2 Climate Change – The Challenge

California's Climate Is Changing

At the heart of the challenge that AB 2800 aims to address is the fact that infrastructure is built to last while the climate is changing. Central to any engineer's professional goal is to build and adequately maintain infrastructure in such a way that it remains reliably functional and safe for public use at the same level over its design life, often many decades. A changing climate means that infrastructure now must be built to withstand conditions in 10, 20, 30, 50 or 100 years from now that are not perfectly predictable but certainly different from those prevalent now. Climate averages will be different, as will be the range and severity of extreme events such as storms, floods and extreme heat, which pose the greatest short-term stresses on the bridges, levees, roads, dams and so on that California's residents, visitors and the economy depend on.

Historically, infrastructure designers, architects and engineers have taken past conditions as reliable guides to the future because the climate could be assumed to be stable within a known range of year-to-year or seasonal variability. This most foundational assumption to all engineering is no longer valid. Engineers and architects must adapt the way they approach engineering design.

Moreover, not only is the climate changing, but many other factors that affect infrastructure use and reliability, ranging from climate-influenced environmental conditions to the number of people that the infrastructure is designed to serve as a result of urbanization and population growth and migration, to the economic conditions, policy priorities and changing cultural norms and expectations that affect what society values, prioritizes and does.

This is why infrastructure engineers and architects want to know what is understood with confidence by climate scientists, and how this scientific understanding can be translated into clear policy, guidance, standards, codes, useful manuals of practice and tools. This section of the report summarizes what we know about climate change, how well we know it, and how these changes may interact with the state's existing and future infrastructure.

Historically, infrastructure designers, architects and engineers have taken past conditions as reliable guides to the future. This most foundational assumption to all engineering is no longer valid.

Significant Scientific Confidence in Global Climate Change

Science has established beyond doubt that the global climate – including California's climate – are changing. Scientific understanding of why these changes are occurring – mostly due to human activities – and how they may unfold in the future has grown significantly more confident over the past four decades or more. The conclusions of the most recent Fourth U.S. National Climate Assessment (NCA4) are telling in the strength of its conclusions[8] (Box 2.1).

Box 2.1: Key Findings from the Fourth U.S. National Climate Assessment

- **Global annually averaged surface air temperature has increased** by about 1.8°F (1.0°C) over the last 115 years (1901–2016). This period is now **the warmest in the history of modern civilization.**
- **It is extremely [95%–100%] likely that human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming** since the mid-20th century. For the warming over the last century, there is no convincing alternative explanation supported by the extent of the observational evidence.
- **Thousands of studies conducted by researchers around the world have documented changes** in surface, atmospheric and oceanic temperatures; melting glaciers; diminishing snow cover; shrinking sea ice; rising sea levels; ocean acidification; and increasing atmospheric water vapor.
- **Global average sea level has risen by about 7-8 inches since 1900**, with almost half (about 3 inches) of that rise occurring since 1993. […] Global average sea levels are expected to continue to rise - by at least several inches in the next 15 years and by 1–4 feet by 2100. A rise of as much as 8 feet by 2100 cannot be ruled out.
- **Heavy rainfall is increasing in intensity and frequency** across the United States and globally and is expected to continue to increase [due to the ability of warmer air holding greater amounts of moisture].
- **Heatwaves have become more frequent** in the United States since the 1960s, while extreme cold temperatures and cold waves are less frequent.
- **Over the next few decades (2021-2050), annual average temperatures are expected to rise by about 2.5°F** [1.4°C] for the United States, relative to the recent past (average from 1976–2005), under all plausible future climate scenarios.
- **The magnitude of climate change beyond [2050] will depend primarily on the amount of greenhouse gases (especially carbon dioxide) emitted globally.** Without major reductions in emissions, the increase in annual average global temperature relative to pre-industrial times could reach 9°F (5°C) or more by the end of this century. With significant reductions in emissions, the increase in annual average global temperature could be limited to 3.6°F (2°C) or less.
- **The global atmospheric carbon dioxide (CO_2) concentration has now passed 400 parts per million (ppm), a level that last occurred about 3 million years ago** [i.e., well before the appearance of the human species], when both global average temperature and sea level were significantly higher than today.

(Source: Excerpted from USGCRP 2017[8], pp. 10-11)

The basic findings and conclusions confirm what many now experience: the climate has become more volatile and some extreme events are more intense or occur more often. Even if the science is clear that the climate is changing, building for a continually changing and more volatile future is another challenge altogether.

Observed and Projected Changes in California's Climate

As this report was completed, so was California's Fourth Climate Change Assessment, which we rely on in this chapter and which informed the Climate-Safe Infrastructure Working Group's (CSIWG) deliberations throughout[9]. Its findings are striking in their importance to the state's economy and the well-being of Californians, and they are similarly confident in tone as those from the NCA4. However, they provide greater regional specificity and thus offer important first-order insights for the state's engineers and architects.

California's Mediterranean Climate

California has a Mediterranean climate, which is characterized by warm to hot, dry summers and mild to cool, wet winters[10]. In addition to being strongly seasonal, California's climate is also highly variable across space. For example, there is a stark climatic gradient from the cool, often foggy coastal areas to hot inland areas, and big climatic differences between the Central Valley and the Sierra Nevada[10,11]. Moreover, California precipitation and other elements of its weather and climate varies greatly from year to year[12,13], in part due to its sensitivity to large-scale ocean-atmosphere oscillations[14]. In fact, California has the greatest precipitation variability among all states in the US[9]. Thus, it is not unusual to find dry years or multi-year droughts where winter storms have avoided California, followed by a year or years with ample moisture from serial North Pacific storms[15], sometimes the mark of "atmospheric rivers"[16-19]. In the past, California has adapted to this variability by, for example, building large reservoirs and dams to store water and control floods[20], by plumbing the entire state to move water from thinly populated areas where most of the precipitation falls to highly populated areas where it is needed most[21] and by pumping groundwater from aquifers to satisfy irrigation needs[22]. But increasingly, as the climate warms and societal demands for water evolve, drought risk will very likely increase[23] and there is a need for better collaboration across agencies and other water users to work out water-related trade-offs[24] and to diversify water resource portfolios[25].

