-setting high intensity precipitation event (see **Box 2.1**) demonstrated the limits of the region's stormwater infrastructure. Since the flooding from the January 22 storm, the City of San Diego has begun improving stormwater systems and is planning several projects to improve the stormwater infrastructure (City of San Diego, 2024b).

Wastewater is managed separately from stormwater throughout San Diego and is discharged into the Pacific Ocean via five major outfalls: South Bay, Point Loma, San Elijo, Encina, and Oceanside (*San Diego County Wastewater Treatment Water Recycling Facilities*, n.d.). Wastewater treatment involves several stages of treatment and disinfection to ensure that treated wastewater meets specific effluent standards prior to discharge. However, extreme weather can overwhelm systems and result in releases of untreated wastewater as in April 2020 when nearly 13 million gallons of untreated sewage were released in Oceanside and San Diego during a storm due to pump failures and flooding (State Water Resources Control Board, 2023, 2024).

4.2.5 Water Quality

Water quality encompasses a wide range of possible pollutants and factors, including naturally occurring minerals and chemicals, agricultural runoff, and industrial waste, algal blooms, and waterborne disease. The County of San Diego Health and Human Services Agency published a report in 2023 that summarized water quality conditions (County of San Diego, Health and Human Services Agency, 2023). Based on data from 2011-2019, the Pauma region has the highest level of drinking water contaminants followed by much of the eastern third of the county, including the Mountain Empire, Anza Borrego Springs, Palomar-Julian, and Pendleton. Further, the report included that, in 2021, there were 290 cases of water-borne illness in San Diego County, with the most frequent being giardiasis.

Rising temperatures introduce new water quality challenges. Although the SDCWA infrastructure is designed to function under high-temperature norms (Wicker et al., 2024), utilities have reduced water residence time in pipes to prevent nitrification and bacterial growth during heat waves. Harmful algal blooms (HABs) in fresh water can lower oxygen levels, emit odors, and produce toxins harmful to humans and wildlife (State of California Water Quality Monitoring Council, n.d.), similar to coastal waters. Likewise, similar approaches to monitoring HABs in fresh water are being developed at a statewide level with a website that shows water quality conditions at selected reservoirs and lakes (Anderson Abba et al., 2016). Additionally, reductions in freshwater runoff, combined with greater evaporation, are likely to increase salinity in inland waters, affecting irrigation and drinking water quality.

Tribes in San Diego County are advancing water resilience. One such pathway is through direct engagement in the Tribal Beneficial Uses (TBU) designation process, an initiative led by the State Water Resources Control Board (SWRCB). TBUs recognize and protect Tribal water uses for cultural, spiritual, ceremonial, and subsistence purposes. This work ensures that water quality standards reflect Tribal values and lifeways, and safeguards the natural resources vital to Tribal health, food sovereignty, and cultural continuity (San Diego Regional Water Board, 2025b). In San Diego (Water Board's Region 9), a regional Tribal Workgroup was established in 2021 to guide the local implementation of TBUs by shaping how TBU designations are defined and applied in the region. In addition, the Rincon Band of Luiseño Indians' newly approved US EPA Water Quality Standards (WQS) significantly advance climate resilience in several important and interconnected ways. The inclusion of culturally significant beneficial uses ensures that both biodiversity and Tribal lifeways are safeguarded. With anti-degradation protections and alignment with downstream water quality goals, these standards also contribute to regional climate resilience. Furthermore, the Rincon Band of Luiseño Indians has granted the San Luis Rey River personhood status within the Tribe's legal system, recognizing it as a living entity with inherent rights to exist, flourish, and be restored. This designation strengthens the protections for a waterway of deep cultural, spiritual, and ecological significance (Rincon Band of Luiseño Indians, 2022).

4.2.6 Water Affordability and Equity

The County of San Diego Water Ways Report (2024) evaluated water affordability by comparing the cost of using 150 gallons per day to median household income. All assessed regions in San Diego County exceeded the US EPA's 1.5% affordability threshold (County of San Diego, 2024c). The assessment shows that water affordability varies in the region, with lowest water affordability identified in the Tribal Nations, Western, and Northern San Diego County areas (**Figure 4.4**). The

report highlights a wide range of currently available resources and recommendations to make water more affordable to communities.

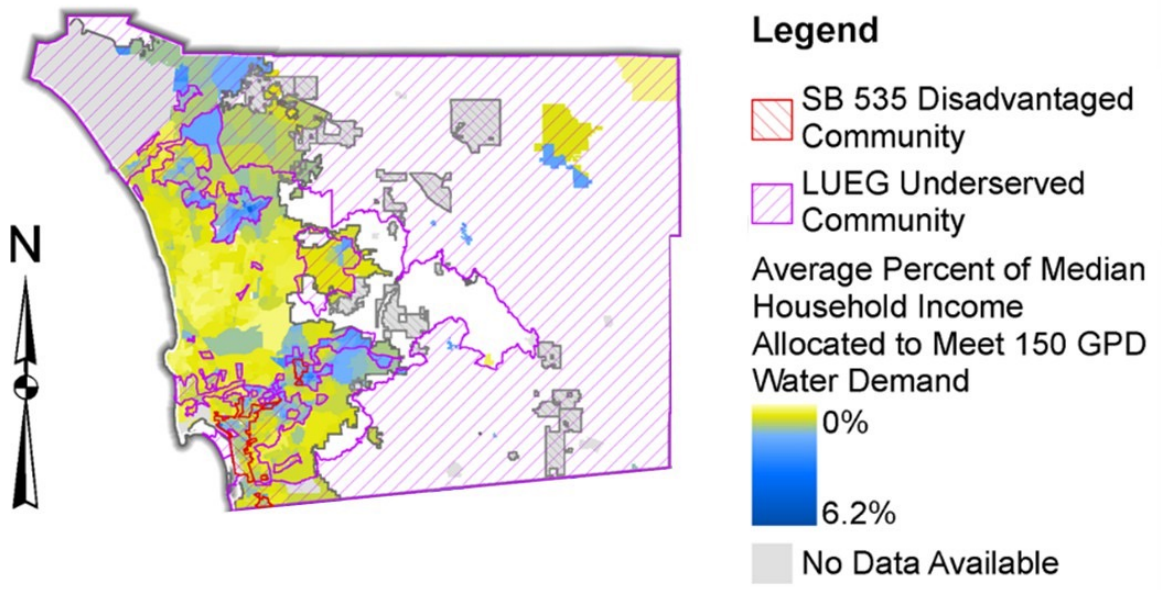


Figure 4.4: *Share of household income allocated to municipal water bills in San Diego County in 2023. Colors show the percentage of median household income required to meet an average daily water demand of 150 gallons per person (blue indicates a higher cost burden). Hatched (stripes) overlays indicate designated communities: SB 535 disadvantaged communities in red, and underserved communities identified by the County's Land Use and Environment Group (LUEG) in purple. Figure based on the County of San Diego's Water Ways Report (2024).*

4.2.7 Climate Adaptation Strategies

Like most adaptation strategies, ensuring San Diego's water and water infrastructure is resilient to climate change requires a multi-pronged approach. San Diego County's recently published Water Ways Report provides detailed information about climate adaptation approaches to meet the needs of the county while advancing equity (County of San Diego, 2024c). Below, we highlight a selection of adaptation strategies that are being tested and deployed.

New state regulations approved in 2024 now allow for direct potable reuse of recycled water (Water Boards, n.d.). Several agencies in the region have been implementing new projects to decrease reliance on imported waters by providing potable water from purified wastewater. The City of San Diego's Pure Water Program is a multi-year project that will deliver 33,625 acre-feet (41,400,000 cubic m) per year, or 83 million gallons (314,000 cubic m) per day (MGD), of purified water, roughly 50% of the city's demand, (City of San Diego, 2025b). The City of Oceanside and the Padre Dam Municipal Water District, in partnership with Helix Water District, the County of San Diego, and the cities of Escondido and El Cajon, also have programs underway producing 3,360-5,600 acre-feet (4,140,000 – 6,910,000 cubic m) per year (3–5 million gallons per day) and up to 12,300 acre-feet (15,200,000 cubic m) per year (11.5 million gallons or 43,500 cubic m per day), respectively. The Padre Dam's project will meet over 30% of the potable water needs of the east county region by 2026 (East County Advanced Water Purification, n.d.).

As discussed throughout this report, using new data and/or applying existing data in new ways are important climate adaptation strategies, including within the water sector. Incorporating climate projections into the calculations engineers use to size basins and estimate water volumes for stormwater infrastructure would strengthen current practices, which often rely solely on historical data (Hathaway et al., 2024). Assembly Bill 30 (2023) established the Atmospheric Rivers Climate Forecasting Program within the California Department of Water Resources (DWR) to support the integration of forecasts into flood and water management.

The California State Water Resources Control Board protects water quality by promoting best management practices (BMPs) and other measures. The State Water Resources Control Board can require BMPs implementation through permitting, though BMPs do not require the consideration of climate adaptation strategies. Municipalities can also evaluate permanent or structural BMPs throughout watersheds, adopting a systems approach to managing overland flow. Encouraging stormwater capture and infiltration in upland areas reduces flooding risks in downstream communities. In addition to structural measures, restoring disconnected floodplains and riparian buffers can provide significant flood attenuation, improve water quality through filtration, and create valuable habitat co-benefits.

Box 4.2: *County of San Diego Water Adaptation Co-Benefits*

The County of San Diego's programs, such as the **Green Streets Clean Water Plan** (GSCWP) (2022) and the **Waterscape Rebate Program** (WRP), offer adaptation co-benefits. Green Streets are intended to help reduce stormwater runoff, improve water quality, and provide a variety of related community benefits, such as increasing access to parks and green spaces. The GSCWP, completed in 2022, is now underway. At the time of writing, 17 green street projects have been initiated with one in construction, 11 in design, and five others in early phases. Of the 17 projects, nine are in Lakeside with others in Fallbrook, Ramona, Spring Valley, Bonsall and Casa de Oro.

The WRP offers additional adaptation co-benefits such as water conservation and encouraging stormwater infiltration. It incentivizes the implementation of water-saving devices and practices, such as rainwater harvesting and turf replacement to sustainable landscaping, on private properties in the unincorporated county. Since its inception in 2021, the WRP has supported the distribution of nearly **18,000 rain barrels** with a total capacity of over **880,000 gallons** (3,330,000 L). Additionally, the WRP has incentivized the removal of over **1.2 million square feet** (0.12 square km) of non-functional grass turf.

4.3 Transportation

KEY MESSAGES

- *Climate change impacts the transportation sector through both acute events like flood and fire that shut down roads and railways, and long-term degradation from exposure to climate extremes.*
- *The San Diego Regional Plan, led by the San Diego Association of Governments (SANDAG), is the primary transportation plan for the region. The new draft 2025 plan introduces new ways to reduce greenhouse gas emissions from the transportation sector and enhance resilience all through an equity framework.*
- *Other transportation agencies throughout San Diego, including the Metropolitan Transit System (MTS), the Port of San Diego, and the San Diego Airport Authority, are assessing climate vulnerabilities and developing resilience plans.*

4.3.1 Introduction

The integrated transportation system includes interstate and state highways, local arterial roadways, public transportation systems, nonmotorized transportation facilities, maritime and aviation facilities, digital networks, and ports of entry (**Table 4.1**). San Diego depends on this essential transportation infrastructure to move people and goods across the region. However, extreme events have increasingly damaged this crucial infrastructure, reducing asset lifespans and diminishing returns on public investments (Neumann et al., 2021). For example, impacts from the flooding caused by high intensity rain during a January 2024 storm (see **Box 2.1**), alone, caused nearly $31 million in regional public infrastructure damage over three days (Newsom, 2024). With such impacts projected to become more frequent, it is vital to assess the region's transportation system, examine past climate impacts, identify future vulnerabilities, and develop a more resilient path forward (Caltrans, 2019).

Table 4.1 *Transportation Networks and Systems*

System	Components
Regional roadway system	Interstates, freeways, highways, toll roads, arterial streets, and local streets
Public transit system	Local and regional bus operations, regional and interregional commuter rail services, and light rail service
Nonmotorized transportation system	Walkways and bikeways, with many bikeways sharing space with roadway facilities
Freight railroad network	Three freight rail lines transporting cargo and goods
Airport system (commercial, general, and military)	Facilities serving passenger, freight, business, recreational, and defense-related needs

4.3.2 Current and Future San Diego Transportation

Every four years, SANDAG conducts a detailed transportation assessment and prepares a long-range regional plan to meet regulatory requirements, reduce traffic congestion, and promote equitable access to jobs, education, healthcare, and other community resources. The Regional Plan, which was adopted by SANDAG in December 2025, integrates four major goals: convenient, equitable, healthy, and safe (SANDAG, 2025a).

