CLIMATE CHANGE IMPACTS, VULNERABILITIES, AND ADAPTATION IN THE SAN FRANCISCO BAY AREA

A Synthesis of PIER Program Reports and Other Relevant Research

A White Paper from the California Energy Commission's California Climate Change Center

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DISCLAIMER

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This paper synthesizes in much abbreviated form the hard work of many other research teams involved in the Public Interest Energy Research (PIER) Program's 2010–2012 Vulnerability and Adaptation study. We fully acknowledge the intellectual labor of those researchers, even if this paper reflects our own interpretation of their work. Several researchers assisted us by producing Bay Area-specific or otherwise revised figures based on their results. We also received helpful input from Bruce Riordan (Bay Area Joint Policy Committee) and David Behar (San Francisco Public Utilities Commission), and assistance from Dan Cayan and Mary Tyree (Scripps Institution of Oceanography) and Guido Franco (California Energy Commission) with several sections of this paper. Jason Su, Meg Krawchuck, and Greg Biging generously redrew figures from their studies to help meet the needs of this paper. We appreciate Rebecca Chaplin-Kramer and Ruth Langridge for reviewing portions of a draft.

ABSTRACT

This paper synthesizes San Francisco Bay Area-focused findings from research conducted in 2010–2012 as part of the state's Vulnerability and Adaptation study sponsored by the California Energy Commission's Public Interest Energy Research (PIER) Program. Historical observations of changes already evident are summarized, as well as projections of future changes in climate based on modeling studies using various plausible scenarios of how emissions of heat-trapping gases in the atmosphere may change. Studies synthesized here show how these climate changes increase risks to society and natural ecosystems in a number of ways. Sectors for which impacts, vulnerabilities, and adaptation options are presented include water, agriculture, energy supply and demand, transportation, ecosystems, public health, wildfire, and coastal resources. Results show that depending on the vulnerability of human and natural communities, and their abilities to respond to these growing risks through adaptive changes, the San Francisco Bay Area could experience either significant impacts or maintain its resilience in the face of a rapidly changing environment.

Keywords: California Energy Commission, San Francisco Bay Area, climate change, adaptation, vulnerability, impacts

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EXECUTIVE SUMMARY

The San Francisco Bay Area is the fifth most populous metropolitan area in the United States and one of the major drivers of California's and the nation's economy. It is a central economic and cultural hub, the beloved home to 7.1 million people in 101 cities and 9 counties, and the tourist attraction for many more millions of visitors each year. The very characteristics that make it such a magnet for people and businesses—its location at the edge of the San Francisco Bay and the Pacific Ocean, its climate, and its rich and unique natural environment—also entail threats that are now being magnified by climate change.

This paper synthesizes Bay Area-focused findings from research conducted in 2010–2012 as part of the state's Vulnerability and Adaptation (study sponsored by the California Energy Commission's Public Interest Energy Research (PIER) Program. For the first time, the Vulnerability and Adaptation study—the third comprehensive California Climate Change Assessment—includes a regional focus: the San Francisco Bay Area. This paper brings together all relevant results from eleven studies focused exclusively on this region, and several other reports, to describe the risks that climate change poses to the region's residents, its economic vitality, and all the infrastructure and services that support them.

Below, historical observations of changes already evident are summarized, as well as projections of future changes in climate based on modeling studies using various plausible scenarios of how emissions of heat-trapping gases in the atmosphere may change. These climate changes increase risks to society and natural ecosystems in a number of ways. Depending on the vulnerability of human and natural communities, and their abilities to respond to these growing risks through adaptive changes, the Bay Area could experience either significant impacts or maintain its resilience in the face of a rapidly changing environment.

Historical Climate Change Trends and Expected Changes in the Future

- *Temperatures are rising:* Historical records spanning the five decades from 1950 to 2000 already show significant trends of increasing average temperatures across the entire western United States, including California and the Bay Area. Temperature projections (from all models and scenarios used in the assessment) show a continuing and accelerating warming trend across the entire Bay Area over the rest of this century. By 2050 annual average temperatures are expected to rise over 2000 annual average temperatures by about 2.7°F (or 1.5°C) under both high and low emissions, largely as a result of past emissions and their delayed impact on the climate. By the end of the twenty-first century, however, the envelope of possible warming widens, in large part because of the uncertainty in society's current and future choices over emissions. Thus, annual average temperatures over the Bay Area could increase between 3.6°F and 10.8°F (~2°C to 6°C). The coastal portions of the Bay Area will continue to have comparatively milder summers and winters than the more inland areas. In terms of seasonal differences in warming, for the Bay Area, as with the rest of California, projections show a greater warming in summer than in winter. Simulations also show a shift in the timing of spring and summer heat extremes in the region. In the future such heat extremes are expected to begin as early as June and extend through September; whereas, historically they have mostly occurred in July and August.

- *Precipitation is changing as snowmelt runs off earlier in the spring and storms bring more intense downpours:* Historical records of the western United States, including California, indicate no clear trends yet in total precipitation, but the relative proportion of snow to the annual total is declining. Moreover, snow has been melting earlier in the spring than in the past, beginning one to four weeks earlier between the years 1948 and 2002. While simulations of future precipitation are more uncertain than temperature projections, simulations show that future annual precipitation over Northern California will not change much, though precipitation in portions of Southern California will decrease by as much as 5 to 18 percent compared to historic averages). The greatest reduction in precipitation is expected to occur in spring; whereas, the main precipitation months (winter) will remain relatively unchanged. Projections also show an increase in the number and intensity of extreme storms and consequent flooding events over the next century. Because Bay Area water suppliers draw their water from both the Sierra Nevada and from local surface-water and groundwater, climate changes in both regions will matter for future water availability.
- *Fire risk is increasing, but how much and where depends as much or more on population growth and development as on climate change:* Projections show an increase in risk of wildfire as temperatures rise and seasons shift as a result of climate change. The drier conditions in the spring will be a particularly important factor, resulting in longer fire seasons. But the extent to which wildfire risk increases depends not only on how much heat-trapping greenhouse gases are emitted, but also (and in some instances more) on the way human development advances, changing the wildland-urban interface.
- *Sea level is already rising, and the rate is expected to increase significantly in the future:* At the Golden Gate tide gauge, sea-level observations have been made since the late nineteenth century. Based on this long-term record it is clear that sea level has risen 7 to 8 inches over the twentieth century. By 2050, sea level could increase another approximately 11 to 19 inches (27 to 48 centimeters, cm) relative to the level in 2000 and, depending on the degree of climate warming, rise a total of 30 to 55 inches (or 77 to 140 cm) above this same level by 2100. This would amount to up to a six-fold increase in the rate of sea-level rise over historical observations. As the sea level baseline rises, there will be a greater number of extreme high sea-level events (e.g., storm surges, unusually high tides), which also increase the duration of extremely high water at Bay shorelines. Over the coming decades extremely high sea level events will thus persist for more hours, causing greater coastal flooding, erosion, and related damages.

  The Sacramento–San Joaquin River Delta is a particular case in point. It is already at high risk of flooding should any of its levees fail, because significant land areas are below sea level at present. Major levee breaks and resulting flooding would have critical implications for regional and statewide water supply, energy infrastructure, agriculture, and populations and residential developments in floodplains. The Vulnerability and Adaptation study provides a higher-resolution dataset of topographic data produced for the entire Bay Area that shows not only low-lying areas but also flood protection structures, which allows for a more accurate assessment of flooding risks.

Climate Change Risks Threatening Bay Area Resilience

These increases in temperature, changes in precipitation, increasing risks of wildfire, and increasing rates of sea-level rise pose significant risks to the Bay Area's people, natural environment, and economic sectors, as well as the critical infrastructure and community services on which they depend. Together, these changes pose a significant threat to the resilience of the Bay Area. In short, climate change could result in the following impacts:

- *Water supply:* The ways and degree to which water supply is vulnerable to climate change depends on the source from which—and how—water is supplied. Marin County, for example, depends on water from a system of local reservoirs within the county, so it is largely sensitive to annual local rainfall. San Francisco and some of the East Bay depend on water supplied from the Sierra Nevada, thus could be sensitive to impacts on timing and quantity of snowmelt runoff. Other water districts rely on water from the Delta, which is at risk from flooding and permanent inundation due to sea-level rise, or from groundwater that is threatened by overdrafting, potentially diminished recharge due to changes in local rainfall, and salt water intrusion into coastal reserves (diminishing water quality) from both sea-level rise and more extreme storm events.

- *Infrastructure*: Increased risk of flooding from sea-level rise and increases in extreme rainfall or high-water events could lead to impairment, damages, and more frequent inoperability or repair to critical infrastructure, including wastewater treatment plants, sewage pipes and pumps in low-lying areas, power plants and substations (especially in the Delta), and transportation (roads, rail, bridges, and two international Bay Area airports). There is a risk of extremely high economic damages from flooding as the sea level rises, especially in San Mateo and Alameda counties.

- *Agriculture*: North Bay agriculture in Napa and Sonoma counties is highly sensitive to increasing temperatures and earlier onset of spring. These areas may become sub-optimal for growing high-quality wine grapes; and while projected climate changes could potentially increase forage production, reliability of forage could be reduced and forage season length could shorten.

- *Ecosystems and biodiversity*: Coastal wetlands—a jewel along the Pacific Flyway—are already at risk under historical development pressure and pollution. With sea level rising, this pressure is bound to increase. Along the coastlines of the Bay's southern counties these wetlands do not have anywhere to go, as landward development is blocking their migration. Wetlands along the shores of Northern Bay counties do still have that opportunity, but only if those adjacent upland areas remain undeveloped. Climate change threatens nearly all the region's native freshwater fish species (including commercially important ones and those already endangered) but is expected to have little negative, or even a positive impact on non-native (and in some instances, invasive) fish species.

- *Transportation and emergency response services*: Future flooding—when sea level is significantly higher than it is now—could cut off access roads of coastal communities from the hinterland in some areas of the region. This would not only affect daily commutes and economic activity, but also the capacity of emergency response to reach those areas.

- *Energy demand, supply, and transmission*: Residential energy demand is expected to increase as temperatures rise, especially in the interior portions of East Bay counties and during heat extremes in the summer. During extreme heat events power production and transmission is also relatively less efficient, making it more difficult to meet the increased demands and avoid brown-outs respond to emergencies. Supply infrastructure could be at increased risk of damage from flooding as sea level increases, and transmission lines both within the region and from outside the region to the Bay Area could be at growing risk from wildfires and related disruptions.

- *Public health*: While the region has had its share of flooding historically, heat extremes are virtually unknown in the Bay Area. This will change in the future, and because of this lack of familiarity, will pose a particular risk to local residents. Increases in the occurrence of heat extremes, more days with bad air quality due to higher temperatures, and possible spread of diseases will increase the threats to human health in the region. Not everyone will be equally vulnerable to these risks, however. Some segments of the population, especially those with pre-existing health conditions, the elderly, infants and children, socially isolated individuals, those not speaking English, and the poor are more sensitive than others, and/or may lack the ability to cope or prepare for such impacts.

Adaptation Options and Constraints

Many local governments in the Bay Area are already aware of the growing risks from climate change and are not only making efforts to reduce their share of emissions (mitigation) but also to assess their risks and prepare for them. Communities, businesses, and residents have a wide variety of adaptation options to increase their resilience and/or adapt to the impacts of climate change. These options vary by climate change risk and affected sector, and are highly context-specific.

Local Bay Area governments are at various stages in their preparation for and adaptation to climate change. Concerted efforts to address climate impacts have begun in some cities, counties, and sectors, and quite likely in the business community. Climate change is still a relatively unfamiliar issue for many, recent economic concerns have tightened local belts, and some adaptation measures involve significant management changes, all of which create significant hurdles for local governments beginning the adaptation process. So far those working on adaptation seem to be mostly engaged in building their own adaptive capacity and overcoming these hurdles rather than making major structural, policy, or management changes. These are important first steps; however, many barriers go beyond the resources and funding limitations that hinder most decision-making and planning efforts in tough economic times. Permitting requirements and lengthy decision-making processes, needs for cross-jurisdictional collaborations, and lack of a mandate or (to date) much technical support for adaptation are examples of institutional and governance-related barriers that local governments predominantly encounter.

Other initiatory efforts under way in Bay Area governments include increasing understanding and expertise through trainings and outreach, pooling resources to develop coordinated efforts, and getting organized internally so as to be ready for guidance anticipated from regional adaptation planning efforts. Innovation, which has driven the region's competitive economy, will be key to helping the region adapt to climate change.

1. INTRODUCTION

1.1 Background

The Third California Climate Change Assessment, referred to as the Vulnerability and Adaptation Study (V&A Study), was coordinated and funded by the California Energy Commission's Public Interest Energy Research (PIER) Program. The research performed for the first two biennial statewide assessments focused on assessing potential climate change impacts, assuming certain emission scenarios and resulting climate change. The 2009 California Adaptation Strategy (CAS) called for a new approach to assessing the climate change threats to the state's economy, environments, and community in a way that reveals more accurately how these threats may unfold on the ground; namely, a vulnerability approach (California Natural Resources Agency 2009).

In addition to beginning to reorient the statewide research from pure impacts research to this more integrative vulnerability perspective, the V&A Study also selected one region of focus for several research endeavors that span across multiple sectors and adaptation-relevant topics. The inclusion of a regional focus came from the recommendation of the Second California Climate Change Assessment (Franco et al. 2011) and the 2009 CAS (California Natural Resources Agency 2009). Thus, in the most recent funding cycle (2010-2012) PIER supported multiple research projects on the San Francisco Bay Area. The purpose of focusing in on a particular region was to explore whether region-specific information could be developed that could better support adaptation planning and implementation processes.

The San Francisco Bay Area was selected as the pilot region for this approach because of its economic importance to the state, coverage of both rural and urbanized land uses, diverse coastal and inland geography, and wide range of potential climate change impacts to multiple sectors. Also important in the selection was the willingness and high interest of regional decision-makers in the region (e.g., Bay Area Joint Policy Committee) in policy- and management-relevant (though not policy–prescriptive) scientific information.

1.2 Purpose of this Paper

This paper synthesizes Bay Area-focused findings from the new research conducted in 2010-2012 as part of the state's V&A Study. It brings together all relevant results from those studies focused exclusively on this region, and several other reports, to describe the risks that climate change poses to the region's residents, its economic sectors, and the infrastructure and services that support them. Together, this research contributes to a better understanding of how the San Francisco Bay Area is vulnerable to climate change, and what is being done already to prepare for and manage the resulting risks.

Research and topics are put into the context of the vulnerability framing described in the 2009 CAS, which is also consistent with the broader impacts, vulnerability, and adaptation literature (e.g., Intergovernmental Panel on Climate Change [IPCC] 2007). While Bay Area-focused PIER-funded reports are this paper's primary focus, other relevant research and work is used to contextualize these new findings in the bigger picture of what is happening and what is already known about the region. The paper distills important findings and contributions to understanding vulnerability and advancing adaptation in the region.

Both historical observations of changes already evident are summarized, as well as projections of future changes in climate based on modeling studies using various plausible scenarios of how emissions of heat-trapping gases in the atmosphere may change. These climate changes increase risks to society and natural ecosystems in a number of ways. Depending on the vulnerability of human and natural communities, and their abilities to respond to these growing risks through adaptive changes, the Bay Area could experience either significant impacts or maintain its resilience in the face of a rapidly changing environment.

1.3 Organization of this Paper

Section 2 provides a brief overview of the San Francisco Bay Area as a region and introduces the vulnerability framing, as well as key concepts used in this synthesis. Section 3 presents findings on observed and projected changes in the physical climate system (temperature, precipitation, wildfire, sea-level rise (SLR), flooding, and other extreme events). Section 4 summarizes research findings on impacts, vulnerability, and adaptation specific to the Bay Area. This information is presented by sector (water, agriculture, transportation, energy supply and demand, ecosystems, public health, and coastal resources). In addition to discussing potential impacts from climate change, available and already-enacted adaptation options to reduce the severity of these impacts are also discussed. The paper ends with a discussion of patterns and themes that appear across sectors and studies regarding vulnerability and adaptation.

2. SETTING AND VULNERABILITY FRAMING

2.1 Geography of the San Francisco Bay Area

The San Francisco Bay, located on the north central coast of California, is the largest estuary along the west coast of the United States. The nine counties that border the Bay form the jurisdictional boundaries of what is considered the San Francisco Bay Area (Figure 1). Overall, the region's coastal Mediterranean climate is characterized by a dry season in the summer and fall and a wet winter, but a variety of geographic features (from mountain ranges to inland valleys, the San Joaquin Delta, and smaller bays) create several distinct climatic zones based on varying topography and coastal exposure (California Energy Commission 2012; Bay Area Air Quality Management District [BAAQMD] 2011). Coastal areas are typically cooler than inland areas, and the northern counties tend to receive more rainfall than the southern counties. Seasonal variations can differ widely:

> "Winter time flooding can occur along the open coast and Bay shoreline during coastal storms and in local watersheds under extended wet conditions when the ground becomes saturated (more common in the North than the South Bay), sometimes accompanied by mud and landslides. During spring and especially in the fall, when offshore winds and generally dry conditions prevail, the region also faces considerable wildfire hazards" (Moser and Ekstrom 2012).

