Navigating a Flood of Information

Evaluating and Integrating Climate Science into Groundwater Planning in California

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[EXECUTIVE SUMMARY]

In California, groundwater contributes more than half of the state's water supply during dry years (DWR 2009). Therefore, understanding the impacts that climate change will have on this critical resource is of importance for the state's long-term water and food security. To that end, Governor Jerry Brown issued Executive Order B-30-15 that, along with setting ambitious greenhouse gas reduction targets, requires that state agencies take climate change into account in their planning and investment decisions. In addition, California's Sustainable Groundwater Management Act (SGMA), passed by the legislature in 2014, requires that Groundwater Sustainability Agencies explicitly assess the impacts of climate change and incorporate these assessments into their Groundwater Sustainability Plans.

As climate change leads to more extreme events, California's groundwater reserves will become even more important, providing a critical water supply during times of drought and an underground "reservoir" in which to store excess water during floods. While we cannot predict all of the relevant effects of climate change, we can and should build the best climate science into our groundwater planning to better cope with our uncertain future.

The consequences of not incorporating climate change projections into water planning can be severe, leading to unforeseen costs and even threatening lives. These vital climate data will be derived from global climate model projections of future climate conditions, and understanding the terminology and choices behind these climate model projections will empower Groundwater Sustainability Agencies to achieve this goal. Yet, when considering the potential impacts of climate change on water management, it can be difficult to understand exactly which climate data and projections are applicable and how to use them. Often, we may not even know the right questions to ask.

It is therefore the intention of this white paper to:

- provide water managers and other decision makers across the state with an overview of climate models, their component parts, and key terminology
- provide a framework for evaluating and comparing the various approaches to incorporating climate change into state-level water planning documents
- recommend a four-step process to incorporate future climate projections into local Groundwater Sustainability Plans

A number of state- and federal agency-produced documents were analyzed to assess their approach to incorporating climate change into water planning. This analysis was carried out as part of a Stanford Law and Policy Lab in collaboration with the Union of Concerned Scientists. The key findings are summarized below.

State and federal agencies operating water infrastructure within the state should develop a consistent approach to incorporating climate change in their planning and guidance documents. California's Department of Water Resources and the US Bureau of Reclamation provide projected water delivery information in the State Water Project's *Delivery Capability Report* and the Central Valley Project's *Integrated Resource Plan*, respectively. However, the approaches undertaken by the two agencies differ considerably. Local agencies may not be aware of the inconsistencies in the two approaches and the resulting uncertainties in projected water supply. Developing a consistent approach to incorporating climate change into projected water supplies would help local agencies to better assess water supply in their planning processes.

Where state-provided climate projections are incomplete or inconsistent, we recommend that local agencies adopt a "rule of thumb" methodology to supplement available data. Increasingly, local Groundwater Sustainability Agencies will need to equip themselves to understand vulnerabilities resulting from climate change. When water suppliers are unable to provide consistent estimates of projected water supply, local agencies may need to review climate change projections and, where necessary, combine historical data with climate change projections to develop "rule of thumb" estimates of future water deliveries. For example, a water manager might be interested in determining how likely the groundwater basin is to not receive its full contract allocation from the State Water Project in the future. To manually create a projection, water managers can take the historical data on the frequency of drought conditions in which the State Water Project did not deliver its full basin allocation, and combine this with the climate change projections in the *Delivery Capability Report* of how frequently those same drought conditions are likely to occur in the future. While this methodology is not perfect, it can provide an indication of how reliable water deliveries for that basin are likely to be in the future.

Local groundwater agencies should stress-test their plans by adopting or constructing worst-case scenario projections and devising appropriate contingency plans in advance. A fundamental aspect of climate change is uncertainty. We may know the basic direction and magnitude of future change with respect to key water variables, but we will not be able to predict the values of those variables for individual basins and water districts with accuracy. Groundwater Sustainability Agencies and other agencies should assess, in advance, how their plans will fare under a range of possible futures in order to identify areas of risk and vulnerability. This exercise is valuable for helping Groundwater Sustainability Agencies to understand what their major liabilities are and communicate this information to stakeholders in advance, preparing them for potential future—sometimes difficult—decisions.

Alternative Plans submitted to the Department of Water should include quantitative analysis of climate change that is specifically linked to the stated management objectives. Only about half of the Alternative Plans submitted under SGMA included quantitative analysis of climate change, and even when they did incorporate climate change, there was often a disconnection between the climate analysis performed and the stated management objectives. This manifested in different ways, from a mismatch between the risk and uncertainty profile of the management actions and the climate modeling performed, to an incomplete integration of the findings of the climate modeling into the proposed management actions. GSAs must develop explicit links between climate change analysis and their management actions if groundwater sustainability is to be achieved under SGMA.

Climate change analysis should take into account the flexibility of proposed management actions and the level of acceptable risk. It is important not to conflate uncertainty and risk. Uncertainty relates to the probability of an event occurring, whereas risk relates to that event's (negative) consequences. We may have high uncertainty about a particular event, but if that event's occurrence presents a low risk to us, we will be less concerned than if we have high uncertainty and the event presents a high risk. For example, a high-risk event for a basin might be a severe multi-year drought. We cannot predict severe droughts with accuracy, making them also uncertain. SGMA requires Groundwater Sustainability Agencies to revise their Groundwater Sustainability Plans every five years. As a result, agencies can and should take an adaptive approach to incorporating climate change into groundwater planning. However, where basins are considering infrastructure or other high-risk projects, it may be necessary for Groundwater Sustainability Agencies to perform additional climate change analysis incorporating projections from multiple models using a variety of future emissions scenarios.

[INTRODUCTION]

In early 2017, northern California experienced record-setting levels of precipitation. The amount of rain and snow from October 2016 through February 2017 was the greatest in the 122 years of California record-keeping. As the reservoir behind Oroville Dam quickly filled to capacity, a torrent of excess water was let out through the main spillway. Shortly thereafter the spillway began to collapse, leading to massive soil erosion and concerns that the erosion could undermine the dam itself. Fears of a catastrophic dam breach led to the evacuation of around 180,000 residents downstream from the dam.

While we do not know how much climate change contributed to this particular event, we do know that climate change is making extreme events more common (Black et al. 2016; Mote et al. 2016; Otto 2016).[1] While reports indicate that management failures may have played in an important role in the Oroville disaster, it is also true that this event took place in the context of extreme weather, and that climate change is increasing pressure on structures and communities. This finding is not limited to high-profile infrastructure such as the Oroville Dam. Much of our water infrastructure, management tools, institutions, and planning mechanisms are not designed for the increased magnitude and frequency of such extremes—making the state, its environment, and its water resources vulnerable to the changes we are likely to see in the coming decades.

In California, groundwater contributes more than half of the state's water supply during dry years (DWR 2009). Therefore, understanding the impacts that climate change will have on this critical resource will be of particular importance for the state's water and food security over the long term. To that end, Governor Jerry Brown issued Executive Order B-30-15 that, along with setting ambitious greenhouse gas reduction targets, requires state agencies take climate change into account in their planning and investment decisions. In addition, California's Sustainable Groundwater Management Act (SGMA), passed by the legislature in 2014, requires that Groundwater Sustainability Agencies (GSAs) explicitly assess the impacts of climate change and incorporate these assessments into their Groundwater Sustainability Plans (GSPs).

Under the legislation, GSAs must develop and implement GSPs to achieve sustainable groundwater management in all high- and medium-priority groundwater basins in the state. Within these plans, GSAs are required to provide "[p]rojected water budget information for population, population growth, climate change, and sea level rise" (CWR 354.18(d)(3)). Additionally, projected water budgets must "identify the uncertainties of these projected water budget components," including uncertainties in projected hydrology, water demand, and surface water supply resulting from sea level rise, land use changes, population growth, and climate change (CWR 354.18(c)(3)). To meet these regulatory requirements, plans must "rely on the best available information and best available science to quantify the water budget for the basin" (CWR 354.18(e)). Yet, it can be difficult to identify the best approach to incorporating climate change into local plans. The purpose of this white paper is to assist in that challenging task.

The consequences of not incorporating climate change into water planning can be severe, leading to unforeseen costs and even threatening lives. It is therefore the intention of this white paper to:

- provide water managers and other decision-makers across the state with an overview of climate models, their component parts, and key terminology
- provide a framework for evaluating and comparing the various approaches currently employed by the state and federal agencies to incorporating climate change into state-level water planning documents
- recommend a four-step process to incorporate future climate projections into local GSPs

Recognizing the importance of climate change impacts on the state's water supply, the California Department of Water Resources (DWR) has devoted a significant amount of time and expertise to integrating climate change into water planning. In 2012, DWR convened the Climate Change Technical Advisory Group (DWR CCTAG) to advise DWR on the scientific aspects of climate change, the impact of climate change on water resources, the use and creation of planning approaches and analytical tools, and the development of adaptation responses. The DWR CCTAG released a report in 2015, *Perspectives and Guidance for Climate*

[1] Further examples can be found at World Weather Attribution, *wwa.climatecentral.org*.

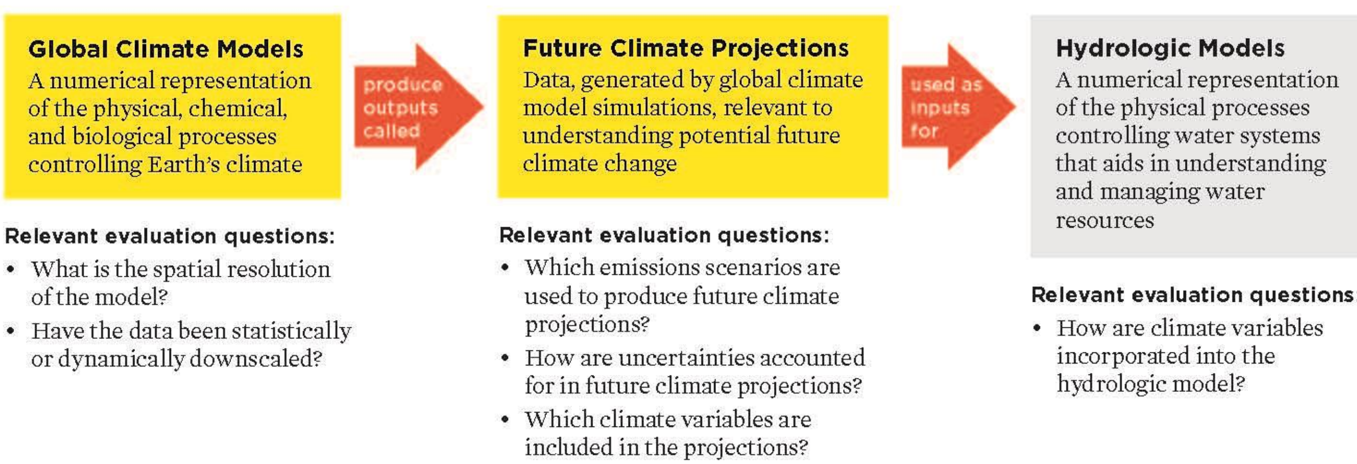
Change Analysis, which makes several recommendations for future work. One central theme is the need to develop guidance and support for water managers and planners.