The climate has become more volatile and some extreme events are more intense or occur more often.

Figure 2.1 From several decades of global, regional and local observations of myriad elements of the climate system, scientists have gained high confidence that climate warming is underway. (Photo: King Tide in Pacifica, CA; Dave Rauenbuehler, flickr, licensed under Creative Commons license 2.0)

The Big Picture of What We Know

From several decades of global, regional and local observations of myriad elements of the climate system, along with a growing production of future projections from numerous climate models, scientists have gained high confidence that climate warming is underway[26]. Furthermore, warming will very likely continue for many decades, along with those climate variables that have a similarly strong thermodynamic response to increasing greenhouse gases[27-29]. For other climate variables, such as rain- and snowfall (precipitation), wind and other variables that are more strongly governed by dynamic interaction of the atmosphere, oceans, land surfaces, ice and the biosphere, changes produced by different climate model projections are not as consistent and confidence is not as high.

Observed and expected changes can be grouped into two basic categories:

(A) **Changes in multi-year averages, resulting in long-term trends** (e.g., average temperatures going up, rising sea level and changes in the length of seasons);

(B) **Changes in some types of weather and climate extremes** (e.g., increases in the frequency, intensity and duration of high temperature extremes or more intense downpours).

In addition to human-driven climate change, the atmosphere, ocean and other parts of the climate system undergo natural variations across the time spectrum from day-to-day to multi-decadal time scales. For forecasts a week or more out, there are inherent limits to the predictability of the details of these fluctuations. As a result, researchers cannot provide precisely certain climate outlooks at time scales pertinent to short-term planning or infrastructure operation, although it is possible to quantify changes in the probability of some relevant conditions.

Spatially, there is also a limit to the predictability owing to geographic differences that result in many small-scale variations (micro-climates)[30,31]. These limits notwithstanding, there are predictable components of future climate because the relatively stable topography bears a strong influence on most meteorological and hydrological variables at or near the Earth's surface. Examples of such stable influences include California's complex topography, the long ocean-land boundary or the stark rain shadow created by the Sierra Nevada mountain range[32,33].

In summary, some elements of future climate are predictable and fairly well understood at the global and at large regional scales and on multi-decadal timescales, while other variables – governed by complex dynamics – are less well understood. Inherently, information at high spatial and temporal resolution is quite uncertain. This has always been the case: the spatial and temporal variability experienced in the past was no more predictable than it is now. In fact, infrastructure decisions that are made now have the benefit of considerably greater data and understanding of climate processes than decisions that were made in previous decades. And engineers and architects also have considerable experience with building infrastructure to withstand variable conditions. It is clear now that in addition to this variability, engineers and architects must account for trends in averages and shifts in the occurrence of extremes around those means, while natural variability will always remain an overlay over these two fundamental changes to our climate.

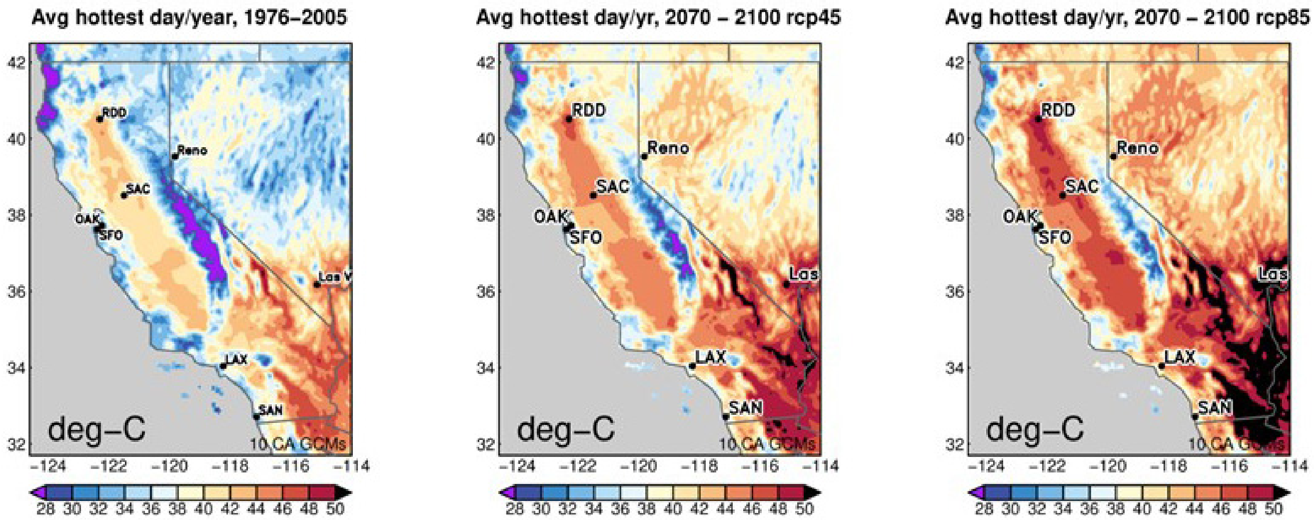


Figure 2.2 Average hottest day of the year (in °C), averaged over 10 Global Climate Models, for the historical period (left) and late-21st Century for RCP 4.5 (middle) and RCP 8.5 (right) emissions scenarios. (Source: Pierce et al. 2018[29], used with permission)

California's Climate Is Changing in Fundamental Ways

Observed climate changes in California over the past five decades are consistent with overall changes observed nationally and globally[9]. The best available climate science for California suggests there will be further changes in the state's climate, which in a number of cases will extend many already-observed trends[29,34].

