CALTRANS CLIMATE CHANGE VULNERABILITY ASSESSMENTS

2019

District 9

Technical Report

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ACRONYMS AND ABBREVIATIONS

ADAP	Adaptation Decision-Making Assessment Process
CalFire	California Department of Forestry and Fire Protection
Caltrans	California Department of Transportation
CCC	California Coastal Commission
CEC	California Energy Commission
CMIP	Coupled Model Intercomparison Project
DVNP	Death Valley National Park
DWR	California Department of Water Resources
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
GCM	Global Climate Model
GHG	Greenhouse Gas
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
LOCA	Localized Constructed Analogues
MACA	Multivariate Adaptive Constructed Analogs
NOAA	National Oceanic and Atmospheric Administration
NRA	Natural Resources Agency
RCP	Representative Concentration Pathway
SHS	State Highway System
SR	State Route
SRES	Special Report Emissions Scenarios
USFS	US Forest Service
UC	University of California

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1. INTRODUCTION

This report, developed for the California Department of Transportation (Caltrans), summarizes a vulnerability assessment conducted for the portion of the State Highway System (SHS) located in Caltrans District 9.[1] Although the SHS can be vulnerable to many different types of disruptions, this assessment specifically examined SHS vulnerabilities from climate change.

Climate change and extreme weather events have received increasing attention worldwide as one of the greatest challenges facing modern society. Many state agencies—such as the California Coastal Commission (CCC), the California Energy Commission (CEC), and the California Department of Water Resources (DWR)—have developed approaches for understanding and assessing the potential impacts of a changing climate on California's natural resources and built environment. State agencies are invested in defining the implications of climate change and many of California's academic institutions are engaged in developing resources for decision makers. Caltrans initiated the current study to better understand the vulnerability of California's SHS and other Caltrans assets to future changes in climate. The vulnerability study had three objectives:

- Understand the types of weather-related and longer-term climate change events that will likely occur with greater frequency and intensity in future years,
- Conduct a vulnerability assessment to determine those Caltrans assets vulnerable to various climate-influenced natural hazards, and
- Develop a method to prioritize candidate projects for actions that are responsive to climate change concerns when financial resources become available.

The current study focuses on all 12 Caltrans districts, each facing its own set of challenges regarding future climate conditions and potential weather-related disruptions. The District 9 report is one of the district reports that are currently in various stages of development.

1.1. Purpose of Report

The *District 9 Technical Report* is one of two documents that describe the work completed for the District 9 vulnerability assessment, the other being the *District 9 Summary Report*. The *Summary Report* provides a high-level overview on methodology, the potential implications of climate change to Caltrans assets, and how climate data can be applied in decision making. It is intended to orient non-technical readers on how climate change might affect the SHS in District 9.

This *Technical Report* is intended to provide a more in-depth discussion, primarily for District 9 staff. It provides background on the methodology used to develop material for both reports and general information on how to replicate those methods, if desired. The report is divided into sections by climate stressor (e.g., wildfire, temperature, precipitation) and each section presents:

- How that climate stressor is changing,
- The data used to assess SHS vulnerabilities from that stressor,
- The methodology for how the data was developed,

[1] This assessment was conducted for the State Highway System in District 9 and does not include other Caltrans assets or state/local roads.

- Maps of the portion of district SHS exposed to that stressor, and
- Mileage of the exposed SHS.

Finally, this *Technical Report* outlines a recommended framework for prioritizing a list of projects that might be considered by Caltrans in the future. This framework was developed based on research of other prioritization frameworks used by transportation agencies and alternative frameworks developed to guide decision making given climate change.

All data used in the District 9 *Technical* and *Summary Reports* were collected into a single database and provided to Caltrans. Caltrans will be able to use this data in its own mapping efforts and technical analyses. This database is expected to be a valuable resource for ongoing resiliency planning efforts. The contents of the District 9 database will also be available to the public in an online, interactive mapping tool.

1.2. District 9 Characteristics

Caltrans District 9 is headquartered in Bishop, California. It is the fourth largest district in terms of area and is responsible for the SHS in Inyo, Mono and eastern Kern Counties. The district includes the highest (Mt. Whitney) and lowest (Death Valley) elevations in the continental United States. Elevations along District 9's SHS range from 120 feet below sea level to 9,945 feet above. The climatic regions in District 9 also vary widely, with mountain ranges on both the eastern and western boundaries. Several State highways traverse the Sierra Nevada mountain range, including a major entrance to the Yosemite National Park. There are 19 US and State-numbered highways in the district. District 9 is primarily rural, with much of the land under the jurisdiction of governmental agencies and Tribal Nations. Estimates of population centers range from 50 people (rural unincorporated areas) to over 28,000 people (incorporated city).

Given its proximity to recreational areas, the district hosts many tourist-related activities and thus many of the major state highways serve tourist trips (an estimated 13 million visitor-days are generated annually from the tourist industry).[2] For example, the US 395/State Route (SR) 14 corridor, serving the western portion of the district, provides a primary route from Southern California into the district's tourist areas. This is the only corridor providing interregional and interstate access and thus is a vital link for both local and regional trip-making. Nearly all people and goods movement, and service provision in District 9 use the routes in this corridor. This corridor has thus been the focus of many district efforts to improve mobility and access.

[2] Caltrans District 9. "District System Management Plan." Bishop, CA. (2015). http://www.dot.ca.gov/d9/planning/docs/D9FinalMar2015DSMP.pdf

There are no significant air cargo or rail services in the district; the economy (especially the agriculture industry) is heavily dependent on the SHS in District 9. In addition, the SHS provides the primary access for outlying communities for emergency services; in most communities, the SHS serves as the "main street."

SRs 14 and 58, and the US 395 corridor, are major transportation corridors in the district. In Kern County, SR 58 is the major east-west corridor linking Bakersfield and the Central Valley (District 6) with Nevada, connecting to I-40 at Barstow. The primary truck routes in the district traverse SR 14, SR 58, US 6, and US 395.

The region has many lakes, rivers, and creeks fed by Sierra snowmelt, many of which lie in federally-designated Scenic Areas. For example, the Owens River headwaters in the Sierra and the Amargosa River (intermittent surface and underground flow) in Death Valley are both designated as Wild and Scenic Rivers.

District 9 has acknowledged that the geography in the district (e.g., mountains and water bodies) constrain how State facilities can be built and maintained. In addition, the geographic and climatic conditions create special challenges with respect to extreme weather events and long-term climate change. According to the District 9 System Management Plan, "seasonal weather variations and related natural events/disasters impact the District’s highways including subzero temperatures, heavy snowfall, ice, avalanche, high winds, blinding dust, wildfire, excessive summer heat, flash floods, and washouts. Geographical constraints (e.g., cliffs and rivers) and sensitive flora/fauna species are also challenging to the planning, designing, building, and maintaining of highways in the district."[3]

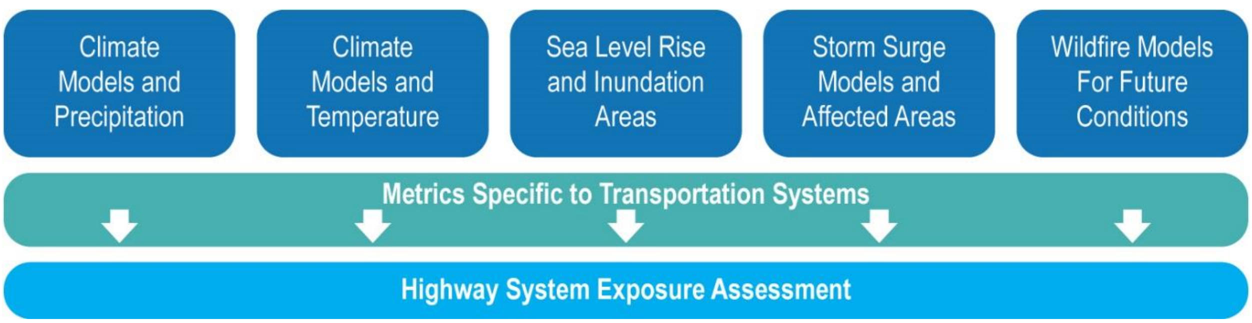
[3] Caltrans District 9. Op cit.

2. POTENTIAL EFFECTS FROM CLIMATE CHANGE ON THE STATE HIGHWAY SYSTEM IN DISTRICT 9

Climate and extreme weather conditions in District 9 are changing as global greenhouse gas (GHG) emissions lead to higher temperatures and changes in precipitation patterns. These changing conditions are anticipated to affect the SHS in District 9 as well as other Caltrans assets throughout the State. These impacts may appear in a variety of ways, but most likely each will increase District 9 infrastructure's exposure to environmental stresses that exceed their original design factors. The project study team, made up of WSP climate and sustainability subject matter experts, considered a range of climate stressors and how they align with Caltrans design criteria/other metrics specific to transportation systems.

Figure 1 illustrates the general process for deciding which metrics should be included in the overall SHS vulnerability assessment (note: this approach was used for all districts and thus sea level rise and storm surge are included in the figure even though such threats are not present in District 9). First, Caltrans and the project study team considered which climate stressors currently affect transportation systems and those that will do so in the future. Then, Caltrans and the project study team identified a relevant metric relating to the climate stressor's impact on assets. For example, precipitation data were formatted to show the 100-year storm depth given that the 100-year storm is a criterion used in the design of Caltrans assets.

FIGURE 1: CONSIDERATIONS FOR THE STATE HIGHWAY ASSESSMENT



Extreme weather events already disrupt and damage District 9 infrastructure. The following examples include weather-related issues and events that Caltrans District 9 has addressed in the past, and which may become more prevalent as climate changes.

- **Temperature –** As GHG emissions rise, so do atmospheric temperatures. Generally, average temperatures in California area expected to be higher in the future. Areas along the coast are expected to experience less temperature rise compared to inland locations. As temperature rises, precipitation patterns could change and become more volatile.[4] Scientists have already

[4] Suraj Polade, Alexander Gershunov, Dan Cayan, Michael Dettinger, & David Pierce, "Precipitation in a Warming World: Assessing Projected Hydro-Climate Changes in California and Other Mediterranean Climate Regions," *Scientific Reports* volume 7, Article number: 10783 (2017) https://www.nature.com/articles/s41598-017-11285-y

suggested that the period of drought in California from 2012 to 2014 was most likely intensified by climate change by anywhere from 15 to 20 percent[5]

District 9 includes a broad climatic diversity with mountainous areas to desert conditions in Death Valley. In July 2018, Death Valley experienced the highest average monthly temperature in recorded history—a month with an average day and night temperature of 108 degrees. During the July 24 to July 27, 2018 period, the high temperature reached 127 degrees—7 degrees shy of Death Valley's all-time high of 134 degrees (recorded in 1913). Average and extreme temperatures are expected to rise in mountainous areas as well. Over the long term, changing temperatures will likely contribute to different patterns of snow melt.

- **Precipitation** – Projecting changes in precipitation for California is complicated as California lies between the temperate and subtropic climatic zones. These zones are expected to become wetter and drier, respectively.[6] Most climate forecasts for the State suggest that it will be hotter and more drought-prone, with infrequent, heavy storm events. However, new research from the University of California, Riverside projects a wetter future.[7] Despite the uncertainty inherent in projections, scientists agree that California will have more volatile precipitation and more extreme events due to a warmer atmosphere heavy with water vapor.[8]

  District 9 regularly faces serious flooding from extreme storms. For example, the Walker River flood in 1997 saw peak discharges greater than the 100-year peak discharge at six Walker River Basin gaging stations. This flood resulted in an estimated $20 million to the surrounding communities. District 9 road closures are often necessary due to flooding, and in fewer instances, from mudslides. Sudden and extreme rain events can exceed the capacities of highway culverts, resulting in inundated roadways. For example, SR 168E was closed due to heavy flooding in August 2018 and US 395 was closed in January 2017. In 2015, SR 58 was closed when the largest mudslide in District 9 in the past 15 years suddenly covered the road, trapping many cars and trucks (see Figure 2). The depth of the mud varied from 2 feet to 12 feet along the 3,000- feet section of road affected by the closure. Flooding and mudslides are expected to increase in frequency in California, with these types of events likely becoming more commonplace in District 9.

  Given its mountainous nature, District 9 also faces challenges associated with snow fall. Heavy snow caused white out conditions on US 395 at least four times in January 2017 and another two times in February 2017. The district maintains highly trafficked roadways like US 395 when it snows, but other areas are left unmaintained until the snow melts. The district is concerned that as temperatures rise, the snowpack will melt faster, and roadway maintenance needs will increase during winter and spring. Future projections suggest that snowpack will continue to decrease, even if overall precipitation increases, but changes to the rate of

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[5] Park Williams, Richard Seager, John Abatzoglou, Benjamin Cook, Jason Smerdon, and Edward Cook, "Contribution of Anthropogenic Warming to California Drought During 2012-2014," *Geophys. Res. Lett*., 42, 6819–6828, doi:10.1002/2015GL064924, (August, 2015), http://onlinelibrary.wiley.com/doi/10.1002/2015GL064924/full

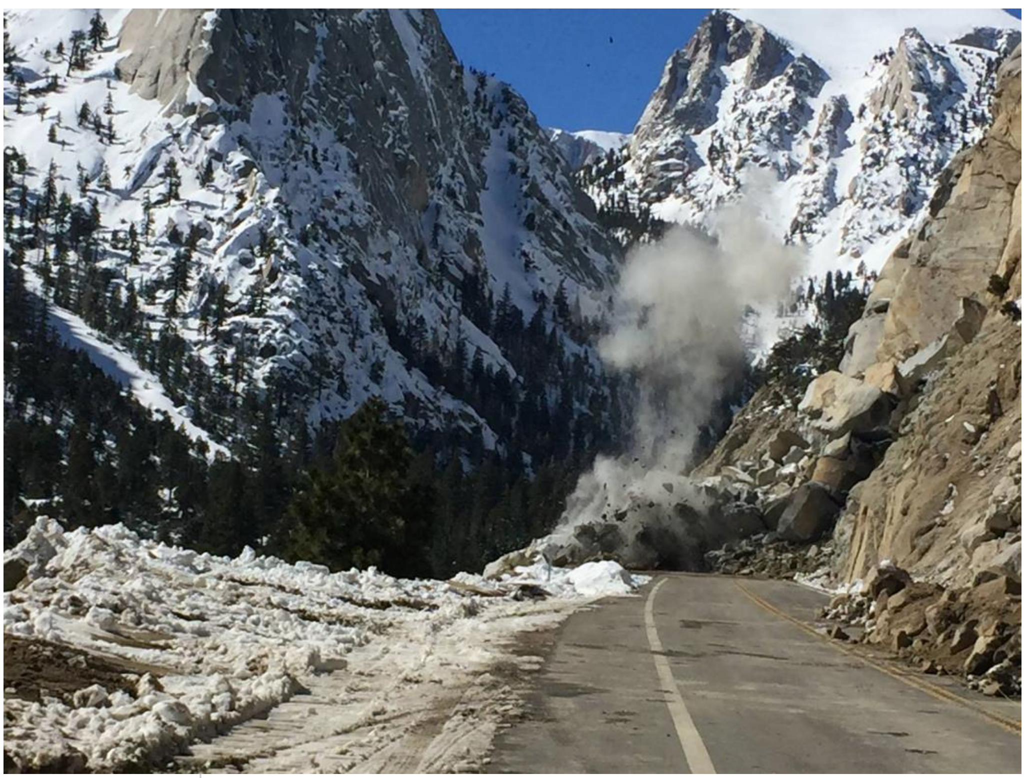
[6] Robert Allen and Rainer Luptowitz, "El Niño-Like Teleconnection Increases California Precipitation in Response to Warming," Nature Communications volume 8, Article number: 16055 (2017), https://www.nature.com/articles/ncomms16055

[7] Ibid.

[8] Suraj Polade, et al. op.cit.

FIGURE 2: SR 58 MUDSLIDE, 2015

FIGURE 3: WHITNEY PORTAL ROAD ROCKFALL, 2017



snowmelt are currently unclear.[9] Snowpack and snowmelt were not scoped for study in this District 9 vulnerability assessment.

