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ENERGY COMMISSION



ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

**Development of Climate Projections
for California and Identification of
General Use Projections**

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CALIFORNIA'S FIFTH
CLIMATE CHANGE
ASSESSMENT

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Contribution to California’s Fifth Climate Change Assessment

This Final Report describes original, energy-related research that contributes to California’s Fifth Climate Change Assessment (Fifth Assessment). The Fifth Assessment comprises a broad portfolio of research and synthesis reports that address California-specific research needs and knowledge gaps related to climate change. To ensure scientific rigor, Fifth Assessment research was peer-reviewed. This research effort was peer reviewed through external journal publications (listed in Chapter 4: Knowledge Transfer).

PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency; renewable energy and advanced clean generation; energy-related environmental protection; transportation; and energy transmission and distribution.

In 2011, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned electric utilities — Pacific Gas and Electric Company, San Diego Gas & Electric Company, and Southern California Edison Company — were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs to promote greater reliability, affordability, and safety for California electric ratepayers. EPIC investments advance these values by:

- Providing societal benefits.
- Reducing greenhouse gas emissions in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs, first with energy efficiency and demand response, next with renewable energy (distributed generation and utility-scale projects), and finally with a clean electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Development of Climate Projections for California and Identification of General Use Projections is the final report for the EPC-20-006, conducted by Scripps Institution of Oceanography, UC San Diego. The information from this project contributes to the CEC Energy Research and Development Division's EPIC Program.

For more information about the Energy Research and Development Division, please visit the [CEC's research website](http://www.energy.ca.gov/research/) (www.energy.ca.gov/research/) or [contact](mailto:ERDD@energy.ca.gov) the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

As recognized in the California Public Utility Commission’s Adaptation Rulemaking (R.18-04-019), planning for a climate-resilient electricity sector requires data that projects how climate and weather may evolve. Because global climate projections are produced at coarse resolution, they must be downscaled to capture California’s complex topography and varied regional climate. This research project delivers one of the world’s most advanced regional climate projections datasets, providing California’s investor-owned utilities with fine-scale, state-of-the-art data to support vulnerability assessments and adaptation planning. By applying cutting-edge downscaling approaches to the latest generation of global climate models and engaging energy sector stakeholders, the project produced an extensive suite of projections tailored to California’s adaptation needs. The dataset includes high spatial (3 kilometer) and temporal (daily to hourly) resolution projections, produced by two downscaling approaches: dynamical and hybrid-statistical. The dynamical approach provides sub-daily to daily projections of more than 30 variables from eight models under one climate change scenario. Because electricity sector modeling requires climate information that extends beyond California’s borders, this approach also includes lower-spatial resolution projections over the western United States. The hybrid-statistical approach generates daily projections of critical climate variables for many models under three different climate change scenarios over California. A subset of this data was further used to produce hydrological projections, portraying variables essential for assessing hydrological climate risks that affect hydropower infrastructure and operations. The project also developed sea-level projections at selected coastal and San Francisco Bay-Delta sites, capturing hourly variation and multi-decadal sea-level rise scenarios. Given the large volume of data, a reduced set of projections was identified as a practical starting point. By providing a rich suite of high-resolution projections and a streamlined subset for general use at the exploratory stage, the project meets a critical need for locally relevant climate information that supports California’s investor-owned utilities, state energy planning and regulatory agencies, California’s Fifth Climate Change Assessment, and applied climate research.

Keywords: hybrid-statistical downscaling, dynamical downscaling, regional climate projections, climate data, high-resolution dataset, climate variables, California climate change, hydrological projections, sea-level projections

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EXECUTIVE SUMMARY

Background

Climate change and weather extremes present increasing challenges throughout California. For example, record-setting heatwaves passed through the state in September 2020 and 2022, many destructive wildfires have taken place from 2015 to present day, and extreme drought during 2020–2022 was followed by severe flooding in 2023. Planning for and adapting to climate change requires detailed climate data, which means that global climate models' output needs to be downscaled to a much finer scale to account for the complex climate of California's varied landscape.

Recognizing the challenges posed by climate change to California's electricity sector, as well as California's leadership in developing publicly available, decision-relevant climate projections, the California Public Utilities Commission initiated its Adaptation Rulemaking (R. 18-04-019) in 2018. This rulemaking applies to gas and electricity investor-owned utilities in the state. Based on a decision issued in November of 2019 (D. 19-10-054), investor-owned utilities are expected to consider climate data adopted by California's Climate Change Assessments as foundational for their analysis and planning. Climate variables for which data are needed to inform adaptation in an electricity system increasingly powered by renewables include temperature, precipitation, wind, humidity, solar radiation, snowpack, runoff, streamflow, and sea-level rise.

Project Purpose and Approach

The primary objectives of this research project were to develop and evaluate methods for generating meaningful regional climate model projections for California's electricity sector and to produce research-driven, downscaled climate datasets. The project set out to create a comprehensive suite of downscaled climate projections that support energy sector adaptation and resilience planning by providing fine-resolution data that reflect the complexity of California's diverse landscape.

The project began by evaluating the international climate community's new set of global climate predictions, the Coupled Model Intercomparison Project Phase 6 models. The research team evaluated these models based on their performance in representing the regional climate of California. This new generation of models includes multiple ensemble members to enable an assessment of how weather and climate variability affect climate projections, which was not previously possible.

Once the research team had selected models relevant for California, useable downscaled climate projections for California were created through two distinct approaches, namely hybrid-statistical and dynamical downscaling, which delivered novel datasets that can address different resilience planning needs at higher spatial (down to 3 x 3 kilometers) and temporal (hourly, daily, and monthly) resolutions. Each of the downscaling approaches has distinct advantages that complement each other. Together, these approaches provide an innovative, robust regional climate projection dataset for California that is on par with or more

comprehensive than decision-relevant climate projections available for any other region worldwide. The dynamical downscaling approach offers more climate variables, with more than 30 at hourly resolution included in this dataset, but due to computational expense, is limited in the number of models and only uses one global emissions scenario (called a shared socio-economic pathway in this generation of global climate models). The hybrid-statistical downscaling provides data for a more limited set of climate variables but downscales more global climate models and includes three global emissions scenarios. Collectively, the two resulting downscaled datasets enable analyses to address a plethora of questions related to California's climate and implications for energy sector adaptation planning. The research team engaged energy-sector stakeholders throughout the project to ensure the data would be useful in practice, gathering valuable feedback on the global climate model evaluation process and on the utility of both the dynamical and hybrid-statistical downscaled datasets.

The downscaled climate projections provided input to drive additional, innovative modeling of weather-related processes relevant to electricity sector adaptation planning and vulnerability assessments. For example, the downscaled climate model data were used to develop hydrologic projections at daily resolution using two different hydrologic models, which enable investor-owned utilities to assess the effects of flooding on energy infrastructure and of drought and flood on hydropower generation resources. The application of two different hydrologic models highlighted the sensitivity of the results to model selection, offering insight into model-driven uncertainty. Hourly sea-level projections were also developed to support the identification of potential effects of coastal flooding in areas where there is considerable energy infrastructure.

Additionally, to support stress-testing of energy systems, specific weather extremes were identified within the projections data through engagement with energy stakeholders. The resulting database of extreme weather events provides users, including investor-owned utilities, with a resource for selecting relevant extreme conditions and building infrastructure and operations stress-testing scenarios.

The comprehensive dataset of projections was more than 780 terabytes of data, which can be challenging to use. To provide a tractable starting point for those with limited analytical resources or for activities that seek to portray general climate risks (e.g., to support community outreach efforts required of investor-owned utilities), the project identified a set of general use projections that was determined with input from end users. The general use projections are an identified minimum set of global climate models that could be used to investigate climate change effects and assessments. They can also serve as a smaller, common set of projections for comparison between cross-sector, cross-jurisdiction, and/or cross-agency work if not all agencies are otherwise using the same set of global climate models. Together all of this data enables California's electricity sector to plan and prepare for climate change.

Key Results

Key results from this project include:

- Identification of a subset of 15 global climate models that are well-suited for regional downscaling over California. These models exhibit large-scale processes and patterns that were determined to reliably represent California’s historical climate and key processes such as atmospheric rivers, Santa Ana winds, and temperature and precipitation variability. The projections constitute about 60 percent of the available latest generation of model projections from the Coupled Model Intercomparison Project Phase 6 archive.
- Delivery of a suite of high-resolution climate projections that leverage the subset of 15 coarser resolution global climate models identified in the previous statement. This climate dataset provides a robust foundation for adaptation planning in California’s energy sector and beyond. At more than 780 terabytes, the dataset includes:
 - Eight dynamically downscaled projections containing more than 30 atmospheric variables at hourly resolution for 1980–2100 under one global emissions scenario (which is referred to as shared socio-economic pathway scenario)
 - One hundred ninety-nine (199) hybrid-statistically downscaled projections across three shared socio-economic pathway scenarios for key surface variables at daily time steps from 1951–2100
 - Daily hydrologic projections using two hydrologic models, enabling analysis of snowpack, runoff, soil moisture, and flood and drought effects across 13 climate models and projections from three shared socio-economic scenarios
 - Hourly sea-level projections for 13 locations spanning the California coast and within the San Francisco Bay Area, from 1950–2100 following long period sea-level rise across three sea-level scenarios
 - A database of five types of climate extremes developed to support scenario-based planning and inform adaptation strategies, such as stress testing of investor-owned utilities’ infrastructure exposure
 - Hourly temperature data at 32 station locations based on the hybrid-statistical data
- Identification of a reduced set of “general use” projections, selected to characterize essentials of the range of downscaled projected changes, including representative high-impact extreme weather events and climate anomalies. This reduced set of projections serves as a practical starting point to support users exploring the full dataset.

Additionally, the project findings include:

- Demonstration of the value of bias correcting raw global climate model data prior to dynamical downscaling to ensure realistic annual cycles and variability

- Development of the hybrid-statistical downscaling approach, designed to avoid the stationarity hypothesis and address concerns that future weather patterns may differ from those observed historically. This approach is unique in the world.

This large collection of climate projections provides California with a dataset that is unparalleled in its ability to support assessment of long-term climatic changes, not only of multi-year average climate, but also of the intensity, duration, and frequency of extreme short-period events such as drought, floods, and heat waves along with the uncertainty in their occurrence over multi-decade planning horizons. Additionally, using drivers from a subset of the hybrid downscaled projections, the project produced a set of surface hydrological projections for California, and developed sea-level projections to assess the change in long-period rise (cyclical, seasonal, and multi-year fluctuations that cause sea levels to rise and fall temporarily) and short-period extremes.

Knowledge Transfer and Next Steps

Through the knowledge transfer and engagement activities, energy sector stakeholders provided practical feedback on choosing relevant global climate models and key climate variables to downscale. The project team also presented the data products to potential users through written communications and presentations and provided guidance on data use to facilitate the integration of the data into studies and resilience planning efforts. The primary audiences for use of the data are California's investor-owned utilities (for example, climate adaptation, risk assessment, community outreach), state agency regulatory and planning processes (for example, the California Public Utilities Commission's Adaptation Rulemaking R.18-04-019, California Energy Commission's California Energy Demand forecast), the California Energy Commission, and Electric Program Investment Charge research and development efforts designed to benefit ratepayers. A secondary audience are research teams with California's Fifth Climate Change Assessment.

Knowledge transfer included discussions with other energy-related research teams through monthly meetings during a two-year period and with other stakeholders through the California Energy Commission's Climate Data and Analysis Working Group. The project's engagement process included six working groups to elicit input on evaluation of the climate models to downscale, the number of model ensemble members to include, locations that would be crucial for hydrologic modeling verification, the weather extremes to identify, and the application of the general use projections.

The research team developed public-facing memoranda, made available on the [working group website](https://www.energy.ca.gov/programs-and-topics/topics/research-and-development/climate-data-and-analysis-working-group-c-dawg) (<https://www.energy.ca.gov/programs-and-topics/topics/research-and-development/climate-data-and-analysis-working-group-c-dawg>), to describe the data development process and the quality control methods, to provide guidance on appropriate uses of data and give an overview of related publications. Furthermore, several peer-reviewed journal publications that describe the data and its use have been published or are under review as of July 2026. Knowledge transfer efforts through specific presentations also engaged other state agencies, associations, researchers, and academics, such as at the American Geoscience Union

meetings, California Adaptation Forum, American Meteorological Society, and the 2021 and 2025 Electric Program Investment Charge Symposium.

While the resulting dataset is robust (more than 700 terra-bytes derived from 15 global climate models using three different shared socio-economic pathways scenarios across multiple 150 model ensemble members), it does warrant further testing, analysis, and verification. To achieve this verification and enhance the data's usefulness in the future, it is critical to have more high-quality, long-duration observations. Variables such as hub-height wind, wind gusts, and solar-relevant radiation are increasingly important for California's energy planning and risk management, yet observational datasets remain limited. As a next step, the research team recommends expanding such observations to provide a stronger empirical basis for future downscaling and validation.

Additionally, the team recommends improving the representation of coastal clouds, especially near California's population centers — an area where global models and downscaling currently struggle because the clouds arise from complex regional and small-scale interactions in the atmosphere and surface (land and ocean) and sharp land-ocean gradients that global models cannot fully resolve. Improving model representation of coastal clouds will ultimately enhance the reliability of energy-modeling relevant outputs, such as those needed for photovoltaic production estimates and temperature-driven energy demand projections.

To improve usability of future applied regional climate modeling efforts, the research team recommends that engagement activities begin several months prior to the start of data development. Initiating dialogue between end users and researchers prior to commencement of data development would — in addition to augmenting overall knowledge transfer — help ensure that data products are appropriately tailored to user needs and would start conversations concerning the limitations of what can be credibly downscaled from available climate models with available downscaling approaches.