The 2022 GHG inventory for the San Diego region found that the transportation sector, including passenger vehicles and heavy-duty trucks, accounts for 45% of the region's GHG emissions (SANDAG, 2025a). To help reduce emissions, SANDAG and local agencies are working to expand the public transit system and increase ridership. The draft 2025 Regional Plan states that congestion is most severe during peak periods, with 71% of commuters driving alone and only 3% using transit. However, the 2025 Regional Plan aims to provide commuters with compelling alternatives to driving alone.

Public transit in San Diego includes rail services such as the Coaster, Amtrak, and Metrolink, as well as the SPRINTER hybrid rail, trolleys, and buses. New trolley lines and rapid transit options are being built throughout San Diego, including the new Copper Line connecting El Cajon and Santee and the proposed Purple Line between San Ysidro and Kearny Mesa. The region plans to increase the number of managed lanes (express lanes, carpool lanes, transit-only lanes) on

highways, such as Interstate 5 (I-5) and State Route 78 (SR-78), to reduce congestion. The 2025 Regional Plan also emphasizes other modes of transportation such as "Flexible Fleets", which provide shared, on-demand services that offer convenient, personalized travel at all times of day. Flexible Fleets help people connect to transit and make short trips to local destinations around the community. Finally, the 2025 Regional Plan aims to increase bicycle ridership by integrating bikeway improvements from local plans into the region's 1,864-mile bikeway network. These improvements help advance goals in local climate action plans and aim to enhance connectivity and sustainable transportation. Transportation is a critical component to preventing social exclusion of the most vulnerable people and low-income communities (Lucas, 2012). The SANDAG Regional Plan has developed an equity framework which is documented in Appendix E of the Regional Plan (SANDAG, 2025a).

4.3.3 Historic and Projected Transportation Climate Vulnerabilities

The San Diego regional transportation system is vulnerable to climate stressors that impact all modes of transportation. Key threats include changes in temperature and precipitation, wildfires, sea level rise, cliff erosion, and storm surge. Understanding the historical impacts of these stressors and their projected future risks is essential for developing effective adaptation strategies.

Higher peak temperatures can accelerate pavement degradation, causing heaving and cracking, while rail infrastructure is at risk of track buckling, increasing maintenance needs, and reducing service reliability (Neumann et al., 2021). In aviation, higher temperatures reduce air density, requiring longer runways for safe takeoff, and potentially limiting flight operations (San Diego International Airport, 2020). Extreme heat also affects active transportation by creating hazardous conditions for walking and biking, discouraging their use and limiting the effectiveness of alternative transportation strategies (US EPA, 2016). Prolonged heat waves, such as those experienced in 2017 and 2022, can increase energy demand for cooling, straining the electrical grid and heightening the risk of blackouts, which can disrupt electric transit systems and traffic signal operations (County of San Diego Health and Human Services Agency, 2023).

Similar to heat waves, wildfires pose immediate vulnerabilities to the transportation system as well as long-term impacts. All modes of transportation are vulnerable, whether through direct damage such as the burning of roadways and rail infrastructure or indirect impacts like reduced visibility and poor air quality, which can disrupt operations. Historically, the San Diego region has experienced major wildfire events, including the 2007 Witch Creek Fire, and the 2014 San Diego County wildfires, which suspended commuter rail service and forced the closure of major roadways such as I-5 and Interstate 15 (I-15). These events caused lasting damage to rail and road transportation infrastructure.

For transportation infrastructure, the primary concern is not a change in total precipitation but the increasing frequency of extreme rainfall events that exceed system capacity (Caltrans, 2019). Such system overloads can cause flooding, washouts, structural undermining, and general damage to transportation assets. On January 22, 2024, an extreme precipitation event crippled regional transportation, shutting down several freeway on- and off-ramps, SR-78, and trolley and rail services, as well as delaying air travel (**Figure 4.5**). As these events become more frequent, improvements to drainage infrastructure will be critical to maintaining system resilience.



Figure 4.5: *Flooding impacts to roadways from the January 22, 2024 storm. Left: Flooded roadway on Hollister Road in the City of San Diego. Right: Mud and debris deposited across Fury Lane in Spring Valley following intense rainfall. Photo credits: City of San Diego (left) and County of San Diego (right).*

Like flooding from rainfall, coastal flooding poses an increasing threat to San Diego's transportation system. Near-term impacts include flooding, wave action, and sediment transfer, all of which can create unsafe roadway conditions, closures, and significant delays. The severity of these disruptions depends on the availability of alternative routes, with key corridors like State Route 75 (SR-75) and certain railroad lines facing particularly high risks due to a lack of proximate alternative paths. Storm surges, combined with wave action, can degrade and destroy hard infrastructure and cause shallow flooding, which can reduce vehicle traction, increasing the risk of accidents. At Cardiff State Beach in Encinitas, years of wave activity, intensified by storm surges from the January 2024 storms, destroyed the state beach parking lot, resulting in lost access and costly repairs (Ramirez, 2024).

SLR-induced flooding, combined with annual storm surge and tidal activity, can disrupt and damage transportation infrastructure due to flooding and erosion. In 2020, SANDAG completed an assessment of the impacts of sea level rise on transit. Under 2.5 feet of sea level, some of the transportation locations subject to flooding include the San Luis Rey Bike Path, several lagoon bridges, SR-75 and the green Trolley line (SANDAG, 2020). Coastal erosion compromises transportation assets like roadways and railroads situated above these cliffs. Coastal landslides and cliff retreat have already created significant challenges for maintaining and operating regional and interregional rail systems. North of San Diego County, Amtrak and Metrolink suspended service south of San Clemente four times in the past three years due to coastal landslides and mudslides, with some closures lasting over a month (Lewis, 2024). Regionally, the LOSSAN corridor in Del Mar has faced multiple closures due to cliff retreat, prompting plans to improve rail service reliability by minimizing risks from climate change, including consideration of SLR, flooding, and the stability of coastal bluffs (see case study in **Box 4.3** below).

4.3.4 Transportation Climate Resilience and Adaptation

Since the Fourth Assessment, state, regional, Tribal, and local entities have invested significant resources toward assessing their transportation systems' specific climate vulnerabilities and developing strategies for resilience. Multiple agencies and cities within the region have conducted climate change vulnerability assessments to better understand historical and projected impacts. The assessments inform climate action plans with concrete adaptation strategies. Resources such as the California Adaptation Planning Guide and SANDAG's Regional Resilience Framework support practitioners in the development of these projects and plans. The Regional Resilience Framework is designed to streamline adaptation planning, offering step-by-step guidance and a unified approach to strengthening transportation resilience. As of 2022, 93% of jurisdictions in San Diego County have either a climate action or adaptation plan that includes climate resilience. Many other local jurisdictions also address climate resilience in the safety element of their general plans (SANDAG, 2023).

In the last decade, the owners and operators of San Diego's major transportation assets, including freeways, railroads, trolleys, ports, and airports, have taken major steps to enhance climate resilience. Caltrans has completed a Climate Change Vulnerability Assessment, an Adaptation Priorities Report, and an Adaptation Project List, while also conducting multiple technical feasibility studies to address SLR, riverine flooding, and other climate hazards (Caltrans, 2019; Caltrans, 2020). The North County Transit District (NCTD) is developing a Climate Adaptation and Infrastructure Resiliency Plan, which outlines high-level strategies and priority resilience improvements to protect the San Diego railroad system from existing and projected climate threats. The San Diego Metropolitan Transit System (MTS) is improving climate-friendly public transit by transitioning to a fully zero-emission bus fleet by 2040 (Metropolitan Transit System, 2025). The Port of San Diego has completed a SLR assessment and coastal resilience report, outlining adaptation strategies and implementing a first-of-its-kind coastal armoring design to enhance both biodiversity and shoreline resilience (Econcrete, 2023). Finally, San Diego International Airport has developed a Climate Resilience Plan that outlines strategies for regional stakeholder collaboration, infrastructure improvements, and GHG reduction efforts to maintain business continuity in a changing climate (San Diego International Airport, 2020).

Alongside adaptation, the region is working to reduce GHG emissions from transportation. According to the 2022 regional GHG inventory in the 2025 Regional Plan, the transportation sector accounts for nearly half of all GHG emissions in the region. The state-mandated target for the San Diego region is a 19% per capita reduction in emissions from cars and light duty trucks by 2035 from 2005 levels. The 2025 Regional Plan achieves a 19.3% reduction in 2035 (SANDAG, 2025a). To achieve these goals, regional stakeholders including NCTD, MTS, and Caltrans have taken significant steps toward decarbonization by transitioning their fleets to zero-emission and electric vehicles. While these efforts represent meaningful progress in reducing transportation emissions, they must be paired with land use changes that enhance travel efficiency and minimize vehicle miles traveled (VMT). To support this, the region is implementing connectivity improvements designed to significantly reduce VMT, further reducing GHG emissions (McCord et al., 2022).

SANDAG also maintains a unique government-to-government framework with the Southern California Tribal Chairmen's Association (SCTCA), through which SCTCA has an advisory seat on the SANDAG Board of Directors and Committees. This long-standing framework includes agreements related to long-range transportation planning and other collaborative efforts, supporting ongoing engagement with the region's 17 sovereign Tribal Nations. Additionally, SANDAG facilitates the Interagency Technical Working Group on Tribal Transportation Issues, which connects Tribal leaders with local, state, and federal agency partners on a quarterly basis. These meetings help align regional planning efforts, including those related to climate action and adaptation planning, with Tribal needs and priorities. As part of its government-to-government approach, SANDAG has historically convened Tribal summits every four years in collaboration with SCTCA. These summits bring together elected officials from the 18 incorporated cities and the County of San Diego, as well as the region's 17 federally recognized Tribal governments to address policy issues of mutual interest in transportation and regional planning.

Box 4.3: *Climate Adaptation Case Study: San Diego LOSSAN Rail Realignment Project*

With significant investments in coastal transportation infrastructure, the San Diego region faces substantial challenges from SLR and coastal cliff retreat, both of which threaten the long-term stability of its transportation network. Over time, these stressors gradually erode and undermine the foundations of rail lines and roadways, requiring costly interventions to maintain safe operations. Traditionally, such interventions include hard armoring solutions like seawalls and revetments, while more recent strategies incorporate nature-based solutions to mitigate wave impacts. Despite these resilience efforts, ongoing cliff retreat can still render transportation assets unstable and unusable, ultimately requiring relocation inland as a more permanent solution. One notable example of such managed coastal retreat is the San Diego LOSSAN Rail Realignment Project.

Constructed in the 1880s, the 60-mile San Diego Subdivision of the LOSSAN Rail Corridor runs along the coast from Orange County to Downtown San Diego. Due to its coastal proximity, this corridor has faced significant impacts from SLR and cliff retreat for decades, with climate change expected to increase the frequency and severity of these threats (Griggs, 2021). One vulnerable segment of the corridor lies along the Del Mar bluffs, where cliff retreat has caused recurring erosion-related closures and slowdowns since 1996. Since 2003, SANDAG, in partnership with NCTD, has completed four bluff stabilization projects to keep the system operational, with a fifth phase underway as of 2025. However, these projects do not offer a permanent, long-term solution to risks posed by SLR and ongoing cliff erosion. As part of the permitting process for the fourth and fifth bluff stabilization projects, the California Coastal Commission required SANDAG to investigate realigning the corridor to a more stable inland location.

Since 2007, SANDAG has worked with its key stakeholders to identify feasible alternatives for realigning the segment of the LOSSAN rail corridor in Del Mar. The coastal bluffs supporting this segment of the corridor have a history of landslides and surficial failures and are also subject to ongoing erosion that could threaten the viability of rail service. After completing several planning studies and public engagement workshops, the environmental phase of the San Diego-LOSSAN Rail Realignment Project formally began in June 2024 through the release of a Notice of Preparation (NOP). An updated NOP, which incorporated feedback received in response to the 2024 NOP identifying four potential alignment alternatives, was released in May 2025 (SANDAG, 2025c). In addition to addressing resilience and operational concerns, the project aims to meet the goals of the 2025 Regional Plan and the 2024 State Rail Plan by double tracking this segment of the bluffs, which would increase track capacity, enhance service, and reduce travel times.

Chapter 5.

