APRIL 2018

Climate Change in the Sierra Nevada

California's Water Future

UCLA Center for Climate Science

Our Mission

Our mission at the UCLA Center for Climate Science is to change the conversation on climate change by producing cutting-edge, actionable climate science and communicating it to decision-makers and the public in innovative and compelling ways. Using fine-scale projections of future climate, we build research collaborations and earth system modeling frameworks so that we can conduct interdisciplinary climate impacts research of practical use to stakeholders. We also train new generations of researchers to think beyond disciplinary boundaries and enable real-world problem-solving.

www.ioes.ucla.edu/climate

Report Citation:

Reich, KD, N Berg, DB Walton, M Schwartz, F Sun, X Huang, and A Hall, 2018: "Climate Change in the Sierra Nevada: California's Water Future." UCLA Center for Climate Science.

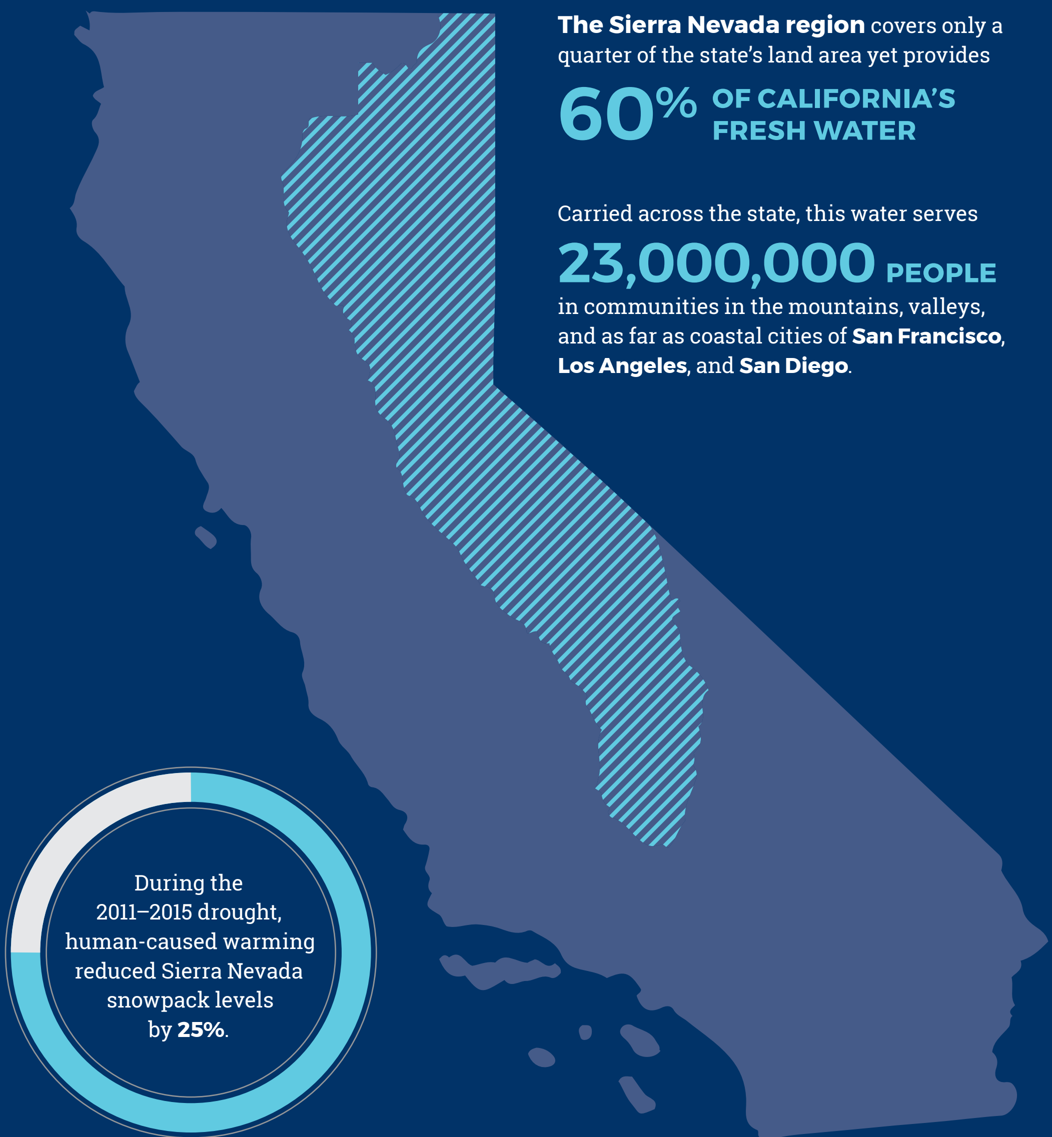
UCLA IoES   UCLA Center for Climate Science