Finally, experience gained in this research could underpin follow-on regional climate modeling and assessments. The project organization (illustrated in Figure 1, Chapter 2) and workflow may be a useful model for other regional climate assessments. The datasets developed by this project could serve as a foundation from which gaps in regional details and effects are identified that may be better described by forthcoming generations of global and regional climate models.

Benefits to California Ratepayers

By delivering a decision-relevant climate projections dataset of unprecedented scope — in terms of the breadth of scenarios as well as the spatial domain and resolution of key energy-related variables — this project has appreciably advanced foundational climate data for energy sector adaptation planning in California. This data has already been used by California investor-owned utilities. For example, on May 15, Southern California Edison filed its 2026 Climate Adaptation and Vulnerability Assessment (more often referred to as CAVA), which assessed climate hazards and their effects on the utility's assets, operations, and services using improved data developed by this project. CAVA results will inform the utility's asset prioritization and capital planning for upcoming general rate cases and support integration of

climate projections into long-term resilience and investment planning, asset standards, and design to improve resilience and reduce future infrastructure retrofit needs.

Beyond use by investor-owned utilities, these data have been foundational to a number of Electric Program Investment Charge research efforts. These efforts have leveraged the data toward climate-informed modeling and analysis that explore implications of climate change on California's increasingly renewable electricity grid. Key models that were already entrained in energy policy modeling exercises were updated to better navigate how a changing climate would affect load, resource build-out, and reliability considerations. And a new model was built designed to evaluate how future energy resource portfolios might withstand climate trends and extremes.

Finally, because these data are publicly available through the [Cal-Adapt: Analytics Engine](https://analytics.cal-adapt.org/) (<https://analytics.cal-adapt.org/>), they have also supported efforts that extend beyond the energy sector. The projections, for example, have been leveraged by California's Fifth Climate Changes Assessment.

CHAPTER 1:

Introduction

Global climate is changing rapidly and will likely continue to do so in coming decades. This will confront California with a broad range of regional and local challenges. Numerous stakeholder interests will be affected, including electricity system infrastructure, operations, supply and demand, and affordability. To identify, plan for, and adapt to these climate-related effects requires state-of-the-art climate change information at a fine spatial resolution.

This project's start was timely, given that the international climate community developed a new generation of global climate models (GCM), made available in 2020 (Eyring et al., 2016). Termed the Climate Model Intercomparison Project Phase 6 (CMIP6), these new models seek to improve upon earlier versions (Intergovernmental Panel on Climate Change, 2023). However, the new CMIP6 models have spatial resolution of about 100 kilometers (km), or 60 miles, which is too coarse to resolve California's extreme topographical and climate zone diversity. This project developed a novel combination of dynamical and hybrid-statistical approaches to downscale a large subset of CMIP6 global climate models to 3 km (1.5 mile) spatial resolution to address this problem. In addition, because GCMs also have systematic errors (biases), bias correction was applied to prepare the data for the intended local and regional applications, such as wildfire risk analysis and energy-demand and energy-generation modeling.

This project builds on earlier work that developed statistically downscaled climate projections for California's Fourth Climate Change Assessment. Those projections were derived from CMIP5, the previous generation of international global climate models (Pierce et al., 2018). The downscaled climate projections developed by this project employed two different downscaling approaches — dynamical and hybrid-statistical downscaling. Dynamical downscaling of global model projections, more than statistical downscaling, has demonstrated the ability to provide deeper insight into processes and physical mechanisms involved in regional climate change (for example, Huang et al., 2020). While most of the statistical downscaling is limited to daily measures, dynamical downscaling provides hourly results that are useful in depicting processes and detailed descriptions of short-period (sub-daily) variability, including extreme events. Furthermore, the applied hybrid-statistical approach uses the dynamically downscaled projections in statistical downscaling to limit the assumption that climate patterns used for downscaling will remain the same in the future. The research team then used the hybrid-statistical localized constructed analogies (LOCA)-2-hybrid data to develop the hydrologic projections.

By combining statistical and dynamical downscaling approaches to develop California's next generation of climate projections, this project brought about the following advances from the previous generation of downscaled climate projection dataset:

1. Employed downscaling approaches of the most recent set of international GCMs (CMIP6) to develop climate change projections to spatial and temporal resolutions relevant for California

2. Increased physical realism of downscaled weather and climate projections over California by using full dynamical downscaling of key scenarios by the Weather Research Forecast (WRF) numerical model (Rahimi et al., 2022). Then, using the LOCA2-WRF hybrid-statistical downscaling approach (Pierce et al., 2023a), the set of downscaled projections was expanded to numerous other models, realizations, and emissions scenarios
3. Increased the spatial detail of the climate projections to a 3-km spatial resolution over California, compared to 6 km previously
4. Included multiple realizations from the same GCM to assess the natural variability generated by the mode and more opportunities to assess future extremes
5. Achieved greater completeness of climate-related variables under the WRF dynamical modeling, which yielded 30 atmospheric variables of interest, while in the previous assessment the number of output variables that could be delivered was limited to those with adequate observations to train the statistical model
6. Used two hydrologic models to provide a range of possible changes in land surface variables such as snowpack, soil moisture, and runoff at daily temporal resolution
7. Integrated a set of engagement activities, improving the applicability of the data by investor-owned utilities (IOUs) and stakeholders

The new climate datasets constituted more than 780 terabytes of data, which can be overwhelming to those not accustomed to working with such large datasets. Therefore, to support data users with less capacity to process such large datasets, the research team identified a small subset of five downscaled CMIP6 GCMs and ensemble members¹ that still capture the range of projected outcomes from the larger set. These “general use projections,” serve as an entry to the data for those users who may not be able to use the data otherwise. In addition, to support users in extreme case scenario development of future climate extremes, the research team developed a database of extreme temperatures and precipitation (considering both extremes in dryness and wetness). This climate extremes database allows users to identify extremes that might be most appropriate for their stress tests, based on the duration, location, and types of extreme. The research team integrated a structured engagement process throughout the project, enabling climate scientists and technical staff who work in the electricity sector to jointly identify priority GCMs and the information needed to meet statutory, operational, and environmental goals. By pairing this continuous stakeholder input with the latest bias-correction, downscaling, and modeling approaches applied to recently developed GCMs, the team produced a comprehensive and practical set of next-generation climate projections to support planning processes.

The project team transferred the newly developed dataset to the [Cal-Adapt: Analytics Engine](https://analytics.cal-adapt.org/) (<https://analytics.cal-adapt.org/>), which made it more readily accessible for the technical,

¹ Ensemble members are multiple model runs with varied initial conditions that sample the range of possible climate outcomes. By comparing their spread, researchers can assess natural climatic fluctuations and identify robust, long-term changes caused by outside factors, such as rising greenhouse gas levels.

semi-technical or research user, with a specific focus on the energy sector users. More broadly, the project delivered one of the world's most comprehensive, high-resolution, regionally relevant, and stakeholder-informed climate datasets for use by California's IOUs, state agencies, researchers, planners, and other stakeholders.

CHAPTER 2:

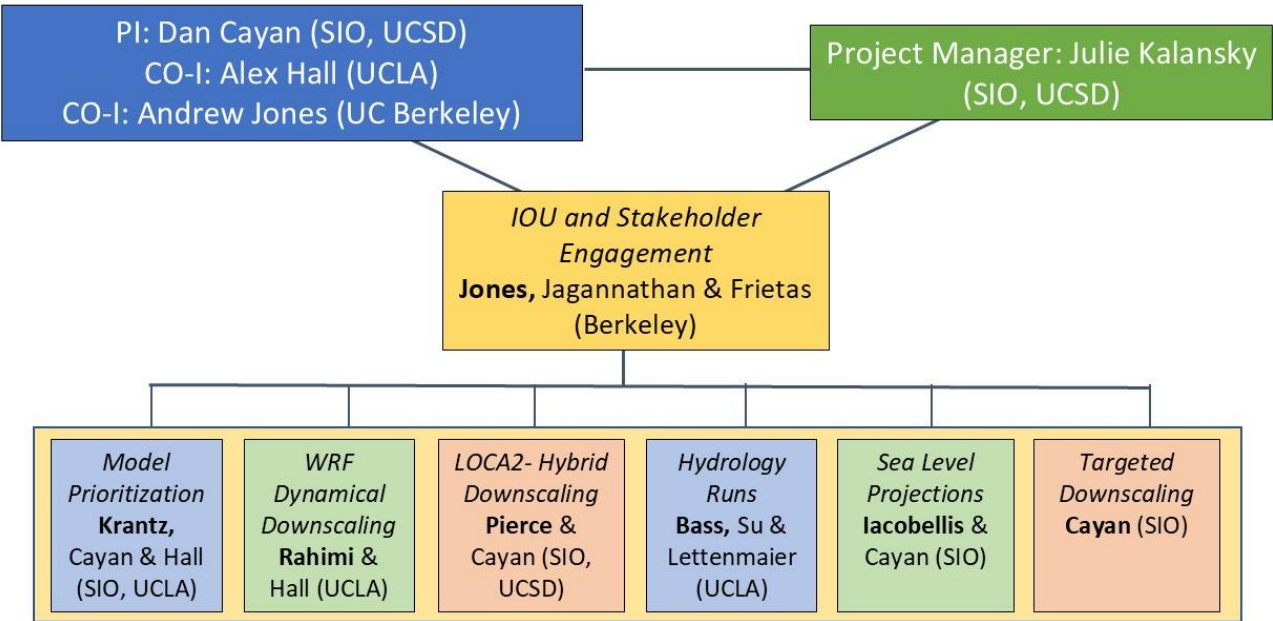
Project Approach

The project used multiple methodologies to create a robust climate projection dataset. This multi-pronged approach was developed through close collaboration and communication within the project research team (Figure 1), with California Energy Commission (CEC) staff, with other CEC-supported researcher groups and through engagement with technical staff who work in the electricity sector. The engagement with the applied energy sector user group helped to identify a set of metrics that can be used to assess the overall distribution of modeled outputs and identify important variables for downscaling and stress cases. This engagement process also provided a manner to communicate how the different data were developed and why certain decisions were made.

Engagement discussions also explored key interdependencies — for example, between the downscaling approaches (the LOCA2-Hybrid approach depended on the dynamical downscaling output), and between a dataset and a downscaling approach (for example, the hydrologic modeling data depended on the LOCA2-Hybrid). These interdependencies are discussed in more detail in the respective project approach sections that follow.

The project researchers, as grouped by associated data product and engagement activity shown in Figure 1, met regularly to ensure capabilities and understanding of the data were being discussed and used in the different processes.

Figure 1: Project Team Organization



Source: Julie Kalansky, Scripps Institution of Oceanography

The primary purpose of the project was the development of a robust and novel climate dataset tailored to electricity sector planning needs that accounts for the complex topography and

regional weather creating the climate of California's varied landscape. Much of the project's work went into designing downscaling methods, techniques, and the overall approach employed in building that dataset. The research team took the following steps to develop the climate projection datasets and to identify a subset of general use models and targeted extremes:

1. Evaluate the international GCMs to select relevant GCMs to be downscaled for California
2. Dynamical downscale the selected GCMs using WRF
3. Hybrid-statistical downscale using the newly developed LOCA2-Hybrid approach
4. Hydrologically model the downscaled projections
5. Develop the hourly sea-level projections
6. Develop the general use projections
7. Develop the targeted extreme cases database

Throughout the project there was regular engagement with IOUs and other energy community stakeholders to develop climate data products that help to meet statutory, operational, and environmental goals.

Global Climate Model Selection

Prior to starting any downscaling, care was taken to evaluate the international GCMs and select GCMs that best represented California Mediterranean climate and some of the primary weather phenomenon that interact to create California's climate (Krantz et al., 2021). In previous efforts, existing metrics for the entire Northern Hemisphere were used as an initial GCM quality filter, after which California-region specific climate model evaluations were applied. However, as part of this research, the screening processes used broad-scale atmospheric circulation metrics (covering not only California but much of the Pacific Ocean) that are key to weather and climate variability alongside regional metrics that evaluate the fidelity of simulated temperature and precipitation over the state. This gave a more targeted evaluation of processes that affect California's climate. As part of the evaluation, metrics were designed to identify GCMs whose historical simulations exhibited a realistic set of large-scale processes that drive weather and climate variation in California, as well as having regional California temperature and precipitation variations that were similar to observations. These processes included global-scale modes of variability (such as El Niño, which was considered in the prior California Assessment) and California-specific phenomena such as the atmospheric circulation patterns that create Santa Ana winds, a major driver of regional wildfire risk, and atmospheric rivers. When CMIP6 GCMs represented these process-based requirements and captured the regional variability well, those CMIP6 GCMs were considered to be more reliable in capturing California's future climate than lesser performing CMIP6 members, and also because presumably they reproduced observed climate patterns with a set of underlying physics and mechanistic components that operate in the same way that nature operated. This process

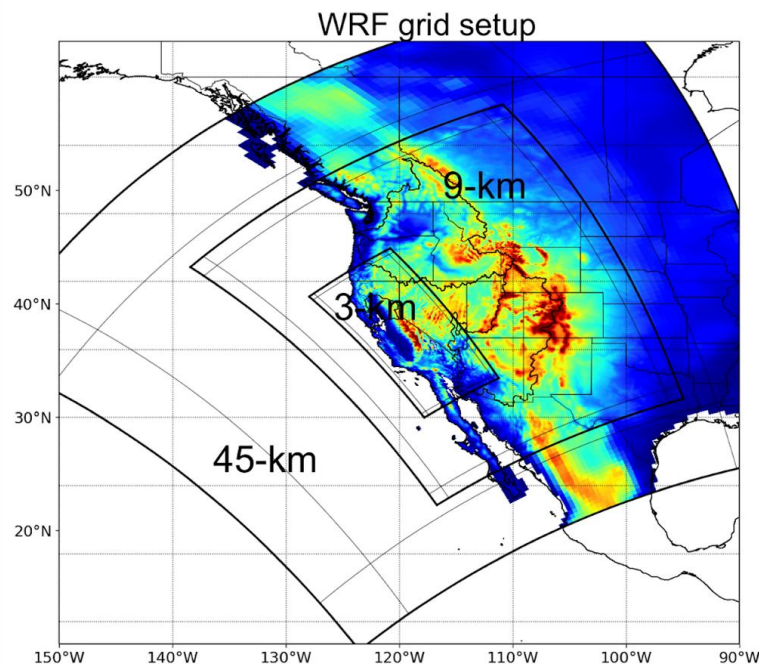
yielded a set of 15 global models that were employed in the subsequent downscaling of CMIP6 GCMs for California climate change scenarios development.