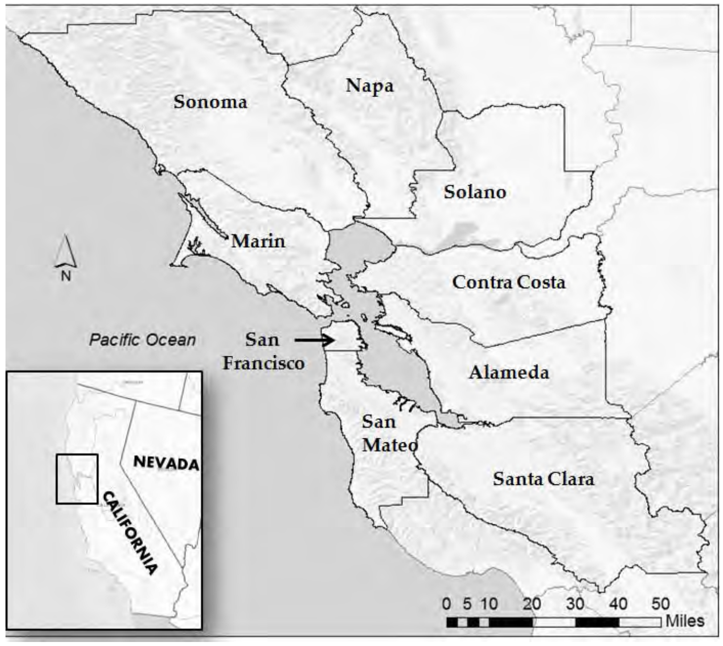

Figure 1. Location of the Nine Counties That Make Up the San Francisco Bay Area

Source: Authors.

The confluence of the Sacramento and San Joaquin Rivers create the Sacramento-San Joaquin Delta, which empties into the northern portion of the Bay. The Delta provides important ecosystem services for both the region and the entire state, as it supplies water for agriculture and consumptive uses (locally and for export to southern California through water projects), and supports a high diversity of species and habitat, including tidal marsh.

As a result of the particular geographic location, topographic and landscape diversity at this confluence of land and sea, the San Francisco Bay region encompasses some of the world's greatest biodiversity in proximity to intense urban development. Nearly 500 contiguous large protected areas support this ecological richness (Ackerly et al. 2012). The Bay also has 90 percent of California's remaining wetlands (San Francisco Bay Watershed Database and Mapping Project, no date); commercially important species such as California's Dungeness crab, California halibut, and Pacific salmon fisheries use it as their nursery; and its marshes offer refuge to several endangered species. "For its ecological, hydrological and aesthetic value, the San Francisco Bay is protected under a variety of policies aimed at preserving its water quality, preventing unmitigated fill of the Bay, protecting endangered species, and making access to the waterfront and to open space" (Moser and Ekstrom 2012).

2.2 Demographics and Economic Importance

With a total population of over seven million people, the Bay Area is one of the largest metropolitan areas on the U.S. west coast. It is a major transportation hub and a critical economic center, not just for the state but also nationally and internationally. There are 101 cities and towns in the nine counties that form the Bay Area, the three largest of which are San Jose, San Francisco, and Oakland. San Francisco is considered the cultural and financial center of the region; San Jose the technological center, and Oakland the central hub for the East Bay, and with its busy intermodal port, a major industrial center. The Bay Area includes the top five California counties in terms of per capita income and two of the 25 wealthiest counties in the United States (Santa Clara and Marin). These indicators of affluence are offset to some degree by the very high cost of living in the region (Moser and Ekstrom 2012).

With a gross domestic product of $535 billion, the Bay Area ranks as the nineteenth largest economy in the world when compared among nations and is the largest business center on the West Coast (Bay Area Economic Council 2012). Historically and still today, innovation has been central to driving the region's competitive economy. The region is home to 30 companies of the Fortune 500, many top-tier universities and research institutions, venture capital firms, successful recent startups (e.g., Twitter, Yelp, Facebook), and innovative corporations (e.g., Hewlett-Packard, Google, Apple). Many of the businesses and research institutes that support the economy are either located or rely on transportation systems that run along the Bay's shoreline. Nearly $30 billion of buildings and contents are already at risk of a 100-year flood on the Bay's shoreline (46 percent of which is commercial or industrial); that risk will substantially increase with rising sea level (Heberger et al. 2012). Innovation will be key to helping the region adapt to climate change in a way that avoids potentially disastrous impacts and even supports the economy and diverse population.

2.3 Vulnerability Framing

As stated in the Introduction, the Third California Climate Change Assessment, building on the previous assessments, sought to advance the understanding of vulnerability and adaptation to climate change. *Vulnerability* is more than "being at risk"; it refers in the most general sense to a susceptibility to harm or change. This concept can apply to any region, community, population, an individual, an economic sector, or technological or social-ecological system of interest. However, its conceptualization, scale of analysis, influences considered, and data available to operationalize it—as well as the methodologies employed to assess it—can be quite different. Hence, as the multiple research projects conducted for the V&A Study span across a variety of academic disciplines, they also use different indicators and methods to assess one or more components of vulnerability. This synthesis uses the vocabulary introduced in the California Adaptation Strategy (see the terms and definitions in Figure 2).

Thus, vulnerability is understood as a function of three components: exposure, sensitivity, and adaptive capacity. The approach and perspective taken here then offers more than just a listing of potential impacts, it examines how these climate-related hazards may interact with vulnerabilities "on the ground" to produce risks. Moreover, it offers insights into the differential levels of vulnerability and related equity concerns, the causes of vulnerability, and the range of interventions that could be used to make a system less vulnerable or more adaptive and resilient.

Most studies reviewed here examined one or two dimensions of vulnerability, rather than all three. Few integrated them into a single index of vulnerability. This synthesis highlights the vulnerability components examined in each paper. Topics covered include projected physical changes, water supply, agriculture, transportation, public health, energy supply and demand, ecosystem services and biodiversity, cumulative stressors and vulnerability at the community level, and local government decision-making related to adaptation and obstacles encountered in those processes (Table 1).

Vulnerability – In the most general sense, a susceptibility to harm or change. More specifically, the degree to which a system is exposed to, susceptible to, and (un)able to cope with and adapt to, the adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of character, magnitude, and rate of climate variation (the climate hazard) to which a system is exposed, as well as of non-climatic characteristics of the system, including its sensitivity, and its coping and adaptive capacity.

> ***Exposure*** – The degree to which a system is at risk, i.e., would experience the threat, if it unfolded. The climate science and health expert communities often equate exposure with potential climate change impact. Social scientists often distinguish external and internal exposure, where the external aspect relates to the physical climatic threat or hazard, whereas the internal aspect considers specific factors relevant to potentially affected populations. For example, outdoor workers have a different population-specific exposure than indoor workers [internal aspect of exposure] in a region where heat extremes are expected to increase [external aspect of exposure].
>
> ***Sensitivity*** – The degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., climatic or non-climatic stressors may cause people to be more sensitive to additional extreme conditions from climate change than they would be in the absence of these stressors).
>
> ***Adaptive Capacity*** – The ability of a system to respond to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, and to cope with the consequences. (Often adaptive capacity is distinguished from related, but not identical terms such as coping capacity, response capacity, and transformative capacity.)

Adaptation – Adjustments in natural or human systems in response to actual or expected climatic stimuli or their effects, which minimize harm or take advantage of beneficial opportunities.

Figure 2. Common Definitions Used in the California Vulnerability and Adaptation Study

Table 1. Research Conducted for the Vulnerability and Adaptation Study Focused Entirely or in Part on the Bay Area

Author(s)	Topic	Exposure	Sensitivity	Adaptive Capacity
Ackerly et al.	Ecosystems and biodiversity	X	X	X
Auffhammer & Arronruengsawat	Energy demand		X	
Biging, Radke & Lee	Transportation and inundation risk	X		
Brooks & Manjunath	Delta levees	X	X	
Bryant & Westerling	Wildfire and population growth	X		
Cayan, Tyree & Iacobellis	Climate scenarios	X		
Chaplin-Kramer	Agriculture		X	
Cornwell et al.	Impacts on vegetation	X	X	X
Heberger et al.	SLR impacts to the Bay Area	X	X	X
Garzón et al.	Community-level analysis	X	X	X
Jerrett et al.	Public health	X	X	X
Krawchuk & Mortiz	Wildfire historical and projected future	X		
Langridge et al.	Groundwater reserves for drought resilience	X	X	X
Moore, Zavaleta & Shaw	Scenario planning		X	X
Moser & Ekstrom	Barriers to adaptation	X	X	X
Moyle et al.	Freshwater fishes		X	X
Pierce et al.	Probabilistic estimates	X		
Sathaye et al.	Energy supply	X	X	X
Sicke, Lund & Medillín-Azuara	Water supply management			X

3. CLIMATE CHANGE AND BIOPHYSICAL CONSEQUENCES

As part of the Vulnerability and Adaptation Study, a common set of climate scenarios were generated by University of California San Diego climate scientists to be used by all participating research teams when possible. Utilizing a common set of projections allows for easier integration of and comparability among studies. Projections were developed with six Global Climate Models (GCMs) simulated for the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment (IPCC 2007) using two greenhouse gas emissions scenarios (SRES); namely a higher emissions scenario (A2) and a lower emissions scenario (B1).[1] The resulting climate projections were downscaled from the coarse resolution of the GCMs to a 7.5 mile (mi) (12 kilometer, km) regional scale grid using two statistical techniques called "bias-corrected statistical downscaling"(BCSD) and "bias corrected constructed analogues" (BCCA) (for detailed description see Cayan, Tyree, Pierce, and Das 2012; Maurer et al. 2010). Outputs from both downscaled projections were then used by the impacts and vulnerability-focused research

[1] For detailed description of these scenarios, see Cayan, Tyree, Pierce, and Das (2012).

teams to assess potential future risks. The same GCMs and emissions scenarios were used for the statewide climate change assessment (Cayan, Tyree, Pierce, and Das 2012). Not all researchers had the capacity to use all of the projections provided by Cayan, Tyree, Pierce, and Das (2012) and Cayan, Tyree, and Iacobellis (2012), thus we note where applicable which scenarios the authors used.

3.1 Warming

3.1.1 Historical Trends

Over the last several decades, air temperatures have risen significantly over the western United States, including throughout California (Bonfils et al. 2008). However, deciphering how much warming has occurred specifically across the Bay Area is difficult. Weather stations throughout the region, mostly maintained by cooperative observers, have collected ambient air temperature for several decades, yet many of these records are affected by changes in the surrounding area (e.g., urbanization of the area surrounding a weather station will elevate temperatures; whereas, irrigation will decrease surrounding temperatures) or the stations themselves have been moved. Nearly all the monitoring stations in the region show a pattern of warming. Modeled simulations of historical temperatures suggest that the warming from greenhouse gas emissions is approximately 1°F (just over 0.5°C). The observed warming has exhibited stronger increases in minimum (nighttime) temperature than daytime temperatures (Cayan, Tyree, and Iacobellis 2012; Figure 3).

The diversity of microclimates within the Bay Area accounts for a broad range of climate conditions at any one time, as well as for trends over time, making averages across the entire region difficult to interpret. Subregional assessments and projections of temperature, therefore, provide more useful information. Because the sharp climate gradients in the Bay Area create major differences in temperature (e.g., from coastal to inland, lowland to upland areas, Figure 3), identifying patterns of change in historical temperature depends on the monitoring location and the time span of observations. Observations therefore report different findings on changes in the region. For the North Bay, for example, Micheli et al. (2010) reported a 2.7°F (1.5°C) temperature increase in maximum monthly temperatures between 1900 and 2010 (roughly 0.24°F [0.13°C]/decade), and even more rapid increases in monthly minimum temperatures, especially between 1971 and 2000. Examining temperature records between 1950–1997, Lebassi et al. (2009) reported a slight warming per decade (0.57°F [0.32°C]/decade) in inland areas of the region, but found patterns of cooling over coastal areas influenced by coastal upwelling, cloud cover, and increased irrigation. In a more recent study, Johnstone and Dawson (2010) found a pattern of coastal areas warming faster than inland areas associated with a 33 percent decrease in fog since mid-century. This pattern may largely be linked to a regional to large-scale natural variability; climate model projections of future temperatures generally indicate that interior areas will experience greater climate warming than coastal areas.

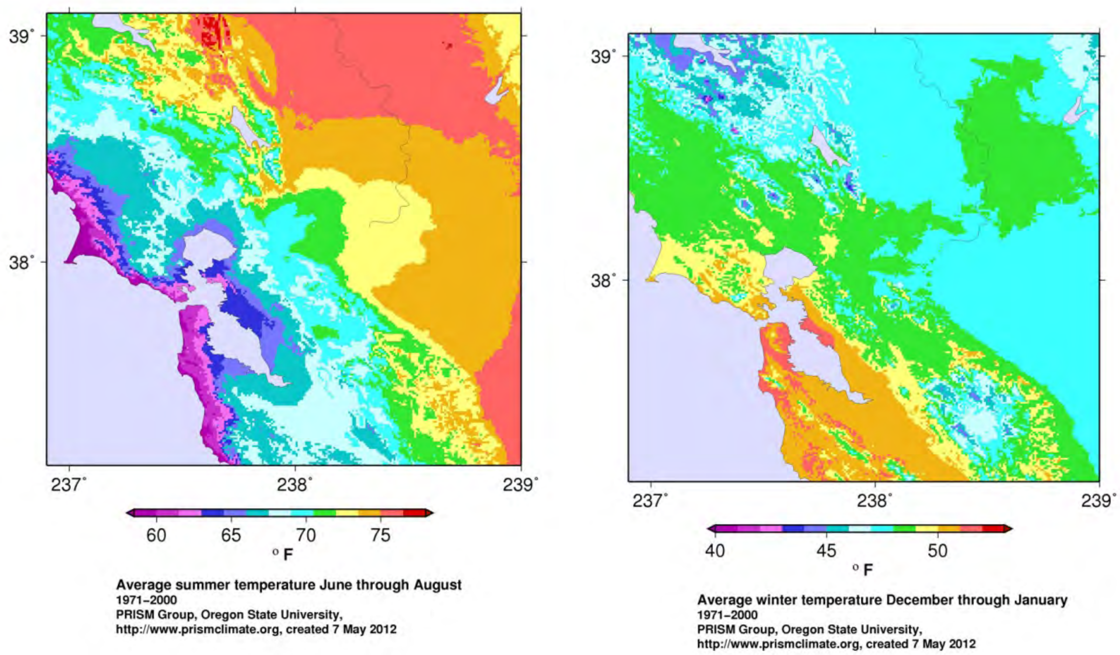

Figure 3. Average Temperature During the Summer (left) and Winter (right) Months Across the San Francisco Bay Area

Source: PRISM data, produced by Mary Tyree.

In general, then, the issue of location-specific trends remains somewhat uncertain. However, consistent with observations elsewhere in the Western United States (and beyond), historical records for the entire region show that between 1950 and 2000, there is a significant warming trend for the three warmest nights annually, with the most notable shift in the East Bay, and a decrease in number of frost days per decade, again with the most notable shift in the East Bay (Mastrandrea et al. 2011).

3.1.2 Projections

Temperature projections from all GCMs and emissions scenarios simulated by Cayan, Tyree, and Iacobellis (2012) show a warming trend across the Bay Area over the rest of the twenty-first century, with an increase in annual average temperatures by 2.7°F (1.5°C) between 2000 and 2050 regardless of the emissions pathway, largely because this increase results from GHGs already emitted to the atmosphere (Figure 4). After mid-century, temperature projections reflect the emissions choices society makes today and in the next few decades: the temperatures in the higher A2 scenario rise significantly faster than those for the B1 scenario. By the end of the twenty-first century, the envelope of possible warming widens to 3.6°F to 10.8°F (2°C to 6°C) above the annual average temperature simulated for the common 1961–1990 baseline period (Cayan, Tyree, and Iacobellis 2012).

Figure 5 shows the geographic differences in regional warming, indicating that temperatures increase in all areas, in both winter and summer, but with coastal areas continuing to have milder seasons than the interior. In terms of seasonal differences, for the Bay Area, as with the rest of California, projections show a greater warming in summer than in winter, and the warming is more pronounced in inland portions of the Bay Area (Cayan, Tyree, and Iacobellis 2012). Simulations also show a shift in timing of extreme warm temperatures in the region to likely begin in June and extend through September; whereas, historically they have mostly occurred in July and August. Extremely cold nights are expected to decrease, though not completely disappear (Pierce et al., forthcoming).

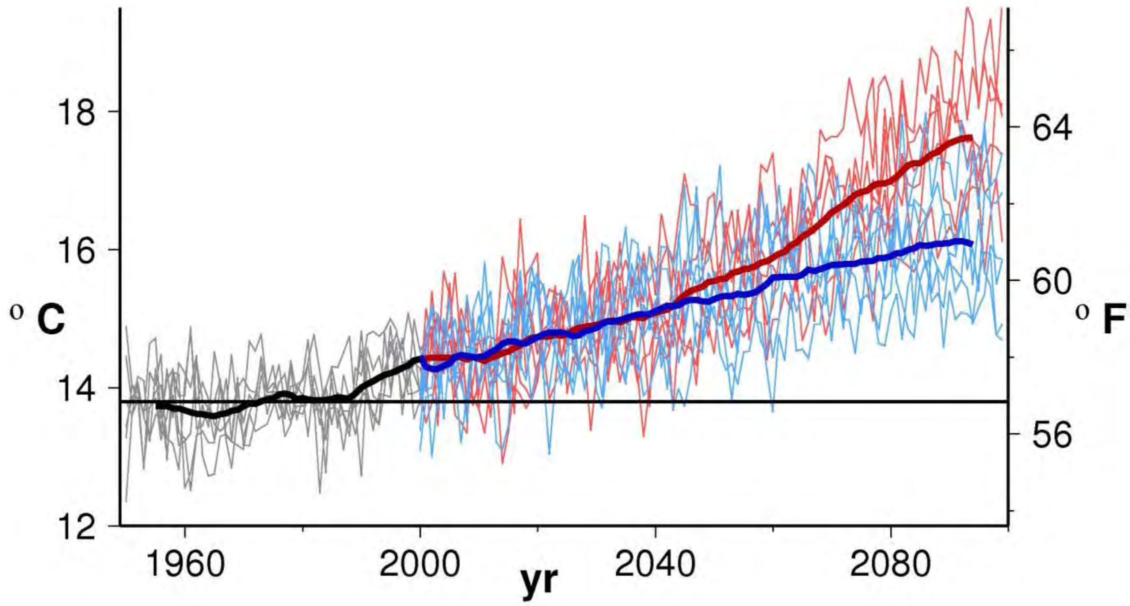

Figure 4. Annual Average Surface Air Temperature Increases (in °C left; °F right) over the East Bay Region (Near Piedmont) from Bias-Corrected, Spatially Downscaled (BCSD) Global Climate Model Simulations for Two Emissions Scenarios (B1 [blue] and A2 [red]). The thin horizontal black line shows the average temperature simulated for 1961–1990. Thin lines show outputs from multiple simulations, reflecting the uncertainty range around the average. Thick lines show the 11-year smoothed median of the respective suite of simulations for B1 and A2. The six GCMs used to produce the simulations are listed in the lower left.