- **Wildfire** – Wildfire risk is expected to increase as temperatures rise and precipitation patterns become more unpredictable. Large portions of the district's population live in high-risk fire areas. For example, in 2010, approximately 36% (6,720 residents) of Inyo County's total population (18,546) lived in fire hazard zones of moderate to very high severity. Recent research has found that the droughts of the last 15 years were "more intense than early- to mid-20th century droughts, with greater temperature and precipitation extremes," which could contribute to more severe fires in drought-affected areas.[10] There were many severe wildfires following the drought from 2011 to 2016 throughout California. From 1980 to 1989, 31 wildfires at least 490 acres in size consumed a total of 97,602 acres in the Southeast Sierra Region, much of which is in District 9.[11] To give a sense of how wildfires in the western Sierra Nevada region has changed over time, in 1910 there were an estimated 500,000 acres burned; the smallest amount since than occurred in 1940 with just less than 400,000 acres. In 2000, there were an approximate 1.75 million acres burned with an estimated 1.83 million acres in 2010.[12]

  One of the serious consequences of changing temperature and precipitation trends in District 9 has been the proliferation of invasive species. Research has shown that such species (e.g., cheat grass) have provided more fuel for wildfires such that over time such fires are occurring more frequently.[13]

FIGURE 4: CHRIS WILDFIRE IN BRIDGEPORT, CA CLOSES U.S. 395

[9] Bedsworth, Louise, Dan Cayan, Guido Franco, Leah Fisher, Sonya Ziaja, (California Governor's Office of Planning and Research, Scripps Institution of Oceanography, California Energy Commission, California Public Utilities Commission), "Statewide Summary Report," *California's Fourth Climate Change Assessment*, 2018, Publication number: SUMCCCA4-2018-013.

[10] Joseph Crockett, A.L. Westerling, Greater Temperature and Precipitation Extremes Intensify Western US Droughts, Wildfire Severity, and Sierra Nevada Tree Mortality." Master's Thesis in Environmental Systems. University of California, Merced. (2017). https://cloudfront.escholarship.org/dist/prd/content/qt3t39d8jq/qt3t39d8jq.pdf?t=osfbdf&v=lg

[11] California Department of Public Health. "Climate Change and Health Profile Report, Inyo County." (2017). https://www.cdph.ca.gov/Programs/OHE/CDPH%20Document%20Library/CHPRs/CHPR027Inyo_County2-23-17.pdf

[12] Sierra Conservancy. " Wildfire in the Sierra Nevada." Website. 2019. Last accessed September 12, 2019, https://sierranevada.ca.gov/sierra-nevada-wildfire-information/

[13] Amy Concillo." The Spread of Cheatgrass Into the Eastern Sierra." *Fremontia*, vol. 41, No. 2, May 2013. Last accessed September 13, 2019, 3http://bristleconecnps.org/conservation/issues/invasive_species/Cheatgrass_article-FremontiaV41.2.pdf

FIGURE 5: BOOT WILDFIRE CLOSED US 395 IN MONO COUNTY

- **Wind** - High wind is one of District 9's most pervasive challenges, and due to its geography of high peaks and low valleys, 60 to 75-mile per hour wind gusts are not uncommon. The district must frequently close its roads to avoid threats to vehicles and overturned big rigs. On November 16, 2016, high winds overturned three big rigs—one near Pearsonville on US 395 and two near the US 395 and SR 14 junction. Two more were overturned near Pearsonville on US 395 the next month. When these events occur, the district and local California Highway Patrol must close the most vulnerable stretches of highway (typically US 395 and SR 14) and redirect traffic. Given these challenges, District 9 is interested in how winds will change due to climate change. Future wind speeds are incorporated into downscaled GCMs applied in California. Luckily for District 9, wind speeds appear to show small decreases over time in the ten GCMs that most closely simulate California's climate.

FIGURE 6: WIND STORM ON SR 190, 2016

- **Combined Effects** – When extreme weather events follow one another, the impacts can become even more severe. A wildfire following a drought can be more severe and widespread than if it happened during a normal year. These types of combined effects can sometimes be predicted and prepared for. For example, if a wildfire burns a slope, Caltrans staff can take steps to stabilize that slope in preparation for the rainy season, thus mitigating the risk of landslides.

3. ASSESSMENT APPROACH

3.1. State-of-the-Practice in California

California has been on the forefront of climate change policy, planning, and research across the nation. State officials have been instrumental in developing and implementing policies that foster effective GHG mitigation strategies and the consideration of climate change in State decision-making. California agencies have also been pivotal in creating climate change datasets that can be used to consider regional impacts across the State. At a more local level, efforts to plan for and adapt to climate change are underway in communities across California. These practices are key to the development of climate change vulnerability assessments in California. The sections below provide some background on the current state-of-the-practice in adaptation planning and how specific analysis methods were considered/applied in the District 9 vulnerability assessment.

3.1.1. Policies

Various policies implemented at the State level have directly addressed not only GHG mitigation, but climate adaptation planning. These policies require State agencies to consider the effects of climate in their investment and design decisions, among other considerations. State adaptation policies that are relevant to Caltrans include:

- **Assembly Bill 32** (2006) or the "California Global Warming Solution Act" was the first California law to require a reduction in emitted GHGs. The law was the first of its kind in the country and set the stage for future policy.[14]
- **Executive Order S-13-08** (2008) directs State agencies to plan for sea level rise (SLR) and climate impacts through the coordination of the State Climate Adaptation Strategy.[15]
- **Executive Order B-30-15** (2015) requires the consideration of climate change in all State investment decisions through full life cycle cost accounting, the prioritization of adaptation actions that also mitigate greenhouse gases, the consideration of the State's most vulnerable populations, the prioritization of natural infrastructure solutions, and the use of flexible approaches where possible.[16]
- **Assembly Bill 1482** (2015) requires all State agencies and departments to prepare for climate change impacts through (among others) continued collection of climate data, considerations of climate in State investments, and the promotion of reliable transportation strategies.[17]

[14] California Air Resources Board. "Assembly Bill 32 Overview." Last modified August 5, 2014. https://www.arb.ca.gov/cc/ab32/ab32.htm

[15] Adaptation Clearinghouse. "California Executive Order S-13-08 Requiring State Adaptation Strategy." Last accessed April 30, 2019. https://www.adaptationclearinghouse.org/resources/california-executive-order-s-13-08-requiring-state-adaptation-strategy.html

[16] Office of Governor Edmund Brown. "Governor Brown Establishes Most Ambitious Greenhouse Gas Reduction Target in North America." April 29, 2015. https://www.gov.ca.gov/news.php?id=18938

[17] California Legislative Information. "Assembly Bill No. 1482," October 8, 2015. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201520160AB1482

- **Senate Bill 246** (2015) establishes the Integrated Climate Adaptation and Resiliency Program to coordinate with regional and local efforts with State adaptation strategies.[18]
- **Assembly Bill 2800** (2016) requires that State agencies account for climate impacts during planning, design, building, operations, maintenance, and investments in infrastructure. It also required the formation of a Climate-Safe Infrastructure Working Group represented by engineers with relevant experience from multiple State agencies, including the Department of Transportation.[19]

These policies represent the type of factors State agencies consider when addressing climate change. Conducting an assessment such as this one for District 9 is a key step towards preserving Caltrans infrastructure against future extreme weather conditions and addressing the requirements of the relevant State policies above.

One of the most important climate adaptation policies out of those listed above is Executive Order B-30-15. Guidance specific to the Executive Order, *Planning and Investing for a Resilient California,* was released in 2017. This guidance helps State agencies develop methodologies in completing vulnerability assessments specific to their focus areas and in making adaptive planning decisions. *Planning and Investing for a Resilient California* created a framework to be followed by other State agencies, which is important in communicating the effects of climate change consistently across agencies.

3.1.2. Research

California has been actively engaged in research and guidance relating to climate change. For example, Executive Order S-03-05, directs that State agencies develop and regularly update guidance on climate change. The research efforts relating to this directive are encompassed in California's *Climate Change Assessments*, the latest (fourth) edition having just been released (*California's Fourth Climate Change Assessment*). To understand the research and datasets from the California *Fourth Climate Change Assessment,* which were utilized in this District 9 vulnerability assessment, some background is needed on Global Climate Models and emissions scenarios.

Global Climate Models (GCMs)

GCMs have been developed worldwide by many academic and research institutions to represent the physical processes that cause climate change, and to project future changes in GHG emission levels.[20] These models reflect the different estimates of GHG emissions or atmospheric concentrations of these gases, which are summarized by the Intergovernmental Panel on Climate Change (IPCC).

The IPCC is the leading international body recognized for its work in quantifying the potential effects of climate change. Its membership is made up of thousands of scientists from 195 countries. The IPCC periodically releases Assessment Reports (currently in its 5th iteration), which summarize the latest research on a broad range of topics relating to climate change. The IPCC updates research on GHG emissions, identifies scenarios that reflect research on emissions generation, and estimates how those

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[18] California Legislative Information. "Senate Bill No. 246," October 8, 2015. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB246

[19] "California Legislative Information. "Assembly Bill No. 2800." September 24, 2016. http://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160AB2800

[20] Intergovernmental Panel on Climate Change. (IPCC). "What is a GCM?" Last accessed April 30, 2019. http://www.ipcc-data.org/guidelines/pages/gcm_guide.html

emissions may change given international economic and fuel technology policies. The IPCC summarizes scenarios of atmospheric concentrations of GHG emissions to the end of the century.

Many different climate models have been developed worldwide. However, the State of California has identified a set of GCMs that are most relevant for use in California as outlined in the California's Fourth Climate Change Assessment section below.

Emissions Scenarios and Representative Concentration Pathways

Two commonly-cited sets of emissions data have been developed by the IPCC:

1. Special Report Emissions Scenarios (SRES)
2. Representative Concentration Pathways (RCPs)

RCPs represent the most recent generation of GHG scenarios produced by the IPCC and were used in this study. The scenarios use three main metrics to estimate future emissions: radiative forcing, emission rates, and emission concentrations.[21] Four RCPs were developed by the IPCC to reflect assumptions on emissions growth and the resulting concentrations of GHGs in the atmosphere. The RCPs are applied in GCMs to identify projected future conditions and enable a comparison of one scenario against another. Generally, the RCPs are based on assumptions for GHG emissions growth and an identified point at which they would be expected to begin declining (assuming varying policies on reducing emissions or socioeconomic conditions). The RCPs developed for this purpose include:

- RCP 2.6 assumes that global annual GHG emissions will peak in the next few years and then begin to decline substantially, reaching negative emissions before the end of century.
- RCP 4.5 assumes that global annual GHG emissions will peak around 2040 and then begin to decline and stabilize by the end of century.
- RCP 6.0 assumes that annual GHG emissions will peak near the year 2080 and then start to decline before the end of century.
- RCP 8.5 assumes that high GHG emissions will continue through the end of the century, and extended outlooks for RCP 8.5 assume constant emissions after 2100 as well.[22]

California's Fourth Climate Change Assessment

California's Fourth Climate Change Assessment was an inter-agency research and "model downscaling" effort for multiple climate stressors. The *Assessment* was led by the California Energy Commission (CEC) with other contributors including agencies such as the Department of Water Resources (DWR) and the California Natural Resources Agency (NRA), as well as academic institutions such as the Scripps Institution of Oceanography (Scripps) and the University of California, Merced.[23]

Model downscaling is a statistical technique that refines the results of GCMs to a regional scale. The model downscaling used in *California's Fourth Climate Change Assessment* is a technique called

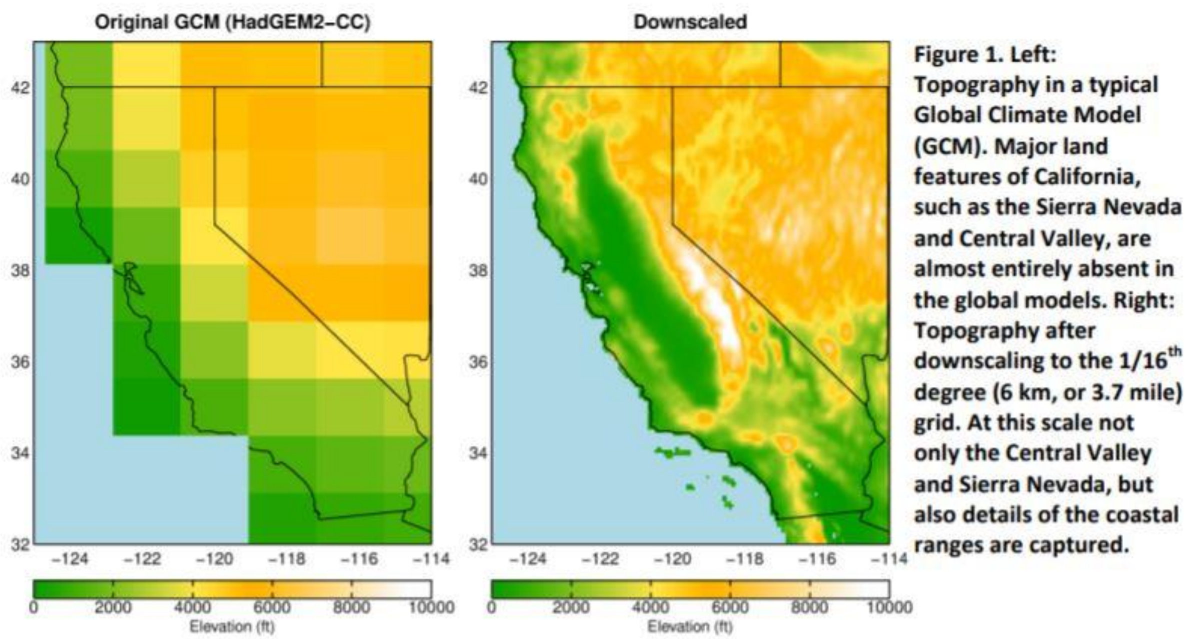
[21] "Representative Concentration Pathways." IPCC, Last accessed April 30, 2019. http://sedac.ipcc-data.org/ddc/ar5_scenario_process/RCPs.html

[22] M. Meinshausen, et al, "The RCP Greenhouse Gas Concentrations and Their Extensions from 1765 to 2300 (open access)," *Climatic Change*, 109 (1-2): 213–241 (2011).

[23] "California's Fourth Climate Change Assessment." State of California website (CA.gov), Last accessed June 5th, 2019, http://www.climateassessment.ca.gov/

Localized Constructed Analogs (LOCA), which "uses past history to add improved fine scale detail to GCMs."[24] This effort was undertaken by Scripps and provided a finer grid system than is found in other techniques. This allows the assessment of changes in a more localized way than was previously available, given that past models had summarized changes with a lower resolution.[25] LOCA data are provided in 1/16th degree, or 3.7 mi (6 km) grid cells, as compared to GCM grid cells, which can span hundreds of miles across one such cell.[26] Figure 7 shows the difference in resolution between GCM data and downscaled GCM data using the LOCA technique. The leftmost image (from the GCM) provides an example of "grid cells" that are easily visible; in the rightmost image (downscaled) these grid cells are so small they are impossible to distinguish individually.

FIGURE 7: LOCA DOWNSCALING RESOLUTION



SOURCE: DAVID PIERCE ET AL.

Out of the 32 LOCA-downscaled GCMs available for California, 10 models were chosen by State agencies as being most relevant for agency assessments and planning decisions.[27] More information on the selection process and the stakeholders involved can be found in the 2015 "Perspectives and Guidance for Climate Change Analysis" document developed by DWR and its Technical Advisory Group.[28] The 10 representative GCMs for California are:

[24] "LOCA Downscaled Climate Projections." Cal-Adapt. Last accessed April 30, 2019 http://cal-adapt.org/

[25] David Pierce, Dan Cayan, Bridget Thrasher. "Statistical Downscaling Using Localized Constructed Analogs." *Journal of Hydrometeorology.* (December 2014). http://journals.ametsoc.org/doi/abs/10.1175/JHM-D-14-0082.1

[26] David Pierce et al., "Creating Climate Change Projections to Support the California 4th Climate Assessment." Division of Climate, Atmospheric Sciences, and Physical Oceanography Scripps Institution of Oceanography. June 13, 2016. http://loca.ucsd.edu/~pierce/IEPR_Clim_proj_using_LOCA_and_VIC_2016-06-13b.pdf

[27] "LOCA Downscaled Climate Projections." Cal-Adapt op. cit.

[28] California Department of Water Resources. Climate Change Technical Advisory Group. "Perspectives and Guidance for Climate Change Analysis." August 2015. https://water.ca.gov/LegacyFiles/climatechange/docs/2015/1_14_16_PerspectivesAndGuidanceForClimateChangeAnalysis_MasterFile_FINAL_08_14_2015_LRW.pdf

- ACCESS 1-0
- CanESM2
- CCSM4
- CESM1-BGC
- CMCC-CMS
- CNRM-CM5
- GFDL-CM3
- HadGEM2-CC
- HadGEM2-ES
- MIROC5

Data from these models are available on Cal-Adapt 2.0, California's Climate Change Research Center.[29] The Cal-Adapt 2.0 data are some of the best available data in California on climate change and, for this reason, selections of data from Cal-Adapt and the GCMs above were utilized in this study.

3.2. Other District 9 Efforts to Address Climate Change

In addition to the work completed and in progress by Caltrans, federal, other state, regional efforts are underway or have been undertaken by other groups in District 9 relating to climate change planning and preparedness. Many of these focus on hazard mitigation (especially for wildfires).