Factoring climate change into water management decisions requires future projections of how climate change will impact water-relevant factors such as temperature and precipitation—projections that are generally derived from global climate models. However, incorporating climate change into water planning for any given community or groundwater basin can be difficult, not only because of the technical expertise required to do so, but also because the effects of climate change are spatially and temporally variable. Although the scientific community has high confidence in a key set of variables for the planet as a whole, translating global estimates of climate change to specific geographical areas creates uncertainty. Fortunately, there are tools and methods to address uncertainty. As is the case for other natural phenomena that are difficult to predict with precision, such as earthquakes, uncertainty cannot be an excuse for inaction. Scientific and technical tools can substantially assist in creating plans that cope with an uncertain future.

This white paper does not directly address the role of hydrologic models themselves, but rather addresses how climate change information can be incorporated into hydrologic models as water managers seek to comply with the requirements of SGMA. The process of incorporating climate change into water management decisions has several steps, starting with running global climate models to produce future climate projections, which are then used as inputs to hydrologic models (Figure 1). We recognize that GSAs are likely to engage at different levels of technical sophistication with climate data and that the majority will seek out the services of technical experts. Ultimately, it is our intent that this white paper equip water managers with sufficient knowledge about climate change projections to understand, evaluate, and direct the work of the technical experts and consultants. Using appropriate climate change information is vital to ensuring that water managers capture potential future water resource conditions.

This white paper is organized into three main sections. The first section provides a general overview of climate models, including their strengths and limitations and the type of information they can provide, and describes a framework for incorporating their output into management decisions. The second section addresses how to incorporate climate change into planning involving imported water supplies. The third section turns to planning for local water supplies and proposes a process for incorporating appropriate climate change data into GSPs. Throughout the text, bolded and italicized terms are defined in the glossary.

FIGURE 1. **DIFFERENT MODEL TYPES AND HOW TO USE THEM**



This flow chart illustrates different types of information used to incorporate climate change into water planning and how they interrelate. This whitepaper focuses on the two yellow boxes, as this information is tends to be the least understood by water managers.

SOURCE: UNION OF CONCERNED SCIENTISTS AND STANFORD UNIVERSITY

[CHAPTER 1]

A Framework to Evaluate Climate Data for Water Planning

Understanding Global Climate Models

In this section, we provide a practical and basic guide to understanding climate models and their outputs. Climate model outputs will provide the input for local hydrologic models, which use the climate change projections of water-relevant variables (e.g., precipitation) to model how hydrological processes such as stream flow and run-off may change with a changing climate. GSAs engage with climate projections as inputs for their local hydrologic models in different ways and at different levels of complexity, and most GSAs will obtain climate change projections via consultants or technical experts. Nevertheless, it is valuable for the boards and staff of GSAs, in addition to water users and other stakeholders, to have a basic working understanding of climate models in order to obtain and apply projections in the most appropriate way for their management objectives and actions.

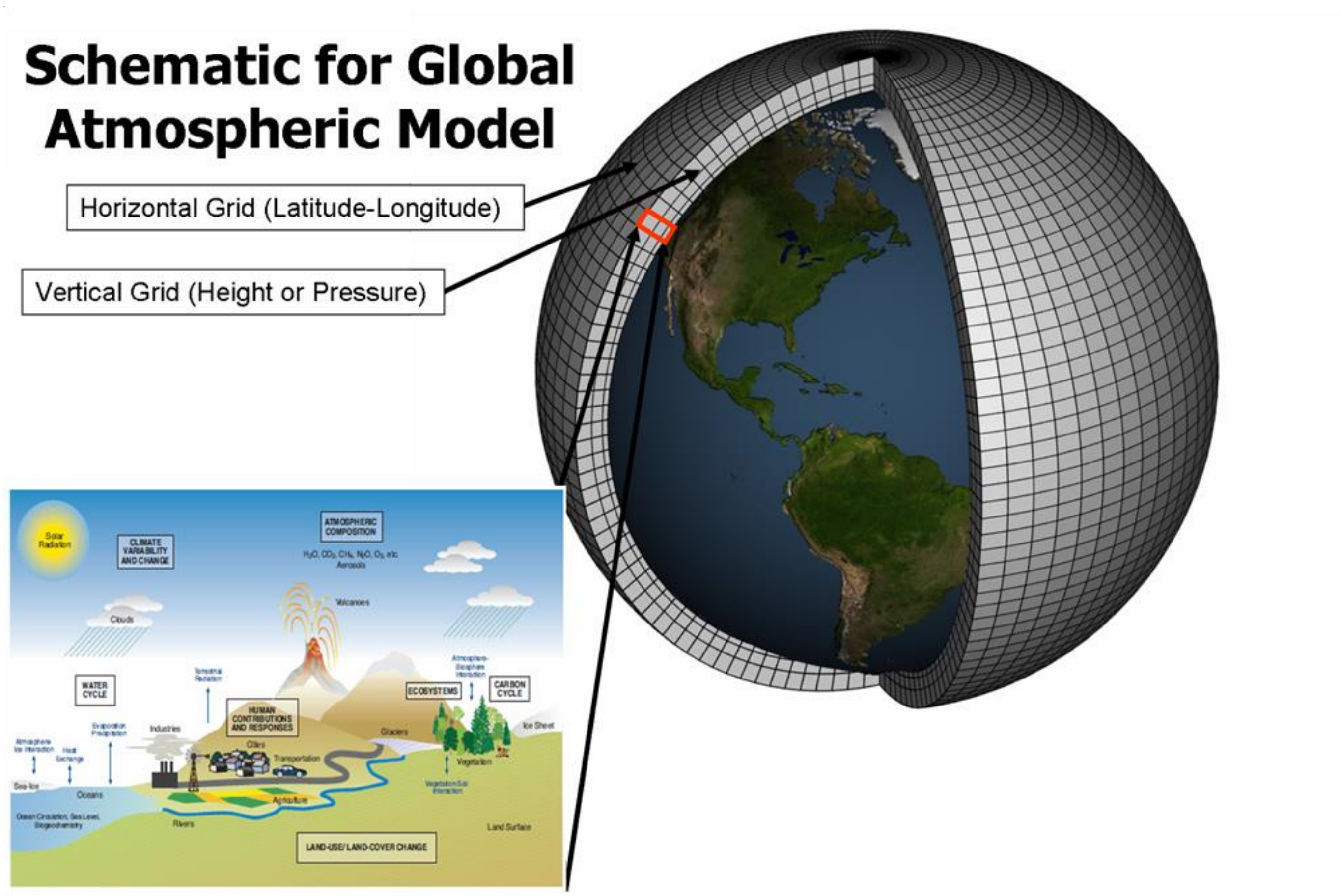
As a society, we rely on different types of models to help us plan for everything from tomorrow's weather to long-term stock market fluctuations. Climate models present similar opportunities for understanding how the Earth's climate is likely to change in the future. We can then use this information to make decision about how best to modify our actions to accommodate these changes. In aggregate, climate models have reliably projected the changes in weather and climate patterns and the climate change impacts we are seeing thus far, though many have been conservative in terms of how quickly these effects would manifest. However, because we are trying to plan for future events, climate models are best utilized with multiple scenarios to capture a range of possible outcomes.

The climate change projections input into local hydrologic models and used for water planning are generated by ***global climate models*** (GCMs), and understanding climate model fundamentals is a first step to understanding best practices for use of the data they generate. Climate models are numerical representations of the physical, chemical, and biological processes controlling the Earth's climate, and they enable us to simulate how ***forcing mechanisms*** (such as rising CO_2 concentrations) affect future climate variables including temperature and precipitation. GCMs overlay a three-dimensional grid over the entire globe to describe the atmosphere, ocean, and land surface, and the interactions and feedbacks among them (Figure 2).

To simulate the Earth's current and potential future climatic conditions, GCMs use equations to quantify the physical processes occurring at each grid cell, such as carbon cycles, ocean currents, and wind patterns. These models' output can include a variety of climate variables, including temperature, precipitation, and relative humidity. These future climate projections can then be used as inputs into local hydrologic models, like MODFLOW or DWR's Integrated Water Flow Model (IWFM), to make predictions about how local hydrology might change with changing climatic conditions.

Future climate projections are created by applying ***radiative forcers***—agents that change the Earth's balance of incoming sunlight and outgoing heat—to a GCM. Examples of radiative forcers include changes in the emissions or the atmospheric concentrations of greenhouse gases, changes in land uses, and natural forcers such as changes in incoming solar radiation or volcanic activity. The ***Intergovernmental Panel on Climate Change*** (IPCC) and ***Coupled Model Inter-Comparison Projects*** (CMIPs) adopt ***emissions scenarios*** for climate modeling that describe different possible futures, varying the levels of greenhouse gas emissions and other human factors through the year 2100. The use of standard emissions scenarios across different GCMs allows for comparison between models. The IPCC continually reviews and refines the emissions scenarios as scientific understanding progresses.

FIGURE 2. **SCHEMATIC FOR GLOBAL CLIMATE MODEL**



Schematic of the horizontal (latitude-longitude) and vertical (height or pressure) grids used in global climate models. The subset image shows an example of the physical processes represented within each grid cell.

SOURCE: NOAA 2016

Because GCMs vary in complexity and the means by which they describe physical processes, the same radiative forcers can produce different climate projections, with certain models being better suited for specific regions or facets of the climate. Water managers working with GSAs generally will not run GCMs themselves, due to the computational demands of doing so and the limited utility of raw GCM outputs for water management decisions, but rather will use available climate change projections provided by processes like the CMIPs (see Box 1). It is often not practical to use climate projections from all of the more than 40 GCMs available today, due to the challenges of processing and interpreting the massive amounts of associated data. Here in

California, the DWR CCTAG has selected a subset of 10 GCMs that best replicate historical hydrologic variables including temperature, precipitation, relative humidity, and extreme events in California.[2]

BOX 1: **WHY DO MULTIPLE GCMS EXIST TO DESCRIBE THE SAME PROCESSES?**

Under the auspices of the Intergovernmental Panel on Climate Change (IPCC), more than 40 GCMs developed by different organizations participate in the Coupled Model Inter-Comparison Projects (CMIPs). Climate model projections resulting from the CMIPs are synthesized in the IPCC's assessment reports and provide the most widely used and accepted suite of climate model projections of future climate conditions.