Contents

1

How is California's climate changing?

The Sierra Nevada is one of California's most beloved natural treasures — and mountain snowpack is a key water resource. As climate change continues to warm the atmosphere, what will become of the frozen reservoir we depend on? To investigate, UCLA's Center for Climate Science created high-resolution projections of future climate in the Sierra. Here is a snapshot of our findings.



The Sierra Nevada region covers only a quarter of the state's land area yet provides

60% OF CALIFORNIA'S FRESH WATER

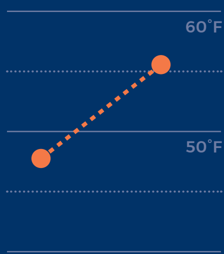
Carried across the state, this water serves

23,000,000 PEOPLE

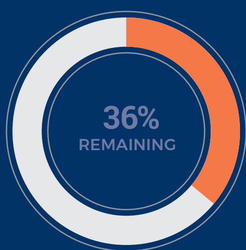
in communities in the mountains, valleys, and as far as coastal cities of **San Francisco**, **Los Angeles**, and **San Diego**.

If nothing is done to curb current levels of greenhouse gas emissions
our "Business as Usual" scenario shows by the end of the 21st century we can expect:

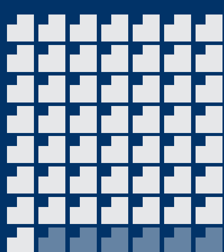
7°
rise in average springtime Sierra temperature



64%
drop in average springtime Sierra snowpack volume



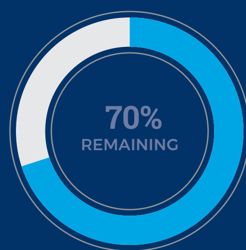
50 DAYS
earlier runoff of snowmelt into mountain streams



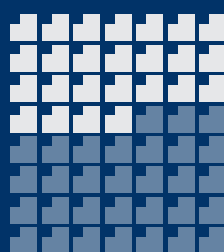
If the world takes action to reduce global greenhouse gas emissions
our "Mitigation" scenario shows by the end of the 21st century we can expect:

4°
rise in average springtime Sierra temperature

30%
drop in average springtime Sierra snowpack volume



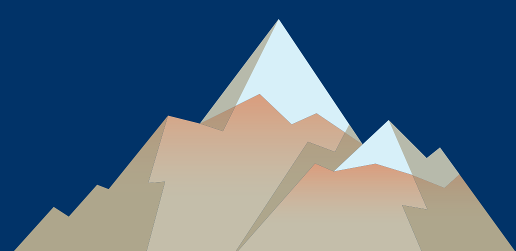
25 DAYS
earlier runoff of snowmelt into mountain streams



The Sierra Nevada elevations most vulnerable to climate change are

5,000–8,000 FEET

This is where snow albedo feedback is occurring — a cycle of amplified warming and snowmelt due to loss of reflectivity. Our project is unique in taking this effect into account.



Find more on this project: **www.ioes.ucla.edu/project/climate-change-sierra-nevada**

Sierra snow is a critical California water resource. Our innovative techniques project future snowpack under climate change in a comprehensive and physically realistic way.

2

Why study Sierra snow?

California's Sierra Nevada is a critical natural resource, providing more than 60% of the water used by communities, agriculture, and industry across the state. The mountain snowpack accounts for about half of this resource. It acts as a natural reservoir, holding water in frozen form until it gradually melts over spring and summer and flows into manmade reservoirs and conveyance systems. Historically, snowmelt and runoff have occurred when temperatures are hottest and crops are thirstiest.

