# CAL-ADAPT: LINKING CLIMATE SCIENCE WITH ENERGY SECTOR RESILIENCE AND PRACTITIONER NEED

*A Report for:*

**California's Fourth Climate Change Assessment**


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Edmund G. Brown, Jr., *Governor*


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Cal-Adapt's design and functionality have been developed with the insight from a variety of beta testers and our helpful Technical Advisory Committee members, who provided valuable feedback throughout several iterations of updates. These individuals represent scientists and climate experts, planners and technicians, and leaders in development of local climate policy, as well as interested participants from the general public. We gratefully thank both the current and past members of the Advisory Committee, whose feedback and insight have greatly improved the climate data visualizations on Cal-Adapt.

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# PREFACE

California's Climate Change Assessments provide a scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. These Assessments contribute to the advancement of science-based policies, plans, and programs to promote effective climate leadership in California. In 2006, California released its First Climate Change Assessment, which shed light on the impacts of climate change on specific sectors in California and was instrumental in supporting the passage of the landmark legislation Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), California's Global Warming Solutions Act. The Second Assessment concluded that adaptation is a crucial complement to reducing greenhouse gas emissions (2009), given that some changes to the climate are ongoing and inevitable, motivating and informing California's first Climate Adaptation Strategy released the same year. In 2012, California's Third Climate Change Assessment made substantial progress in projecting local impacts of climate change, investigating consequences to human and natural systems, and exploring barriers to adaptation.

Under the leadership of Governor Edmund G. Brown, Jr., a trio of state agencies jointly managed and supported California's Fourth Climate Change Assessment: California's Natural Resources Agency (CNRA), the Governor's Office of Planning and Research (OPR), and the California Energy Commission (Energy Commission). The Climate Action Team Research Working Group, through which more than 20 state agencies coordinate climate-related research, served as the steering committee, providing input for a multisector call for proposals, participating in selection of research teams, and offering technical guidance throughout the process.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. It includes research to develop rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health.

The Fourth Assessment includes 44 technical reports to advance the scientific foundation for understanding climate-related risks and resilience options, nine regional reports plus an oceans and coast report to outline climate risks and adaptation options, reports on tribal and indigenous issues as well as climate justice, and a comprehensive statewide summary report. All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor and relevance to practitioners and stakeholders.

For the full suite of Fourth Assessment research products, please visit www.climateassessment.ca.gov. This report contributes to energy sector resilience by providing an interactive tool enabling exploration, visualization, and analysis of data portraying climate-related risks to the energy system.

# ABSTRACT

Energy sector operations, management, and planning require rigorous, peer-reviewed information on projected climate and weather-related risks to maintain safe, reliable, and affordable energy for California's current and future populations. California's energy infrastructure—including electric transmission and distribution lines, thermal power plants and substations, and natural gas facilities and pipelines—is vulnerable to climate-related impacts and extreme weather events that may differ significantly from historical records as a result of changes in our climate. Research supported by the State of California has provided high-quality, peer-reviewed data and scientific analysis of climate-related factors that impact the energy sector, including sea level rise, inland flooding, storms, wildfire, and extreme heat events. These data have been made freely available to the public through the Cal-Adapt web application, which has been developed in response to energy sector needs and continues to evolve to be more directly integrated into energy sector decision support and planning.

With funding and oversight from the California Energy Commission, UC Berkeley's Geospatial Innovation Facility (GIF) built Cal-Adapt to provide stakeholders with actionable information regarding local climate-related risks through interactive, compelling, and useful visualizations and tools. Through this research funding, we have developed and released Cal-Adapt 2.0, which includes updates and enhancements that increase its ease of use, information value, visualization tools, and data accessibility. Cal-Adapt 2.0 has been designed by incorporating feedback from a variety of sources to present interactive visualizations of high-resolution downscaled data and offers an open Application Programming Interface (API) that allows other organizations to access Cal-Adapt climate data and build domain specific visualization and planning tools. Cal-Adapt continues to evolve and seeks to further engage stakeholders in the design of tools directed toward energy sector decision support.

Cal-Adapt has already made a difference in adaptation practice and policy planning in California by providing an easy-to-use, freely available tool that can serve as a resource for many climate resilience applications. Although Cal-Adapt is still under development to become an operational decision support tool, it has already been used by California's Investor-Owned Utilities (IOUs) for a range of applications that leverage data and visualizations from the website. Moreover, as a publically available tool, it has been embraced by additional users from a variety of sectors. Cal-Adapt has been explicitly recognized by California's legislature as a key resource to support local hazard mitigation efforts and has helped California move forward on climate policy by providing a point-of-access for, and harmonizing with, data adopted by the state for energy sector planning as well as adaptation guidance.

**Keywords:** Cal-Adapt, Energy Sector Climate Resilience, Climate Services, Climate Tools, Climate Change Adaptation, Localized Constructed Analogues (LOCA)

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# HIGHLIGHTS

- Cal-Adapt 2.0 presents peer-reviewed science on regionally downscaled climate change in California through interactive, visually compelling, and useful data visualizations.
- Cal-Adapt directly addresses energy sector needs by providing for easy access and exploration of high-resolution, regionally downscaled climate projections based on global climate models (GCMs) and emissions scenarios that are sanctioned at the state level to be used in energy research and planning.
- Cal-Adapt 2.0 is built on an entirely free and open source web platform and includes a new publically available API (Application Programming Interface) that enables programmatic access to climate data hosted on Cal-Adapt. New features allow users the ability to aggregate data both spatially and temporally through pre-loaded boundary files or for their own private data via a boundary file upload function, or directly through the API.
- California's Investor Owned Utilities (IOUs) have employed Cal-Adapt tools and data to support vulnerability assessment as a part of their participation in the U.S. Department of Energy's Resilience partnerships, including PG&E's use of Cal -Adapt's extreme heat tool to explore intensity and duration of projected mid-century heat waves.
- California IOUs have also used Cal-Adapt to support on-the-ground resilience efforts. For example, SDG&E has used Cal -Adapt 2.0 to support climate-resilient design of a compressor station in Blythe, California, to investigate implications of climate related to SDG&E's Design Standards, and to explore climate dimensions of system hardening projects.
- Cal-Adapt has affected climate policy and practice in California. As a freely available tool, it has been embraced by users from a variety of sectors. It has also been explicitly recognized by California's legislature as a key resource to support local hazard mitigation, and it has helped the state advance a consistent approach to resilience planning for California's energy system as well as other sectors.
- Future development includes enhanced communication and outreach targeting development of decision-support tools as well as building more outreach materials and training around using the publically available API. Energy sector users are interested in accessing an array of climate variables at a large number of private assets. This can be processed through the API but many users are not yet aware of these capabilities or do not have the staff expertise to exploit this functionality.

WEB LINKS

http://cal-adapt.org/

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# 1: Introduction

California's energy infrastructure—including electric transmission and distribution lines, thermal power plants and substations, and facilities and pipelines that store, transmit, and distribute natural gas—is vulnerable to climate-related impacts and extreme weather events that may differ significantly from historical records as a result of changes in our climate. Understanding potential climate-related threats such as sea level rise, inland flooding, storm events, wildfire, and extreme heat events is critical to energy sector planning. Research supported by the California Energy Commission (Energy Commission) has provided high-quality, peer-reviewed data and analysis of many climate-related factors of interest to the energy sector.

Data and visualizations of many local climate-related risks, including projected changes in sea level rise, wildfire risk, temperature, precipitation, snowpack, and more have been made available through Cal-Adapt, the State's resource for exploring climate change research. Cal-Adapt is a comprehensive, interactive, publically accessible web-based application developed by UC Berkeley's Geospatial Innovation Facility (GIF) with the funding support and advisory oversight of the Energy Commission. Cal-Adapt provides easy-to-understand visualizations of locally relevant climate-related risks that enable exploration of research results and climate projections. Cal-Adapt continues to evolve with the ultimate goal of directly supporting climate-resilient planning and decision-making.

Through California's Natural Gas Public Interest Energy Research (PIER) funding (500-14-003), in addition to EPIC-funded EPC-15-008, we have developed and released Cal-Adapt 2.0, which includes updates and enhancements that increase its ease of use, information value, visualization tools, and data accessibility. Cal-Adapt 2.0 has been designed in response to feedback from a variety of sources to present interactive visualizations of high-resolution downscaled data and offers an open Application Programming Interface (API) that allows other organizations to access Cal-Adapt climate data and build domain specific visualization and planning tools.

Cal-Adapt provides stakeholders with actionable information through a combination of locally relevant information, visualization tools, and access to primary data which can help to identify vulnerable populations and infrastructure locations at risk from climate-related factors. This report describes the development of Cal-Adapt 2.0, introduces the new data and features, and provides an overview of the web application's capabilities as well as examples of how it has been used to aid resilience planning and policy in California. Chapter 2 describes the process for developing Cal-Adapt 2.0 including our user outreach and engagement efforts which have greatly informed the new features and tools on Cal-Adapt. Chapter 3 presents the peer-reviewed climate data sets currently available through Cal-Adapt, details the site's interactive data visualizations and climate tools, and reviews the web architecture underlying Cal-Adapt. In Chapter 4 we present examples of how Cal-Adapt is being used to address energy sector resilience and introduce additional use cases from local and state adaptation initiatives. Feedback from stakeholders has been instrumental in planned future enhancements to Cal-Adapt, which is described in Chapter 5.

# 2: Development, Outreach, and Communication

Cal-Adapt was initially released to the public in 2011 as a web-based resource to showcase the innovative climate change research being produced by the scientific community in California, as documented in the 2009 California Climate Adaptation Strategy (Koy et al., 2016). The original web application was developed under funding from the California Energy Commission's Public Interest Energy Research (PIER) program and was designed to make complex scientific research on climate change accessible and useful for a wide range of practioners requiring climate information for local applications. By fall of 2017, Cal-Adapt has been visited by more than 159,000 unique visitors from all 50 states and over 190 countries.

## 2.1 Development of Cal-Adapt 2.0

The GIF and Energy Commission launched a more powerful Cal-Adapt 2.0 in August 2017 which leverages new advances in web applications, data infrastructure, and data visualization technologies. This next generation Cal-Adapt was designed to meet the challenges of presenting newer, higher resolution data and to also address user needs and feedback gathered since its launch. The original web application served key modeled climate variables including temperature and precipitation at a resolution of approximately 7.5 miles x 7.5 miles (roughly 12 km x 12 km). New statistically downscaled projected climate variables described in section 3.1 have an improved spatial resolution of 3.7 miles x 3.7 miles (approximately 6 km x 6 km) at a daily temporal resolution. Improvements to Cal-Adapt's web architecture were required to be able to provide users with fast, dynamic, interactive exploration of these variables.

