ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Climate Science Support for the Cal-Adapt Enterprise

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These natural gas research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with RD&D entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater gas reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency
- Industrial, Agriculture and Water Efficiency
- Renewable Energy and Advanced Generation
- Natural Gas Infrastructure Safety and Integrity
- Energy-Related Environmental Research
- Natural Gas-Related Transportation

Climate Science Support for the Cal-Adapt Enterprise is the final report for the Contract Number PIR-17-014, conducted by Owen Doherty and Victoria Ford of Eagle Rock Analytics. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

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

ABSTRACT

Cal-Adapt serves a critical need as a reliable source of climate data for the fossil fuel sector. This work increased the trustworthiness and utility of the Cal-Adapt enterprise through developing scientific and statistical best practices with cutting-edge tools and visualizations. Visualizations developed by Cal-Adapt provide insight into how climate change will impact fossil fuel operations and highlights the urgent need to rapidly decarbonize the global energy system to both improve the environment and advance California's ambitious environmental mandates. This work also identifies key gaps in climate data and climate services and outlines solutions by presenting a pathway for future California climate assessments that avoid climate related pitfalls and delays. A forward-looking, expanding Cal-Adapt enterprise creates opportunities for increasing ratepayer benefits at a lower cost through cloud computing and narrowing the gap between climate and energy system modeling through informed tool development. This work supports Cal-Adapt's move away from educating users and instead leads Cal-Adapt toward a comprehensive climate data service for a more resilient fossil fuel system.

Keywords: Cal-Adapt, geospatial data, GIS visualization, climate change, extreme weather events, climate resiliency

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Background

For more than 10 years Cal-Adapt (https://cal-adapt.org/), which is a collaboration between state agency funding programs, university, national lab and private sector researchers, has provided free public access to data relating to climate change in California, drawing primarily from peer-reviewed climate projections in California's Climate Change Assessments. Cal-Adapt provides a climate change geospatial data tool for California, developed and maintained by the University of California, Berkeley's Geospatial Innovation Facility, with funding and oversight provided by the California Energy Commission. Originally released in 2011, Cal-Adapt's web application provides access to primary data as well as interactive visualizations of projected climate changes at local levels. It has been used within the energy sector (for example, supporting California's investor-owned utilities that participated in the United States Department of Energy's Climate Resilience Partnership) and in other activities such as input for climate action plans by city, county, and tribal entities throughout the state.

Cal-Adapt's web application has evolved substantially since its original release, with improvements since 2016 providing both access to climate projections developed in support of California's Fourth Climate Change Assessment and enhanced functionality since the first generation of Cal-Adapt. However, while Cal-Adapt has been recognized by legislators and state agencies including the California Public Utilities Commission as a key resource to rely on for climate adaptation, there remains a gap between resources provided and the capacity to provide support.

Project Purpose and Approach

This project provided scientific guidance to help narrow the gap between existing Cal-Adapt web application features and what is needed to address the climate resilience of California's fossil fuel sector.

First, this work supported the development of scientific and statistical best practices with cutting-edge tools and visualizations. These visualizations use advanced statistics to provide representations of climate change and include probabilistic formulations of interest to fossil fuel sector utilities. These visualizations move beyond providing access to primary data and interactive visualizations to providing increasingly complex datasets that speak to energy-sector resilience.

Second, this work identified key gaps in climate data and services (as well as opportunities and challenges) with a cloud-based Cal-Adapt tool. This report also provides suggestions for negotiating these challenges and opportunities by presenting an organizational pathway for many interdependent elements to avoid pitfalls and delays, which can have cascading impacts on both scientific resources and development of Cal-Adapt features.

Key Results

Cal-Adapt is a widely recognized source of information for fossil fuel applications, and its data are quality-controlled and sanctioned by the state (for example, formally approved by the California Public Utilities Commission for use in adaptation planning, as well as in multiple pieces of legislation and for state guidance). This project makes several key research contributions, which follow. The following key contributions from this research further enhance Cal-Adapt features.

- Visualizations developed by Cal-Adapt provide new insight into how short-term and long-term climate change impacts will influence fossil fuel operations and highlight the urgent need to rapidly decarbonize the global energy system.
- New Cal-Adapt tools build upon scientifically robust concepts emerging from extreme value theories and exploratory data analyses.
- The gap between historical weather observations, real-time weather risk, and climate projections have been narrowed through Cal-Adapt's *Extreme Weather Tool,* for which additional refinements are easily achievable.
- Newly developed best practices and metadata documentation contributed by this research further increase the usefulness of the Cal-Adapt tool.