Some examples of these efforts include:

- **Death Valley National Park Action Plan[30]** – Death Valley, which is managed by the National Park Service, participates in the Climate Friendly Parks Program. This program promotes "climate friendly behavior" within park operations and educates park visitors on climate change and about ways individuals can help mitigate impacts. Given that the impacts of climate change pose risks to the balance of a park's ecosystems and the well-being of the park's species, the Death Valley National Park has adopted the following strategies:
    - Reduce greenhouse gas emissions from activities within and by the Park: This goal is comprised of several sub-goals, which include improving energy use management, transportation management, and waste management. Some strategies Park officials have taken or plan to take include encouraging visitor behavioral changes like reducing idling in vehicles, encouraging carpooling, and retrofitting Park facilities to improve energy efficiency.
    - Educate and provide information on climate change and likely impacts to Park staff, Park visitors, and the local community: Park officials intend to incorporate climate change educational elements into staff training and visitor programs and build relationships with local community groups to foster educational opportunities outside of the Park.

[29] For more information, visit http://cal-adapt.org/

[30] National Park Service. "Death Valley National Park Climate Action Plan. Last accessed May 10, 2019. https://www.nps.gov/subjects/climatechange/upload/DEVA-CFP-Action-Plan-508compliant.pdf

  - Evaluate progress and identify areas for improvement: Park officials intend to review the efficacy of strategies to achieve the first two goals and the progress the Park is making toward reducing greenhouse gas emissions across sectors. Additionally, the Park will continue to review and update the plan as necessary.

- **Climate Change and Health Profile Reports for Mono and Inyo Counties –** Mono and Inyo Counties, in cooperation with the California Department of Public Health (CDPH), produced reports about climate change and future health impacts to county residents. Both reports include regional climate projections for temperature, heat waves, fire, precipitation, and snowpack, and describe how these changes in climate could impact public health (both counties are in the Southeast Sierra climate impact area). Climatic changes can cause a range of impacts to water and air quality, weather, and the local environment that can subsequently lead to disease, injuries, malnutrition, and mental health effects in humans. These impacts may be disproportionately felt by vulnerable populations such as the very young or elderly, disabled, low income, or those with other health conditions. To identify the size of these population groups who are at the highest risk, both county reports provide local population demographic profiles. Some of these statistics are summarized below for Mono County:

  - In 2010, approximately 25% (3,501 residents) of the county's total population (14,202) lived in fire hazard zones of moderate to very high severity.
  - In 2012, nearly 38% of adults (pooled for the Eastern Counties) reported one or more chronic health conditions including heart disease, diabetes, asthma, severe mental stress, or high blood pressure.
  - Among climate-vulnerable groups in 2010 were 893 children under the age of 5 years and 1,377 adults aged 65 years and older. In 2010, there were approximately 192 people living in nursing homes, dormitories, and other group quarters where authorities would need to provide transportation in the event of emergencies.
  - In 2010, Mono County had approximately 580 outdoor workers whose occupation increased their risk of heat illness. In 2010, roughly five percent of households did not own a vehicle that could be used for evacuation (statewide average was 8%).

  Each report suggested ways that the counties can act to protect their population against the projected climate-related health impacts. Some of these suggestions can be enacted in the near-term, like starting a public outreach campaign, improving heat warning systems, and further research on the nexus between climate change and health. Other suggestions are long-term goals, such as developing resiliency funding opportunities, reducing urban heat islands, and promoting access to health care. [31]

- **US Forest Service, Pacific Southwest Research Station** – The US Forest Service has conducted numerous studies of wild fires in the Sierra Nevada mountains. According to one of the more recent studies, temperatures are expected to increase "between 3-6°C in the Sierra Nevada over the next 50 to 80 years. Some computer models predict an increase in net precipitation while

[31] California Department of Public Health. 2017. Op cit.

others predict a decrease."[32] As noted in the study, by late 21st Century, the Sierra Nevada will experience:

- Decreasing annual precipitation in the form of snow, and loss of snowpack.
- Increasing temperatures that drive increasing dry season soil moisture stress.
- A higher fraction of annual precipitation in fewer storm events (i.e. more intense storms and flooding).
- An increased frequency of drought.

These trends were expected to have impacts on fire frequency and magnitudes and insect infestations and disease.

- **University of California–Davis (UC Davis)** – A UC Davis study examined historic and future climatic conditions in the Inyo National Forest.[33] The study noted that:
  - By 2100, the volume of flow during the highest flow days could more than double in many Sierra Nevada rivers. The Inyo climate change trend assessment predicted increases in peak flow were most pronounced in higher elevation river basins, due to the greater reliance on snowmelt.
  - Increases in extreme hydrologic events across the western US are predicted to be especially pronounced in the mountains of the California coast range and the Sierra Nevada. Such events could facilitate unprecedented debris flow and landslide events.
  - Results of studies on fire intensity predict that large proportions of the Sierra Nevada landscape may see mean fire intensities increase over current conditions by the end of the century, with the actual change in intensity depending on future precipitation patterns.

University of California Los Angeles (UCLA) Center for Climate Science – UCLA recently completed a study of the impact of climate change on the Sierra Nevada mountain region. The study concluded that:

- By 2081–2100 under the "Business as Usual" scenario, temperatures across the Sierra could increase by as much as 10 degrees Fahrenheit, depending on the month and elevation, compared with 1981–2000. The most severe warming occurs at elevations of 5,000–8,000 feet.
- Warming sets the stage for snow loss by causing more precipitation to fall as rain instead of snow, and snow to melt faster.

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[32] US Forest Service. "Fire and climate change." Pacific Southwest Research Station. Website. Last accessed September 13, 2019, https://www.fs.fed.us/psw/topics/fire_science/ecosystems/climatechange.shtml

[33] Chris Mallek, Hugh Safford, and Sarah Sawyer. "A Summary of Current Trends and Probable Future Trends in Climate and Climate-driven Processes in the Inyo National Forest and Adjacent Lands." Inyo National Forest Climate Change Trend Assessment. (2013) last accessed May 17, 2019, https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprd3820115.pdf

- On the average end-of-century April 1, the Sierra's total snowpack will be just 36% as large as it was in 1981–2000.
- Future climate change will cause even greater reductions in snowpack in extreme years. Under end-of-century Business as Usual warming, a period like the 2011–2015 drought loses 85% of its snow, and a wet year like 2016–2017 loses two-thirds of its snow."[34]

3.3. General Methodology

The adaptation planning methodology used in this study varied by stressor. Given that each stressor is analyzed with a different set of models, emissions scenarios, and assumptions, this leads to stressor-specific data and information on which to develop an understanding of potential future climate conditions. The methods employed are further defined in each stressor section; however, there are some general practices that apply across all analysis approaches.

3.3.1. Time Periods

It is helpful to present climate projections in a way that allows for consistent comparison between analysis periods for different stressors. For this study, those analysis periods have been defined as the beginning, middle, and end of century, represented by the out-years 2025, 2055, and 2085, respectively. These years are chosen because some statistically-derived climate metrics used in this report (e.g., the 100-year precipitation event) are typically calculated over 30-year time periods centered on the year of interest. Because currently available climate projections are only available through the end of the century, the most distant 30-year window runs from 2070 to 2099. The year 2085 is the center point of this time range and the last year in which statistically-derived projections can defensibly be made. The 2025 and 2055 out-years follow the same logic but applied to each of the prior 30-year periods (2010 to 2039 and 2040 to 2069, respectively).

3.3.2. Geographic Information Systems (GIS) and Geospatial Data

Developing an understanding of Caltrans assets exposed to projected changes in temperature, precipitation, and wildfire required complex geospatial analyses. The geospatial analyses were performed using ESRI geographic information systems (GIS) software. The general approach for each stressor's geospatial analysis went as follows:

Obtain/conduct stressor mapping: The first step in each GIS analysis was to obtain or create maps showing the presence and/or value of a given hazard at various future time periods, under different climate scenarios. For example, extreme temperature maps were created for temperature metrics important to pavement binder grade specifications; maps of extreme (100-year) precipitation depths were developed to show changes in rainfall; and burn counts were compiled to produce maps indicating future wildfire frequency.

Determine critical stressor thresholds: Temperature, precipitation and wildfire stressors vary in intensity across the landscape. In many locations, the future change in these stressors is not projected to be high enough to warrant special concern, whereas other areas may see a large increase in hazard risk. To highlight the areas most affected by climate change, the geospatial analyses for these stressors defined the critical thresholds for which the value of (or the change in value of) a stressor would be a concern to Caltrans. For example, the wildfire geospatial analysis involved several steps to indicate

[34] UCLA. :Climate Change in the Sierra Nevada California's Water Future." (2018). https://www.ioes.ucla.edu/wp-content/uploads/UCLA-CCS-Climate-Change-Sierra-Nevada.pdf

which areas are considered to have a moderate, high, and very high fire exposure based on the projected frequency of wildfire.

Overlay the stressor layers with Caltrans SHS to determine exposure: Once high stressor areas had been mapped, the next general step in the geospatial analyses was to overlay the Caltrans SHS centerlines with the stressor data to identify the segments of roadway most exposed to each stressor.

Summarize the miles of roadway affected: The final step in the geospatial analyses involved running the segments of roadway exposed to a stressor through Caltrans' linear referencing system. This step, undertaken by Caltrans, provided an output GIS file indicating the centerline miles of roadway affected by a given stressor. Using GIS, this data can then be summarized in many ways (e.g., by district, county, municipality, route number, or some combination thereof) to provide useful statistics to Caltrans.

Upon completion of the geospatial analyses, GIS data for each step was saved to a database that was supplied to Caltrans after the study was completed. Limited metadata on each dataset was also provided in the form of an Excel table that described each dataset and its characteristics. This GIS data will be useful to Caltrans for future climate adaptation planning activities.

4. TEMPERATURE

Increased concentrations of GHGs in the atmosphere are generally believed by climate scientists to be a major cause of predicted temperature rise. Temperatures in the western US are projected to continue rising and heat waves may become more frequent.[35] The potential effects of extreme temperatures on District 9 assets will vary by asset type and will depend on the specifications followed in the original design of the facility or asset. For example, the following have been identified in other studies in the US as potential impacts of increasing temperatures.

4.1. Design

- Temperature changes might affect in the long-term the most appropriate pavement material.
- Ground conditions and more/less water saturation could alter the design factors for foundations and retaining walls.
- Temperature might affect expansion/contraction allowances for bridge joints.

4.2. Operations and Maintenance

- Extended periods of high temperatures will affect safety conditions for employees who work long hours outdoors, such as those working on maintenance activities.
- Right-of-way landscaping and vegetation must survive higher temperatures and drought.
- Extreme temperatures could cause pavement discontinuities and deformation, which could lead to more frequent maintenance.
- Higher temperatures combined with drought conditions can lead to more wildfires, requiring more evacuations (and thus emergency traffic management plans).

Resources available for this study did not allow for a detailed assessment of all the impacts that changing temperatures might have on Caltrans activities. Instead, it was decided to take a close look at one of the ways in which temperature will affect Caltrans--the selection of a pavement binder grade. Binder is essentially the "glue" that ties together the aggregate materials in asphalt. Selecting the appropriate and recommended pavement binder relies, in part, on the following two temperature variables:

- **Low temperature** – The mean of the absolute minimum air temperatures expected over a pavement's design life.
- **High temperature** – The mean of the average maximum temperatures over seven consecutive days.

[35] "Extreme Weather." U.S. National Climate Assessment. Last accessed April 29, 2019. http://nca2014.globalchange.gov/report/our-changing-climate/extreme-weather
US Global Change Research Program. "US National Climate Assessment." 2014. http://nca2014.globalchange.gov/report/our-changing-climate/extreme-weather

These climate metrics are critical in determining the extreme temperatures a roadway may experience over time. This is important because a binder must be selected that maintains pavement integrity under both extreme cold conditions (which leads to contraction) and high heat (which leads to expansion).

The expected low and high temperatures for pavement binder specification were examined in this study for the three future 30-year periods mentioned earlier centered on the years 2025, 2055, and 2085. Understanding the metrics for these periods will enable Caltrans to gain insight on how pavement design may need to shift over time. Per the Caltrans Highway Design Manual (HDM), the pavement design life for new construction and reconstruction projects shall be no less than 40 years. For roadside facilities, such as parking lots and rest areas, 20-year pavement design life may be used. The design life of asphalt pavements is close to the 30-year analysis periods used in this report. Because asphalt overlays of different specifications are often used to prolong roadway life, they can be used as short-term actions until it is clear how climate conditions are changing.

The LOCA climate data developed by Scripps and used for the analysis of temperature[36] had a spatial resolution of 1/16 of a degree or approximately three-and-a-half to four miles.[37] This dataset was queried to determine the annual lowest temperature and the average seven-day consecutive high temperature. Temperature values were identified for each 30-year period. The values were derived separately for each of the 10 California appropriate GCMs, for both RCP scenarios, and for the three time periods noted.

Figure 8 to Figure 13 show the results for the model that represents the median change across the State among all California-approved climate models for RCP 8.5 (data for RCP 4.5 were analyzed, but for brevity are not shown here). This is also referred to as the "50th percentile of downscaled climate model outputs under the RCP 8.5 scenario," as calculated across the State using the area weighted mean.

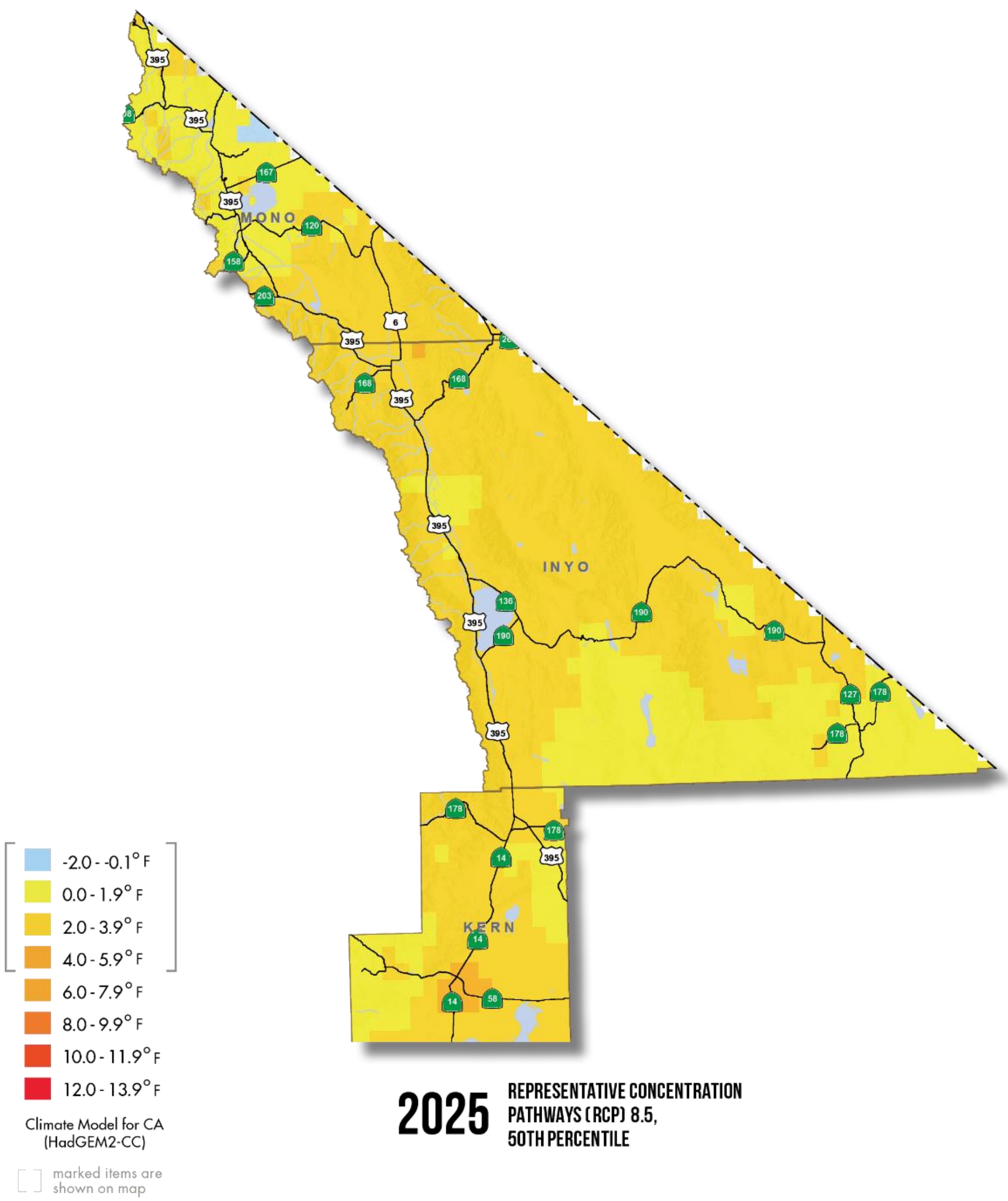
The figures highlight the temperature change expected for both the maximum and minimum metrics. Both temperature metrics increase over time with the maximum temperature changes generally being greater than the minimum changes. Some areas may experience change in the maximum temperature metric upwards of between 6°F and 10°F by the end of the century, depending on the area of the district.