Development of Cal-Adapt 2.0 was also greatly informed by user feedback on the original site. An extensive user survey of Cal-Adapt 1.0 was conducted in 2014 by the Energy Commission, who interviewed over forty people representative of local practitioners, non-profits, academic, and private sector leaders in climate adaptation efforts. The resulting Memorandum detailing community feedback on Cal-Adapt led directly to many of the enhancements seen in Cal-Adapt 2.0. Key findings from this survey revealed that Cal-Adapt was seen as a visually appealing and valuable resource for publically available climate change information, but that many users needed additional support around how to properly use climate projections and how to apply the data on Cal-Adapt to their own applications.

Many specific suggestions from this survey have been implemented in Cal-Adapt 2.0, including: allowing users to input their own custom boundary files; improving data download so users can easily download data as charts in addition to raster and text files; improving the guidance on how to use climate data and easy-to-understand descriptions of tools; information on social vulnerability (in the form of CalEnviroScreen); showcasing work being done at the State Level through the addition of the Research Catalog from the Research Working Group of California's Climate Action Team; creating a Cal-Adapt Newsletter that updates users on new features and tools; and many others. Some helpful suggestions, such as funding a staffed help desk, have yet to be realized.

In addition to improvements suggested by the survey and other user feedback, Cal-Adapt 2.0 dramatically expands the capacities of the initial version of Cal-Adapt in four main ways: new climate projections, improved access to data, more powerful visualizations and tools, and the Cal-Adapt API. A detailed description of the many new advances can be found in Chapter 3 and on the Cal-Adapt blog: http://cal-adapt.org/blog/

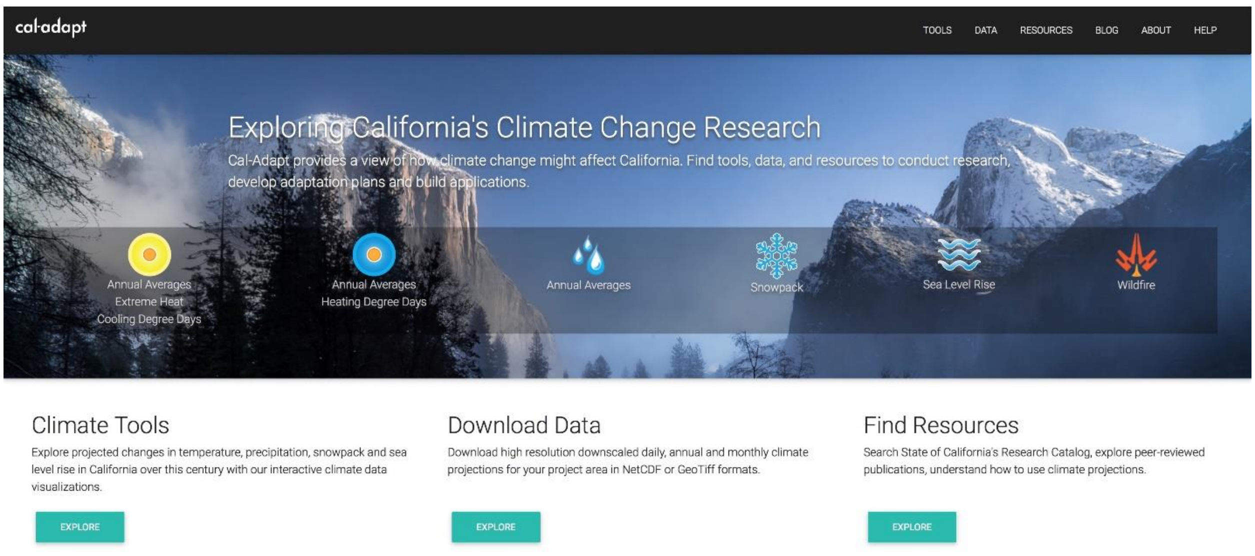


**Figure 1: Cal-Adapt 2.0 Main Landing Page**

## 2.2 User Outreach and Engagement

The GIF employed a user-centered website development approach to Cal-Adapt 2.0 that solicited feedback from stakeholders throughout the development process. Regular ongoing discussions biweekly with the Energy Commission and biannually with the Technical Advisory Committee (TAC) provide critical direction during tool development and beta testing. Initial design for new tools and features was discussed with the Energy Commission and used to build a wireframe or mock-up of the envisioned web pages. The resulting draft web tool or visualization can then be shared with the Energy Commission and others for review. This iterative development of visualizations and tools allows us to present initial tools to stakeholders, generate feedback, and then refine tool design.

TAC members include scientists and climate experts, planners and technicians, and leaders in development of local climate policy. Current and past members of our TAC have included IOUs (PG&E, SoCal Edison, and SDG&E) as well as representatives from local governments, non-profit groups, climate consultants, and state agencies such as the California Public Utilities Commission, the Governor's Office of Emergency Services, California Independent System Operator, California Department of Water Resources, and the Governor's Office of Planning and Research.

### 2.2.1 Stakeholder Meetings

Outreach to energy sector stakeholders under this grant has included personal communication with IOU's and an on-site meeting with PG&E (planning is underway for additional on-site meetings at IOU's). These meetings are intended to foster further discussion among energy stakeholders and the Cal-Adapt team to ensure that the tools and features continue to be useful and accessible. Stakeholders in several of these meetings noted that one of the most important aspects of Cal-Adapt is that it provides standardized climate scenarios that have been approved at the state level to be used in energy research and planning. These common scenarios can now be used by utilities and other state agencies to better inform climate adaptation and mitigation strategies.

In addition to IOU meetings, the GIF held a User Needs Assessment Workshop for Energy Sector stakeholders that was open to the public on September 12, 2017 under the related EPIC-funded award EPC-15-008. Participants at that workshop included natural gas sector stakeholders as well as a wide range of additional Cal-Adapt users. This workshop was designed to achieve the following goals:

- Introduce participants to the new features, tools, and data available in Cal-Adapt 2.0.
- Gather feedback regarding the current visualizations and tools on Cal-Adapt 2.0 and what additional features would be most helpful to users.
- Elicit discussion and identify new tools, visualizations, or features that can help support energy sector climate adaptation and resilience.

We organized four Focus Group sections so that we could hear directly from Cal-Adapt users in a smaller group setting. The Focus Group topics included: Climate Tools; Projected Wildfire Risks; Snowpack, Streamflow, and other Hydrological Projections; and the Cal-Adapt API. For each of these groups, facilitators had some planned questions and also allotted sufficient time for general questions and feedback.

Feedback generated during this workshop has proven to be extremely valuable and has helped to shape ongoing and future developments in Cal-Adapt. For example, suggested improvements to the Extreme Heat tool that allow user-input thresholds has recently been implemented. Another suggested feature that is being developed is a new tool that allows for batch processing of multiple point locations uploaded by users in a simple spreadsheet file such as .csv. This function is currently accessible through the API but requires some level of computer programming expertise. Building a simple tool that enables this function would alleviate the need for users to write any computer code.

Additional feedback focused on developing data visualizations for new datasets and expanding on the current visualization tools. Attendees specifically mentioned expanding on the Wildfire visualization tool with additional variables, including ways to explore the timing and severity of projected wildfires throughout the year. The inclusion of additional datasets such as CoSMoS sea level rise and urban heat islands index were identified as adding value for Cal-Adapt users. Several new visualizations were suggested that we intend to explore in future iterations of Cal-Adapt, including atmospheric rivers, landslide risk, freeze and thaw cycles, and the range of temperature within 24 hours. The full notes from each of these Focus Groups can be found online at the Cal-Adapt blog.

### 2.2.2 Natural Gas Sector Survey

The UCLA Institute of the Environment and Sustainability conducted a stakeholder engagement process to collect information to improve the usefulness of Cal-Adapt to the natural gas industry during January – March 2018. This engagement was facilitated through phone surveys of eight people who have both unique perspectives on the natural gas industry and an understanding of how planning and forecasting will be affected by climate change. The main questions asked in the survey were 1) whether the current version of Cal-Adapt is helpful for you and your industry, and 2) how Cal-Adapt can be improved to make it more useful to your business and customers.

An important finding from this survey is that utilities are currently using Cal-Adapt. One example was from Southern California Edison's use of the wildfire data, which they downloaded and integrated into their own GIS system to overlay with their infrastructure maps. The Heating Degree Day/Cooling Degree Day tool was also identified as being relevant for planning and forecasting residential demand.

Several suggestions for improvements mirror the information gathered during the User Needs Assessment workshop. Almost all respondents noted that more in-depth studies on subsidence, drought, and flooding are needed. The central valley is of particular interest, as a substantial quantity of underground natural gas infrastructure is located in that region. Participants also mentioned that urban heat island maps, along with land use and population changes, would be additional helpful data layers to include. In addition, users would like to see all expected climate impacts for a region on one map or report, instead of needing to examine each impact separately.

Energy sector stakeholders are particularly interested in being able to easily download climate projections from Cal-Adapt, so that they can overlay this data with their own private infrastructure layers. While Cal-Adapt offers a robust API through which users can aggregate data to their required timeframes or values, many users are not aware of these capabilities or do not have the staff expertise to fully exploit this capability. A working group among utilities to better define what models they would like to see on Cal-Adapt was also suggested as a way to facilitate communication regarding Cal-Adapt capabilities and future tool development.

### 2.2.3 The Cal-Adapt Newsletter

In order to connect directly with users, we launched the Cal-Adapt Newsletter in August 2015. Since then, a total of 355 subscribers have signed up to receive the Cal-Adapt Newsletter. The initial version of the newsletter on Cal-Adapt 1.0 was hosted by the GIF and was delivered by email to subscribers on a monthly basis. The newsletter was integrated with the Cal-Adapt Blog and pulled content directly from the blog into a compact layout. The blog included categories like Climate Change News, Events and Funding Opportunities, Adaptation Resources and Case Studies, and User Stories. During the transition from Cal-Adapt 1.0 to Cal-Adapt 2.0, the Cal-Adapt newsletter service was paused.