Because the Sierra snowpack is so important to our way of life, scientists and water managers have become increasingly concerned about the effects of climate change. As people and industries across the globe continue to burn oil, coal, and other fossil fuels, they release heat-trapping gases like carbon dioxide into the atmosphere. As more of these so-called greenhouse gases are emitted, temperatures rise in the atmosphere and oceans.

Past studies have shown that human-caused warming will shrink the Sierra snowpack and lead to earlier melting. If California is to adapt to these changes, we need a better understanding of the specifics:

- How much warmer will it get?
- How much snow will we lose?
- How much earlier will snow melt and run off?
- Will all elevations and all watersheds be affected to the same degree?
- What happens during droughts and extremely wet years?
- If we act to reduce greenhouse gas emissions, can we prevent these changes?

To answer these questions, we used global climate models, powerful computing tools that simulate the climate system.

Global climate models are the best tools we have for projecting future climate, but they are too low in spatial resolution to accurately simulate climate in areas where the topography is complex. In the Sierra Nevada, different elevations experience very different climatic conditions — details that global climate models miss.

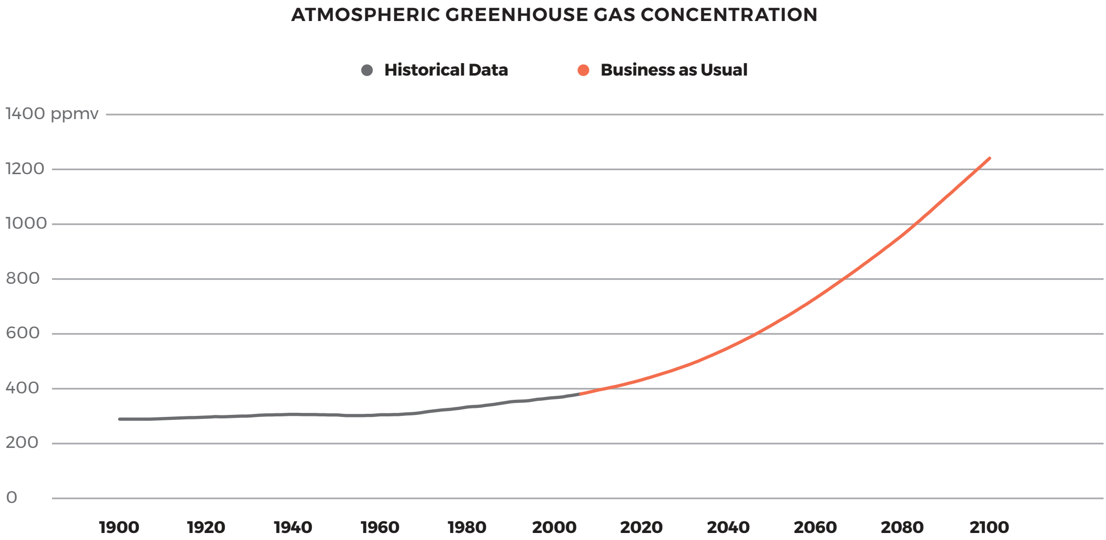
That's where ***downscaling*** comes in. Downscaling is the collective term for methods to create higher-resolution simulations from global climate model information. Some of these methods are "dynamical," meaning they use a regional climate model (a high-resolution cousin of a global climate model) to simulate future climate. Dynamical downscaling is physically realistic but very expensive in terms of computing time. Other downscaling methods are "statistical," using mathematical shortcuts to produce higher-resolution projections. Statistical models are computationally cheap and quick to run, but they don't necessarily represent the physical dynamics of local climate.

Representing these local physical dynamics is important, because they can have a big impact on the local changes caused by global warming. When you're studying snowy places, it's especially important for a climate model to represent a phenomenon called ***snow albedo feedback***. (See page 14 for more about this.) In this project, we paid special attention to snow albedo feedback, using dynamical downscaling to make sure our simulations captured it.