Social Systems

5.1 Public Health

KEY MESSAGES

- *As a coastal region with a diverse population, San Diego County faces unique challenges from both worsening existing climate-related health issues and the emergence of new ones. Rising temperatures, more frequent wildfires, and extreme precipitation events are increasing cases of heat-related illness, respiratory conditions, waterborne infections, and vector-borne diseases.*
- *Older adults, children, outdoor workers, unhoused individuals, and people with pre-existing conditions face greater health risks from climate hazards. These impacts are especially severe for communities of color, low-income residents, and non-English speakers who often live in hotter areas, face greater exposure to pollution, and have less access to healthcare and adaptation resources.*
- *Addressing climate change through sustainable, community-driven strategies is key to building a more resilient and equitable future. By involving residents in adaptation and mitigation planning, San Diego County can develop culturally relevant solutions that strengthen health systems, improve disaster preparedness, and reduce climate-related health disparities.*
- *Climate adaptation and mitigation strategies, such as building resilient food systems and promoting active transportation, further improve public health by lowering rates of obesity, chronic disease, respiratory illness, injuries, and supporting overall community well-being.*

5.1.1 Climate Change and Public Health in San Diego County

Climate-related hazards pose significant threats to health in the San Diego region by exacerbating heat-related illnesses, causing or inflaming cardiovascular and respiratory conditions from wildfire smoke, causing injuries from wildfires and storms, and spreading of vector- and waterborne diseases (Erickson et al., 2019; McMichael et al., 2010). Similar to elsewhere globally, hazards also adversely affect the ecological determinants of health, life-sustaining resources such as clean air, safe water, and healthy food systems, which are essential for human survival and well-being (Public Health Communications Collaborative & Planetary Healthy Alliance, 2025). Mental health impacts, such as trauma from displacement and property loss, are also major climate health concerns (**Figure 5.1**) (McMichael et al., 2010; Patz et al., 2014). Health risks disproportionately affect communities and individuals already facing barriers to accessing social determinants of health like housing, access to healthcare, and economic stability, as well as children, older adults and those who have pre-existing health conditions (Akerlof et al., 2015; Hulley et al., 2020).

Studies on the health impacts from climate change are widely applicable; but can differ based on location and exposure, among many other factors mentioned above. Below, we summarize the state of understanding of how climate drivers impact public health throughout the county. For more information, see the Fifth Assessment's "Public Health" report prepared by the California Department of Public Health.

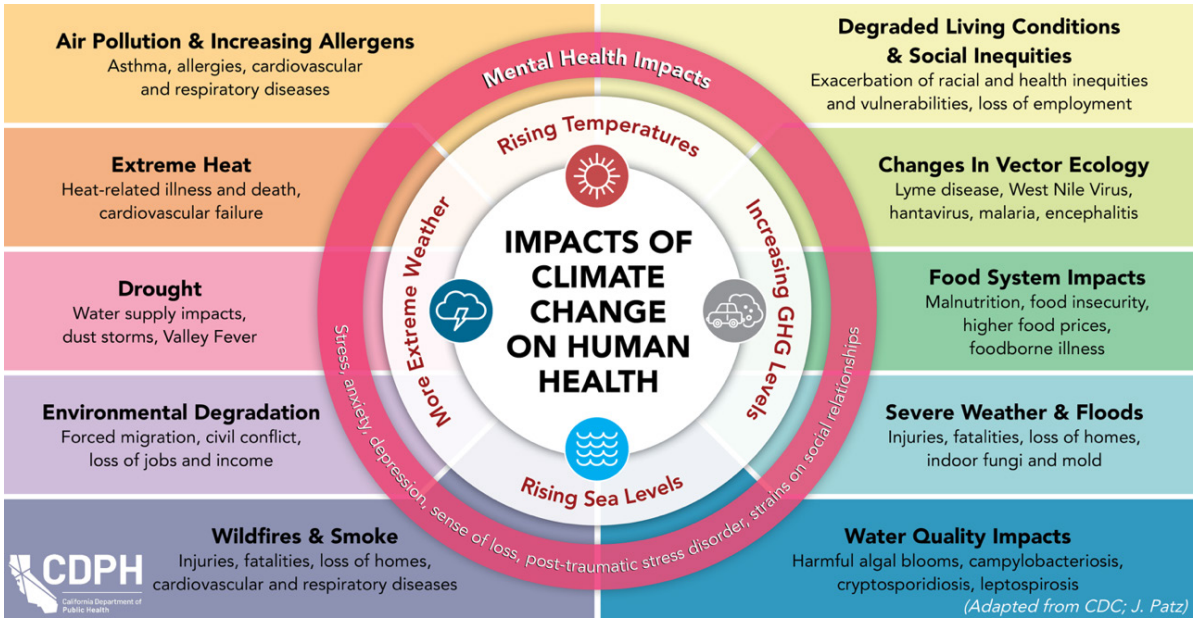


Figure 5.1: *Impacts of Climate Change on Human Health. Provided by the California Department of Public Health and adapted from Centers for Disease Control and Prevention.*

5.1.2 Extreme Heat and Public Health Risks

Extreme heat is linked to increased mortality and morbidity globally and in California, with vulnerable populations facing greater risks (R. Basu et al., 2008; R. Basu & Ostro, 2008; Benmarhnia et al., 2015; Ebi et al., 2021; Green et al., 2010; Guirguis et al., 2014; Knowlton et al., 2009; Ye et al., 2012). Rising heat-related deaths are expected due to climate change (Guo et al., 2018). Heat waves are becoming more frequent, intense, and prolonged (Gershunov & Guirguis, 2012), leading to around 7,000 excess hospitalizations annually in California (Vaidyanathan et al., 2019). Heat affects multiple bodily systems and exacerbates pre-existing conditions (Ebi et al., 2021), increasing hospitalizations for conditions such as heart disease, ischemic stroke, cardiac dysrhythmia, hypotension, diabetes, intestinal infection, dehydration, and acute renal failure (Basu et al., 2012). Pregnant women face additional threats as heat exposure is linked to preterm birth, stillbirth, maternal morbidity, and pregnancy complications (Basu et al., 2010, 2017, 2018; Ilango et al., 2020; Jiao, 2023a; Jiao, 2023b; Sun et al., 2020; Teyton et al., 2024). In Southern California and the San Diego region, extreme heat events can also occur outside of summer months due to Santa Ana winds, increasing health risks in cooler months (Schwarz et al., 2020). Unhoused individuals and outdoor workers face additional exposure risks (Riley et al., 2018; Schwarz et al., 2022).

Race, ethnicity, geographic location, and socioeconomic status shape heat exposure risks. Neighborhoods that were historically redlined, which are still often home to communities of color, are 4.7–7.6°F (2.6–4.2°C) hotter than neighborhoods that were not subject to redlining in Southern California (Berberian et al., 2022; Deivanayagam et al., 2023; Hoffman et al., 2020). In San Diego, inland and desert areas of San Diego highest daily maximum temperature currently

are about 5°F and 10°F (2.7°C and 5.5°C) warmer than the coast respectively (**Figure 2.3**), with even greater warming projected in these regions as compared to the coast (**Table 2.1**). While the coast is cooler, health impacts in part depend on acclimation to the heat. A San Diego focused study suggests that the coastal populations may have more heat-related health impacts due to lower air conditioning saturation; in 2009 only 13% of coastal households had air conditioning as compared to 43% in inland areas or deserts. (Guirguis et al., 2018). A modeling study focused on Los Angeles, which has a similar climate to San Diego, suggested that improvements in indoor thermal conditions are responsible for a large portion of the health benefits during extreme heat waves (Sailor et al., 2021).

Box 5.1: *Case Study: Extreme Heat*

One of the most impactful recent heat waves to affect San Diegans occurred from August 31st–September 9th, 2022. This 10-day long heat event broke temperature records across the state and ultimately led to 395 deaths, an increase in mortality of 5% over non-heat wave periods (Milet et al., 2023). Geographically, the event was most impactful in the south coast region of California, including Los Angeles, Orange, San Diego, Santa Barbara, and Ventura counties, perhaps due to lower air conditioning saturation. While the study found that heat was a contributing cause in the 395 excess deaths, only 20 were specifically coded as heat-related on death certificates, demonstrating the indirect path through which heat affects human health, and how easy it is to underestimate its risk.

5.1.3 Air Pollution and Wildfire Events

Climate-related hazards in San Diego, including extreme heat, drought, and wildfires, worsen air pollution by increasing levels of particulate matter, tropospheric ozone, and volatile organic compounds. These pollutants pose serious health risks, particularly for children, older adults, and low-income communities (Demetillo et al., 2019; Lee et al., 2023).

Wildfire smoke contributes to extreme air pollution levels, and this risk is increasing with climate change (Ford et al., 2018; Goss et al., 2020; McClure & Jaffe, 2018; Williams et al., 2019). Wildfire smoke exacerbates respiratory and cardiovascular conditions, particularly among vulnerable populations (Jiao et al., 2024). It has also been linked to adverse pregnancy outcomes, including low birth weight and preterm birth (Bekkar et al., 2020; Fernández et al., 2023; Heft-Neal et al., 2022; Picciotto et al., 2024), and long-term exposure is associated with increased dementia diagnoses (Elser et al., 2025). People who rely on electricity-dependent durable medical equipment are also at heightened risk, as wildfires and public safety power shutoffs can disrupt access to lifesaving devices (McBrien et al., 2023). Importantly, wildfire smoke can affect communities located far from the fire itself.

In San Diego County, 20.1% of residents lived in high wildfire-risk areas in 2010 (Maizlish et al., 2017). Communities of color, outdoor workers, low-income populations, and Tribal citizens face disproportionate exposure due to occupational and residential factors (Kondo et al., 2019; Liu et al., 2017; Reid et al., 2023). Unhoused individuals in San Diego also experience a higher number of emergency department visits related to wildfire smoke exposure (Schwarz et al., 2023). Tribal lands, rural areas, and disadvantaged communities remain among the most at risk, exacerbating existing health inequities (US Department of Health and Human Services, 2024).

Dust-related health impacts have also been widely documented, though most studies are based outside the United States (Aghababaeian et al., 2021; Morman & Plumlee, 2013; UC Dust, 2024). Dust exposure can trigger inflammation, immune responses, respiratory illness, and cardiovascular disease. Climate change is projected to increase dust and dust storm frequency, primarily due to rising temperatures and more frequent droughts, though multiple interacting factors also play a role (UC Dust, 2024). In San Diego County, dust primarily affects desert regions, where it poses the greatest health risks (UC Dust, 2024).

5.1.4 Waterborne Diseases

Extreme precipitation is a growing public health concern in California (Purohit & Narayanan, 2024). In Southern California, 75% of fecal pollution spikes in coastal waters are linked to atmospheric rivers (ARs), which overwhelm sewage and stormwater systems, contaminating beaches and waterways (Aguilera et al., 2019). This leads to an increase in waterborne illness risks, particularly among surfers. Studies have found a rise in acute illnesses following rainstorms (Schiff et al., 2016) and linked urban sea water exposure to gastrointestinal and respiratory diseases (Arnold et al., 2017). As climate change intensifies ARs (see Chapter 2), coastal water quality will continue to deteriorate, posing risks to recreation, tourism, and food sources.

Water pollution also threatens low-income communities in the Tijuana River Watershed, spanning the US–Mexico border. Rain-driven contamination exacerbates health disparities (Stigler Granados et al., 2024). The January 2024 floods (see **Box 2.1**) disproportionately impacted under-resourced neighborhoods, deepening existing inequities in flooding, pollution, and healthcare access. Addressing these risks requires cross-border cooperation and stronger public health strategies.

5.1.5 Infectious and Vector-Borne Diseases

Climate change is increasing the risk of infectious and vector-borne diseases in San Diego County, including coccidioidomycosis (Valley Fever). The *Coccidioides* fungus thrives in southwestern US and northern Mexico, benefiting from heavy winter rains that promote mold growth, followed by dry summers that disperse spores into the air, increasing infection risks (Crum, 2022; Jenks et al., 2020; Tong et al., 2017). Wildfire smoke can further transport spores (Kobziar & Thompson, 2020). As droughts and extreme precipitation intensify, Valley Fever cases are expected to rise, requiring greater monitoring and public awareness.

Vector-borne diseases are also expanding due to rising temperatures, which increase mosquito habitat suitability. *Aedes aegypti*, the vector for Zika, Dengue, and Chikungunya, poses an increasing risk (Bethel & Waterman, 2010; Morin & Comrie, 2013). San Diego reported local transmission of two cases of Dengue Fever in 2024 (Lopez Halvorson, 2024). *Culex quinquefasciatus*, a West Nile Virus carrier, has been detected, with human cases reported. As climate patterns shift, mosquito-borne disease risks will grow, necessitating enhanced surveillance and control measures to protect public health in the region.

5.1.6 Climate Adaptation for Healthier Communities

Climate adaptation and mitigation efforts in San Diego County aim to improve public health and health equity. Local programs reduce emissions, improve health outcomes, and support

vulnerable communities through collaborative efforts (**Table 5.1**). Local and regional climate adaptation plans engage residents in co-developing equitable, culturally relevant strategies. The National Indian Health Board (NIHB)'s *Climate-Ready Tribes Initiative* leads Tribal adaptation efforts across the US. Locally, the Pala Band of Mission Indians is strengthening climate solutions with Indigenous Knowledges (Pala Band of Mission Indians, 2019; Schramm et al., 2020).