Dynamical Downscaling with Weather Research Forecast

From the selected GCMs that were determined to be most reliable in capturing California's future climate as previously described, a subset of GCMs were selected to be dynamically downscaled based on their containing the necessary data for that process. Via dynamical downscaling, which calculates the high-resolution weather and climate based on the physics of the atmosphere, the original GCM data were transformed to high-resolution sub-daily data. This process was developed in the late 1980s but requires enormous computational power, which is why dynamical downscaling has not been used in previous California Climate Change Assessments. Improvements in computing speeds and lowering of costs for computing have made it possible for dynamical downscaling to be applied to a limited set of GCM projections as part of this project. Eight CMIP6 GCM simulations, all run using the Shared Socioeconomic Pathway (SSP) 370 scenario, were dynamically downscaled; one of the eight was downscaled a second time to explore effects of bias correction — hence nine dynamically downscaled projections were produced. For more details on this selection and process, please see Rahimi et al., 2024.

Specifically, the dynamical downscaling was done by embedding a Regional Climate Model, called the WRF Model (Skamarock et al., 2019), within the selected GCMs across the California region to focus its computer power in a way that resolved high-resolution topography (3-km grid length and 40 vertical levels), coastlines, and small-scale features in the overlying weather and climate. GCMs were dynamically downscaled to 45 km, then to 9 km, and then 3 km (Figure 2) so each of the models that have a 3-km domain also has a 45-km and 9-km domain. All dynamically downscaled simulations used the third Shared Socioeconomic Pathway (SSP3, herein also called SSP 370; Nakicenovic et al., 2014) covering the 1980–2100 time period. The nine dynamical downscaled simulations were broken into two groups: an initial four simulations and a second set of *a priori* bias corrected simulations (Appendix A). For the second set of four simulations, the climatological biases in the GCMs were removed before dynamical downscaling (described in more detail in the bias correction section that follows) and variables associated with wind and solar energy creation were added to support energy sector planning. One model, EC-Earth3-Veg, was part of the initial set of simulations and served as a test case for the new set of models by running a second simulation with *a priori* bias correction; however, it was bias corrected and dynamically downscaled prior to the discussion of the need to save the additional variables. Thus, five of the dynamical downscaling simulations have *a priori* bias correction (BC) applied, but of those only four contain results with new additional variables. The processed variables from the dynamically downscaled models are listed in Appendix A. Additionally, the European Centre for Medium-Range Weather Forecast reanalysis version 5 (ERA5) (Hersbach et al., 2020) was also downscaled to evaluate the project's dynamical downscaling methodology and adjust biases for both sets of dynamically downscaled GCMs, as well as to provide a set of observationally based patterns in the statistical-dynamical hybrid downscaling.

Figure 2: The Three WRF Domain Coverage Grids



The filled color contours represent the terrain height in the highest-resolution domain that covers the given pixel.

Source: Stefan Rahimi, University of Wyoming

Hybrid Downscaling with LOCA2-Hybrid

This project developed and implemented a hybrid-statistical approach called LOCA2-Hybrid (Pierce et al., 2023a) that built upon the localized constructed analogs (LOCA) statistical downscaling method (Pierce et al., 2014, 2015), which is an analog-based method that is used to downscale relatively coarse scale global climate model projections to finer scale regional projections. Since LOCA is designed to reproduce the statistics (for example, seasonal variation, seasonal averages, and so forth) of a training dataset, that dataset was a foundation of the results and was critical for reproducing reliable downscaled climate projections. Statistical modeling, which underpins the LOCA2-Hybrid technique, can be accomplished with fewer computing resources than are required by dynamical downscaling. Consequently, the LOCA2-Hybrid modeling effort was able to produce a larger volume of downscaled global climate model projections than did the dynamical downscaling effort, enabling a better range of possible climate change futures, including a broader assortment of possible extreme events.

Prior to any downscaling, the first step of the LOCA process was developing a historical training dataset. These data were used for 1) bias correction and 2) to provide a library of observed weather patterns that, after spatial coarsening, were matched to the GCM day being downscaled. Importantly, in this project, the research team used a new form of the training data: the dynamically downscaled (WRF) ERA 5 output was used to supply information between stations rather than using a spatial analysis of station observations. This approach was motivated by the hypothesis that the dynamically downscaled simulation of physical processes and topographical effects (via WRF) yielded a better estimate of meteorological

variables at unobserved locations than did the nearest neighbor interpolation. Hence, the historical training dataset was an adjusted version of the WRF dynamically downscaled ERA5 reanalysis (Hersbach et al., 2020), in this case bias corrected using station observations. This ERA5-WRF downscaled simulation yielded a full suite of meteorological variables at the desired spatial resolution. More details on this approach can be found in Pierce et al., 2023b and Pierce et al., 2025.

This observationally based dataset derived from ERA5, coined ERA5-WRF-BC, was used in bias correction that occurred throughout the downscaling process (Pierce et al., 2025). The LOCA downscaling method proceeded in two steps: 1) from the original GCM grid (which varied by GCM) to a common 0.5 x 0.5-degree grid and 2) from the common 0.5-degree grid to the final, fine scale 3 km grid. These two steps were used so that all models could be bias corrected using information from the same 0.5 degree grid, even though the GCMs have different grid resolutions (Pierce et al., 2014). Other schemes sometimes interpolate the different GCM grids to a common grid before downscaling, but this analysis found that the interpolation can lead to a poorer representation of spatial variability in the final downscaled result.

Also new in this project was the development of a hybrid-statistical downscaling scheme (Pierce et al., 2023a). This approach, termed the LOCA2-Hybrid methodology, is considered a form of hybrid downscaling since it couples the statistical downscaling approach of LOCA with a pattern library of historical and future patterns obtained from the dynamically downscaled GCM future projections (from WRF) for creation of future weather-pattern libraries. The approach was developed to avoid the stationarity hypothesis, addressing concerns that future weather patterns may differ from those observed historically. For example, a warmer future climate may reduce snowpack, leading to altered surface temperature patterns in locations that will experience systematic snow loss compared to past observations. The GCM-WRF runs extended to the year 2100, providing the needed catalog of future weather patterns. The hybrid approach was implemented using WRF dynamically downscaled runs CESM2 and EC-Earth3-Veg under the Shared Socioeconomic Pathways scenario SSP 370. These particular GCM-WRF runs were selected on the basis of their performance in the Krantz et al. (2021) GCM evaluation process, showing high skill in simulating historical climate variables over the California domain and the availability of data.

In implementing the LOCA2-Hybrid methodology, the downscaling was split into three future periods with separate pattern libraries; this separation was required to fit an individual library into the memory of the National Aeronautics and Space Administration (NASA) Pleiades supercomputer where the runs were performed. The periods included the standard CMIP6 historical period ending year of 2014, and three future periods of 2015–2044, 2045–2074, and 2075–2100. The pattern library for each of these three periods was obtained from the contemporaneous GCM-WRF downscaled (and bias corrected) run; for example, when LOCA2 was processing years 2075–2100, the pattern library was taken from WRF years 2075–2100. This meant that end-of-century GCM days were downscaled by LOCA2 using a pattern library from WRF simulations also at the end of the century, and therefore included any WRF-simulated changes in weather patterns in that time frame. This approach was used for downscaling daily maximum temperature (Tmax), minimum temperature (Tmin), precipitation,

relative humidity minimum and maximum, surface downward short wave, and wind direction and speed. The resulting set of GCMs, ensemble members, and Shared Socioeconomic Pathways scenarios that were downscaled using LOCA2-Hybrid are reported in Appendix B.

Although most of the LOCA2-Hybrid downscaling yielded gridded data at daily resolution, energy sector modeling efforts sometimes require hourly temperature projections at individual locations. To address the need for this information, a set of future projections of hourly temperatures from 1950–2100 was developed for 32 key meteorological stations throughout California (plus one station in Nevada) that are used by California state agencies for understanding and forecasting the state’s energy demand. Following LOCA matching methodology, existing daily LOCA2 Tmax and Tmin, along with hourly analog data derived from observations at each station, were used to construct the hourly temperature projections. This procedure yields a better representation of hourly variability compared to the traditional approach that extracts hourly temperatures from an assumed climatological diurnal cycle. Advances made in this project included a revised station adjustment process to account for the difference in the hourly temperature progression between wet and dry days and an improved matching of the daily maxima and minima of the hourly output to the daily Tmax and Tmin that is input. More information can be found in Yao et al. (2024).

Bias Correction Approaches

All models have errors and some portion of this is systematic model error, called biases. Examples of climate model biases include overly wet winters or heat waves that are not as extreme as observed. Biases vary in complex ways depending on both seasonal timing and the amplitude of the underlying values. For example, temperature biases may be different in winter than summer due to model errors in depicting snow processes, or precipitation biases may be different on “average” wet days than extreme wet days due to how atmospheric rivers are simulated. Accordingly, bias correction methods often are applied by month or season and sometimes consider how the bias changes as values become more extreme. The process of reducing model biases is called bias correction. Different forms of bias correction were employed in this project for dynamical (WRF) and hybrid-statistical downscaling (LOCA2-Hybrid), described as follows and in more detail in Pierce et al., 2023c.

The WRF downscaled GCM model runs were produced with different bias correction treatments — some with bias correction prior to the downscaling (*a priori* bias correction), some with bias correction applied after downscaling (*posteriori* bias correction), and some with no bias correction. Of the eight WRF simulations, only five (MIROC6, TaiESM1, EC-Earth3, MPI-ESM1-2-HR, EC-Earth3-Veg) included *a priori* bias correction. A monthly mean bias correction to the GCM values was applied before dynamically downscaling (Colette et al., 2012). The GCM climatological mean wind and temperature fields were forced to match the ERA5 when *a priori* bias correction was applied to WRF. Four (CESM2, CNRM-ESM2-1, EC-Earth3-Veg, FGOALS-g3) of eight of the WRF runs had a similar bias correction applied after the WRF downscaling step, which is termed “*a posteriori* bias correction” since it happens after the WRF run. The bias correction of projected future climate also differed between LOCA2 and WRF. In WRF, monthly mean biases computed from historical period model versus observation results were applied and unchanged as applied to the future projections.

In the LOCA2-Hybrid methodology, bias correction of the GCM values was accomplished using the PresRat (Pierce et al., 2015) bias correction scheme before the downscaling step. This approach was similar to the bias correction approach used in the projections leveraged by California’s Fourth Climate Change Assessment. For precipitation, PresRat computed the bias correction by season and according to the magnitude of the precipitation. All of the LOCA2 runs applied a seasonal bias correction after the downscaling step to preserve the match between the projected results and observations. LOCA2’s PresRat approach preserved the GCM-projected changes in variables by quantile in the downscaled projections.

Hydrology Modeling

To understand how projected atmospheric conditions would affect land surface variables such as snowpack and runoff, dynamically and hybrid-statistically downscaled GCM atmospheric output from the projections previously described were used as input to two different hydrological models in developing daily 1951–2100 simulations over the California region. Two widely used and well recognized hydrology models were employed: the Noah land surface model with multi-parameterization options (Noah-MP), run via the WRF-Hydro platform and the variable infiltration capacity (VIC) macroscale hydrologic model. Noah-MP simulations were performed using the same 3 km x 3 km grid as WRF, while VIC simulations were performed at 1/16th degree resolution (roughly 3 km). The hydrology models were initially calibrated to improve the representation of daily natural streamflow during the historical period using the ERA5-WRF-BC dataset previously discussed. Since the hydrology models required a finer time resolution to run, the ERA5-WRF-BC dataset the GCMs were converted from daily time resolution to 3-hour time steps using MetSim (the python version of MTCLIM) — a model commonly used in the hydrology community for such purposes (Bennett et al., 2020).

Calibration of the hydrology models was performed for 120 basins throughout California using observed daily natural streamflow records. The calibrated parameters were regionalized to ungauged basins throughout California based on the similarity of calibrated and ungauged basins. The general workflow of the calibration followed the methods outlined for the western United States in Bass et al. (2023) and Su et al. (2024), with details on the methods and results for the California domain. The calibration procedure provided more accurate simulations of runoff as well as other associated variables, which are relevant to water resources, hydroelectric power, and flood analyses, that are representative of realistic conditions for the historical and GCM simulations. After calibration, snowpack, runoff, and additional land surface variables were produced at a daily time resolution. The CMIP6 projections that were used to force the hydrologic models were 21 LOCA2-Hybrid downscaled projections that included 13 SSP 370, 4 SSP 245, and 4 SSP 585 projections. Additionally, hydrological model runs were made based upon the four post-downscaled bias-corrected WRF downscaled SSP 370 WRF GCMs; these runs were made to test results using dynamically downscaled meteorological drivers, for which, at the time that these runs were conducted, were limited to the posteriori bias corrected projections. The LOCA2-Hybrid forced runs included SSP 245 and SSP 585 climate scenarios from four CMIP6 GCMs that also had simulations available under the SSP 370 scenario. Using these runs allowed sampling of climate responses across multiple emissions scenarios, providing a wide range of potential

precipitation and temperature changes that are representative of the larger ensemble of GCMs and their possible outcomes.