Continuing warming trend and more heat extremes

- Average annual temperature in California has already increased by 1-2°F compared to the average in the early decades of the 20th century[35], updated data provided by NOAA to G. Franco). The amount of future warming depends mainly on the emissions pathway society will follow. Under any plausible greenhouse gas emissions scenario, the state will see warming of about 4°F (2.4°C) by 2050[9,29]. After mid-century, the higher greenhouse gas emissions pathway (RCP 8.5) – which does not reflect any substantial emissions reduction policies implemented from now onward – yields considerably higher greenhouse gas concentrations, and thus greater additional warming than lower emissions scenarios. The high-emissions scenario would result in warming projections of another 2.7-9°F (1.5-5°C) by 2100 (Figure 2.2).
- Under all emissions scenarios, but particularly under the high emissions scenario, extremely warm years become statistically commonplace[23] and heat waves become more intense and more frequent, last longer and occur over a longer warm season[29,36].
- Simultaneously, cold extremes will occur less frequently[37-39].
- Interior regions of California will experience greater amounts of warming than coastal margins because the latter remain under the cooling influence of marine air[40].
- Due to warming alone, California will see less of its precipitation fall as snow, which will result in diminished mountain snow packs, more rain and less snow in lower and intermediate elevations (which have historically generated spring snow accumulations). Together, these changes will result in earlier run-off and less "natural water storage" in the form of snow, demanding that California adjust its water management approaches[41-45].

Accelerated sea-level rise, worsening coastal storm impacts

- Sea level has already risen by 7 inches between 1900 and 2000, and the pace of rise has been increasing since the early 1990s[46]. In the future, sea level will be rising at a further accelerating rate, with the amount depending on emissions pathways and resulting global warming trends, as well as the consequences of this warming for the large ice sheets of the world (Antarctica and Greenland).
- The main sources of this rise include 1) the expansion of ocean water as it warms and 2) additions to the amount of water in the ocean basins from melting of land-based ice. The latter is expected to become an increasingly important factor. In fact, the rate of ice loss from the Earth's largest ice sheets – the Greenland and Antarctic Ice Sheets – is already observed to be increasing[47,48].

- Sea-level rise projections for California vary by location, which is available for all California tide gauges[49]). For San Francisco, for example, the median projection of sea-level rise by 2050 is 0.9 ft and could range from 2.54 ft (0.77 m) to ~4.5 ft (1.37 m) over 2000 levels by the end of the century, depending on the underlying assumptions about society's emissions pathway[29,46]. However, recent scientific studies point to the (as yet unquantifiable) possibility of extreme sea-level rise, resulting in a possible rise of ~10 ft. (3 m) by 2100[46,50-52].
- Over the near term, the greatest impact on coastal infrastructure will be felt from the coincidence of large winter storms with high astronomical tides and El Niño, each of which temporarily elevates sea levels, albeit by different amounts and for varying duration. But as sea level rises further, these common events and processes will unfold on an ever-higher baseline of local sea level[46].
- The greatest damages in coastal areas arise from wind-driven waves which are generated as storms move toward shore from remote North Pacific regions and build up in near-shore areas[53-55].
- Most coastal storms involve the effects of flooding from the ocean side superimposed on flooding from inland run-off sources[56]. The result is a growing compound flooding risk, resulting in greater exposure and greater loading on coastal infrastructure and buildings[57]. The ability to project these compound flooding risks for California locations has been shown but is not yet available for all locations[58,59].
- In addition, sea-level rise causes saltwater intrusion in low-lying areas such as San Francisco Bay and the Delta, as well as into coastal groundwater aquifers along many parts of the California coast. Saltwater intrusion – to date mostly driven by over-pumping of coastal aquifers – will be exacerbated in the future by rising sea level, affecting agricultural areas, underground infrastructure, and the stability of levees [60-63]. Moreover, higher sea level in low-lying areas means higher sub-surface groundwater levels and less capacity of the soil to absorb large amounts of rainfall, runoff or overland flood waters, thus altering the soil conditions in nearshore areas that are just beginning to be understood and modeled[62, 63].
- Finally, increased wave activity in concert with rising seas leads to increased coastal erosion impacting the coast's beaches, bluffs and cliffs[64,65].

Changing precipitation regime toward greater volatility

- While California's climate has always been variable in terms of daily, monthly and interannual precipitation totals[12], over the past several decades, California has already observed changes in its rain- and snowfall[66, 67], with a tendency toward greater dryness[19,67,68].
- Different causes have been implicated for recent dryness in California including Pacific Ocean-atmosphere effects[69] and effects of human-caused warming[23,70,71]. Some studies also suggest that these already observed shifts (and more in the future) could be linked to Artic sea ice loss[72-78].
- Going forward, one of the more difficult-to-project changes in climate are those related to changes in precipitation. Studies point to more dry days and more dry years in the future[23,33,79,80], but also occasionally to more intense rainfall events[81-83] (Figure 2.3).
- Geographically, scientists expect to see drier parts of the state (southern and inland) to get even drier,