With Cal-Adapt 2.0, the Cal-Adapt newsletter has been migrated to MailerLite, a hosted newsletter service. MailerLite provides several powerful but easy to use features including simplified user subscription management, tools and examples for designing newsletters and subscription forms, and tools for tracking statistics on how users are interacting with the newsletter content. The newsletter no longer pulls content automatically from the blog. This enables design of a more customized newsletter that can include different news, content, and event announcements which may not be featured on the Cal-Adapt blog. This updated newsletter service was used to announce the Cal-Adapt and Climate Adaptation Clearinghouse Energy Sector User Needs Assessment Workshops. We will resume the regular delivery of the Cal-Adapt newsletter in June 2018 and use it to highlight new blog entries, new tutorials on using Cal-Adapt API, and new tools and data added to Cal-Adapt.

# 3: The Cal-Adapt Web Application

Cal-Adapt delivers fast, interactive, and dynamic access to best-available climate data, allowing users to explore how climate is projected to change in their region of interest. This chapter describes the data available through Cal-Adapt, details the climate visualization tools and features currently on the web site, and introduces the underlying web architecture and API that power Cal-Adapt.

## 3.1 Data Available through Cal-Adapt

The state of California has been at the forefront of climate science, funding and promoting numerous advances in climate modeling across a range of domains. Cal-Adapt provides access to this wealth of data produced by California's scientific and research community. The datasets currently hosted through Cal-Adapt are briefly described below.

### 3.1.1 LOCA Downscaled Climate Projections

The high-resolution projections presented on Cal-Adapt 2.0 align with the suite of global climate models (also known as general circulation models or GCMs) as well as the emissions scenarios that form the foundation of the United Nations' Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report or AR5 (IPCC 2014, Taylor et al., 2012). There is a vast body of literature built on this suite of models – known as CMIP5 -- and its use aligns Cal-Adapt with current, peer-reviewed science that is broadly used as a basis for policy-relevant analyses.

Because CMIP5 data describe the earth's climate system in three dimensions, it maintains a relatively coarse resolution for computational tractability. Thus, it cannot directly support local analyses of climate-related risks. To enable adequate temporal and spatial resolution for local climate analyses, global climate model results must be "downscaled" through methods that use some combination of underlying physics, local geographical features, and/or statistical relationships between historical broader-scale and local climatic observations.

Cal-Adapt 2.0 makes available new, high-resolution climate projections developed by researchers at the Scripps Institution of Oceanography at the University of California, San Diego (Pierce et al., 2018). The underlying statistical downscaling technique, known as LOCA (for **LO**calized **C**onstructed **A**nalogues), was developed to address prior methods' limitations with regard to representing temperature extremes and spatial distribution of precipitation (Pierce et al., 2014). These improvements are critical, because extreme events associated with temperature and precipitation drive many of the economic and health-related impacts of climate change. LOCA results are highly-resolved in both space (1/16˚ grid, ca. 3.7 miles × 3.7 miles) and time (daily resolution).

#### *3.1.1.1 Underlying Data and Climate Model Selection*

Through Cal-Adapt, users can download LOCA downscaled projected climate data associated with 32 General Circulation Models (GCMs) for two Representative Concentration Pathways (RCPs), which address varying possible future greenhouse gas and emissions scenarios. The RCP 4.5 scenario represents a medium emissions future where societies work to reduce greenhouse gas emissions. The RCP 8.5 scenario represents a "business as usual" future that is used to explore a higher emissions scenario.

However, the full set of 32 LOCA downscaled climate models produces a large amount of data (approximately 40 TB), which is unmanageable for many potential users. A subset of 10 representative models was selected to provide a range of possible climate futures while reducing the data volume. These 10 models were identified by the California Department of Water Resources (DWR) Climate Change Technical Advisory Board (CCTAG), a diverse team of professional scientists and practitioners. Model selection was based on their performance with regard to simulating historical climate means and variability related to water resources and hydrological extremes at a variety (global, regional, California) of scales, and is described in detail in the *Perspectives and Guidance for Climate Change Analysis* (DWR, 2015). This contribution is important because it offers a more tractable subset of the vast body of available data, and the subset is strategically selected to be suitable for California climate and water resource planning. The majority of data visualizations on Cal-Adapt showcase these 10 California GCM's.

Many researchers and practitioners with climate change-related concerns do not presently have the resources to consider even the full subset selected by DWR's CCTAG. With that in mind, a more manageable subset of those ten models was identified by the Climate Action Team Research Working Group with input from researchers contributing to California's Fourth Climate Change Assessment and in coordination with the Governor's Office of Planning and Research Adaptation Technical Advisory Group. Based on systematic statistical analyses delineated by Scripps Institution of Oceanography (Pierce et al., 2018), four global climate models were chosen to represent a range of possible futures for California: HadGEM2-ES ("warm/dry"), CNRM-CM5 ("cool/wet"), CanESM2 ("average"), and MIROC5 ("complement" or "diversity"). The statistical analyses consider the models' LOCA downscaled projections over the state of California for criteria of significance with regard to climate change. These criteria relate to temperature (maximum daily temperatures and variability thereof) and precipitation (average, dry spells, and variability).

The following points are important to note:

- Although the models are described as "warm/dry", "cool/wet", "average", and "complement", these monikers are apt only in a statistical sense based on analysis of the entire state of California over the 2015-2100 timeframe. In other words, the so-called "hot/dry" model should not be assumed to be the "hottest/driest" for a particular visualization or analysis.
- The so-called "cool/wet" model still describes a warming climate, but one that (in a statistical sense over the 2015-2100 timeframe) is relatively cooler and wetter than the other DWR CCTAG models.

#### *3.1.1.2 LOCA Projections Hosted through Cal-Adapt*

Downscaled climate projections from global models using LOCA (Localized Climate Analogues) for maximum temperature, minimum temperature, precipitation, and relative humidity are available on Cal-Adapt. The daily LOCA projections for the full set of 32 GCM's is available as NetCDF files from the Cal-Adapt Data Server. Data for the 10 California GCMs (CESM1-BGC, CMCC-CMS, CNRM-CM5, CanESM2, GFDL-CM3, HadGEM2-CC, HadGEM2-ES, MIROC5, ACCESS1-0, and CCSM4) selected by DWR's CCTAG (DWR, 2015) are also available through the Cal-Adapt API in additional formats (e.g. GeoTIFF, CSV, JSON).

The spatial extent available on Cal-Adapt covers the entire states of California and Nevada and parts of Oregon, Mexico, and Arizona. Details are described in Pierce et al. (2014). The LOCA output are available for the following scenarios:

- A historical run from 1950–2005.
- Two future GHG emissions scenarios (Middle: "RCP 4.5" and High: "RCP 8.5") from 2006–2100 (or 2099).

The daily maximum temperature, minimum temperature, and precipitation LOCA output has been further processed to create the following summaries available on Cal-Adapt:

- An envelope of modeled variability that represents the range of highest and lowest annual average values from all 32 LOCA downscaled climate models.
- Annual averages of the daily LOCA projections for selected 10 models.

### 3.1.2 Historical Gridded Data

A gridded dataset of historical observed daily temperature and precipitation data over 1950-2013 is available on Cal-Adapt. Observation-based meteorological data sets offer insights into changes to the hydro-climatic system by diagnosing spatio-temporal characteristics and providing a historical baseline for future projections. As with the LOCA projections, the spatial resolution of this data is 1/16° (approximately 3.7 miles x 3.7 miles). The spatial extent available on Cal-Adapt covers California and Nevada and parts of Oregon, Mexico, and Arizona. The daily historical data is available as NetCDF files from the Cal-Adapt Data Server. The daily data and annual averages are also available through the Cal-Adapt API in other formats (e.g. GeoTIFF, CSV, and GeoJSON). Details are described in Livneh et al. (2015).

### 3.1.3 Additional Climate Variables (VIC)

Cal-Adapt provides additional high-resolution projections for climate variables derived from the Variable Infiltration Capacity (VIC) Model, a land surface/hydrology model, originally developed by Xu Liang at the University of Washington (Liang et al., 1994). The VIC derived climate variables are forced by both the LOCA downscaled climate projections and the gridded historical data. The following list of VIC variables are available in NetCDF format on Cal-Adapt Data Server:

- Evapotranspiration
- Runoff
- Soil moisture (3 layers)
- SWE (snow water equivalent)
- Daily change in SWE
- Snowfall rate
- Rainfall rate
- Snow melt rate
- Dew rate
- Sensible heat

- Latent heat flux
- Potential evapotranspiration (PET) from vegetation
- Air temperature (2 m daily average)
- Relative humidity (2 m above surface)
- Specific humidity (2 m above surface)
- Albedo (surface reflectivity) (fraction)
- Shortwave down radiation
- Shortwave net radiation
- Longwave net radiation
- Sublimation net

### 3.1.4 Sea Level Rise CalFlod-3D

This data provides predicted inundation location and depth for the San Francisco Bay area, the Sacramento-San Joaquin River Delta, and the California coast during extreme storm events occurring in conjunction with different sea level rise scenarios (No rise, 0.5 m, 1.0 m, 1.41 m). Details are described in Radke et al. (2016). The San Francisco Bay and Sacramento-San Joaquin Delta are modeled at spatial resolutions ranging from 3m x 3m to 12m x 12m tiles. Due to the large extent of the California coast, coastal areas are modeled at a coarser resolution of 50m x 50m tiles and do not include surface object elevations. The data is available for download in GeoTIFF format and can be accessed through the Cal-Adapt API.

This research is unique and innovative in its dynamic spatial detail and the fact that it incorporates real, time series water level data from past (near 100-year) storm events to capture the dynamic effect of storm surges in modeling inundation using 3Di, a three-dimensional hydrodynamic model along with high resolution earth surface models (Stelling, 2012).

#### *3.1.4.1 Spatial Resolution and Extent*

Cal-Adapt provides inundation depth mosaics derived from the original tiles for the San Francisco Bay area, the Sacramento-San Joaquin Delta and the entire California coast. The mosaics were produced using the following steps:

- Resampling the inundation depth layer for each tile to 3m x 3m spatial resolution for the San Francisco Bay and Sacramento-San Joaquin Delta. The coastal data retains the original resolution of 50m x 50m.
- Rounding the inundation depth values (in meters) to 3 decimal places.
- Mosaics are assembled as maximum of source layers.

Data is available for inundation based on a real near 100-year storm event coupled with 0.0, 0.5, 1.0, and 1.41 meters of sea level rise.