Multiple climate models exist due to differences in how they represent both resolved and parameterized processes. ***Resolved processes*** are those processes that occur at a larger scale than a single grid cell, such as ocean circulation, whereas ***parametrized processes*** are those processes that occur at a smaller scale than a single grid cell, such as the formation of clouds. Processes occurring at both larger and smaller scales than the grid cell cannot be modeled with complete accuracy, and hence the decisions made in a particular GCM about how to represent them introduce uncertainty. Therefore, multiple GCMs are generally used to better capture the range of possible future climates for a given region. Each model is calibrated and tested based on its ability to reproduce historical climate measurements.

A Framework for Understanding and Evaluating Climate Data

When the potential impacts of climate change on water management are being considered for a specific region, it can be difficult to understand exactly which climate data and projections are applicable and how to use them. Often, we may not even know the right questions to ask. This section presents a framework for evaluating different types of climate data for water planning purposes.

A quantitative assessment of climate change impacts on local water systems requires using climate data projections from GCMs, which are then used as inputs into local hydrologic models in order to better understand how local hydrology is likely to change based on the climate scenarios selected. It will require water managers to make choices about the type of analysis to pursue, given limited resources. Ultimately, the analysis will need to be informed by the nature of a water project, the associated risks, and the level of precision needed; along with the adaptive capacity—the ability or capacity of a plan or project to adapt to changing conditions—and the risk tolerance of the relevant agency and the local community. Where possible, we indicate where such tradeoffs may occur, and ***stress-testing*** (discussed in Section III) provides a framework for evaluating these tradeoffs. Ultimately, even the most technically sound options for climate data use will not resolve all of the uncertainty that water managers face in planning for decades into the future. We discuss how to cope with and communicate that uncertainty also in Section III.

Before applying this evaluation framework, water managers should have a specific management objective in mind; for example, the construction of a water storage project. The framework can then help water managers understand the type of climate data they require, any potential weaknesses or limitations of existing climate data, and the sources and level of uncertainty inherent in the climate change data. Using evaluation framework in this white paper, water managers should be able to answer the following questions about the climate change information that they are using. Each is explained in more detail below:

1. What is the spatial resolution of the model?
2. Have the data been statistically or dynamically downscaled?
3. Which climate variables are included in future climate projections?

[2] DWR CCTAG was empaneled for DWR's own purposes and was not envisioned as a state-wide or water-sector-wide advisory group. It is nevertheless a valuable resource for water managers and state agencies looking to understand more broadly the types of climate models and emissions scenarios that will be appropriate for use in California.

4. Which emissions scenarios are used to produce future climate projections?
5. How are uncertainties accounted for in future climate projections?
6. How are climate variables incorporated into the hydrologic model? (e.g., averages or extremes?)

1) SPATIAL RESOLUTION

What is it? Climate models represent the Earth in a three-dimensional grid, and areas of the globe falling within a given grid box will all have the same value for a variable of interest, much like an individual pixel in a digital image can only be a single color. The size of the grid—the dimensions of a grid box—for a given projection is referred to as its ***spatial resolution.*** The resolution of data produced directly by GCMs is relatively coarse with horizontal grid sizes typically ranging from 250 to 600 km (IPCC 2013), making a grid box much larger than a California groundwater basin. This can create uncertainties in the simulation of local climate processes that occur at a scale smaller than the grid.

Low resolution can also create biases in areas like California that have complex topography, as water-relevant climate variables will appear more uniform in lower resolution models than they actually are. However, during the process of creating a climate projection dataset, lower resolution data can be re-gridded and ***bias-corrected*** (to account for known differences between the model data and observed historical data) to higher resolutions (i.e., smaller grid sizes) using a process called ***downscaling*** (see next item), which can often bring the data to basin-scale or smaller.

How should I evaluate it? Consider how high the resolution of the climate projection data, and the original resolution of the GCM (or GCMs) used to generate data of interest, is in relation to your area of interest. Data produced at a resolution that is much coarser than the size of your management area may have lower utility in informing management decisions that require knowledge of sub-basin differences. The DWR CCTAG has selected models that represent California's conditions well, including some with higher resolution (smaller grid size) that may more accurately capture local climate processes relevant to your groundwater basin (Wiel et al. 2016). For example, if you simply need to know the total average precipitation that your basin will receive, a grid size similar to your basin area may be sufficient. But if you need to know which sub regions or management areas in your basin are likely to receive the most rainfall, then a much smaller grid size will be required.

Example. A GSA managing a basin of 24 km^2 has the option of using GCM data that have been downscaled to a resolution of either 6 km^2 available from the LOCA (Localized Constructed Analogs) dataset or 12 km^2 from the Lawrence Livermore National Laboratory's CMIP5 dataset. Considering resolution alone, the 6 km^2 data are preferable, as they will provide more data points within the small area in question. However, GSAs must also consider aspects of the datasets such as the number of projections and models used and whether, for example, a larger number of projections are more important than a higher resolution for their particular management decision.

2) DOWNSCALING

What is it? Because of the low resolution of most GCMs (discussed above), data from GCMs often must be downscaled in order to adequately reflect specific, watershed- and basin-level conditions. Downscaling is useful, but also adds another potential source of uncertainty in model results.

Statistical downscaling uses statistical relationships between local historical climate observations and lower-resolution GCM historical simulations to estimate climate variables at the local scale. This assumes that the historical statistical relationships will apply to future climate conditions simulated by GCMs.

Dynamical downscaling is conducted via process-based, regional climate models using larger-scale GCM outputs at its boundaries; these regional climate models are run at a higher resolution than most GCMs—often 10 to 50 km, but over a smaller domain—between 10 and 20 degrees' longitude by latitude. Dynamical downscaling often better describes local-scale conditions because it has been achieved by directly simulating local-scale processes. Yet, dynamical downscaling is much more computationally demanding and often requires significantly more time and resources, and therefore statistical downscaling is more commonly applied.

How should I evaluate it? Be aware of the type of downscaling, if any, conducted to bring the data of interest to their current resolution. Dynamical downscaling is generally considered a better method because it is based on physical processes rather than historical empirical relationships, which may or may not remain constant in a changing climate. However, due to the lower availability of dynamically downscaled data, statistically downscaled data may be more practical for GSAs to access and use.

The DWR CCTAG evaluates statistical downscaling as "acceptable to meet immediate needs" (DWR CCTAG 2015, 59) and also provides some guidance on conditions in which it may be insufficient. Statistically downscaled climate projections are available from several sources and can be directly downloaded, processed, and used for various applications. In California, currently the state-recommended dataset is the LOCA downscaled climate projections, available from the California Climate Portal known as Cal-Adapt.[3] LOCA is statistically downscaled from 32 models, run using the RCP 4.5 and RCP 8.5 emissions scenarios (see the next framework item below). A number of Alternative Plans already submitted to DWR, including Tahoe South and Martis Valley, use data from Lawrence Livermore National Laboratory that provide bias-corrected, statistically downscaled data from 112 climate projections produced by 16 GCMs.

Example. A GSA has commissioned a consultant to produce a series of climate change projections specifically for its basin. The consultant is able to find both dynamically and statistically downscaled data for the region and can use either to generate the climate change projections. If possible, the GSA should make use of the downscaled data that provide the most complete assessment of uncertainty. This may involve using both the statistically and dynamically downscaled data, depending on the range of emissions scenarios and/or models for which each is available. However, in making its final assessment, the GSA should keep in mind that the dynamically downscaled data are likely to better capture local processes.

3) WATER-RELEVANT CLIMATE VARIABLES

What are they? Temperature, precipitation, and evapotranspiration are GCM outputs that influence water resources and are subject to the effects of climate change. Precipitation (or lack thereof) is often the strongest control on the availability of water resources. However, increased temperature can also exacerbate drought conditions and affect run-off patterns that place stress on water management by, among other mechanisms, shifting more precipitation from rain to snow and changing snowmelt patterns. Evapotranspiration—which describes the rate at which moisture evaporates from the land surface or is transpired by vegetation—is dependent on, among other things, air temperature, soil moisture content and soil properties, wind speed, and relative humidity.

How should I evaluate them? It is important to consider which climate variables are most relevant for water management in your region and how those variables may interact with one another. For example, since reduced precipitation coupled with higher temperatures will likely increase water stress more than reduced precipitation alone, it is ideal to incorporate climate model projections of all of the climate variables relevant for your particular management decision. If this is not possible, it is important to consider uncertainties introduced by the exclusion of certain variables—for example, by recognizing that drought estimates that do not include future temperature changes may underestimate drought effects and adjusting planned actions accordingly.

Example. A GSA must calculate the water budget for its basin in order to try to remain within the sustainable yield into the future, taking into account water demand, population growth, and climate change. Ideally, this calculation will be done using projections of precipitation, temperature, and evapotranspiration that incorporate climate change as inputs to the local hydrologic model. Temperature and evapotranspiration are two key variables that interact with precipitation, as hot and dry conditions may reduce the water budget more than cool and dry conditions, due to increased evapotranspiration.

4) EMISSIONS SCENARIOS

What are they? Emissions scenarios are descriptions of possible future trajectories in human-caused atmospheric levels of greenhouse gases and other climate-active pollutants, and changes in land use or characteristics of the land surface, and are used to drive a climate model's future projections. Multiple different emissions scenarios are created and used in order to capture ***scenario uncertainty*** in climate projections, which results from the unknown future amount of greenhouse gases and other uncertain human management decisions. The current set of emissions scenarios used by the IPCC are called the ***representative concentration pathways*** (RCPs). The RCPs were chosen based on a wide-ranging review of existing research that the IPCC synthesized into a set of scenarios that achieve four different levels of radiative forcing: 8.5, 6.0, 4.5, and 2.6 watts per square meter (W/m^2) by 2100, where 8.5 W/m^2 represents the highest level of radiative forcing and 2.6 W/m^2 the lowest. These emissions scenarios generally sample a range of possible societal futures from high emissions (RCP 8.5, or business-as-usual emissions) to low (RCP 2.6, or much

[3] Cal-Adapt synthesizes downscaled climate change projections and climate impact research from California's scientific community.

lower emissions resulting from intensive mitigation efforts). A given climate model will usually be run with each of these many emissions scenarios to provide a range of possible futures depending on the future societal trajectory.