The projected change in temperature could be added to Caltrans' current source of historical temperature data to determine a final pavement design value for the future. Summarized data can be used by Caltrans to identify how pavement design practices may need to shift over time given the expected changes in temperature.

[36] A more detailed description of the LOCA data set and downscaling techniques can be found at the start of this report.
[37] Cal-Adapt op cit.

FIGURE 8: CHANGE IN THE ABSOLUTE MINIMUM AIR TEMPERATURE, 2025

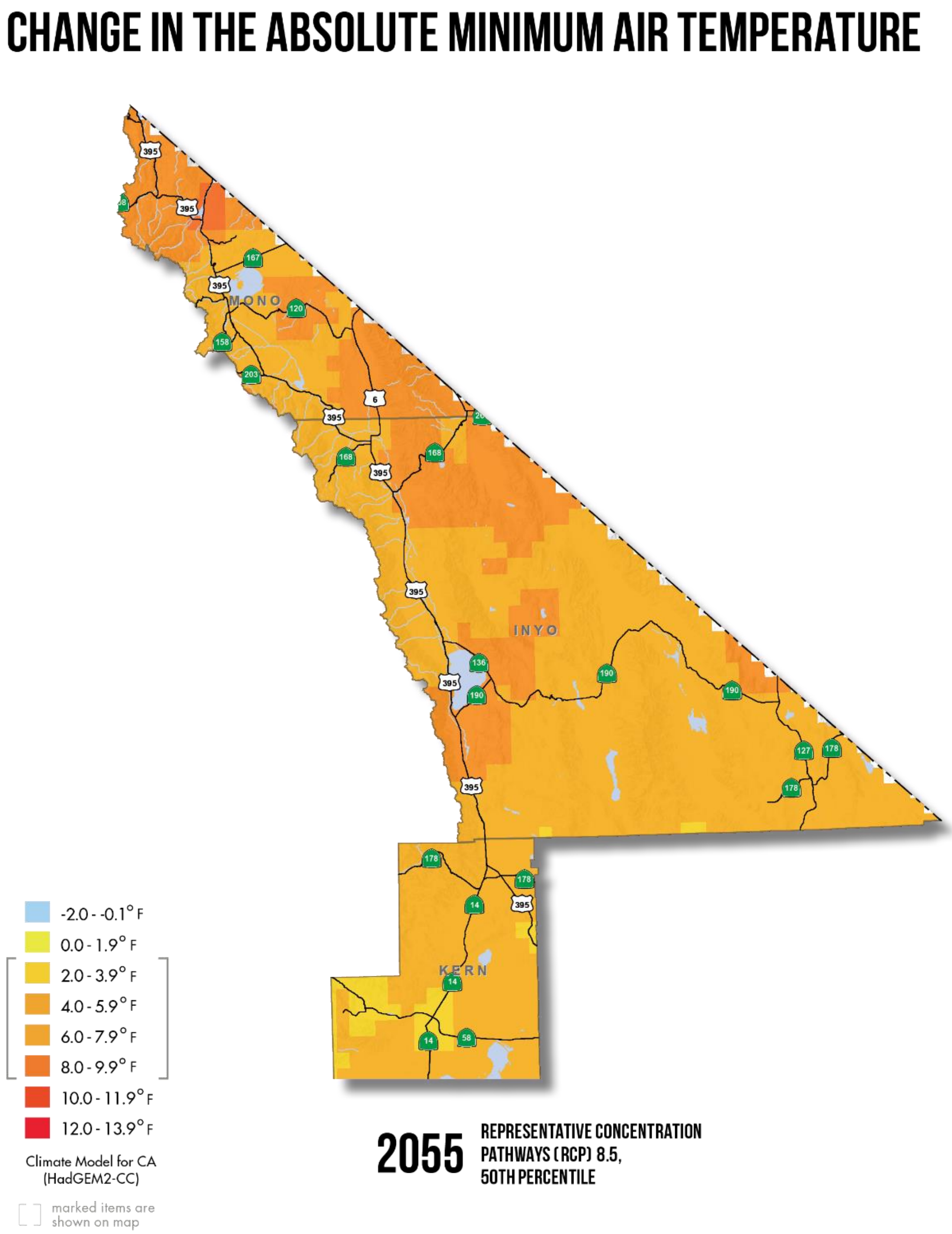
CHANGE IN THE ABSOLUTE MINIMUM AIR TEMPERATURE



Future Change in the Absolute Minimum Air Temperature within District 9, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 9. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

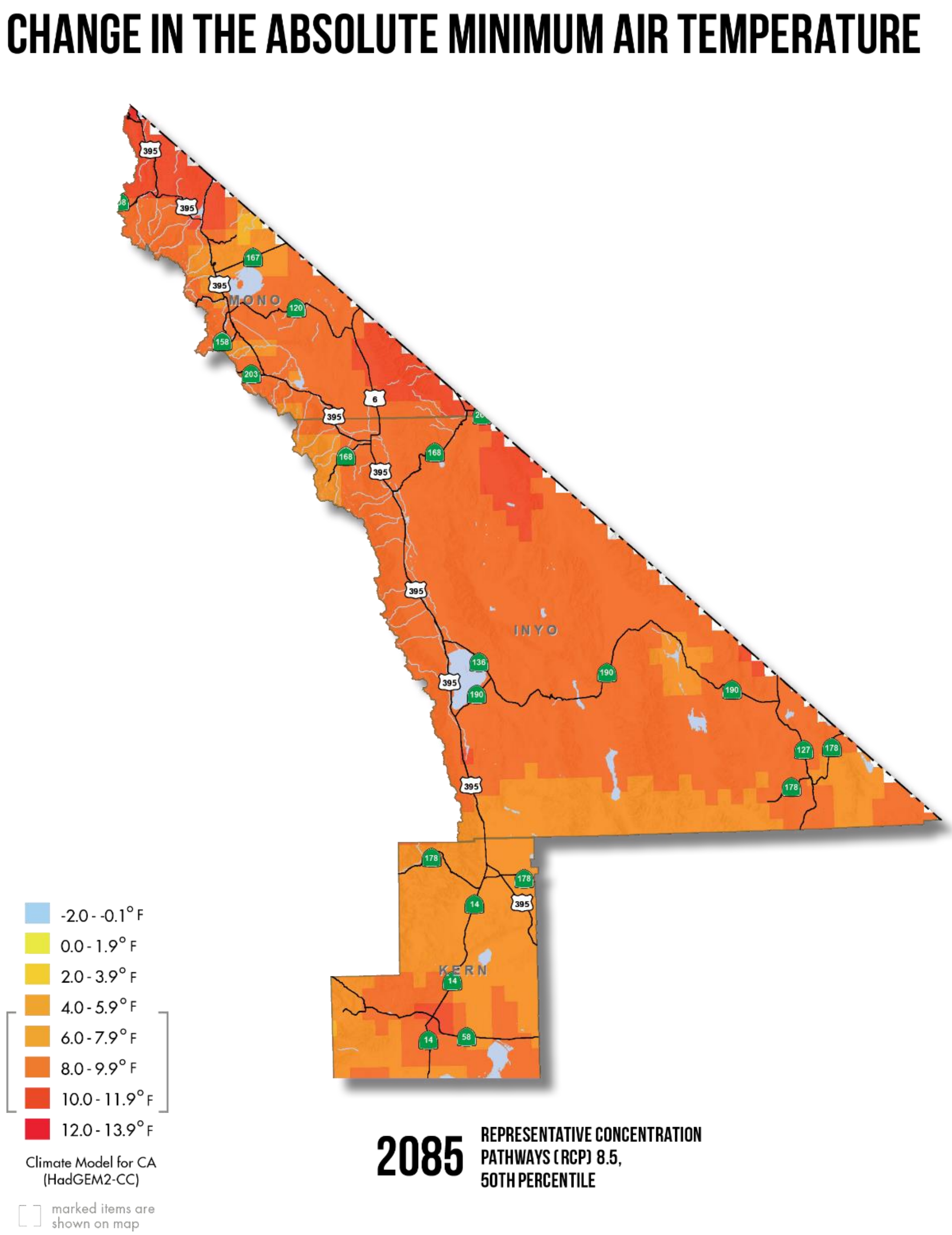
FIGURE 9: CHANGE IN THE ABSOLUTE MINIMUM AIR TEMPERATURE 2055



Future Change in the Absolute Minimum Air Temperature within District 9, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 9. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 10: CHANGE IN THE ABSOLUTE MINIMUM AIR TEMPERATURE 2085

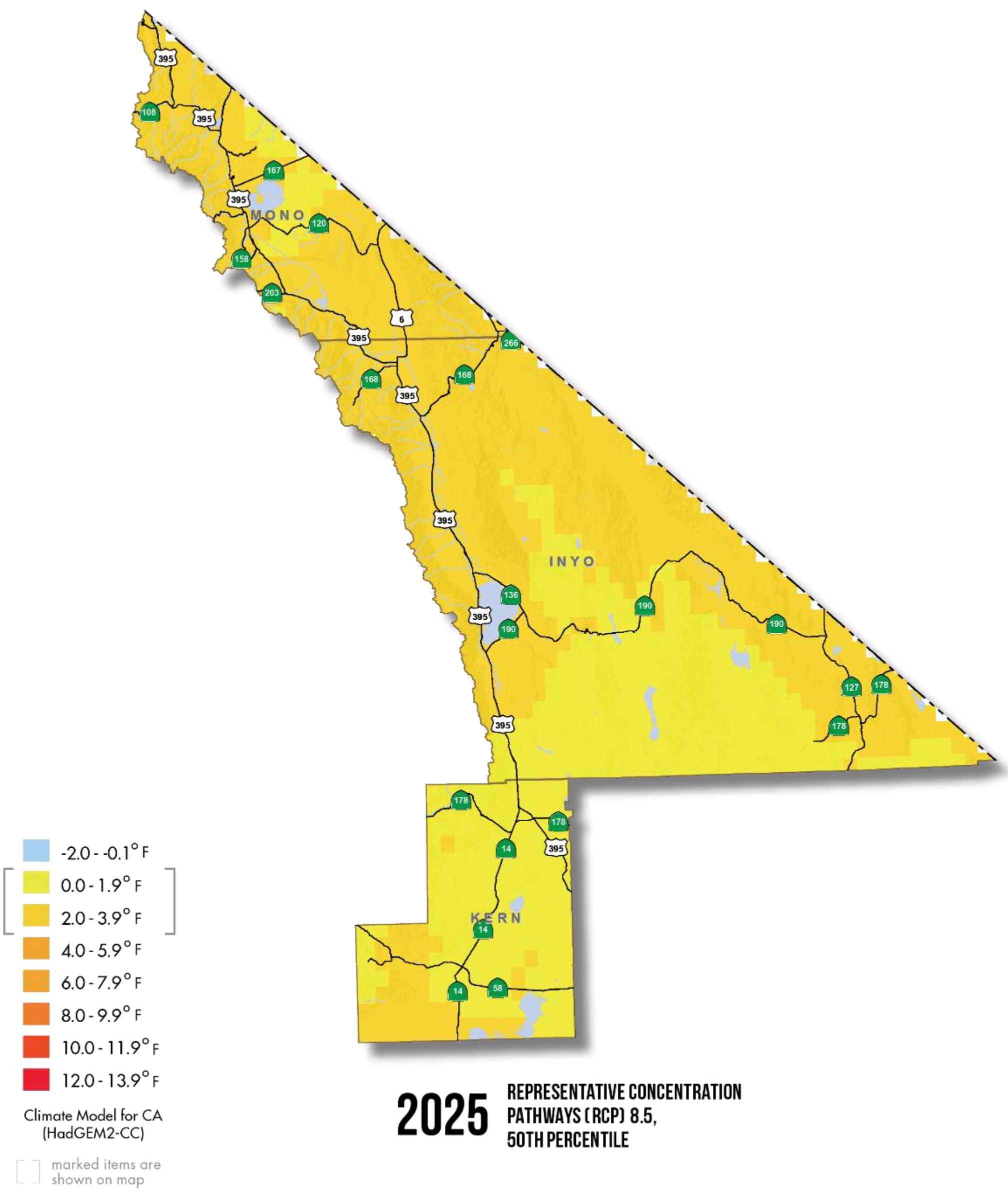


Future Change in the Absolute Minimum Air Temperature within District 9, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 9. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 11: CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS 2025

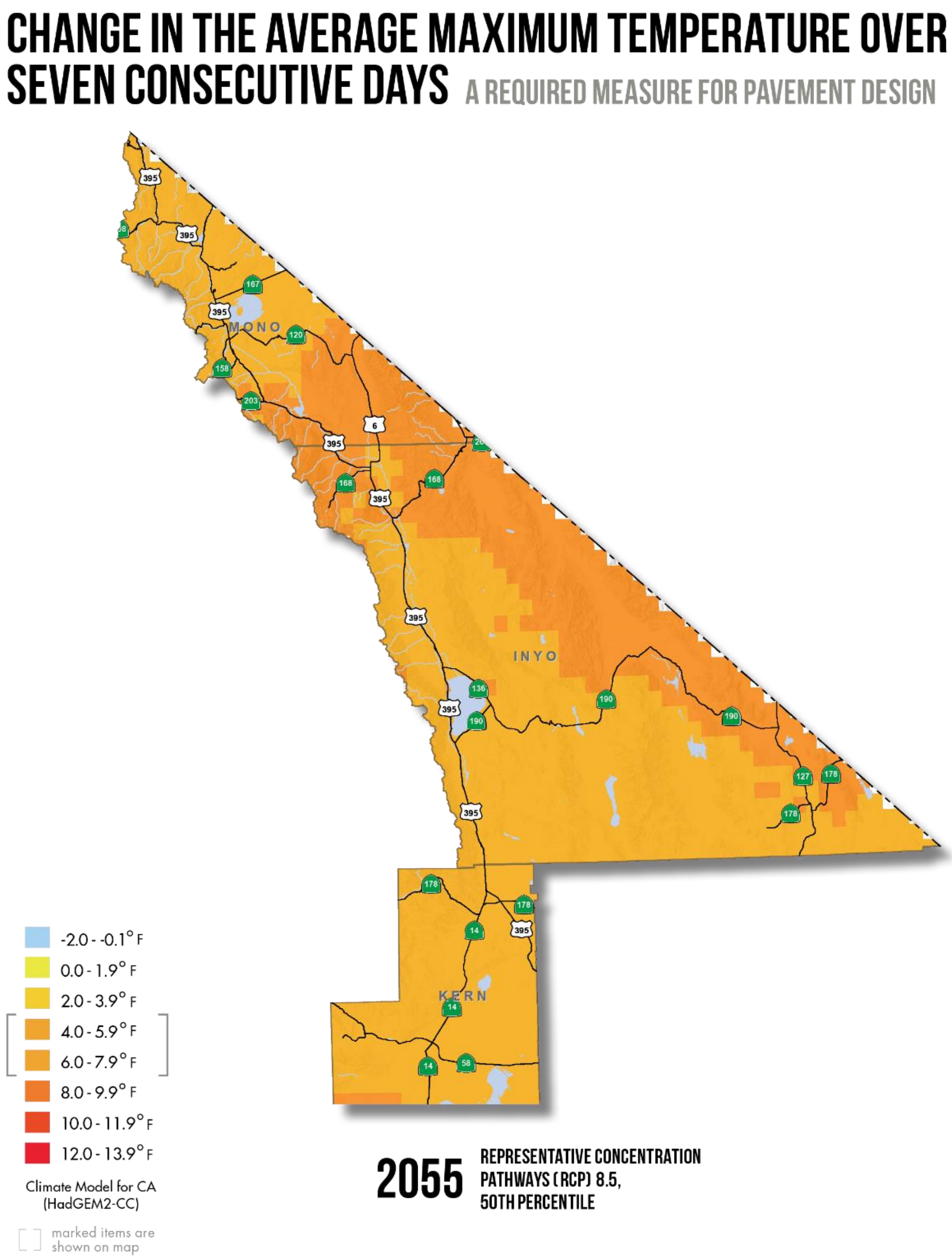
CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS
A REQUIRED MEASURE FOR PAVEMENT DESIGN



Future Change in the Average Maximum Temperature over Seven Consecutive Days within District 9, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 9. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 12: CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS 2055