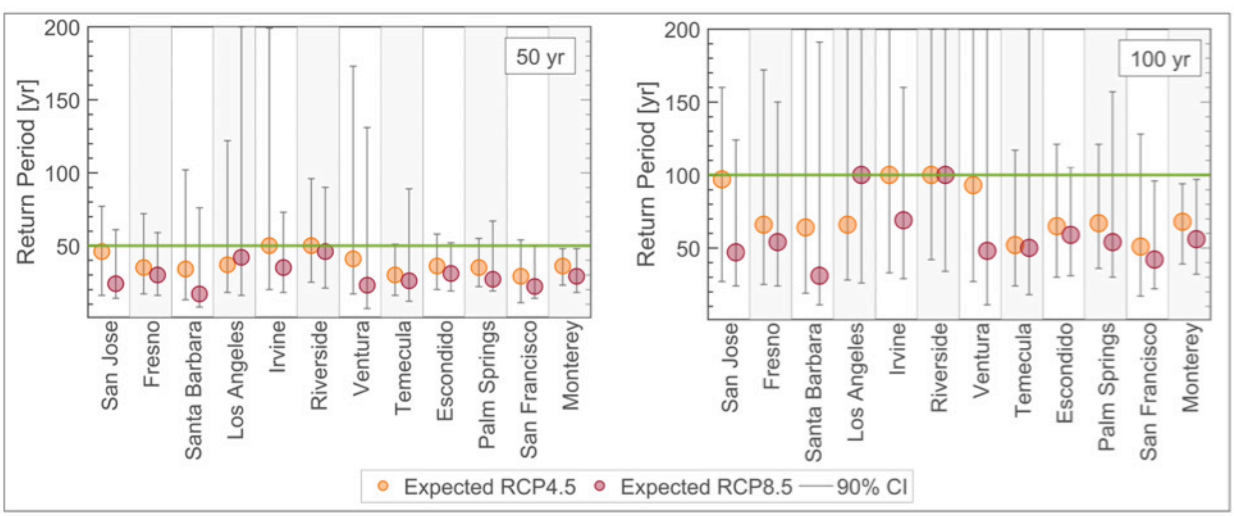


Figure 2.3 Return periods of events historically associated with return periods of 50-, and 100-year in California under climate change. The dots show the expected projected return periods and the gray lines display the 90% confidence intervals (Source: Ragno et al., 2018[58], used with permission).

while wetter (mainly northern) parts get wetter[29,34]. Thus, overall, there may not be a large statewide shift in average precipitation, but regionally specific shifts and a climate marked overall by greater precipitation extremes[29,79].

- Seasonally, models indicate that core winter months (DJF) remain wet or become even slightly wetter, but shoulder spring (MAM) and fall (SON) seasons become drier than they were on average over the historical period[23,29,81]. This would result in a "peakier" wet season separated by a longer warm dry season[33,39,79,83]. A longer warm dry season would heighten some important climate impacts including fire risk, water and energy demand and ecosystem stress[84-86].
- As temperatures increase, the rain/snow line will move to higher elevations, and more of each storm will fall as rain than as snow, resulting in greater immediate storm runoff, especially in historically snow-affected catchments[87,88]. This increased run-off poses increasing problems for dam operators as they must manage for flood protection and water storage under increasingly volatile conditions[89-91].
- At the same time, less precipitation is stored in the snowpack and thus not available for slow release over the dry warm summer season. This is particularly challenging as dry spells in the future will also be warmer, thereby intensifying water loss from soils, water surfaces and vegetation while demand for water and energy will be heightened[89].

Other changes and extremes

- The impact of climate change on high-wind events is not well understood, in part because high winds are rare, often localized, and caused by multiple factors and in the context of different large-scale patterns. Globally, average near-surface wind speeds have been reported to have declined in recent decades[92], but regionally, Santa Ana winds have not exhibited significant trends[93].
- Dry coastal winds (Santa Ana, Sundowner, Diablo) aggravate the risk of wildfires[94,95]. Observation does not suggest any weakening of these wind systems, but future projections remain contested, although most research points to hotter dry winds and the continued importance of Santa Ana winds in the future[93,96].
- The observed changes in California's climate have already contributed to more frequent and more severe wildfires[97-99]. Depending on the assumptions about climate and land use change in the underlying scenarios, future projections point to modest to large increases in wildfire risks in many parts of California, placing more buildings, infrastructure and a growing population at risk[97,98,100,101].

Figure 2.4 Observed changes in California's climate have already contributed to more frequent and more severe wildfires, and future projections point to modest to large increases in wildfire risks. (Photo: Department of Defense).

- Future changes in cloudiness over California are not well understood, in part because clouds are driven by multiple factors, some of which occur at scales smaller than represented in global climate models. Relatively low-altitude coastal stratus clouds and fog – the pre-dominant cloud type along the California coastal margin – occurs throughout the year but more frequently in spring and summer[102]. Historically, periods of anomalous cloud cover are driven by anomalous ocean and atmospheric patterns[103,104], with substantial variations over decades[103,105].
- Urban heat island effects have diminished coastal cloud cover in developed coastal areas such as Los Angeles[86,106]. As cloud cover decreases, particularly late-afternoon temperatures increase, posing growing public health risk and increasing demand for improved building envelopes and/or more air conditioning. The latter would increase energy demand to run air conditioners to mitigate those heat-related health risks[107].

Uncertainties in Climate Projections: The Plain English Digest

Climate scientists have gained significant confidence in historical (i.e., observed) and future (i.e., projected) climate changes, but uncertainties will always be an inherent part of the future[108,109]. What is certain – given the global climate changes now underway and accelerating – is that continuing to rely solely on historical data and the assumption of stasis as a basis for infrastructure-related decisions from now on would ignore empirical reality and the best science available to inform planning for the future.

These uncertainties are described below to make an emphatic case for why engineers and architects must build for change and volatility if the goal is to build the climate-safe infrastructure of the future.

Natural climate variability is the type of uncertainty already familiar to engineers. It is present in the climate now.

Natural Climate Variability

High-resolution global climate models have much improved in their ability to capture and reproduce natural climate variability, such as decadal swings in climate, periodic events such as El Niño-Southern Oscillation (ENSO), and even interannual variability. Research has vastly improved our understanding of the underlying dynamics and thus in improving the ability to forecast such interannual- and interdecadal variability. These forecasts have become increasingly important for emergency planning and for infrastructure operation and maintenance planning. That said, regardless of the future trajectory of global warming, there will always remain a stochastic, or randomly determined, element to the actual climate that unfolds in any place and time. This can be statistically analyzed for patterns but can never be predicted with absolute certainty. Natural climate variability is the type of uncertainty already familiar to engineers. It is present in the climate now.