The IPCC is continually refining these emission scenarios, making it important for GSAs to be aware of the most recent scenarios and how they may affect the strength or timing of climate change in climate model projections. The preceding generation of emissions scenarios adopted by the IPCC were those contained in its *Special Report on Emissions Scenarios* (SRES), and are therefore referred to as the SRES scenarios. The next generation of scenarios will be called the Shared Socioeconomic Pathways (SSPs). The emissions pathway that society will actually follow over the 21st century will be determined both by economic factors and by our ability to reduce our emissions of greenhouse gases. Using multiple climate projections that are driven by a range of different emission scenarios allows us to better account for these unknown societal choices that may impact future emissions and other factors. However, it should be noted that these societally driven scenarios do not have relative probabilities—in other words, we do not know which are more or less likely to occur. For this reason, climate projections resulting from different emissions scenarios should be evaluated separately.

How should I evaluate it? It is important for GSAs to determine which emissions scenario a climate change projection is based on, as this may substantially affect its projections. Is it a high- or low-emissions scenario? For example, if a low-emissions scenario is used, such as RCP 2.6, the best estimate and range of predictions are likely to involve less climate change than if a higher-emissions scenario were used. The DWR CCTAG recommends using RCPs 4.5 and 8.5 when modeling scenario uncertainty, which are most commonly available across all GCMs and in the DWR CCTAG's assessment "appear as reasonable choices to represent low- and high emissions scenarios, given current rates of global fossil fuel consumption and economic development" (DWR CCTAG 2015, 23).

It should be noted that, because there is no relative probability assigned to different emissions scenarios (the actual scenario will depend on future human actions), ***scenario averaging*** is not useful or scientifically valid, because different emissions scenarios have unknown and unequal relative probabilities of occurring. Cal-Adapt specifically warns users to avoid scenario averaging and instead advises users to "think of each greenhouse gas scenario as a separate possible future" (Reich 2017). It is better to select a specific pathway or set of pathways for your purposes—in California, RCPs 4.5 and 8.5 are recommended by the DWR CCTAG.

Example. A GSA realizes that it has based its sustainability planning through 2040 on a series of climate projections using the lowest emissions scenario, RCP 2.6. This means that the climate change scenario they are planning for is a mitigation scenario and, to become a reality, would require not just emissions reductions but the removal of carbon from the atmosphere. In contrast, the DWR CCTAG and Water Storage Investment Program use RCPs 4.5 and 8.5. The California Energy Commission now requires the use of RCP 8.5 for all planning beyond the year 2050 due to the world's current level of greenhouse gas emissions, which tracks most closely with the highest emissions scenario. The GSA's use of RCP 2.6 in this example would likely underestimate the impacts of climate change and lead to decisions that do not adequately protect the sustainability of its groundwater basin. It would be advisable for the GSA, if considering any decisions or infrastructure that extend beyond 2050, to use RCP 8.5.

5) TREATMENT OF UNCERTAINTIES

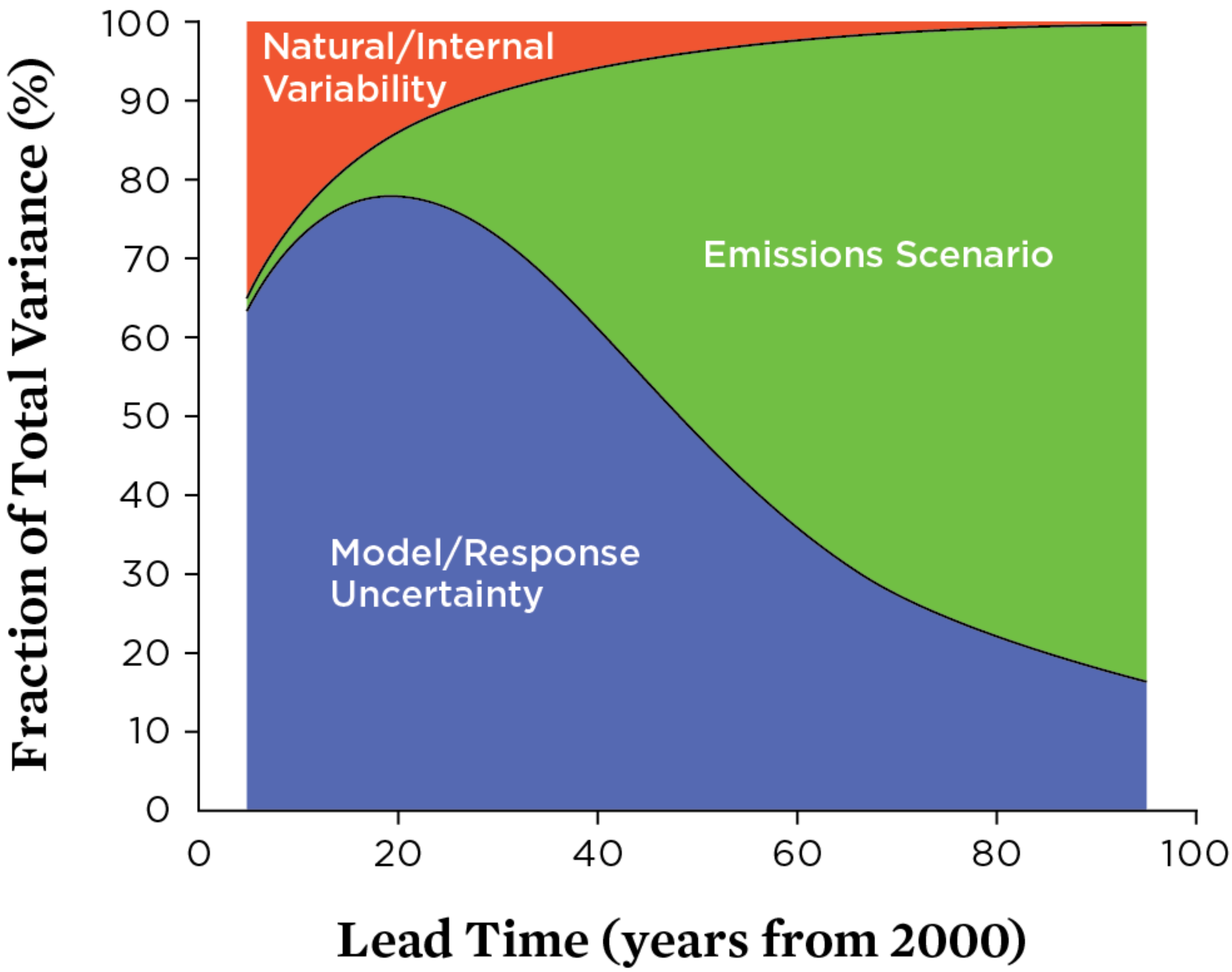
What is it? Uncertainty is inherent in any projection of the future. There are two types of uncertainty that will manifest in ***simulations*** by a climate model or set of climate models, and each factors differently into decision making: natural (or internal) variability and model (or response) uncertainty. In addition (as discussed above) actual future emissions of greenhouse gases are uncertain, and will in fact be determined by future choices of societies and individuals.

Natural (or internal) variability relates to the unpredictable processes internal to the climate system, such as the El Niño-Southern Oscillation, that can cause significant shifts in climate change trends (Collins et al. 2013; Flato et al. 2013; Kirtman et al. 2013; Kay et al. 2014). We cannot accurately predict this variability very long in advance, and climate models simulate different degrees of it. Because of this variability, the same climate model can produce a range of different projections when given identical inputs and slightly different starting assumptions. One way to address this uncertainty is to run the same simulation many times with different starting assumptions. These repeated simulations are called ***ensemble members***, and they can be averaged into an ***ensemble average*** or presented independently as an ***ensemble range***. The ensemble average for a given climate model produces the statistically most likely estimate, whereas the ensemble range can help to identify the potential extremes, including best and worst scenario outcomes.

Model (or response) uncertainty is a result of scientific uncertainty in the details of complex physical processes that affect climate, and it manifests through differences in the ways that different GCMs choose to represent those processes. This uncertainty can be accounted for by running the same scenario across a range of climate models that model physical processes in different ways. The results from different models can be averaged together into a ***multi-model average*** or presented independently as a ***multi-model range***.

Note that although agencies may use the term "ensemble" to refer to multi-model data, the climate modeling community does not use these terms interchangeably. Beware of this potential point of confusion: ensemble data come from a single model run multiple times, whereas multi-model data come from multiple models. When using "ensemble" data, look for additional detail that clarifies whether one or several climate models were used in its generation. For the purposes of management decisions, it is

FIGURE 3. **UNCERTAINTY IN PROECTIONS OF AVERAGE SURFACE AIR TEMPERATURES**



The total variability in predictions of average surface air temperature is a combination of three types of uncertainty: uncertainty around which future emissions scenarios society will follow (green), uncertainty in the model (blue), and natural variability (orange).

SOURCE: HAWKINS AND SUTTON 2009.

important to know that looking just at either ensemble average data or multi-model average data can miss the potential extremes simulated by individual models.

How should I evaluate this? It is important to evaluate whether you have available to you climate projections produced via ensemble or multi-model averaging or the full range of climate projections produced by multiple models or multiple ensemble members. Whether you choose an average or a range depends on what you need to know. In general, ensemble averages are appropriate where a representative value of climate change impacts is useful; the ensemble range is appropriate when best and worst case scenarios are desired (Kay et al. 2014). The ensemble average result does not capture the full range of possible futures, and if it is important to you to understand the range of possible futures—for example, to stress-test a water management plan using the most extreme potential drought—an ensemble range may be most appropriate.

Stress testing was one of the DWR CCTAG's central recommendations as a way to understand the conditions under which potential management choices fail and, conversely, how to develop robust plans. An increasing body of scientific literature on decision making in the presence of unavoidable uncertainty advises managers and technical staff to look for robust decisions that have satisfactory performance across a large range of plausible futures (Kwakkel, Haasnoot, and Walker 2016).

Regarding the use of multi-model data, when your GSA considers whether to use averages or ranges, it is important to prioritize the use of models that have been shown to well represent the historical behavior of the water-relevant climate variables that are most important for your water management decisions (see DWR CCTAG 2015 for GCMs that best recreate California's historical hydrological conditions). If available, the wettest and driest (in the annual average or in some extreme precipitation measure, depending on the management decision at hand) ensemble members from the wettest and driest climate models for the location of interest are also useful for stress-testing.