Strategies to address public health impacts from climate change include monitoring, issuing effective warnings, and addressing risks among specific populations. Extreme heat is a growing concern as heat waves intensify, requiring improved tools to assess vulnerability (Benmarhnia et al., 2015). Highly reflective surfaces and greening are shown to reduce urban heat in many locations; however, the most effective adaptation strategy depends on the particular conditions in any location (Taleghani, 2018). While existing programs such as the Excessive Heat Response Plan and Cool Zones provide important resources, gaps persist in addressing population-specific risks (Basu & Ostro, 2008). Wildfire risk is increasing, worsening air pollution and impacting public health (Jiao et al., 2024; Reid et al., 2023). While air quality monitoring and public health advisories have helped (Hutchinson et al., 2018), enhanced air quality monitoring programs, research on long-term smoke exposure, and tailored interventions for vulnerable populations are needed (Jiao et al., 2024). Waterborne and vector-borne diseases are rising due to shifting weather patterns (Aguilera et al., 2019). Programs like San Diego's Beach and Bay Water Quality Program monitor contamination, but long-term health effects require further study. Mosquito-borne diseases are also an increasing threat (Crum, 2022; Morin & Comrie, 2013) which requires improved monitoring and early detection programs.

Table 5.1: *Examples of Local Climate Adaptation and Resilience Strategies that Address Health Topics*

Climate Hazard	Local Climate Adaptation and Resilience Strategies
Extreme Heat	Excessive Heat Response Plan[1] Annual Excessive Heat Report [2,3] Cool Zone Site Program [2,4]
Air Pollution and Wildfire	Air Pollution Control District [1] Climate Resilient SD Program [5]
Waterborne Diseases	Beach and Bay Water Quality Program [6]
Infectious and Vector-Borne Diseases	County Vector Control Program [1] County Reportable Diseases and Conditions by Year [1]

[1] San Diego (SD) County;
[2] SD County Health and Human Services;
[3] Public Health Services;
[4] Aging & Independence Services;
[5] City of SD;
[6] SD County Department of Environmental Health and Quality

Traditional public health approaches often focus on isolated events, but a compound-impacts perspective is needed to address interacting climate hazards, such as heat waves combined with wildfires or floods that amplify health risks (Chen et al., 2024; Kc et al., 2021; Zscheischler et al., 2018). The COVID-19 pandemic exposed vulnerabilities among children, Indigenous communities, and socioeconomically diverse populations (Aguilera et al., 2022; Schwarz, et al., 2023; Wheat et al., 2022). In the San Diego–Tijuana border region, cross-border health concerns include shared air pollution, sewage-related water quality issues, and the spread of vector-borne

diseases, all of which exacerbate disparities and highlight the need for integrated public health strategies (Schwarz et al., 2023). Within San Diego County, compound climate-related hazards disproportionately affect communities of color and unhoused populations (Schwarz et al., 2022). Coordinated strategies across health, climate, and emergency services are needed, yet research gaps remain in understanding how climate, social, and environmental factors interact to influence health outcomes (Zscheischler et al., 2018).

Climate action provides many public health co-benefits, including healthy food systems, which sequester carbon, reduce food waste, and improve nutrition. Programs such as the Active Transportation Program, promote walking, cycling, and public transit, reducing emissions while improving physical and mental health. These initiatives help lower obesity, chronic diseases, respiratory illnesses, and injuries, enhancing community well-being. Addressing climate change through sustainable, community-driven strategies creates a healthier, more resilient San Diego.

5.2 Governance

KEY MESSAGES

- *San Diegans benefit from a region where governments and agencies at multiple levels—federal, state, county, city, and Tribal—work together to address climate challenges. While funding, jurisdictional responsibilities, and capacity for climate adaptation are still evolving, the spirit of collaboration in the San Diego region remains fundamental to building resilience and ensuring successful adaptation.*
- *As of November 2022, 71% of jurisdictions in the San Diego region have adopted Safety Elements in their General Plans or are updating them to include climate resilience. Additionally, 50% of jurisdictions had Local Coastal Programs that included climate resilience measures for sea level rise.*
- *Limited capacity to address climate adaptation highlights the importance of leveraging regional plans to support local planning efforts. Developing shared metrics and databases can further support adaptation planning.*
- *Tribal Nations in San Diego lead adaptation planning on their lands and across many climate resilience planning projects throughout the region. Tribal participation and engagement at the early stages of climate and resilience planning is a cornerstone to effective adaptation.*

5.2.1 Regional Roles and Partnerships in Climate Resilience

The San Diego region faces increasing climate-related risks, requiring proactive adaptation strategies to enhance regional resilience. A critical component of this resilience is a strong governance framework that enables cross-jurisdictional and collaborative projects, including securing the necessary funding for implementation.

The San Diego region benefits from a streamlined governance structure, as it is both a single county and a single council of governments, unlike other councils of governments that span multiple counties. This unified structure allows for more effective coordination among county and city agencies on climate adaptation efforts. Depending on the type of adaptation planning and implementation, the roles and responsibilities can vary significantly among different levels of government and local agencies (**Figure 5.2**). The lead agency, noted as circles, is typically

responsible for securing funding, obtaining regulatory approvals and coordinating among partners, while the supporting agency is typically assisting or in a supplemental role. More details about regional plans in San Diego can be found on the San Diego Regional Climate Collaborative's Regional Plan Tracker website.

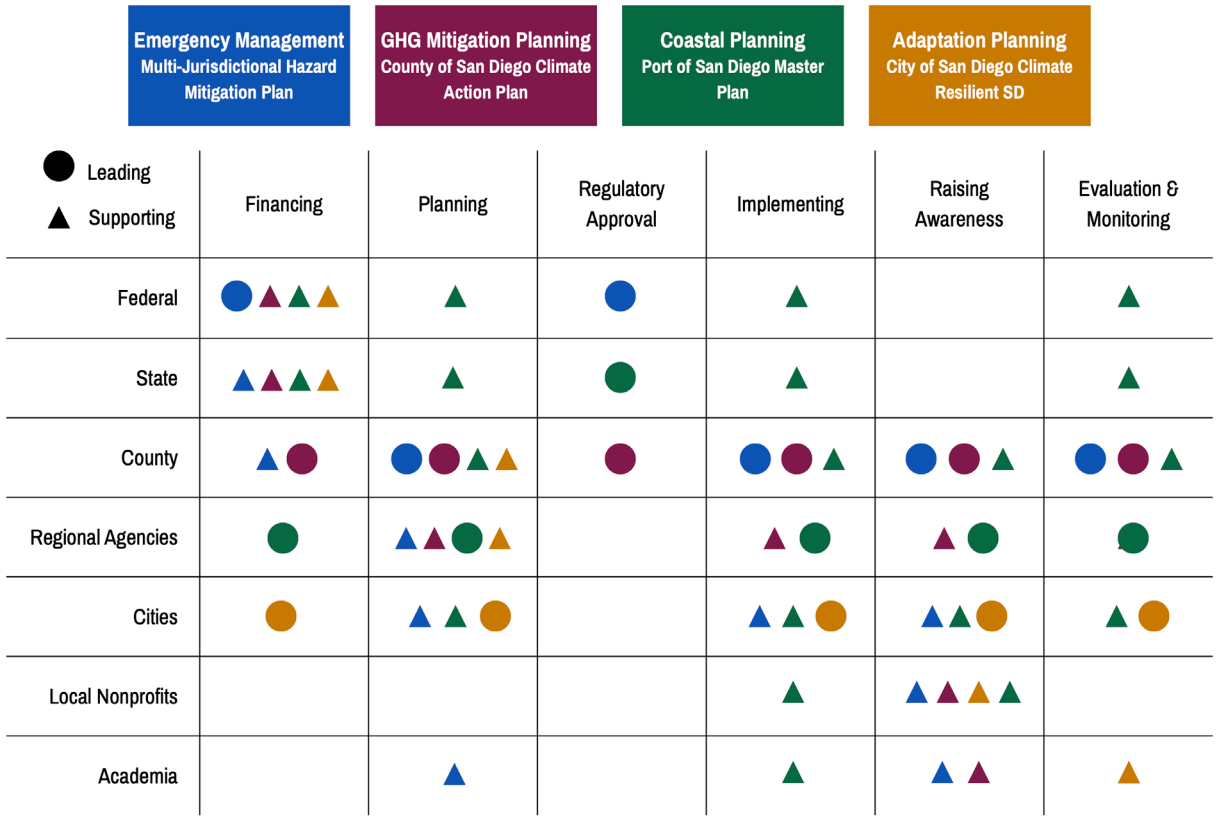


Figure 5.2: *Roles played by different levels of government, regional agencies, community-based organizations, and academia across a set of climate-related plans. Symbols are colored by plan (e.g., Climate Resilient SD in orange), circles denote lead agencies, triangles denote supporting agencies. "Financing" includes plan development and/or implementation, "regulatory approval" refers to the approving agency, not the underlying statute. Agencies include the Port of San Diego, SDG&E, SANDAG, and the Airport Authority. Tribal governments and the military always lead on their lands. San Diego Multi-Jurisdiction Hazard Mitigation Plan 2023 (County of San Diego, 2023b); County of San Diego Climate Action Plan 2024 (County of San Diego, 2024b); Port Master Plan 2024 (Port of San Diego, 2024); Climate Resilient SD 2021 (City of San Diego, 2025a).*

While not listed in the table, partnerships with the US Navy and Port of San Diego have established collaboration on resilience projects related to San Diego Bay. A recent example is the Shoreline Atlas Project. With support from the Office of Local Defense Community Cooperation, the US Navy and Port of San Diego are working with a contractor to develop a Shoreline Atlas that divides the San Diego Bay shoreline into Operational Landscape Units and evaluates potential nature-based solutions.

Tribal governments are actively engaged in climate resilience efforts and, because of Tribal sovereignty, they are separate from other government structures. Several Tribal Nations in San Diego have developed climate adaptation or resilience plans, such as the Campo Band and Manzanita Band of the Kumeyaay Nation, La Jolla Band of Luiseño Indians, and Pala Band of

Mission Indians. The Manzanita Band Resilience Project plan's central focus is on ’Snyaaw, coast live oak, noting the closeness between the people and the tree (Manzanita Band of the Kumeyaay Nation, 2020). All the plans emphasize the importance of Traditional Ecological Knowledges (TEK). The La Jolla Band of Luiseño Indians does this by quoting elders throughout their plan (La Jolla Band of Luiseño Indians, 2019).

Regional collaboration is further strengthened through the San Diego Regional Climate Collaborative (SDRCC), which convenes climate practitioners from local governments, nonprofit organizations, academia, and the private sector to facilitate knowledge-sharing and relationship building across different scales. One example of an innovative, multi-agency initiative is SDRCC’s Accelerating Regional Heat Action Planning Across San Diego project, which is particularly significant given the complexity of addressing extreme heat events where responsibilities span multiple agencies and require well-established governance frameworks (**Box 5.2**; Schmeltz et al., 2023). Similarly, Tribes are working in a collaborative framework on extreme heat. A new project—Interactive Exposures, Impacts, and Strategies Inventory Tool for Extreme Heat—is a collaborative pilot initiative led by the Pala Band of Mission Indians, with partners Prosper Sustainably and the Public Health Alliance of Southern California.

Box 5.2: *Heat Planning*

The ***Accelerating Regional Heat Action Planning Across San Diego*** project is a cross-jurisdictional and cross-agency collaboration. Its overarching goal is to mitigate extreme heat, protect public health in the most affected populations, and develop scalable initiatives that strengthen long-term resilience across California. Led by the SDRCC in partnership with the Cities of San Diego, Chula Vista, and La Mesa, as well as researchers from Scripps Institution of Oceanography at UC San Diego, the project facilitates information sharing and coordination across jurisdictions, recognizing that planning for extreme heat impacts must extend beyond municipal boundaries. By leveraging long-term partnerships, the project directly addresses key barriers to climate adaptation planning, including technical expertise, capacity, and funding, that challenge local governments both regionally and statewide. This multi-jurisdictional approach is designed to foster peer-to-peer learning opportunities, ensuring that cities can share best practices and insights. Close collaboration with academic partners further enhances the project by creating new research pathways and data support mechanisms to inform and improve local adaptation efforts.