Emissions Trajectories

One of the largest uncertainties in predicting future climate is the course human society chooses in terms of energy and land use, resulting in different greenhouse gas emissions pathways. Ultimately only one such path will be realized, but we will only know which path by hindsight. Because it is very difficult to predict which pathway society will take, scientists use a range of plausible emissions scenarios, resulting not in a single projection, but in an envelope of possible rates of warming, sea-level rise and other measures of climate change.

While California – now the fifth largest economy in the world – is continuing on its course of stringent emission reductions, the federal government is currently in the process of rolling back previously made emission reduction commitments. At the same time, many subnational actors and virtually all nations around the globe have formally committed to achieving the goals of the 2016 Paris Agreement[110-112]. This agreement aims to limit global average temperature increases to 3.6°F (2°C) above the pre-industrial average, and ideally to less than that. Emission reduction pledges made to date, however, would result in a global temperature increase of 4.7-5.8°F (2.6-3.2°C), and actual emission reduction achievements and policies in place so far point to an even larger temperature increase of 5.6-6.7°F (3.1-3.7°C) above pre-industrial levels by 2100. Many nations that have committed to the Paris targets are finding it extremely difficult to make the necessary changes (see assessment by country, especially of highly developed nations, at the Climate Action Tracker), while many others, especially least developed countries, insist on their right to development, which, still often, is energy-intensive[113,114]. These kinds of challenges are faced, in fact, at all levels and across the world, namely to decouple the economy and human well-being from high consumptions of fossil fuels. Until this succeeds and the greenhouse gas emissions stabilize, it is thus prudent to plan for a more dangerous future despite California's stringent mitigation goals.

Researchers and policy observers have concluded that it is technically feasible to achieve the lower warming targets of the Paris Accord by deploying stringent policies, market signals, available energy technologies and other technologies that draw carbon out of the atmosphere (so-called "negative emissions technologies"), perhaps after a period of overshooting that target[115-120]. However, any delays result in greater future cost[121] and increase the likelihood of creating severe impacts and passing irreversible tipping points in the climate system[122,123]. Feedback mechanisms may also result in difficult-to-impossible to predict responses of the climate system given the rapid pace at which it is being altered by greenhouse gas emissions[124,125]. Thus, the ultimate warming trajectory, particularly beyond the middle of the century, remains uncertain. Projections of future climate changes, even probabilistic projections as provided in California's Fourth Climate Change Assessment[29] or the Ocean Science Trust's recent sea-level rise report[46], will remain contingent on assumptions about the course of global emissions (Box 2.2).

Projections of future climate changes, even probabilistic projections will remain contingent on assumptions about the course of global emissions

Box 2.2: “A 90% Chance that Sea-Level Rise Will Be No More Than …” – A Word on Probabilistic Projections of Future Climate Change

One of the key advances in climate science over the past decade – aided by increasingly powerful computer models – has been the ability to provide probabilistic climate change projections. To say that “there is a 30% chance of rain in the San Francisco Bay area tomorrow” or “a 50% chance that a particular storm will come onshore on the Mendocino Coast” is fundamentally different, however, from saying, “there is a 66% chance that average warming in 2050 will be within a certain temperature range.” Why is that?

Weather predictions for the next few days use high-resolution meteorological models (i.e., mathematical equations representing the changing state of the atmosphere built from past observations and adhering to the laws of physics) that receive current observations of atmospheric and surface conditions as initial conditions and then are run forward to produce tomorrow’s weather. Tomorrow, we will know whether the prediction hit the mark. Their skill can be measured and subsequently forecasting models can be improved with yet another observation.

Climate projections 50 or 100 years out rely on global climate models that use essentially the same types of equations as weather forecasting models. These equations account for the conditions of the land, ocean, ice and atmosphere and integrate across time and space. They are run with historical data to validate them, for example, by starting a model in 1750 with the greenhouse gas concentrations known to have existed at that time, and then run forward to 2018 with the greenhouse gas concentrations increasing as they were observed in each year. But the key difference is the basic input into these equations. Rather than current weather conditions, climate models start out from the amount of heat-trapping greenhouse gases in the atmosphere, along with whatever else is known about natural climate variability and its causes, and the simulated outcome are climate variables, such as the surface temperature over land at a particular point in time.

Assuming known natural variability will continue into the future, superimposed on the basic state of the climate at any one time, the critical question then becomes: how much is the concentration of greenhouse gases in the atmosphere going to be changed from its current (or pre-industrial) state? No climate scientist, economist, or policy maker in the world is in a position to foresee what the exact concentration will be in 2100. Why? Because the concentration will depend on a suite of policy choices and economic incentives created by humans, as well the individual and societal responses to those policy choices and incentives. These individual and collective decisions involve countless factors – including free will – and while we all may speculate what humanity will do, no one can say for sure. This is why scientists have developed a set of internally consistent, plausible scenarios of how global emissions might unfold. These emissions scenarios (also sometimes called trajectories or pathways) are the basis for running their models.

Climate projections start out from the amount of heat-trapping gases in the atmosphere and what is known about natural factors affecting the climate. The balance of policies and incentives for either renewable energy and fossil fuel sources will shape the future climate. (Photo: Kevin Dooley, flickr, licenses under Creative Commons License 2.0).