Hourly Sea Level

The team also produced hourly sea-level projections over the 21st century at 13 tide gauge stations along the California coastline and within the San Francisco Bay. These sites had sufficiently long and complete historical data from tide gauges that measured the height of the water at that location. Hourly sea level was estimated as a combination of the predicted astronomical tide, regression model estimates of sea-level deviations due to meteorological and short period climate (such as due to *El Niño-Southern Oscillation*, [ENSO]) influences (Cayan et al., 2008), and contribution from long-term sea-level rise. The three long term, secular, sea-level rise projections were the same as those used in the California Sea-Level Rise Guidance (2024), adopted from the recent National Oceanic and Atmospheric Administration (NOAA) study by Sweet et al., 2022. The hourly time sequences deployed upon the secular sea-level rise were developed from meteorological forcing from 11 CMIP6 GCMs that were downscaled with the LOCA2-Hybrid methodology (Iacobellis & Cayan, 2024). Future values of the meteorological and short period climate-driven sea-level components² were projected by applying the regression model with forcing data derived from each available SSP2-4.5, SSP3-7.0, and SSP5-8.5 and all available ensemble members of 11 CMIP6 GCMs. The 11 GCMs that were employed had saved all the required data for sea-level projections (such as wind, temperature, and sea-level pressure). Hourly values of future astronomical tides at each tide or water gage location were obtained from the NOAA website (tidesandcurrents.noaa.gov). In total, 38 hourly sea-level projections were produced, from which data users can investigate different forms of projected sea-level metrics (for example, annual maximum, frequency above a threshold) for each of the modeled locations. At each location, the dataset provided modeled total sea level for each hour from January 1, 1950 through December 31, 2099. Any effects of surface waves and run-up were not included in the hourly derived sea-level projections developed by this project.

General Use Projections and Extreme Identification

To lower the barrier created by the enormous amount of data contained across the full suite of downscaled climate projections, a smaller subset of individual projections was desired that might be considered to sample the high volume of outcomes. Thereupon, the research team set out to identify a subset of the downscaled CMIP6 GCMs and ensemble members that were called "general use projections" (Kalansky et al., 2024). Five model projections were identified as the general use projections, which are meant to serve as an entry point to working with the larger full suite of LOCA2-Hybrid climate data and to begin to explore the range of possible outcomes.

² Short-period, climate-driven sea-level components are the parts of sea-level change that fluctuate on short time scales (hours, days, weeks, seasons) because of weather and short-term climate variability, rather than long-term trends such as ice melt or ocean warming.

The hybrid-downscaling method led to development of a full suite of data for 15 GCMs with a total of 199 ensemble runs (see Appendix B for more details). To select the general use projections from the full suite, several criteria were considered, listed here with associated rationales:

1. Ensured the models selected captured much of the range of projected future changes in the GCMs and ensemble members for selected metrics, scenarios, and time periods
2. Prioritized LOCA2-Hybrid GCMs and ensemble members that had also been dynamically downscaled by WRF with *a priori* bias correction
3. Prioritized ensemble members for which the full set of LOCA2-Hybrid downscaled variables were available
4. Assessed future changes in California in both means and extremes (hot days, floods, and droughts) to ascertain that the general use subset of the LOCA2-Hybrid data suite covered a plausible range of extremes. A limited set of metrics was employed in this evaluation because having too many uncorrelated variables and metrics would have reduced the ability of the metrics to distinguish among models. Model range was assessed using temperature, precipitation, and wind.
5. Avoided metrics that were derivatives of several variables for the same reason as described in number 4 of this list
6. Focused the assessment on the range of model outcomes for SSP370 with a 2045–2074 mid-century period based on input from the energy sector
7. Excluded GCMs that have a climate sensitivity that is unrealistically high compared to historical observations, based on Tokarska et al., 2020 and Hausfather et al., 2022

The metrics (and variables) for the general use projections selection process were based on input from the energy stakeholders (gathered via this project’s stakeholder engagement processes) and scientific considerations. Precipitation, maximum temperature, and wind were the variables of interest to the energy sector in terms of their extreme expressions such as heat waves, droughts, and fire weather. As a result, these variables were used to select the general use projections. Primary climate variables (seasonal or annual mean temperature and precipitation) were used rather than the extremes because the extremes can be defined in numerous ways; however, analyses revealed strong correspondence between projected changes in the seasonal or annual means and various extremes of interest to the energy community. Further, statewide variables were examined, rather than a regional specific variable (such as Tmax in Southern California), to identify general use projections that were broadly representative of California as a whole.

Separately from the general use projections, to guide the identification of a handful of different extremes from the entire LOCA2-Hybrid dataset extremes, a database of different extremes (Excel files) was developed. To identify the type of extremes that would support research efforts and vulnerability assessments, the project’s stakeholder process received input from the CEC staff, other CEC-supported research projects using the projections, and IOUs. The various stakeholders had different uses for and definitions of relevant weather-

related extremes; for almost all extremes, the duration was balanced by the intensity. In addition, users had different regions of interest. Therefore, the extremes were identified in three regions covering the northern, central, and southern parts of California over four separate historical and future periods (1950–2014, 2015–2040, 2041–2070, 2071–2100). These time periods were based on the GCM’s historical period (1950–2014) and climatological periods of approximately 30 years that are currently and widely used as standard reference periods for calculating [climate normals](https://www.ncei.noaa.gov/products/land-based-station/us-climate-normals) (https://www.ncei.noaa.gov/products/land-based-station/us-climate-normals). The time periods also align with the periods used in California’s Fifth Climate Change Assessment.

The extremes were calculated from area average precipitation and area average temperature for each of the three regions and for each of the four time periods. A set of durations were determined based on the typical effects of the selected extremes — for example, floods range from 1 to 30 days, whereas dry and wet periods were provided over a range from 1 to 20 years, to address extremes of different and longer duration that are needed by various users. The extremes and the associated durations are listed in Table 1. In addition to values in millimeters (mm) or degrees Centigrade, the extremes are presented as fractions (percentage of precipitation) or difference (in degrees Centigrade) of/from the historical (1950–2014) downscaled GCM modeled climatological values. To facilitate using the dynamically downscaled data in extreme case studies, the table identifies which models were dynamically downscaled by WRF in the databases.

Table 1: Identified Extremes and Their Durations

Variable	Extreme	Duration of Events Identified
Precipitation	Drought; driest	Water years*: 1, 2, 3, 5, 10 and 20 years
Precipitation	Wet Years; wettest	Water years: 1, 2, 3, 5, 10 and 20 years
Minimum Daily Temp (Tmin)	Cold Snaps; lowest Tmin	Day Average: 1, 2, 3, 7, 14, 30 days in Dec – Feb
Maximum Daily Temp (Tmax)	Heatwaves; highest Tmax	Day Average: 1, 2, 3, 7, 14, 30 days in Jun-Aug
Precipitation	Flood (inferred) highest precipitation	Accumulated Precipitation: 1, 2, 3, 7, 14, 30 day

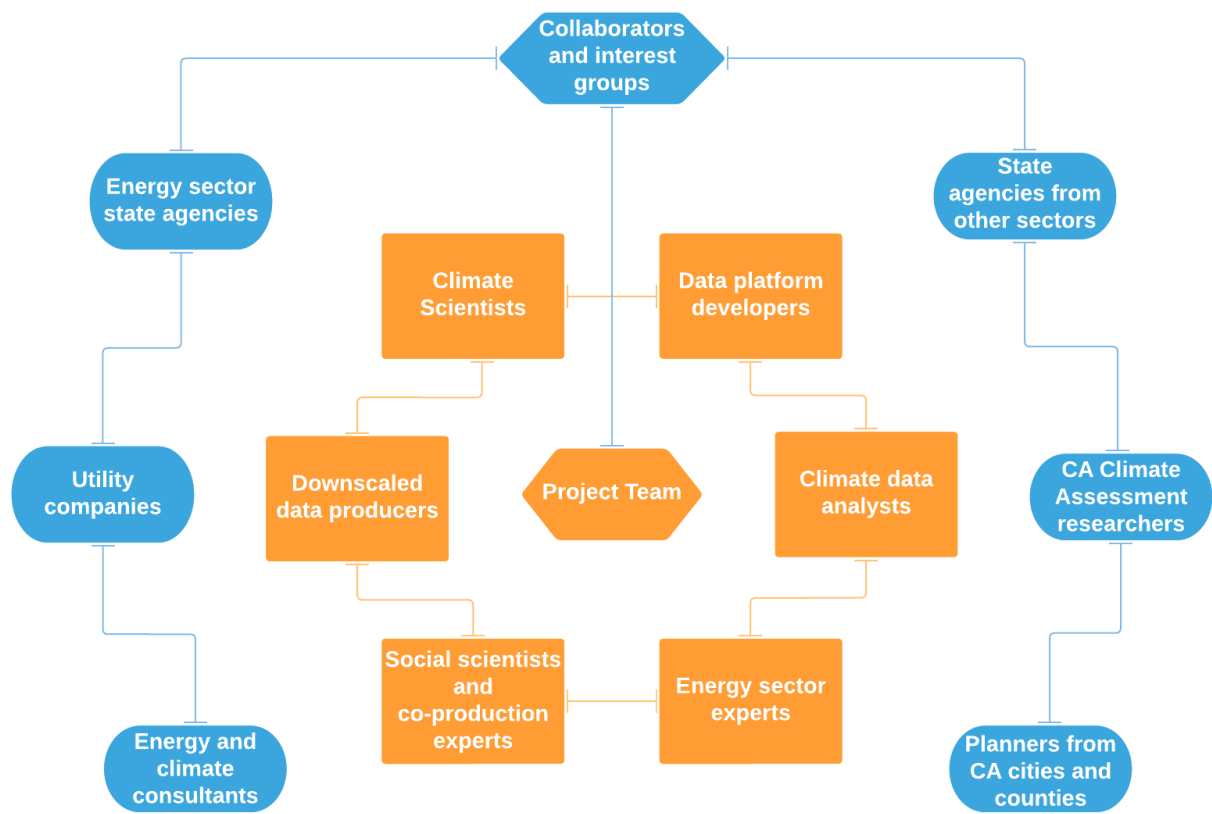
*A water year begins on October 1 and extends through September 30 the following year.
Source: Cayan, et al., 2024.

Stakeholder Engagement

The project’s engagement team, consisting of Jones, Jagannathan and Frietas (as show in Figure 1), led a multi-faceted co-production process that brought together the expertise of California’s leading scientists and data platform developers with the know-how of on-the-ground energy-sector data users, state agencies, and energy sector researchers (Figure 3). This approach included both top-down (science-driven) and bottom-up (practice-driven)

perspectives to collaboratively develop improved climate data, as well as to facilitate a shared learning process between scientists and practitioners. The approach drew from best practices and lessons learned in academic literature and practical case studies on developing actionable climate data and services. The engagement team facilitated these interactions through a mix of structured methods (semi-structured interviews, focus groups, workshops, surveys) and unstructured methods (seeking feedback on the project approach, progress, and written products through email, phone, or other conversations). The use of mixed approaches addressed potential differences in viewpoints or conflicting priorities that might arise when engaging with diverse groups. Each interaction gathered direct and indirect technical feedback from user groups. There were several engagements through the period of performance, highlighted in Figure 4. Stakeholder input was used especially for identification of extremes, development and proposed purpose of the general use projections, and selection of stream gauges for the hydrologic modeling.

Figure 3: The Co-Production Approach

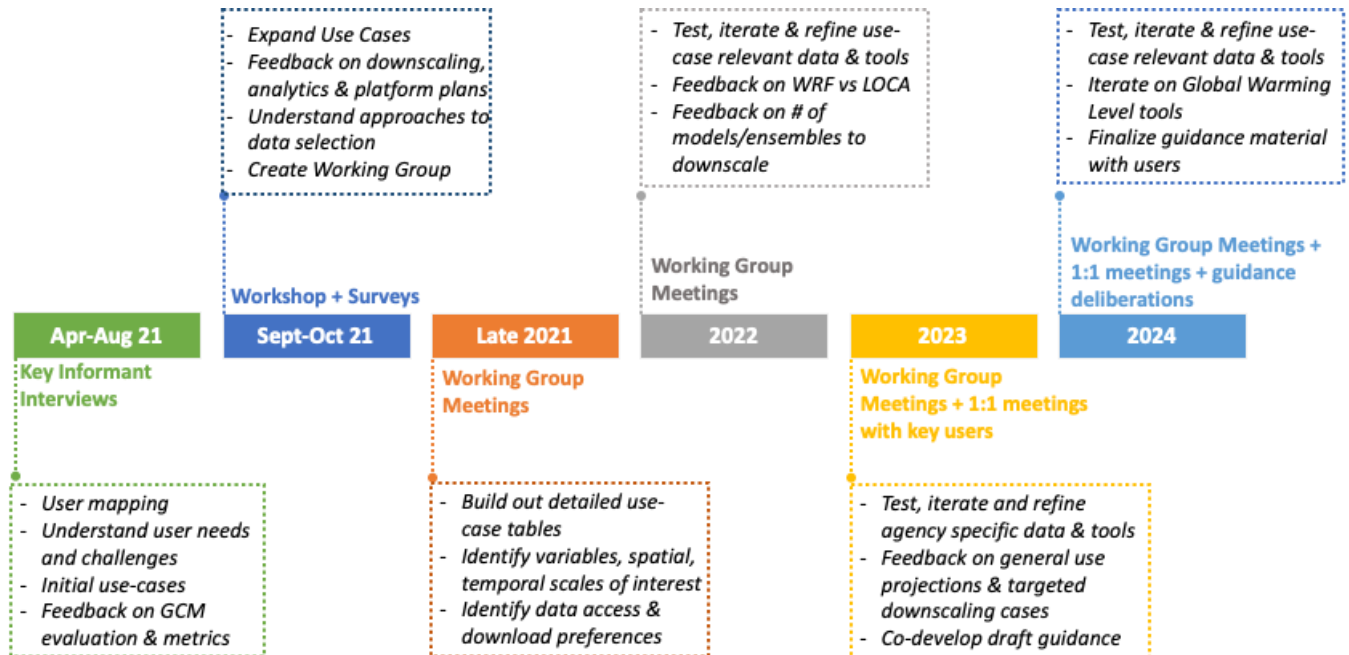


Blue represents data users; orange represents the project teams for both EPC-20-006 and EPC-20-007³.