Source: Cayan, Tyree, and Iacobellis (2012).

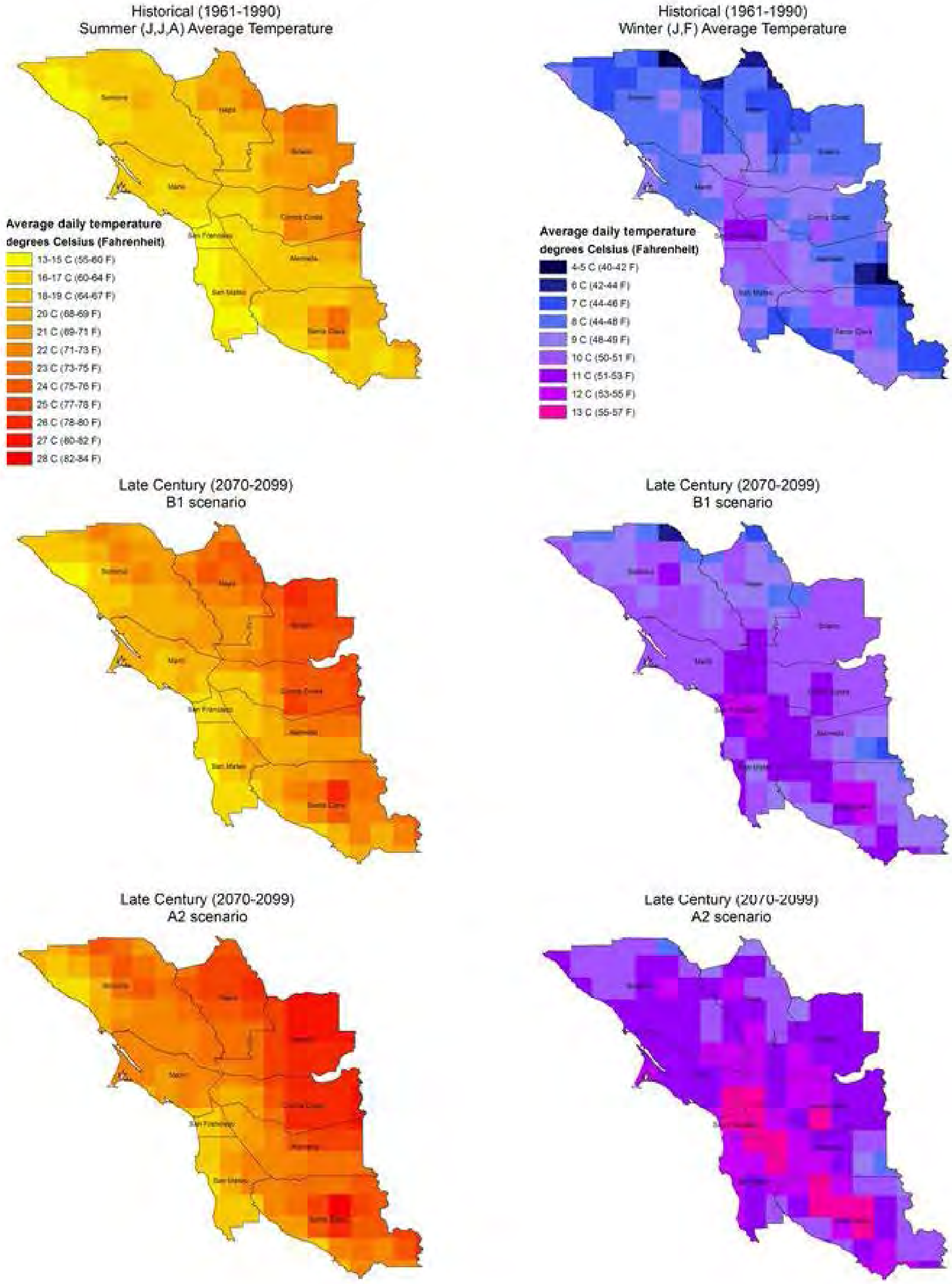

Figure 5. Historical and Projected Temperatures Across the SF Bay Area for Summer (June, July, and August) and Winter (December, January, and February) Months

Source: Maps from Chaplin-Kramer 2012, using projections produced from Cayan, Tyree, Pierce, and Das 2012 and the BCCA downscaling technique.

Extreme heat days are also expected to increase with climate change (Figure 6). Because summer temperatures range widely within the Bay Area, the threshold for what is considered an "extreme heat day" differs based on historical average temperatures for a given place. This means that temperatures in the high 70s (°F) in coastal areas (including San Francisco) are considered extreme heat days; by contrast, Livermore and other inland areas can get up to nearly 100°F to be considered an extreme heat day. So even if coastal areas do not warm as much as interior areas, the number of days above the historical threshold can be greater for coastal locations like San Francisco than for an already hot location like Livermore. By the end of the century extreme heat days are expected to increase dramatically for all areas in the Bay Area, but coastal areas (including San Francisco) are estimated to endure a much higher number of such events (Figure 6).

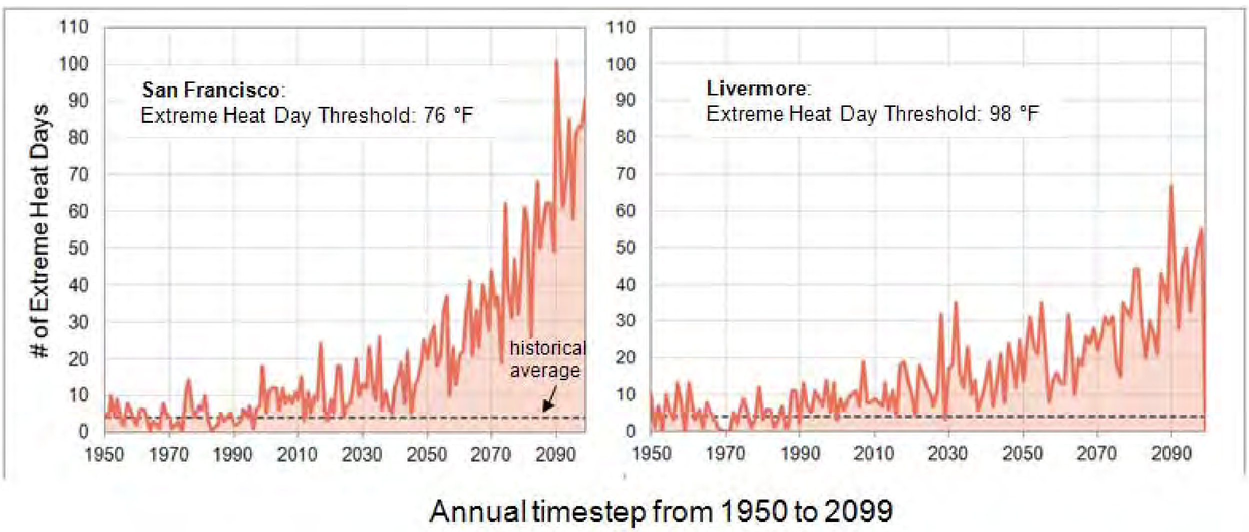

Figure 6. Number of Extreme Heat Days by Year Modeled Using Geophysical Fluid Dynamics Laboratory (GFDL) Data from CalAdapt. The data are the results of modeled simulations using the GFDL climate model and the A2 scenario, consisting of historical model simulations for 1950–1999 and climate change projections for 2000–2099. The two sites of San Francisco (coastal Bay Area, left frame) and Livermore (interior Bay Area, right frame) show the range of projected changes in extreme heat within the Bay Area.

Source: Data exported from CalAdapt, 04/17/2012, provided by Scripps Institution of Oceanography

3.2 Precipitation

3.2.1 Historical Trends

Historical records of the western United States, including California, indicate no clear trends yet in total precipitation, but the proportion of snow to the annual total is clearly declining. Moreover snow is melting 5 to 30 days earlier in the spring than in the past (based on an analysis of historical data from 1948–2002; Stewart, Cayan, and Dettinger 2005), resulting in approximately a 10 percent decrease in the Sierra Nevada average early spring snowpack (Department of Water Resources [DWR] 2009). Records show that run-off between April and July has decreased for the Sacramento and San Joaquin basins by 23 and 19 percent, respectively (cited in Moser et al. 2009), though no significant trends in precipitation specifically for the Bay

Area are apparent from historical records (Mastrandrea et al. 2011). Across the Bay Area annual precipitation averages vary widely over short distances. Based on historical observations between 1900 and 1960, on average northern portions of Sonoma County receive up to 55–85 inches (140–216 cm) annually; whereas, the South Bay only receives an average of 11–17 inches (28–43 cm) per year (FRAP 2000, Figure 7).

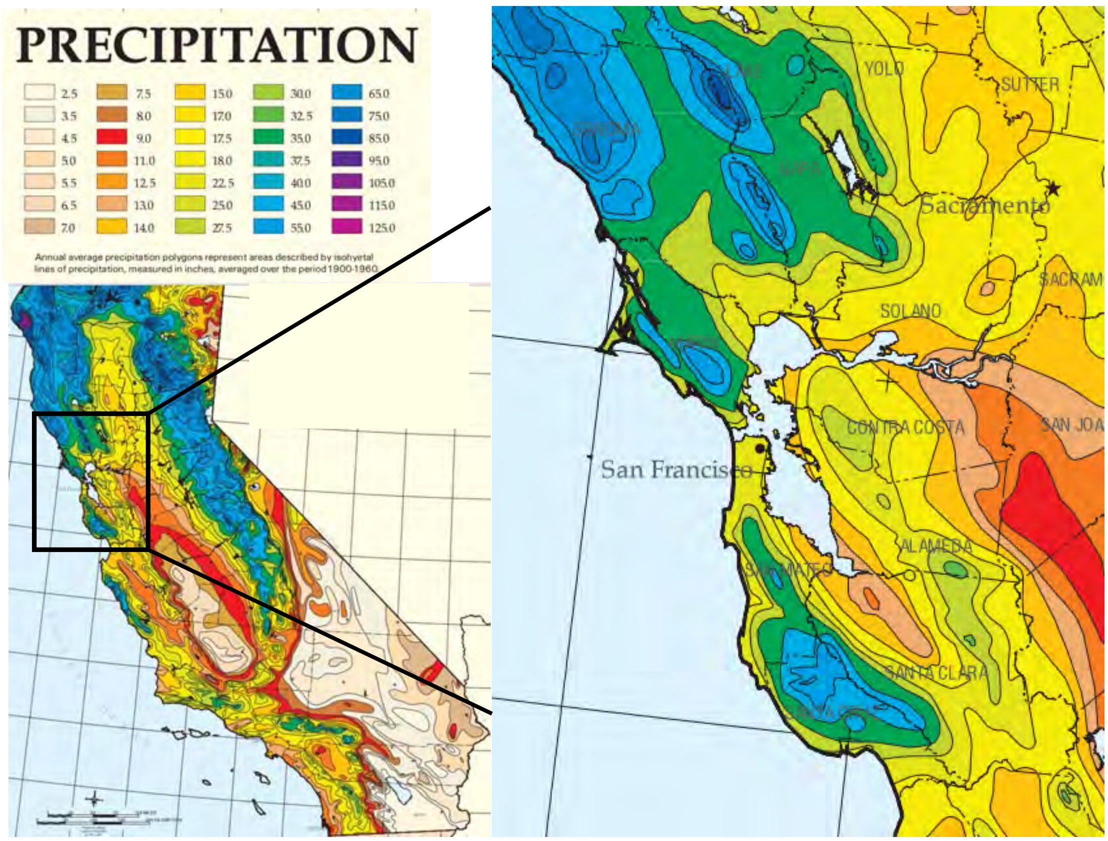

Figure 7. Mean Annual Precipitation 1900–1960 Across the Bay Area

Source: FRAP 2000

3.2.2 Projections

While simulations of precipitation are more uncertain than those for temperatures, projections show that future annual precipitation over Northern California will not change much, while the majority of those over the southern two-thirds show a decrease (e.g., in the region around San Diego, simulations show a decline by 5 to 18 percent). The greatest reduction in precipitation is expected to occur in spring, whereas the main precipitation months (winter) will remain relatively unchanged (Cayan, Tyree, Pierce, and Das 2012). Along California's coast, including the Bay Area, extreme storms and consequential flooding events are commonly associated with "atmospheric rivers" (Ralph et al. 2006). These massive systems are narrow in width, but can extend across the entire Pacific Ocean and carry enormous amounts of moisture that are delivered in successions of storms once they come onto land over California. Historically, California has received about 35 to 45 percent of its annual precipitation from atmospheric river events (Dettinger 2011). In the future, they are projected to increase by up to 7.2 additional days and increase in intensity by up to 11 percent by the end of the century (Dettinger 2011, his

Tables 1 and 2, pp. 519–520, the highest increases of these measures are derived from the third generation coupled GCM developed by the Canadian Centre for Climate Modelling and Analysis). Not only can such extreme storms cause local flooding, but they can also produce significant amounts of runoff, increasing the risk of levee breaks and flooding once it comes through the Delta (DWR 2009).

3.3 Wildfire

3.3.1 Historical Trends

Wildfires have been common occurrences in the Bay Area over at least the past sixty years (Association of Bay Area Governments [ABAG] 2010). Large wildfires occurred in 1961, 1962, 1964, 1965, 1970, 1981, 1988, 1991, and 2008. The largest fire at the urban-wildland interface in the Bay Area was in 1991 in the East Bay Hills, and it resulted in $1.7 billion in insured property losses (ABAG 2010). Historical patterns of fire using backcasting modeling techniques show that "fire-climate relationships have varied spatially over the twentieth century, leading to increased and decreased likelihoods of burning" in different areas (Krawchuk and Moritz 2012, p. 42). Figure 8 shows the historical probabilities of fire across the region (Parisien and Moritz 2009), illustrating which areas have been at higher risk than others in the Bay Area. For example, southern Santa Clara County and northern portions of Sonoma and Napa counties have been at much higher risk historically than San Francisco and Solano counties.

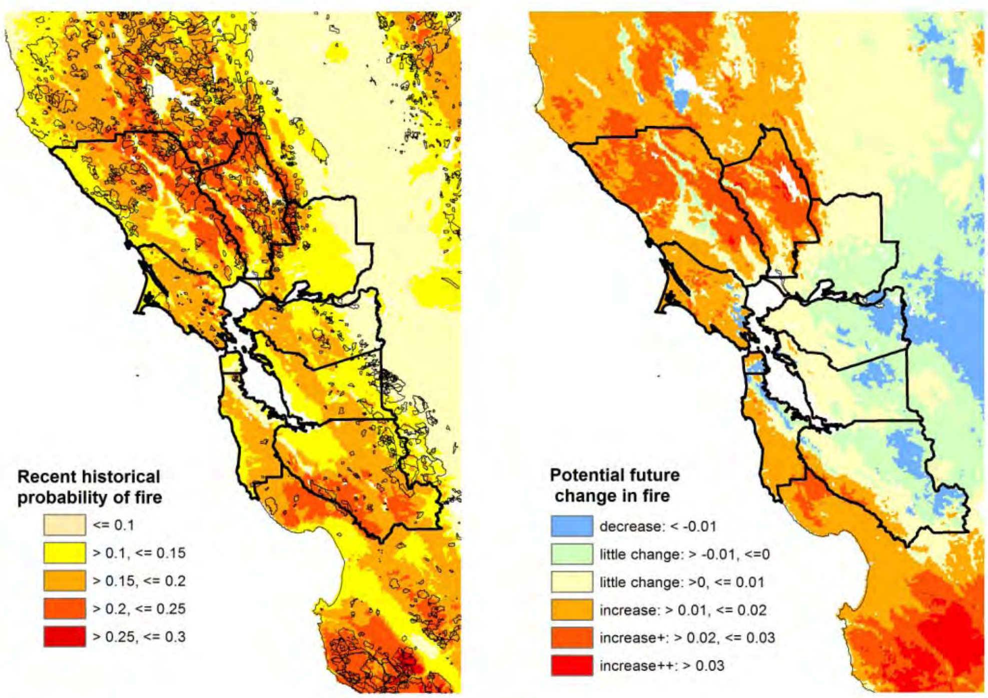

Figure 8. Probability of Fire Occurrence over the Recent Historical Period 1971–2000 (left frame). Bay Area counties are shown in bold, and perimeters of observed fires catalogued in the CDF FRAP archive from 1878 to 2009 are shown in thin black lines. Modeled future probability of fire occurrence is based on underlying climate gradients (right frame).