How do we get to probabilities then, if we cannot say how likely a particular scenario is? We get to probabilities by running climate models with the same scenario often enough that we can develop probability distributions for a given emissions pathway. More specifically, scientists can run selected emission scenarios many times on a particular model; they can also run the same scenario on many different models; and they have done this now for all basic scenarios considered by the Intergovernmental Panel on Climate Change (IPCC). Pooling the results of multiple model runs for a particular emissions scenario together, scientists are able to say what the average of all these model runs is, or the distribution of projections for a given climate variable within a particular confidence interval. So, when scientists say, "there is a 66% chance that warming by 2050 will be in a particular temperature range", that statement reflects the statistical result of many model runs for a particular emissions scenario. Alternatively, scientists may run sea-level rise projections on one or multiple climate models for a lower and higher-emissions scenario, combine all outputs, and thus be able to say that "there is a 90% chance sea-level rise by 2050 will be no more than…"

The resulting probabilities reflect the best available scientific understanding of relevant factors influencing a particular climate outcome (as reflected in the climate models used) but are conditional on the underlying emissions scenario. Such probabilities are useful to infrastructure designers only after they have made up their minds about how risk averse or risk tolerant they choose to be. Once the risk tolerance is determined, infrastructure planners can use these probabilities in a risk management process that considers sensitivity to future changes in the probability estimates. For example, if the infrastructure being considered is long-lived and of high value, and damage to it would cause very high or irreversible damages, an infrastructure owner might choose to build it so that it can withstand the climate conditions associated with a fossil-fuel heavy/high-emissions scenario. Designers can then use probabilistic climate projections for that high-emissions scenario to evaluate their design choices.

This type of probabilistic projection is the best science there is, which is considerably better than assuming that there will be no change, or simply extrapolating historical trends into the future.[4] But in the end, only one climate future out of all of these projections will unfold in reality. Infrastructure designers, along with their stakeholders and ultimate decision-makers, are thus faced with the need to become clear about how willing they are to take on the risk to be unsafe or how willing they are to pay for greater safety. The result of this values-based choice and professional judgment will manifest in the contingencies they will or will not build into their plans and designs so as to deal with the one inherently unpredictable reality that will unfold in time.

Model Uncertainties

Climate models are another source of uncertainty in climate projections. To project future climate, scientists select one or more plausible greenhouse gas emissions scenarios (as discussed above) and use them as inputs into global climate models. Climate models are linked sets of mathematical equations derived from the laws of physics, such as Newton's equations of motion and the Ideal Gas Law. They are based on the same mathematical equations as the models that are used to make weather forecasts but are run over much longer time horizons and represent physical processes in the atmosphere, ocean, ice and land surface. In some cases, models also account for important processes in chemical, biological and human systems[126]. In recent decades, research groups around the world have developed more than 50 such global climate models of varying complexity. They vary in the degree of sophistication in representing these physical, chemical, biological and human-driven processes, as well as in the spatial and temporal detail that they can provide. Climate models also vary in how well each is capable of reproducing the natural variability that has been observed over different regions of the world in the past. Research groups continually improve models, validate them against past climate observations, and learn from thousands of analyses by the much larger group of international scientists that are not involved in the climate model development through a global inter-model comparison project (now in its sixth round of inter-model comparisons[127,128]).[5]

With growing computational speed and data storage capacities, models can now be run many times with multiple emissions scenarios, or many times with the same emissions scenario. These enhanced computational resources have significantly improved modeling approaches; enabled insights into the relationship between observed trends, extreme events, and underlying causal mechanisms (e.g., attribution of individual extreme events to natural variability vs. human-caused climate change); and give scientists the ability to develop probabilistic climate projections.

One of the most important findings from this inter-model comparison over the past few years has

[4] Scenario planning can be a viable alternative to understand the sensitivity of systems to different climate (or other) conditions.

[5] See: see: https://www.wcrp-climate.org/wgcm-cmip.

been the insight that, at the regional scale, differences between models are often neither smaller nor greater than the normal variability in climate. Put another way: when analyzing the trajectory of climate in a given region, running one emissions scenario ~40 times in one climate model often produces a range of climate outcomes that is similar in size to the range obtained when running that same emissions scenario once in each of the ~40 global climate models available[36,129,130]. In practice, however, decision-makers do not rely on 40 models to capture this full range of possible outcomes; rather, they typically only have a small number of model results available. Thus, for planning purposes and to guard against possibly missing important information, a divergent range of model outputs should be used. This range of outcomes in a single climate model run in a single emissions scenario arises from the natural climate variability described above. The resulting range of projected variables reflects the irreducible uncertainty that is inherent to all climate futures.

Future climate will never be more predictable or more certain than the past or current climate.

As a result, a general "rule of thumb" is that future climate will never be more predictable or more certain than the past or current climate: day to day, season to season, year to year, there is variability in the climate and that fact remains. However, in general, climate variables that are strongly dependent on temperature exhibit the least irreducible uncertainty, while variables that are dependent on precipitation exhibit the greatest irreducible uncertainty[34]. For example, for California, the irreducible uncertainty lies only in the magnitude of warming, but not in whether warming will occur if greenhouse gas concentrations continue to increase[129]. Likewise, although there is substantial irreducible uncertainty in the sign of precipitation over California and the broader western United States over the next few decades, the definitive likelihood of continued warming overcomes that precipitation uncertainty to create an unambiguous trend towards diminished snowpack and earlier snowmelt timing[42].

Uncertainties in Downscaling

Global climate models are – as the name denotes, global in scale – and thus use a global grid to map their outputs onto the Earth's surface. Each grid cell can be tens to hundreds of miles on one side, thereby covering large areas of different types of terrain, land cover and land use. Over the past decade or more, scientists have made significant progress in increasing the spatial (and temporal) resolution of their models (Figure 2.5), but any increase in the resolution of grid cells results in a corresponding multifold increase in the number of equations that need to be solved to obtain results, and thus in a dramatic increase in computational demand (for example, resolving the processes that produce Santa Ana winds and associated wildland fires[95], or atmospheric rivers[131], thus further increasing the need for computational capacity.)