Further, this effort provides critical perspective on streamlining Cal-Adapt toward development of more powerful data that support energy resilience, as well as more efficient use of scientific and development resources, noting that:

- Progress toward locally granular climate projections has been slowed due to a lack of observational data, especially variables critical to energy modeling (e.g., time-resolved winds above the surface and surface solar radiation data). An enhanced Cal-Adapt tool can provide historical observational data in a way that more clearly leads to further innovation within the energy sector and long-term climate data that are more responsive to fossil fuel stakeholder needs.
- Cloud computing has created both opportunity and risk for Cal-Adapt. A long-term, climate-informed approach can and should be developed that strategically maps Cal-Adapt cloud computing approaches in coming years.
- A forward-looking, expanding Cal-Adapt tool creates opportunities for increasing ratepayer benefits from lower costs through cloud computing, and narrowing the gap between climate and energy system modeling through stakeholder-informed tool development.

Knowledge Transfer and Next Steps

Knowledge transfer from this research was provided in three ways. The first is publicly available, interactive visualizations that incorporate advanced statistics that provide a probabilistic perspective on extreme events as well as information regarding uncertainty. Second, this effort supported the development of a webinar aimed at helping energy stakeholders more broadly understand and use climate data in their work. This webinar has been the most popular of any developed programs supporting Cal-Adapt, and investor-owned utility feedback regarding the webinar indicated broad support for other similarly themed educational materials. Finally, this research provided a critical synthesis of some of the challenges and opportunities associated with interdependent research efforts and the foundational cloud computing environment.

CHAPTER 1: Introduction

Cal-Adapt provides tools and visualizations that make climate information available to fossil fuel utilities and associated stakeholders. As climate change impacts have become more apparent, and in response to evolving regulations, the need for actionable, specific forms of climate information has grown. This effort supported developments to help Cal-Adapt evolve from providing education and scientific context, to more actionable, usable climate information.

This report documents an effort funded by the California Energy Commission's (CEC) Gas Research and Development Program, which supports applied research and development projects designed to produce ratepayer benefits in the form of increased reliability, improved safety, and reduced fossil fuel costs and to ultimately achieve the state's statutory energy goals. This project continued the development of Cal-Adapt, an interactive website for visualizing local climate change-related risks, with aims to improve informed resilience for the fossil fuel sector. Enhancements to Cal-Adapt through this project provided scientific support of tools and visualizations that incorporate complete data and statistical analyses and built upon the principles of exploratory data analysis to clearly convey uncertainty and range of data.

This work provided scientifically robust enhancements to the Cal-Adapt framework that improved support for fossil fuel sector stakeholders and integrated more data resources, specifically:

a. Ensuring that the tools and visualizations incorporated scientific and statistical principles, and that the computational structure of Cal-Adapt was built using technical best practices

b. Developing analyses guided by user needs, including the tools that represented multiple climate-related risks, demand forecast tools, extreme precipitation visualizations, and visualizations identified in collaboration with fossil fuel sector stakeholders as new data sets become available

c. Remaining flexible and adaptable to meet evolving future stakeholder needs

This work provided ratepayer benefits of greater fossil fuel reliability and increased safety measures by helping investor-owned utilities (IOUs) to understand fossil fuel infrastructure vulnerability in the context of risk from wildfire, sea-level rise, and other extreme climate events. Informed use of fossil fuel infrastructure will increase reliability through reducing damage, decreasing costs through reduced losses, and increasing safety of the delivery system. This project developed breakthrough technological advancements, which advance California's statutory energy goals by providing key climate informatics to natural gas IOUs, governmental stakeholders, elected officials, and energy sector stakeholders. Data and algorithms hosted on Cal-Adapt continue to be used to understand shifts and changes in peak fossil fuel consumption.

This work addressed a critical knowledge gap in the climate resilience capacity of the fossil fuel sector. Specifically, comprehensive climate data services — defined as scientifically based information and products that enhance users' knowledge and understanding about the impacts of climate on their decisions and actions (AMS, 2022) — are needed. Prior to this work Cal-Adapt was unable to provide the full scope of requisite climate expertise and information to make climate-informed investment decisions. Cal-Adapt is frequently externally referred to as a "decision-support tool," but as noted in California's Fourth Climate Assessment (Thomas et al., 2018), it has not developed to the point where it directly supports adaptation decision making.

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

This report highlights the gap between external expectations and the historical development path, recognizing that at this point, Cal-Adapt is neither a decision support tool nor a climate services provider (Thomas, et al., 2018). Ongoing and future work funded through the CEC support the goal of increasing decision-making capacity, and conveyance of complex scientific principles, via a more robust, expanded Cal-Adapt tool. The gap between decision support needs and what is currently available via Cal-Adapt is the source of much misunderstanding and must be better understood to support development of features that support energy sector resilience.