Example. A GSA is developing the water budget for its basin and would like to stress-test its GSP. It decides to develop a worst-case scenario for its groundwater basin to provide a sense of the management actions that might be necessary for the basin to achieve sustainability should the basin be subject to severe drought conditions in the future. Drought conditions arise from a combination of precipitation and temperature extremes, and the extremes in each of these variables may not necessarily occur in the same climate change projection (the warmest individual ensemble member will not necessarily be the driest). To capture the worst-case drought conditions for its basin, therefore, the GSA may wish to run its local hydrologic model with two sets of future climate inputs: one set of inputs based on the warmest ensemble member and another set based on the driest ensemble member (if the warmest is not also the driest). The GSA can then use the hydrologic model output that leads to the worst water budget outcome in its basin as its worst-case scenario. Where individual ensemble members are not provided in a future climate projections dataset, the warmest and driest ensemble averages should be used, but the GSA will get the best estimate of the worst-case drought scenario by looking at the edge of the ensemble range for each variable. Where ensemble averages are also not provided—that is, only a single multi-model average value is available—the GSA should be aware that it may be missing the warmest and driest possible projections.

6) INCORPORATION OF CLIMATE VARIABLES INTO HYDROLOGIC MODELS

What is it? Different water-relevant variables influence water management decisions in different ways, and data on these variables can be expressed in a number of different forms in future climate projections that water managers may encounter. For example, precipitation can be presented as an annual average, a range of annual averages, a maximum or minimum amount over a specified interval, and so on. Depending on the management decision at hand, different presentation of climate variables may be most useful. Climate change projections may present a given climate variable in several different ways, or they may provide a time series of the climate variable, which can be processed and presented in one of the above ways.

How should I evaluate it? It is important to choose the optimal way of presenting the climate variables of interest in order to ensure that the behavior of the variable most relevant to your management decision is being captured. Average annual precipitation, for example, may be useful for establishing long-term water allocations. Alternatively, more detailed metrics such as extreme precipitation (e.g., 10-day maximum) or the range of precipitation (e.g., maximum and minimum precipitation events over a 10-year period) may help in planning the capacity and operation of infrastructure projects that need to be resilient to extremes. Many times, the potential true extremes predicted by models may be imbedded in summaries of multiple models runs, and you may need to tease apart individual runs to see the full range of extremes predicted by a given model (see framework item 5 above).

Example. A GSA is planning to build a new groundwater recharge project to capture more run-off from extreme precipitation events in the future, but is unsure of the appropriate capacity of the associated underground reservoir. In this scenario, measurements such as the 10-day maximum rainfall and the annual maximum rainfall may be most helpful, whereas average and minimum rainfall amounts would be less useful.

[CHAPTER 2]

Evaluating Climate Change Projections in State and Federal Water Supply Plans

One key factor for many GSAs to consider is water supply from state and federal water projects. Large water supply projects play a crucial role in water management in California by storing water and moving it from relatively wet areas of the state to relatively dry areas through canals and aqueducts. In particular, deliveries from the State Water Project (SWP) and the Central Valley Project (CVP), owned and operated by DWR and the US Bureau of Reclamation, respectively, provide an important "imported" water supply for many areas of the state that have contracts to purchase and use this water. The availability of imported water supplies is a crucial factor for GSAs looking to project their future water supplies. This section focuses on incorporating climate change into GSAs' planning regarding imported water supplies; Section III focuses on incorporating climate change for local water supplies.

Overview of the SWP and CVP Planning Documents

State and federal agencies have developed a variety of documents related to climate change and water management. Here, we focus on the SWP *Delivery Capability Report* and CVP *Integrated Resource Plan* as two important guidance documents to help plan for future "imported" water deliveries from the major state federal water supply projects. The methodologies for incorporating climate change differ between these two foundational documents. While both reports use data from the Bay Delta Conservation Plan's future climate projections, the *Integrated Resource Plan* adopts a more comprehensive approach. The *Integrated Resource Plan* includes three socioeconomic scenarios and six climate change scenarios, which are then combined to produce 18 future scenarios for the period October 2011 to September 2099. By contrast, the *Delivery Capability Report* develops one base scenario—which is based only on historical hydrologic data—and one scenario that uses quantitative modeling to estimate SWP deliveries under changing climate conditions.[4] Table 1 below, using the climate data framework presented in Section I, outlines the similarities and differences in how the *Delivery Capability Report* and *Integrated Resource Plan* incorporate climate change into water delivery estimates.

For water managers integrating water delivery estimates from both water systems into their GSPs, the *Integrated Resource Plan* provides agencies with a range of water delivery estimates that may result from a range of future climate scenarios. A range of water delivery estimates based on a range of future climate scenarios is not currently available in the *Delivery Capability Report* analysis.

Application to Groundwater Sustainability Plans

The *Delivery Capability Report* and *Integrated Resource Plan* provide some of the most critical data for GSAs as they work to achieve groundwater sustainability over the long term. State and federal agencies delivering water within California should work to develop a consistent approach to incorporate climate change into water delivery estimates. Until such coordination occurs, GSAs are in need of a working basis for their local planning that incorporates the effect of climate change on imported water projections.

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[4] The SWP *Delivery Capability Report* develops four future scenarios. These are all based on the same climate scenario (the early long-term scenario) and vary only in regulatory and infrastructure assumptions.

TABLE 1: **OVERVIEW OF CLIMATE CHANGE APPROACHES USED IN THE STATE WATER PROJECT *DELIVERY CAPABILITY REPORT* (SWP-DCR) AND THE CENTRAL VALLEY PROJECT INTEGRATED RESOURCE PLAN (CVP-IRP)**

	SWP-DCR (2015)	CVP-IRP (2015)
Overview	Aims to estimate the amount of water that SWP contractors can expect to receive. The report includes one base scenario and four alternative (future) scenarios. Here, the base and early long-term scenarios are the most relevant. The base scenario is based on historical hydrologic conditions from water years 1922 to 2003, adjusted for land-use changes and upstream flow regulations in 2015. The early long-term scenario uses the same existing condition assumptions, but rather than historical hydrologic data, uses historical hydrologic data adjusted to reflect climate conditions at 2025 (climate period 2011–2040) and 15 cm of sea level rise at the Golden Gate Bridge.	Aims to better understand future challenges facing the CVP by assessing potential climatic and socioeconomic uncertainties and their impact on key CVP management objectives. A suite of scenarios was developed, comprising three future socioeconomic scenarios and six future climate scenarios—one reflecting historical hydrology without climate change and five statistically representative climate change projections. The social scenarios and future climates were combined to form a suite of 18 future scenarios, each covering the period October 2011 to September 2099. Each of the 18 future scenarios were modeled to project future water supply and demands.
Climate variables	Early long-term scenario: Temperature, evapotranspiration, precipitation, snowmelt, sea level rise	Temperature, precipitation, evapotranspiration, sea level rise. Future atmospheric humidity is also simulated using projected maximum and minimum daily temperatures.
Presentation of variables	Early long-term scenario: monthly averages of temperature, evapotranspiration, precipitation, snowmelt, and sea level rise from 2011 to 2040	Average annual temperature, annual precipitation, change in temperature and precipitation as perturbation from historical average, average daily maximum and minimum temperature, average daily dew point temperature, projected annual sea level rise
Treatment of model uncertainty	Early long-term scenario: Uses the *hybrid delta ensemble* approach	Statistical adjustments are made to the historical observed data set based on an ensemble of GCM projections by applying future changes in the means and variability of climate variables from the GCM projections to the historical data.
Emissions scenario	Early long-term scenario: A2, A1b, B1 (from the earlier SRES generation of IPCC emissions scenarios)	A2, A1b, B1 (from the earlier SRES generation of IPCC emissions scenarios). Societal variability is additionally addressed through the use of three future socioeconomic scenarios and the effect of this on water demand.
Resolution	12 km x 12 km	12 km x 12 km
Downscaling	Statistical	Statistical

Below we make a number of recommendations for GSAs to consider when planning for climate change within the limitations of currently available data. In large part, this consists of reviewing climate change projections critically, and, where necessary, combining historical data with climate change projections to produce "rule-of-thumb" estimates. In the future, DWR will be providing data, tools, and guidance to assist GSAs with incorporating climate change into their GSPs online at www.water.ca.gov/groundwater/sgm/data_Tools_reports.cfm.

First, similar to our review of the *Delivery Capability Report* and *Integrated Resource Plan* above, GSAs can use the evaluation framework developed in Section I to review documents provided by state and federal agencies and determine how climate change is incorporated into their analyses or whether additional information or analysis is needed to make appropriate decisions for the local management area.

Where information provided is not granular enough to draw meaningful conclusions for the management area in question, or where the impact of climate change is not included at all in projections, GSAs can manually create this information using historical data and climate change data for the relevant variable. For example, a water manager might be interested in determining how likely they are not to receive their full contract allocation from the SWP in the future. To manually create a projection, water managers can take the historical data of how frequently drought conditions occurred in which the SWP did not deliver their full basin allocation and combine this with the *Delivery Capability Report* climate change projections of how frequently those same drought conditions are likely to occur in the future. While this methodology is not perfect, as a rule of thumb it will indicate how reliable SWP deliveries for that basin are likely to be going forward.

It is also possible to apply this methodology to processes or data that do not incorporate climate change. For example, the DWR *Water Available for Recharge* report uses a methodology that does not account for the effects of climate change. GSAs may, however, want to know the effect of increased frequency of extreme precipitation events under climate change on recharge. In this case, combining a climate analysis of the likelihood and intensity of extreme precipitation events with the *Water Available for Recharge* methodology could help water managers to establish what their maximum water available for replenishment would be under climate change and the likelihood and frequency with which this maximum will be reached. This could help to inform planning activities around the number and capacity of recharge projects that a basin will need in future until a more direct estimate from DWR is available.

Finally, in the face of uncertainty or inconsistent data, GSAs can stress-test their GSPs by adopting or constructing worst-case scenario projections and devising appropriate contingency plans in advance. Undertaking this exercise is valuable for GSAs to understand what their major liabilities are and communicate this information to stakeholders in advance, preparing them for potential future decisions that may be difficult. GSAs can use contingency planning as a useful tool to inform stakeholders about risk and trade-offs between different approaches, e.g., it can be more expensive to prepare for more extreme climate futures.

As we have seen, applying the framework can be extremely useful in evaluating or designing climate models to identify the likely future climate conditions that water managers and GSAs must be prepared for. The next step is to apply these data appropriately to the management challenges and objectives of your groundwater basin. The following section describes a process for effectively incorporating these climate change projections into local GSPs.