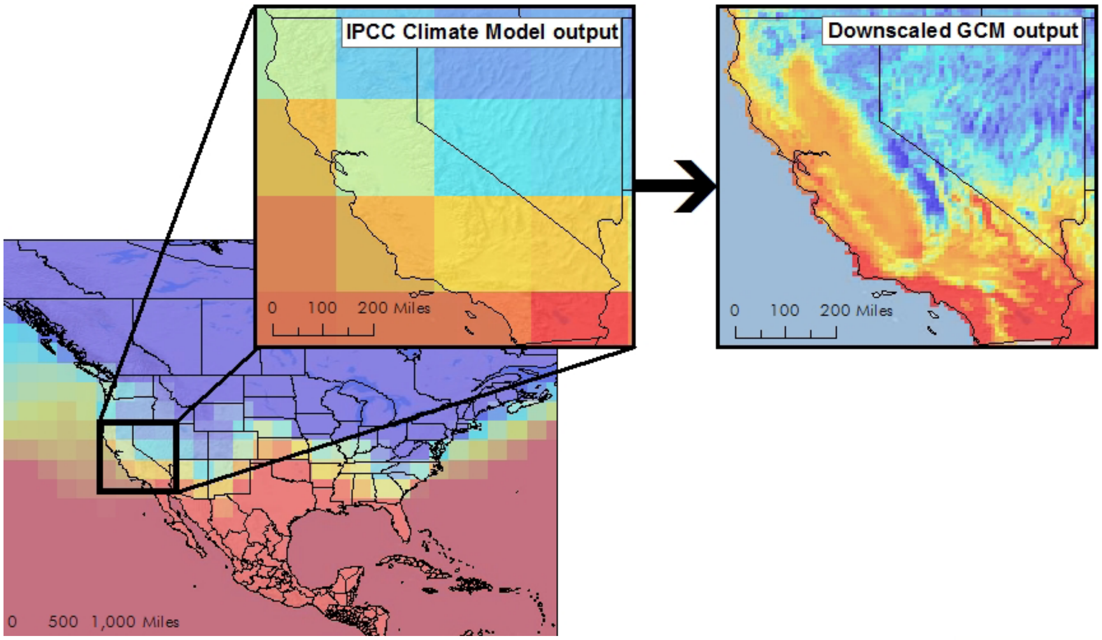


Figure 2.5 Scientists have made significant progress in increasing the spatial and temporal resolution of their models. But just because data are more highly resolved and provide a more localized picture does not mean they are more reliable or accurate. (Source: Cal-Adapt).

Scientists have developed two ways to relate global climate changes to regional and sub-regional changes, (e.g., on the scale of the Western United States, or within California): the first, called dynamical downscaling, links climate dynamics observed at larger scales to those witnessed at smaller scales through equations that represent how these processes interact across scales. The second, called statistical downscaling, mathematically relates (i.e., correlates) climate variables projected at larger scales to corresponding variables observed at smaller scales. Dynamical downscaling offers a more comprehensive representation of the finer-scale physical processes that govern the regional and local response to global warming, but is slower and more computationally demanding, and is subject to uncertainty arising from the physical representation of those processes[132]. Statistical downscaling is quicker and less computationally demanding, but it ignores the finer-scale physical processes, meaning that it can underestimate the magnitude of local and regional change[41].

Many planners and infrastructure designers wish for ever higher-resolution data and the scientific community, including in California, is rapidly advancing to produce the desired level and types of outputs (Box 2.3). Research shows that higher-resolution data are much preferred by practitioners because they illustrate locally familiar situations and lend themselves more easily to local planning and decision-making[133]. But just because data are more highly resolved and provide a more localized picture does not mean they are more reliable or accurate. Put another way, higher resolution data create the illusion of greater reliability, but this may not always be the case.

Conclusions

In this chapter we have synthesized the state of knowledge on observed and projected climate change with particular emphasis on California. The scientific community is unequivocal on the existence of global climate change, and there is very high confidence that it is mostly human caused. A large number and wide variety of independent observations as well as detailed studies to rule out alternative explanations have created this solid scientific understanding.

What we know with considerable confidence includes the following:

- Climate is no longer stationary and the past is no longer a reliable guide to future conditions;
- Climate warming will continue, likely at an accelerating rate;
- Sea level will continue to rise, also at an accelerating rate;
- Extreme weather and climate events will continue to occur amidst an envelope of these changing average conditions. Many will occur more frequently and/or be more intense than historically, a finding of particular significance to infrastructure planners;
- The most likely times of heightened risk of coastal flooding will be those when naturally-occurring events such as astronomically high tides coincide with coastal storms on an ever-higher baseline of rising sea level;
- Compounded extremes (e.g., coastal storms coinciding with freshwater floods; or Santa Ana winds coinciding with a heat wave and drought, leading to wildfires) need to be considered in planning for future climate impacts, including combinations of conditions that have not occurred historically; and
- Sequences of events also need to be considered (e.g., a wet fall that saturates soils, followed by a series of winter storms typically leads to flooding). This includes sequences of events that have been rare historically, and so are not well informed by extensive historical records, meaning that models must be called into play in order to assess the likelihood and better understand mechanisms.

Just because data are more highly resolved and provide a more localized picture does not mean they are more reliable or accurate.

This chapter also detailed in what ways future projections of climate change are uncertain. Some of these uncertainties are familiar to infrastructure planners already, such as natural climate variability. Patterns of this variability can be established, but it cannot be reduced or eliminated. Other uncertainties can be quantified, such as model uncertainty, but models will always only be approximations of reality, thus, they cannot fully be eliminated. The possibility of surprises (i.e., unforeseen changes in the climate system) remains. Finally, some uncertainties are extremely difficult to reduce, if at all, such as knowing the emissions pathway society will choose to take over the coming decades. Climate projections, even probabilistic ones, will therefore always be contingent on the emissions scenario selected to make those projections.