FIGURE 1

A Scenario of Greenhouse Gas Increases

*In the first part of this report, we focus on future climate projections for 2081–2100 under a **Business as Usual** scenario in which atmospheric greenhouse gas concentrations (shown in parts per million) keep rising.*



At the same time, we wanted to look at a large set of global climate models. There are more than 30 global climate models currently in use, and they vary in how they are constructed to represent different climate phenomena. As a result, they give different answers about the future. For this reason, climate scientists generally prefer to look at the behavior of large sets of models, rather than depending on just one or two. However, doing this with dynamical downscaling typically isn't feasible from a computational standpoint. In our study, we developed a statistical model that essentially mimics our dynamical model. With this statistical model, we were able to incorporate all of the latest-generation global climate models.

The result is an innovative method we call ***hybrid downscaling***, which takes advantage of the strengths of dynamical and statistical downscaling while minimizing the downsides. For more about hybrid downscaling's advantages, see page 43.

In our study, we focused on two future time periods:

- 2041–2060, or "mid-century"
- 2081–2100, or "end-of-century"

To measure change, we compared the future periods with a historical period of 1981–2000.

We made future projections under two different greenhouse gas scenarios:

- A scenario in which greenhouse emissions keep rising throughout the century. We call this ***Business as Usual***.
- A scenario in which greenhouse gas emissions level off at about mid-century. We call this ***Mitigation***.

You can learn more about Mitigation on page 29. The first few chapters of this report focus on Business as Usual at 2081–2100 (see Figure 1).

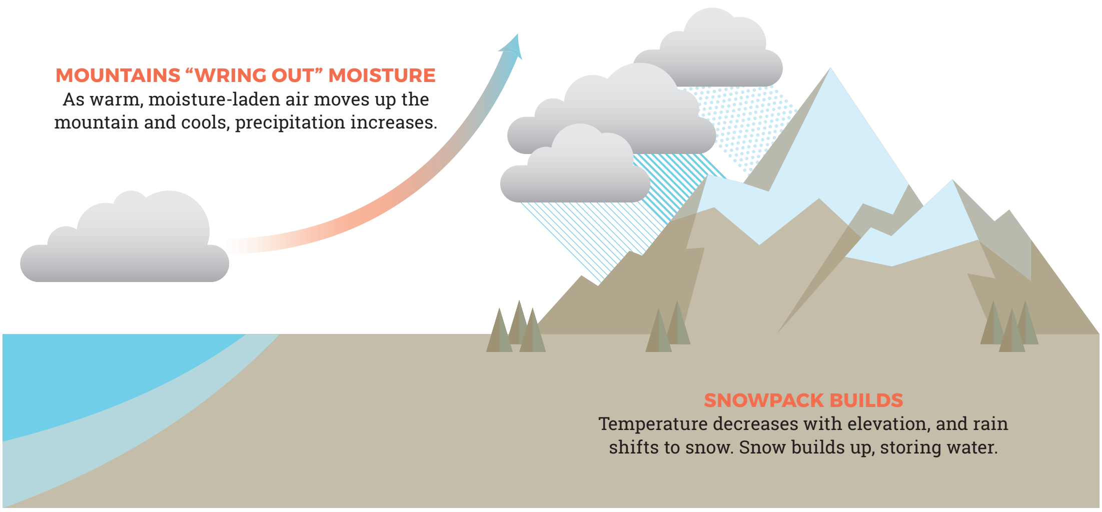
CONCEPT SPOTLIGHT

Climate and Water in the Sierra Nevada

FIGURE 2

How the Snowpack Accumulates

In winter, moisture-laden air from the Pacific moves eastward. When it rises over the mountains, it cools rapidly and releases precipitation. Above the freezing line, precipitation falls as snow, and the greatest snowfall occurs at the highest elevations.



Why is the Sierra is so snow- and water-rich compared with other parts of California? The short answer is that mountain ranges are precipitation traps. Here's why.