### 3.1.5 Wildfire

Wildfire scenario projections exploring large (>400 ha) wildfires were provided by Dr. LeRoy Westerling at the University of California Merced, using a statistical model based on historical data of climate, vegetation, population density, and fire history coupled with regionally downscaled LOCA climate projections. The modeled data is available for 4 GCMs (CanESM2, CNRM-CM5, HadGEM2, and MIROC5), 2 scenarios (RCPs: 4.5 and 8.5) and 3 population growth conditions (high, low, and business as usual [i.e., central]). The modeling uses the downscaled LOCA climate projections as inputs and therefore is considered as secondary scenarios in the Fourth Assessment. The GCMs and RCPs used are the "priority" scenarios recommended for California's Fourth Climate Change Assessment. Details are described in Westerling (2018).

Population and vegetation projections were developed by external collaborators of the Fourth Assessment. California Department of Finance (DOF) projections of county-level population at five-year increments through 2060 were extended by Ethan Sharygin of DOF to 2100 with three trajectories — Central, Low, and High scenario. These population projections were used to drive a land use change simulation model (LUCAS) by the USGS (Sleeter et al., 2017). The land use/land cover scenarios represent changes in a suite of classes of land use and land cover related to urbanization, agricultural expansion and contraction, forest harvest, wildfire, and other processes. Development was simulated based on the DOF population projections, whereas all other land use changes were based on historical data. The LUCAS scenarios generated a set of 10 Monte Carlo simulations at 1 km spatial resolution and one-year time steps for each DOF population projection, which was converted into proportion of the 1/16° grid cells that were vegetated (i.e., burnable wildland fuel). The population and land use scenarios are described in Sleeter et al. (2017).

List of Global Climate Model (GCM), Representative Concentration Pathway (RCP) and Population/Vegetation (Cond):

- GCMs: CanESM2, CNRM-CM5, HadGEM2, and MIROC5
- RCPs: 4.5 and 8.5
- Conditions: H, L, and bau (high, low, and business as usual [i.e., central])

#### *3.1.5.1 Wildfire Modeling*

For each combination of GCM, RCP, and Cond, 100 simulations were run with the stochastic modeling framework. Area burned was aggregated by year and grid cell. If the burned area was larger than the average amount of vegetation in a grid cell, burned area was allocated to the surrounding grid cells. Thus 24 wildfire scenarios were generated (4 GCMs * 2 RCPs * 3 Cond), with 1000 simulations each (10 land use simulation * 100 fire simulations). The mean area burned was also calculated for all 10 stochastic variations for each GCM/RCP/condition combination.

The fire severity modeling estimated the fraction of burned area in various severity classes, which is defined by the proportion of basal area removed by fire. Land managers were also interested in the potential effect on fire severity of the massive tree mortality experienced by California's conifer forests during the recent historic drought. Researchers at UC Merced conducted a sensitivity analysis that varied the historical probability of high severity fire (greater than 90% of basal area of vegetation removed by fire) in cells with greater than 50% tree mortality based on mapping data from the US Forest Service. The sensitivity analysis was only performed in the Sierra Nevada region because of lack of data from conifer forests in other forested regions and because wildfire in non-forest vegetation is typically high severity (e.g., grassland and chaparral).

#### *3.1.5.2 Outputs*

- Annual Area Burned - Each float precision element corresponds to hectares of burned area in the cell. The four NetCDF dimensions for annual simulations of area burned are:
    - lon: Longitude in degrees west
    - lat: Latitude in degrees north
    - sim: Simulation numbers 1—10, one for each stochastic variation
    - time: Years since 1953
- Average Annual Area Burned - Each float precision element corresponds to hectares of burned area in the cell, averaged across all 10 stochastic variations. The three NetCDF dimensions for annual averages across the 10 land use (cond) simulations are:
    - lon: Longitude in degrees west
    - lat: Latitude in degrees north
    - time: Years since 1953
- Fire Severity (forthcoming).

### 3.1.6 Extended Drought Scenarios

Cal-Adapt provides data for two scenarios portraying extended (20-year) drought conditions in order to investigate the implications of long droughts under expected rising temperatures (Pierce et al., 2018). Regions of particular interest for this investigation were the North Central Coast and Sierra Nevada which are critical to California's water supply. In order to determine what constitutes an extended drought scenario in these regions, researchers looked at the observed precipitation record as provided by the California Climate Tracker. Severe droughts that extend for 20 years were identified as reaching deficit precipitation levels that are 80-90% of the historical median in these regions. LOCA data was investigated and one 20 year span (2051-2070) associated with the HadGEM2-ES downscaled projection for RCP 8.5 was found to exhibit

78% of historical median annual precipitation, averaged over the North Coast and Sierra regions.

An additional drought sequence from earlier in the century (2023-2042) was also constructed by adjusting the temperatures for the later century drought to cohere with an earlier time frame (Pierce et al, 2018). The time periods include 5 years pre-drought and 4 years post-drought in addition to the 20 extended drought years. In addition, VIC hydrological models were run for the extended drought scenarios. Additional details on these extended drought scenarios can be found in Pierce et al., 2018.

Daily data is available over two periods, 2018–2046 and 2046–2074 for the following variables:

- Maximum Temperature
- Minimum Temperature
- Precipitation
- Select VIC parameters: Evapotranspiration, Base flow, Runoff, Soil Moisture (3 layers)

### 3.1.7 Streamflow

Along with projected increased temperatures and decreased snowpack, streamflows are also projected to shift in their timing. Of particular concern in California is the spring snowmelt, which feeds streamflow when it is needed most for irrigation and energy purposes. The Streamflow tool on Cal-Adapt enables the user to explore the timing and magnitude of streamflow in selected months of the water-year, which runs from October 1 to September 30th (i.e. water year 2018 runs from October 1, 2017 to September 30, 2018).

Because California's major watersheds have been altered by large-scale projects—such as dams and diversions, which enable human management of water to meet needs related to agriculture, urban uses, energy, and ecology —it would be misleading to directly compare observed stream flows at a given location. Streamflow is instead calculated for "unimpaired" flows, which would occur if flows were not subjected to storage in reservoirs or to diversions such as irrigation, power generation, or water supply.

Bias-corrected streamflow projections have been developed at UCSD's Scripps Institution of Oceanography (Pierce et al., 2018). Streamflows were calculated at 11 selected locations in the Central Valley tributary to the Sacramento-San Joaquin Delta, for which sufficient historical data are available for bias correction. Projected, bias corrected streamflow (1950-2099, RCP4.5 and RCP8.5) was generated through first routing runoff results of the VIC model driven by the daily temperature and precipitation LOCA projections. Then, the streamflows were bias-corrected based on the Department of Water Resources' estimates of unimpaired flows through 2014 (California Department of Water Resources, 2016).

Monthly average bias-corrected unimpaired streamflows (cubic feet per second) are available through over the period 1950-2100 at 11 point locations for the 10 recommended California GCM's.

### 3.1.8 Vector Boundaries

In addition to climate data, the Cal-Adapt API also has endpoints for vector datasets representing administrative boundaries, hydrological boundaries and the LOCA model grid.

- LOCA Model Grid (1/16˚ - Approximately 6 km)
- California counties
- Watersheds (HUC10)
- Census Tracts with CalEnviroScreen 2.0 scores
- 114th congressional districts
- Incorporated & census designated places, 2015
- Integrated Regional Water Management (IRWM) Regions
- SWITCH Load Zones
- Climate Zones
- Investor and public owned electrical utilities
- California's Fourth Climate Change Assessment Regions
- State of California

## 3.2 Data Access

The GIF employs a hybrid data storage structure to host the large stores of climate data available through Cal-Adapt. Selected data that form the basis for the powerful visualization tools are available through the Cal-Adapt API on Amazon Web Services (AWS) within an optimal extra-large Elastic Compute Cloud (EC2) instance type that allows for fast, interactive, and dynamic visualizations on the web. Primary datasets which are not used to generate interactive web visualizations but are important to climate science research are available in NetCDF format and hosted on the Cal-Adapt Climate Data Server, which is a 25 Terabyte server managed by the GIF.

Cal-Adapt 2.0 enables access to data through a number of options:

- **Primary NetCDF data:** Cal-Adapt 2.0 provides direct access to data for all 32 LOCA downscaled CMIP5 models for 2 RCP scenarios (RCP4.5, RCP8.5) plus the historical modeled period as well as historical observed gridded data. These data are available directly from a server maintained by the Geospatial Innovation Facility at UC Berkeley as well as through several resources for which links are provided on Cal-Adapt 2.0.

- **GeoTIFF:** Users can download data for a user-specified geographic extent and for selected variables, scenario, period (daily vs. annual averages), and GCM in GeoTIFF format from the Data page.

- **.CSV** download of data depicted on charts: time series shown on Cal-Adapt 2.0 charts can be downloaded directly into a .csv file for easy exploration with other software programs.
- **Cal-Adapt API:** The API provides programmatic access to climate data hosted on Cal-Adapt. The API returns data in different formats, e.g. JSON, GeoTIFF and CSV.

### 3.2.1 Data Download Tool

Users are able to access and download the primary scientific data for all of the climate variables identified in section 3.2 through the Data Download page shown in Figure 2. For the selected variables that are maintained on the API and used to generate data visualization tools, the data can be accessed using a map interface, where users can select their spatial extent, climate variable, climate scenario, time period, GCM, and desired output format (csv, JSON, or GeoTiff). Options for spatial sub- setting include drawing a rectangle on the map or selecting one of the pre-defined boundary layers.