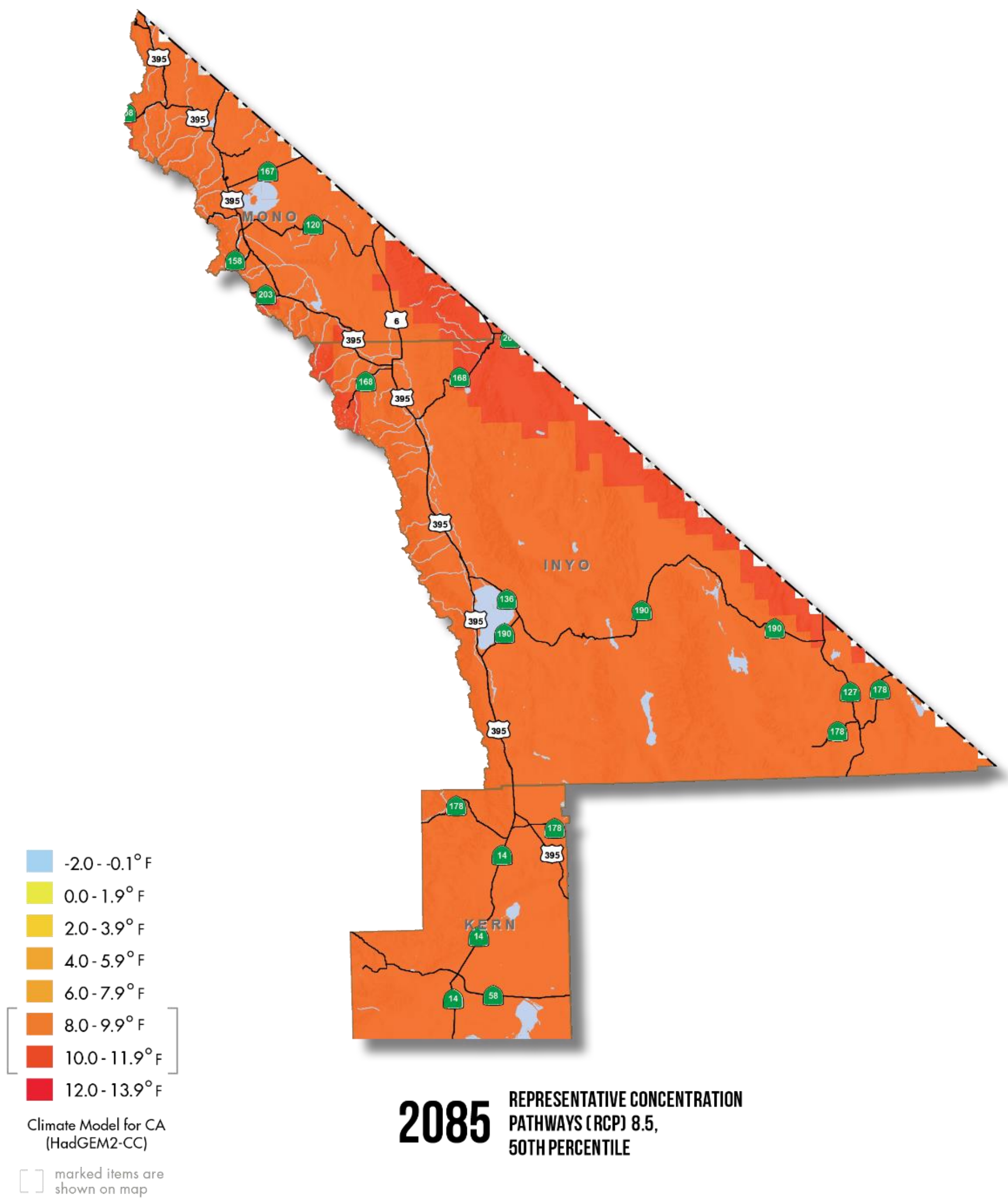


Future Change in the Average Maximum Temperature over Seven Consecutive Days within District 9, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 9. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 13: CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS 2085

CHANGE IN THE AVERAGE MAXIMUM TEMPERATURE OVER SEVEN CONSECUTIVE DAYS A REQUIRED MEASURE FOR PAVEMENT DESIGN



Future Change in the Average Maximum Temperature over Seven Consecutive Days within District 9, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 9. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown was generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

5. PRECIPITATION

The US Southwest is expected to experience less precipitation overall[38], but with the potential for heavier individual events, and with more precipitation falling as rain. This section of the report focuses on how these heavy precipitation events may change and become more frequent over time.

Analysis of future precipitation is, in many ways, one of the most challenging tasks in assessing long-term climate risk. Modeled future precipitation values can vary widely. Thus, analysis of trends is considered across multiple models to identify predicted values and help drive effective decisions. Future precipitation was analyzed through a broad range of potential effects predicted by a set, or ensemble, of models. There are several methodological challenges with using downscaled global climate model projections to derive estimations of future extreme precipitation events, addressable through vetted and available methods. Results should be compared across multiple models to conduct a robust assessment of how changing precipitation conditions may impact the highway system, and to make informed decisions.

Transportation assets in California are affected by precipitation in a variety of ways—from inundation/flooding, to landslides, washouts, or structural damage from heavy rain events. Current transportation design uses return period storm events as a variable to include in asset design criteria (e.g. for bridges or culverts). A return period storm event is the historical intensity of storms based on how often such level of storms have occurred in the past. A 100-year flood design standard is often applied in the design of transportation facilities and is cited as a design consideration in Section 821.3, Selection of Design Flood, in the *Caltrans Highway Design Manual*.[39]

Assessing the true risks of a 100-year flood requires complex and expensive flood modeling. This level of analysis is done by the Federal Emergency Management Agency (FEMA) to understand which US properties lie within floodplains. This type of assessment has rarely been completed using future precipitation projections and would be a major effort to complete across the entire state, or even just within SHS ROW. Given the challenges associated with this level of flooding analysis, the project study team needed to find an alternative way to understand future flood risks to Caltrans assets. Therefore, the 100-year storm was analyzed to determine how 100-year storm rainfall is expected to change, using best available precipitation projections available for the state.

The Scripps Institution for Oceanography, other academic institutions, and state agencies are working to better understand future precipitation projections. The most up-to-date precipitation research for the state was compiled as a part of *California's Fourth Climate Change Assessment*. Scripps and the researchers behind *California's Fourth Climate Change Assessment* developed daily rainfall data for a set of climate models, and RCPs 4.5 and 8.5, for every day to the year 2100. Climate change specialists from the study team worked with researchers from Scripps to estimate extreme precipitation changes over

[38] Jerry Melillo, Terese (T.C.) Richmond, and Gary W. Yohe, Eds., 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. US Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

[39] Caltrans, "Highway Design Manual," July 2, 2018, http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm

time. Specifically, the team requested precipitation datasets across the set of 10 international GCMs that were identified as having the best applicability for California, for both RCPs 4.5 and 8.5.[40]

These raw datasets were then processed to provide the percent change in the 100-year storm precipitation depth over a 24-hour period. The historical data used to calculate the percentage changes are synthetic historical backcasted data from the climate models over the period 1950 to 2005.[41] Standard practice in climate science is to derive the percentage changes using backcasted historical modeled data and future projected modeled data. This mitigates against model bias affecting the derivation of the percent change.

This newly processed data were analyzed for three time periods to determine how precipitation might change through the end of century. The years shown in the following figures represent the mid-points of the same 30-year statistical analysis periods used for the temperature metrics and explained in the Time Periods Section. To reiterate, these time periods are: 1) 2010 to 2039, where the mid-point year is 2025, 2) 2040 to 2069, where the mid-point year is 2055, and 3) 2070 to 2099, where the mid-point year is 2085.

The results of this assessment are shown in the District 9 maps below. The three maps depict the percentage change in the 100-year storm rainfall event predicted for the three analysis periods, and for the RCP 8.5 emissions scenario (the RCP 4.5 results are not shown). The median precipitation model (HadGEM2-CC) was used in this mapping.[42] Note that the change in 100-year storm depth is positive throughout District 9, indicating heavier rainfall during storm events.

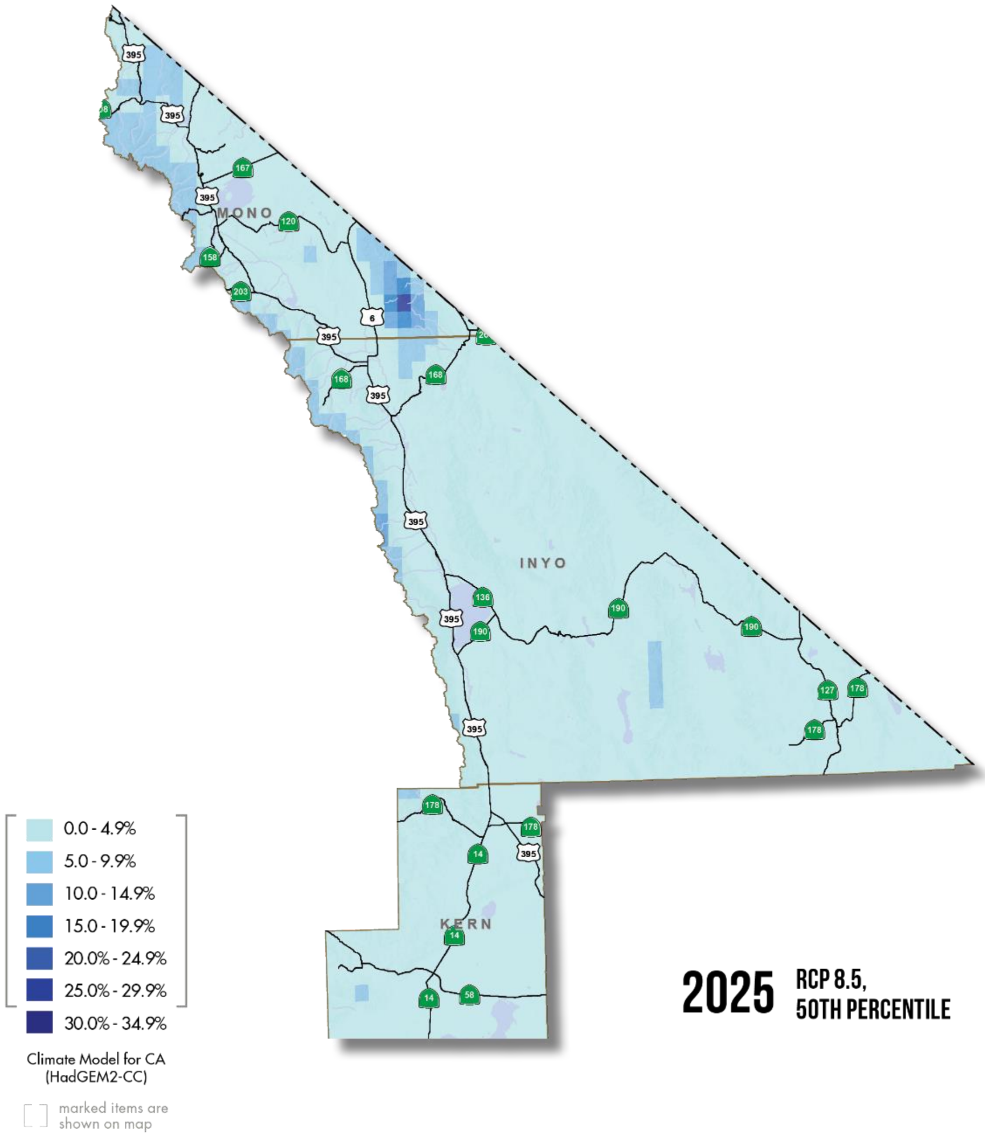
The 100-year storm precipitation depth is projected to increase by anywhere from 0-34.9% in District 9, depending on the timeframe and in specific locations (note that the high percentage increases are primarily due to the low levels of precipitation currently...an incremental change in a small number leads to large percentage increases). The mountainous areas show higher likely precipitation increases, which could increase flash flood frequency. The district can use several mitigation strategies to reduce flooding and landslide risk, including changing drainage design requirements, adding vegetation to reduce runoff, and building barriers to protect roadways from land or rockslides. Potential increased precipitation in District 9 means that Caltrans should assume higher rainfall and flooding levels in project design for high-risk areas, and plan SHS improvements accordingly. Complex topographic and environmental conditions at project sites will require a longer-term view of flood response in facility design to ensure that facilities remain operational to the end of their design lives. Improving long-term highway system resiliency will require that Caltrans conduct a comprehensive assessment of future conditions and incorporate new precipitation data in design when warranted.

Heavy storm events could have serious implications for the SHS. Understanding those implications will help Caltrans engineers and designers implement designs that are more adaptive to changing conditions. That said, site-specific, hydrological analysis of flood flows is necessary to determine how future projections of precipitation will affect bridges and culverts. These site-specific analyses should consider a range of models and future conditions to determine the best possible responses.

[40] These were the only RCPs available.
[41] "Backcasted" data is when a GCM is ran in "reverse," or provides outputs for historical periods.
[42] There were two models that lay at the center point of the distribution. Only one of these models was chosen (HadCEM2-CC) because the best practice in climate science is not to merge the results of multiple climate models.

FIGURE 14: PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH 2025

PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH

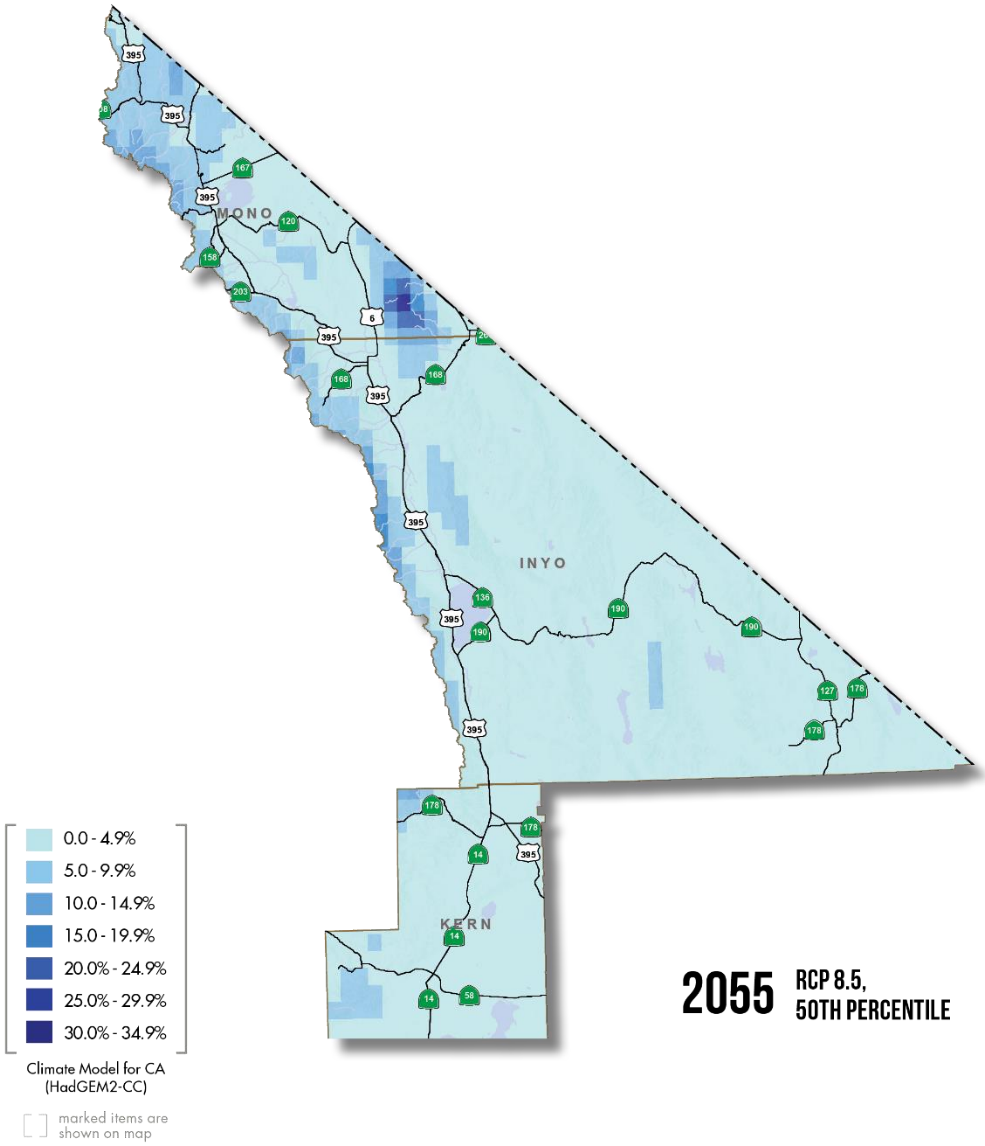


Future Percent Change in 100-year Storm Precipitation Depth within District 9, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 9. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 15: PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH 2055

PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH

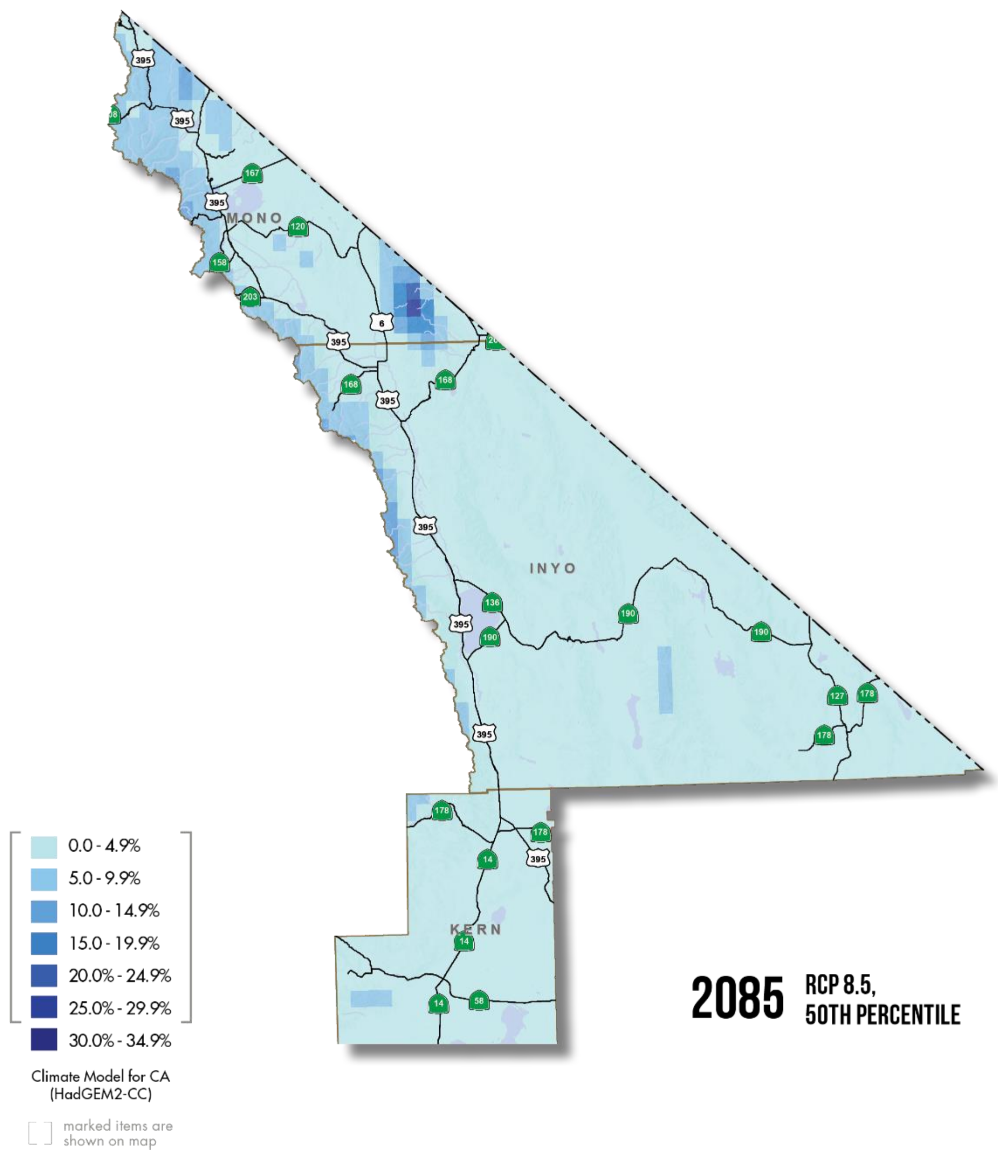


Future Percent Change in 100-year Storm Precipitation Depth within District 9, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 9. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

FIGURE 16: PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH 2085

PERCENT CHANGE IN 100-YEAR STORM PRECIPITATION DEPTH



Future Percent Change in 100-year Storm Precipitation Depth within District 9, Based on the RCP 8.5 Emissions Scenario

Caltrans Transportation Asset Vulnerability Study, District 9. Caltrans No. 74A0737. Climate data provided by the Scripps Institution of Oceanography. The data shown were generated by downscaling global climate outputs using the Localized Constructed Analogs (LOCA) technique.

6. WILDFIRE

Increasing temperatures, changing precipitation patterns, and resulting changes to land cover, are expected to affect wildfire frequency and intensity. Human infrastructure, including the presence of electrical utility infrastructure or other sources of fire potential (mechanical, open fire, accidental or intentional), might also influence the occurrence of wildfires. Wildfire is a direct concern for driver safety, system operations, and Caltrans infrastructure, among other issues.

Wildfires can indirectly contribute to:

- Landslide and flooding exposure, by burning off soil-stabilizing land cover and reducing the capacity of the soils to absorb rainfall.
- Potential expansion of invasive species in areas that are prone to wildfires.
- Wildfire smoke, which can affect visibility and the health of the public and Caltrans staff.

The years 2017 and 2018 were notable for the significant wildfires that occurred both in northern and southern California. These devastating fires caused property damage, loss of life, and damage to roadways. The wildfires in many cases stripped the land of protective cover and damaged the soils, such that subsequent rainstorms led to disastrous mudslides that caused catastrophic damage to State highways in several locations. The costs to Caltrans for repairing such damage can extend over months for individual events and could require years of investment to maintain the viability of the SHS for its users. The conditions that contributed to these impacts, notably a wet rainy season followed by very dry conditions and heavy winds, are likely to occur again in the future as climate conditions change and storm events become more dynamic.

The information gathered and assessed to develop wildfire vulnerability data for District 9 included research on the effect of climate change on wildfire recurrence. This is of interest to several agencies, including the US Forest Service (USFS), the Environmental Protection Agency (EPA), and the California Department of Forestry and Fire Protection (CalFire), who have developed their own models to understand the trends of future wildfires throughout the US and in California.

6.1. Ongoing Wildfire Modeling Efforts

Determining the potential impacts of wildfires on the SHS included coordination with other agencies that have developed wildfire models for various applications. Models used for this analysis included the following:

- **MC2 - EPA** Climate Impacts Risk Assessment (CIRA), developed by John Kim, USFS
- **MC2 - Applied Climate Science Lab (ACSL)** at the University of Idaho, developed by Dominique Bachelet, University of Idaho
- **University of California Merced model,** developed by Leroy Westerling, University of California Merced

The MC2 models are second-generation models, based on the original MC1 model developed by the USFS. The MC2 model is a Dynamic Global Vegetation Model, developed in collaboration with Oregon State University. This model considers projections of future temperature, precipitation, and changes these factors will have on vegetation types/habitat area. The MC2 model outputs used for this assessment come from the current IPCC Coupled Model Intercomparison Project 5 (CMIP5) dataset. This model was applied in two different studies of potential wildfire impacts at a broader scale by researchers at the USFS and the University of Idaho. The application of the vegetation model and the expectation of changing vegetation range/type is a primary factor of interest in the application of this model.

The second wildfire model used was developed by Leroy Westerling at the University of California, Merced. This statistical model was developed to analyze the conditions that led to past large fires (defined as over 1,000 acres) in California and uses these patterns to predict future wildfires. Inputs to the model include climate, vegetation, population density, and fire history. The model then incorporates future climate data and projected land use changes to project wildfire recurrence in California to the year 2100.

Each of these wildfire models used inputs from downscaled climate models to determine future temperature and precipitation conditions that are important for projecting future wildfires. The efforts undertaken by the EPA/USFS and UC Merced used the LOCA climate dataset developed by Scripps, while the ACSL/University of Idaho effort used an alternative downscaling method, the Multivariate Adaptive Constructed Analogs (MACA).

For the purposes of this report, these three available climate models will be noted from this point forward as:

- MC2 - EPA
- MC2 - ACSL
- UC Merced

6.2. Global Climate Models Applied

Each of the efforts used a series of GCM outputs to generate projections of future wildfire conditions. In this analysis, the project study team used the four recommended GCMs from Cal-Adapt for wildfire outputs (CAN ESM2, CNRM-CM5, HAD-GEM2-ES, MIROC5). In addition, all three of the modeling efforts used RCPs 4.5 and 8.5, representing realistic lower and higher ranges for future GHG emissions. Table 1 graphically represents the wildfire models and GCMs used in the assessment.

TABLE 1: WILDFIRE MODELS AND ASSOCIATED GCMS USED IN WILDFIRE ASSESSMENT

Wildfire Models								
MC2 - EPA			MC2 - ACSL			UC Merced		
CAN ESM2	HAD-GEM2-ES	MIROC5	CAN ESM2	HAD-GEM2-ES	MIROC5	CAN ESM2	HAD-GEM2-ES	MIROC5

6.3. Analysis Methods

The wildfire projections for all model data were developed for the three future 30-year time periods used in this study (median years of 2025, 2055, and 2085). As before, these median years represent 30-year averages. These are represented as such on the wildfire maps that follow.

The wildfire models produce geospatial data in raster format, which are data expressed in individual "cells" on a map. The final wildfire projections for this effort provide a summary of the percentage of each of these cells that burns for each time period. The raster cell size applied is 1/16th of a degree square for the MC2 - EPA and UC Merced models, which matches the grid cell size for the LOCA climate data applied in developing these models. The MC2 - ACSL effort generated data at 1/24th of a degree square to match the grid cells generated by the MACA downscaling method.

The model data were collected for all wildfire/GCM combinations, for each year to the year 2100. Lines of latitude (the east to west lines on the globe) are essentially evenly spaced when measuring north to south; however, lines of longitude (the north-south lines on the globe, used to measure east-west distances) become more tightly spaced as they approach the poles, where they eventually converge. Because of this, the cells in the wildfire raster are rectangular instead of square and are of different sizes depending on where one is (they are shorter when measured east-west as you go farther north). The study team ultimately summarized the data into the 1/16th grid to enable comparisons and to summarize across multiple models. The resulting area contained within these cells ranged in area between roughly 8,000 and 10,000 acres for grid cells sizes that are 6 kilometers on each side.

An initial analysis of the results of the wildfire models for the same time periods for similar GCMs noted differences in the outputs of the models, in terms of the amount of burn projected for various cells. This difference could be caused by any number of factors, including the assumption of changing vegetation that is included in the MC2 models, but not in the UC Merced model.

6.4. Categorization and Summary

The final method for determining future wildfire risks throughout the State took advantage of the presence of three modeled datasets to generate a broader understanding of future wildfire exposure in California. Three model results would provide a more robust result than applying only one of the available wildfire models. A cumulative total of percentage cell burned was developed for each cell in the final dataset. These data are available for future application by Caltrans and its partners.

To establish a level of concern for wildfire impacts, a classification was developed based on the expected percentage of grid cell burned. The classification was:

- Very Low 0-5%,
- Low 5-15%,
- Medium 15-50%,
- High 50-100%,
- Very High 100%+. [43]

[43] A cell can have greater than 100% burn if burned twice or more in the same time period.

Thus, if a cell were to show a complete burn or higher (8,000 to 10,000 acres+) over a 30-year period, that cell was identified as a very high wildfire exposure cell. Developing this categorization method included removing the CNRM-CM5 data point from the MC2 – ACSL and UC Merced datasets to have three consistent points of data for each cell in every model. This was done to provide a consistent number of data points for each wildfire model.

Next, the results across all models were examined to see if any one wildfire model/GCM model combination indicated a potential exposure concern in each grid cell. The categorization for any one cell in the summary identifies the highest categorization for that cell across all nine data points analyzed. For example, if a wildfire model identified the potential for significant burn in any one cell, the final dataset reflects this risk. This provides Caltrans with a more conservative method of considering future wildfire risk.

Finally, a score for each cell was assigned where a relative agreement was found on the categorization across all the model outputs. An analysis was completed to determine whether 5 of the 9 data points for each cell (a simple majority) were consistent in estimating the percentage of cell burned for each 30-year period. Figure 17 through Figure 19 on the following pages show the results of this analysis, using the classification scheme explained above. These figures show projections for RCP 8.5 only and red highlights show portions of the SHS that are likely to be most exposed to wildfire.[44] Table 2 and Table 3 summarize the miles of the District 9 SHS that are exposed to Medium to Very High wildfire risk, by county and by RCP Scenarios 4.5 and 8.5.

The more-densely forested areas in the northern portion of the district have the highest wildfire risk, with the greatest occurring in Mono County's Inyo National Forest and areas surrounding Mt. Patterson. District 9 can mitigate wildfire risk in these areas by using fire-resistant materials and maintaining defensible space for district assets and using fire-safe landscaping along roadways. The district can also limit wildfire concern by actively reducing fuel through dead or diseased tree removal, thinning practices, and coordinating with/supporting partner agencies such as CalFire and the US Forest Service.

[44] Areas on the maps shown in white do not necessarily have no associated wildfire risk - the classification is below medium.

TABLE 2: CENTERLINE MILES OF HIGHWAY EXPOSED TO WILDFIRE CONCERN AREAS UNDER RCP 8.5

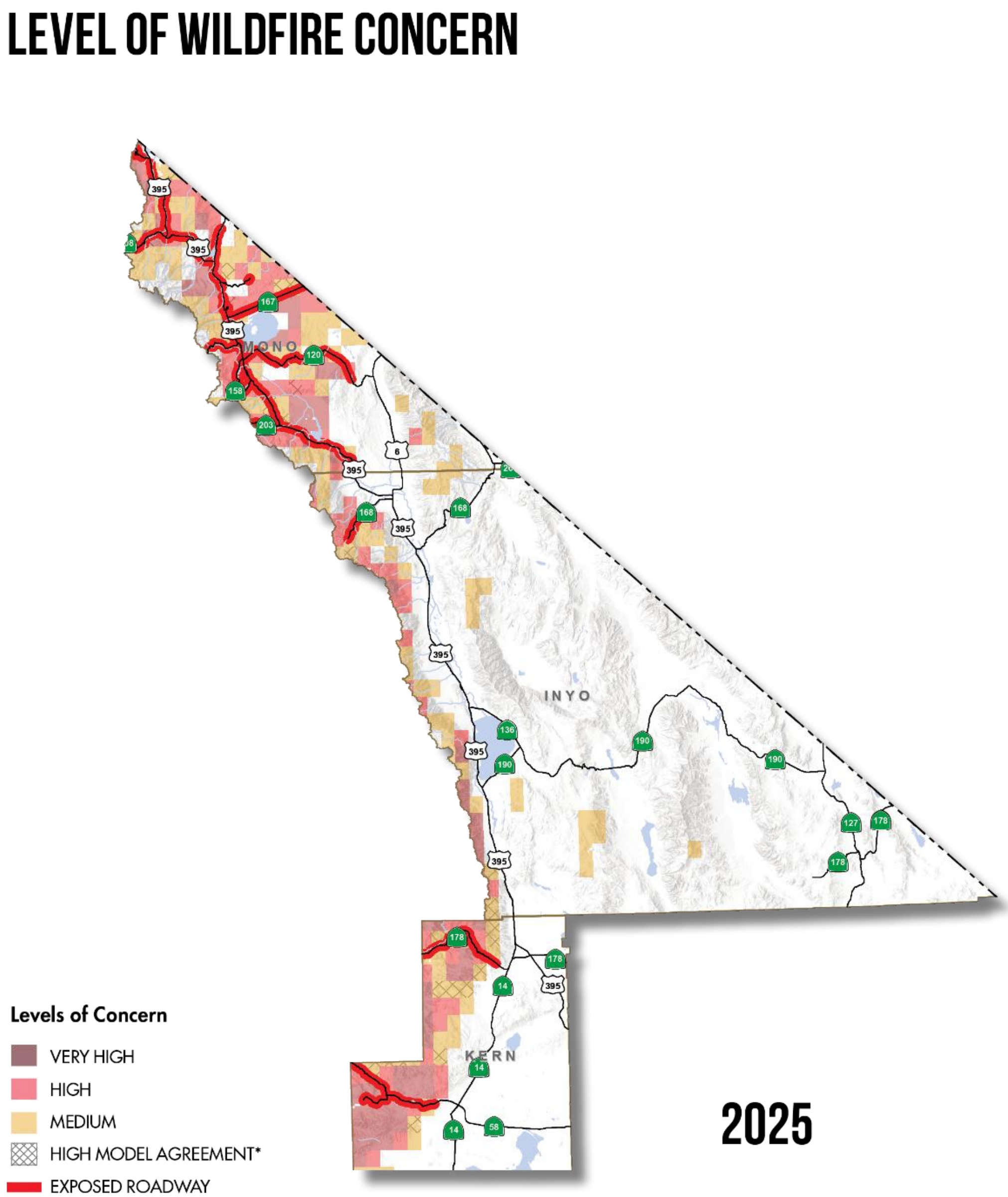
District 9 County	2025			2055			2085		
	Med	High	Very High	Med	High	Very High	Med	High	Very High
Inyo	6	0	3	6	3	17	25	3	6
Kern	31	20	12	51	7	2	37	26	0
Mono	68	84	73	25	66	155	16	91	146
District 9 Totals by Level of Concern and Year	**104**	**104**	**88**	**83**	**76**	**174**	**78**	**119**	**152**
District 9 Total by Year	**296**			**333**			**349**		

TABLE 3: CENTERLINE MILES OF HIGHWAY EXPOSED TO WILDFIRE CONCERN AREAS UNDER RCP 4.5

District 9 County	2025			2055			2085		
	Med	High	Very High	Med	High	Very High	Med	High	Very High
Inyo	8	0	5	3	3	6	7	3	6
Kern	30	24	8	52	0	6	51	7	2
Mono	76	87	93	58	53	151	44	87	135
District 9 Totals by Level of Concern and Year	**114**	**110**	**106**	**114**	**56**	**163**	**102**	**97**	**143**
District 9 Total by Year	**330**			**333**			**341**		

NOTE: KERN COUNTY MILEAGE ONLY COVERS THE EASTERN PORTION OF THE COUNTY.