Source: Kripa Jagannathan, Lawrence Berkeley Lab

³ ["A Co-Produced Climate Data and Analytics Platform to Support California's Electricity Resilience Investments"](https://www.energy.ca.gov/filebrowser/download/2856) led by Eagle Rocks Analytics. The EPC-20-007 project developed the Cal-Adapt Analytics Engine which hosts the climate projection data produce from this project. Additionally, the data platform generates actionable, user informed climate analytics based on the projection data. <https://www.energy.ca.gov/filebrowser/download/2856>

Figure 4: Key Engagement Activities Timeline and Relevant Outcomes



Source: Kripa Jagannathan, Lawrence Berkeley Lab

CHAPTER 3:

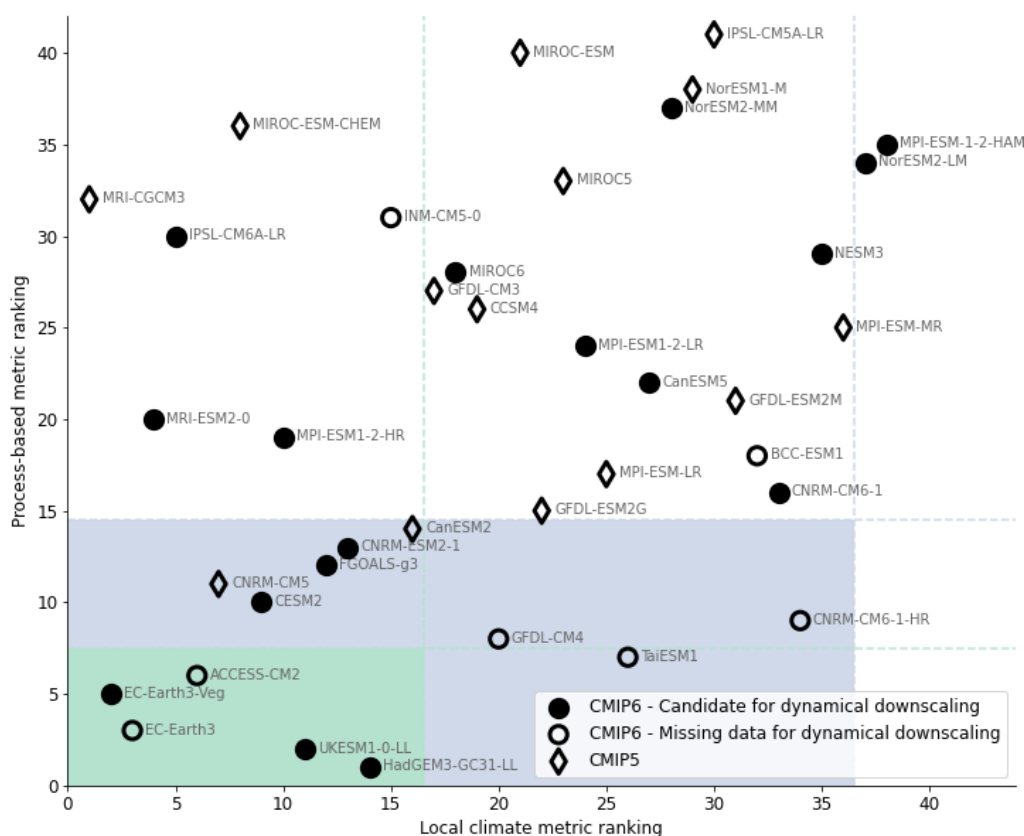
Results

As mentioned previously, the primary output from the project was the production of a novel and robust climate dataset for the energy sector. This chapter describes the resulting datasets and initial research findings about the methodologies used in the data development. Please refer to the previous chapter for the steps taken and methods applied to develop the data.

Model Selection Results

As described in Chapter 2, a critical first step in the project was the evaluation of CMIP6 GCMs to select a set that best captured California’s climate, with an emphasis on finding those having realistic large-scale processes that drive regional climate patterns. In other words, this process identified models that not only exhibited realistic regional climate patterns, but also captured patterns associated with important weather phenomena. Notably, CMIP6 GCMs were not eliminated because of unusually high climate sensitivity or often referred to as being “hot” models, because these models may still contain useful information about how the climate system evolves as it warms. Results from this evaluation are shown in Figure 5; more details are provided in Krantz et al. (2021). Rankings, based on performance of multiple large-scale process and regional climate metrics, became the basis for the selection of models that were downscaled. Through the engagement process, IOUs had specified that they wanted “good performing models” and models that captured a range of outcomes, though they deferred to the project’s climate scientists to determine the set of models that best met these objectives.

Figure 5: Comparison of GCM Rankings by Local Climate and Process-Based Metric Performances



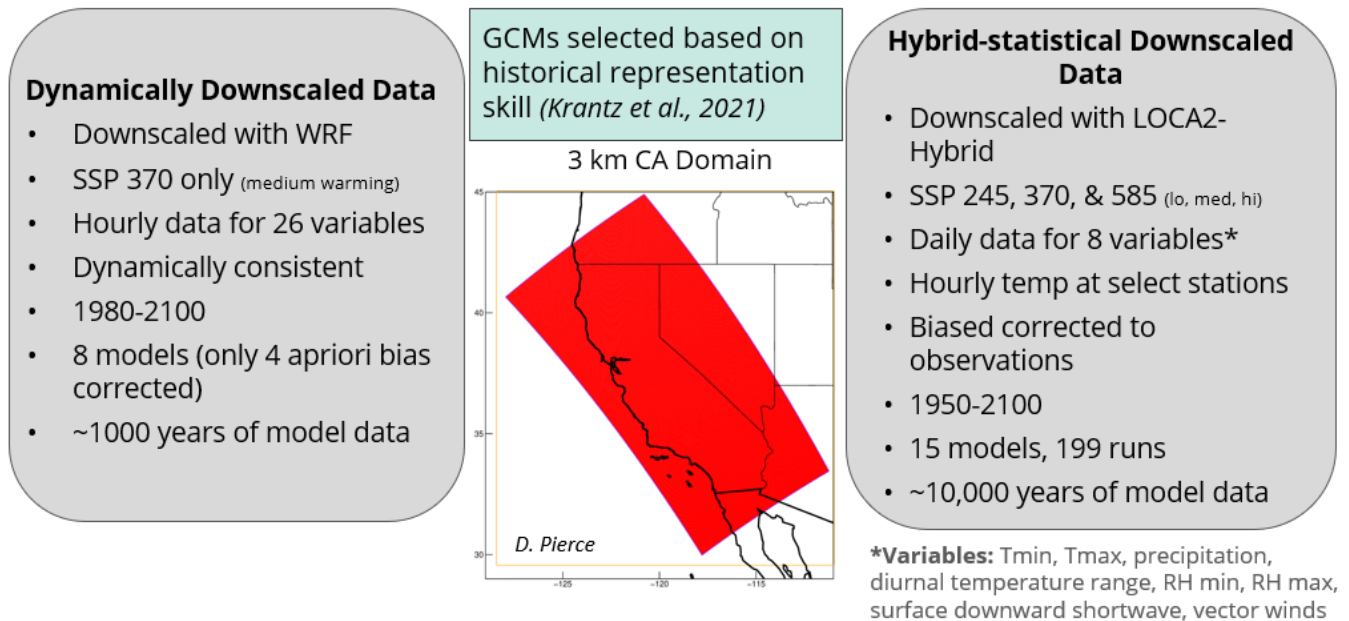
Source: Krantz et al., 2021

The lower score in Figure 5 indicates better-performing models. Models that appear in one ranking but not the other are not included. CMIP6 models with sufficient data for dynamical downscaling are indicated by solid circles. The top two statistical groupings of models are shown in green and blue.

Downscaled Climate Projections

As mentioned previously, the primary objective of this project was the creation of the downscaled climate projections. The downscaled climate projections that were developed included dynamically downscaled data and hybrid-statistically downscaled data at 3 km over the California domain (red square in Figure 6). These data are the end result of the models downscaled and variables produced by the different downscaling methods described in Chapter 2. The data are summarized in Figure 6 and listed in Appendices A and B. All the data were made available via the [Cal-Adapt Analytics Engine](https://analytics.cal-adapt.org/) (<https://analytics.cal-adapt.org/>), which also includes [guidance](https://analytics.cal-adapt.org/guidance/) (<https://analytics.cal-adapt.org/guidance/>) on how the projections could be used to answer pertinent questions concerning climate effects and adaptation.

Figure 6: Summary of Data Produced by This Research



Summary of data produced from both the WRF dynamical downscaled climate projections (left) and LOCA2-Hybrid statistically downscaled climate projections (right). Domain for which the data covers is shown in red (middle).

Source: Julie Kalansky, Scripps Institution of Oceanography

Effects of *A Priori* Bias Correction for Dynamically Downscaling

Initially the dynamically downscaled GCMs were not *a priori* biased corrected; however, the research team realized that GCM biases were amplified in the dynamical downscaling process. As a result, a second set of GCMs were dynamically downscaled with *a priori* bias correction. Further, engagement with energy sector researchers and downstream research grants identified additional variables to be included in the post-processed dataset. As a result, an additional four GCMs (from the set of selected GCMs for California) were dynamically downscaled (Rahimi et al., 2024). The resulting two dynamically downscaled datasets enabled an examination of the dynamical downscaled climate projections with and without *a priori* climate projections.

Comparative results between outcomes from WRF dynamically downscaling of GCM projections with and without a bias correction led the research team to recommend using *a priori* biased correction as a pre-conditioning in most cases. *A priori* climate projections have much-reduced simulated spread in the experiments compared to the non-biased corrected experiments, which perhaps is an intuitive result given that this bias correction methodology forces the GCM climate means to match the mean-state climate of native ERA5 observational reanalysis. Evaluation showed that the mean surface air temperature cold bias was effectively removed in the *a priori* bias correction experiment. The research team's hypothesis was that, for maximum and minimum temperature, the differences between the with and without bias correction experiments stem in part from differences in low cloud coverage between the two sets of

simulations. Further, the difference between the experiments was likely related to an overly snowy landscape in experiments without bias correction. This could partially explain why simulations without bias correction had maximum surface air temperatures that were colder than those with bias correction. Relative to non-bias correction experiments, the bias corrected experiments were warmer and drier in the ensemble mean. Additionally, the bias corrected experiments have a smaller future precipitation spread and a broader warming spread than their non-biased corrected counterparts. More details of these analyses and results are presented in Rahimi et al. (2024).

Comparison of Data Training Sets for LOCA2-Hybrid and LOCA2

To evaluate the statistical downscaling process, it is helpful to consider differences in downscaling outcomes produced by the LOCA2-Hybrid methodology developed as part of this project and a previously developed LOCA methodology that solely used historical observations as its training dataset. Comparing the two different training datasets, which lie at the heart of the scheme, is therefore essential for any comparison between the LOCA data. The purpose of the training data was twofold: 1) to provide unbiased estimates of meteorological values across the year and at different quantiles for use in any bias correction process; 2) to provide spatial patterns of the meteorological variable with the correct spatial patterns, means, and variability for use in a spatial downscaling analog day matching process.

As described earlier, this research developed the new hybrid-statistical downscaling scheme producing a set of projections over California at 3 km grid, called LOCA2-Hybrid (Pierce et al., 2023a). Used for comparison to the LOCA2-Hybrid was a version of LOCA downscaling that was similar to the method used previously in California's Fourth Climate Change Assessment, but that applied slightly updated methodology termed "LOCA2" that addresses multiple ensemble members provided by the CMIP6 data and improved extreme precipitation downscaling as described in Pierce et al. (2023). The LOCA2 training datasets consisted of gridded sets of historical observations at 6 km resolution, Livneh unsplit precipitation (Pierce et al., 2021), and the Livneh Tmax and Tmin dataset (Livneh et al., 2015). In contrast, creating the LOCA2-Hybrid training datasets were generated by dynamical atmospheric models, albeit guided by observations.

A brief comparison of precipitation between the training set developed for this project (ERA5-WRF-BC) and the Livneh unsplit gridded precipitation training dataset used for LOCA2 provided a reasonable evaluation of the methodology; precipitation has characteristics that present challenges for estimation, being heavily influenced by topography, covering a wide dynamic range across the landscape, and in some locations being locally patchy. Results from the cross-validated analysis showed that the Livneh gridded nearest-neighbor methodology was superior to ERA5-WRF-BC for capturing the specific day-by-day evolution of historically observed precipitation, presumably because neighboring stations were likely to experience precipitation at the same time as the omitted station. By contrast ERA5-WRF-BC produced precipitation via simulated processes that were close to, but not perfectly synchronized with, observed precipitation on any given day. Therefore, if one wishes to know whether precipitation fell on a particular day (for example, for forensic meteorology applications), the nearest-neighbor re-gridding is preferable. On the other hand, over longer periods, errors in

daily ERA5-WRF-BC tend to cancel out; the RMS error in yearly mean precipitation in cross-validated ERA5-WRF-BC is 5.9 percent, about half the error seen in the cross-validated Livneh style nearest-neighbor interpolation (10.2 percent). Similar results were seen in winter, spring, and autumn. ERA5-WRF-BC likewise outperformed the nearest-neighbor method for extreme precipitation values, specifically for daily precipitation return periods between 2 and 20 years. By 50 years the difference in RMSE between the two methods falls to only about 1 percentage point. More details and graphics addressing the two training datasets are available in Pierce et al. (2025).