Source: Maps redrawn from Krawchuk and Moritz 2012

3.3.2 Projections

Climate change is expected to generally increase wildfire risk through several mechanisms across the state and in many other regions across the globe. However, at a regional scale—such as the Bay Area—the underlying factors can combine in ways that make confident projections difficult. The most direct influence of climate change on wildfire is that it will favor those conditions across the region that can lead to fire occurrence (such as drought, higher temperatures, and winds over a longer and longer fire season); indirectly, wildfire occurrence will also be influenced by changes in the vegetation's structure and abundance, and through changes in ignition potential due to shifting spatial or temporal patterns of lightning and human behavior (Krawchuk and Moritz 2012). By 2085, the acreage burned by wildfire is projected to increase substantially in forested areas of Northern California (Westerling and Bryant 2008). Under climate change scenarios, projections indicate that the Bay Area will be at risk to endure some of the highest increases in property damage (in terms of economic value) relative to the rest of the state (Westerling and Bryant 2008; Bryant and Westerling 2012). However, the distribution of how and to what degree wildfire risk increases in the region will largely be driven by changes in land use and development (Bryant and Westerling 2012) (Figure 9). For example, Bryant and Westerling (2012) found that under a low population growth scenario with little or no increase in the interface between wildland and urban areas, modeled simulations for the Bay Area show little difference in the distribution of wildfire risk between scenarios simulated under the B1 and A2 emissions scenarios, regardless of the climate model used (in that study, NCAR PCM1 and GFDL CM2.1) (Figure 9).

In terms of regional differences, Bryant and Westerling (2012) show that even under the lower emissions scenario (B1), wildfire risk increases for most of the Bay Area, with the exception of a slight reduction in risk in the western portion of Contra Costa County and a small portion of San Mateo County. However, under high population growth under both B1 and A2 emissions scenarios, the study projects that large portions of the Bay Area counties will experience much higher risk of wildfire than observed historically. While population growth and development scenarios account for far more variability in residential wildfire risks than do climate scenarios, the most extreme increases in residential fire risks result from the combination of high-growth/high-sprawl/extreme climate change scenarios (Bryant and Westerling 2012).

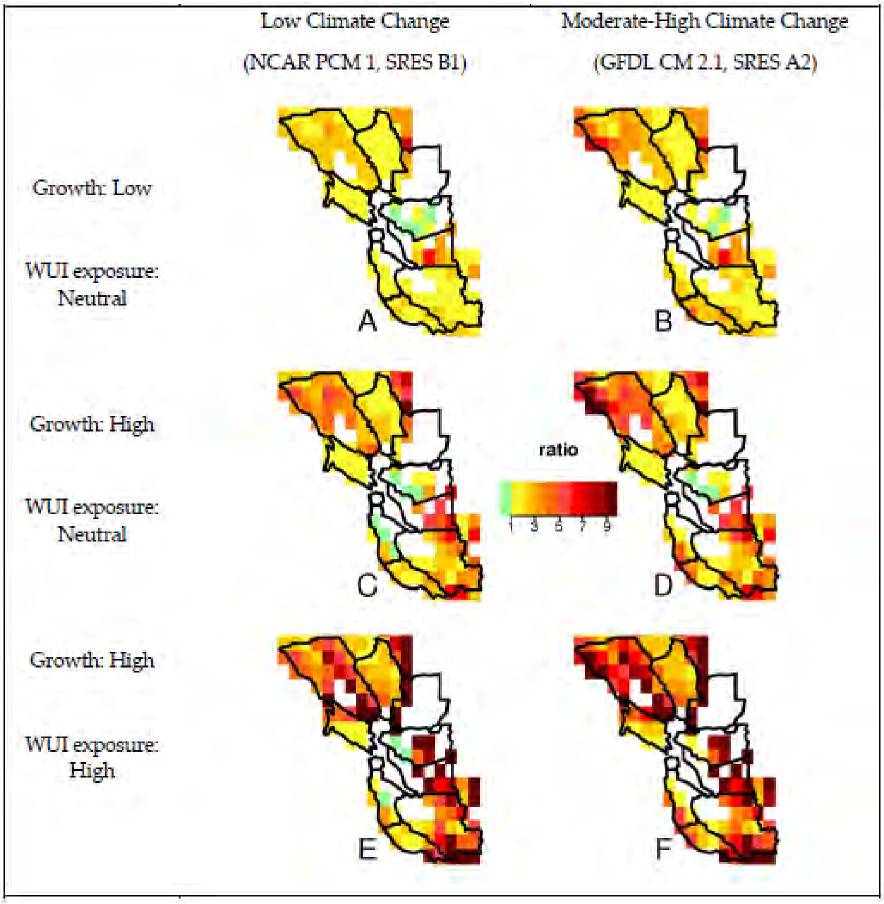

Figure 9. Spatial Variation in Wildfire Risk for the San Francisco Bay Area Using Population Growth Scenarios Produced by the U.S. Environmental Protection Agency (EPA) (using the Integrated Climate and Land Use Scenarios [ICLUS] Data Set) for 2070–2099 and Different Climate Scenarios. Colors from greens and yellows to reds and browns indicate the increased fire risk compared to that during the base period (expressed as a ratio). The six scenarios illustrate the effects of climate change, growth scenario, and exposure at the wildland-urban interface (WUI) on residential property risk. A relative risk (or ratio) of 1 is equal to no change; therefore, green cells represent reductions in risk. White cells are not modeled; yellow, red, and brown cells indicate increases in risk.

Source: Bryant and Westerling 2012 (their Figure 6, p. S247).

3.4 Sea-Level Rise

3.4.1 Historical Trends

San Francisco has one of the longest (1854 to the present), nearly continuous hourly tide gauge records in existence, not just along the California coastline, but anywhere. Observations from tidal stations at the entrance of the San Francisco Bay (the Golden Gate) show that sea level has risen ~0.9 inches (2.2 cm) per decade since the 1930s, an increase that is consistent with the global average (Cayan et al. 2008). Moreover, since 1915, the frequency of extreme tides has increased 20-fold (Cayan et al. 2008), which has important implications for coastal flooding, erosion, and related damages, and also for maintenance of shipping channels, clearance under bridges, and so on. While measurements show that global sea level has continued to rise (increasing at a rate of 3 millimeters per year since 1993), regional sea level along the Pacific Coast of North America has been suppressed during this period by a warm/positive phase of the climate pattern referred to as the Pacific Decadal Oscillation.[2] However, research indicates that conditions may be shifting into a cool/negative phase, which would cause regional sea level to resume to be similar to (or even exceed) global sea levels (Bromirski et al. 2011). Despite this recent decadal "flat trend," long-term records at the Golden Gate tide gauge are generally similar in overall trend to other locations along the California coast.

3.4.2 Projections

To generate estimates of sea-level rise for the San Francisco Bay, Cayan et al. (2012) employed Vermeer and Rahmstorf's (2009) semi-empirical method, which uses global surface air temperatures and relates them to sea-level changes. Calibrated against historical and paleo-temperature and sea level records, modeled future projections indicate that sea level over the next 50 years could increase considerably, with the rate of rise accelerating over the historical one. By 2050, sea level could rise approximately 11 to 19 inches (27 to 48 cm) over 2000 levels, and by 2100 reach anywhere between 30 to 55 inches (77 to 140 cm) above the 2000 baseline (Cayan, Tyree, Pierce, and Das 2012).

As sea level rises, there will also be a greater occurrence of extreme high sea-level events, and a greater tendency for these events to last longer, as shown in Figure 10 (Cayan, Tyree, Pierce, and Das 2012). This in turn results in a higher exposure to potential flooding, scour, and erosion of shorelines and at the base of bridges and other critical infrastructure. A higher baseline combined with El Niño events and/or winter storms and the attendant high winds and high ocean waves can be expected to cause the greatest impacts on Bay shorelines, even long before sea levels reach the upper end of projected ranges (Cayan et al. 2008; Caldwell et al., accepted for publication).

Importantly, coastal flooding not only depends on the height of the surface of the ocean (which tide gauges are designed to measure) but also on the energy associated with the ocean waves. The more energy the waves have, the farther they can reach inland. Scientists calculated how winds in the middle of the Pacific Ocean would affect the energy of the waves reaching California and how far inland sea water would penetrate. They estimated that extreme coastal flooding in the San Francisco Bay region that has a one percent probability of occurring in any one year (the so-called 100-year flood) at present would become an annual event by the end of this century (Bromirski et al. 2012).

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[2] The Pacific Decadal Oscillation (PDO) is a pattern of Pacific climate variability that varies between warm/positive and cool/negative phases. The oscillation is driven by changes in wind patterns, which affect upwelling, sea surface temperature, and regional sea level height. Positive phases are characterized by strong upwelling (i.e., bringing dense, colder waters to the surface) off the California coast, which suppresses sea level; whereas, negative phases are characterized by downwelling (cold water sinks down while warmer waters are at the surface), which raises sea level regionally.

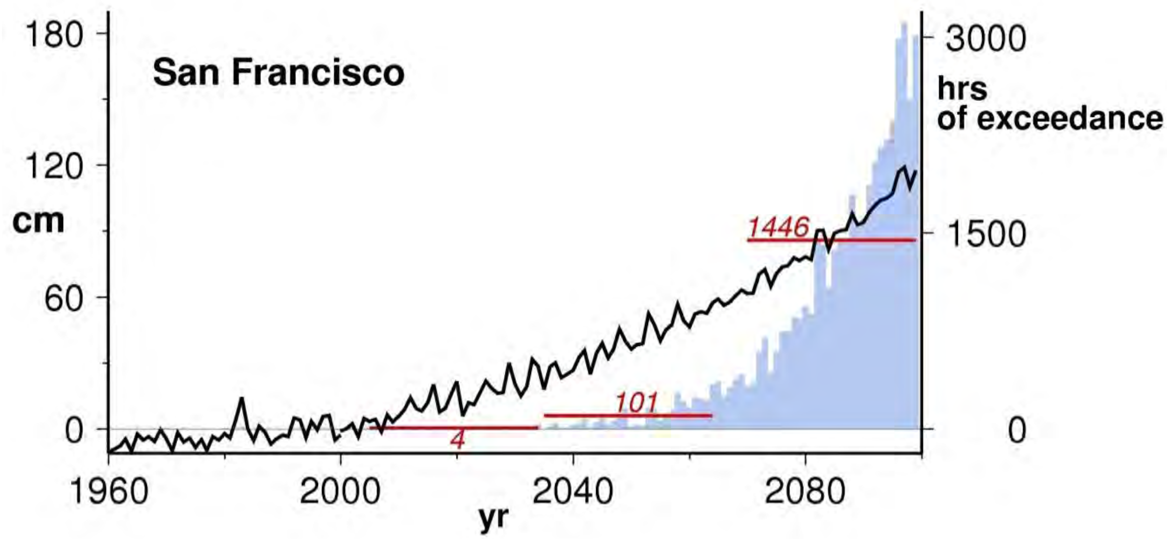

Figure 10. Sea Level at San Francisco near Golden Gate Has Been Rising For More Than a Century (Black Curve, Based on GFDL Model Air Temperatures and Vermeer and Rahmstorf (2009) Sea Level Rise), and Future Rates of Increase Are Expected to Rise. Using a simulation of future sea-level rise driven by an A2 emissions scenario superimposed upon historically well-understood tide, weather, and El Niño/Southern Oscillation components (Cayan et al. 2008) results in improved projections (blue curve) for the Bay Area. Blue bars show, for each year, the number of hours that sea level exceeds the historical 99.99 percentile (i.e., an extremely rare high sea level stand) using the modeled historical series. The numbers in red indicate the average number of hours per year during which the projected sea level is expected to exceed the historical 99.99th percentile (i.e., the level associated with a 100-year flood) for the periods 2005–2034, 2035–2064, and 2070–2099. By the latter part of the century, flooding commonly expected with that type of storm could thus occur for about 60 days out of the year.

Source: Cayan, Tyree, and Iacobellis (2012)

3.5 Coastal Marine Upwelling and Currents

Three Bay Area counties border the Pacific Ocean (i.e., the region's outer coast), which will see different climate conditions due to their direct exposure to the open ocean. Those shorelines also support considerably different habitats than those within the estuary and delta. While sea-level rise expectations for the outer coastlines along these Bay Area shorelines are not significantly different from those along the inner shore (small-scale local differences cannot be accounted for in these global models), other climatic and marine influences will be significant. The Bay Area coastal watersheds and open ocean coastline are located with the California Current Large Marine Ecosystem, which is characterized by its seasonal wind-driven upwelling (Bottom et al. 1993). Upwelling brings cold nutrient-rich waters to the surface, supporting high primary productivity and thus abundant populations of fish species. Currently, projections indicate a possible weakening of upwelling as a result of warmer air and ocean temperatures. Fewer nutrients provided by the upwelling could then lead to changes or reductions in food availability for fish species, and warmer ocean waters could shift the geographic distribution of populations northward (Mazur and Milanes 2009; Johnstone and Dawson 2010).

Ocean acidification is also a concern for the region as the ocean continues to absorb carbon dioxide from the atmosphere. While research has only begun to estimate the impacts of this phenomenon, changes in ocean chemistry, particularly within the California Current, are already being observed (Hauri et al. 2009). The impacts on marine organisms with carbonate skeletons or shells are expected to be devastating, as higher acidity alters their physiology and respiration, reducing the ability of zooplankton and larger shellfish to take up and secrete carbonate to make their protective shells (Fabry et al. 2008).

Given the sometimes significant, but in virtually all cases rapid changes expected in the ocean and climate—both globally and locally—it is important to understand how existing climate-related risks change as climate change proceeds. As is apparent from the discussion so far, some of these changes are now inevitable due to the time lags in the climate and ocean system, whereas the magnitude of climate change beyond 2050 is still largely a matter of society's choices over emissions. In the next section, the potential impacts from a changing climate under different climate scenarios are discussed, and where possible integrated with a better understanding of concurrent stresses and options to minimize the risks.

4. IMPACTS, VULNERABILITIES, AND ADAPTATION

Climate change will affect different segments of the population and a range of sectors that uniquely characterize the Bay Area or are critical to its economic vitality. This section summarizes research on climate stressors and their consequences for each of these sectors. It discusses potential impacts and, where possible, additional insights about key vulnerabilities (in terms of what aspect of the sector will be exposed to the projected climate changes, how they are sensitive to this exposure, and discussion of adaptive capacity). In addition, each section will include a discussion of potential or ongoing adaptation strategies, along with identified needs, challenges, and barriers.

4.1 Water

4.1.1 Water Supply Management

Impacts and Vulnerability

Climate change is projected to affect water supply in California through two primary avenues: hydrology (including timing and distribution of precipitation, evapotranspiration from soils, plants and water surfaces, streamflow, and groundwater recharge) and sea-level rise (DWR 2009). Climate warming may result in a shift in timing and amount of water supply (Sicke, Lund, and Medillín-Azuara 2012) and also in changes in quality of that supply (Micheli et al. 2010). The way in which each water district is sensitive and exposed to impacts of climate change differs widely, however, based on the source of the water and how it is supplied. For example, Marin County depends on water from a system of local reservoirs within the county, so its supplies are largely sensitive to annual precipitation locally. San Francisco and the East Bay Municipal Utility District, by contrast, depend on water supplied through systems of aqueducts from the Sierra Nevada, so they are sensitive to how climate change affects snowfall, snowmelt, and runoff changes in that region. The Delta supplies Contra Costa and parts of other water districts. To maintain adequate water quality, the Delta requires sufficient freshwater flow from the rivers (and Sierra Nevada) to resist the saltwater inflow from the

Pacific Ocean, making it especially sensitive to changes in runoff from the Sierra Nevada and increases in sea level.

Sicke, Lund, and Medillín-Azuara (2012) explored how urban water supply in the Bay Area could potentially be affected by climate change, testing the sensitivity to extreme dry climates and varying levels of sea level. The study did not take into account existing rules, regulations, and laws limiting water transfers, but rather focused only on the structural limitations of the existing system. They used the California Value Integrated Network (CALVIN), an engineering optimization model of California's statewide intertied water supply system (Sicke, Lund, and Medillín-Azuara 2012). This model assesses existing water management capacity and needs based on different assumptions about how climate change could manifest. They looked at five climate cases that represent differences in hydrology and SLR, including reduced (and entirely removed) capacity of the Delta for exports and diversions. Results show that the existing water systems in the Bay Area do have the potential capacity to meet the region's water demands. However, realizing this capacity would require substantial costs (e.g., for purchasing water from agricultural allocations, expenses associated with supply alternatives) and water use reduction, as well as assuming operational flexibility by water providers and regulators (Sicke, Lund, and Medillín-Azuara 2012). Realizing this potential at these costs and implementing operational flexibility may encounter major legal, socio-political, and economic barriers (Hanemann, Lambe, and Farber 2012; Sicke, Lund, and Medillín-Azuara 2012).

Adaptation

Several studies in the V&A Study also explored possible adaptation strategies to increase capacity of the water supply systems to deal with climate stressors in the Bay Area and on the state level. Langridge et al. (2012) looked at the adaptation strategies for drought of five California water agencies and their motivations for increasing the adaptive capacity of their water supply system to shortages, including the development of local groundwater drought reserves. Included in the study was the Sonoma County Water Agency in the northern Bay Area. The Endangered Species Act mandated reductions in surface water diversions which led the agency to evaluate the region's groundwater resources and to explore approaches for more sustainable groundwater management. By carefully managing its groundwater resources in conjunction with its surface water supplies, at this time the agency's potential resilience to future droughts is high. Careful resource assessments and participation of local water manager and stakeholders, as occurred in Sonoma, may prove to be a constructive way forward in adaptive water management at that scale.