A key component of regional climate resilience is the role of community-based organizations (CBOs) that often serve socially vulnerable and historically disinvested communities. SANDAG, SDRCC, and other regional partners collaborated to develop an “Equity-First Approach to Climate Adaptation”, emphasizing the critical role of CBOs in connecting government agencies with community needs to ensure equitable adaptation strategies (SANDAG, 2021a). Local jurisdictions, such as the Cities of San Diego and of Chula Vista, have worked closely with CBOs to develop climate equity indices tailored to their communities (City of Chula Vista, 2021; City of San Diego, 2019). These indices identify potential climate impacts and disparities in access to resources, guiding the implementation and investment of climate plans. In San Diego, the climate equity index led to the formation of the Climate Equity Working Group, composed of CBOs serving communities of concern (defined census tracts with *Very Low, Low,* and *Moderate* Access to Opportunity by the climate equity index). Since 2019, this group has facilitated ongoing communication and partnerships between the City of San Diego and community organizations.

Another significant regional effort is SANDAG's CBO partner network, established in 2017 to formally engage CBOs in regional planning processes, including climate resilience planning. The network for the 2025 Regional Plan includes 12 CBOs representing underserved communities across the San Diego region. These organizations serve on a CBO outreach team and a SANDAG Working Group where they provide input on key planning efforts and related topics including climate resilience (SANDAG, n.d.). By integrating CBOs into climate resilience efforts, regional agencies and local governments can better address the needs of vulnerable communities, ensuring that adaptation strategies are inclusive, equitable, and effective.

5.2.2 Adaptation Planning: Guidance, Capacity, and Collaboration

In addition to collaborative efforts, various laws and frameworks require climate resilience planning across the region. California Senate Bill 379 (SB 379), signed into law in 2015, requires municipalities to update their Safety Element of their General Plans to include risks associated with climate change and strategies to protect the public (California State Legislature, 2015). To support local governments with guidance on climate adaptation planning and implementation efforts, SANDAG developed the Regional Resilience Framework. The Framework included an assessment of climate resilience planning in the region as of November 2022 and can support local jurisdictions in meeting SB 379 requirements. That assessment found that 71% of jurisdictions in the San Diego region have Safety Elements or are in the process of updating theirs to include climate resilience. Additionally, 50% of jurisdictions had Local Coastal Programs that included climate resilience measures for sea level rise (SANDAG, 2023). Applying SB 379 looks different across the jurisdictions in San Diego County and varies between standalone climate adaptation plans, General Plan Safety Elements, Climate Action Plans, Hazard Mitigation Plans, or Local Coastal Programs (California State Legislature, 2015). For example, the City of San Diego has developed a standalone climate adaptation plan and incorporated SB 379 compliance into their General Plans (City of San Diego, 2022a, 2024a). While legislation such as SB 379 provides a foundation for climate adaptation planning, the varied implementation approaches across jurisdictions and agencies in San Diego highlight the need for continued coordination and alignment to ensure effective climate resilience efforts.

Clarity in adaptation planning is essential for advancing climate resilience efforts across the region. Clearly defined roles and responsibilities help jurisdictions establish structured processes, leading to more effective adaptation planning (The San Diego Foundation et al., 2020). A central challenge in adaptation planning and implementation is the capacity of local government offices to collect and analyze the necessary data and locally relevant information. Region-specific resources, such as this report, can provide a foundational understanding of the state of climate adaptation science and practice in San Diego. The concept paper, *Collaborative Planning for Climate Resilience: An Integrated Science-Based Framework for San Diego* (Leiter et al., 2021), highlights the value of leveraging regional plans to strengthen local adaptation efforts. Collaboration across jurisdictions is also crucial. A shared database of adaptation strategies and plans, implementation metrics, success criteria, and monitoring strategies would help local governments identify tested approaches that could be adapted for use in San Diego cities. Establishing such a resource would streamline knowledge-sharing and support evidence-based decision making in climate resilience planning.

Developing metrics to assess resilience would further support adaptation planning and implementation. However, identifying effective adaptation metrics remains challenging due to differences in scale, authorship, and timescales (Dilling et al., 2019; Goonesekera & Olazabal, 2022). Nonetheless, researchers have proposed frameworks for developing adaptation metrics (Dilling et al., 2019; Reckien et al., 2023). The Safeguarding California Plan 2018 Update advanced this effort by creating an extensive list of adaptation metrics in Appendix E of the plan (CNRA, 2018). Unlike GHG mitigation plans, which have primary metrics across all actions, the reduction of GHGs, adaptation does not have a widely accepted set of adaptation metrics across California, or even San Diego. The lack of a consolidated list of metrics makes it difficult to communicate the adaptation strategy and benefit to the public, track project value, and assess cost/benefit of adaptation strategies.

Adequate capacity also requires sufficient funding and political will. Sufficient funding for resilience planning and implementation remains a challenge (Climate Resolve & Farallon Strategies, 2023). To help mitigate this, many cities and agencies have a history of collaborating to gather the resources and financing to implement adaptation. The Beach Nourishment case study (**Box 5.3**) highlights a collaborative approach enabling a much larger project than any single government or agency could implement individually. A newer funding mechanism for eligible climate-related projects is the Climate Resilience District (CRD) designation, authorized under Senate Bill 852 (California State Legislature, 2021). CRDs primarily rely on tax increments to fund public infrastructure projects, facilities, and economic development, with a focus on climate resilience initiatives, particularly those that utilize natural infrastructure or serve under-resourced communities. As of 2025, only a few CRDs have been designated in California, making them a relatively new tool for funding climate adaptation. The County of San Diego has begun exploring the CRDs for the region, mentioning Imperial Beach as a potential pilot (Lynch, 2024). Beyond CRDs, many cities and agencies collaborate to secure funding and resources for adaptation projects.

Box 5.3: *Beach Nourishment*

SANDAG leads regional coordination for San Diego's coastal cities through the Shoreline Preservation Working Group to implement beach nourishment projects that protect coastal communities and transportation infrastructure. Two Regional Beach Sand Nourishment Projects (RBSPs) have been completed (2001, 2012), with a third project currently in the planning phase. For these projects, SANDAG facilitates coordination among local jurisdictions and oversees key project components, including feasibility studies, economic analysis, implementation, and monitoring. The RBSPs provide an example of regional collaboration in climate adaptation, demonstrating how coordinated efforts can expand the capacity of individual jurisdictions. Undertaking these projects independently would impose significantly higher costs on local governments and, in many cases, be financially prohibitive. SANDAG's latest initiative, ***RBSP III*** (also mentioned in ***Box 3.2***), includes eight San Diego jurisdictions and builds upon the success of RBSP I and II. Additionally, SANDAG is collaborating with the Cities of San Clemente and Dana Point to enhance regional efficiency and coordination of beach sand nourishment efforts across three Southern California littoral cells.

5.2.3 Tribal Priorities and Intergovernmental Collaborations

As alluded to previously, intergovernmental collaborations include partnerships with the Tribes. Respecting the sovereignty and authority of Tribal governments and preventing the compounding of past injustices of dispossession and exclusion from traditional lands is fundamental to Tribal

collaborations. Currently, the primary legally mandated interactions between Tribal and non-Tribal governments are activated by SB 18 and AB 52, and these laws are structurally oriented toward cultural resources (California State Legislature, 2004, 2014). These laws, however, are very limited. The laws do not create space for the Tribal implementation of TEK, which includes proven, regionally specific, sustainable environmental practices that have been developed and refined over millenia into broader planning efforts. Recognizing this gap, efforts are underway to create more inclusive spaces for Tribal engagement and to support collaborative climate adaptation planning and implementation that honors the Tribes' deep knowledge of climate adaptation in the region. Practices and policies that are structured to include meaningful Tribal partnership and engagement at the early stages of climate and resilience planning are a cornerstone of effective collaborations.

The County of San Diego fosters relationship-building with Tribal Nations across the region to understand each Tribe's unique climate adaptation priorities and to integrate TEK into climate action planning and land use practices. In 2023, the County's Office of Sustainability and Environmental Justice created a Tribal Liaison position to promote inclusion through reciprocity, respect, and equity principles. Additionally, the County is establishing a Tribal Liaison Community of Practice, bringing together County staff who regularly engage with Tribes to coordinate Tribal engagement, facilitate learning, and develop best management practices. The County's Planning and Development Team has also convened two working groups, the Native Landscapes Project Working Group and the Cultural and Tribal Resource Guidelines Working Group, with Tribal participation to ensure that Tribal perspectives are included in planning efforts.

5.3 Economy & Climate

KEY MESSAGES

- *The region has evolved into a diverse, innovation-driven economy anchored by high-tech industries, education, healthcare, the military, and tourism, with strong cross-border ties to Baja California. Military investment, higher education institutions, and cross-border advanced manufacturing have helped shape San Diego's competitive edge.*
- *The high cost of living and housing affordability strain residents, with disproportionate impacts on low-income communities. Rising temperatures, sea level rise, wildfires, and shifting precipitation patterns increase costs across sectors, disrupt infrastructure, and deepen inequities.*
- *Both market-driven responses (e.g., insurance adjustments and technological innovation) and public interventions (e.g., climate-smart housing and resilient infrastructure) are needed to build resilience. Strategic investment in adaptive infrastructure, equitable workforce participation, cross-border cooperation, and energy transition can help turn climate risk into long-term economic opportunities.*

5.3.1 Climate Change and the San Diego Economy

San Diego has evolved over the past 50 years from a regional fishing hub and Navy town into a dynamic, multi-sector metropolitan economy. Today, San Diego hosts mature high-technology, education, healthcare, military, and tourism sectors, benefiting from a high quality of life, strategic proximity to the US–Mexico border, and a diverse, multicultural population. San Diego is also

home to the world's busiest land border crossing, facilitating substantial economic interchange with Baja California, Mexico.

Three primary forces have shaped San Diego's economic evolution. First, the military has played a central role, not only through its direct presence but also by driving innovation in defense technologies, particularly those related to ocean systems (*Census Profile*, n.d.). Second, the region's educational infrastructure fuels an advanced workforce across life sciences and innovation-driven sectors. San Diego hosts more than 20 institutions of higher education, with UCSD, SDSU, and USD alone enrolling about 97,000 students in 2024 (National Center for Education Statistics, 2024). Third, the region's integration with advanced manufacturing in Tijuana allows for production and supply-chain efficiencies.

Despite its economic strengths, San Diego faces serious affordability challenges, particularly a high cost of living and housing costs that have outpaced wage growth (Bentz, 2025). Although San Diego County's poverty rate of 10.1% is below the state (12.0%) and national (12.5%) levels, more than one-third of San Diegans struggle to earn a living wage or secure affordable housing. These burdens fall disproportionately on Black and Hispanic or Latino residents, who face much higher rates of poverty, at 18.6% and 12.7%, respectively (PIC, 2023).

Climate change poses risks to San Diego's economic stability, infrastructure, and equity goals. But climate risks also provide opportunities for adaptations that can strengthen the local economy, and make San Diego more prosperous, resilient, and equitable. The Fifth Assessment's "Climate Impacts to the Economy Statewide Topical Report" provides a statewide examination.

5.3.2 Economic Disruption from Climate Change

Climate change is already affecting the region's economy through wide-ranging, sector-specific, and interconnected disruptions. This section highlights the major economic impacts across the region's foundational systems and sectors.

Water: Prolonged droughts increase dependence on expensive imported water, raising costs for households, businesses, and agriculture (Stone et al., 2025), while heavy precipitation events cause flash flooding, damaging homes, roads, and public utilities, leading to direct repair costs and service disruptions.

Sea Level Rise and Flooding: Key coastal assets, waterfront properties, and recreational areas, are at heightened risk (California Ocean Protection Council & California Ocean Science Trust, 2024). The associated economic consequences include both direct property damage and indirect effects such as increased insurance premiums which may, for example, affect housing prices (Hsiang et al., 2023; Industrial Economics, Inc., 2024; Schuetz et al., 2023). Public infrastructure, including the region's airport, port facilities, and wastewater treatment systems, will require expensive adaptation investments, such as seawalls and flood barriers (ICF, 2020). The regional maritime and tourism sectors, which generated approximately $14 billion in combined economic activity in the latest reporting year, are particularly vulnerable (Cambridge Systematics, Inc., 2024; Lindbergh et al., 2022).

Heat Impacts: Inland communities in San Diego County are disproportionately affected by rising heat, with extreme temperatures, for example, reducing labor productivity and increasing

the strain on electrical grids (Graff Zivin & Neidell, 2014; Neidell et al., 2021). These burdens are especially severe for low-income residents who may lack access to cooling systems, resulting in elevated risks for heat-related illness and associated economic costs (see *Section 5.1 Public Health*).