At present, both the climate data services provided by Cal-Adapt and climate data service needs beyond Cal-Adapt are summarized here:

Climate Data Services Provided by Cal-Adapt:

- Authoritative and trustworthy data curation
- Data access that supports a range of user technical capacity
- Visualizations that inform and educate
- Incorporation of statistically robust approaches in tools
- Training and assistance in accessing data, tools, and visualizations
- Summaries of climate change on municipal and county levels

Climate Data Services Needs Outside of Cal-Adapt:

- Authoritative and trustworthy data about recent climate events
- Helping users find the right data for their needs

- Development of actionable data and metrics
- Decision-making support for users
- Translations of data into impacts
- Education and outreach to educate users on climate
- Vulnerability assessment capacity
    - Disadvantaged communities
    - Asset and property level risks

This report describes the enhancements to narrow the gap between stakeholder climate data service needs and those that the Cal-Adapt web application currently provides, with a focus on outcomes, lessons learned, and next steps and recommendations to increase the accessibility of climate information to fossil fuel providers via the expanding and evolving Cal-Adapt enterprise (CEC Staff, 2021).

CHAPTER 2: Project Approach

This research effort provided climate science support and guidance to the Cal-Adapt development team. Through weekly or bi-weekly meetings with developers and CEC staff, this work supported the planning and execution of nearly every tool and feature developed by Cal-Adapt in the prior four years. Contributions ranged from developing best practices for data use, curating data sets, designing statistical tests, informing tools and visualizations with state-of-the-art scientific knowledge, calculating climate metrics, engaging stakeholders, developing educational webinars, and testing developed features. All tools designed and implemented by the Cal-Adapt development team during this agreement were carefully reviewed in order to ensure that tools conformed to scientific best practices.

Beyond scientific support, a central approach for this work was identifying technical and scientific collaborations through workshops and sessions at scientific conferences and by developing an understanding of Cal-Adapt with agency employees across multiple state agencies. Building capacity for climate data use by fossil fuel stakeholders and treating state decision makers as critical stakeholders are as important to creating fossil fuel ratepayer benefits as climate research and technical development. Technologists are keen to advocate for cloud computing as a means of progress, using slogans like "democratize data" to suggest that resilience and adaptation work will proceed by making the data freely available to stakeholders. The overall experience throughout this research suggests that democratizing data is a critical first step but must be followed by building human capacity within the fossil fuel sector for using such data, and spending time with state decision makers and technical staff to raise awareness of state policies and guidelines in order to take full advantage of both scientific and data progress. Put more succinctly, while cloud computing helps Cal-Adapt make climate data readily available to stakeholders, successful technology transfer will only occur if accompanied by concerted and informed efforts in stakeholder engagement and outreach.

A priority throughout this project was to engage the Governor's Office of Planning and Research (OPR) early in the Cal-Adapt development process, ensuring that developed methods are compliant with OPR guidance on climate data used by state agencies. Both the California Public Utility Commission (CPUC) and the CEC consider such guidance in their applications. The fossil fuel sector, in turn, uses guidance from the CPUC and CEC in its own decision making. Outreach to government agencies is imperative to provide ratepayer benefits to fossil fuel customers.

Two specific project objectives were developed as a part of this effort: the *Extreme Precipitation Events Tool*, and the *Extreme Weather Tool*.

CHAPTER 3: Results

Two key project milestones are highlighted here, with ramifications for future support of fossil fuel sector resilience and adaptation planning: the *Extreme Precipitation Events Tool* and the *Extreme Weather Tool*.

Extreme Precipitation Event Tool

The role of climate change on precipitation is often visualized as changes in annual precipitation, or as mean precipitation rates. In contrast, and as stakeholders in California's fossil fuel systems have noted, the impacts of climate change on precipitation are often manifested in extremes, specifically heavy short-duration precipitation (flash flooding) or long-duration extreme deficits (drought). The *Extreme Precipitation Events Tool* was developed to address this, providing fossil fuel providers with actionable information on how climate change is expected to impact heavy precipitation events.

Scientists, and prior versions of Cal-Adapt, often represent "extreme" conditions as maps of the 90th, 95th or 99th percentile events that by definition occur infrequently. Such visualizations can be either educational or informational (particularly when paired with a comparison of previous or current climates), but they are not actionable or directly usable by the engineers and technical staff charged with assessing risk to infrastructure and planning for reliable service under future climate conditions. This is primarily because the metrics used within fossil fuel workflows typically do not use maps of 90th, 95th, or 99th percentile events.

The *Extreme Precipitation Events Tool* applies the extreme value theorem to climate projections and produces usable metrics designed for actionable decision making. Specifically, this tool provides data and visualizations in a format to which engineers and technical users are accustomed, by representing "1-in-x" events. Users select the return period (referred to by stakeholders as 1-in-x), "x" by choosing between commonly used intervals (for example, 2, 5, 10, 20, 50, 100 or 500 years). the expanded tool shows how much precipitation would occur with such an event, and how much rainfall is associated with such an extreme event historically, as well as at two future intervals: mid-century (2032 to 2064) and end of century (2069 to 2099).