Null and Viers (2012) contributed to a better understanding of how climate change could affect California's water supply allocations if current criteria, decision-making procedures, and models continue to be utilized. This study illustrated how existing water policy and allocation frameworks used in California were designed under the assumption of a stable climate. Many water management decisions in California rely on a classification scheme of the year's water flow (classified into "wet," "normal," "dry," and "critically dry" years based on a comparison with historical conditions). The classification is used to determine how much water is allocated among the many sectors and districts. Using the six GCMs and two emissions scenarios provided by Cayan, Tyree, Pierce, and Das (2012) along with the current allocation thresholds, Null and Viers (2012) projected changes in streamflow for the Sacramento Valley and San Joaquin Valley. They showed that by the latter half of this century, critically dry water years could occur 8 and 32 percent more frequently in these water basins, respectively, compared to the historical period (1951–2000). The long-term implication of the increased frequency of critically dry years is that, if the framework is not adapted to incorporate climate change (i.e., how water supply is allocated to different uses under different climate conditions), there will be less water available for environmental purposes. As a result, species, habitats, and ecosystems may no longer receive sufficient freshwater to meet their survival needs.

Several of the water districts within the Bay Area are engaged in ongoing efforts to better understand how their water portfolios will be affected by climate change. Adaptation strategies already considered or being implemented include the following:

- Increasing efficiency, reducing losses during water transfer, and promoting conservation (all aimed at reducing demand)
- Building a coalition between experts on national (e.g., Piloting Utility Modeling Applications, PUMA) and regional levels to improve development and use of scientific information in water management
- Assessing drought sensitivity within water districts
- Improving planning for shortages by exploring the feasibility of desalination plants

Barriers identified in case studies in the Bay Area include the need for advancement in how accurately the scientific models could project water supply so that they are less uncertain and more useful for decision-making (Moser and Ekstrom 2012). Additionally, the concern (and political support for) actions that reduce local risk of insufficient supplies during droughts tends to fluctuate with short-term variability in perceived risk (Moser and Ekstrom 2012). Hanemann, Lambe, and Farber (2012) provided an assessment of state-level legal barriers to preparing the state's water supply system for climate change. The study emphasized that the single most important step for adaptation for this sector is to better account for how much water is diverted in the state, and to whom. To do this, the researchers propose several politically feasible changes, including expansion of requirements to groundwater monitoring, reporting, and planning; increased monitoring; and enforcement of reporting surface water diversions; among others (Hanemann, Lambe, and Farber 2012).

4.1.2 Wastewater Management

Impacts and Vulnerability

Rising sea level, combined with increasing tidal extremes and the possible increase in extreme runoff events, will affect the outflow path and treatment of wastewater. Such climate change impacts could lead to potential infrastructure damage, operational interruptions, flooding into streets, and/or increased release of untreated (polluted water) into the Bay, resulting in water quality declines in Bay and coastal waters during extreme storm events. Potential increases in street flooding could affect transportation corridors (Biging, Radke, and Lee 2012), create public health risks, and induce businesses to look for safer locations elsewhere. Heberger et al. (2012) identified the region's infrastructure at risk of inundation in a 100-year flood event with an SLR of 4.6 ft (1.4 m). Using Knowles (2009) projections of SLR for the Bay, they report 8 or 10 regional wastewater treatment plants would be at risk of inundation in a 100-year flood event with a 3.3 ft (1.0 m) and 4.6 ft (1.4 m) rise in sea level, respectively. Some wastewater systems in the Bay Area already face the problem of aging infrastructure. This creates both a challenge and an opportunity for this sector: as systems are being replaced or upgraded, sea-level rise and the increasing risks from more frequent and more extensive coastal flooding can be incorporated into planning and budgets.

Adaptation

The vulnerability of wastewater treatment facilities and related infrastructure has already triggered assessments in multiple locations along the Bay shore. The Adapting to Rising Tides project, a partnership between federal, state, and local agencies led by the San Francisco Bay Conservation and Development Commission (BCDC), is currently conducting a stakeholder-intensive process to produce a vulnerability assessment that examines the risk of inundation of selected treatment plants in Alameda County along the Bay shoreline.

All but one of the 101 cities in the Bay Area have separate systems for sanitary wastewater and runoff (e.g., roads), which means that the extreme rain events do not affect sewage treatment except potentially at the discharge location into the Bay where higher sea level and wave heights could prevent discharge. The City and County of San Francisco is the exception: it has a combined sewer and stormwater discharge system, in which all of the city's runoff water is treated together with its sewage. Recognizing the threat of rising sea levels to the wastewater system, this city has examined the increasing risk of backflow resulting from SLR and storm surge or heavy precipitation events (City and County of San Francisco 2009). In 2011 the city moved forward on upgrading the outflow pipes, as part of its Sewer System Improvement Program, in a way that will protect it from backflow as sea level rises to at least 2050 based on projected 1.5 ft (0.5 m) rise above the 1990 base level (Bellows 2011). Over the longer term, the San Francisco Public Utilities Commission is considering a number of strategies to accommodate expected SLR, especially as it plans new or upgrades existing facilities (City and County of San Francisco 2009).

4.2 Agriculture

4.2.1 Impacts and Vulnerability

Agriculture is inherently dependent on and sensitive to climatic conditions. The reliance on and sensitivity to changes in temperature and precipitation, and the tendency in the Bay Area for much of agriculture to be located in flat, low-lying areas (high risk of flooding) makes agriculture one of the most threatened sectors by climate change. Agriculture is also an economically and culturally important industry in the Bay Area, and the majority of it takes place in Marin, Sonoma, and Napa counties, as well as eastern portions of Alameda and Contra Costa counties. The value of the industry in the nine-county region is an estimated $2 billion (Chaplin-Kramer 2012; National Agricultural Statistics Service 2008), with grapes contributing nearly half that value. The wine industry of Napa County alone, when its tourism value is included, is estimated to generate $9.5 billion annually, attracting three million visitors annually (MKF Research 2005). Pastureland, largely used for the beef and dairy industries, covers 40 percent of the land of the Bay Area and 80 percent of the total land used for agriculture (Chaplin-Kramer 2012; California Department of Conservation 2009). Animal products and nursery products each generate over $300 million annually. Mushrooms ($65 million), vegetables ($58 million), hay ($40 million), flowers ($35 million), tomatoes ($28 million), and walnuts ($23 million) are also among the top ten crops in the region (Chaplin-Kramer 2012; National Agricultural Statistics Service 2008).

Jackson et al. (2012) provided an overview of climate change impacts to agriculture throughout the state and developed an agriculture-focused vulnerability index providing an objective, albeit coarse view of the sector's vulnerability to climate change in California. The index uses 22 variables to represent multiple facets of exposure, sensitivity, and adaptive capacity. When integrated into a single index, the researchers produced a map of the most (and least) vulnerable areas in California to climate change and other stressors. Indicators include crop sensitivity, crop diversity, and threat of urbanization, among several others. Results indicate that the Sacramento-San Joaquin Delta is one of the most vulnerable agricultural areas in the state to impacts of climate change as a result of:

- land area in crop production,
- soil production capacity,
- land area converted to urban land use,
- soil salinity,
- land in the 100-year floodplain, and
- socioeconomic factors (Jackson et al. 2012).

In addition to the vulnerability index, the authors also assessed how scenarios of future urbanization could affect different agricultural regions in California. Bay Area-specific findings include that Santa Clara County could be especially affected by urbanization, as will eastern portions of Alameda and Contra Costa counties. Urbanization is also projected to replace agricultural land in much of the Livermore Valley (currently used for grazing and wine grapes), and in Contra Costa County south, east, and west of Brentwood.

Chaplin-Kramer (2012) examines how projected changes in climate could affect agricultural crops in the Bay Area, focusing on grapes and forage for rangeland cattle (beef and dairy). Expanding on previous work (Shaw et al. 2009; George et al. 1988), the study is the first to model the impact of climate change-induced warming on seasonal rangeland productivity and reliability. Results show a notable increase in peak forage production by the late century under the A2 emissions scenario, with as much as 40 percent increases in production in Napa, southern Marin, and northern Sonoma counties. Nevertheless, models show that climate change is projected to lead to a decline in the availability of high-quality forage as the length of the seasons during which forage grows shortens. This could force ranchers to rely more frequently on supplemental feed for livestock, an expensive option for already strained businesses (Chaplin-Kramer 2012).

Wine grape production modeling conducted by Chaplin-Kramer (2012) builds on models produced by Lobell et al. (2006, 2007) and Lobell and Field (2009) that established the relationship between temperature and quantity of grape yields, and those of Hayhoe et al. (2004) for quality of grapes in relation to temperature. Models for the Bay Area show increases in grape yield under both the B1 and A2 scenarios; however, impacts on grape *quality* (rather than *quantity*) related to temperature patterns is of greater importance, and thus of concern to the wine industry, given the dominance of wine grape production in the Bay Area and the revenue that can be generated with high-quality wines. The ambient air temperatures reached during the grape-ripening period are responsible for the particular quality of the wine grapes (Hayhoe et al. 2004). Currently the Bay Area's climate provides an optimal environment for producing the highest quality in wine grapes, which has largely contributed to and supported the $900 million industry in this region (National Agricultural Statistics Service 2008). Results of the modeling conducted by Chaplin-Kramer (2012) show that under the A2 scenario by late century temperatures during the ripening period exceed the threshold above which "high-quality wines are rarely produced" (p. 30). Results are consistent with another study, which used different methods, but also showed decreases in the highest-quality wine grape growing areas in Napa (Diffenbaugh et al. 2011). In addition, results from Hannah et al. (2012) show that Napa will no longer be suitable for high-quality grape production by the end of the century, though new coastal regions may emerge as promising wine-growing areas in the future (Hannah et al. 2012).

Finally, Ackerly et al. (2012) emphasized that climate change increases several threats to the Delta region, where 66 percent of land is in agricultural production (see also Isenberg et al. 2008): increases in risk of inundation from SLR, storm surge, and levee failure, and decreases in availability of water supply (Ackerly et al. 2012). Declines in pollination by insects and bats on agriculture in the Bay Area and statewide has been of concern for farmers in recent years, yet no research to date has provided insights on the impacts from climate change for this region.

4.2.2 Adaptation

Jackson et al. (2012) emphasized the need for place-based planning to develop adaptation strategies considering a particular community's vulnerabilities, concerns, and needs. They also highlighted the need for developing and strengthening existing partnerships that advocate for the protection of the sector against the threat of urban development on agricultural lands.

Cahill and Durham (2012) examined farm-level adaptation strategies that Napa and Sonoma winegrowers undertake in response to environmental stressors (such as climatic factors), including what motivates growers to adapt and what obstacles inhibit the use of certain options. Details of vineyard-level decision-making for different stressors illustrates specific adaptation options and how they relate to dealing with reducing vulnerability by reducing exposure and sensitivities or increase adaptive capacity. The study found that most of those interviewed prefer to rely on their own or other growers' experiences to guide their management decisions, which could be a disadvantage for adapting to climate change since they may need to prepare for conditions with which they have no prior experience. Collaboration among growers could be particularly useful for increasing this sector's resilience to climate change.

Ackerly et al. (2012) proposed that temporary carbon storage capacity in soils in the Bay Area could be increased by converting agricultural land used for crop production from annual to more perennial crops. In many instances, farmers make little distinction between mitigation and adaptation strategies, such as carbon storage, improved water retention and/or drainage, and soil fertility improvements, as such interventions can have benefits for both. Further research is needed to support this industry as it determines how to adapt (Ackerly et al. 2012; Chaplin-Kramer 2012; Jackson et al. 2012).

4.3 Energy Supply and Demand

Energy supply and prices in the Bay Area are expected to be affected by physical climate changes in the Bay Area, those occurring beyond (at the state, national, and global levels), and by non-climate factors (such as policy and pricing changes). Local impacts felt directly on the energy sector arise from SLR and flooding, increased heat waves, and wildfires. While all of these impacts can affect great numbers of people at once in urban agglomerations, rural areas may be particularly sensitive, as outages or service disruptions can cut off communication at critical times. Impacts on demand, supply, and transmission are discussed in turn.

4.3.1 Demand

Higher temperatures in the summer months, and particularly heat waves, can lead to increased energy demand through more widespread and longer use of air conditioners (Perez 2009; Auffhammer and Aroonruengsawat 2012). Auffhammer and Aroonruengsawat (2012) simulated how increased temperatures from climate change would affect residential electricity consumption for the nine Bay Area counties for the end of the century (2080–2099) compared to 1961–1990 consumption levels. Results of simulated electricity demand show a significant increase in the interior portions of Contra Costa, Alameda, and Santa Clara counties for the B1 scenario (5–8 percent) and even more so for the A2 emissions scenario (12–15 percent). Results showed very little increase, and even a slight decrease under lower emissions, in energy demand for areas closer to the Bay's shoreline and Pacific coast, including San Francisco, Marin, Oakland, and most of the peninsula. However, the model used did not include possible increase of air conditioner ownership (and use) in residences in these coastal areas.

The study presented several conclusions that advance the understanding of how climate change and population growth could affect energy demand. First, temperature response varies greatly across the climatic zones in the Bay Area—from relatively little response in energy demand in some places as temperatures change compared to other areas in the interior portion of counties that have substantial increases in energy demand when ambient temperature warm (Auffhammer and Aroonruengsawat 2012). This sub-regional variation in response demonstrates that aggregating data over the entire Bay Area could ignore important differences in energy use behavior. The study also reported that future population growth will have a greater impact on energy demand than climate change has by itself (Auffhammer and Aroonruengsawat 2012).

The study by Sathaye et al. (2012) confirmed some of these findings. They examined the capacity of the energy system to respond to increases in demand during peak periods. Preliminary results show that increases in high temperatures in August, representing peak demand, could constrain the production of electricity and reduce delivery capacity (Sathaye et al. 2012).

4.3.2 Supply

Climate change is also expected to affect energy supply. Understanding impacts of climate change on power generation, and specifically hydroelectric generation, requires looking both within and beyond the nine Bay Area counties. Three PIER studies from this assessment (Guegan, Mandani, and Uvo 2012; Null and Viers 2012; Rheinheimer, Ligare, and Viers 2012) contributed to improving the understanding of how climate change could impact hydropower generation from Sierra Nevada reservoirs, part of which serve the Bay Area.

Local power generation infrastructure also needs to be considered. Sea-level rise and inflow are projected to affect the Delta region and the energy infrastructure located there, especially with increased winter inflows into the Delta, increasing the potential for levee failures (many of which are already at high risk of failure) (Sathaye et al. 2012; Brooks and Manjunath 2012). Of particular concern to the energy sector are underground natural gas storage facilities and transmission lines that could be damaged by being exposed to impacts of climate change (Mount and Twiss 2005; Sathaye et al. 2012).

The study by Sathaye et al. (2012) is one of the few comprehensive studies on the impacts of climate change on energy infrastructure, looking at several different types of impacts simultaneously, including temperature increases, wildfire, and sea-level rise and storm surge. This study, expanding on previous studies that assessed these impacts separately (including Perez 2009; Westerling et al. 2009; Bryant and Westerling 2009; and Heberger et al. 2009), estimated impacts on power generation, transmission line and substation capacity during heat spells; wildfires near transmission lines; sea-level encroachment upon power plants, substations, and natural gas facilities; and peak electrical demand (Sathaye et al. 2012). Using the common set of climate scenarios chosen for this study (Franco et al. 2011; Cayan, Tyree, Pierce, and Das 2012), they tested how increased air temperature could affect performance of natural gas-fired generation, substations, and major transmission lines. Their results show decreases in performance of gas-fired power plants, and growing short-term and long-term damage potential from wildfires (Sathaye et al. 2012).

4.3.3 Transmission

Sathaye et al. (2012) also estimated projected wildfire impacts on energy transmissions lines using Westerling et al. (2009) estimates of wildfire probability for three 30-year time periods. Results suggest that there would be a low probability of wildfire affecting transmission lines in the Bay Area. In fact under both B1 and A2 emissions scenarios and all three GCMs used (GFDL, CNRM, and PCM1)[3], the South Bay's probability of wildfire decreases, likely due to the expected urbanization and changes in vegetation. However, projections of increased extent of wildfire beyond the bounds of the Bay Area (Westerling et al. 2009) could affect the transmission of energy to the Bay Area.

Sea-level rise and storm surge is expected to inundate some important energy infrastructure, not just affecting energy generation but also its transmission. Using Knowles (2009) projections of inundation from SLR, the Pacific Institute estimated that 30 power plants statewide would be at risk of inundation in a 100-year flood event with 4.6 ft (1.4 m) of SLR (Heberger et al. 2009). Building on the Pacific Institute's 2009 study, Sathaye et al. (2012) used an updated and more accurate spatial dataset of power plant and substation locations from the California Energy Commission, overlaid with the same SLR dataset used by Heberger et al. (2009), and found fewer plants at risk: 25 in the state and 13 in the Bay Area (Figure 11 and Figure 12). The researchers noted that many of the plants shown to be at risk will likely be retired over the next few years. This study also expressed a concern for the nexus of energy infrastructure in the Delta (the western Delta Islands), given that this area is already at especially high risk of levee failure that will be exacerbated by climate change (Sathaye et al. 2012).