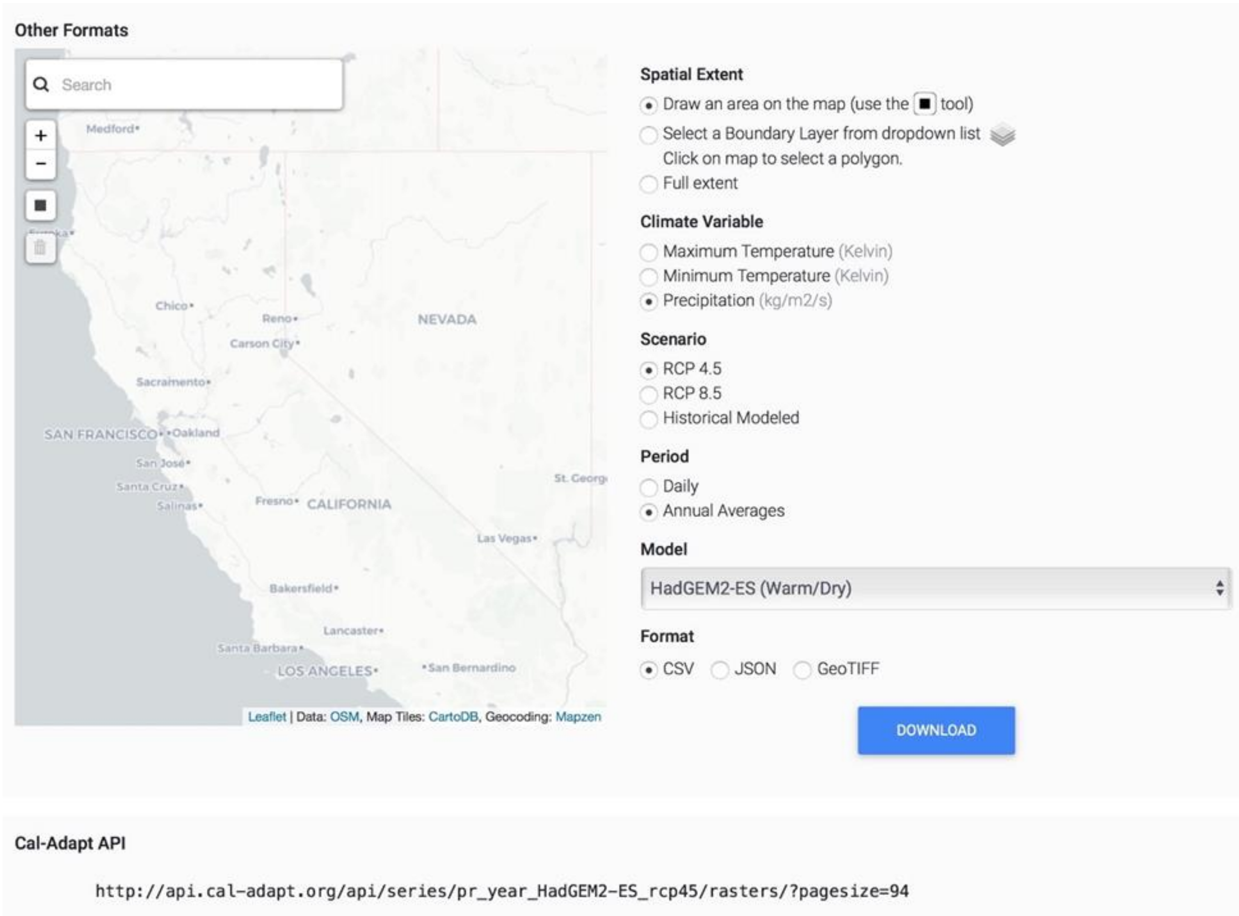


**Figure 2: The Data Download Map Interface. This tool allows access to the primary scientific datasets hosted by Cal-Adapt in a variety of file formats. This example is for the LOCA downscaled climate variables: maximum temperature, minimum temperature, and precipitation. The API call is included on the page so users can access data with additional filters directly via the API.**

## 3.3 California Climate Data Visualizations and Tools

Development of Cal-Adapt 2.0 has included the creation of many enhanced and updated features that improve climate data exploration. These new features have been developed in response to user feedback, including suggestions from the Technical Advisory Committee as well as through general comments to support@cal-adapt.org. Updates include:

- *Boundary choices for aggregation and visualization of data*: In addition to the default 1/16° grid used by LOCA, Cal-Adapt enables users to view and aggregate data according to a number of different boundary options, including: counties, census tracts, and congressional districts, incorporated and census-designated places, watersheds, and electric utility service territories. Most tools also enable users to aggregate and view data for integrated regional water management regions, climate zones, load zones associated with the SWITCH-WECC model, and the state of California as a whole.

- *Ability to investigate disadvantaged communities using CalEnviroScreen*: To facilitate investigation of climate risks in disadvantaged communities (DACs), Cal-Adapt's census tract selection tool presents CalEnviroScreen 2.0 scores and color codes census tract by score.
- *Enable user to upload their own boundary for aggregation and visualization of data*: Cal-Adapt 2.0 also enables users to upload a custom shape file as the basis for aggregation and visualization of data, to facilitate direct investigation on Cal-Adapt of areas that are highly specific to a particular user. The boundary can be uploaded in a variety of different formats e.g., ESRI Shapefile, GeoJSON, KML, WKT. This feature is useful for users who want to work with sensitive or proprietary information.
- *Slider Widgets*: Cal-Adapt 2.0 provides slider widgets for visualizations of climate and hydrological projections as well as wildfire risk. These sliders enable the user to average the graphed value over a user-specified historical period as well as a user-specified projected period.
- *Improved descriptions*: Visualizations on Cal-Adapt include brief descriptions of the underlying emissions scenario and location depicted, as well the data depicted in the chart.
- *Representation of envelope associated with CMIP5 models*: Time series charts for climate and hydrological parameters include a shaded "envelope" defined by the maximum and minimum values from the CMIP5 ensemble of climate models (n=32) that allows users to visualize the full range of modeled climate projections.
- *Visualization of historical observed data through 2005*: Time series charts for climate and hydrological parameters include observed historical data (temperature, precipitation) or data derived from historical observations of temperature and precipitation in the case of hydrological parameters (e.g., snowpack).
- *Ability to zoom in on a particular time interval*: For time series charts, Cal-Adapt enables the user to select a subset of the full-time interval shown (1950-2100), enabling the user to zoom in on a period of interest.
- *Save chart*: Charts can be downloaded directly from Cal-Adapt as PNG files. Planned improvements will also allow users to save charts in full resolution SVG format, which will better enable publication quality graphics.

### 3.3.1 Climate Exploration Tools

Cal-Adapt provides a suite of visualization tools that depict climate-related risks to a location of interest for stakeholders who are responsible for protecting energy infrastructure and planning for future reliability. Users are able to explore charts, maps, and data of observed and projected climate variables for California. The tools show projections for two possible climate futures, one in which emissions peak around 2040 and then decline (RCP 4.5) and another in which emissions continue to rise throughout the 21st century (RCP 8.5).

A key feature of the Cal-Adapt climate tools is the ability to quickly download the data shown in the data visualization, either by saving the chart as a .png graphic file or by downloading the timeseries data as a .csv file. Users can then easily include the graphic files directly into a report or document and further analyze the data in a variety of spreadsheet applications.

For most tools, the default climate models shown are for the four California selected models, although users can also select additional models from the set of 10 recommended models for analysis. The **Quick Stats widget** allows users to select their time period of interest. Tools automatically default to a historical (1961-1990) and an end-of-century (2070-2099) time periods. However, users can easily change the time period of interest by using the slider bars. Associated charts are dynamically updated for the selection, allowing users to explore climate variables and compare projections to observed and modeled historical data. The values displayed are the average values from the models selected by the user.

Users can also select their geographic region of interest by selecting individual grid cells, using the pre-loaded boundary layers, or by uploading their own region of interest. The **Change Location widget** allows users to define their geographical area of interest in a variety of ways. The Search bar allows users to input a place name or address to find a particular location. Users can also navigate by using the map interface and double-clicking on a grid cell of interest. Data can be visualized either at the LOCA raster grid cell level, or by aggregating the data over a boundary layer. Users can select one of the eleven pre-loaded boundary layers available or can choose to upload their own spatial layer in shapefile, GeoJSON, KML, or WKT file format. Boundary layer information can also be selected through a list format. In addition, California's electrical grid as supplied by the California Energy Commission can be visualized on top of the map, including Substations, Power Plants, and Transmission Lines. Interactive pop-ups display additional information for the electrical grid features. Click on the Update Chart button to explore the selected region through the charting tools. The GIF development team worked with the original data authors to develop visualization and exploration tools to help others understand the most important findings in the data. Our process includes review of tools with key users and CEC partners and then refining tools based on user-generated feedback. Additional information included on each tool includes a brief description to clarify use of the tool. The data sources used for each tool are included along with a link to related peer-reviewed publications. Any additional processing that was performed at the GIF is also noted on each tool.

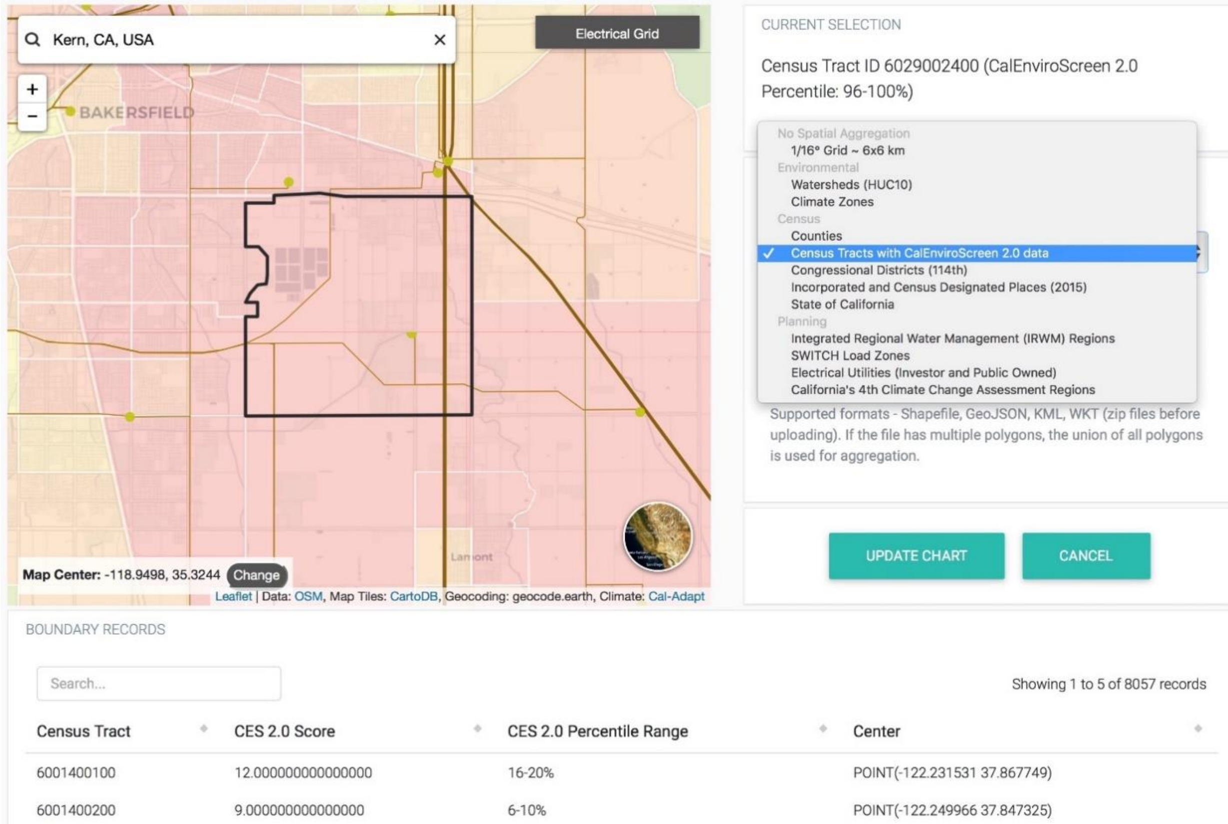


**Figure 3: The Change Location widget allows users to define their geographical area of interest in a variety of ways. The example shown here is for a Disadvantaged Community in Bakersfield, using the CalEnviroScreen 2.0 data layer with the Electrical Grid displayed on the map.**

Cal-Adapt Climate Tools allow users to explore:

- Annual Averages: projected annual averages of maximum temperature, minimum temperature, and precipitation.
- Extreme Heat: projected frequency and duration of extreme heat events.
- Sea Level Rise: CalFloD-3D: maps of inundation location and depths for the San Francisco Bay Area, the Sacramento-San Joaquin Delta, and the California Coast during near 100 year storm events coupled with projected Sea Level Rise scenarios.
- Snowpack: time-lapse animation and monthly averages of projected Snow Water Equivalent (SWE), a common measurement of snowpack.
- Wildfire: annual averages of area burned for a combination of 4 GCMs, 2 RCPs and 3 population growth scenarios.