Critical to scientific best practices, uncertainty is visually represented two ways: vertical bands represent 95-percent confidence intervals, which account for uncertainty within a model, and inter-model variability. The tool uses four models for default, but users can select up to 10 models. With this capability, a user can compare the range of the historical period (Figure 1) with a single model, or instead consider it across a selection of models to better understand how likely extreme precipitation events will be.

The incredible power and utility of the extreme value theorem, which is the foundation for this visualization, accommodates deep customization. Users can visualize the likelihood of a given extreme event over time, the seasonality of extreme events during the year, or assess if extreme events are likely to persist for multiple days. Additionally, users may change the length of extreme events, for example selecting single day, multi-day, or week-long extreme events. Furthermore, the tool also provides functionality for advanced users who may wish to change the underlying statistical method for determining what constitutes an extreme event, on which events are included or excluded from the underlying distribution. Regretfully, the tool fails to take advantage of its ability to invert the extreme value theorem. For example, instead of visualizing how many inches of rain correspond to a 1-in-100-year event, the tool could allow users to specify a value of precipitation (such as 2 inches) and identify how often an event of the specified magnitude is expected to occur in the future. California's fossil fuel sector would benefit from assessing how a given extreme event is anticipated to change over time. This functionality is critical for fossil fuel safety and reliability since specific thresholds are often used in the industry as the basis for reliability planning.

Figure 1: Output Example From the Cal-Adapt Extreme Precipitation Events Tool

Figure 1 illustrates a projected 1-in-20 year event in Lake County, California under a Medium Emissions (RCP 4.5) Scenario. The y-axis displays the estimated intensity of extreme precipitation events in inches. Grey vertical bars depict the 95 percent confidence interval of model uncertainty.

Source: Cal-Adapt.org, Extreme Precipitation Events tool developed with guidance from Eagle Rock Analytics.

Bridging the Gaps Between Climate and Real-Time Decision Making With the Extreme Weather Tool

Though climate projections aim to represent yearly, decadal, and longer conditions, their impacts to the safe and reliable operation and delivery of fossil fuel are made on both daily and hourly bases. Fossil fuel demand rises during periods of extreme heat and extreme cold. Prolonged extremes lead to stress on fossil fuel supplies. The frequency and intensity of extreme events that stress the ability of California's IOUs to reliably deliver gas have changed and will continue to evolve with climate change. This research supported the development of tools and visualizations that bridge the gap between climate and operations and required Cal-Adapt backend development to merge real-time predictions and observations with historical climate data. The Extreme Weather Tool, available at (https://cal-adapt.org/tools/extreme-weather/), provides context for current heat or cold, and includes information about expected conditions in the next seven days by graphically illustrating how common or extreme such conditions are expected to be.

Stakeholders need timely information on the nature of extreme conditions in both recent and future time periods to determine implications to energy system functionality. Because stake-holders vary in their technical acumen and ability to use statistics, providing summaries in easy-to-understand, non-technical language makes such a tool more accessible to a larger user base (Deas, 2014; Deas, 2015). Output of the *Extreme Weather Tool* (Figure 2) includes four major components: text overview, historical context, recent observations, in context, and expected upcoming conditions, in context. At the top of the tool display there is a plain-language description of how frequently a particular extreme temperature has occurred histori-cally. Information is also provided about the absolute extremes that have occurred in a static 30-year reference period (1991 to 2020). The summary is a visual representation of the frequency of historical temperatures (histogram), with superimposed reference lines (dotted black lines) showing the 90th and 99th percentile temperatures, as well as a red dot showing where the event in question falls within the distribution (note that users have the capability to change or set the event in question). The third row shows the events in the prior 10 days, specifically so that users can quickly and visually assess if their experience was common, uncommon, or extreme. Upcoming predicted temperatures, provided by the National Weather Service, are shown in the bottom panel and allow energy-sector stakeholders to anticipate and react to upcoming extreme events. Figure 2 describes a hypothetical fall maximum temperature event for Los Angeles International Airport, California.

Figure 2: Graphical Output From the Cal-Adapt Extreme Weather Tool

Weather Station at Los Angeles International Airport, Los Angeles (LAX), California (-118.389°, 33.938°)

Distribution of daily **Maximum Temperatures** around **September 25** (**±10 days**) from 1991-2020.