[3] GFDL = Geophysical Fluid Dynamics Laboratory , CNRM = Centre National De Recherches Météorologiques, and PCM1= NCAR Parallel Climate Model

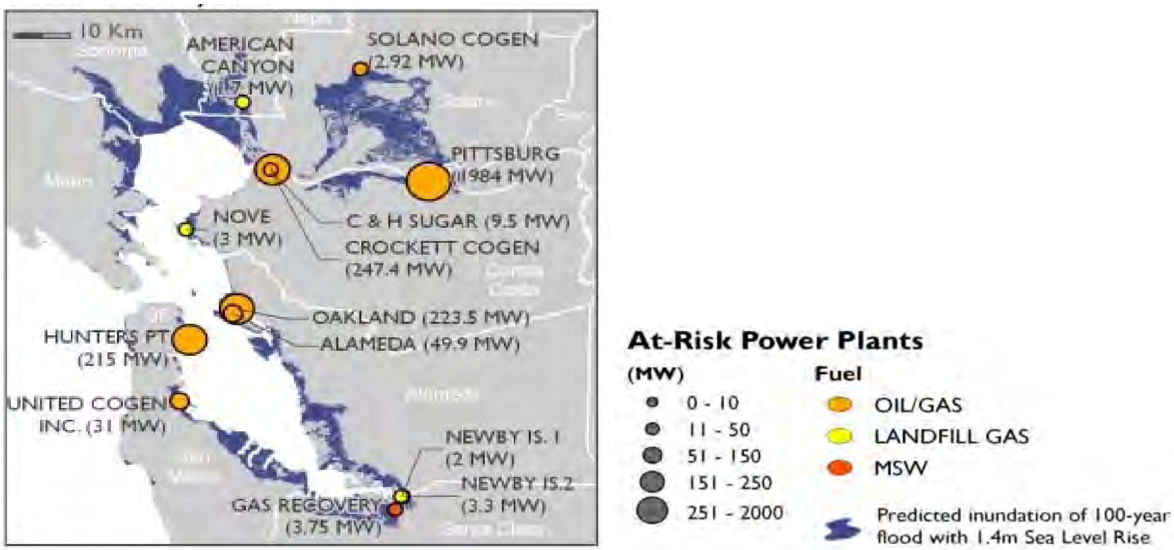

Figure 11. Power Plants at Risk to a 100-year Flood with a 1.4m Sea-Level Rise

Source: Sathaye et al. (2012) [from Pacific Institute]

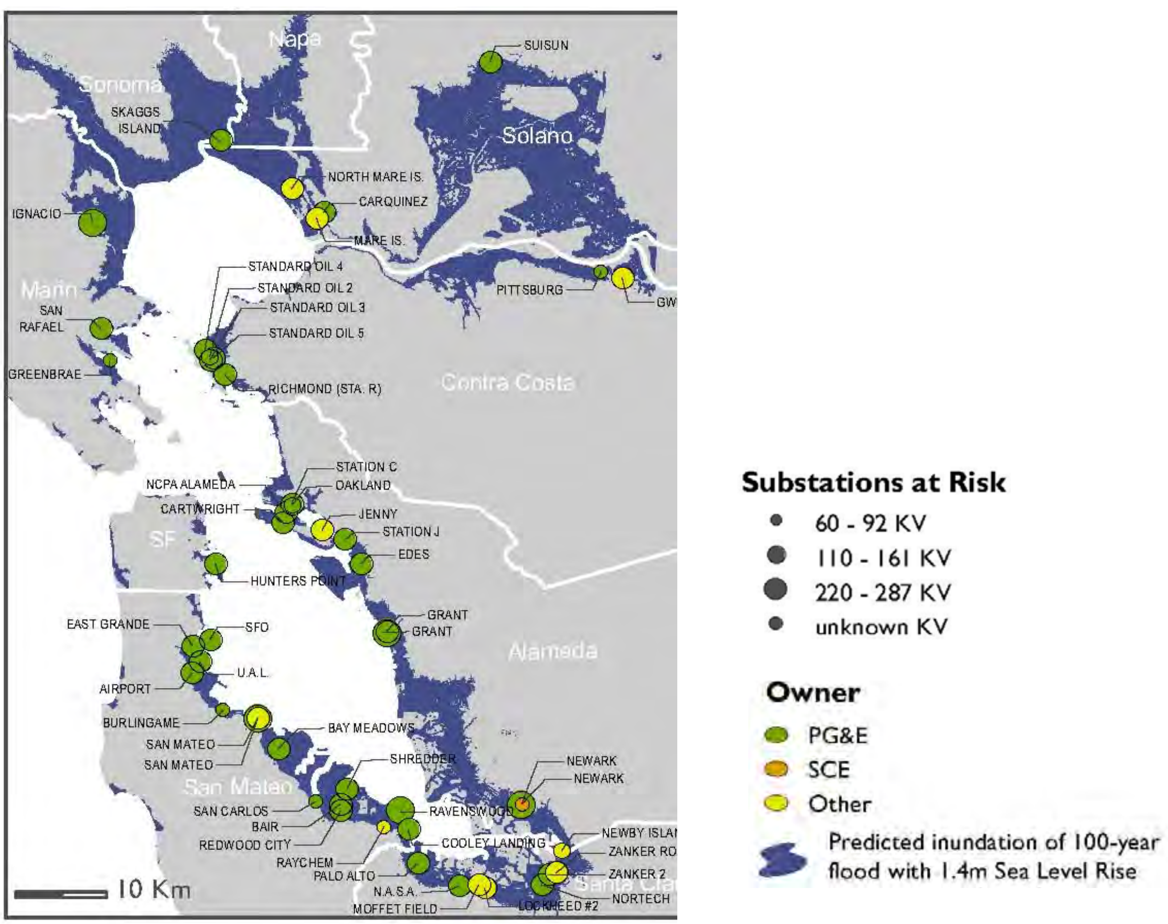

Figure 12. Substations at Risk to a 100-year Flood with a 1.4m Sea-Level Rise

Source: Sathaye et al. (2012) [from Pacific Institute]

4.3.4 Adaptation

To date, responses to climate change in the energy sector have largely focused on greenhouse gas emission reductions, although there is growing awareness in the sector to extreme events and exposure to climate change impacts (California Natural Resources Agency 2009). Many mitigation efforts (such as demand reduction efforts through conservation and efficiency) can also help reduce vulnerability to future impacts from climate change. Additional adaptation planning is in the relatively early stages in the Bay Area, in California, and elsewhere.

There are important opportunities for including climate change considerations and greater preparedness in infrastructure planning and maintenance. For example, as with adaptation in the transportation sector (see below), there is an opportunity as soon-to-be-retired power plants get replaced, to build them higher or outside of risk zones, and to better maintain transmission corridors to make them less susceptible to wildfires. More research is needed to understand the options, costs, and barriers to adaptation in the energy sector.

4.4 Transportation

The San Francisco Bay Area is an important transportation center in the State of California. It provides critical services to residents and visitors, with three international airports, four major ports, over 600 miles of rail tracks moving both freight and passengers, and over 1,400 miles of freeways and state highways (Biging, Radke, and Lee 2012).

4.4.1 Impacts and Vulnerability

Biging, Radke, and Lee (2012) assessed the impacts that coastal flooding aggravated by climate change and sea-level rise could have on the region's transportation infrastructure. This research expanded previous studies conducted by Heberger et al. (2009), Knowles (2009), and BCDC (2009) by using higher-resolution elevation data that better represent topographic features such as existing flood protection (seawalls and levees). For this project they produced a more accurate dataset of surface elevations (digital surface model) from light detection and ranging (LiDAR) data compiled by the National Oceanic and Atmospheric Administration (NOAA) and the United States Geological Survey (USGS) in 2010 and 2011 for the Bay Area. Using SLR estimates of 4.6 ft (1.4m) by 2100 (Cayan et al. 2008), they calculated peak water levels associated with a 100-year flooding event with that amount of SLR (employing the same methods as Heberger et al. 2009). The output from Knowles (2009) TRIM-2D hydrodynamic modeling was used to define the water levels of a 100-year flood event.

Biging, Radke, and Lee (2012) examined three types of indicators of vulnerability: (1) exposure of roads, (2) potential coping capacity of residents and emergency first responders who depend on these roads, and (3) reduction of accessibility to and from the hinterland if roads are flooded. To determine which roads would be inundated they used elevation data and water path connectivity (previous studies had only included elevation data). Results showed that these previous studies, which did not account for water connectivity and used less accurate elevation data, slightly overestimated inundation potential. The study also modeled how accessibility to the hinterland will be affected by SLR and flooding by examining where traffic interchanges/nodes would be cut off from potential flooding. Access to alternate routes is an important indicator of how well affected populations may be able to cope during times of flooding and how much disruption of local and regional business may result from flooding.

Results show that in a 100-year flood event with 4.6 ft (1.4 m) of SLR, nearly 1,700 miles of roadway are at risk of flooding, of which 169.5 miles are major highways. The same extreme storm events may cause inundation on the runways of San Francisco and Oakland International Airports (Figure 13). The Port of Oakland showed a different pattern of potential flooding than estimated previously by Knowles (2009). Biging, Radke, and Lee (2012) thus were able to calculate the proportion of the region's three primary ports that could be potentially inundated: 80 percent of the Port of San Francisco, 60 percent of the Port of Oakland, and about 50 percent of the Port of Richmond during a 100-year flood event after 4.6 ft (1.4 m) SLR, if no further protective actions are taken (Figure 13).

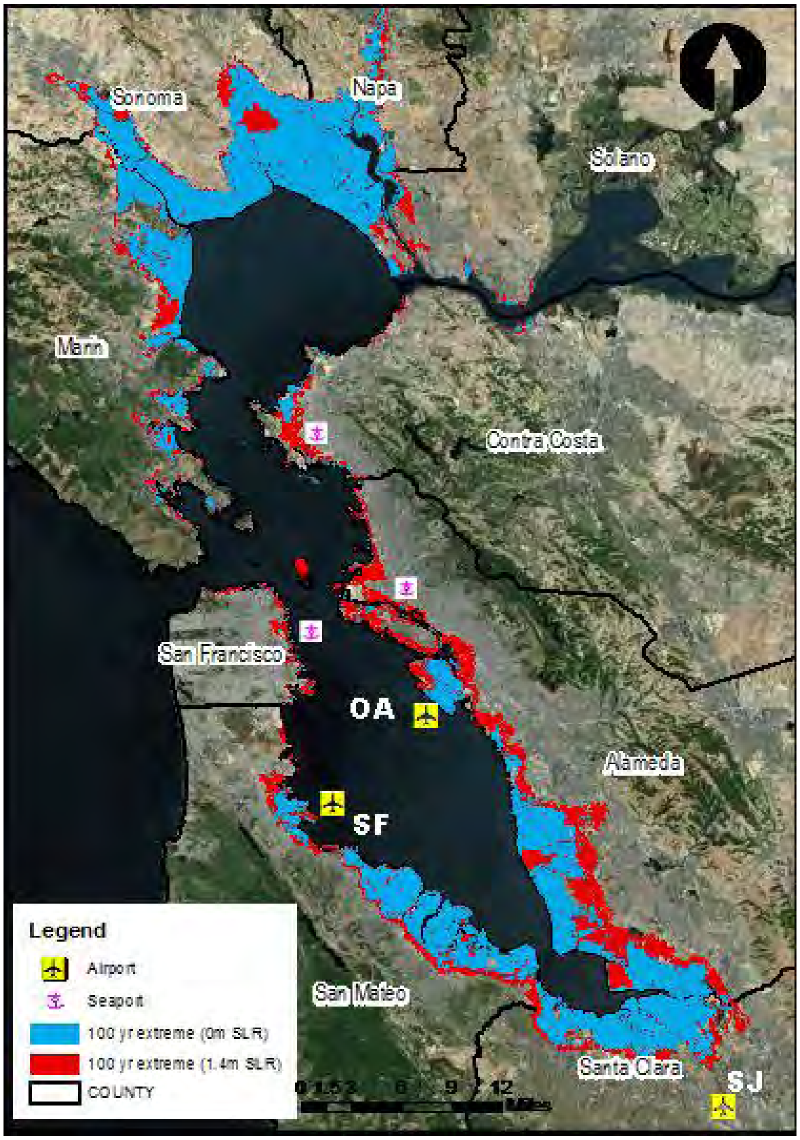

Figure 13. Location in the San Francisco Bay Area Projected to Be Inundated by a 100-Year Flood Event Without and With 5 ft (1.4 m) Sea-Level Rise

Source: Biging, Radke, and Lee. 2012

Previous findings on accessibility reported by BCDC (2009) and Heberger et al. (2009) indicated that in addition to challenges for transportation, 11 stations, 42 healthcare facilities, and 9 police stations would also become inaccessible during flooding events. Finally, Biging, Radke, and Lee (2012) assessed the impact of flooding on traffic networks and commutes. They show that flood-related traffic disruptions will increase travel times, both in the east-west and north-south directions. For the trans-regional commuter network, they showed that, "access to the hinterland in the North Bay is devastated by inundation and there are areas such as north San Mateo County where access to major road transportation is impacted" (Biging, Radke, and Lee 2012, p. 73).

4.4.2 Adaptation

Assessment of risk of roadway inundation, funded by the Federal Highway Administration, is being conducted for part of Alameda County as part of the Adapting to Rising Tides project. Adaptation considerations are also increasingly raised in the context of land use and transportation planning projects planned under the (originally only mitigation-focused) Sustainable Communities Strategy (SB 375)[4]. While ongoing road building and maintenance allow for relatively frequent opportunities to upgrade, repair, and elevate stretches of roadways, many road, rail, airport, and port elevation projects are major capital improvement projects, dependent on local, state, and federal funds. Railways, which cannot be elevated in just one exposed place but require elevation of long stretches of tracks, are a good example of the structural and financial challenge of adaptation in the transportation sector (AECOM and Arcadis 2011). Similarly, elevating the seawall surrounding a coastal airport is in principle not difficult, but it could be expensive. For example San Francisco International Airport would require extension of its runways, along with a higher seawall (so the angle of approach for airplanes would not be too steep), which would involve overcoming legal barriers currently preventing the infill of San Francisco Bay with additional sediment (Moser and Ekstrom 2012).

The Biging, Radke, and Lee (2012) study illustrates the benefit of improved elevation data, as it captures existing shoreline protection structures and more clearly identifies the most vulnerable transportation access and connection points. Adaptation efforts—for example to maintain and elevate existing levees and seawalls—thus can be focused on priority areas to retain overall regional functionality during storm events.

4.5 Biodiversity and Ecosystem Services

4.5.1 Biodiversity

Impacts and Vulnerability

As described in the introduction, the San Francisco Bay Area supports high biological diversity across a variety of landscapes and climate gradients. Cornwell et al. (2012) examined how the distribution of vegetation is shifting due to climate change in the region. They produced a probability-based quantification of the likelihood of "long-term, climate-driven vegetation change" at a high resolution (30 x 30 meters). The likelihood of these changes jointly represents the sensitivity of the vegetation to climate change in its particular place (exposure) (Cornwell et al. 2012). Results of these downscaled projections show major transitions in the distribution of

[4] California's Sustainable Communities and Climate Protection Act (SB 375, Steinberg, Chapters 728, Statutes of 2008)

vegetation, the most common of which is a shift from forest ecosystems to shrub-dominated landscapes.

Cornwell et al. (2012) also projected spatial transition potential of vegetation types, producing estimates for how far away vegetation needs to move as climate advances in order for species to remain in suitable climate conditions. Results show that 54 percent of all cases where vegetation types have to transition to new locations, less than one kilometer of movement is required to be successful. Still, a significant amount of the landscape (nearly 8 percent) is not suitable for vegetation to reestablish itself at all (Cornwell et al. 2012).

Ackerly et al. (2012) conducted an extensive literature review of how climate change will affect Bay Area ecosystems, habitats, species diversity, and species—focusing largely on terrestrial areas with some discussion of intertidal areas. They reviewed scientific literature on climate impacts on Bay Area species distribution and losses, diversity of endemic flora, wildfire and impacts on distribution of vegetation, invasive plants, terrestrial animals, herbivory, and briefly on estuarine, intertidal, and coastal nearshore habitats. Their report suggests that some of the most significant changes in diversity can be expected for tidal marshes, given their sensitivity to SLR and flooding, and the limited capacity for those habitats and species to migrate further inland (migration barriers). The region may also experience a major decline in endemic plant species, more so inland than in coastal areas (Loarie et al. 2008; Ackerly et al. 2012). Soil moisture will be affected by increases in temperature and evaporation, impacting vegetation distributions. Coastal redwood forests are habitats of special concern, given their sensitivity to warmer temperatures (which are projected to increase with climate change) and possible decreases in fog (see the discussion in Section 2 above). Sudden Oak Death, already a problem over the past decade in the Bay Area and thought to be at least partially driven by climate change, could also increase as warming continues (Ackerly et al. 2012). The literature review also highlighted that as disturbances increase with climate change (e.g., fire, severe drought, disease), the establishment and expansion of invasive species may also increase (Ackerly et al. 2012).

The rate at which climate change occurs over time will largely dictate how and whether species can adapt. Lines connecting points of similar temperatures (e.g., average annual temperatures, or certain seasonal temperatures of ecological significance) are called *isotherms.* Climate warming will shift these lines to new locations either at higher elevations, or in more coastal or more northern locations. How fast this shift occurs in the landscape is an important indicator, as it can be compared to the ability of species to disperse and migrate. Whenever the velocity of warming is faster than the pace at which species can move, species may find themselves in climatic conditions that are no longer suitable for them. In turn, if they can keep up with the pace of warming, they may well be able to adapt to climate change. Velocity of change in isotherms was estimated by Loarie et al. (2009). They found that coastal areas will experience less pressure because the velocity is lower there, and all things being equal, coastal species will experience less pressure to adapt rapidly.

The Bay Area has an extensive system of protected areas, including open space preserves and natural reserves covering multiple climate gradients and habitat types. However, as climate change advances, this system—in its current configuration— may no longer be able to support and protect the intended ecosystems, habitats, and species (Ackerly et al. 2012). Many of the large reserves in the region span across multiple climate zones supporting several habitat types, but climate change may decrease the heterogeneity of habitats covered. Ackerly et al. (2010)

estimates that by the end of the century (under the A1b emissions scenario) only eight percent of the Bay Area's existing protected areas will cover the same high and low climate (temperature) gradients, thus reducing the heterogeneity of habitat types supported in this system of reserves (Ackerly et al. 2010). This finding is consistent with estimates by Loarie et al. (2009) for a global analysis of the suitability of protected areas.

In a complementary study, Hannah et al. (2012) assessed the consequences of climate change for native vegetation and conservation practices. They point out the need for connected areas, to help species migrate to more suitable habitats. Their study identified priority areas for protection from other types of potential land use—essential information for adaptation planning in the conservation sector. It suggests that private land owners and local, state, and federal entities would benefit from collaborating in this regard, because land ownership varies over small distances.