- Heating Degree Days and Cooling Degree Days: projected changes in HDD and CDD, which are a common proxy for energy needed to heat and cool buildings.
- Stream Flow: charts of VIC routed and bias corrected streamflows driven by LOCA downscaled temperature and precipitation.

All of these tools allow users to visualize, graph, and download the data that shows how climate is projected to change for their own area of interest. For example, a utility could upload the boundary or location of a particular infrastructure asset and generate information detailing the number of extreme heat days expected by mid-century and end-of-century to identify assets that may be vulnerable to new conditions under a changing climate. We describe a few of the tools designed to aid the energy sector in greater detail here:

#### *3.3.1.1 Annual Averages*

With this tool users can explore projections of annually averaged maximum temperature, minimum temperature, and precipitation. These climate projections have been downscaled from global climate models from the CMIP5 archive, using the Localized Constructed Analogs (LOCA) statistical technique developed by Scripps Institution of Oceanography. Users are able to explore the Annual Averages results for a selected scenario (RCP 4.5 or RCP 8.5), select a geographic region of interest, select one or more out of 10 available GCM's, and select modeled historical data in addition to the observed historical data. Historical observed daily temperature and precipitation data developed from NOAA Cooperative Observer (COOP) stations form the basis of the gridded dataset from 1950–2013 at a spatial resolution of 1/16° , approximately 3.7 miles x 3.7 miles (Livneh et al., 2015). When the "show modeled historical" button is checked, the Quick Stats widget is updated to include the mean values for both modeled and observed historical data.

In order to create the data layers used in this visualization tool, we calculated annual averages of daily values of maximum temperature (daily high), minimum temperature (daily low), and precipitation for each year (1950–2100). This process was done for each of the 32 LOCA downscaled climate models for the historical scenario and the future scenarios - RCP 4.5 and RCP 8.5. An envelope of modeled variability for each variable-scenario combination was generated by selecting the highest and lowest values from annual averages of all 32 LOCA downscaled climate models which allows users to visualize the full range of values from all 32 downscaled CMIP5 models.

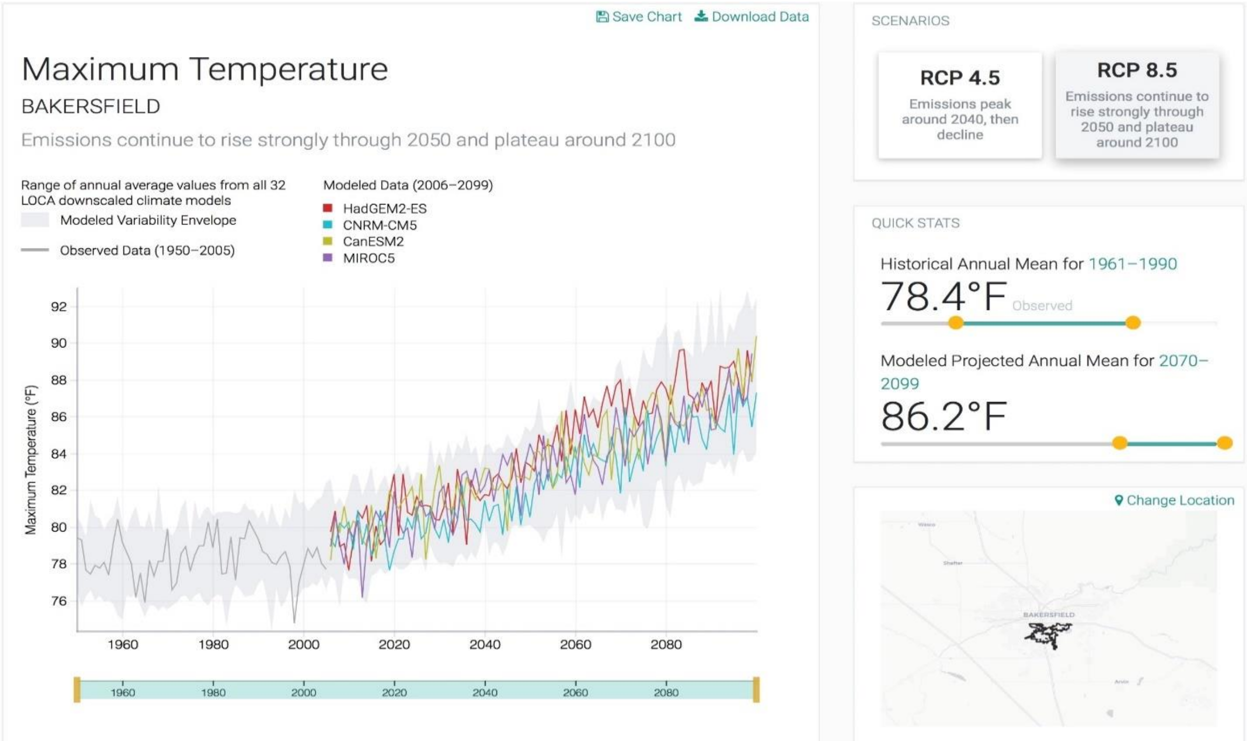


**Figure 4: The Annual Averages Visualization Tool. This tool allows users to explore the LOCA projections of annually averaged maximum temperature, minimum temperature and precipitation. The example shown here is for maximum temperature in the City of Bakersfield, CA with the high emissions scenario RCP 8.5 selected. This tool includes several interactive features including selection of scenario and GCM's (default 4 priority models are shown); option to include the modeled historical data as well as the observed historical; time sliders in the Quick Stats widget which allow users to examine different time horizons; and the Change Location widget to explore different geographical locations.**

#### *3.3.1.2 Wildfire Tool*

The wildfire tool explores wildfire scenario projections generated by Dr. LeRoy Westerling at the University of California Merced, using a statistical model based on historical data of climate, vegetation, population density, and fire history coupled with regionally downscaled LOCA climate projections. This dataset is described briefly in section 3.1.5 and in depth in Westerling (2018).

The wildfire visualization tool allows users to select among 4 GCMs (CanESM2, CNRM-CM5, HadGEM2, and MIROC5), 2 scenarios (RCPs: 4.5 and 8.5) and 3 population growth conditions (high, low, and business as usual [i.e., central]). Users can view charts illustrating the projected annual average of area burned for the identified area of interest. As in other Cal-Adapt tools, users can customize their area of interest by using the pre-loaded boundary layers or their own uploaded boundary file.

This tool also includes an animated map visualization, along with the charting capabilities seen in our other tools. The animated map allows users to vary the GCM, scenario, and population growth conditions of interest. Interactive features include buttons to play and pause the animation, the ability to zoom and pan on the map, and an option to change the basemap in the background to satellite imagery. For the map animation, the annual area burned can be averaged over either a 5 year or 10 year time interval.

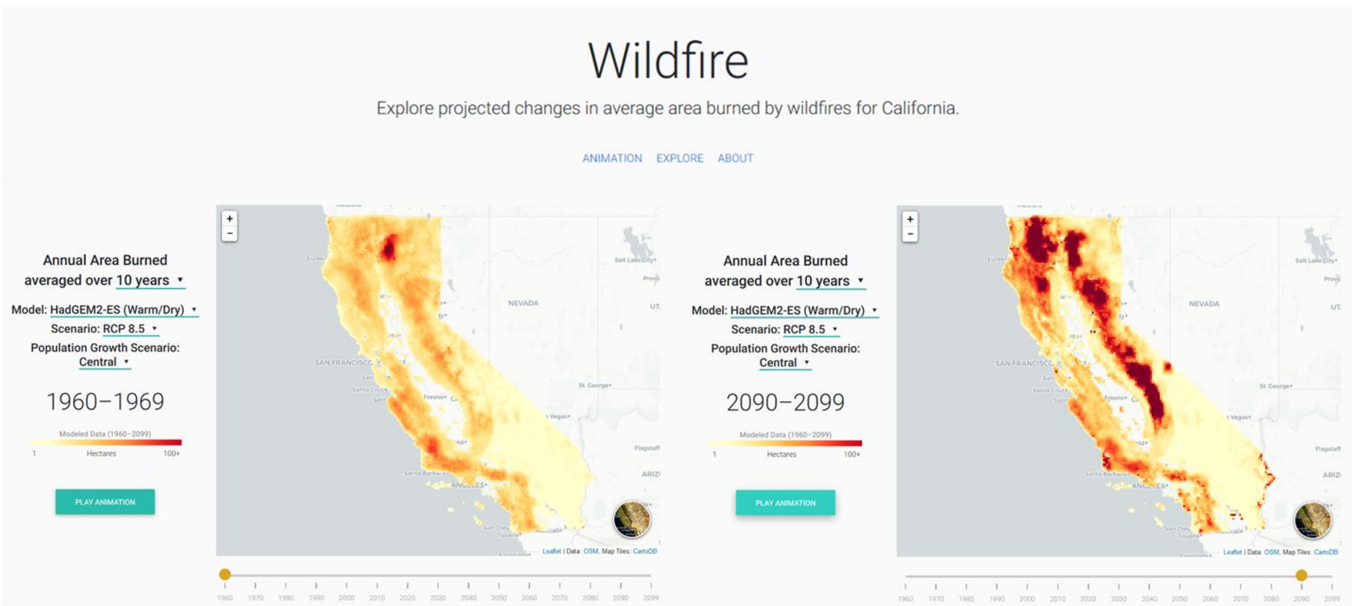


**Figure 5: The Wildfire Map Animation. The Wildfire map animation allows users to visualize wildfire projections on an animated loop. This graphic shows the start and end points of the animation. Modeled annual area burned can be averaged over either a 10 year or 5 year time span in this data visualization. Users can interactively select the GCM, RCP scenario, and population growth scenario of interest. The image on the left is showing modeled data for the 1960-1969 time period, and the image on the right shows projected annual area burned at the end of century, 2090-2099. Both images represent the HadGEM2-ES model with RCP 8.5 and a medium population growth scenario, averaged over 10 years.**

#### *3.3.1.3 Cooling Degree Days (CDD) and Heating Degree Days (HDD) Tool*

With this tool, users can explore how Cooling Degree Days (CDD) and Heating Degree Days (HDD), which are proxies for energy used to heat and cool buildings, are expected to change under different emissions scenarios and climate models. Users can customize the metric for CDDs and HDDs by selecting the entire year or a specific portion of the year for inquiry.