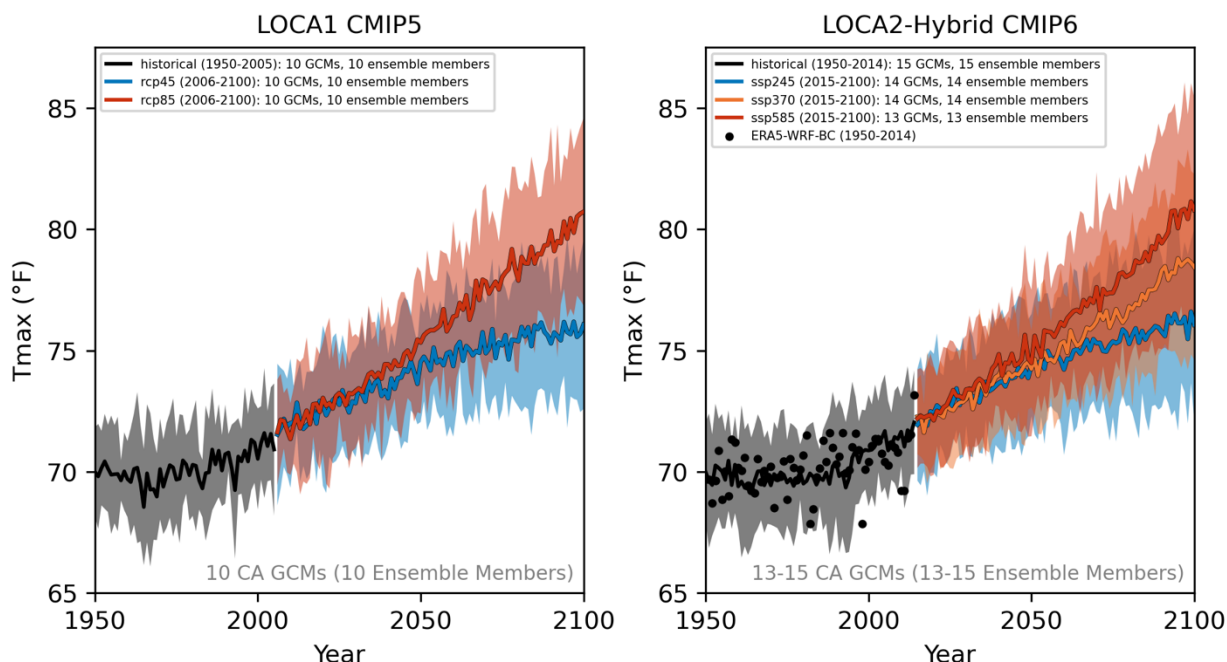
Considering temperature, the climatologies of the two different training datasets, ERA5-WRF-BC of LOCA2-Hybrid and the Livneh 6 km LOCA2 gridded, Tmax and Tmin were in reasonably good agreement. For example, January Tmax ERA5-WRF-BC and Livneh training datasets were nearly the same. But in July, the ERA5-WRF-BC Tmax training dataset exhibited higher temperatures in a narrow zone near the California coast and somewhat lower temperatures over the Sierra Nevada than that of Livneh. Also in July, the ERA5-WRF-BC Tmin training dataset was broadly warmer than that of Livneh, except for the California Central Valley, where ERA5-WRF-BC training was slightly cooler.

Regarding the projections, the differences or agreement between magnitude and spatial structure of future minus historical between the two methodologies is essential to understand the effect on downscaled projections. As a brief foray into distinctions between the LOCA2-Hybrid and the LOCA2 downscaled projections, differences in the future changes in Tmax and Tmin were investigated. For example, using common multi-model SSP 370 projections from each downscaling set, Tmax and Tmin 2045-2074 minus 1950–2014 changes in most of California were similar between LOCA2-Hybrid and LOCA2, but there were some distinct differences along the California coastal zone, wherein LOCA2-Hybrid exhibited greater warming by about 34°F (1°C) than LOCA2. Given the result that the regions of relatively large differences between the two methods tend to occur in regions having the highest spatial gradients, the higher spatial resolution of LOCA2-Hybrid (3 km) versus traditional LOCA (6 km) must be contributing to these differences. More details and graphics addressing the differences between the two datasets are available in Cayan et al. (2026), but considerably more analysis is needed to describe and explain these differences.

Comparison of Future Changes in CMIP6 LOCA2-Hybrid versus CMIP5 LOCA Projections

Often-asked questions regard how this latest generation of climate model projections, as represented in the downscaled CMIP6 results produced here, compares with those from the previous generation of projections from the downscaled CMIP5 results, such as those used in the 4th California Climate Change Assessment — for example, what is the nature and magnitude of model changes in temperature and precipitation over the historical period and through the 21st century, how do the model projections compare with historical observations, and how do modeled changes compare with those from previous California Climate Change Assessments? The statewide annual average temperature (Tmax) and precipitation plots in figures 7 and 8 provide a brief, regional-scale response to these questions.

Figure 7: LOCA California Average Annual Daily Maximum Temperature



Created by Peter Yao, Scripps Institution of Oceanography Apr 27, 2026 20:09:28 UTC

California statewide annually averaged Tmax from a number of LOCA-CMIP5 (left) and LOCA2–CMIP6 (right) historical and future projections, with ensemble means (dark lines), ± 2 -SD spreads (shaded), and observed ERA5-WRF-BC Tmax overlaid on the LOCA2 panel (black dots).

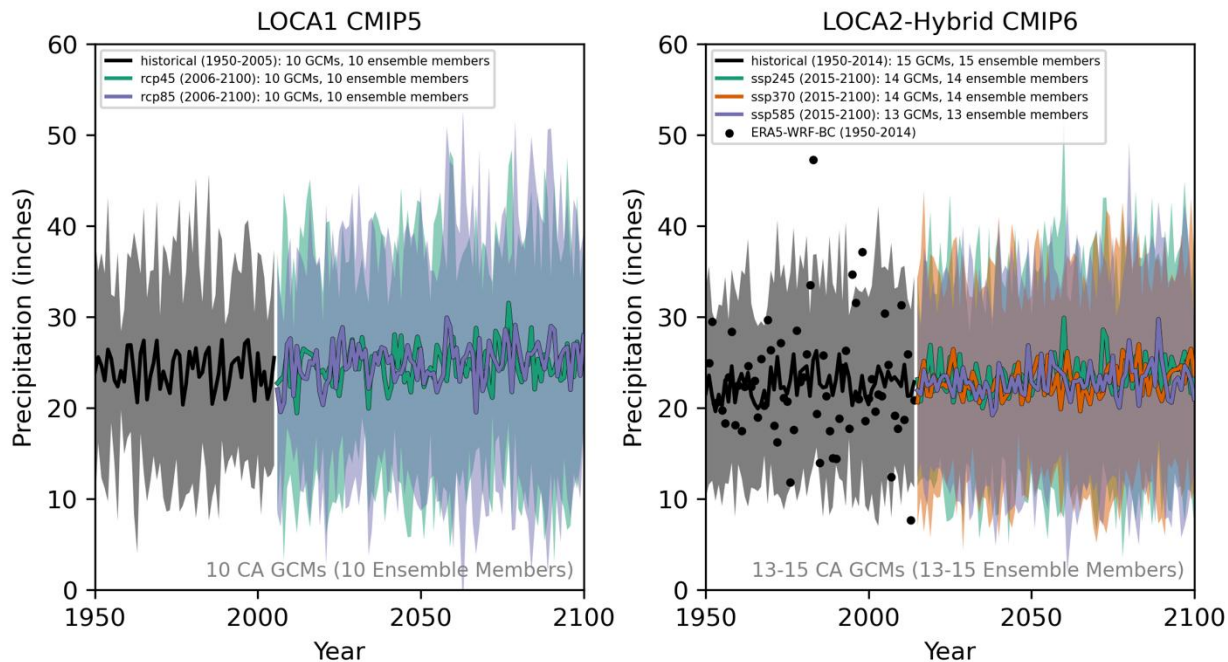
Source: Peter Yao, Scripps Institution of Oceanography

In Figure 7, observed warming during the historical period becomes evident in approximately 1960 to 1970, as shown by both the LOCA1 and LOCA2-Hybrid ensemble means. The envelope of LOCA2-Hybrid downscaled CMIP6 model Tmax projections are largely consistent with the approximately 1.5°F (0.8°C) of warming observed over 1970 to 2014. Almost all of the observed annual Tmax values fall within the $\pm$ envelope of the LOCA2-hybrid model ensemble in the right panel (black dots). Moving into the future projections, across the respective scenarios, warming rates are similar until about 2050 with the uncertainty in warming increases over the 21st Century, as gauged by the width of the model ensemble envelope. In the CMIP6 SSP585 and CMIP5 RCP8.5 (representative concentration pathways), a similar high emission scenario used in the prior set of GCMs, most model runs exhibit a continuing high rate of warming over the 21st Century, producing about 6°F (3°C) to 12°F (7°C) of additional warming by 2100. In contrast, under the LOCA2-Hybrid downscaled CMIP6 SSP245 and CMIP5 RCP4.5 scenarios, a more moderate emission scenario used in CMIP5 GCMs similar to SSP245, the rate of warming diminishes in approximately 2060 such that the warming amounts to between 2°F (1°C) to 8°F (4°C) by 2100. From the top of the CMIP5 and CMIP6 envelopes, the “hottest” CMIP6 GCMs exhibit approximately 2°F (1°C) higher warming by 2100 than the warmest CMIP5 models.

Similar comparisons can be made for precipitation (Figure 8). Reflecting the great amount of year-to-year and longer-term variability, the envelopes of both the CMIP5 and CMIP6 ensembles are quite broad, but over the 150-year period from 1950 to 2100 there is little

overall difference between the two generations of projections. The observational record also exhibits great year-to-year variation, but little overall change. In both the CMIP5 and CMIP6 results, there is little difference in the projected changes among the different emission/socioeconomic scenarios. The ± 2 standard deviation envelope of the projected CMIP6 outcomes includes most, but not all, of the observed calendar year precipitation values.

Figure 8: LOCA California Average Annual Precipitation



Created by Peter Yao, Scripps Institution of Oceanography Apr 27, 2026 20:12:50 UTC

California statewide annually averaged precipitation from a number of LOCA-CMIP5 (left) and LOCA2-CMIP6 (right) historical and future projections, with ensemble means (dark lines), ± 2 -SD spreads (shaded), and observed ERA5-WRF-BC Tmax overlaid on the LOCA2 panel (black dots).

Source: Peter Yao, Scripps Institution of Oceanography

Hydrologic Model Performance

Quality assurance and quality control of hydrologic model projection data were conducted through a calibration and validation of the models' ability to represent natural streamflow. The validation process assessed the performance of 120 gauged basins by comparing their simulated streamflow against observational streamflow data. This assessment illustrated that both VIC and Noah-MP reasonably captured the historical streamflow across the majority of California's basins; however, a few individual basins demonstrated poor performance, which could be due to a variety of factors ranging from forcing data to the hydrologic modeling parameters to the observational data quality. VIC and Noah-MP demonstrate similar performance in representing climatological, monthly, and annual streamflow conditions. While VIC demonstrates slightly better performance in representing daily streamflow conditions, flood events are generally better represented by Noah-MP. The project team additionally ensured that the historical climatology and mean-state of the downscaled GCMs runoff and snowpack matched the historical simulation of ERA5-WRF-BC, which is expected given the bias

correction of the downscaled GCMs to ERA5-WRF-BC. More information is available in Bass et al., (2023) and Bass et al. (in revision).

General Use Projection Models

As explained in Chapter 2, based on a set of several prioritized criteria, a subset of model projections was selected as a minimal set of models that could be used to examine climate change effects. The following five SSP 370 model projections best met these criteria.

- ACCESS-CM2 r1i1p1f1 (no WRF dynamical downscaled 3 km run)
- MPI-ESM1-2-HR r3i1p1f1
- EC-Earth r1i1p1f1
- FGOALS-g3 r1i1p1f1 (was not *a priori* bias corrected)
- MIROC6 r1i1p1f1

Selection of the general use projections did not explicitly consider how the subset of models captured the range of future changes during different time periods, for example, mid (2041–2070) versus end-century (2071–2100). However, examination of the change in Tmax and precipitation at the end of the century showed that the general use projections do capture the range of projections during these periods as well. Nonetheless, the reduced number of models cannot account for all the variability between the different downscaled models and ensemble members for end-of-century precipitation, which is especially true for climate extremes. More details of the analyses and figures about the general use projection models can be found in Kalansky et al. (2024). Users should not interpret the general use projections as a “preferred” set or “recommended” set of models, but rather as a smaller set of projections to serve as a good starting point for examining climate data.

CHAPTER 4:

Knowledge Transfer

Knowledge transfer activities were designed to communicate the project's (interim) results effectively and in forms usable by decision makers and other stakeholders.

Stakeholder Engagement and Technical Advisory Committee – Besides the stakeholder engagement task (described in Chapter 2), the project team established a Technical Advisory Committee (TAC) composed of representatives from electric utilities, state and federal agencies, regulators, and the research community. TAC members provided guidance on project scope, methods, timelines, and coordination with other research initiatives.