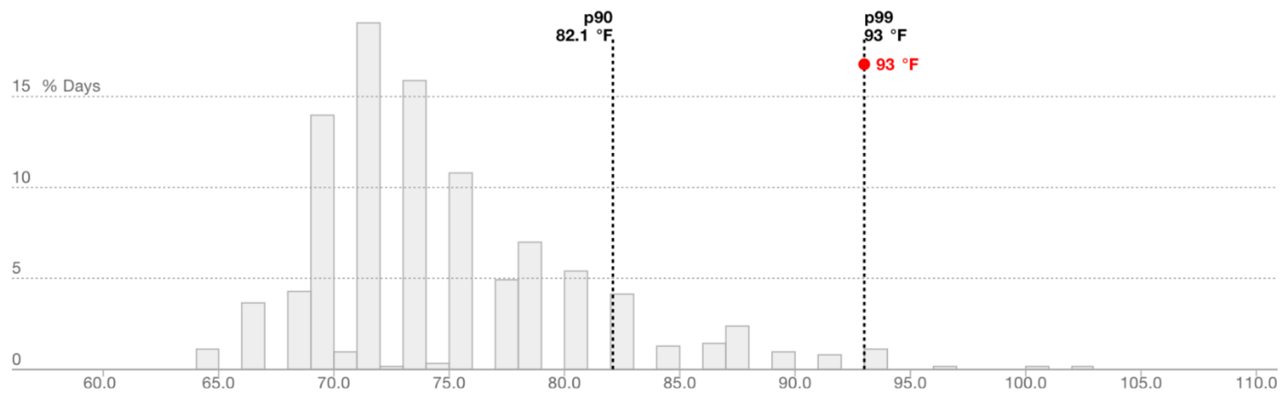
A daily **Maximum Temperature** of **93 °F** around **September 25** is a **Rare** event. Based on Extreme Value Theory and historical observations (1991-2020), the probability of daily **Maximum Temperature** being higher than **93 °F** at least once between **September 15** and **October 5** is **20%**.

In the Baseline Period (1991-2020), a daily **Maximum Temperature** higher than **93 °F** occurred **10** times between **September 15** and **October 5**.

From the available record (1943-2021) between **September 15** and **October 5**:

- A **Record Low** of **63.0 °F** was observed on **September 23, 1986**
- A **Record High** of **102.9 °F** was observed on **September 26, 2010**

Baseline Period (1991-2020)



Recent Observations

Forecast for June 28, 2023

Source: Cal-Adapt. Data: Hourly Observed Historical Data (Met Office Hadley Centre), GHCN-Daily (NCEI), Near-Term Forecast (NWS).

Source: Cal-Adapt.org, Extreme Weather tool developed with guidance from Eagle Rock Analytics

This research also builds on the extreme value theory work discussed in the Extreme Precipitation Events section, as well as the development of quality-controlled, station-based weather observations data supported by an earlier CEC-funded effort (Doherty and Evan, 2020). A curated set of observations, along with long station records and quality-controlled data, are necessary to examine extreme events. Users can also review historical wind events, which are important for energy-sector applications, including public safety power shutoff events.

The inclusion of forecasted weather events, recent observations, and historical observations opens the door to many exciting developments within Cal-Adapt. An obvious extension is using future climate projections to establish the degree to which an event is extreme. For example, a user could observe that a maximum daily temperature of 102 degrees Fahrenheit (38.89 degrees Celsius) in Riverside was historically an extreme event but, in the future, would be considered common.

Building Capacity for Use of Climate Data by the Gas Sector

Cal-Adapt has come a long way in its capacity to communicate complex information about uncertain futures. However, it is not clear if fossil fuel technical staffers have likewise evolved in their ability to (or interest in) incorporating complex, uncertain projections into their workflows and processes. Three steps are proposed that could collectively guide fossil fuel sector stakeholders to use climate data in a way that improves the safety and reliability of their systems in the face of rapidly changing climate conditions:

General, Not Specific Education. Historically, Cal-Adapt's training and education have focused on helping users access and use specific tools and visualizations. This has included webinars, tutorials, and in-person workshops. Lacking in this approach is general education regarding climate data use, statistics, and best practices for uncertain data designed for fossil fuel users and other energy stakeholders. The research team supported development of a webinar for helping energy stakeholders more broadly understand and use climate data in their workflows. This Cal-Adapt Quarterly Webinar – Introduction to Climate Data can be accessed at (https://www.youtube.com/watch?v=DGBzmyejws0) and has been the most popular of any developed in support of Cal-Adapt. Feedback from the state's IOUs indicated broad support for other similarly themed educational materials. Unfortunately, this foundational educational based work does not always fit neatly into technology innovation and advancement funding plans, where Cal-Adapt has historically received most of its funding. Education designed for engineers and other technical staff is also essential and enhances technical developments that support a safe, reliable fossil fuel system, and should be a critical component of any decision support tool development process and funding.