FIGURE 17: INCREASE IN WILDFIRE EXPOSURE 2025

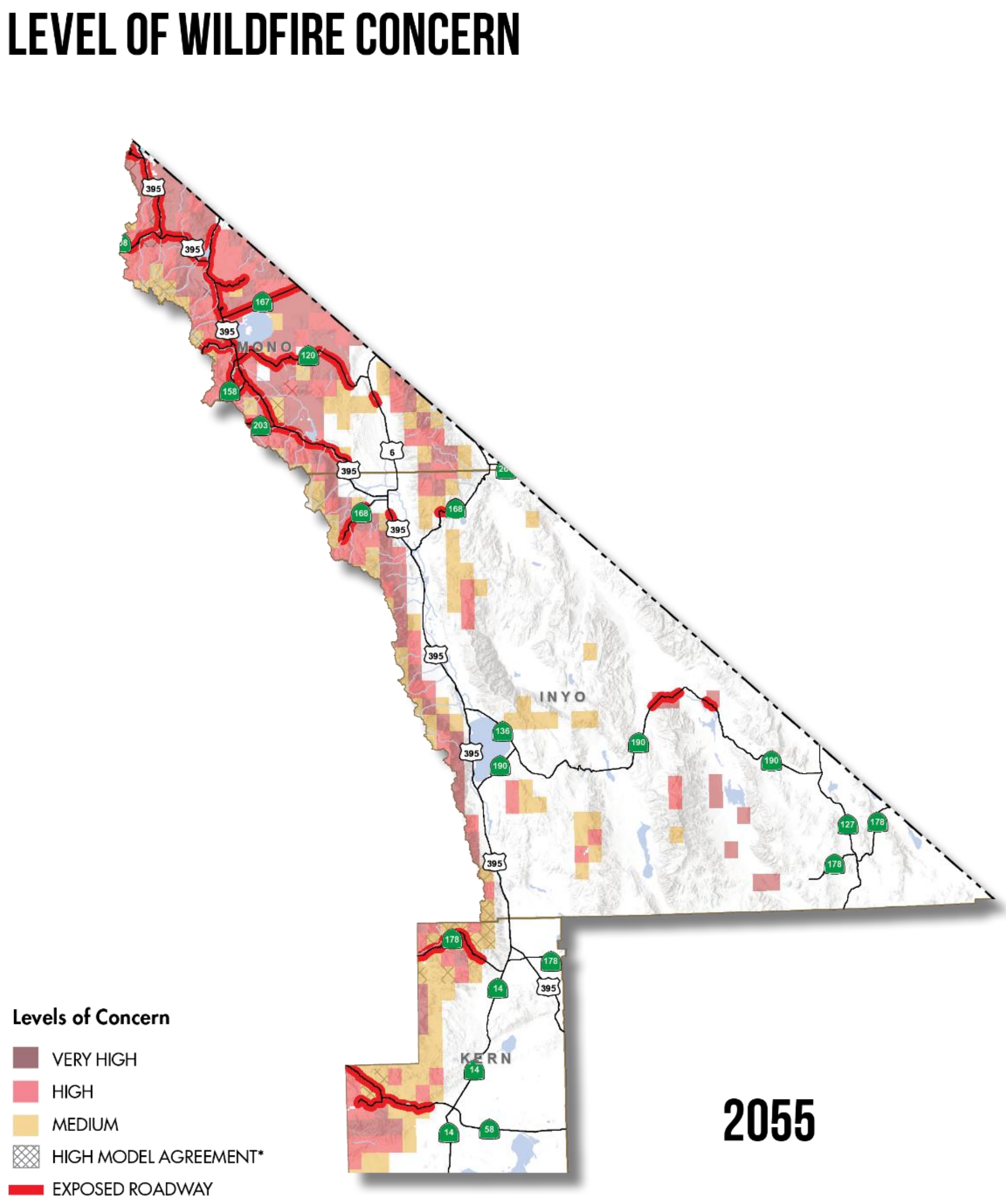


Future Level of Wildfire Concern for the Caltrans State Highway System within District 9, Based on the RCP 8.5 Emissions Scenario

The fire model composite summaries shown are based on wildfire projections from three models: (1) MC2 - EPA Climate Impacts Risk Assessment, developed by John Kim, USFS; (2) MC2 - Applied Climate Science Lab at the University of Idaho, developed by Dominque Bachelet, University of Idaho; and (3) University of California Merced model, developed by Leroy Westerling, University of California Merced. For each of these wildfire models, climate inputs were used from three GCMs: (1) CAN ESM2; (2) HAD-GEM2-ES; and (3) MIROC5. The maps show the multi-model maxima for each grid cell across the nine combinations of the three fire models and the three GCMs.

* The hashing shows areas where 5 or more of the 9 models fall under the same cumulative % burn classification as the one shown on the map.

FIGURE 18: INCREASE IN WILDFIRE EXPOSURE 2055



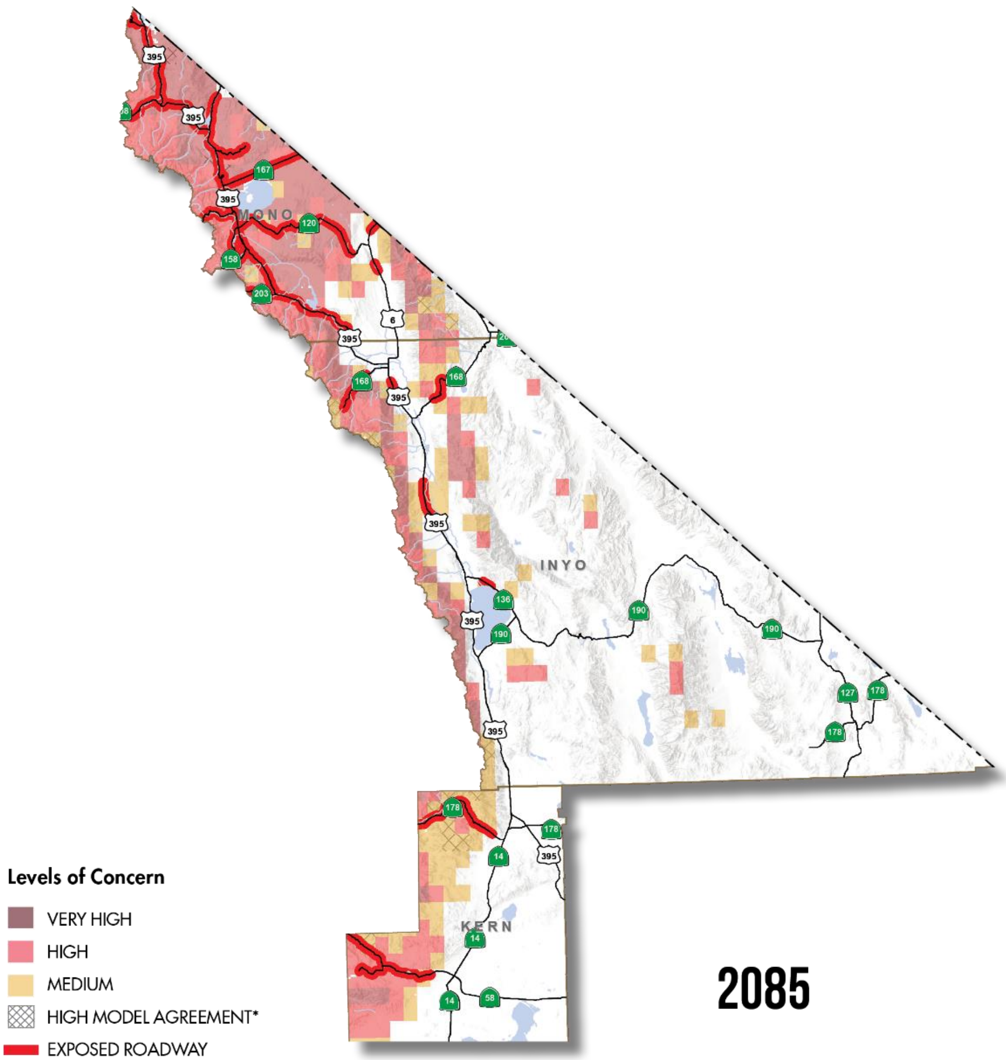
Future Level of Wildfire Concern for the Caltrans State Highway System within District 9, Based on the RCP 8.5 Emissions Scenario

The fire model composite summaries shown are based on wildfire projections from three models: (1) MC2 - EPA Climate Impacts Risk Assessment, developed by John Kim, USFS; (2) MC2 - Applied Climate Science Lab at the University of Idaho, developed by Dominque Bachelet, University of Idaho; and (3) University of California Merced model, developed by Leroy Westerling, University of California Merced. For each of these wildfire models, climate inputs were used from three GCMs: (1) CAN ESM2; (2) HAD-GEM2-ES; and (3) MIROC5. The maps show the multi-model maxima for each grid cell across the nine combinations of the three fire models and the three GCMs.

* The hashing shows areas where 5 or more of the 9 models fall under the same cumulative % burn classification as the one shown on the map.

FIGURE 19: INCREASE IN WILDFIRE EXPOSURE 2085

LEVEL OF WILDFIRE CONCERN



Future Level of Wildfire Concern for the Caltrans State Highway System within District 9, Based on the RCP 8.5 Emissions Scenario

The fire model composite summaries shown are based on wildfire projections from three models: (1) MC2 - EPA Climate Impacts Risk Assessment, developed by John Kim, USFS; (2) MC2 - Applied Climate Science Lab at the University of Idaho, developed by Dominque Bachelet, University of Idaho; and (3) University of California Merced model, developed by Leroy Westerling, University of California Merced. For each of these wildfire models, climate inputs were used from three GCMs: (1) CAN ESM2; (2) HAD-GEM2-ES; and (3) MIROC5. The maps show the multi-model maxima for each grid cell across the nine combinations of the three fire models and the three GCMs.

* The hashing shows areas where 5 or more of the 9 models fall under the same cumulative % burn classification as the one shown on the map.

7. INFRASTRUCTURE IMPACT EXAMPLES

As climate changes, California could be affected by more frequent, extreme weather events. In recent years, California has been through a severe drought (2011 – 2017), a series of extreme storm events that caused flash flooding and landslides across the state (2017 – 2018), the most deadly and severe wildfire season on record (2018), and deadly mudslides in Southern California (2018). These emergencies demonstrate what could become more commonplace for California in the future. It is important to learn from these events, take actions to prevent them wherever possible, and increase the resiliency of transportation infrastructure for near- and long-term threats. This section provides two examples of District 9 efforts to protect against weather-related disruptions.

Lee Vining – US 395

US 395, a Priority Interregional Facility on the Interregional Road System, is a major transportation corridor connecting the Eastern Sierra, Southern California, and Western Nevada. The corridor is a major north-south route that allows for the movement of goods, services, and travelers and is vital for the economy of the Eastern Sierra. There is a history of rock falls that reach the shoulders and travel lanes of the highway on US 395 north of the community of Lee Vining. The Marina Fire left severe burn scars that furthered the vulnerability of this section of the highway. Caltrans District 9 Maintenance personnel reported removing fallen rocks as a daily task throughout the year and with more frequency during the spring periods of rainy weather and when snowmelt was high. Boulders up to 3,000 pounds are known to have fallen in this area. They also report anecdotal occurrences of vehicles colliding with fallen rocks despite frequent maintenance. Caltrans District 9 has taken steps to mitigate against further threats to the traveling public due to these rockfalls.

In 2013, the Lee Vining Rock Fall Project began, which included rock scaling on six slopes to remove large, unstable boulders, debris, and trees. Portions of the slopes were groomed and shaped for erosion mitigation, seeding, and the installation of steel cable mesh netting that was affixed to the slopes with drilled-in ground anchors. While working on this project, the Marina Fire started northwest of Lee Vining, burning approximately 654 acres adjacent to the project area. To mitigate the risk of flooding and erosion as a result of the fire, the "Marina Fire Emergency Restoration Project" was undertaken to install k-rail (known as Jersey barriers elsewhere), repair and replace guardrail, and construct numerous rock fall barriers. To prevent excessive debris flow, channels and detention basins were constructed, and pipe risers and debris guards were installed at all culverts in the project boundary. Three years since the Marina Fire occurred, the emergency restoration actions have prevented debris flow in the area and reduced the number of boulders impacting the highway.

SR 190

Located in one of the most remote parts of California, travelers from all over the world use SR 190 as the gateway to Death Valley National Park (DVNP), which has 1.3 million visitors annually. Classified as an interregional two-lane minor arterial, SR 190 elevations vary considerably from 5,200 feet near Darwin Road, down to 245 feet below sea level in Death Valley.

The combination of the topography, dry landscape, and monsoonal rains can produce annual flash flooding. In October 2015, a major flash flood severely damaged SR 190, utilities, and historic buildings at Scotty's Castle in the Death Valley National Park. Such flash flooding events commonly close the highway and create multiple hazards for the traveling public. To mitigate the impacts of flash flooding on SR 190, Caltrans District 9 added to a project to realign six curves and increase site distance on a dangerous section of the highway some improvements to culverts to increase their capacity to handle flash floods.

Other projects in the district include new culverts, channeled water flows in sediment basins, installed down drains and catchment basins, and captured debris flow (while assisting National Park resource staff to restore the water and habitats). Given expected changes in projected precipitation conditions in the district, these types of projects are expected to be more common in the future.

FIGURE 20: SR 178 FLOODING AND ROCK SLIDES, 2018

FIGURE 21: SR 158 FLOODING, 2018

FIGURE 22: OVERTURNED TRUCK DUE TO HIGH WINDS

8. INCORPORATING CLIMATE CHANGE INTO DECISION MAKING

8.1. Risk-Based Design

A risk-based decision approach considers the broader implications of damage and economic loss in determining project design. Climate change is a risk factor that is often omitted from design but is important for an asset to function over its design life. Incorporating climate change into asset-level decision making has been a subject of research over the past decade, much of it led or funded by the Federal Highway Administration (FHWA). The FHWA undertook projects to assess climate change and facility design – including the Gulf Coast II project (Mobile, AL) and the Transportation Engineering Approaches to Climate Resiliency (TEACR) study. Both assessed facilities of varying types, which were exposed to different climate stressors. They then identified design responses that could make the facilities more resilient to stresses.

One outcome of the FHWA studies was a step-by-step method for completing facility (or asset) design, such that climate change was considered and inherent uncertainties in the timing and scale of climate change were included. This method, termed the Adaptation Decision-Making Assessment Process (ADAP),[45] provides facility designers with a recommended approach for designing a facility when considering possible climate change effects. The key steps in ADAP are shown in Figure 23: FHWA's Adaptation Decision-Making Process.

The first five steps of the ADAP process cover the characteristics of the project and the context. The District 9 Vulnerability Assessment has worked through these first steps at a high level and the data used in the assessment has been provided to Caltrans for future use in asset level analyses. These five steps should be addressed for every exposed facility during asset level analyses.

Step Five focuses on conducting a more detailed assessment of the performance of the facility. When analyzing one facility, it is important to assess the highest impact scenario. This does not necessarily correspond to the highest temperature range, or largest storm event. In this case, the analysis should determine which scenarios will have the greatest effect on a facility. For example, a 20-year storm may cause greater impacts than a 100-year storm, depending on wind and wave directions. If the design criteria of the facility are met even under the greatest impact scenario, the analysis is complete. Otherwise, the process moves on to developing adaptation options.