[CHAPTER 3]

Incorporating Climate Change Information into Groundwater Sustainability Plans

As discussed above, GSPs developed under SGMA must incorporate climate projections. As yet there is little guidance as to the most appropriate or standardized ways to do so. In this section, we address how the evaluation framework developed in Section I can be used to evaluate and select the most appropriate climate projections for a range of different local water management issues. Some GSAs have already engaged in this difficult work and provide lessons for others. Table A-1 in the appendix provides an overview of climate change approaches taken in Alternative Plans already submitted to DWR in order to meet the requirements of a GSP.

We developed the four-step process below after analyzing these submitted Alternative Plans. Our analysis found that, of the plans that included quantitative modeling of climate change (10 out of the 24 plans), there was often a disconnection between the climate analysis performed and the GSA's priority management objectives and actions. This disconnect manifested in different ways, from not matching the risk and uncertainty profile of the management objectives and actions to the climate modeling performed, to not fully incorporating the findings of the climate modeling into the subsequent management actions. The four-step process was developed as a means to address this issue in GSPs and encourage GSAs to explicitly link the climate modeling performed with management objectives and actions throughout the analysis process. While GSAs will face different challenges in their respective basins, the process is intended to be applicable for all.

A Four-Step Process

In order to avoid some of the pitfalls mentioned above, we recommend a four-step process to incorporate climate change projections into GSPs or Alternative Plans:

1. Determine your management objectives
2. Evaluate existing climate change information
3. Select the climate change information appropriate for your management objectives and anticipated management actions
4. Use the appropriate climate change information to stress-test your potential management actions

Stakeholders must be engaged throughout this process. SGMA is clear that GSPs must follow a public process that encourages the active involvement of a wide range of interested parties and stakeholders, including but not limited to agricultural water users, domestic well owners, municipal well operators, public water systems, local land-use planning agencies, environmental users of groundwater, surface water users, the federal government, California Native American Tribes, and disadvantaged communities (CWR 10723.2). While not the focus of this white paper, stakeholder engagement is critical for success, and there are a number of excellent resources available to assist GSAs in engaging stakeholders specifically in groundwater planning, such as *Collaborating for Success: Stakeholder Engagement for Sustainable Groundwater Management Act Implementation* (Dobbin et al. 2015) and *Getting Involved in Groundwater: A Guide to California's Groundwater Sustainability Plans* (Weintraub and Christian-Smith 2017).

Below, we elaborate on each step of the process and then review the submitted Napa Valley Alternative Plan as a case study of putting this process into action (Box 2).

(1) DETERMINE YOUR MANAGEMENT OBJECTIVES

The GSA should first identify the key objectives needed to manage its groundwater basin sustainably. SGMA defines sustainable management as maintaining the basin within its sustainable yield and avoiding undesirable results. This is likely to include managing water supply, recharge, and demand so that the sustainable yield is not exceeded. For basins already struggling with overdraft or water quality issues such as salt water intrusion, appropriate remedial measures could involve significant changes in water management, including infrastructure projects, reductions in water use, and shifts to other water sources. For those basins not experiencing overdraft or other undesirable results, the GSA will want to maintain sustainability and anticipate any future threats. Each of these objectives implies a need for different management actions and therefore different climate change data to inform these decisions. Once the GSA identifies the priority objectives and potential management actions needed by the basin, it can develop an approach to accessing and analyzing appropriate climate data and projections.

(2) EVALUATE EXISTING CLIMATE CHANGE INFORMATION

At this stage, the GSA may wish to evaluate existing climate change projections for its own use or develop its own approach with the support of technical experts and consultants. In either case, the evaluation framework described in Section I can be used to evaluate the appropriateness of existing data sources for the GSA's needs.

To assess how groundwater supplies can be expected to respond to climate change, the GSA should use projections at an appropriate resolution with the local basin groundwater model; relying only on historical data or qualitative assessments is unlikely to capture the full range of risks posed by climate change and will not satisfy the requirements of SGMA. Ideally, the GCM outputs should account for model uncertainty and natural variability, and use a current suite of emission scenarios.

A number of climate projections are free and publicly available and are already being used in a number of water planning documents. These downscaled, bias-corrected climate projections—in some cases also including the resulting hydrological conditions from hydrologic models run with those climate projections—include the following:

- 6 km^2 resolution (statistically downscaled) using the LOCA Cal-Adapt dataset
- 270 m^2 resolution (dynamically downscaled) using the California Basin Characterization Model
- 12 km^2 resolution using the Bay Delta Conservation Plan Climate Model
- 12 km^2 resolution using CMIP5 model data housed at LLNL

General guidance on using climate data can be found in the *Perspectives and Guidance for Climate Change Analysis* (DWR CCTAG 2015).

Each projection dataset uses somewhat different combinations of climate models, emissions scenarios, spatial resolutions, and downscaling methodologies. The GSA can use the evaluation framework provided in Section I to evaluate the important characteristics of each dataset and determine its appropriateness for its particular management decisions.

The Napa Valley and Martis Valley plans are good examples of Alternative Plans that have used the aforementioned publicly available datasets and refined these for the local basin with the support of technical experts.

(3) SELECT APPROPRIATE CLIMATE CHANGE INFORMATION FOR YOUR MANAGEMENT ACTIONS

Here again, the evaluation framework developed in Section I can help to determine what type(s) of climate data, and in what form, are appropriate to meet your GSP's stated objectives. First, in terms of climate variables, temperature and precipitation are most commonly incorporated into climate change projections for water management, but it is important to consider what other climate variables may impact management decisions—for example, evapotranspiration or outdoor water demand is the largest water user in most water systems and is linked to temperature. Once the appropriate climate projections have been input into local hydrologic models, the streamflow projections will be extremely important to most basins. Water managers will need to rely on statewide projections for some climate-affected issues, such as availability of water from the SWP and CVP.

Another important element to consider is the way climate variables are measured and whether average or extreme values of a given variable are more appropriate for certain types of management decisions. For example, average annual rainfall, the range of total annual rainfall over a 10-year period, or the maximum daily amount of rainfall in a given climate scenario may be relevant to different decisions. The GSA may want to look at any combination of these elements depending on what question it is trying to address.

In general, in cases where uncertainty and risk are both low, you may find it appropriate to use averages. For example, it might be appropriate to set a long-term water budget based on averages. However, where either uncertainty or risks are high, it is more appropriate to use a range to ensure a robust approach (see Figure 4) and to assess your GSP's ability to cope with potential extremes. It is important not to conflate uncertainty and risk. Uncertainty relates to the probability of an event occurring, whereas risk relates to the (negative) consequences of that event occurring. We may have high uncertainty about a particular event, but if that event occurring presents a low risk to us, we will be less concerned than if we have high uncertainty and the event presents a high risk. For example, a high-risk event for a basin might be a severe multi-year drought. We cannot predict severe droughts with accuracy, making them also uncertain.

Because severe drought is a high risk to the sustainable management of the basin, the GSA will want to take additional precautions to understand the projected worst-case drought scenario in order to stress-test the GSP and ensure that it will continue performing under adverse conditions (see Step 4), or will want to plan in advance for potential future adaptation. In addition, the GSA may want to evaluate the impact of extremes in order to assess the risk that expensive infrastructure could be made less useful under certain projected extremes. The GSA would wish to know the range of ensemble and multi-model projections, also looking at the more extreme emissions scenarios such as RCP 8.5.

(4) STRESS-TEST POTENTIAL MANAGEMENT ACTIONS

Once the GSA has defined a set of management actions based on the basin objective and available climate change data, the final step, given the inherent uncertainty in any long-term planning effort, is to ensure that the plan is stress-tested. GSPs may be amended every five years, and that flexibility will be important as the GSA deals with an uncertain future. The GSA will use climate change projections to drive the local hydrologic models that will calculate how water resources in its basin are likely to evolve under changing climate conditions. To help define the climate conditions under which a particular management action would fail to meet its objective, the GSA can stress-test its GSP using climate change projections that include climate model outputs and emissions scenarios that capture worst- and best-case outcomes. Ensemble and multi-model ranges are useful for this purpose, as they can identify the best- and worst-case projections for given climate variables and apply high emissions scenarios such as RCP 8.5. For example, to stress-test their management actions against extreme drought events that may threaten the viability of a GSP, water managers could use climate projections from the driest and hottest climate projections available to them as inputs into their local hydrologic model to identify the maximum potential intensity and duration of extreme drought events. Understanding the potential intensity and duration of drought events should provide GSAs with insights into the conditions under which a GSP would be under pressure or even fail to meet its stated objectives.

A GSA may be reluctant to stress-test and allocate scarce resources to address the findings of stress-testing given that it is often difficult to establish the probability that adverse conditions will occur. However, there are potentially huge benefits to identifying possible causes of stress. When GSAs identify and map out potential changes to their management actions to respond to specific future climate changes, as well as identify early warning signs, they will be able to put in place appropriate contingency plans that can be activated if needed. One example of such contingency planning is getting advance agreement from community stakeholders to reduce demand or change water rate structures in the case of severe drought. This advance agreement enables the GSA to act quickly in a drought, potentially avoiding the worst outcomes and difficult negotiations with stakeholders during a critical, stressful time. Stress-testing and contingency planning does not have to be extensive and therefore costly, but it should at least offer GSAs a first line of defense in the event of adverse conditions and help them to understand potential vulnerabilities in their GSPs.

BOX 2: **INCORPORATING CLIMATE SCIENCE IN WATER PLANNING: NAPA VALLEY ALTERNATIVE GROUNDWATER MANAGEMENT PLAN**

STEP 1: DETERMINE YOUR MANAGEMENT OBJECTIVE(S)

Napa County filed an Alternative Plan for the Napa Valley sub-basin on the basis that this groundwater basin had been sustainably managed for more than 10 years. Going forward, the objective of the plan is to stay within the sustainable yield of 18,000 acre-feet per year in the basin and avoid "undesirable results." The plan establishes five sustainability objectives:

(1) Initiate and carry out outreach and education efforts
(2) Optimize existing water supplies and systems
(3) Continue long-term monitoring and evaluation
(4) Improve scientific understanding of groundwater recharge and groundwater-surface water interactions
(5) Improve preparedness to address groundwater issues that might emerge

STEP 2: EVALUATE EXISTING CLIMATE CHANGE INFORMATION

Napa County selected the existing US Geological Survey's California Basin Characterization Model (Flint et al. 2013), which is a hydrologic model outputting future hydrological conditions based on bias-corrected statistically downscaled climate model projections. The plan relies on results from the Basin Characterization Model using one GCM (CCSM4) and assuming an RCP 8.5 emissions scenario to estimate precipitation and evapotranspiration, which are then input to a global information system-based Root Zone model to calculate net recharge (Napa Valley 2016, ES-15). The Basin Characterization Model provides hydrological data at a high spatial resolution (270 m^2) and is used from 2016 to 2025 for the purposes of the Napa Valley plan, although the data are available through 2099.