Encourage Climate Scientists to Adopt Decision Making Under Uncertainty Frameworks. Cal-Adapt demonstrates cutting-edge science in visualizations that discretely represent multiple climate scenarios, models, and time periods. Such an intentional approach makes tremendous sense given how climate data is both generated and consumed. However, the outputs of these visualizations and tools can be difficult to address since planning and decision making is not predicated on climate scenarios or climate models with multiple future outcomes, but rather on specific metrics (for example, "mean") or events (for example, a "95th percentile event"). Further complicating the use of climate data is an understanding that the energy systems of California are changing rapidly, creating an additional dimension of uncertainty. One potential approach that Cal-Adapt should consider is pursuing a decision making under uncertainty framework, which (amongst other things) presents climate information based upon combinations of human behavior choices. By coupling Cal-Adapt with various energy system models, combinations of different potential energy system outcomes can be assessed as either resilient or failing, under climate change scenarios (for example, Visualization 5 of this assessment (Groves and Syme, 2022) of water system reliability, under climate change scenarios).

Support Development of Climate-Informed and Climate-Savvy Energy System Models. The classical point of friction between energy-system stakeholders and climate scientists is what is sometimes referred to as the "just give me a number" problem. Stakeholders often seek a single value representing future climate conditions. Climate scientists resist providing such simplifications, viewing single numbers as inappropriate and scientifically indefensible. Understandably, the request often arises from technical or modeling approaches within energy systems that can only accommodate a single number or parameter to represent weather. There is no visualization or advanced analytic capable of representing future climate in such a way. Simply put, energy system models must evolve to the point of both accepting a range of future conditions and planning systems that can function within such a range. Climate resilience and adaptation represent a relay race with multiple partners across industries. Cal-Adapt's speed can be improved and trained to perform better, but to win the race a relay partner is needed that is capable of grabbing the baton. At present many critical stakeholders, including some in the fossil fuel sector itself, are not positioned to do so.

Increasing the Efficiency of Observation to Downscaled Climate Projection Process Within California's Climate Assessment Framework

Progress toward locally granular climate projections has been slowed due to a lack of observational data, particularly of variables critical to energy modeling (for example, winds above the surface, radiation data). A framework for the enhanced Cal-Adapt enterprise (Figure 3) can use real-time observational data in a way that leads to further innovation and climate data, which is more responsive of fossil fuel stakeholder needs.

Figure 3: Idealized Data Flow From Observation to Outcomes Within Cal-Adapt

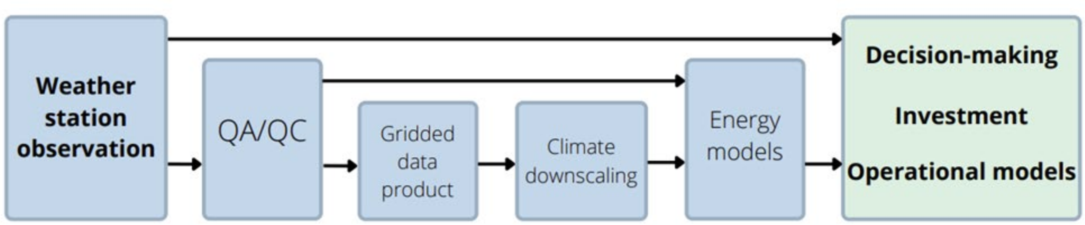


Figure 3 illustrates an idealized data flow between weather station observations towards decision making.

Source: Adapted from Doherty et al., 2022.

Build on Progress to Fill Observational Data Gaps

Missing hourly, localized weather observations limit climate scientists' ability to downscale projections to the resolution needed in investments and planning. Currently, the scientists charged with generating downscaled climate data must scramble to find observational datasets to train and validate their statistical and dynamical models. Cal-Adapt is accumulating historical weather observations within the cloud (Doherty and Evan, 2020), meaning that the observations are available and can be assimilated into a data product using cloud computing resources. The leading methods to interpolate observations to a grid are well known and established in the literature (such as kriging, inverse distance weighting, surfacing), and in many cases are open source.

Limiting such an approach is the lack of above-surface wind data and solar radiation observations, both of which are critical for understanding the future availability of low-carbon, renewable energy generation. The following steps are needed to address and fill these data gaps:

1. Assess the current availability of variables critical to energy modeling, current spatial coverage, costs to deploy, and optimal sensor positioning for climate modeling.
2. Develop a centralized repository of high-quality weather observations within Cal-Adapt. This repository could serve as the basis for a California-wide weather-observing mesonet system, which in turn requires optimized weather station siting analyses (Doherty et al., 2022).
3. Support research efforts to use the centralized repository for weather observations to generate assimilated gridded historical weather products that can be used for downscaling, bias correction, and other climate-focused measures.
4. Enhance planning and coordination across connected research endeavors for future California Climate Assessments.