Options should be developed that will adapt the facility to the highest impact scenario. If these options are affordable, they can move to the final steps of the process. If not, other scenarios can be considered. These alternative design options will need to move through additional steps to critique their performance and economic value. Then, they move to the final steps of the process. The last three steps are critical to implementing adaptive designs. Step Nine involves considering other factors that may influence adaptation design and implementation. For example, California Executive Order B-30-15 requires consideration of:

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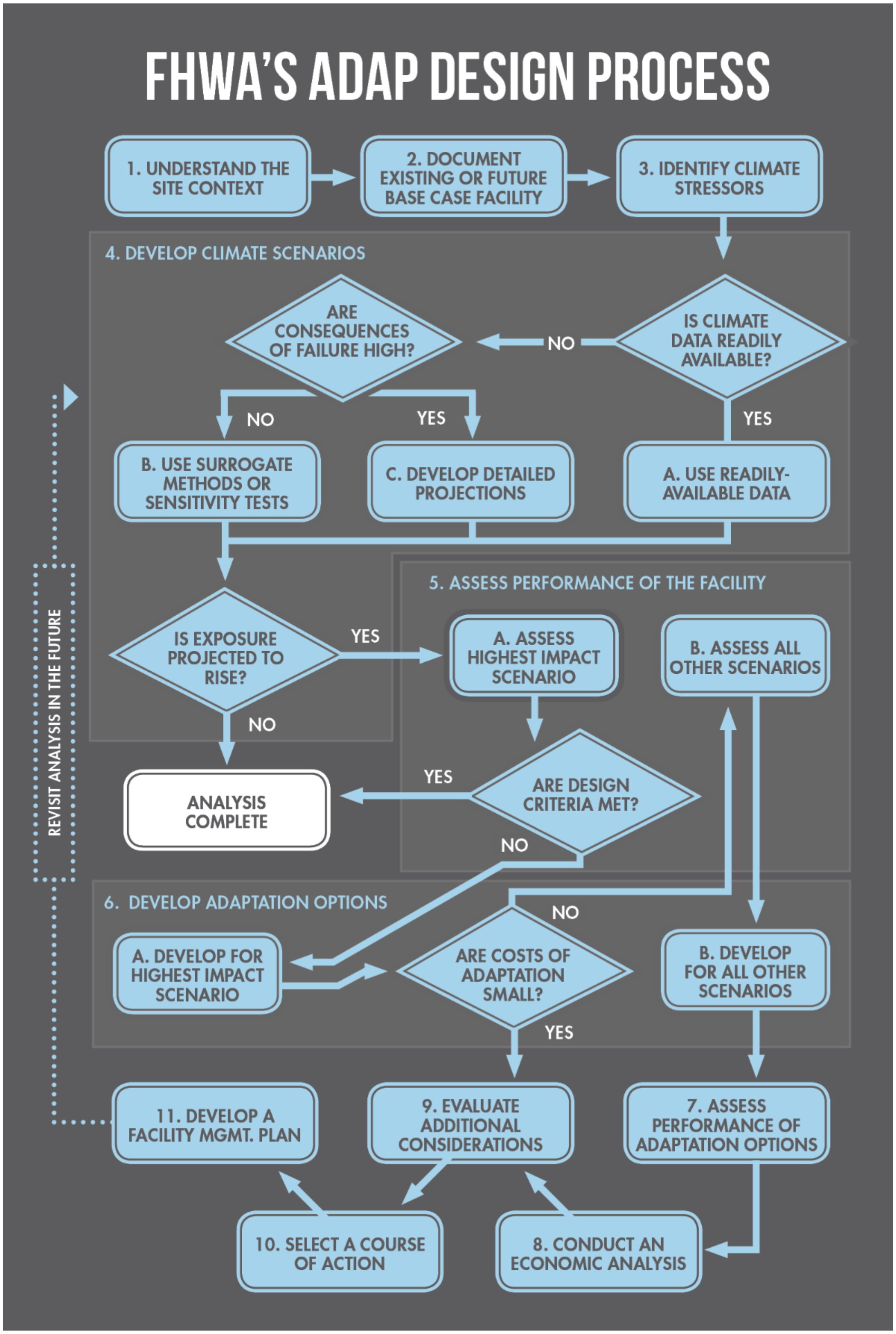
[45] "Adaptation Decision-Making Assessment Process," Federal Highway Administration, last modified (ADAP)." January 12, 2018, https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/adap/index.cfm

- Full life cycle cost accounting
- Maladaptation,
- Vulnerable populations,
- Natural infrastructure,
- Adaptation options that also mitigate greenhouse gases, and
- Use of flexible approaches where necessary.

At this step in the ADAP process, it is important to understand the greater context of the designs developed and whether they meet State, Caltrans, and/or other requirements. This also allows for the opportunity to consider potential impacts of the project outside of design and economics, including how it may affect the surrounding community and environment. After evaluating these additional considerations, a course of action can be identified and a facility management plan implemented.

The District 9 vulnerability assessment is the first step in a multi-part effort to identify SHS exposure to climate change, to identify the consequences and impacts of climate change to the system, and to prioritize actions based upon those impacts. A final prioritization step will be key to identifying which assets are at the greatest risk and should be prioritized first for more detailed, ADAP-style assessments and risk-based design responses.

FIGURE 23: FHWA'S ADAPTATION DECISION-MAKING PROCESS



FOR ADDITIONAL INFORMATION ABOUT ADAP PLEASE SEE THE ASSOCIATED PAGE ON FHWA'S WEBSITE:
HTTPS://WWW.FHWA.DOT.GOV/ENVIRONMENT/SUSTAINABILITY/RESILIENCE/ONGOING_AND_CURRENT_RESEARCH/TEACR/ADAP/INDEX.CFM

8.2. Prioritization of Adaptive Response Projects

The project prioritization approach outlined below is based on a review of methods used in other transportation agencies, and lessons learned from other adaptation efforts. These methods—mostly developed and used by Departments of Transportation in other states—address long-term climate risks and are intended to inform project priorities across the range of diverse project needs. The method outlined below recognizes the following issues when considering climate change adaptation for transportation projects:

- The implications of damage or failure to a transportation facility due to climate change-related stresses.
- The likelihood or probability of occurrence of an event.
- The timeframe at which the events may occur, and the shifting of future risks associated with climate change.

The recommended prioritization method is applied to those facilities with high exposure to climate change risk; it is not applied to the entire transportation network. The method assumes that projects have been defined in sufficient detail to allow some estimate of implementation costs.

Some guiding principles for the development of the prioritization method included the following:

- It should be straightforward in application, easily discernable, describable, and it should be relatively straightforward to implement with common software applications (Excel, etc.).
- It should be based on best practices in the climate adaptation field.
- It should avoid weighting schemes and multi-criteria scoring, since those processes tend to be difficult to explain and are open to interpretation among professionals with varying perspectives.
- It should be focused on how departments of transportation do business, reflect priorities for program delivery to stakeholders, and recognize the relative importance of various assets.
- It should have the ability to differentiate between projects that may have different implications of risk—like near-term minor impacts and long-term major impacts—to set project priorities.
- It should facilitate decisions among different project types, for example, projects for repairs or for continuous minor damage as compared to one-time major damage events.
- It should enable the comparison among all types of projects, regardless of the stressor causing impacts.

The prioritization method requires the following information:

- Facility loss/damage estimates (supplied by Caltrans engineering staff) should capture both lower level recurring impacts and larger loss or damage. These should include a few key pieces of information, including:

    What are the levels for stressors (SLR, surge, wildfire, etc.) that would cause damage and or loss?

What are the implications of this damage in terms of cost to repair and estimated time to repair?

- System impacts (supplied by Caltrans planning staff) examine the impacts of the loss of the facility on the broader system. This could be in terms of increase in Vehicle Hours Traveled (VHT) if using a traffic model, or an estimated value using volume and detour length as surrogates.
- Probability of occurrence (supplied by Caltrans climate change staff through coordination with State climate experts) provides the probability of events occurring as estimated from the climate data for chosen climate scenarios. Estimated for each year out to the end of the facility lifetime.

A project annual impact score is used to reflect two conditions, summarized by year:

- The expected cumulative loss estimated for the project over the project lifetime (full impact accounting).
- A method of discounting losses over years– to enable prioritization based on nearer term or longer-term expected impacts (timeframe accounting).

These two pieces of information are important to better understand the full cost of impacts over time.

Various approaches for calculating values for prioritization could be used. One could use indicators that reflect costs to system users. Another approach could be to use a full impact accounting that basically sums all costs to the end of the asset useful life. Annual discounting to reflect “true costs” or current year dollar equivalent values would also be important to calculate the final impact score for the asset.

The prioritization method needs estimates of at a minimum repair/replacement cost (dollars) and, if broadened, a system users impact (in dollar equivalents). System user costs would be summarized for this effort as transportation service impacts, and would be calculated in one of two ways:

- Estimate the impacts to a transportation system by identifying an expected detour routing that would be expected with loss of access or a loss/damage climate event. This value would be combined with average daily traffic and outage period values to result in an estimate of VHT increase associated with the loss of use of a facility.
- Utilize a traffic model to estimate the impacts on the broader SHS from damage/loss of a facility or facilities anticipated to occur as a result of a climate event. The impact on the system would be summarized based on the net increase in VHT calculated in the model.

The advantage of the system method is that it determines impacts of multiple loss/failure assessments consecutively and is not confined to only the assessment of each individual project as an individual project concern. It also allows for comparisons to the broader system and scores facilities with heavier use and importance to an integrated system as higher in terms of impact and prioritization.

Probabilities of an event occurring over each year would be used to summarize costs per year as well as a summarized cumulative total cost for the project over the lifetime. The resulting values would set the prioritization metric in terms of net present value for Caltrans to apply in selecting projects. The identification of an annual cost metric, which includes discounting, enables the important decision-making process on which project should advance given limited project resources.

Table 4 highlights how the method would be implemented, with the project selected in the out years selected by the calculated annual cost metric. The impacts noted in the time period beyond the selected year (shown in shaded color) would be expected to have been addressed by the adaptation strategy. Thus, in the table, Project 1 at year 5 has the highest annual cost associated with disruptions connected to an extreme weather event. The project with the next greatest annual cost is Project 2, where this cost is reached at year 15. The next project is Project 3 at year 35 and the final project is Project 4 at year 45.

TABLE 4: EXAMPLE PROJECT PRIORITIZATION

Year	5	10	15	20	25	30	35	40	45	50
Project 1	$5	$5	$5	$5	$7	$7	$7	$9	$9	$9
Project 2	$4	$4	$6	$6	$6	$6	$8	$8	$8	$8
Project 3	$3	$3	$4	$4	$4	$6	$8	$8	$8	$8
Project 4	$2	$2	$2	$4	$4	$4	$6	$8	$10	$10

The project prioritization method outlined above requires the development of new approaches to determining how best to respond to climate change risks. It does not rely on existing methods as they are not appropriate to reflect climate risk effectively and facilitate agency level decision making. Climate change, with its uncertain timing and non-stationary weather/climate impacts, requires methods that incorporate this reality into Caltrans' decision-making processes.

It would be possible to implement a tiered prioritization process once work required to complete the steps as outlined above has been completed. Assets at risk from climate change with comparable present values could be compared for their capability to address other policy concerns – like goods movement, access for low income / dependent communities, sustainability measures, or other factors that would help Caltrans meet statewide policy goals. The primary focus of this assessment should be on the impacts to the system; however, these secondary measures can help clarify or reorder the final list and help guide implementation.

9. CONCLUSIONS AND NEXT STEPS

This report represents an initial effort to identify areas of exposure to potential climate change for facilities owned and operated by Caltrans District 9. The study utilized various data sources to identify how climatic conditions may change and where these areas of high exposure to future climate risks appear in District 9. The study distilled the larger context of climate change down to a more localized understanding of what such change might mean to District 9 functions and operations, District 9 employees, and the users of the transportation system. It is intended, in part, as a transportation practitioner's guide on how to include climate change into transportation decision making.

Much of today's engineering design is based on historical conditions, and it is emphasized throughout this report that this perspective should change. A review of climate data analyzed for this study shows that, for those stressors analyzed (wildfire, temperature, and precipitation), there are clear indications that future conditions will be very different from today's, with likely higher risks to highway infrastructure. These likely future conditions vary in terms of when threshold values will occur (that is, when precipitation and temperature values exceed a point at which risks will increase for assets) and on the potential impact to the SHS. This is an important consideration given that transportation infrastructure investment decisions made today will have implications for decades to come given the long lifetimes for roadway facilities.

This report provides District 9 with the information on areas of climate change exposure it can utilize to proceed to more detailed, project-level assessments. In other words, the report has identified where climate change risks are possible in District 9 and where project development efforts for projects in these areas should consider changing future environmental conditions. There are several steps that can be taken to transition from a traditional project development process based on historical environmental conditions to one that incorporates a greater consideration for facility and system resiliency. This process can incorporate the benefits associated with climate change adaptation strategies and use climate data as a primary decision factor. District 9 staff, with its recent history of assessing long-term risks associated with climate change, has the capacity to adopt such an approach and ensure that travelers in the region are provided with a resilient system over the coming years.

The following section provides some context as to what the next steps for Caltrans and District 9 may be, building upon this work, and creating a more resilient SHS.

9.1. Next Steps

The work completed for this effort answers a few questions and raises many more. The scope of this work was focused on determining what is expected in the future and how that may affect the Caltrans SHS. This analysis has shown that climate data from many sources indicates an expanded set of future risks – from increased extreme precipitation, to higher temperatures, and an increase in wildfires – all concerns that will need to be considered by District 9.

There are a few steps that will be required to improve decision making and help Caltrans achieve a more resilient SHS in District 9. These include:

- Policy Changes
  - Agency leadership will need to provide guidance for incorporating findings from this assessment into decision making. This area is a new focus and requires a different perspective that will not be possible without strong agency leadership.
    - Addressing climate change should be integrated throughout all functional areas and business processes; including Planning, Environmental, Design, Construction, Maintenance, and Operations.
  - Risk-based decision-making. The changing elements of climate change require the consideration of the implications of those changes and how they may affect the system. Caltrans will need to change its methods to incorporate measures of loss, damage and broader social or economic costs as a part of its policies. (See 8.1 Risk-Based Design).
- Acquisition of Improved Data for Improved Decision Making
  - Determining potential impacts of precipitation on the SHS will require additional system/environmental data to complete a system-wide assessment. This includes:
    - Improved topographic data across District 9 (and California).
    - Improved asset data – including accurate location of assets (bridges, culverts) and information on the waterway openings at those locations.
  - The assessment of wildfire potential along the SHS is an ongoing effort. Follow up will be required to determine the results of new research and whether updated models indicate any additional areas of risk.
  - The precipitation and temperature data presented in this report is based off a dataset that is newly released. Methods to summarize this data across many climate models is ongoing and the conclusions of that work may yield information that may more precisely define expected future changes for these stressors.
  - There are efforts underway to refine the understanding of other stressors, including landslide potential. Further refinements of those efforts will require additional investment and coordination. Research efforts are constantly being refined and Caltrans will need to be an active partner in participating in, and monitoring, the results of these efforts to determine how to best incorporate the results of these efforts into agency practices.
- Implementation
  - The data presented in this report indicate directions and ranges of change. These data points will need to become a part of Caltrans practice for planning and design for all future activities.
  - The use of this data will require the development of educational materials and the training of Caltrans staff to ensure effective implementation.

Not every concern and future requirement could be addressed or outlined in this report. Thus, the report should be considered the first step of many that will be required to address the implications of climate change to the SHS. Much work remains to create a resilient SHS across California.

10. GLOSSARY

100-year design standard: Design criteria for highway projects that address expected environmental conditions for the 100-year flood. Considered Base Flood Elevation by the Federal Emergency Management Agency.

Cal-Adapt: A web-based data hub and information guide on recent California-focused climate data and analysis tools. Visualization tools are available to investigate different future climate scenarios.

Climate change: Change in climatic conditions expected to occur due to the presence of greenhouse gas concentrations in the atmosphere. Examples include changing precipitation levels, higher temperatures, and sea level rise.

Downscaling: An approach to estimate climate predictions at a more localized level based on the outcomes of models that predict future climate conditions at a much larger scale of application.

Emissions Scenarios: Assumed future states of greenhouse gas concentrations in the atmosphere.

Exposure: The degree to which a facility or asset is exposed to climate stressors that might cause damage, disrupt facility operations, or otherwise asset condition.

Global Climate Model (GCM): Models used by climate scientists to predict future climate conditions. This term is sometimes used interchangeably with General Circulation Model.

Representative concentration pathways (RCP): Scenarios of future greenhouse gas emission concentrations based on assumed future greenhouse gas emissions given economic development, population growth, technology, and other variables.

Resilient transportation facilities: Transportation facilities that are designed and operated to reduce the likelihood of disruption or damage due to changing weather conditions or other impacts.

Return period storm event: Historical intensity of storms based on how often such level of storms have occurred in the past. A 100-year storm event is one that has the intensity of a storm that statistically occurs once every 100 years (1% chance of occurring each year).

State Highway System (SHS): The designated highway network in California, which Caltrans is responsible for operating and maintaining.

Stressor/stresses: Climate conditions that could possibly apply stress to engineered facilities. Examples include temperature rise and precipitation change.

Vulnerability assessment: A study of those areas likely to be exposed to future climate and weather conditions that will add additional stress to assets, in some cases, levels of stress that might exceed the assumed conditions when the asset was originally designed.

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