CDDs and HDDs are often used by utilities and other energy sector planners to understand energy demand for cooling and heating. As California's climate changes, historical observed climate is becoming an increasingly poor proxy for future energy demand for cooling and heating. For example, warming temperatures are expected to decrease demand for home heating in the winter. The underlying data are derived from daily climate projections that have been downscaled using the [Localized Constructed Analogs] (LOCA) statistical technique developed by Scripps Institution of Oceanography.

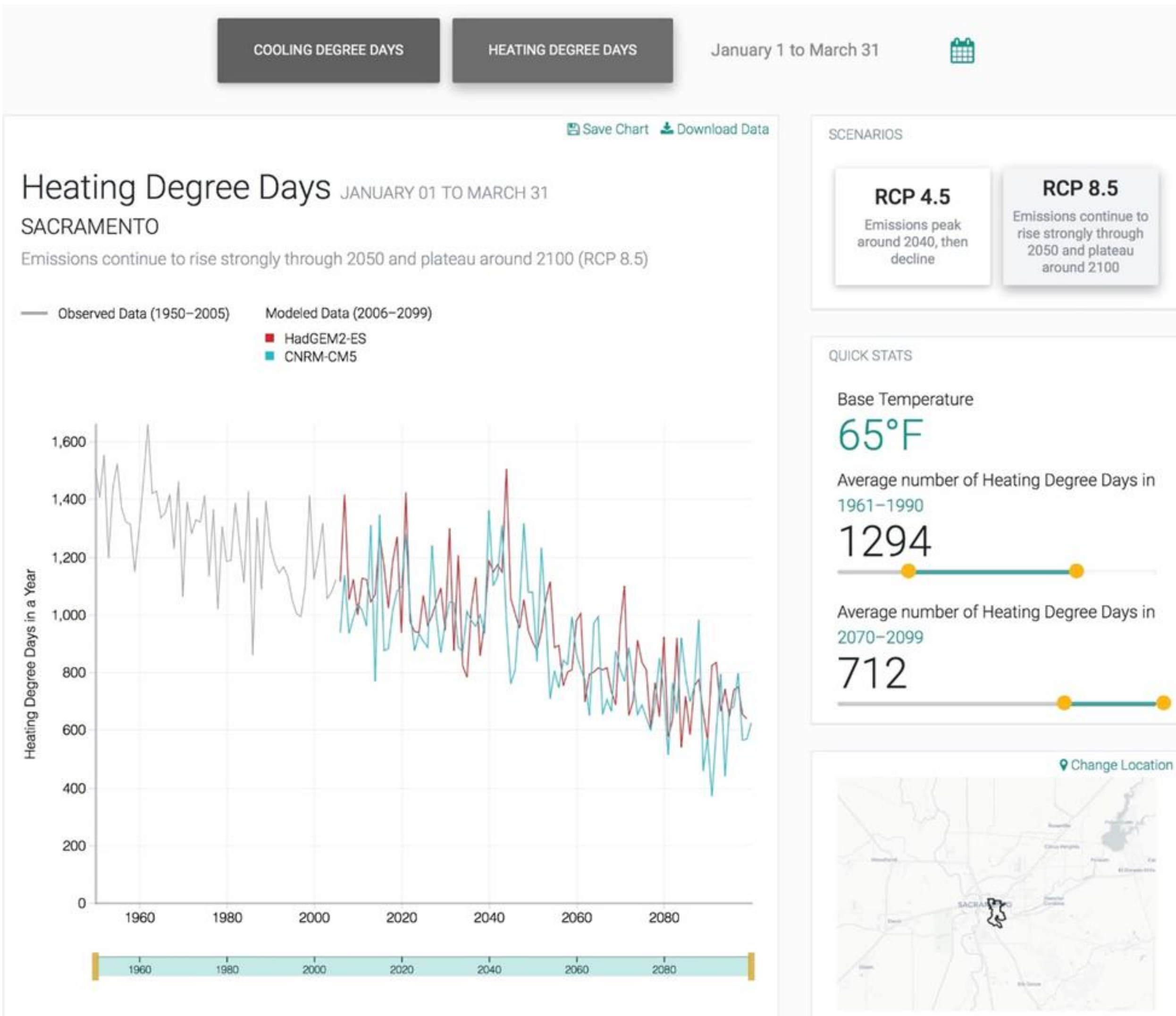


**Figure 6: The Heating Degree Day Tool. The Heating Degree Day tool is shown for the City of Sacramento under the high emissions RCP 8.5 scenario, for two climate models. Note that users can interactively select the time period over which to calculate the CDDs and HDDs. In this case we are looking at winter months from January 1- March 31st. Warming temperatures are expected to result in a decline in HDD throughout California, and a consequent decline in natural gas demand for space heating.**

*What is a Heating Degree Day?*

A Heating Degree Day (HDD) is defined as the number of degrees by which a daily *average* temperature is below a *reference* temperature. The *reference* temperature is typically 65 degrees Fahrenheit, although different utilities and planning entities sometimes use different *reference* temperatures. The reference temperature loosely represents an average daily temperature above which space heating is not needed. The *average* temperature is represented by the average of the maximum and minimum daily temperature. HDDs can be summed over the entire year or over a portion of the year (e.g., the month of February) as a rough indicator of heating energy over that period.

*What is a Cooling Degree Day?*

A Cooling Degree Day (CDD) is defined as the number of degrees by which a daily *average* temperature exceeds a *reference* temperature. The *reference* temperature is typically 65 degrees Fahrenheit, although different utilities and planning entities sometimes use different *reference* temperatures. The reference temperature loosely represents an average daily temperature below which space cooling (e.g., air conditioning) is not needed. The *average* temperature is represented by the average of the maximum and minimum daily temperature. CDDs can be summed over the entire year or over a portion of the year (e.g., the month of July) as a rough indicator of cooling energy over that period.

Mathematically, HDDs and CDDs are constructed thus for a given location:

$$HDDs = \Sigma[(MAX((T_{ref} - T_{central}),0))\times 1 \text{ day}]$$

$$CDDs = \Sigma[(MAX((T_{central} - T_{ref}),0))\times 1 \text{ day}]$$

The summation is over a given number of days. $T_{central}$ represents a central estimate of (approximately "average") temperature at the location in question and $T_{ref}$ is a reference temperature used for the purposes of the calculation. Because daily $T_{max}$ and $T_{min}$ are more readily available from both modeling and historical observations than is the actual daily average temperature, the $T_{central}$ is typically constructed as the "mid-point" temperature that is the average of $T_{min}$ and $T_{max}$. Typically, $T_{ref}$ is 65° F, but some utilities may use other reference temperatures for calculating CDDs and HDDs.

As with other Cal-Adapt climate tools, the user is able to calculate the CDDs and HDDs for a variety of pre-loaded shape files as well as for a user-defined shape file or a single grid cell. One crucial difference in this tool is that calculations are summed over the CDDs and HDDs for grid cells within the area under consideration, rather than averaged over the boundary as is seen in other tools.

As shown in Fig. 6, users are also able to select the time period over which to calculate CDDs and HDDs. Users can either use the default of calculating over a year or can explore individual months or seasons over which to calculate degree days. Users can also change the date range to explore using the Quick Stats widget slider bars. This allows greater user flexibility: for example, one user might choose to explore CDDs during the month of July for 2070-2099; another might want to calculate historical HDDs over the entire cold season (e.g., December-March) for 1961-1990.

## 3.4 Web Architecture and API

Cal-Adapt is built on top of the Django web framework along with supporting libraries such as the Geospatial Data Abstraction Library (GDAL), NumPy, and Mapnik. GDAL allows for the reading and translation of raster inputs while NumPy treats these inputs as multidimensional arrays with flexible summarization capabilities for dynamic spatial and temporal aggregation. Additional capabilities for spatial querying and manipulating geo-formats are provided by the Django-Spillway package, an open source library developed at GIF. The combined web framework provides fast and dynamic temporal aggregation of time series data and spatial aggregation by different vector boundaries.

The Cal-Adapt API (Application Programming Interface) is built using the REST (Representational State Transfer) framework which provides a powerful and flexible toolkit for building Web APIs. Compared to other forms of web services, simplicity, ease of use, and interoperability are among the main advantages. An API makes it possible for different software applications to communicate effectively with each other by defining a set of requirements for how applications can share data and defining what actions can be taken (for example, directly subsetting the climate data by a private uploaded boundary file). The Cal-Adapt API enables programmatic access to climate data hosted on Cal-Adapt and provides developers, researchers, and climate specialists with a new tool for working with the wealth of data and information that has been, and continues to be, produced by State of California's scientific and research community. The API allows users to access only the data they actually need, without having to download the entire dataset.

Climate variables including maximum temperature, minimum temperature, precipitation, wildfire, and snow water equivalent are aggregated into annual or monthly summaries and served through the Cal-Adapt API. These variables can also be spatially aggregated using either pre-loaded vector boundary datasets (e.g. counties, climate regions, watersheds, census tracts, legislative districts, and more) or user-input boundary layers in different formats (ESRI shapefile, KML, GeoJSON). Data can be reduced and downloaded in temporal and/or spatial subsets.