Guarding against inevitable, and in many instances worsening, extremes as the climate changes and accommodating these uncertainties thus requires particular attention from infrastructure designers. Global climate impacts that occur under global warming levels

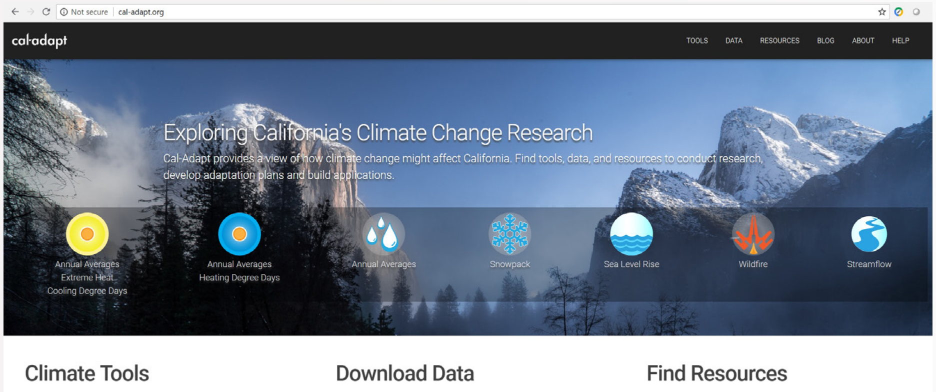
Box 2.3: Use of Climate Scenarios in California for Research and Long-Term Planning

Since 2003 California has supported the development of climate scenarios designed not only for scientific research on climate impacts and adaptation, but also to support long-term planning by State agencies[134]. California research efforts are aimed to complement federal climate research initiatives to provide insights that are more specific to California. Under direction and funding from the California Energy Commission (CEC), researchers in California tested multiple ways to translate (downscale) the outputs from global climate models to the California region at adequate temporal and geographical resolutions for practical applications[39,135]. The geographical resolution of the global climate models is roughly 100 miles, while information is needed at resolutions of 7 miles or less. Researchers used the downscaling techniques to bring the latest outputs of the global climate model runs produced for the IPCC Assessments to the California region. Under support from CEC, Scripps Institution of Oceanography developed the more recent and most advanced downscaling techniques known as Localized Constructed Analogs (LOCA)[43]. LOCA was used to develop the climate scenarios for California's Fourth Climate Change Assessment[29]. Outputs from LOCA drove a statewide hydrologic model to obtain information such as water flows and soil moisture. Recently, federal agencies adopted LOCA at the national scale and funded the application of LOCA for the nation as a whole for the 2018 (Fourth) National Climate Assessment.

The climate scenarios used in California's Fourth Climate Assessment[29] include daily maximum and minimum temperature, daily precipitation, relative humidity, wind speed, solar radiation, soil moisture, runoff and other variables. The level of geographical resolution is about 3.6 miles with daily time steps from 1950 to the end of the 21st century. The information is in the public domain and available from Cal-Adapt and other data repositories.

Since the release of the last IPCC Assessment in 2013, research groups around the world have improved their global climate models with the latest science and are running the models for the Sixth IPCC assessment cycle (2021-23). As before, under support from CEC, Scripps Institution of Oceanography is developing a new downscaling technique with improvements, such as the effects of small particles in the air, known as aerosols, on the formation and behavior of clouds and the use of an improved hydrological model. The new downscaling technique will be ready when the IPCC global climate scenarios are available, again, to develop California-specific scenarios to explore adaptation options for the energy sector and other sectors of the economy. Constant advances in science result in more advanced global climate models that should be matched by improved downscaling techniques.

In the last few years additional research groups in California have started to produce their own downscaling techniques with climate projections for different regions in California. The most notable effort is the work at the University of California at Los Angeles that has produced very sophisticated climate projections for certain periods in the future for the Los Angeles region and the Sierra Nevada. For the next California Assessment, the hope is to take advantage of these products to complement what the State is funding directly.



Source: Cal-Adapt landing page.

of, or exceeding, 3.6°F (2°C) have been described as "dangerous"[136]. California has made a policy commitment – along with many state, local, private sector and international counterparts – to work toward this target, even though the current federal administration has announced its intention to withdraw the United States from the international agreement[111, 137]; see also http://www.under2coalition.org/).

Extreme weather and climate events will continue to occur amidst an envelope of changing average conditions. Many will occur more frequently, a significant finding for infrastructure planners.

Despite this laudable commitment by California and others, it is important to note that even if all human-driven heat-trapping emissions were eliminated today, the Earth system would continue to warm because it is still reaching equilibrium with the excess greenhouse gases that have accumulated in the atmosphere over the past decades (for example, CO_2 has a residence time in the atmosphere of 100 years or more). Research suggests there are tipping points in the Earth system beyond which the global climate would enter a "hothouse" state, even if emissions continue to be reduced[138]. Thus, even under the best (but unrealistic) circumstances, further warming would occur, and sea level would continue to rise for the foreseeable future. And even under the next best (but difficult to achieve) scenario, i.e., if the global community were to meet the Paris targets, the Earth's climate and environmental conditions would continue to change, since even the most ambitious targets guarantee further emissions and warming beyond what has already occurred. The prospect of less advantageous futures, unfortunately, cannot be excluded. Given this outlook, it is accordingly prudent to consider the highest (or at least very high) warming scenarios in planning for climate change impacts to ensure the safest infrastructure possible.

In light of these trends in averages and extremes and the associated uncertainties, engineering will need a range of new approaches to ensure that safety and functionality remain viable goals. From a scientific perspective, these approaches should include scenario planning; risk-management approaches; the use of probabilities and safety factors; building-in redundancy, adaptability and resiliency; and contingency planning for when climate events overwhelm even the best engineered infrastructure.

Figure 2.6 Even if the global community were to meet the Paris Accord's targets of limiting warming to 2°C or less above preindustrial levels, the Earth's climate and environmental conditions would continue to change. But the prospect of less advantageous futures cannot be excluded. (Photo: Fremont Weir in Knights Landing, California; Florence Low, DWR, used with permission).