*First, **temperature decreases rapidly with elevation**. As you go up in elevation, atmospheric pressure drops, and air temperature falls. Warmer air can hold more moisture, and cooler air can hold less. When moistened air cools, it loses its ability to hold water, and what can no longer be held falls to the ground. The colder the air gets, the more moisture "falls out" of it. Therefore, **precipitation increases significantly with elevation**. When the air temperature is above freezing, precipitation falls as rain; when it's below freezing, it falls as snow. As a result, **the higher the elevation, the more snow** that collects over the course of the winter. Figure 2 shows these concepts in action.*

*Another important fact to keep in mind is that **precipitation in California is seasonal**. We live in a Mediterranean-type climate, where most precipitation occurs between November and March. That's when mountain temperatures are coldest and snowpack can build. But it's also when human water demand is relatively low — we use more water in the summer months when temperatures are hotter and our crops and gardens are thirstier. Being able to save water that comes in winter for the hotter months is critical to our economy and way of life. Manmade reservoirs can store some of that water, but not all of it. Therefore, snowpack is a natural water reservoir that our manmade water system depends on.*

By the end of this century under our current greenhouse gas pathway, temperatures across the Sierra rise by as much as 10 degrees Fahrenheit.

3

Where will warming happen?

The first set of questions we took up relates to future temperatures. How much will the Sierra warm by the end of this century if we follow the Business as Usual greenhouse gas pathway? And where will warming be most severe?

These questions build the foundation for our investigation of changes to snow. If temperatures warm from below freezing to above freezing, less precipitation falls as snow in the first place. Plus, warmer temperatures cause any snow that does fall to melt faster. And when warming causes a snow-covered area to lose its snow, it kicks off a phenomenon called snow albedo feedback, which makes warming — and snow loss — even worse. (See page 14 for more about snow albedo feedback.)

Because snow albedo feedback is not only caused by warming but also increases warming, it's critical that our project takes this phenomenon into account. If we neglected snow albedo feedback in our projections, we would end up underestimating warming and the ensuing snow and runoff changes. So an early focus of our project was making sure our methodology incorporated snow albedo feedback. For more about how we did this, see page 43.

Once we developed our snow albedo feedback–inclusive study methods, we ran our climate simulations. First, we re-created the climate of a historical period, 1981–2000; this gave us a baseline climate we could compare future projections to.

Figure 3 shows the average springtime temperatures in our historical period, 1981–2000. Here we focus on March–May because this is historically when the snowpack reaches its peak and begins to melt. Temperatures range greatly with elevation: The foothills and valleys see average temperatures in the 50's and 60's, whereas the highest elevations see those in the 20's or even lower.

Next, we created future climate projections representing the end of this century (2081–2100) under "Business as Usual" greenhouse gases. In these projections, warming averaged across the entire study domain ranges from about 7 to more than 10 degrees Fahrenheit, depending on the month.

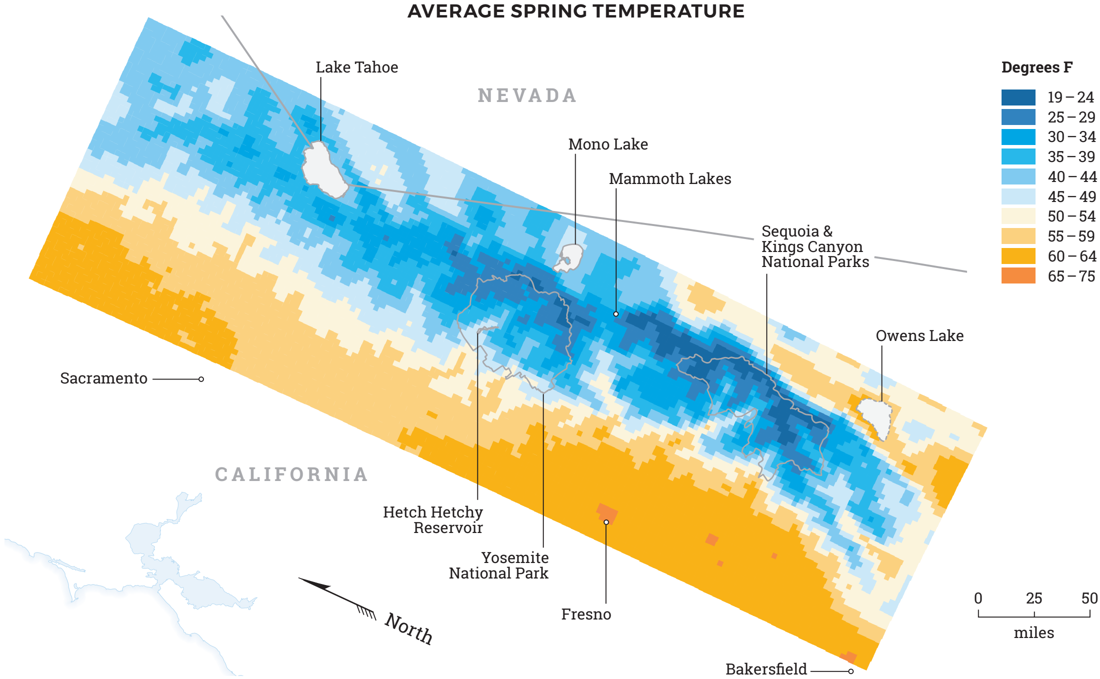
Figure 4 (top panel) shows warming across the Sierra averaged over March–May. In the foothills and valleys, temperatures increase by 5–7 degrees. At mid-elevations, about 5,000–8000 feet, the greatest temperature increases are seen: from 8 to more than 10 degrees. The highest elevations see slightly less severe warming than the mid-elevations, on par with the foothills.