The CCSM4 GCM that the group selected represents moderate climate change ("warm and moderate rainfall"), and the emissions scenario (RCP 8.5) currently represents business-as-usual emissions. Napa Valley justified these choices as "the closest future to the mean of all rainfall projections" in the Basin Characterization Model, and the most similar to recent conditions (Micheli et al. 2016). But for management actions such as investing in recharge projects or formulating contingency plans, it is also important to consider a range of future scenarios. For example, the data selected by Napa Valley project an average annual groundwater surplus of 8,000 acre-feet—whereas the GCM that simulates more extreme climate conditions ("hot and low rainfall") projects an average annual *deficit* of almost twice that amount (-14,300 acre-feet), which would necessitate very different management actions.

STEP 3: SELECT APPROPRIATE CLIMATE CHANGE INFORMATION FOR YOUR MANAGEMENT ACTIONS

The Root Zone hydrologic model used by Napa Valley incorporates mean monthly precipitation and evapotranspiration climate data from the "warm and moderate rainfall" GCM (Napa Valley 2016, 103). The inclusion of evapotranspiration rates in particular is a significant element in groundwater use and recharge rates in Napa Valley, which has a large agriculture and viticulture industry.

Napa Valley's objective "to improve preparedness to address groundwater issues that might emerge" is likely to require the use of climate and hydrological variable extremes rather than averages to ensure that infrastructure and processes can handle crises when they arise.

The Napa Valley plan uses total monthly evapotranspiration and precipitation values to model the time period 2016 to 2025. (While the plan stops its analysis at 2025, SGMA requires sustainability be achieved through 2040.) The choice not to collapse these values into an average helps them capture some of the potential variability over this time period that the GSA will need to be cognizant of in its management decisions.

STEP 4: STRESS-TEST POTENTIAL MANAGEMENT ACTIONS

As described above, the Napa Valley plan is limited by its use of a single, moderate climate scenario over a truncated time period, which reduces its ability to help the community prepare for multiple possible futures and to choose robust management actions that would work well across a range of possible climate conditions, including extreme ones. The analysis would be strengthened by examining a greater range of GCMs to stress-test the management decisions planned/modeled. The plan notes that the "hot and low rainfall" scenario constitutes the most severe future scenario analyzed within the Basin Characterization Model, and as such advance contingency planning is crucial.

BOX 2 (CONTINUED): **INCORPORATING CLIMATE SCIENCE IN WATER PLANNING: NAPA VALLEY ALTERNATIVE GROUNDWATER MANAGEMENT PLAN**

Stress-testing the management plan is in order—assessing how the stated management actions would perform under the more severe conditions. Since the plan assumes only relatively moderate climate impacts even as one model projects a deficit of -14,300 acre-feet for the basin between now and 2025, if these more extreme climate conditions occur, the GSP is in grave danger of failing to manage the basin's needs successfully.

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The Role of Adaptive Management

In addition to aiming to make the best choices in the selection and processing of climate data, GSAs need to remain cognizant of the continually evolving nature of climate science and the inherent uncertainties that remain in even the most rigorous GSP. Ongoing adaptive management is therefore an important aspect of any GSP (Christian-Smith and Abhold 2015).

The state of the art is continually evolving in climate science, as models become more refined and the scientific community's understanding of climate processes improves. While the RCPs are currently the global standard for emissions scenarios, SSPs will be the new pathways introduced in the IPCC's *Sixth Assessment Report* to be published in 2022. Regular updates are also a part of the SGMA, which has an explicit requirement to review GSPs every five years. We strongly recommend that the state and GSAs use this review time frame to remain abreast of climate change science. Staying up to date on probable emissions scenarios will help GSAs ensure that their management plans remain realistic over the long term.

In the selection and planning of management activities and projects, water managers should be aware of the adaptability of their portfolio and how this corresponds to their risk management approach. As discussed above, probability is part of the risk management equation, and consequence is another. A low consequence might lead one to be less concerned while a high consequence, even with a low probability, might prompt one to action. In the first instance, stress-testing allows GSAs to better understand both the probability and consequence elements of their potential future and make more informed decisions about their risk management approach as a result. In this respect, GSPs are likely to be a combination of demand management strategies and infrastructure projects, which have very different levels of adaptability. Adaptive management is therefore an important element of any GSP to address the time lag on any potential response to adverse conditions. Periodic review and realignment of the GSP using the latest climate science will help to ensure that the GSP remains well calibrated over the short to medium term, while putting in place flexible strategies such as demand management that will enable fast reactions during critical periods.

More generally, stress tests should be adopted for all management actions as a matter of best practice. This can have very tangible benefits, first and foremost of which is the ability of the GSA to recognize warning signs early. They also allow GSAs to develop detailed and informed contingency plans, so that these can be deployed more quickly and with better agreement and coordination among stakeholders in the event of a crisis or rapidly changing conditions. Contingency plans that incorporate some form of demand reduction can help to introduce additional flexibility when it is most needed, and within a short timeframe.

Conclusion and Recommendations

SGMA presents an important opportunity for local agencies managing groundwater in California to develop robust and sustainable GSPs that ensure the protection of groundwater supplies for all groundwater users long term. Meeting long-term sustainability goals under SGMA will mean that GSPs incorporate climate change in a meaningful way that is directly linked with management actions in the groundwater basin. Achieving these goals requires groundwater managers and their consultants to understand the potential effect of climate change on local and imported water supplies, to quantify the uncertainties in water supply projections and water budget estimates, and to continually update their plans as the climate science evolves or as indicated by changing groundwater conditions in the basin. Meeting long-term sustainability goals also requires clarity around the capabilities and limitations of different climate models. The importance of empowering water managers to make informed choices in relation to climate change cannot be overstated. The key recommendations of this white paper are summarized below.

- GSAs should use an evaluation framework when considering climate data and the trade-offs inherent in certain types of data selection. The framework we have provided is intended for GSAs to use to either assess existing climate model projections or engage with technical experts and consultants in commissioning new projections.
- Following from our analysis of the SWP *Delivery Capability Report* and the CVP Integrated Resource Plan using the evaluation framework, we recommend that the state (and agencies operating water infrastructure within the state, including federal entities) develop a consistent approach to incorporating climate change in its planning and guidance documents. We consider the findings of the DWR CCTAG to be an important first step toward identifying a common methodology at the state level.
- When water suppliers are unable to provide consistent estimates of projected water supply, local agencies may need to review climate change projections and, where necessary, combine historical data with climate change projections to develop "rule-of-thumb" estimates of future water deliveries.
- We recommend that GSAs follow our four-step process to effectively incorporate climate projections into GSP design. This process was designed after our analysis of submitted Alternative Plans, which suggested that water managers may need additional support to identify and incorporate the most appropriate climate projections for their management objectives. Developing explicit links between climate change analysis and the management actions will be critical to ensuring groundwater sustainability under SGMA.
- Stress-testing forms the final stage of our four-step process and is an important recommendation for all GSAs, given the inherent uncertainty related to an unknown climate future and the associated potential risks. We emphasize that lack of certainty cannot be an excuse for inaction and that appropriate stress-testing can help GSAs to conceptualize their risks and respond proactively. Undertaking this exercise is valuable to help GSAs understand what their major liabilities are and communicate this information to stakeholders now, preparing them for potential future decisions that may be difficult.
- Finally, we highlight that the complexity of the climate change analysis should be commensurate with the level of risk associated with particular management actions. Where GSAs are considering infrastructure or other high-risk projects, additional climate change analysis incorporating projections from multiple models using a variety of future emissions scenarios will likely be necessary. SGMA requires GSAs to revise their GSPs every five years, so water managers can and should take an adaptive approach to incorporating climate change into groundwater planning with special emphasis on regularly evaluating data that may impact the management of high-risk projects.

[RESOURCES]

Acronyms

CMIPs	Coupled Model Inter-Comparison Projects
CVP	Central Valley Project
DWR	Department of Water Resources
DWR CCTAG	Department of Water Resources Climate Change Technical Advisory Group
GCM	Global climate model
GSA	Groundwater Sustainability Agency
GSP	Groundwater Sustainability Plan
IPCC	Intergovernmental Panel on Climate Change
RCP	Representative Concentration Pathway
SGMA	Sustainable Groundwater Management Act
SRES	*Special Report on Emission Scenarios*
SSP	Shared socioeconomic pathways
SWP	State Water Project

Glossary

Bias-corrected. The process of adjusting GCMGCM output to account for known differences between the model and historical observations.

Climate projection. A description of possible future climate conditions that is obtained from climate model output.

Coupled Model Inter-Comparison Projects (CMIPs). A framework for coordinated experiments with global climate models, conducted under the auspices of the Intergovernmental Panel on Climate Change.

Downscaling. The process of transforming GCM data output from its original, coarser resolution to finer resolutions in order to make the data applicable to scales such as the watershed or basin level. See dynamical downscaling and statistical downscaling.

Dynamical downscaling. The process of transforming global climate model output to a finer resolution through the use of process-based, local climate models using the larger-scale GCMGCM output as boundary conditions. Dynamical downscaling is computationally demanding as it requires the use of regional climate models and is therefore less commonly applied compared to *statistical downscaling*.

Emissions scenario. A possible future scenario describing the emission of substances or changes in human and natural activities that act as radiative forcers, and are used to drive a climate model's future projection. Radiative forcers include climate-active substances such as greenhouse gases and aerosols. See also RCP, SRES, and SSP.

Ensemble average. The average of the data generated by multiple simulations with a single model.

Ensemble members. Individual climate projections of a given climate scenario in a given climate model, often grouped together to produce an ensemble average or ensemble range.

Ensemble range. The range between the maximum and minimum projections for a given variable from a group of projections from a single climate model (see ensemble members).

Global Climate Model (GCM). A numerical representation of the physical, chemical, and biological processes controlling the Earth's climate.

Hybrid delta ensemble. Statistical adjustments are made to the historical observed data set based on relative changes predicted by an ensemble of GCM projections. This method preserves the month-to-month pattern of variability observed in the historical record in its projection of future conditions. For more information see USBR 2010.

Intergovernmental Panel on Climate Change (IPCC). Formed in 1988, the IPCC is an intergovernmental group within the United Nations that reviews current research on climate change and publishes synthesis reports every five to seven years. The reports provide an overview of the science of climate change, potential impacts, and adaptation and mitigation strategies.

Model/response uncertainty. Model or response uncertainty is a result of scientific uncertainty in the details of complex physical processes that affect climate, and it manifests through differences in the ways that different global climate models represent those processes.