Open-Source Data – The data developed by this research were made available on the [Cal-Adapt Analytics Engine](https://analytics.cal-adapt.org/) (https://analytics.cal-adapt.org/) – with thanks to the EPC-20-007 research team with Eagle Rock Analytics. Inc.:

- Dynamically Downscaled Projections of eight CMIP6 GCMs. One model includes both *a priori* and *non-a priori* dynamically downscaled data
- LOCA2-Hybrid Downscaled Output from 15 CMIP6 GCMs

Additional model output data is accessible through links also provided on a [webpage](https://analytics.cal-adapt.org/data-tools/data-catalog.html) on the Cal-Adapt Analytics Engine (https://analytics.cal-adapt.org/data-tools/data-catalog.html), and at the links provided below:

- Hydrologic Model Output Data
 - [Data Justification Memorandum](#) available on the C-DAWG page (California Energy Commission's Climate Data and Analysis Working Group)
 - **Links:** [NOAH-MP simulations](https://wrf-cmip6-noversioning.s3.amazonaws.com/index.html#ben_temp/d03_3km/CEC/2_NOAH_MP_SIMULATIONS/) (https://wrf-cmip6-noversioning.s3.amazonaws.com/index.html#ben_temp/d03_3km/CEC/2_NOAH_MP_SIMULATIONS/), [VIC simulations](https://wrf-cmip6-noversioning.s3.amazonaws.com/index.html#lusu/CEC/VIC_SIMULATIONS/GCMs/) (https://wrf-cmip6-noversioning.s3.amazonaws.com/index.html#lusu/CEC/VIC_SIMULATIONS/GCMs/)
Description: UCLA generated daily hydrology data from VIC and NOAH-MP forced with a subset of LOCA2-Hybrid and four non-biased correct WRF dynamically downscaled data.
- Hourly Sea-Level Rise Projections Data
 - [Data Justification](https://www.energy.ca.gov/media/9330) (https://www.energy.ca.gov/media/9330) and [Detailed Memorandum](https://www.energy.ca.gov/media/11144) (https://www.energy.ca.gov/media/11144) available on the C-DAWG page
 - **Link:** Hourly [Sea-Level Rise Projections](https://cadcat.s3.amazonaws.com/index.html#hmet/) (https://cadcat.s3.amazonaws.com/index.html#hmet/)
Description: Hourly sea-level rise projections data generated by Scripps Institution of Oceanography for 13 tidal stations along the California coast and San Francisco Bay covering the 1950–2100 time period.

Data Summaries and Memos

The team developed California Climate Change Assessment Data Summaries (also known as Data-Justification Memos) to provide detailed information to those who wanted to use the data. The memos describe the methods used, prior relevant-related work, and the quality assurance and quality control processes employed and provide guidance or caveat on the best practices for use of the data products. They were reviewed by the leadership team for California's Climate Change Assessment from the Governor's Office of Land Use and Climate Innovation and were shared on the [CEC's Climate Data and Analysis Working Group \(C-DAWG\) website](https://www.energy.ca.gov/programs-and-topics/topics/research-and-development/climate-data-and-analysis-working-group-c-dawg) as they became available during the agreement term (<https://www.energy.ca.gov/programs-and-topics/topics/research-and-development/climate-data-and-analysis-working-group-c-dawg>):

- 01 - Bias Correction in the WRF and LOCA2-Hybrid Projections
- 02 - Dynamical Downscaling using WRF
- 03 - LOCA2-Hybrid (for California) – Training Data
- 04 - Hybrid Downscaling
- 05 - Hydrology Projections
- 06 - Hourly Sea-Level Projections from CMIP6 climate and weather
- 07 - General Use Projections for California
- 08 - Targeted Extremes Database

In addition to the data summaries, more elaborate memos were written to support transparent and timely consideration of interim deliverables that were relevant for energy stakeholders and all those interested in California's next generation of climate projections. These were also shared via the C-DAWG page:

- a. General Use Projections for California
- b. Evaluating CMIP6 GCMs for California Report
- c. Development and Availability of Dynamically Downscaled Projections of 1st Set using WRF
- d. Performance Evaluation of 1st Set of WRF Projections
- e. Development of 2nd Set of Dynamically Downscaled Projections using WRF
- f. LOCA2 Hourly Station Temperature Projections
- g. Hourly Sea-Level Projections Memorandum
- h. LOCA2-Hybrid Downscaling

The project researchers also documented project findings through peer-reviewed publications, conference abstracts, dissertations, thesis, and technical reports.

Scientific Publications

- Bass, B., S. Rahimi, N. Goldenson, A. Hall, J. Norris, and Z. Lebow. 2023. [Achieving Realistic Runoff in the Western United States with a Land Surface Model Forced by Dynamically Downscaled Meteorology](#). *Journal of Hydrometeorology*, 24(2). <https://doi.org/10.1175/JHM-D-22-0047.1>
- Bass, B., C.W. Thackeray, A. Hall, S. Rahimi, L. Huang. 2024. [A Novel Emergent Constraint Approach for Refining Regional Climate Model Projections of Peak Flow Timing](#). *Geophysical Research Letters*, 51(12). <https://doi.org/10.1029/2024GL108575>
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- Pierce, D., D. Cayan, D. Feldman, and M. Risser. 2023. [Future Increase in North American Extreme Precipitation in CMIP6 Downscaled with LOCA](#). *Journal of Hydrometeorology*, 24(5). <https://doi.org/10.1175/JHM-D-22-0194.1>
- Rahimi, S., W. Krantz, Y. Lin, B. Bass, N. Goldenson, A. Hall, J. Lebo. 2022: [Evaluation of a Reanalysis-Driven Configuration of WRF4 Over the Western United States from 1980-2020](#). *JGR Atmospheres*. <https://doi.org/10.1029/2021JD035699>

- Rahimi, S., L. Huang, J. Norris, A. Hall, N. Goldenson, W. Krantz., B. Bass, C. Thackeray, H. Lin, D. Chen, E. Dennis, E. Collins, Z.J. Lebo, E. Slinskey, S. Graves., S. Biyani, B. Wang, S. Cropper and UCLA Center for Climate Science team. 2023. [An Overview of the Western United States Dynamically Downscaled Dataset \(WUS-D3\)](#). *Geoscientific Model Development* 17(6). Copernicus GmbH: 2265-2286. doi:10.5194/gmd-17-2265-2024. <https://doi.org/10.5194/gmd-17-2265-2024>
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Presentations at Conferences

2025:

- Cayan and Pierce, Understanding Decision-Relevant Climate Data Products, LOCAv2 Downscaling
- Graves, Bass, and Hall, American Meteorological Society (2025), A climate change-informed decision-making framework for Mono Lake diversions and recovery

2024:

- Cayan et al., American Geophysical Union 106th (2024), Hydroclimatic Challenges of the 21st Century Drought
- Jagannathan et al., American Geophysical Union (2024), Co-producing guidance on the use of climate data for scientific and decision applications
- Jagannathan et al., American Geophysical Union (2024), "TH33H Climate Information and Services: A Whole-of-Government Approach", Invited Panelist for Townhall
- Rahimi et al., American Geophysical Union 106th Annual Meeting (2024), The California Megaflood: Bias correction and GCM choices matter, Invited
- Rahimi et al., NASA's Jet Propulsion Laboratory's workshop on Usable Climate Risk Science (2024), Bias correction in dynamical downscaling: Friend or foe?, Invited
- Su et al., American Geophysical Union 106th (2024), Increased Dry Years mid-21st Century, Delta Watershed

2023:

- Freitas et al., American Geophysical Union (2023), Creating actionable science for climate adaptation planning – challenges and opportunities identified during co-production of the Cal-Adapt Analytics Engine”, Talk and Panel Discussion.
- Freitas et al., California Adaptation Forum. Pomona (2023) Learn to Use Climate Data & Tools for Decision-Making in CA through Cal-Adapt, Talk and Workshop
- Freitas et al., California Adaptation Forum. Pomona (2023), Actionable Data & Tools to Enable Climate-Informed Decision-Making in California, Session and Panel Discussion
- Graves, Bass, Rahimi, and Hall, American Geophysical Union (2023), California's Sierra Nevada will experience more frequent droughts, extreme wet years, and whiplash events based on hybrid-downscaling of large ensemble GCMs
- Kalansky et al., California Water and Environmental Modeling Forum (2023), New CMIP6 Climate Projections for California
- Rahimi et al., U.S. Global Change Research Program Workshop on Understanding Decision-relevant Regional Climate Projections (2023), An overview of the Western U.S. Dynamically Downscaled Dataset (WUS-D3), Invited
- Rahimi et al., American Meteorological Society 103rd Annual Meeting (2023), Bias correction-induced trend interpretability in dynamical downscaling, Invited

2022:

- Jagannathan et al., American Geophysical Union (2022), How does co-production improve the actionability of complex urban systems research?
- Jagannathan et al., American Geophysical Union (2022), Reflections from the practice and theory of coproduction of knowledge
- Jones et al., American Geophysical Union (2021), Actionable Analytics - Co-producing Climate Information for Electricity Sector Adaptation
- Jones, American Geophysical Union (2020), Co-Convener for Session SY030 - Beyond Statistics: Providing Science-Based Guidance to Support Resilient Investment in an Uncertain Future
- Rahimi et al., American Geophysical Union 104th Annual Meeting (2022), Mean-state CMIP6 GCM biases are a predictor of precipitation biases in dynamical downscaling
- Rahimi et al., World Climate Research Program (WCRP) workshop: Modeling the Climate System at Ultra-High Resolution (2022), Mean-state CMIP6 GCM biases are a predictor of precipitation biases in dynamical downscaling
- Rahimi et al., US National Center for Atmospheric Research (NCAR) HPC User's Group (2022), Dynamically downscaling CMIP6 across the western United States to quantify climate change uncertainty down to landscape scales: WRF experiments conducted down to convective-permitting scales, Invited

- Yao, P. et al., poster to American Geophysical Union 104th Annual Meeting (2022), Projected Changes in Specific Humidity from CMIP6 are Drier than Expected.

2021:

- Rahimi et al., NCAR Research Applications Laboratory (2021), Dynamical downscaling & climate change: What the Heck are we looking at?, Invited
- Rahimi et al., Northwest Climate Conference (2021), Multi-resolution dynamical downscaling of CMIP6 GCMs across the western United States using WRF4: Quantifying climate change across scales
- Rahimi et al., American Geophysical Union 102nd Annual Meeting (2021), Multi-resolution dynamical downscaling of CMIP6 GCMs across the western United States using WRF4: Quantifying climate change uncertainty down to the convective scale

CHAPTER 5:

Conclusions

The project developed a robust, state-of-the-art climate projection dataset, with input from IOUs and other stakeholders, to provide California with a dataset that is needed and useful to inform climate change assessment and adaptation planning processes. The project used the latest set of GCMs, CMIP6 models. The project also included and married together two different approaches to downscaling (dynamic and hybrid-statistical), which place California in the forefront of regional climate change assessment. The dataset enables users to address a plethora of climate change questions to help build a more resilient energy sector. For example, the dynamically downscaled data provide hourly data for 30 hourly climate variables that could be used in case studies of extreme weather or short-period climate events; the LOCA2-Hybrid data from three scenarios, 15 GCMs, and multiple ensemble member simulations enable analyses of the likelihood of extreme weather occurring and consideration of that occurrence under a range of different climate scenarios. The additional hydrologic and sea-level projections data along with the downscaled climate projections provide a comprehensive dataset to understand and prepare for effects from climate changes.

The climate projection data developed through this research included:

- Identification of a subset of 15 CMIP6 GCMs that best represent California climatology and important weather phenomenon
- Dynamically downscaled hourly data at 3-km resolution from eight different GCMs from 1980–2100 under SSP 370 (via WRF)
- Statistical-hybrid downscaled daily data at 3-km resolution over California, for 15 GCMs under three different scenarios from 1950–2100 (via LOCA2-Hybrid)
- Daily temperature data at 32 station locations based on the LOCA2-Hybrid data
- Daily projections of a set of hydrologic variables from two different hydrologic models (NOAH-MP and VIC)
- Hourly sea-level scenarios at 13 tide gauges along the coast and within the San Francisco Bay and Sacramento/San Joaquin Delta
- A selection of five general use projections from the GCM ensemble member variants to characterize essentials of the range of downscaled projected changes, including representative high impact extreme weather events and climate anomalies
- An Extremes Database that identifies and quantifies a set of short, weather time scale and longer annual to multi-annual time scale extremes of precipitation and temperature within the historical and early-, mid- and later 21st century projections from the LOCA2-Hybrid dataset

The data delivered by this project have been made available on [Cal-Adapt Analytics Engine](https://analytics.cal-adapt.org/) (<https://analytics.cal-adapt.org/>). Documentation about the data is available on the [California Energy Commission’s Climate Data and Analysis Working Group \(C-DAWG\)](#) website

(<https://www.energy.ca.gov/programs-and-topics/topics/research-and-development/climate-data-and-analysis-working-group-c-dawg>) under the *Data Justifications Memos* and *Supporting Information to Climate Data Summaries* pull-downs.

Continuing efforts to downscale the latest GCMs and produce robust climate projection datasets are critical for enabling electricity IOUs and energy policy and planning agencies to keep pace with rapid advances in climate science, evolving grid needs, and changing climate conditions across California. The dataset developed through this research provides a strong foundation for additional electricity-sector applications and targeted research to support California ratepayers. Additionally, the value of hourly data for many of the energy sector models became apparent throughout the project as discussions on data use came up in the engagement process. Thus, testing and comparing methodologies to create hourly downscaled climate projections could provide foundational information for approaches that could be used to downscale the next generation of GCMs.

This project made significant advances in the downscaling of wind data by including both speed and direction, rather than only speed as in prior research assessments. However, for the energy sector, having climate projections at the height appropriate for wind generation is critical and this research team recommends further efforts on research to develop this. There are different approaches to develop hub-height wind data; however, sufficient observations of wind speeds and direction at this height would be needed to validate any approach.