Why are middle elevations the hardest hit by temperature increases? This is where snow albedo feedback is occurring. Retreating snow cover is exposing darker land surfaces, and instead of mostly reflecting sunlight, as snow would have, they absorb it. This results in even higher temperatures, even more snow cover loss, and so on in a vicious circle. Snow albedo feedback's enhancement of warming is particularly severe in the months of May–July (not pictured), and at some elevations it accounts for more than 3.6 degrees Fahrenheit of additional warming, on top of what would be expected from atmospheric warming alone.

FIGURE 3

Historical Climate, 1981–2000

This map shows average 24-hour temperatures, in degrees Fahrenheit, for March–May during the study's historical period. Temperatures decrease rapidly with elevation, dropping from the 50's in the foothills to the high teens at the highest peaks.



In Figure 4 (bottom panel), we "zoom in" on part of the study domain so we can see warming in more detail. This map shows the watersheds feeding the North, Middle, and South forks of the American River, which is the main freshwater source for Sacramento. The American River is also important habitat for steelhead trout and Chinook salmon and home to a number of hydroelectric power plants that provide electricity to Sacramento. At the end of the century under the Business as Usual scenario, springtime temperatures increase by at least 7 degrees over much of the land area feeding the American River. Watersheds like these, which predominantly drain elevations of 5,000 to 8,000 feet, are more vulnerable to warming than those that drain predominantly higher elevations.

The warming patterns we see in our future projections indicate that certain elevations and watersheds are more vulnerable than others in a changing climate, and that greater changes in snow and runoff will occur at these elevations. Next, we turned our investigation to snow.

Key Points

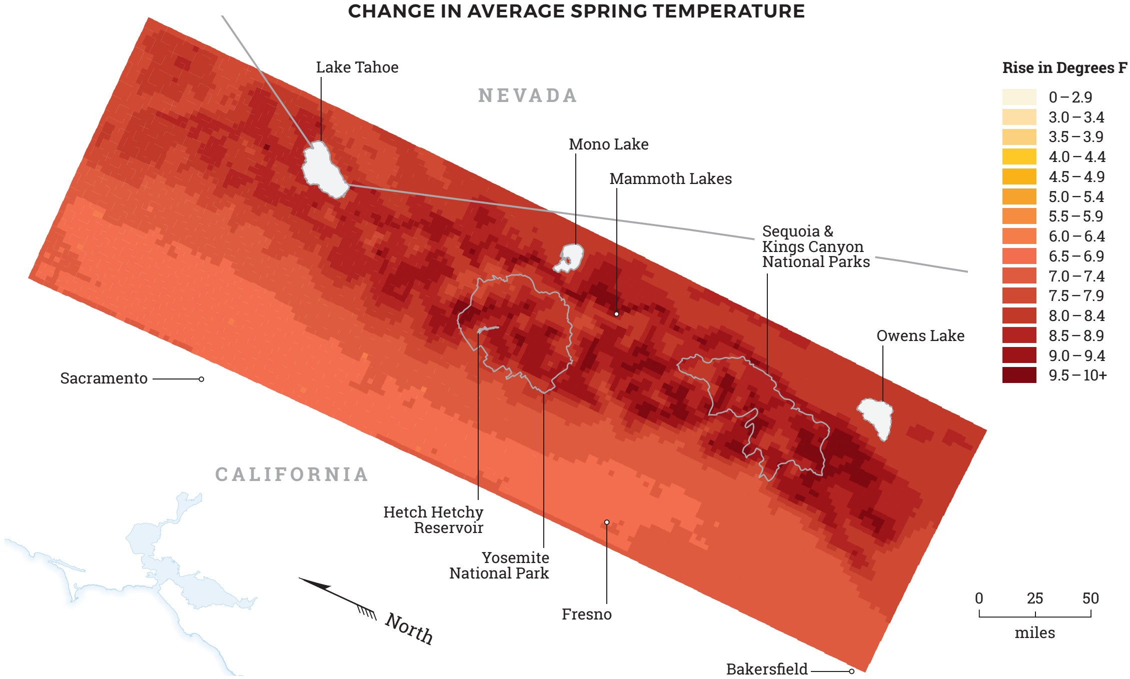
- By 2081–2100 under the Business as Usual scenario, temperatures across the Sierra increase by as much as 10 degrees Fahrenheit, depending on the month and elevation, compared with 1981–2000.
- The most severe warming occurs at elevations of 5,000–8,000 feet. This is where snow albedo feedback is occurring.
- Warming sets the stage for snow loss by causing more precipitation to fall as rain instead of snow, and snow to melt faster.