Wildfire: Fifteen of the 20 most destructive fires in California history have occurred since 2015 (ABC7 Los Angeles, 2025). The January 2025 wildfires in Los Angeles were particularly catastrophic, prompting a $1 billion bailout for the California Fair Access to Insurance Requirements (FAIR) Plan, the state's insurer of last resort (Flavelle, 2025). Insurance providers are increasingly retreating from fire-prone areas, raising premiums and limiting availability (Brennan, 2025; Fleming, 2025; Liao et al., 2022). Increased fire risk also affects utility companies. San Diego Gas & Electric (SDG&E) has received approval to raise rates by $2 billion for wildfire mitigation and related insurance coverage (Sieren-Smith et al., 2024).

Land Development: Recent forecasts by SANDAG project modest population growth, peaking at 3.4–3.5 million mid-century before stabilizing or slightly declining (SANDAG, 2024). In parallel, regional planning emphasizes infill and multi-family housing in place of sprawling development (SANDAG, 2021b). Environmental and fire regulations have further constrained greenfield expansion, such as recent legal action halting projects in fire-prone backcountry zones (Smith & Davis, 2021). Additionally, San Diego is recognized as a biodiversity hotspot, with over 50% of its land protected through public ownership or conservation easements (Kalansky et al., 2018), areas that underpin recreation, tourism, and residential real estate value.

Agriculture: San Diego agriculture represents a small share of the regional economy (approximately 0.2% of jobs and 0.5% of gross product) but occupies a prominent land-use role (Bureau of Labor Statistics, 2025; County of San Diego, 2023a). Climate change threatens the region's $1.7 billion agricultural output, primarily from small and family farms producing high-value nursery and flower products (County of San Diego, 2023a). Avocado production, historically the largest food crop, has declined over 50% over 20 years due to drought, water costs, and price pressure from Mexican growers (County of San Diego, 2023a; Smith, 2022). Carbon farming, in which producers are compensated for sequestering carbon in soils and vegetation, may offer new opportunities to maintain viability while contributing to climate goals.

Energy Systems: The transition to cleaner energy presents challenges. While SDG&E is actively investing in renewable energy and smart grid systems, electricity in San Diego remains among the most expensive nationwide. The most recent Net Zero scenario modeling by SDG&E shows that adopters, households that electrify and implement energy efficiency upgrades, may maintain 2022-level costs through 2045. Without intervention, non-adopters of energy upgrades will face 19% higher energy costs than their peers (SDG&E et al., 2022). To address affordability and accelerate decarbonization, local Community Choice Aggregators such as San Diego Community Power and Clean Energy Alliance are expanding their role in electricity procurement and rate design while advocates are exploring the potential for municipal or public power to reduce long-term costs (Public Power San Diego, 2025). In parallel, lawmakers are debating proposals to shift wildfire-related utility expenses from ratepayers to taxpayers, a move that could lower household electricity bills while raising broader questions about equitable cost-sharing (Roth, 2025).

Transportation: Transportation, including both on-road and off-road transportation, is the single largest contributor to GHG emissions in the region, accounting for about 45% of the total (SANDAG 2025a). Private vehicles remain dominant, but low-carbon alternatives such as transit

and active transportation are often more spatially efficient and economically beneficial over the long term (Power, 2024). San Diego's transportation infrastructure is itself highly vulnerable to climate change. Sea level rise and flooding threaten critical corridors, and heat and flooding also reduce the lifespan of infrastructure, increasing long-term maintenance costs (Davenport, 2024).

Environmental and Climate Justice: San Diego's most vulnerable populations, including seniors, disabled persons, non-English speakers, people of color, and unhoused residents, face greater risks from heat, wildfire smoke, poor air quality, and inadequate infrastructure (County of San Diego, 2021; Monroe, 2024). These disparities are reflected in outcomes: higher healthcare costs, more missed workdays, lower life expectancy, and reduced economic mobility. Households in these regions often spend 50% or more of their income on housing (PIC, 2023), leaving them vulnerable to water and energy price increases (Elmer, 2023; San Diego County Water Authority, 2024b).

Cross-Border Coordination and the Tijuana River: The San Diego–Tijuana relationship is essential to both regions' economic health, with Tijuana providing labor, production capacity, and consumers (World Population Review, 2025). Cross-border infrastructure and planning, such as joint efforts under the North American Development Bank, are critical to preventing disproportionate costs on businesses from climate transitions (North American Development Bank, 2023). The Tijuana River, an ecological corridor with deep cultural significance for the Kumeyaay, exemplifies cross-border climate risk: inadequate wastewater treatment combined with informal settlements results in severe pollution, closing parts of Imperial Beach's shoreline for over three years and affecting coastal ecosystems, Tribal cultural practices, tourism, property values, and public health (Anastas & Castillo, 2024).

Tourism: Tourism, responsible for around 8% of global GHG emissions (Sustainable Travel International, 2025), supports about 12% of county employment (Bureau of Labor Statistics, 2025). Climate change may deter visitors through rising temperatures, wildfires, and sea level rise, or may draw more travelers from hotter regions, positioning the city as a climate refuge. Sustainable tourism policies can help ensure the sector remains resilient.

5.3.3 Economic Drivers and Adaptation

Climate change will increase costs across sectors and necessitate economic adaptation. Many of these adaptations will be market-driven, in response to higher prices driven by increased costs. The insurance sector illustrates this dynamic: rising claims and losses translate into higher premiums. Markets evolve to incorporate new types of coverage as well as incentives or penalties for risk-related behaviors (e.g., home hardening against wildfire). Such adjustments can drive innovation and create new opportunities, as markets continually respond to changing conditions.

Public interventions and adaptations arise through different mechanisms than market-driven responses. While higher costs can push governments to adjust policies and revenue structures, the decision-making process is shaped by institutional priorities and competing stakeholder interests. At the same time, government interventions can catalyze structural change, enabling adaptation on a scale that individual or market responses cannot achieve. For example, California's strong economic position is partly the result of past public investments in military technology and higher education, which expanded opportunities for many residents. Similarly,

focused investments in climate adaptation can foster a more resilient and higher-performing economy that is also more equitable. Housing and transportation are key areas where climate-smart policies and innovations can increase efficiency and address inequities, for instance, through smart-growth strategies that enable denser, more affordable housing and improved transportation options in those communities.

Climate change poses multifaceted threats to San Diego's economy, borne unevenly across geographies, income groups, and industries. Well-designed interventions can protect vulnerable communities, reinforce infrastructure, and position the region as a leader in sustainable development. Building on San Diego's longstanding culture of innovation, climate adaptations piloted by local businesses, public agencies, and Tribes could generate jobs, revenue and enhanced regional reputation. Tribal businesses could become incubators of adaptation policies, including traditional ecological management strategies, furthering Tribal sovereignty. These opportunities could be particularly important for disadvantaged communities if investments are designed to expand workforce participation, lower utility costs, and improve access to climate-resilient housing and infrastructure (Schuetz et al., 2023). Economic resilience will depend on the region's ability to invest in adaptive infrastructure, energy transitions, binational cooperation, and equitable public health strategies.

5.4 San Diego and Baja California Cross-Border Resilience

KEY MESSAGES

- *The Cali-Baja region, with a population of 7 million and a GDP of $250 billion, is the largest integrated economic zone on the US–Mexico border; its resilience to climate extremes depends on binational cooperation across shared watersheds, ecosystems, and cultural ties.*
- *Chronic drought and aging infrastructure threaten both San Diego and Tijuana, where wastewater treatment systems operate beyond capacity and major storm events carry sewage, urban runoff, and solid waste into the Tijuana River Valley, producing contaminant levels that exceed water quality standards.*
- *Rapid population growth and expanding coastal development on both sides of the border amplify exposure to flooding, erosion, and pollution, heightening climate risks in already vulnerable coastal zones. Strengthening plurinational coastal resilience requires expanding real-time data sharing and integrating ecological, hydrodynamic, and socioeconomic models to guide adaptation across the Cali-Baja coastline.*
- *Wildfire activity is increasing across Southern California and Baja California Norte, extending into spring and autumn; smoke from these events exposes communities to harmful $PM_{2.5}$ pollution, with unequal health impacts shaped by socio-demographic differences across the border.*
- *Funding and collaboration are central to moving resilience forward. While neighbors, the plurinational nature of the work can require different structures and mechanisms than in San Diego alone, and must include Indigenous Stewardship.*

5.4.1 Introduction



Figure 5.3: *The San Diego-Tijuana region. Source: Dr. Alejandro Hinojosa, Ensenada Center for Scientific Research and Higher Education*

San Diego is strongly interconnected with Mexico, and building resilience to climate extremes and long-term trends requires partnerships that span the international border. Geographically, the region is linked by the Peninsular Ranges (**Figure 5.3**); ecologically, by the shared Mediterranean California and Sonoran Desert ecoregions on land and the California Current offshore; and hydrologically, by the Tijuana River watershed and water imports from the Colorado River. In the Pacific Ocean, the region's iconic kelp forests extend from San Diego southward along the Baja California peninsula (Ezcurra et al., 2021). Beyond its natural landscapes, the "Cali-Baja" region is unified by shared history, culture, and language. The Cali-Baja region is a plurinational area encompassing San Diego and Imperial Counties in Southern California, the Méxican municipalities of Baja California Norte (including Tijuana, Tecate, Mexicali, Rosarito, Ensenada, and San Quintín), and the territories of the Kumeyaay and Kiliwa Nations. With a combined population of 7 million and a GDP of $250 billion, Cali-Baja represents the largest integrated economic zone along the US–Mexico border (Canedo Rivas et al., 2022).

This connectivity is evident at the region's two major ports of entry: San Ysidro–Puerta México and Otay Mesa–Mesa de Otay, which together formed the busiest border crossing in the US in 2023, handling nearly 16 million cars and over 1 million commercial trucks (United States Department of Transportation, Bureau of Transportation Statistics, 2024). A robust cross-border workforce further strengthens regional ties, with over 54,000 Baja California residents employed in the US and more than 12,000 students crossing the border daily for education (Canedo Rivas et al., 2022).

While these strong connections provide a foundation for collaboration, the international border also introduces complex challenges for coordinating climate resilience and adaptation efforts. One such example is the sovereignty of Tribal communities in the US and Mexico. The Kumeyaay in Mexico (Kumiai) have a different legal relationship with the federal government. While Mexico

does recognize and acknowledge Indigenous Peoples in the nation and lands collectively owned as Indigenous Ejidos, they do not have the level of self-governance authority that is present in the sovereign nation status of US Tribes. However, because both the Kumeyaay and Kumiai collectively view their traditional relationship to the land as both temporally and geographically continuous, this cultural connectivity supports climate adaptation on both sides of the border. This section is a brief review highlighting key vulnerabilities and adaptive efforts across the Cali-Baja region. The more in-depth report by the Climate Science Alliance, *Collaboration Advances Climate Resilience in the Cross-Border Region*, highlights many stories of collaboration across the border in the Cali-Baja region (Lopez et al., 2025).

5.4.2 Climate Vulnerabilities and Adaptation

WATER

California and Baja California are semi-arid regions facing chronic drought and dependence on shared sources such as the Colorado and Tijuana Rivers. Rapid urbanization and aging infrastructure compound these challenges, though conditions differ across the border. In San Diego, facilities such as the South Bay International Wastewater Treatment Plant (SBIWTP) face strain from deferred maintenance and increasing demand (International Boundary and Water Commission, 2019). In Tijuana, wastewater conveyance and treatment systems operate beyond their design capacity and experience frequent breakdowns due to limited resources for upgrades and rapid population growth that outpaces infrastructure investment (Comisión Nacional del Agua, 2023). These systemic pressures are intensified by extreme precipitation events, which can trigger flooding, marine debris, sewage overflows, sedimentation, and invasive species dispersal in sensitive areas such as the Tijuana River Valley.

During major storm events, floodwaters carry contaminants into the Tijuana River Valley, including sewage, urban runoff, and illegally dumped solid waste, affecting both sensitive habitat and surrounding communities. Past storms have produced bacteria, chemical, and heavy metal concentrations exceeding water quality standards (Pendergraft et al., 2023). In California, Imperial Beach has experienced near-continuous closures, including more than 700 consecutive days between 2022 and 2024, the longest in state history (Rodriguez, 2024). On the Mexican side, organizations like Proyecto Fronterizo de Educación Ambiental report to the public on their bacterial monitoring of beaches near Tijuana via their Facebook page (*Proyecto Fronterizo de Educación Ambiental*, 2025). Extreme precipitation and flooding also strain the region's water systems, causing erosion, infrastructure damage, and water quality challenges. In Tijuana, erosion from unpaved roads and stream channel modifications threatens urban infrastructure, including water supply lines and private property (Gudino-Elizondo et al., 2022; Taniguchi-Quan et al., 2018). Inadequate culverts under the border often fail to accommodate storm flows and debris, leading to blocked drains and intensified flooding (Goodrich et al., 2020). Although dams help reduce peak flows, channelization and floodplain development increase local flood risks.