Multi-model average. The average of simulations produced by multiple models. Multi-model averaging is useful for accounting for physical uncertainty.

Multi-model range. The range of simulations, from maximum to minimum, produced by multiple models for a given climate scenario. The multi-model range is useful for establishing best and worst case scenarios across multiple models.

Natural/internal variability. Natural or internal variability relates to the unpredictable processes internal to the climate system, like the El Niño-Southern Oscillation, that can cause significant changes in climate. We cannot accurately predict this variability very long in advance, and climate models simulate different degrees of it.

Parametrized processes. Processes, such as the formation of clouds, that occur at a smaller scale than a single grid cell in a global climate model. See also spatial resolution.

Radiative forcers. Human and natural inputs to the climate system that drive changes in the Earth's energy balance and, consequently, its climate. Radiative forcers include greenhouse gas emissions, changes in solar radiation, and volcanic activity.

Representative Concentration Pathways (RCPs). Representative concentration pathways are the basis for possible future scenarios describing the emission of substances that contribute to radiative forcing and were developed under the auspices of the IPCC. The RCPs are the set of emissions scenarios first used in the 2013 IPCC Fifth Assessment Report.

Resolved processes. Processes, such as ocean circulation, that occur at a larger scale than a single grid cell in a global climate model. See also spatial resolution.

Scenario averaging. The average of projections produced using multiple emissions scenarios. This is not a useful form of data processing, as different emissions scenarios have unknown and unequal relative probabilities of occurring. This practice is explicitly discouraged by the California Climate Portal, Cal-Adapt.

Scenario uncertainty. Scenario uncertainty in climate projections is uncertainty associated with the future amount of greenhouse gases and other future human management decisions that are fed into a climate model. Scenario uncertainty is generally accounted for by using multiple future emissions scenarios for greenhouse gases and other climate-active pollutants, and changes in land-use and land cover as a result of human activity.

Simulation. An individual run of a climate model, similar to an ensemble member.

Spatial resolution. Climate models represent the Earth in a three-dimensional grid, and areas falling within a given grid box will all have the same value for a variable of interest, much like an individual pixel in a digital image is a single color. The size of the grid for a given projection is referred to as its resolution.

SRES (Special Report on Emissions Scenarios) emissions scenarios. Possible future scenarios describing the emission of substances that contribute to radiative forcing, including climate-active substances such as greenhouse gases and aerosols, developed under the auspices of the IPCC. The SRES are the generation of emissions scenarios first used in the 2001 IPCC *Third Assessment Report* and again in the 2007 IPCC *Fourth Assessment Report*.

SSP (Shared Socioeconomic Pathways) emission scenarios. Possible future scenarios describing the emission of substances that contribute to radiative forcing, including climate-active substances such as greenhouse gases and aerosols, developed under the auspices of the IPCC. The SSPs are the generation of emissions scenarios planned for use in the 2022 IPCC *Sixth Assessment Report*.

Statistical downscaling. The use of historically observed statistical relationships between local climate variables and larger-scale variables to transform simulated climate variables from coarser GCMGCM output scales to finer local scales. Statistical downscaling is more common than dynamical downscaling because it requires less computer power to achieve.

State and Federal Guidance and Planning Documents

California DWR Best Management Practices

California DWR Climate Change Technical Advisory Group

California DWR Climate Change Handbook for Regional Water Planning

California DWR State Water Project Delivery Capability Report

California DWR Water Available for Replenishment

California Water Storage Investment Program

US Bureau of Reclamation Central Valley Project Integrated Resource Plan

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[APPENDIX A]

We reviewed the 24 submitted Alternative Plans, as of June 2017, to identify how they incorporated climate change projections. Ten plans used some form of quantitative approach. For these 10 plans we assessed the climate modeling approach they used, the stated priority management objectives and actions, and ways the selected data could be made more appropriate to the challenges of the basin in question.

TABLE A-1: **SUMMARY OF CLIMATE CHANGE APPROACHES AND PRIORITY MANAGEMENT ACTIONS IN SUBMITTED ALTERNATIVE PLANS (AS OF JUNE 2017)**

Alternative Plan	Climate Data Used	Priority Management Objectives and Actions	Our Evaluation and Findings
Livermore Valley (Zone 7)	Future imported water supplies were based on the SWP *Delivery Capability Report* projections. Precipitation projections for local water sources used Cal-Adapt's outputs from four GCMs, downscaled to 12 km^2.	To counteract the decreased reliability of existing water sources that is projected in the future, the following were targeted as potential alternative water sources for development, combined with conservation as a key management action: ▪ California WaterFix, securing 8,000 acre-feet per year (AFY) of SWP water to Zone 7 ▪ Bay Area Regional Desalination Project, potentially providing 5,600 AFY to Zone 7 ▪ Potable reuse in addition to existing non-potable reuse	▪ As discussed in Section II, the SWP-DCR projections are based on a single average scenario, and hence may not adequately reflect the range of potential climate futures. ▪ Given the significant infrastructure decisions being considered to bolster SWP deliveries, this plan would benefit from consideration of the full range of climate projections rather than averages only, to ensure that mitigating actions are sufficient for the worst-case scenario. ▪ Given potentially unreliable deliveries from the SWP at short notice in the future, building flexibility into the plan through demand management-based contingency planning is also advisable.

Tahoe South (two plans submitted)	Temperature and precipitation were projected using the Bay Delta Conservation Plan climate model, which downscales multiple GCMs to 12 km^2 grid cell resolution using the emission scenarios A1, B, B1, and A2 from the IPCC AR4. Projections for the South Tahoe area were run from 2010 to 2100.	The plan predominantly aims to maintain a sustainable long-term groundwater supply. The plan recognizes the effect of changes in precipitation on aquifer recharge in particular and chose to plan for the most extreme case, a 20% decrease in precipitation.	▪ Aside from providing recharge estimates, it is not clear how the projections are being incorporated into specific planning and management activities. ▪ All GCM models used projected that rising snow-level elevations may reduce snowpack volumes and snowmelt throughout the Sierra Nevada Range. However, the models do not agree on the impact this will have on recharge, which suggests that an adaptive approach combined with further research in this area is warranted.
Scotts Valley	Projected hydrology drew on 50 years of data. State-wide climate data were downscaled to the Clear Lake watershed, of which Scotts Valley is a part.	The basin management objectives focus on minimizing winter-to-summer drawdown, maintaining groundwater levels, and preventing long-term decline. The flexibility of the plan to changing conditions is highlighted.	▪ Limited information is provided on how the projections were modeled, making it difficult to evaluate them. ▪ It is not clear how the climate projections are incorporated into the management actions of the basin authority.
Ojai Valley	Simulated precipitation through water year 2020 was used to evaluate anticipated groundwater elevations under three scenarios: median precipitation, continued dry conditions, and wet conditions.	The GSA plans to implement artificial recharge and continue existing water conservation efforts.	▪ Limited information is provided on how the projections were modeled, making it difficult to evaluate them. ▪ It is not clear what the implications are of the different projected groundwater elevations and whether they are acceptable under the sustainability plan. ▪ The projections should be extended beyond 2020 to comply with the SGMA planning time-frame.

Coachella Valley (Indio and Mission Creek)	Additional water supplies needed by 2045 were evaluated for four water supply scenarios, incorporating uncertainties associated with current supply sources and excluding climate change. Climate change uncertainty was addressed by applying a 10% supply buffer to these four scenarios. Projections for future SWP supplies were based on the final 2009 SWP *Delivery Reliability Report*.	The plan highlights that climate change may affect the long-term reliability of deliveries from the SWP and Colorado River, as well as water demand within the valley. The plan therefore emphasizes the need for flexibility and regular updates. The plan currently accounts for climate change uncertainty by applying a 10% buffer to its estimates of future water demand, which (including the buffer) range from 299,700 AFY to 461,100 AFY of additional supply required by 2045.	▪ The assumed 10% buffer does not provide sufficient certainty or reflect in detail how climate change may impact groundwater supplies in the region. A true quantitative approach is recommended to provide more valuable data for planning purposes.
Martis Valley	The Bay Delta Conservation Plan climate model was used, providing an ensemble average of 112 climate projections and using emissions scenarios A1B, A2, and B1. One historical and five statistically representative projections were developed to characterize the best estimate and range of ensemble uncertainty. The projection of daily precipitation and maximum and minimum daily temperature was run from 1981 to 2098. Results were downscaled to 300 m^2 grids.	The plan aims to maintain operation within the sustainable yield of 22,000 to 25,000 AFY and avoid undesirable results.	▪ The projections highlight that reduction in snowpack and earlier melt is a particular risk in this region that will complicate the seasonally dependent nature of water resources and add stress to groundwater resources in the Martis Valley Basin. ▪ Current management actions, however, do not account for this and adopt a business-as-usual approach. It would be worthwhile to explicitly address the implications of changing snowpack and snowmelt within the plan and consider the most appropriate management actions to address this in the short and long term.

Pajaro Valley	Simulated precipitation data from 1976 through 2009 were inverted (run backward from 2009 to 1976). Water deliveries from outside the basin were held constant at 2011 levels. Sea level rise was based on downscaled projections for the Monterey Bay area from the IPCC A2 report.	The plan proposes seven management actions over a 30-year period to combat a basin shortfall of approximately 12,000 AFY and seawater intrusion of approximately 1,900 AFY. The management actions broadly fall into the categories of: ▪ Conservation (5,000 AFY) ▪ Optimizing existing supplies (3,000 AFY) ▪ Building new supply infrastructure (4,100 AFY)	▪ The short time frame of the data used, as well as the plan's reliance on purely historical data, raises concerns that the model outputs do not reflect the potential future conditions under climate change. ▪ Temperature should also be included in the model to account for changes in surface water availability and increased evapotranspiration. ▪ The sea level rise data should be updated with the latest IPCC (2013) estimates. ▪ Extremes data should be considered in addition to averages in order to stress-test management actions.
Napa Valley	This plan utilized the US Geological Survey's Basin Characterization Model, which uses one GCM (CCSM4) to estimate the climate variables of precipitation, temperature, and evapotranspiration. A "warm and moderate rainfall" scenario was selected, assuming business-as-usual emissions projections for 2010 through 2099 (RCP 8.5). The analysis was performed for the time period 2016 through 2025.	The plan aims to maintain operation within sustainable yield of 18,000 AFY and avoid undesirable results.	▪ The use of a single scenario, "warm and moderate rainfall," limits the range of projections and may not capture the full range of potential future scenarios. Since the priority management actions will be particularly impacted by extremes, it is important to consider this in more depth.