FIGURE 4

Business-as-Usual Warming, 2081–2100

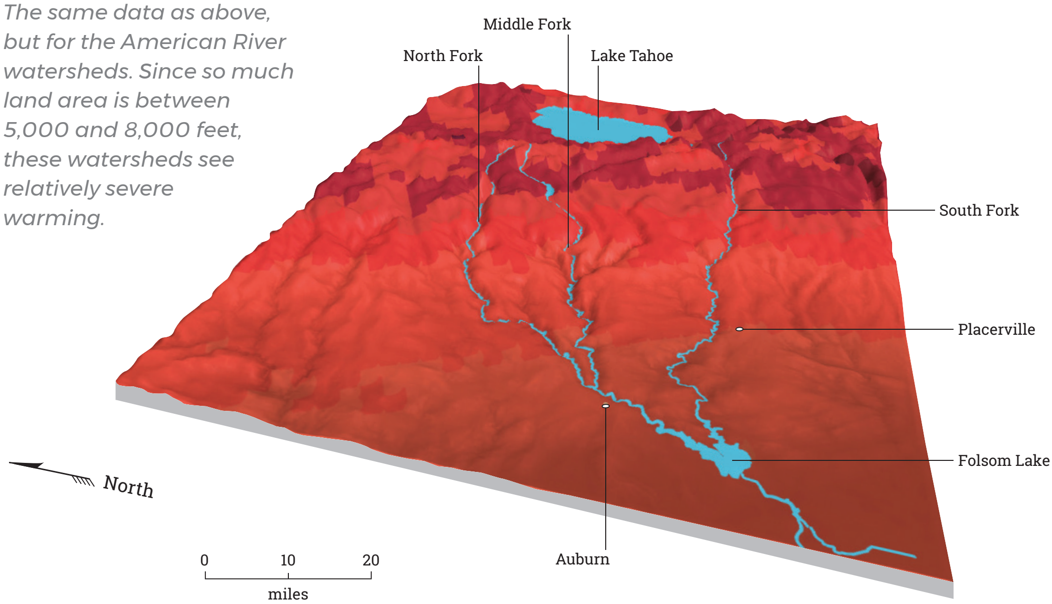
This map shows the change in average 24-hour temperatures, in degrees Fahrenheit, for the months of March, April, and May at the end of the century. Warming is greatest at elevations between 5,000 and 8,000 feet, where snow albedo feedback is occurring.

CHANGE IN AVERAGE SPRING TEMPERATURE



CHANGE IN AVERAGE SPRING TEMPERATURE: AMERICAN RIVER REGION

The same data as above, but for the American River watersheds. Since so much land area is between 5,000 and 8,000 feet, these watersheds see relatively severe warming.