Downscaling global models to the scale necessary for fossil fuel stakeholders to incorporate in their workflows requires observations at a local scale. The efforts to create such projections for the next generation of Cal-Adapt have been bedeviled and delayed by a myriad of challenges, including critical difficulties in identifying and obtaining local historical weather data. These delays have negatively impacted the timelines of other sector efforts. Moving forward, such processes should be safeguarded by identifying historical data products to serve as the bases for downscaling *ahead of efforts to downscale models*. This will benefit Cal-Adapt by creating a reliable reference historical dataset that would serve as the default historical product within Cal-Adapt.

Figure 4 shows a hypothetical timeline outlining the preferred order of operations for assessing user needs, generating historical observations, generating climate projections, and kicking off a statewide climate assessment. This approach is based on the foundations of the Waterfall style project management. Building on the progress made in identifying important variables prioritized in California's Fifth Climate Assessment, stakeholders should identify gaps and collectively develop a data framework. Having identified these key variables, the required timescales and needed resolution for historical data can then be addressed.

Figure 4: Idealized Schedule of Events for a Successful Statewide Climate Assessment

Figure 4 illustrates a Waterfall schedule approach of tasks for California's Fifth Climate Assessment.

Source: Eagle Rock Analytics

Additional collaboration and planning, beyond what is occurring today, is necessary between data hosts (Cal-Adapt), historical data producers, and climate projection producers. Ideally such conversations would be facilitated by funding agencies involved with California's Climate Change Assessments. Increasing complexity of the data hosted on Cal-Adapt — from model selection, socioeconomic scenarios, post-processing efforts (specifically multiple bias correction approaches, multiple projected grids (WRF [Weather Research and Forecasting Model] and LOCA [Localized Constructed Analogs], and metadata/variable names) — requires intentional pre-planning to develop data structures and computer architecture. Climate data producers and Cal-Adapt should discuss this both before work begins and after user needs assessments have begun. Given the scale and expense of the work and the many uses of data products generated, periodic check-ins via teleconferencing are insufficient to address complex issues around coordination. We recommend that funding agencies involved with California's Climate Change Assessments consider a multi-day planning workshop ahead of project kickoff.

Following a climate data planning workshop, climate projections efforts can begin, followed by data-user assessments of data, analytics, and visualization provisioning. Cal-Adapt development can begin in earnest after the structure and format of climate projections are known. Once observations, climate projections, and data platform work are established, larger assessment activities and research should be conducted. A second phase of climate projections can occur concurrently to support energy-specific research applications. This approach would increase benefits to ratepayers by creating a structure where expectations for each team are clear, delays in one project can be identified early, and impacts to dependent research efforts are minimized.

CHAPTER 4: Conclusion

This expanded Cal-Adapt enterprise found a home in the cloud. At its root, the entire Cal-Adapt project is a technology transfer activity, conveying research project outcomes to energy system stakeholders. The future of effective climate research is bright, with major developments in geospatial data storage, cloud computing, and climate model downscaling. However, advances are ongoing, requiring navigation of unforeseen challenges, increased coordination between research teams, and proactive efforts to reduce cloud computing expense. In this section the project results are discussed in terms of the opportunities and challenges associated with Cal-Adapt in the cloud, and proposed recommendations for increasing ratepayer benefits in a future cloud environment.

Grand Opportunities

The amount of climate data on Cal-Adapt has increased from 10 gigabytes, to 300 terabytes, to 2.5 petabytes of storage in recent years, creating the potential for computational resource challenges for users. To address this, Cal-Adapt is moving to a future where users can perform advanced computations on massive climate datasets without the need to download and process gigabytes to terabytes of data. The next generation of visualizations and tools developed for Cal-Adapt should build on the computer architecture, and analytical capacities developed within this project as well as those under development at Cal-Adapt: the Analytics Engine.[1] The *Extreme Weather* and *Extreme Precipitation Events* tools are recognized as models for future tool and visualization development.

Cloud-Related Challenges on the Horizon

While the cloud as the home for California's climate data enterprise presents excellent opportunities to support advanced computations relating to energy-sector resilience, the cloud also presents a number of challenges that must be planned for.

Cloud Computing Is Cheap, Data Storage Is Expensive

As climate projections become more localized and able to resolve daily weather cycles, the amount of storage capacity needed to serve the data has increased exponentially. Storage expenses accrue continually, creating onerous funding requirements. In contrast, the cost to perform computations on data is steadily decreasing. Cal-Adapt can be run in a more cost-effective manner by shifting capacity towards on-the-fly computations rather than extensive pre-processed and long-term data storage. In practice, this translates to reducing the quantity of projections while increasing the number of analytical tools to localize and bias-correct data within Cal-Adapt.

[1] The Cal Adapt: Analytics Engine brings data and computational resources together in the cloud, allowing users to work with Petabytes of stored data supported by scientific guidance. These data and code facilitate informed decision-making for climate resilience and investments (https://analytics.cal-adapt.org/).