Unlike previous efforts to produce downscaled climate, this project incorporated regular engagement with users throughout the development process. For future projects, the project team recommends that user needs assessments begin several months before the data downscaling work starts to ensure that key methodological decisions can be informed by user input. Consequently, future research project planning should account for both the user-engagement timeline and the schedule for key deliverables. Each workstream, along with any related offshoot projects, would need to be sequenced so that there is sufficient time to incorporate user feedback and, when needed, adjust the project approach in response to that input.

This project has provided the climate projection data to serve as fertile ground for continuing growth and resilience planning in the electricity sector and more broadly throughout California. The lessons learned from the project can serve as a basis for future advances in developing climate projections for California, continuing the long history using the latest technology and scientific advances to strengthen the state's adaptation planning. The current project and future downscaling of climate projections are a cornerstone to ensuring that California's electricity system is prepared for the challenges presented by climate change.

List of Terms/Glossary

Term	Definition
BC	bias corrected
C-DAWG	California Energy Commission's Climate Data and Analysis Working Group
CEC	California Energy Commission
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
ENSO	El-Nino Southern Oscillation, a reoccurring climate pattern that centers in the tropical Pacific but can affect climate in California among other locations
EPIC	Electric Program Investment Charge
ERA5	the fifth generation European Center for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate covering the period from January 1940 to present
ERA5-WRF-BC	the training dataset used in this research for bias correction — that is based on the ERA5 downscaled data with WRF and bias corrected using California weather station data
GCMs	global climate models, the numerical models that are designed by specialized international modeling centers to simulate earth systems and climate in locations around the world. Note that in other literature GCM can also sometimes refer to general circulation models which is a synonym for global climate models with respect to climate projections.
IOUs	investor-owned utilities
LOCA	localized constructed analogs statistical downscaling method (Pierce et al. 2014; Pierce et al. 2015)
LOCA2-Hybrid	the newly developed version of the localized constructed analogs statistical approach that used dynamical downscaling for the pattern library
km	kilometer
mm	millimeter
NASA NEX	National Aeronautics and Space Administration Earth Exchange
NOAA	National Oceanic and Atmospheric Administration
NWSC	National Center for Atmospheric Research-Wyoming Supercomputing Center

Term	Definition
RCP	Representative Concentration Pathways, the scenarios from the prior group of global climate models
SSP	Shared Socioeconomic Pathway, the name of the different climate scenarios in the newest generation of global climate models
Tmax	maximum temperature
Tmin	minimum temperature
VIC	variable infiltration capacity hydrologic model
WRF	Weather Research and Forecasting model, one of the most widely maintained and used regional climate models

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- Bass, B., S. Rahimi, N. Goldenson, A. Hall, J. Norris & Z.J. Lebow. 2023. "[Achieving Realistic Runoff in the Western United States with a Land Surface Model Forced by Dynamically Downscaled Meteorology](#)." *Journal of Hydrometeorology*, 24(2), 269–283. <https://doi.org/10.1175/JHM-D-22-0047.1>
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- [Cal-Adapt Analytics Engine](https://analytics.cal-adapt.org/): <https://analytics.cal-adapt.org/>
- California Energy Commission: [Climate Data and Analysis Working Group \(C-DAWG\)](https://www.energy.ca.gov/programs-and-topics/topics/research-and-development/climate-data-and-analysis-working-group-c-dawg)
<https://www.energy.ca.gov/programs-and-topics/topics/research-and-development/climate-data-and-analysis-working-group-c-dawg>

Project Deliverables

The following provides an overview of major project deliverables that are available on the Energy Commission's Climate Data and Analyses Working Group (C-DAWG) website:

- Evaluation of CMIP6 GCMs Relevant for California Report (Task 3)
- Memorandum on General Use Projections for California (Task 3)
- Dynamically Downscaled Projections of 1st Set of WRF Projections (Task 4)
- Development of 2nd Set of Dynamically Downscaled Projections using WRF (Task 4)
- Memorandum on LOCA Downscaled Output from 15 CMIP6 GCMs (Task 5)
- Memorandum on LOCA2 Hourly Station Temperature Projections (Task 5)
- Memorandum on Hydrologic Modeling of Climate Projections (Task 6)
- Memorandum on Hourly Sea Level Projections Memorandum (Task 7)
- Targeted Extremes Database Memorandum (Task 8).

Other project deliverables, including interim project reports of the above, are available upon request by emailing pubs@energy.ca.gov and providing the project agreement number (EPC-20-006).

- Stakeholder Engagement Plan (Task 2)
- Stakeholder Engagement Report (Task 2)
- Knowledge Transfer Plan (Task 10)
- Summary of TAC Comments (Task 1)
- Technology Transfer Summary Report (Task 10)



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APPENDIX A: Dynamically Downscaled Models and Variables Post Processed Available

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Appendix A:

Dynamically Downscaled Models and Variables

Post-Processed Available

Table A-1. Dynamical Downscaled GCMs delivered as part of EPC-20-006, classified by the use of bias correction (BC). GCM nicknames are given in paratheses.

GCM	Country
Initial four GCMs: No BC of GCM boundary conditions	
CESM2 r1i1p1f1 (CESM2)	United States
CNRM-ESM2-1 r1i1p1f2 (CNRM)	France
FGOALS-g3 r1i1p1f1 (FGOALS)	China
EC-Earth3-Veg r1i1p1f1 (ECE)	Sweden
A Priori Bias Corrected GCMs	
MIROC6 r1i1p1f1 (MIROC)	Japan
TaiESM1 r1i1p1f1 (TaiESM)	Taiwan
EC-Earth3 r1i1p1f1 (ECEnoVeg)	Sweden
MPI-ESM1-2-HR r3i1p1f1 (MPI)	Germany
EC-Earth3-Veg r1i1p1f1 (ECEnew)	Sweden

Table A-2. The 30 **hourly** variables we provide. The additional variables that are available for BC GCMs are noted in blue. Note, EC-Earth3-Veg does not contain the new PV and wind variables of the other bias corrected experiments.

Name	Units
1. 2-m temperature	[K]
2. 2-m specific humidity	[kg kg-1]
3. Surface pressure	[Pa]
4. 10-m u-component of the wind (grid relative)	[m s-1]
5. 10-m v-component of the wind (grid relative)	[m s-1]
6. Snow water equivalent	[mm]
7. Skin temperature	[K]
8. Non-convective precipitation (cumulative)	[mm]
9. Convective precipitation (cumulative)	[mm]
10. Cumulative snowfall equivalent	[mm]
11. Diffuse downwelled solar radiation	[W m-2]

Name	Units
12. Surface upwelled solar radiation (all sky)	[W m-2]
13. Surface upwelled solar radiation (clear sky)	[W m-2]
14. Surface downwelled solar radiation (all sky)	[W m-2]
15. Surface downwelled solar radiation (clear sky)	[W m-2]
16. Surface upwelled longwave radiation (all sky)	[W m-2]
17. Surface upwelled longwave radiation (clear sky)	[W m-2]
18. Surface downwelled longwave radiation (all sky)	[W m-2]
19. Surface downwelled longwave radiation (clear sky)	[W m-2]
20. Surface runoff	[mm s-1]
21. Sub-surface runoff	[mm s-1]
22. Time-varying roughness length	[m]
23. Shortwave surface downward diffuse irradiance	[W m-2]
24. Shortwave surface downward direct normal irradiance	[W m-2]
25. Shortwave surface downward direct irradiance	[W m-2]
26. 3-D perturbation pressure	[Pa]
27. 3-D perturbation potential temperature	[K]
28. 3-D perturbation geopotential	[m ² s-2]
29. 3-D zonal wind (grid relative)	[m s-1]
30. 3-D meridonal wind (grid relative)	[m s-1]

Table A-3. The 42 variables post-processed **daily** time scales. The additional variables that are available for BC GCMs are noted in blue. Note, EC-Earth3-Veg does not contain the new PV and wind variables of the other bias corrected experiments and convective precipitation is only nonzero in the 45- and 9-km simulations.

Name	Units	Label
1. 2-m average temperature	[K]	't2'
2. 2-m minimum temperature	[K]	't2min'
3. 2-m maximum temperature	[K]	't2max'
4. Maximum hourly precipitation	[mm h-1]	'prec_max'
5. 2-m specific humidity	[kg kg-1]	'q2'
6. Maximum 10-m wind speed	[m s-1]	'wspd10max'
7. Snow water equivalent	[mm]	'snow'
8. Precipitation rate	[mm d-1]	'prec'
9. Snow precipitation rate	[mm d-1]	'prec_snow'

Name	Units	Label
10. Relative humidity	[0-100]	'rh'
11. Integrated vapor transport (zonal and meridional components; earth relative)	[kg s-1 m-1]	'ivt'
12. Ice water path	[kg m-2]	'iwp'
13. Liquid water path	[kg m-2]	'lwp'
14. Soil moisture	[m3 m-3]	'soil_m'
15. Soil temperature	[K]	'soil_t'
16. Skin temperature	[K]	'tskin'
17. Surface pressure	[Pa]	'psl'
18. Surface runoff	[mm d-1]	'sfc_runoff'
19. Sub-surface runoff	[mm d-1]	'subsfc_runoff'
20. Evaporation	[mm d-1]	'evap_sfc'
21. Evapotranspiration	[mm d-1]	'etrans_sfc'
22. Downwelled SW at surface (> 0 into sfc)	[W m-2]	'sw_dwn'
23. Downwelled LW at surface (> 0 into sfc)	[W m-2]	'lw_dwn'
24. Net SW flux at the surface (> 0 into sfc)	[W m-2]	'sfc_sfc'
25. Net LW flux at surface (> 0 into atm)	[W m-2]	'lw_sfc'
26. Sensible heat flux at surface (> 0 into atn)	[W m-2]	'sh_sfc'
27. Latent heat flux at surface (> 0 into atm)	[W m-2]	'lh_sfc'
28. Ground heat flux at surface (> into atm)	[W m-2]	'gh_sfc'
29. 3-D q	[kg kg-1]	'q_3d'
30. 3-D w	[m s-1]	'w_3d'
31. 10-m u, v (earth relative)	[m s-1]	'uv10'
32. 3-D u (earth relative)	[m s-1]	'u_3d'
33. 3-D v (earth relative)	[m s-1]	'v_3d'
34. 3-D geopotential height	[m2 s-2]	'phi_3d'
35. 3-D temperature	[K]	't_3d'
36. Convective precipitation	[mm d-1]	'prec_c'
37. Mean 10-m wind speed	[m s-1]	'wspd10mean'
38. Convective available potential energy	[J kg-1]	'cape'
39. Convective inhibition	[J kg-1]	'cin'
40. Planetary boundary layer height	[m]	'pblh'
41. Level of free convection	[m]	'lfc'

Name	Units	Label
42. Maximum 10-m wind speed	[m s-1]	'wspd10max'

The full 6-hourly WRF datastream for all grids (45-, 9-, and 3-km) in its native output form can be found in the Amazon S3 bucket described in the data access section below. The best way to examine the file contents is by loading a 6-hourly file into memory and examining the data keys. More than 200 variables are provided in each 6-hourly file.



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APPENDIX B: Appendix B: LOCA2-Hybrid Models and Variables Available

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Appendix B:

LOCA2-Hybrid Models and Variables Available

Table B-1. A list of the LOCA2-Hybrid downscaled simulations and the available variables for each of the simulations.

ACCESS-CM2		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar
historical											
ssp245	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp370	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp585											
ssp585	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
CESM2-LENS		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar
historical											
ssp370	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r2i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r3i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r4i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r5i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r6i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r7i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r8i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r9i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r10i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
ssp370	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r2i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r3i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r4i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r5i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r6i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r7i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r8i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r9i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
	r10i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	.
CNRM-ESM2-1		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar

historical											
	r1i1p1f2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp245											
	r1i1p1f2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp370											
	r1i1p1f2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp585											
	r1i1p1f2	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
EC-Earth3		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar
historical											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp245											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp370											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp585											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
EC-Earth3-Veg		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar
historical											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r3i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r4i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp245											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r3i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r4i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp370											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r3i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r4i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp585											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r3i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r4i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
FGOALS-g3		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar

historical	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
	r3i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
	r4i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
ssp245	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
	r3i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
	r4i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
ssp370	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
	r3i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
	r4i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
ssp585	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
	r3i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
	r4i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
GFDL-ESM4		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar
histori	cal										
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp245											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp370											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp585											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
HadGEM3-GC31-LL		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar
historical											
	r1i1p1f3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp245											
	r1i1p1f3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp585											
	r1i1p1f3	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
INM-CM5-0		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar
historical											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp245											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp370											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

ssp585	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
IPSL-CM6A-LR											
		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar
historical											
	r1i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r3i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r4i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
ssp245	r1i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r3i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r4i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
ssp370	r1i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r3i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r4i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
ssp585	r1i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r3i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r4i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
KACE-1-0-G											
		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar
historical											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
	r3i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
ssp245	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
	r3i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
ssp370	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
	r3i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
ssp585	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
	r3i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
MIROC6											
		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar

historical	r1i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r3i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
ssp245	r1i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r3i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
ssp370	r1i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r3i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
ssp585	r1i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
	r3i1p1f1	Y	Y	Y	.	.	.	Y	Y	Y	Y
MPI-ESM1-2-HR		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar
historical	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp245	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp370	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp585	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	r2i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
MRI-ESM2-0		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar
historical	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp245	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp370	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
ssp585	r1i1p1f1	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

TaiESM1		Precip	Tmax	Tmin	SpecH	RH_max	RH_min	Wspeed	U10	V10	Solar
historical											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
ssp245											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y
ssp370											
	r1i1p1f1	Y	Y	Y	Y	Y	Y	.	.	.	Y