In addition to ecological impacts on terrestrial biodiversity, the V&A study also included a study focused on aquatic species. Moyle et al. (2012) evaluated the climate change impacts on freshwater fish species in California. They combined literature review with expert opinion to document the current status ("baseline vulnerability") of 164 taxa and the likely impact of climate change on these fish ("climate change vulnerability"). To assess the potential impact of climate change, the researchers considered ten measures of adaptive/coping capacity and sensitivity to climatic-induced stressors, including responses of fish to water temperature increases, physiological and behavioral tolerance to changes in precipitation, and sensitivity to extreme weather events. They found that both statewide and in the Bay Area region, native species are significantly more vulnerable (for both baseline and climate change conditions) compared to non-native species (Figure 14). The paper ranked each fish species in terms of its baseline and climate change vulnerability, which can be used in designing or adapting conservation and management strategies. Species differ in terms of what makes them currently vulnerable and in terms of what attributes make them most vulnerable to climate change. Hence, the study illustrated the importance of developing conservation strategies at a regional scale so that plans may be specially designed to meet the needs of local species, their attributes, and external conditions (Moyle et al. 2012).

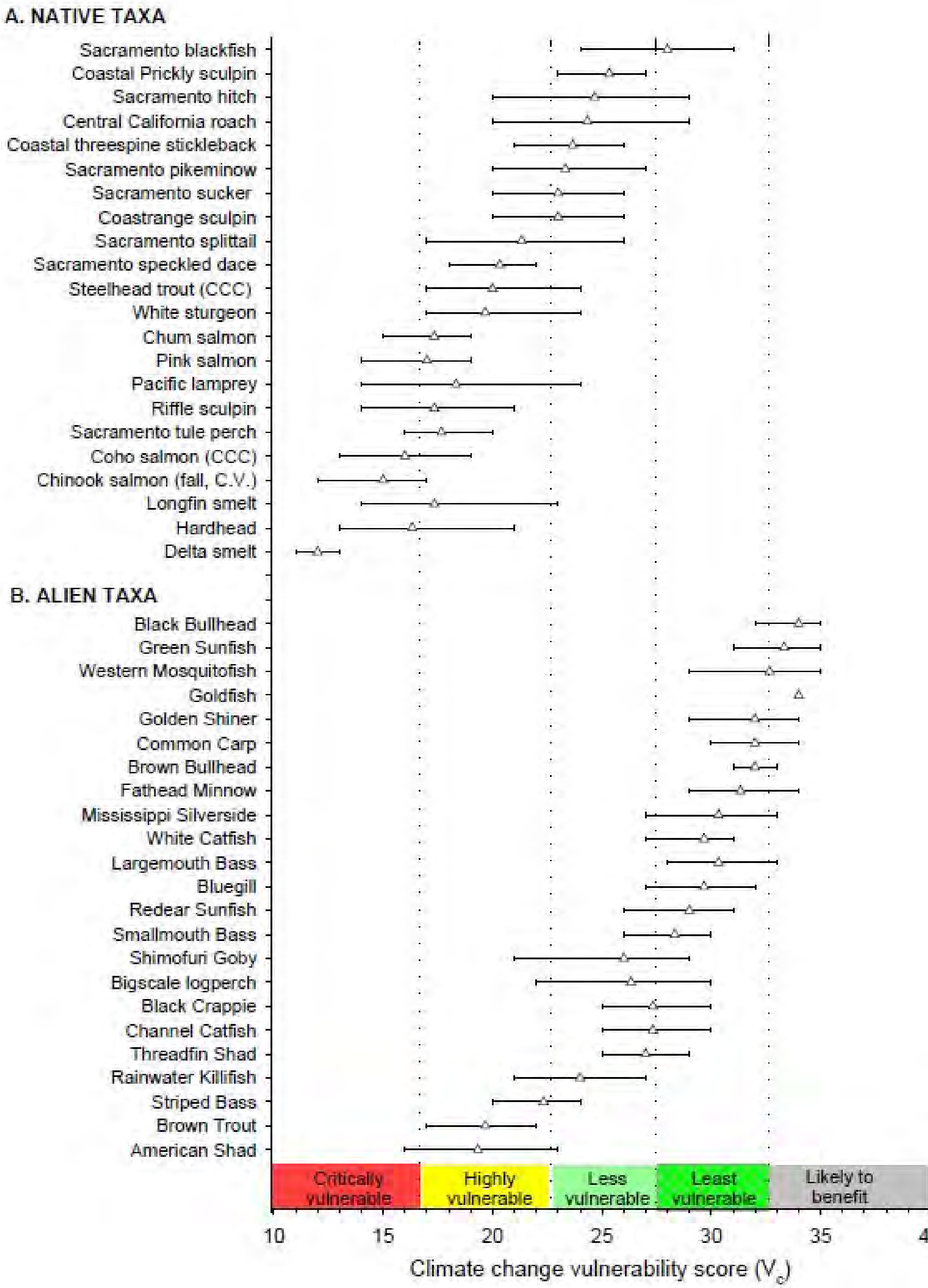

Figure 14. Climate Change Vulnerability Scores for Native (A) and Alien (B) Fishes in the San Francisco Bay Area, Arrayed from Highest to Lowest Scores. The triangle indicates the best vulnerability score for the species, while the lines indicate the uncertainty range around that best estimate.

Source: Moyle et al. 2012, p. 30

4.5.2 Ecosystem Services

Impacts and Vulnerability

Climate change directly affects individual species, each responding as it can. But species live in complex interactions with multiple other species, and they will not respond in unison to the changing conditions. Thus, climate change is likely to disrupt species interactions and disperse individual members at different rates. This will inevitably change the goods and services that ecosystems have been able to provide to date.

Ecosystem goods and services, the provisioning, regulating, and cultural benefits (both tangible and intangible) that society derives from ecosystems for its well-being (Millennium Ecosystem Assessment 2005) will change substantially as the climate changes. Shaw et al. (2011) projected that provisions and economic value supplied by existing ecosystem services will decline considerably throughout the state. In terms of ecosystem services of importance in the Bay Area, Ackerly et al. (2012) provided a thorough review of the state of the science on carbon storage, forage production (also covered in more detail by Chaplin-Kramer, see Agriculture Section 4.2), water supply and quantity, pollination, and outdoor recreation. They noted, for example, the potential for adaptation in agricultural practices (e.g., changing crop types) to increase carbon storage capacity in the Bay Area. Additionally, they highlight the need for improved understanding about how climate change will affect pollination and outdoor recreation.

Adaptation

In terms of adaptation strategies, several studies have begun to contribute both quantitatively and qualitatively to a better understanding of possible options. Moore et al. (2012) conducted a scenario-planning workshop with open space reserve managers in Marin County, demonstrating how practitioners can collaboratively develop adaptation strategies even in the face of considerable uncertainty. The scenario-planning approach helped participating agencies identify critical management-relevant variables (e.g., increased wildfires, decreased water availability), brainstorm robust adaptation strategies, and realize the benefit of working together across jurisdictional boundaries.

For example, to maintain coastal wetlands as sea level rises, many low-lying bay and coastal areas need to preserve upland habitat to which wetland species can migrate to survive. This will require integrated planning across integrative jurisdictional boundaries, greater flexibility, and consideration of both sea level and other climatic changes occurring simultaneously (Cloern et al. 2012). Whether this is possible, however, depends much on the degree of development to date. Heberger et al. (2012) estimated the migration viability of potential coastal wetlands in the Bay Area with increased SLR and reported that with a 4.6 ft (1.4 m) rise the counties of San Francisco, San Mateo, and Santa Clara had very little feasible migration area. Thus, in those areas, coastal wetlands are at high risk of being permanently inundated. Counties in the northern portion of the Bay (Sonoma, Solano, Napa, Contra Costa, and Marin) show more promise for potentially supporting wetland migration, as long as the adjacent upland habitats remain undeveloped.

Several activities in the Bay Area are working to increase capacity for understanding climate change impacts on ecosystems, which will then enable more strategic adaptation planning and decision-making relating to conservation and maintenance of ecosystem services. Multiple coalitions have formed to begin to connect climate science with policy and managers. The Bay

Area Ecosystems Climate Change Consortium (BAECCC) is a partnership of federal, state, and local government agencies, organizations, and universities that joined forces to leverage expertise, financial support, and other resources seeking to effectively address ecological challenges of climate change. On a more sub-regional focus, the North Bay Climate Adaptation Initiative (NBCAI) "is a coalition of natural resource managers, policy makers and scientists committed to working together to create positive solutions to the problem of climate adaptation for the ecosystems and watersheds of Sonoma County" (http://www.northbayclimate.org).

Such collaborative efforts will prove essential for success. As Ackerly et al. (2012, p. 29) note,

> "The San Francisco Bay Area is a region of high priority for ongoing efforts to conserve native biodiversity and maintain high levels of ecosystems services in the face of twenty-first century climate change. The challenge in the Bay Area, as elsewhere, will be to manage for continued ecological change that fosters biodiversity conservation and ecosystem services. An integrated approach that incorporates terrestrial and freshwater ecosystems, the Bay itself, and the adjacent coastal and marine environments will be critical. Actions to expand the network of protected open space and enhance the biodiversity value of the working landscapes will contribute both to biodiversity preservation and the maintenance of ecosystem services in the twenty-first century. […] The array of academic, governmental and non-governmental organizations, combined with public support for environmental protection and conservation, make the Bay Area ideally suited to pursue innovative climate adaptation strategies, as well as research and monitoring efforts, that could set strong precedents in California and beyond."

4.6 Public Health

4.6.1 Impacts and Vulnerability

Climate change is expected to have major repercussions for public health throughout California (California Department of Public Health 2008). Specifically in the Bay Area, climate change effects on environmental conditions that affect public health include increased frequency of extreme heat events (to which the region is not accustomed historically), increased air pollution, reduced and changed timing in precipitation (which could result in droughts), and flooding aggravated by SLR and high-intensity runoff events. Public health could further be affected by climate through less-extreme winters in cities, expanded ranges for vector- and tick-borne diseases, and increased air pollution (from wildfires, pollen, and/or higher ozone concentrations), among others.

Stressful environmental conditions exacerbated by climate change, such as heat waves, can have disproportional impacts on different segments of the population. Some are more sensitive than others or have less ability to prepare for, cope with, or adapt to changing conditions, and hence will be affected disproportionally (Morello-Frosch et al. 2009). The 2009 California Adaptation Strategy highlights "elderly, infants, individuals suffering from chronic heart or lung disease, persons with mental disabilities, the socially and/or economically disadvantaged, and those who work outdoors" as particularly vulnerable (California Natural Resources Agency 2009). Therefore, certain population characteristics (age, sex, race, education level, income, air conditioner ownership, and others) are often used as indicators of sensitivity and adaptive capacity to understand the social vulnerability of a given region's population to climate change.

The brief review below provides highlights from studies that examined heat extremes and flooding, illustrating which population segments are more sensitive or tend to have less adaptive capacity than others. It also describes results of indices developed to assess social vulnerability based on an integration of population characteristics to quantitatively reveal where overall vulnerabilities may exist across the Bay Area.

Heat

The majority of research thus far on the connections between climate change and public health has focused on temperature- and air pollution-related impacts (Jerrett et al. 2012; CDPH 2008). Because of the typically cool summers, relative to other regions in the state, the Bay Area is not usually considered to be at risk of extreme heat events. But precisely this lack of historical experience with extreme heat is currently limiting the capacity for dealing with such events. For example, large portions of the Bay Area residents do not have air conditioners because of the historically cool summer temperatures; whereas, many more residences in the Central Valley have air conditioners (Ostro et al. 2010). Campaigns to alert Bay Area residents to heat extremes and convince them to take protective actions need to take this historical experience into account (Moser and Ekstrom 2012).

At the individual level, ownership of an air conditioner can be a useful indicator of short-term coping capacity in times of extreme heat (Ostro et al. 2010). Ostro et al. (2010) examined the effects of temperature and use of air conditioners on hospitalizations in 16 cities of California, including Sunnyvale, Santa Rosa, and Oakland in the Bay Area. They observed significant connections between heat and several disease-specific types of hospital admissions. They also found that the use of air conditioners significantly reduced the risk brought on by higher temperatures. This finding is reported with caution, however, suggesting that increased use of air conditioners should not necessarily be relied on as an effective long-term strategy, because risks of power outages are higher during peak demand periods and air conditioners increase energy demand, which increases cost to individual households and greenhouse emissions if the electricity comes from fossil fuel sources such as natural gas (Ostro et al. 2010).

Basu and Ostro (2008) assessed different populations' sensitivity to high ambient temperature in terms of mortality rates. Each 10°F (~4.7°C) increase in mean daily apparent temperature corresponded to a 2.6 percent increase in mortality from cardiovascular conditions, with the most significant risk found for ischemic heart disease (i.e., reduced blood supply of the heart due to narrowing of the coronary artery). Elevated risks were also found for persons 65 years and older, infants 1 year or less, and for African Americans. To reduce mortality caused by the extreme heat events, immediate response (within three days or less) is critical (Basu and Malig 2011). Illustrating the sensitivity of pregnant women, Basu, Malig, and Ostro (2010) found a significant relationship between high ambient temperatures and the incidence of pre-term births, using records from several counties in California (including four in the Bay Area: Contra Costa, Santa Clara, Alameda, and Solano). Given that both average temperatures and the incidence of extreme heat are projected to increase across the Bay Area, populations sensitive to warm temperatures will be at increased risk unless adaptive measures both at the individual and community level are taken to reduce their sensitivity and exposure.

How these sensitivities and adaptive capacities within a population coincide with exposure to certain climatic stressors reveals a fuller picture of social vulnerability to climate change. The population characteristics described above, along with others, can be integrated into a single index representing relative social vulnerability (Cutter, Boruff, and Shirley 2003). Jerrett et al. (2012) developed an index that represents the three dimensions of vulnerability (exposures, sensitivity, and adaptive capacity). They assessed health-related vulnerabilities in the Bay Area (and Fresno County), focusing on heat stress and air pollution. This study developed an approach to vulnerability that integrated four factors (heat stress, air pollution, social and health vulnerability, and adaptive capacity) and displayed them in a single cumulative vulnerability map (Figure 15).

Results show parts of San Francisco, Alameda, Santa Clara, and Contra Costa counties as the most “vulnerable” areas to these threats. When the cumulative index is disassembled, underlying drivers of that vulnerability become apparent, and thus can serve as useful indicators of how to intervene to reduce overall vulnerability. Heat stress, for example, made up of absolute and relative temperature exceedances in the past 30 years, showed the highest relative exposure in eastern portions of Alameda County, followed by areas in northwest Marin, northern Sonoma, and Napa counties. Air pollution exposure exhibited a very different pattern than heat stress exposure, closely aligning with the population (and industrial use) densities and transportation corridors (e.g., all along the spine of Silicon Valley). Indicators for adaptive capacity exhibit similar patterns, with generally higher vulnerabilities in urban areas than in rural ones (Jerrett et al. 2012). Jerrett et al. (2012) also applied a previously developed method (Su et al. 2009) to quantify how regional environmental inequalities (represented by race and socioeconomic status) aligned with heat stress, air pollution, and adaptive capacity. This analysis aimed to expose any areas of social inequality. Very little inequality was found for heat stress, but more so for air pollution. Inequality was especially high in terms of the distribution of wealth and poverty as indicators of adaptive capacity. However, the strongest inequalities were found in the structural factors affecting people’s coping capacity, whereby poor and non-white populations tended to live in areas with less tree cover, more impervious surfaces, and lower levels of penetration of air conditioning. These three factors are related to a greater urban heat island effect aggravating regional heat extremes and lower capacity to cope with those extreme temperatures.

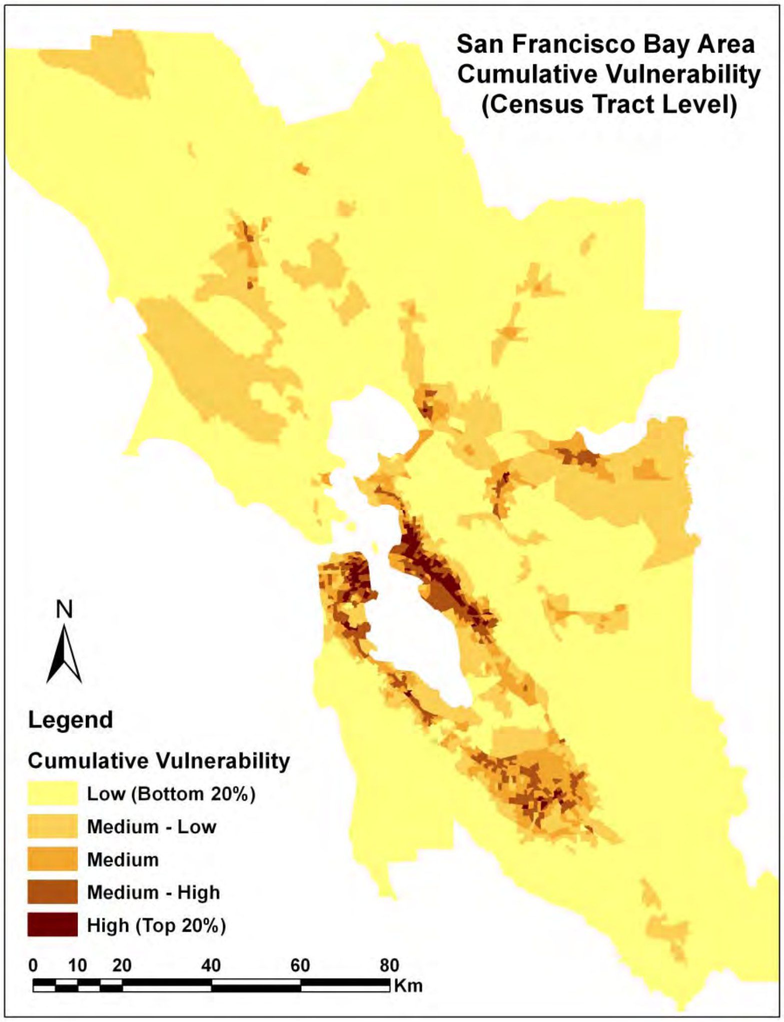

Figure 15. Quantiles of Climate Change Cumulative Vulnerability Scores at the Census Tract Level to Heat Stress and Air Pollution. Darker colors indicate higher vulnerability, while lighter shades indicate lower vulnerability.