What Does a Data Download Tool Look Like in the Future?

Perhaps the most popular tool and feature in the current iteration of Cal-Adapt are the data download tool and Application Programming Interface (API) access. Transitioning data structures to cloud-native formats (for example, transforming a file into the cloud-optimized Zarr format) open up new possibilities and capacities for user access to climate data. A comprehensive user assessment of needs, informed by the understanding of new technical capacity and data capabilities, is needed. Recreating the current capacity on new architecture and data should only be considered as a crutch (or temporary fix) since new capacities should be embraced to enable the energy sector to take advantage of those advances.

Long-Term Storage of Climate Projections

Hard questions need to be answered in order to develop a plan for dealing with legacy data. For example: What aspect of California's downscaled climate data should be archived? Is there value to fossil fuel ratepayers in being able to compare projections? Should the record be preserved for historical or legal purposes? Who decides this? What should happen to the current data (California's Fourth Climate Change Assessment) when new data arrives (California's Fifth Climate Change Assessment)? These questions identify the need for the larger Cal-Adapt enterprise to develop a plan for dealing with legacy data.

What is known is that preserving the data in its current form is prohibitively expensive, particularly if the data are to be maintained indefinitely. The cloud does provide some significantly less expensive options for long-term, infrequently accessed, archived data. Generally, these types of archival storage are referred to as "cold storage," which feature low costs to store but come with the drawback of very slow retrieval times, meaning long waits for users to access the data. If this option was chosen, Cal-Adapt would be exposed to the cost of transferring data to users, requiring long-term support and budgeting flexibility.

Ensuring Reproducibility of All Climate Data Products

Cal-Adapt provides peer-reviewed, state-sanctioned data that fossil fuel stakeholders can access with confidence that the data is appropriate for use in regulatory applications. Cal-Adapt has developed scientifically informed tools and visualizations, best practices for data use, and metadata standards. The platform itself is open-sourced and reviewable. Each of these developments is in line with findable, accessible, interoperable, and reusable data principles. Historically, much of the climate data hosted by Cal-Adapt have not met these standards. Moving forward, climate projections that underpin both Cal-Adapt and California's Climate Change Assessments should be open-sourced, with the methods and code used to generate the data available free of charge for everyone to review and study.

System Agnostic Futures

Cal-Adapt has found a home and a partner in Amazon Web Services (AWS), with AWS providing free storage and cloud compute credits, reducing the cost of maintaining Cal-Adapt for fossil fuel ratepayers. While this agreement is anticipated to continue for the foreseeable future, alternate arrangements for cloud computing services must be considered for what happens if or when Cal-Adapt has to bear the full cost of maintaining service without subsidies. The annual cost to store data of the core products of the Fifth Assessment is nearly $600,000, and closer to $1,500,000 if including the full suite of dynamically downscaled WRF data products. Additionally, cloud compute costs range between $20,000 to $25,000 per year for the full enterprise. Presently data egress fees are covered by AWS, so the expense is unknown. In total, in a non-subsidized scenario the annual technical cost to maintain the Cal-Adapt enterprise is $650,000 to $1,550,000, not including labor costs for researchers and developers.

Minimizing annual expenses is critical. Funding research and engagement provides more benefits to fossil fuel ratepayers, making climate data more actionable, rather than paying for a server. One approach is to ensure that Cal-Adapt is service provider agnostic, meaning able to be run in any computing environment. There is robust competition in cloud services, with many providers offering resources to public-good efforts such as Cal-Adapt; ensuring that Cal-Adapt is movable and able to take advantage of such opportunities is critical. Furthermore, one could imagine a future where the state of California has invested resources in its own high-performance computing environment, where Cal-Adapt could find a permanent home. Presently, Cal-Adapt achieves this flexibility through containerizing (via an independent environment docker) applications that can be run on any virtual server, and in turn sit on top of data storage capabilities. System agnostic development should be enshrined as a core philosophy of Cal-Adapt, and a requirement for future funding opportunities.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
API	Application Programming Interface
AWS	Amazon Web Services
CEC	California Energy Commission
CPUC	California Public Utilities Commission
LOCA	Localized Constructed Analogs
OPR	Governor’s Office of Planning and Research
IOU	investor-owned utility
WRF	Weather Research and Forecasting Model

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Project Deliverables

Products of this research include, in addition to this report:

- Owen Doherty, January 23, 2020. "Cal-Adapt Quarterly Webinar – Introduction to Climate Data." Available at https://www.youtube.com/watch?v=DGBzmyejws0.
- Analytical support, scientific vision, and thought leadership for "extreme" visualization tools on https://cal-adapt.org, e.g., Extreme Precipitation Events Tool, Extreme Weather Tool
- Memorandum on Metadata Best Practices (interim deliverable available upon request by email to ERDDpubs@energy.ca.gov.