The front-end data visualization tools featured on Cal-Adapt have been designed to allow users to easily interact with and explore key scientific research on climate change using modern JavaScript based libraries. Leaflet is a widely used open source JavaScript library used for building interactive maps on the web. It is small and modular and can be easily extended through a rich library of plugins that provide additional capabilities, e.g. clustering, heat maps, animations, spatial analysis, and editing. D3 is a JavaScript library for building powerful and highly effective interactive data visualizations. Using the Leaflet and D3 libraries together along with components from other libraries as needed provides a powerful framework for developing exploratory visualizations where users can explore different datasets and compare multiple scenarios to generate new information and insights.

This powerful combination of tools has enabled the creation of a stable, spatially-enabled Cal-Adapt through which developers and researchers can access the best available peer-reviewed environmental and climate variables available for California. It is impossible for a single organization to build tools that might satisfy every potential use of this information. With an API, other organizations are able to easily access the data and build domain specific visualization and planning tools on top of it. Detailed instructions on using the Cal-Adapt API can be found at: https://berkeley-gif.github.io/caladapt-docs/index.html

# 4: Cal-Adapt's Impact on Climate Adaptation Practice and Policy in California

## 4.1 Cal-Adapt Use Cases: Energy Sector

Energy sector stakeholders including the Energy Commission and Investor-Owned Utilities (IOU's) are working to better understand climate change-related risk to energy infrastructure. Of primary importance to stakeholders is that Cal-Adapt is able to provide a common set of climate scenarios that have been sanctioned by the state so that energy sector actors can move forward with research and planning. The need for common scenarios was expressed by the 2016 Integrated Energy Policy Report Update (IEPR), which assesses trends and challenges facing the energy sector and provides policy recommendations (California Energy Commission, 2016).

Although planning for a changing climate is still in early stages, there are several key climate factors that are important to energy stakeholders tasked with continuing to provide clean, safe, and reliable energy to California, as detailed in Risk Assessment and Mitigation Phase (RAMP) reports filed by PG&E and by SoCalGas/ SDG&E. PG&E has identified six key drivers as top priorities in building resilience to climate change-related risk: Major Storm Events, Sea Level Rise, Subsidence, Heat Waves, Wildfire, and Drought (PG&E 2017). These priority climate drivers inform current and planned tools within Cal-Adapt.

California's IOU's have begun to leverage Cal-Adapt climate tools and data to support resilience efforts, such as San Diego Gas & Electric's exploration of climate dimensions of system hardening projects and Southern California Edison's work on integrating climate projections into existing planning models. IOU's have also employed Cal-Adapt tools and data to support vulnerability assessment as a part of their participation in the U.S. Department of Energy's Resilience partnerships. Examples of those vulnerability assessments include:

- PG&E: used Cal -Adapt's extreme heat tool to explore intensity and duration of projected mid-century heat waves.
- SoCal Edison: used Cal -Adapt in conjunction with spatial overlays of infrastructure and as a basis for exploring uncertainty.
- SDG&E: used Cal -Adapt to support a comprehensive, GIS -based vulnerability study.

Moving beyond vulnerability assessments, California IOUs have used Cal-Adapt to support on-the-ground resilience efforts, including:

- SDG&E: Used Cal -Adapt 2.0 to support climate-resilient design of a compressor station in Blythe, California, to investigate implications of climate related to SDG&E's Design Standards, and to explore climate dimensions of system hardening projects.
- SoCal Edison (SCE): Data available on Cal -Adapt 2.0 improved analyses regarding projected climate (e.g., Mesa Substation Project in Monterey Park, California); plans to integrate climate projections into existing planning models.
- General Rate Cases that incorporate climate adaptation actions are envisioned, relying on data available on Cal –Adapt.

## 4.2 Cal-Adapt Use Cases beyond the Energy Sector

As an easy-to-use, free, and publicly available tool that aligns with data endorsed by the state for research and planning, Cal-Adapt has been adopted by resilience initiatives beyond the natural gas and electricity sectors for which it was primarily developed. Cal-Adapt is being used to support the Climate Adaptation Guide prepared by the Governor's Office of Planning and Research, and many local agencies and their consultants are using maps and graphs from Cal-Adapt directly in their climate planning documents. Additional uses of Cal-Adapt beyond the energy sector include:

- The California Department of Public Health used climate risks portrayed by Cal-Adapt as the foundation of work to "Build Resistance Against Climate Effects" (BRACE) by preparing local and county-level public health departments for projected risks
- The United States Forest Service (USFS) has already used Cal- Adapt for planning at least one fuel treatment (Tatham Ridge Project) with future climate conditions in mind.
- Caltrans' Transportation Adaptation Planning Grant Program, which distributes $20M to local and regional agencies for adaptation planning, points to Cal -Adapt as a tool to support applicants.
- The California Government Operations Agency (GovOps) leveraged Cal-Adapt's publicly available Applications Programming Interface (API) to develop an automated tool supporting incorporation of adaptation into Sustainability Roadmaps.
- The Governor's Office of Planning and Research (OPR) is interested in supporting General Planning through custom Cal -Adapt tools designed to fulfil statutory requirements related to climate change adaptation.

- Cal-Adapt has been used to create graphics detailing climate change trends in a recently published review paper on impacts to California's agricultural sector (Pathak et al., 2018).

### 4.3 Cal-Adapt: Impact on Adaptation Policy and Guidance in California

Cal-Adapt has already made a difference in adaptation practice and policy planning in California. Because it enables users to readily explore local climate-related risks at a location of interest (see section 3.3.1), Cal-Adapt has provided a means of communicating climate change that is accessible to a variety of users. Cal-Adapt offers easy access to key climate models and scenarios that have been sanctioned by the state for energy planning as well as adaptation guidance, helping California to make progress towards a more coherent climate policy. Cal-Adapt has been explicitly recognized by California's legislature as a key resource to support local hazard mitigation efforts, with examples below:

- Cal-Adapt is named as a resource by landmark legislation (SB 379) that requires the integration of climate-related risks into local hazard mitigation plans.
- General Planning Guidelines (2017 update) direct local governments to Cal-Adapt as resource to support assessment of climate -related vulnerabilities and development of adaptation policies.
- *Planning and Investing for a Resilient California* (January 2018), which provides adaptation guidance from the TAC established by OPR, directs state agencies to Cal-Adapt as a source for peer-reviewed, state-sanctioned data depicting projected climate risks and for map overlays to facilitate planning and investment.
- In March 2017, the State Water Resources Control Board (SWRCB) approved a resolution (no. 2017- 0012) on "Comprehensive Response to Climate Change" directing staff to consult "the most current data available through Cal-Adapt."
- Safeguarding California (2017 update) notes that Cal-Adapt "is at the forefront of resources for specific communities to understand how climate change will raise temperatures and exacerbate extreme heat events, drought, snowpack loss, wildfire, and coastal flooding."
- OPR's Adaptation Clearinghouse (the Integrated Climate Adaptation and Resiliency Program), development of which was mandated by SB 246, refers users to Cal-Adapt for exploration of local climate risks through high resolution climate projections.

# 5: Conclusions and Future Directions

California's energy system will contend with a changing climate that is projected to vary considerably from historic patterns. Climate change is expected to impact California's natural gas and energy infrastructure through projected increased temperatures, sea level rise, wildfire risk, subsidence, storms, landslides, flooding, and severe droughts. Preserving reliable, safe, and cost-effective operations in the face of a changing climate requires integration of projected climate and weather-related parameters into decision making. Through Cal-Adapt, users are able to examine locations of interest to assess vulnerabilities to a changing climate. By being able to identify assets and communities that may be at risk, the energy sector will be better prepared to secure infrastructure and develop actionable response plans that will safeguard vulnerable populations and ratepayers.

Cal-Adapt has already been a factor in affecting climate change practice and policy in California and has provided a basis and resource for moving forward in an integrated manner across sectors. Legislation as outlined in section 4.3 point to Cal-Adapt as a key resource to support local hazard mitigation efforts and resilience planning. While Cal-Adapt is already actively being used throughout the energy sector and beyond, additional work remains to more fully support climate planning and adaptation through targeted visualizations and tools. Future Cal-Adapt development in support of the energy sector is planned under two soon-to-be initiated grants through the Energy Commission (GFO-16-311 and GFO-17-502).

Next-generation enhancements to Cal-Adapt will integrate new research results from California's Fourth Climate Change Assessment and other climate related data into decision-support tools that energy sector stakeholders can use to evaluate climate related risks and vulnerabilities to California's energy infrastructure. Cal-Adapt's decision-support capabilities will be expanded by incorporating distributed cloud processing infrastructure into Cal-Adapt's existing web architecture that will enable increased computation power and advanced user-defined variables for data processing, visualization, and downloads.

Several ideas generated from user feedback discussed in section 2.2 are being implemented to further improve usability and accessibility for energy stakeholders. For example, we learned from stakeholders that more training and direction is required for users to exploit the advanced functionality that is available through the Cal-Adapt API. Energy sector users are interested in accessing an array of climate variables at a large number of private assets. This type of task can be successfully handled through the API but requires a certain level of computer programming skill. We plan to build more outreach materials around using the API and also to create additional intermediary tools that will allow users to more easily implement this functionality, such as the batch tool mentioned in section 2.2.1.

Planned improvements to Cal-Adapt will also better address a wider range of climate impacts, including an expansion of the current sea level rise and wildfire tools, as well as new datasets and visualizations that focus on extreme storm events, droughts, and other climate factors. An enhanced sea level rise tool will help energy sector stakeholders consider decision-making and planning under uncertainty, providing a central place to consider multiple datasets related to risks from rising seas, including research portraying probabilistic sea level rise as a function of time and emissions scenario, hydrodynamical modeling, and the United States Geological Survey's Coastal Storm Modeling System (CoSMoS).

Frequent communication with stakeholders will be key to successfully developing a more powerful and useful next generation Cal-Adapt. Our process for engaging stakeholders will continue with close collaborations with the Energy Commission and TAC. User outreach to energy sector stakeholders will also include on-site meetings at each IOU, enabling the development of tools targeted towards specific user needs. In addition, user outreach and communication is being expanded to include quarterly webinars which will allow us to regularly beta-test new tools and features to wide audiences. These webinars will be open to the public and are designed as hour-long sessions on targeted topics, introducing draft designs and eliciting questions and feedback from attendees. Further outreach efforts will include an on-line survey on site usability to identify gaps in design and function and additional user workshops.

Cal-Adapt is continuously evolving to become a more accessible and powerful support tool that will enable decision makers to use research results and climate projections to inform effective adaptation decisions and policies. An enhanced Cal-Adapt including expanded data services, visualizations, custom tools, and regular, ongoing communication with users will continue to provide crucial real data on the changing climate and its impacts on California’s energy infrastructure, communities, and natural resources.

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