Source: Redrawn from Jerrett et al. 2012.

Floods

Climate change is also expected to increase the incidence of floods and vector-borne diseases. The exposure of residences and businesses that are at risk of flooding are reported by Heberger et al. (2012). Their study reported that 140,000 employees work within the 100-year flood zone in the Bay Area at present, and with a 3.3 ft (1m) rise in sea level, an additional 90,000 employees would be at risk (these estimates would be higher if accounting for potential commute disruptions). Counties of San Mateo, Alameda, Marin, and Santa Clara are of special concern because of the high numbers of employees working in the potential flood zone with SLR (Heberger et al. 2012).

Cooley et al. (2012) developed and applied a social vulnerability index to climate change for all of California (different from Jerrett et al.) and specifically for the City of Oakland (Garzón et al. 2012), focusing particularly on sensitivity and adaptive capacity. Variables included income, race, age, and existing respiratory illness, among several others. That indicator was overlain onto different exposure maps showing existing and projected climate-related stressors[5] to provide an integrated view of vulnerability. For the City of Oakland, they found that the vast majority of the residential population exposed to the 100-year flood after 3.3 ft (1 m) and 4.6 ft (1.4 m) of SLR were ranked as "highly vulnerable" (Garzón et al. 2012).

4.6.2 Adaptation

The California Department of Public Health recognizes the threats of climate change to public health and has begun to prepare adaptation plans (California Natural Resources Agency 2009). Moreover, several communities and counties where heat extremes and flooding are already common have emergency plans and heat warning systems in place. However, for much of the Bay Area, where heat extremes in the past have been uncommon, preparations for the potential impacts of climate change are still in the early stages (Moser and Ekstrom 2012). This is of particular concern given that many parts of the region are not prepared to deal with the extreme heat events that may arise with climate change. This means communities may not have the infrastructure, public education, social networks, and response procedures in place or the overall capacity for dealing with these events, making them more vulnerable than communities in the Central Valley, where communities have a long history of preparing for and dealing with impacts of high temperatures and heat waves (Moser et al. 2009).

One exception is ongoing work by the San Francisco Public Health Department (SFDPH). In collaboration with University of California-Berkeley scientists and financial support from the Center for Disease Control, the SFDPH is conducting an assessment of the city's vulnerability to increased heat from climate change. This assessment will be used to develop and implement adaptation strategies, including public education and outreach about the ways to prepare for and the risks of climate change to public health (Moser and Ekstrom 2012). Moser and Ekstrom (2012) found a number of obstacles experienced in the public health sector preventing relevant agencies from taking measures to adapt and integrating public health considerations in land use planning. These included the following:

- Lack of decision-making authority over land use planning in urban areas
- Not traditionally being included in long-term planning processes undertaken by local governments (e.g., general plan updates) with other departments and sectors (although the Department of Public Health is being included in general plan updates now in Santa Clara County)
- Lack of leadership and making adaptation a priority in health departments
- Common frustrations about lack of financial support from external sources

[5] While Garzón et al. (2012) applied their social vulnerability indicator to air quality, high heat days, coastal flooding, and wildfire, only the flooding-related results are reported here, and wildfire is discussed in Section 4.7.

4.7 Other Areas and Resources

4.7.1 Coasts

Impacts and vulnerability

Beyond water, energy, and transportation infrastructure, other critical investments in the immediate San Francisco Bay shorefront areas could be affected by climate change and related impacts. Garnering perhaps the greatest concern is the potential impact on buildings, their contents, and the economic assets and activities they house. Replacement value of buildings and their contents at risk of a 100-year flood more than doubles with a 4.6 ft (1.4 m) SLR, from $29 billion within current 100-year flood zone to $62 billion. Even with only a 20 in (0.5 m) rise in sea level, San Mateo's estimated potential losses go from $16 billion to $18 billion; with a 4.6 ft rise (1.4 m) estimates reach $23 billion in potential property damage, assuming no change in development in the affected areas (Heberger et al. 2012). The City and County of San Francisco currently has the lowest economic risk from flooding with "only" $110 million in property value at risk, but this exponentially increases with 3.3 ft (1.0 m) of SLR to $1.4 billion, and then up to $4 billion of property value at risk with a 4.6 ft (1.4 m) rise. In addition, Heberger et al. (2012) reports that under projected SLR, as many as 81 schools, 42 healthcare facilities, 11 fire stations and training facilities, and nine police stations would be within the 100-year flood zone in the nine-county region by 2100 (under a 4.6 ft [1.4 m] SLR).

Shoreline erosion and cliff failures are already a problem in a number of locations along the outer coast of San Francisco and Marin counties. Occasionally publicized imminent threats to roads, infrastructure, and apartment buildings (e.g., in Pacifica or along San Francisco's Ocean Beach) or private homes (e.g., Stinson Beach) give a glimpse already today of what is expected to become more common in the future as sea level rises. During King Tides,[6] Bay Area residents can get a taste of what the future may hold (Figure 16).

Adaptation

The Departments of Public Works in several cities and counties in the Bay Area are beginning to be concerned about the increasing flood and erosion risks. Moser and Ekstrom (2012) reported several ongoing efforts by local governments in the region to prepare for and adapt to the impacts on coastal resources. For example, Marin County is including consideration of SLR in its Local Coastal Plan update, and its Department of Public Works adopted a watershed approach to improve its flood management. San Francisco's Public Utility Commission and Department of Public Works are developing more extensive measures to deal with repeated erosion and flooding along the Great Highway. Most prominent of efforts in the region has been the amendment to BCDC's Bay Plan in 2011 that mandates the consideration of SLR in permitting decisions. Also notable at the regional level is the next round of implementing the Sustainable Communities Strategy (SB 375), which includes consideration of climate impacts affecting future land use and development (Moser and Ekstrom 2012).

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[6] King Tides do not have an official scientific definition, but are commonly understood as the highest tides known in an area. Typically they occur when "the sun and moon's gravitational forces reinforce one another. King tides tend to be more dramatic in the winter when storms cause increased wind and wave activity along the coast" (see FAQs of the California King Tide Initiative, http://californiakingtides.org/).

Figure 16. San Francisco's Pier 14 During the King Tide in the Winter of 2010/2011. The extremely high tide flooded sidewalks and pounded the base of the Oakland/Bay Bridge (in the background). King tides provide a glimpse of the future when sea levels are permanently higher, thus elevating regular tides, base flood elevations, and the risk of coastal erosion.

Source: M. Schweizer

4.7.2 Wildfire

Impacts and Vulnerability

Wildfire can have direct impacts on human life, property, and ecological systems, but also can affect energy and communication transmission infrastructure, transportation routes (including emergency response), air quality, and water supply. Models for California show that climate change could affect the size and frequency of wildfires (Westerling and Bryant 2008; Lenihan et al. 2003), but how they will change will differ widely across the state and even within the Bay Area. Figure 8 shows the areas in the region where probability of wildfire is projected to increase. These areas include most of Napa, Sonoma, Marin counties and less so for San Mateo, San Francisco, and the western boundary of Santa Clara County. The extent and distribution of how wildfire risk could be affected by climate change was explored by Bryant and Westerling (2012), showing that the influence of future land use and development plays a major role in determining the extent of increases in wildfire risk (see Figure 9).

In assessing vulnerability in Oakland, Garzón et al. (2012) reported that the area with the highest wildfire risk, current and projected, is in the Oakland Hills. Based on their social vulnerability index, this area of high exposure coincides with the population that is least vulnerable due to a combination of low sensitivity and high adaptive capacity. The current high adaptive (response) capacity in the high-risk area (exposure) creates a cumulative "moderate" vulnerability score. This result shows that it is important to disentangle the vulnerability scores to design appropriate response strategies. Even with high adaptive capacity among affected social groups, potential losses could be substantial. The region's largest urban-wildland fire on record was in the Oakland-Berkeley Hills in 1991, and it caused $1.7 billion in insured losses.

Adaptation

Several papers contributing to the V&A study made valuable contributions to adaptation strategies and options for wildfire. Garzón et al. (2012) suggested several adaptation strategies for wildfires, including those catering to coping with and responding to wildfires and ways to reduce overall risk of wildfire from occurring. These included vegetation management, land use planning, burial of energy infrastructure at risk, emergency response preparations (adequate shelters, air quality warning systems, community-based evacuation and response plans, and others). Westerling and Bryant's (2012) study pointed to a major opportunity for adapting to climate change in regards to wildfire risk. Specifically in the Bay Area (Figure 9), they found that the highest estimated future wildfire risk was produced from a combination of land use decisions supporting a high-sprawl, wildland-urban scenario combined with higher greenhouse gas emissions. Thus long-term reduction of wildfire risk can be best achieved through careful land-use decisions, whereas disaster preparedness and insurance mechanisms can help reduce catastrophic impacts for when the actual events occur.

4.8 Community-Engagement in Vulnerability Assessment

Garzón et al. (2012) in their research focused on the City of Oakland, and illustrated ways to conduct a vulnerability assessment at the city level that is done in collaboration with community partner organizations, resident leaders, and city representatives. Researchers first worked with partners to develop indicators of vulnerability that were applicable and meaningful to the community. For example, rather than just reporting projected temperature changes for the City of Oakland, stakeholders suggested that future temperatures for Oakland be presented as geographic analogous (i.e., by comparison to existing temperatures in another California city). Under the lower emissions scenario (B1) for the end of the century (2070–2099), Oakland was shown to be similar to present-day Santa Cruz; whereas, under the higher emissions scenario (A2), the distribution of daily maximum temperatures in Oakland resembled those of present-day Los Angeles (Garzón et al. 2012). The assessment also was able to incorporate stakeholder values, providing a more refined/accurate depiction of concerns and prioritization for developing adaptation strategies. For example, wildfire risk was projected to increase in the Oakland Hills, but the involved stakeholders showed little interest for this impact compared to coastal flooding projections where current development pressures are dominant and integrated census data indicated high social vulnerability.

Experience with participatory vulnerability assessments such as those demonstrated in Oakland, and scenario planning exercises such as those explored in Marin County, show great promise for future local research and adaptation planning. They offer opportunities for researchers to work directly with affected stakeholders and local decision-makers, and produce locally more relevant and meaningful science. Through active engagement of those directly affected, stakeholders also show greater interest and trust in the information available. Similar efforts underway in Alameda County through the BCDC-led Adapting to Rising Tides project and in other parts of California (e.g., San Luis Obispo, Fresno, San Diego, and Los Angeles) suggest that local decision-makers are eager to work on climate change and begin adaptation planning.

5. DISCUSSION

5.1 Cumulative Stressors and Vulnerability

In the above sections, the summarized research highlights the ways in which many important sectors in the San Francisco Bay Area are vulnerable to a changing climate. The impacts of climate change will neither transpire in isolation from one another nor in isolation of other stressors on the well-being of the region's populations, economies, and infrastructure. Multiple stressors can combine in one place, creating more severe damage sooner than they might individually. For example, a wildfire may coincide with a heat wave, both of which could occur during a drought year. This puts pressure not only on already-stressed water supplies but also on the energy supply system. Those segments of the population with lower income may not have access to air conditioning in their homes or may have limited resources to run an air conditioner, and they also may live in higher-crime areas and be afraid to open their windows for improved air circulation. Together, these climatic, social, and economic factors put them at increased risk of heat illness, more than climate change alone would.

Cumulative stresses will also be felt at the community (city and county) and regional level, as local governments and regional agencies face multiple impacts on their jurisdictions and spheres of responsibility. The studies by Garzón et al. (2012) and Moser and Ekstrom (2012) illustrated how this manifests in cities and counties across the Bay Area, and how effective collaboration across agencies and departments will be critical to integrate preparedness and adaptation efforts.

Future research will have to explore in more detail how impacts on one sector percolate to other sectors (e.g., the "domino effect" of impacts of extreme events in the energy sector affecting businesses and households across the region, or impacts on the water sector affecting rural and urban areas). Early indications from some of the integrative vulnerability indices developed in the health sector suggest that certain segments of the population will also experience relatively greater or more severe impacts due to their exposure, sensitivity (reflecting preexisting conditions and non-climatic stressors), and limited adaptive capacity. The same principle appears to hold true for already endangered species and ecosystems.

5.2 Common Patterns Across Studies

<u>Useful to tease apart dimensions of vulnerability</u>: Most research on adaptation strategies to date focuses on increasing adaptive capacity as a way to reduce the identified vulnerability within the sector, rather than proposing to reduce exposure and sensitivity. This focus may shift in the future, but by framing assessments through the vulnerability lens, decision-makers can obtain insights that help them discover a wider range of possible interventions and leverage points for adaptation.

- *Population growth and development matters:* Several studies showed that future population growth and its distribution is at least as impactful as climate change in causing significant impacts. These same studies illustrated that uncertainties about these social patterns may be more uncertain than projections of climate change. This finding might give those more skeptical of climate science pause; more importantly, it gives those charged with adaptation planning considerable leverage in affecting future outcomes through directing local development to safer locations.

- *Scale of analysis matters:* Compared to other regions in California, the nation, and even globally, the Bay Area ranks as one of the more "blessed" ones, with a mild climate and high adaptive capacity. However, the studies summarized here demonstrate that—with a closer look —the Bay Area displays a remarkable variation in exposure, sensitivity, and adaptive capacity. Regional averages may not provide sufficient information for local-level adaptation because of the region's physical and social heterogeneity. For example, temperature records and projections differ widely across the Bay Area; ZIP code-level energy usage data illustrate the usefulness of high-resolution behavioral information for developing location-specific adaptation strategies. Regional averages would not be reflective of on-the-ground behavior. Species-specific assessments of migration potentials reveal vulnerability hotspots and priority areas for adaptation interventions.
- *Place-based planning is critical for effective adaptation:* The great benefit of a regional focus, such as this one on the Bay Area, reveals considerably greater detail in local patterns and complexities. The results are more interesting, relevant, and useful for local decision-makers, but also improve scientific understanding about the underlying dynamics. In particular, the regional focus allowed for integration of multi-disciplinary perspectives, thus enriching the understanding of climate change impacts and "on-the-ground" vulnerabilities; as well as assessment of realistic response options, the barriers that hinder their realization, and the strategies that help overcome them.
- *Importance of working across sectors:* Findings reported here demonstrate the need to integrate across sectors and levels of government to avoid possible unintended consequences and to identify resource-sharing options. Working across sectors also offers opportunities to overcome barriers to adaptation not otherwise seen. Relying on air conditioners, for example, as a coping strategy during extreme heat events can lead to the inability of the energy system to meet the demand during peak periods. Similarly, interties in the water supply system in times of drought affect multiple users and economic sectors. Ensuring the capacity of these to withstand earthquakes and other hazards becomes even more valuable as climate change potentially reduces water supply.
- *Collaborative research with decision-makers:* Several research projects in the V&A study directly interacted with decision-makers. This is an important innovation in PIER-funded research, as it helps to better understand decision-makers' needs and the context in which adaptation takes place. Such close interactions can not only inform future research questions, but increase the likelihood that practitioners will use the produced information.

5.3 Conclusion

The integrative summary of recent research conducted in the Bay Area is an important step forward in informing state, regional, and local (county, city, and neighborhood) efforts in assessing vulnerabilities to climate change and planning for adaptation. But these efforts are only the beginning, and they will need to be continued and strengthened for the region to be able to adequately prepare for and adapt to climate change impacts and maintain its economic resilience and vitality—as well as its beauty and attraction for residents and visitors in decades to come. Innovation, which has been central to driving the region's competitive economy, will be key to helping the region adapt to climate change.

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GLOSSARY

A2	IPCC higher emissions scenario
ABAG	Association of Bay Area Governments
B1	IPCC lower emissions scenario
BAAQMD	Bay Area Air Quality Management District
BAECCC	Bay Area Ecosystems Climate Change Consortium
BCCA	bias corrected constructed analogues
BCDC	San Francisco Bay Conservation and Development Commission
BCSD	bias-corrected statistical downscaling
CALVIN	California Value Integrated Network
CAS	California Adaptation Strategy
CDF	California Department of Forest and Fire Protection
CDPH	California Department of Public Health
CM2.1	climate model
CNRM	Centre National De Recherches Météorologiques
DWR	California Department of Water Resources
EPA	U.S. Environmental Protection Agency
FAQs	frequently asked questions
FRAP	CAL FIRE Fire and Resource Assessment Program
GCM	Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory
ICLUS	Integrated Climate and Land Use Scenarios
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
NBCAI	North Bay Climate Adaptation Initiative
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
OEHHA	Office of Environmental Health Hazard Assessment
PDO	Pacific Decadal Oscillation

PCM1	parallel climate model
PIER	Public Interest Energy Research
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PUMA	Piloting Utility Modeling Applications
SFDPH	San Francisco Public Health Department
SLR	sea-level rise
SRES	Special Report on Emissions Scenarios
TRIM-2D	A 2-dimensional, depth-averaged, finite-difference hydrodynamic model for simulating inland water flows
USGS	United States Geological Survey
V&A	Vulnerability and Adaptation
WUI	wildland-urban interface