Joint monitoring efforts, community outreach, and urban greening initiatives remain important strategies for improving resilience to climate-driven water quality challenges. Cross-border collaboration among universities, including San Diego State University, UC San Diego, Universidad Autónoma de Baja California, and the Centro de Investigación Científica y de Educación Superior

de Ensenada (CICESE), and government agencies such as the US EPA, is advancing efforts to monitor erosion sources and model the combined impacts of land use and climate change (Gudino-Elizondo et al., 2018). Other organizations, including the Tijuana River National Estuarine Research Reserve, the San Diego Foundation, and the Surfrider Foundation, also contribute to monitoring, planning, and floodplain protection, as well as community-focused educational outreach programs.

Binational frameworks such as Minute 328 (Environmental Protection Agency & CONAGUA, 2022) provide coordination on sanitation infrastructure, treatment expansion, and pollution reduction (Comisión Internacional de Límites y Aguas, 2022; International Boundary and Water Commission, 2019). In December 2024, $250 million in US federal funds was allocated to repair and expand the SBIWTP, raising the IBWC's total 2024 budget to $650 million (Governor of California, 2024; Higgs, 2025). On July 24, 2025, the United States and Mexico signed a Memorandum of Understanding (MOU) to accelerate implementation of Minute 328. The agreement outlines key actions including interim and long-term expansion of the SBIWTP, feasibility studies on additional treatment facilities, and binational monitoring systems (US EPA, 2025). Despite these advances, wastewater treatment inefficiencies continue to affect Tijuana, where resource limitations and rapid urbanization constrain large-scale reuse and modernization efforts. As a result, elevated bacteria levels frequently cause beach closures along the Southern California coast (Comisión Nacional del Agua (CONAGUA), 2023). San Diego has expanded reuse through projects such as Pure Water, while Tijuana reports 2.8% reuse of treated water (Comisión Estatal del Agua de Baja California, 2022). Decentralized initiatives such as Ecoparque and planned desalination in Playas de Rosarito illustrate pathways for diversifying supplies and improving resilience in the context of constrained resources (Garcia et al., 2022).

COASTAL MANAGEMENT

The coastal regions of San Diego, California, and Baja California, Mexico, form a unique cross-border ecological zone characterized by shared ecosystems, such as the Tijuana River Estuary and the California Current Marine Ecosystem. These areas are rich in marine biodiversity, with iconic kelp forests that support various species and critical fishing industries on both sides of the border. However, these ecosystems are increasingly vulnerable to climate pressures, including rising temperatures, ocean acidification, and coastal erosion, contributing to habitat loss and disruption of marine life (Lonhart et al., 2019; Marshall et al., 2017). With support from the San Diego Foundation, in 2023, Reef Check and Ecología Cielo Mar y Tierra: Conservación sin Fronteras (ECOCIMATI) partnered to expand community science and kelp forest monitoring across the Baja California, Mexico and the US border and to increase engagement of ocean communities on both sides of the border with each other.

California and Baja California have launched several binational adaptation initiatives to address these shared challenges. Collaborative oceanographic monitoring by organizations like the California Cooperative Fisheries Investigations (CalCOFI) and Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE) have aligned practices to support fisheries management and resilience planning. Community science programs, such as CoastSnap and Border Bioblitz, engage local communities in both regions in data collection and conservation efforts, fostering a shared commitment to ecological stewardship (Ezcurra et al., 2021). Emerging opportunities for enhancing plurinational coastal resilience include: expanding data-sharing

frameworks focusing on real-time data sharing; integrating comprehensive coastal hazard assessments combining hydrodynamic, ecological and socioeconomic models; and strengthening Indigenous-led resilience efforts. Further, alignment of resilience planning with industry needs would allow the region to create a "blue economy" that supports economic growth while enhancing coastal ecological integrity. Data-driven insights supported by a skilled workforce offer a transformative pathway for the cross-border region and creates a model of binational cooperation and innovation (Le-Alvarado et al., 2024).

However, many major environmental data products, including hydrometeorological, ecological (terrestrial and marine), and coastal geomorphological datasets, end at the US border. This limitation hampers the ability to fully assess climate vulnerabilities and implement coordinated cross-border policy solutions. Extending large-scale data collection efforts and integrating monitoring networks into northern Baja California is essential for developing consistent, science-based adaptation strategies that align across both sides of the border.

WILDFIRE AND SMOKE IMPACTS

Wildfire activity in Southern California and Baja California Norte has increased over the past three decades, driven by rising temperatures, reduced precipitation, and greater atmospheric aridity. This trend is expected to continue throughout the 21st century with the changing climate (Dong et al., 2021; Goss et al., 2020; Keeley & Syphard, 2016; Williams et al., 2019). The seasonal window for extreme fire weather is expanding into the spring and late autumn, heightening the risk of large wildfire ignitions and spread. Southern California's coastal and mountain ecoregions along the Mexican border are particularly vulnerable to extreme weather and wildfire events.

In addition to the direct impacts of fire, wildfire smoke poses significant public health risks. Exposure to fine particulate matter (PM2.5) in wildfire smoke can lead to increased cardiovascular and respiratory illnesses and related hospitalizations (Schwarz et al., 2023), particularly among vulnerable populations such as outdoor workers (Reid et al., 2016; US EPA, 2019). Although the San Diego–Tijuana border region may experience the same wildfire smoke events, socio-demographic differences can result in unequal health impacts across populations. Socio-demographic factors are critical in shaping vulnerability and can inform regional strategies to protect communities on both sides of the border from the health effects of wildfire smoke. Further research is needed to better quantify the interactions between climate change, shifting fire regimes, and population vulnerability in the Cali-Baja region.

In response to these growing challenges, new workforce development initiatives are building local capacity for fire management and resilience. The Stewardship Pathways Program, led by the Climate Science Alliance and supported by the Southern California Interagency Wildland Fire and Fuels Cadre, provides training that strengthens regional climate science with Indigenous knowledge systems (Climate Science Alliance, 2025a). The program fosters collaboration across US and Mexican partners and emphasizes co-stewardship of ancestral lands.

5.4.3 Addressing Financial Barriers

Funding for projects and collaborations is central to building resilience, and working across countries often makes this more difficult. There are numerous collaborations and funding mechanisms that are ongoing through universities, NGOs, and government partnerships. An

example is the San Diego Foundation Binational Resilience Initiative (BRI) which demonstrates how dedicated, place-based funding can successfully advance binational collaboration on climate resilience. In 2022, BRI started in partnership with the International Community Foundation focusing on the Cali-Baja coastal region, from Oceanside in North San Diego County to Ensenada in northern Baja California. The initiative addresses the region's shared climate vulnerabilities by supporting binational collaborations among civil organizations, scientists, community leaders, and other stakeholders. It also serves as an important funding model for future resilience investments by directing resources to cross-border collaborations in climate change and environmental justice projects.

5.4.4 Climate Adaptation Focused Collaboration

The Climate Science Alliance Tribal Working Group focuses on natural and cultural climate stewardship rooted in respect, relationships, and reciprocity (Climate Science Alliance, 2025b). Through binational, interdisciplinary collaboration, the Climate Science Alliance's Working Groups are advancing climate science and adaptation solutions throughout the Baja California Peninsula and surrounding regions to address climate change impacts and support solutions. Included in these working groups is Tipey Joa Native Warriors, which is an international organization that promotes health and cultural preservation in Indigenous communities in Kumeyaay Nations on either side of the border, helping to link together the binational and Tribal working group efforts. In 2024, members convened in Ensenada for a Binational Coastal Resilience gathering to share knowledge across the border region (Climate Science Alliance, 2024). Hosting this event in Baja California added a unique dimension, emphasizing the importance of collaboration and shared efforts in addressing the challenges of coastal and climate resilience beyond borders. These kinds of efforts strengthen community ties and enhance adaptive capacity by aligning regional resilience efforts with Indigenous land stewardship practices, acknowledging the essential role of Traditional Knowledges in ecosystem conservation (Ezcurra et al., 2021).

To address resilience needs for the transportation system and related infrastructure in the cross-border region, SANDAG is working on the California-Baja California Border Resilience Plan. The Plan is a US-Mexico binational effort to study how climate stressors are impacting border region communities and ways for cross-border transportation infrastructure to better adapt to those conditions. The Plan will study existing conditions and identify strategies, programs, and projects that will help enhance and protect transportation infrastructure and the people who depend on it.

Additionally, in 2023, the Tijuana River National Estuarine Research Reserve (TRNERR) convened the Marine Debris Leadership Academy, a cross-border cohort of professionals from various backgrounds such as local nonprofits, academics, and federal, state, and municipal agencies for a multi-day program that provided training, site experiences, and sharing technical and practical knowledge on the challenge of marine debris and solid waste within the Tijuana River Watershed. In 2024, TRNERR was awarded a grant through the National Sea Grant Marine Debris Community Action Coalitions Competition to further develop and launch future Marine Debris Leadership Academies. Programs such as these contribute to increasing the region's adaptive capacity to climate change and components that compound its impact, such as marine debris and habitat loss.

Chapter 6.

Conclusion: Looking Forward



Summary of Findings

Historically, San Diego has faced significant challenges from weather and climate extremes. Notable events include severe flooding in January 2024; beach erosion and storm impacts during the 2022–2023 winter season; the August 31–September 9, 2022, heat wave; the Cedar and Witch Creek Fires in 2003 and 2007, respectively; severe flooding during the strong El Niño winter of 1982–1983; and damaging floods in February 1980. With climate change, the risks from such extremes are projected to intensify and become more frequent. San Diego is working to better understand these risks, develop plans to reduce their impacts, and test and implement solutions as discussed in this report and summarized below.

6.1 Climate Science: Historical and Projected Trends

- San Diego's climate will continue to be shaped by interactions between subtropical and mid-latitude systems, with atmospheric rivers, Santa Ana winds, heat waves, and marine layer cloud cover remaining defining features. Sustained monitoring, forecasting, and downscaled climate information are essential for decision-making across sectors.
- Average temperatures are projected to rise about 4°F (2.2°C) by mid-century relative to 1981–2010, with interior areas warming more than coastal zones and heat waves becoming more frequent and longer lasting.
- Wildfire risk will remain strongly linked to dry fuels and Santa Ana wind events. Although Santa Ana wind frequency is predicted to decrease overall, the onset of winter precipitation, which significantly reduces fire risk, is projected to continue to occur in early November with high year-to-year variability.
- Annual precipitation totals are projected to decrease modestly, but rainfall is expected to occur less often and in more intense events, driven by increased winter atmospheric river precipitation and reduced fall and spring precipitation.
- Drought severity will be most affected by warming temperatures causing the landscape to dry out, making 12-month droughts and 36-month drought five times more likely for much of San Diego.
- Coastal marine layer clouds do not show a long-term trend in the 75-year observational record, and discerning future trends remains an active area of research.

6.2 Natural Systems

- Sea level rise will increase coastal flooding and beach erosion, threatening coastal recreation. In the coming decades, the most significant coastal threats will come from the combination of large storms and high tides, with the South Bay and Imperial Beach likely to be among the most impacted areas in the region. Beach and cliff erosion poses additional risks to public safety, property, and infrastructure.
- Coastal adaptation projects underway include beach nourishment, dune restoration, living shorelines, and improved coastal monitoring and warning systems.

- Urban development constrains the inland migration of estuaries as sea levels rise. Adaptive management, strategic habitat restoration, and coordinated land-use planning can help sustain estuaries as natural flood buffers and critical ecosystems.
- Terrestrial ecosystems face increasing stress from heat, drought, wildfire, invasive species, and extreme precipitation. Climate-smart conservation efforts are expanding to fill data gaps, apply nature-based approaches, manage multiple species in a system approach, and advance Indigenous stewardship through Tribal partnerships.
- Agriculture and food systems face growing constraints from extreme heat, water scarcity, and high land and labor costs. Ongoing adaptation efforts include expanding applied research on local high-value crops, supporting climate-adaptive practices, and strengthening community-based urban agriculture and sustainable aquaculture initiatives.

6.3 Built Systems

- San Diego's electrical grid faces rising threats from climate extremes, while gas infrastructure is increasingly susceptible to landslides and inland flooding. To meet ambitious local zero-carbon targets and rising demand, the region is working to upgrade distribution and transmission systems while integrating climate adaptation into energy planning.
- Over the past several decades, the region has bolstered its drought resilience by reducing per-capita water use and shifting toward local supply sources. However, stormwater and wastewater systems remain highly vulnerable to extreme precipitation, prompting adaptation efforts that can improve water quality, protect ecosystems, and reduce flood impacts.
- The transportation sector is threatened by both acute disruptions, such as fires and floods that close roads and railways, and long-term structural degradation from repeated exposure to climate extremes. These physical risks require new approaches to maintaining, upgrading, and protecting regional transit assets over their lifecycles.
- Climate projections are increasingly being incorporated into design standards, infrastructure upgrades are being prioritized in high-risk areas, and agencies are coordinating on resilience planning.

6.4 Social Systems

- San Diego County's diverse population faces intensifying health risks from climate change, including heat-related illness, respiratory conditions, and vector-borne diseases. These hazards disproportionately impact vulnerable groups, who often face higher exposure and have less access to healthcare resources. Community-driven, culturally relevant strategies can help reduce chronic disease and injuries while fostering a more equitable, health-focused future.
- San Diego's climate resilience is driven by collaboration across federal, state, Tribal, and local levels. As of 2022, 71% of jurisdictions had adopted or were updating climate-integrated General Plan Safety Elements. To address capacity and funding gaps, the region can leverage regional plans to support local efforts while developing shared metrics and databases.

- San Diego's high-tech, military, and cross-border economy can turn climate risks into opportunities by combining market-driven innovation with public investment in resilient infrastructure, energy transitions, and equitable workforce development.
- The Cali-Baja region, with a $250 billion economy and 7 million people, faces rising flood and pollution risks that require binational cooperation across shared ecosystems. Strengthening resilience across the border region will require Indigenous stewardship, diverse funding sources, and real-time data sharing to align ecological and socioeconomic models for adaptation.

6.5 Gaps and Opportunities

San Diego's capacity for resilience is rooted in a long history of adaptation, beginning with the land stewardship of the region's first peoples, the Tribal Nations of the Cahuilla, Kumeyaay (Diegueño), Kuupangaxwichem (Cupeño), and Payómkawichum (Luiseño). Building on Tribal knowledge systems, along with rapidly evolving science and technology, the San Diego region is finding new ways to anticipate and respond to a changing climate. Artificial intelligence and machine learning are improving climate projections, event attribution, and climate model emulation, helping make climate information more useful for regional decision-making (Watson-Parris, 2021). These methods can better capture fine-scale temperature and precipitation patterns in complex regions like San Diego County (Baño-Medina et al., 2020; Harder et al., 2024), while also supporting event attribution and faster scenario analysis for planning (He et al., 2020; Watson-Parris et al., 2022). From the increasing support for Indigenous stewardship and Tribal leadership to the rise of machine learning tools, San Diego draws on a diverse set of approaches to understand and respond to climate change. To continue this culture of forward-looking resilience, this report identifies gaps and opportunities where the San Diego region can build greater climate resilience.

6.5.1 Climate

- Improve understanding of compound events, including their impacts and predictability, particularly as they evolve in a changing climate.
- Enhance representation of marine layer clouds, which strongly influence San Diego's coastal margin, but which are difficult to resolve in global climate models. Better methods for translating model projections into marine layer changes would improve planning for heat risk, solar energy production, water demand, and ecosystems.
- Identify which types of real-time data and presentation formats are most useful in climate dashboards and applications, especially those that support public awareness and decision-making.

6.5.2 Coastal

- Assess whether and how wetlands can adapt or migrate inland to inform land use planning, habitat conservation, floodplain management, and sea level rise adaptation policy.
- Expand data, analysis, and modeling to better understand where inland flooding intersects with coastal inundation, particularly during compound events.

- Conduct performance evaluations and cost–benefit analyses of nature-based solutions, such as dunes, oyster reefs, ecotone levees, living shorelines, and wetland restoration, supported by long-term observational studies to inform future investments.
- Develop best practices, economic modeling, and case studies for community-driven relocation. Guidance should include both technical and participatory planning strategies.

6.5.3 Ecosystems

- Expand research on regional ecosystem services to quantify their value for climate resilience, equity, and long-term planning. Highlight both the economic benefits of functioning ecosystems and the costs of degradation.
- Improve communication about the interconnectedness of ecosystems with urban infrastructure, including impacts on public health, flood risk, and water quality.
- Advance research on compound impacts and cascading failures across ecosystems.
- Elevate Indigenous Knowledge systems, recognizing that humans are part of, not separate from, ecosystems. Support Indigenous-led stewardship, restoration, and monitoring efforts that reflect reciprocal relationships with land, water, and ecosystems.

6.5.4 Agriculture and Food Systems

- Strengthen farmer-to-farmer collaboration to share adaptation practices.
- Invest in food hubs and shared infrastructure to reinforce local networks and resilience. Assess agricultural land trust models and their role in supporting climate-buffering services and long-term land access.
- Use geospatial data to identify farmland most likely to transition because of climate change, development pressures, or conservation initiatives.
- Communicate findings on the economic multiplier effects of investment in local food systems and resilience strategies.

6.5.5 Energy

- Collect wind data at turbine hub height to verify and downscale climate projections and improve cloud representation to support clean energy planning.
- Conduct research on how energy policies and infrastructure changes, such as time-of-use rates, electrification mandates, distributed energy resources, and grid updates, affect vulnerable communities and cost-effectiveness, especially during extreme events.
- Develop case studies or regional assessments of energy infrastructure upgrades, such as undergrounding and microgrids, and evaluate their performance during heat waves, blackouts, and wildfires.
- Promote equitable workforce pathways and community education around the energy transition, particularly for low-income, rural, and Tribal communities.

6.5.6 Water

- Assess interactions between drought periods and surges of urban water from non-rain sources, including impacts on water quality.
- Investigate the effects of warming, vector migration, and emerging pathogens on water systems and water quality.
- Expand the network of gauging stations on creeks and rivers to track flow variability and inform adaptive management.

6.5.7 Transportation

- Provide regular public communication on how transportation networks are evolving, emphasizing safety, access, equity, and climate benefits.
- Improve modeling and projections of the lifespan and vulnerabilities of transportation infrastructure, especially for elevated structures in changing coastal environments.
- Evaluate the effectiveness and scalability of shade structures, water-based cooling, and green infrastructure in transit spaces.
- Increase coordination with cities, communities, and businesses to develop roadways that support proximity to essential goods and services.

6.5.8 Public Health

- Expand observational analyses to identify areas of heightened exposure and vulnerability to climate-related health risks in San Diego.
- Train healthcare professionals to diagnose and treat climate-related health impacts, such as heat illness, respiratory distress, and vector-borne disease.
- Improve tracking of health trends and recording symptoms to better capture the hidden impacts of climate change on mental health and the true mortality and morbidity rates associated with climate-related illnesses.
- Evaluate the effectiveness of adaptation and mitigation measures, such as cool zones and urban design changes, on health outcomes.

6.5.9 Governance

- Regularly document and share adaptation case studies to enable learning and replication across jurisdictions.
- Develop consistent metrics to assess adaptation measures, communicate progress, and evaluate success.
- Create a visual guide that clarifies how plans and documents such as General Plans, Climate Action Plans, Local Coastal Programs, and Hazard Mitigation Plans relate to policies and legal responsibilities across agencies.
- Establish durable practices for incorporating citizen data and community voices that can withstand staff and leadership turnover. Regularly solicit community input and feedback to ensure responsiveness to community needs.

6.5.10 Economics

- Increase cross-disciplinary collaboration among economists, ecologists, engineers, and other experts to contextualize cost data and climate impacts.
- Work with experts to refine benefit–cost analysis methods for climate-related projects, especially in public and nonprofit sectors. Use these analyses to quantify the benefits of adaptation compared with baseline or business-as-usual scenarios.
- Integrate non-market values, such as shade and recreation, into benefit–cost models using improved observational data.
- Identify and coordinate funding sources across local, state, federal, and philanthropic programs to support climate adaptation and resilience investments.

6.5.11 Cross-Border

- Deepen understanding of cultural, economic, and environmental relationships among urban, rural, and Tribal communities in the Cali-Baja region, including water access and resource flows.
- Develop shared datasets spanning the US–Mexico border, especially in inland areas, including environmental and governance data relevant to US, Mexican, and Tribal governments.
- Conduct comprehensive, integrated evaluations of climate issues across the border region, reflecting shared ecosystems, populations, and risks, while mapping shared resources.

This report presents a state-of-the-science review of San Diego's historical climate trends, future projections, associated extremes, and risks across key regional systems. Climate resilience planning and implementation that is grounded in science and centered on equity can strengthen communities and help sustain long-term prosperity. While this report identifies vulnerabilities to multiple sectors, it also highlights the wide range of efforts underway to reduce the impacts of climate hazards and build adaptive capacity. These examples are not exhaustive but illustrate the breadth and momentum of adaptation efforts across the region.

The threats posed by climate change are too complex and far-reaching for any single agency or organization to address alone. With continued investment and coordinated action, San Diego has all the elements needed to enhance climate adaptation efforts: leading academic researchers focused on the region, forward-thinking local governments and agencies, Tribal leadership, engaged community organizations, cross-border coordination, and a strong culture of collaboration. Because of these strengths, we conclude this report with optimism that San Diego can continue to thrive in a changing climate.

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Acronyms

AB	Assembly Bill
AR	Atmospheric river
BMP	Best management practices
BRI	Binational Resilience Initiative
CA	California
CAISO	California Independent System Operator
CAP	Climate action plan
CARB	California Air Resources Board
CAVA	Climate Adaptation and Vulnerability Assessment
CBO	Community-based organization
CCA	Community choice aggregation
CCE	California Current Ecosystem
CDPH	California Department of Public Health
CEA	Clean Energy Alliance
CEC	California Energy Commission
CEQA	California Environmental Quality Act
CMIP	Coupled Model Intercomparison Project
CNRA	California Natural Resources Agency
CPUC	California Public Utilities Commission
CRD	Climate Resilience District
DO	Dissolved oxygen
DOT	Department of Transportation
DWR	Department of Water Resources
ENSO	El Niño–Southern Oscillation
EPA	Environmental Protection Agency
FAIR	Fair Access to Insurance Requirements
FEMA	Federal Emergency Management Agency
FIRO	Forecast-Informed Reservoir Operations
FRAP	Fire and Resource Assessment Program
GCM	Global climate model (or general circulation model)
GDP	Gross domestic product
GHG	Greenhouse Gas
GSCWP	Green Streets Clean Water Plan
GSOB	Goldspotted oak borer
HAB	Harmful algal bloom
HABDAC	Harmful Algal Bloom Data Assembly Center
HUC	Hydrologic Unit Code
IB	Imperial Beach
IID	Imperial Irrigation District
IOU	Investor-owned utility
IPCC	Intergovernmental Panel on Climate Change
LOCA2	Localized Constructed Analogue (downscaling method, version 2)
LOSSAN	Los Angeles–San Diego–San Luis Obispo Rail Corridor
ML	Machine learning
MOU	Memorandum of understanding

MSL	Mean sea level
MTS	San Diego Metropolitan Transit System
MWD	Metropolitan Water District
NCEI	National Centers for Environmental Information
NCTD	North County Transit District
NOAA	National Oceanic and Atmospheric Administration
NOP	Notice of Preparation
OPC	Ocean Protection Council
PDSI	Palmer Drought Severity Index
PSPS	Public Safety Power Shutoffs
RBSP	Regional Beach Sand Project
RCP	Representative Concentration Pathways
RPS	Renewables Portfolio Standard
SANDAG	San Diego Association of Governments
SAW	Santa Ana winds
SB	Senate Bill
SBIWTP	South Bay International Wastewater Treatment Plant
SCCOOS	Southern California Coastal Ocean Observing System
SCWRP	Southern California Coastal Water Research Project
SDCWA	San Diego County Water Authority
SDG&E	San Diego Gas & Electric
SDRCC	San Diego Regional Climate Collaborative
SDREN	San Diego Regional Energy Network
SDSU	San Diego State University
SGIP	Self-Generation Incentive Program
SGMA	Sustainable Groundwater Management Act
SIO	Scripps Institution of Oceanography
SLR	Sea level rise
SPEI	Standardized precipitation-evapotranspiration index
SR-75	State Route 75 (or similar for other state routes)
SSAP	Shellfish and Seaweed Aquaculture Program
SSP	Shared socioeconomic pathways
SST	Sea surface temperature
SWP	State Water Project
SWRCB	State Water Resources Control Board
TBU	Tribal beneficial uses
TEK	Traditional Ecological Knowledges
TRNERR	Tijuana River National Estuarine Research Reserve
UC	University of California
US	United States
USD	University of San Diego
USDA	United State Department of Agriculture
USGS	United States Geological Survey
VMT	Vehicles miles traveled
WQS	Water Quality Standards
WRP	Waterscape Rebate Program



CALIFORNIA'S FIFTH
CLIMATE CHANGE
ASSESSMENT