CONCEPT SPOTLIGHT

Snow Albedo Feedback

FIGURE 5

Snow Albedo Feedback Cycle

Snow albedo feedback occurs when warming causes snow cover loss, which in turn causes greater warming. Our climate projections incorporate snow albedo feedback and the resulting enhanced warming.

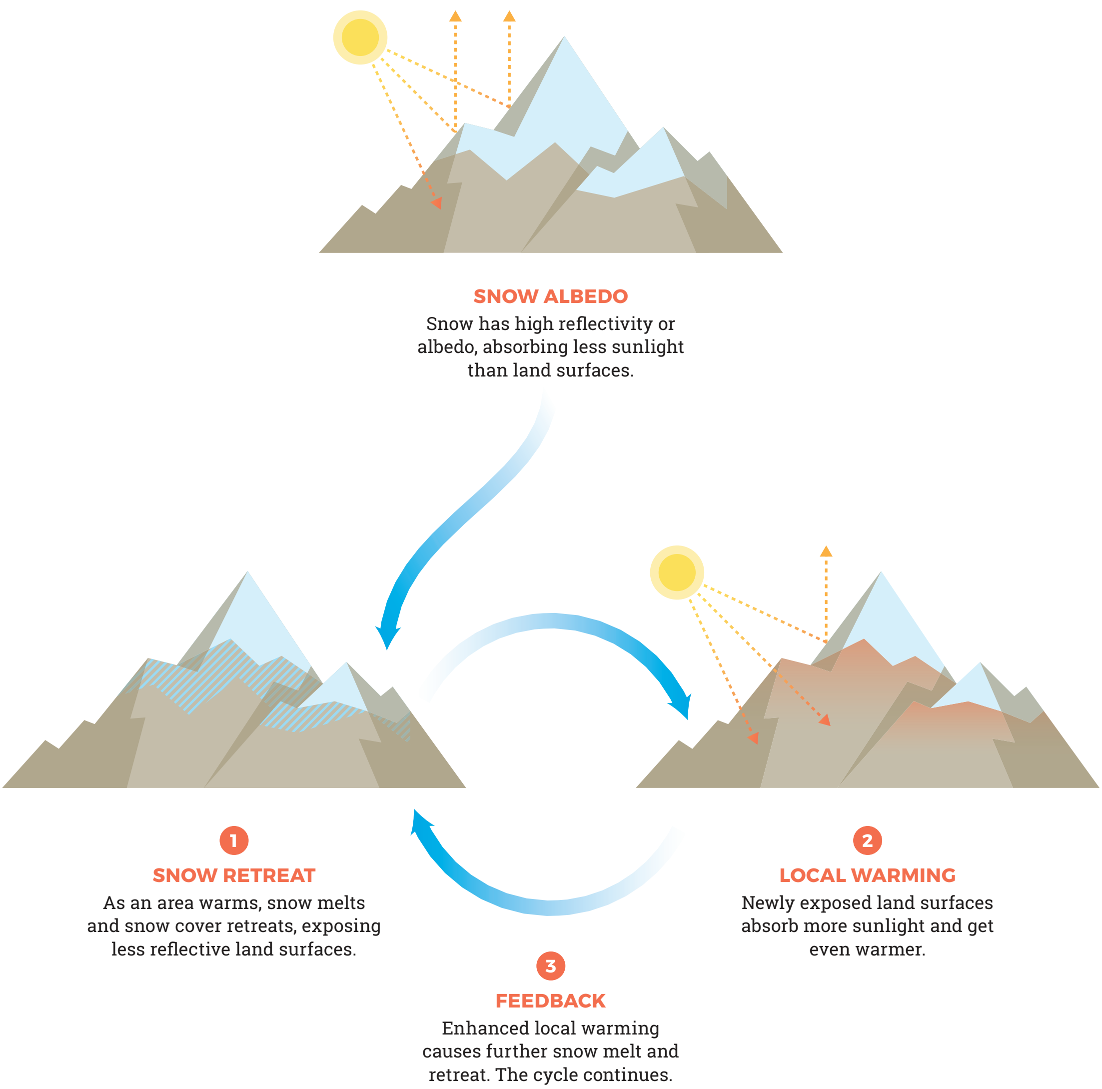
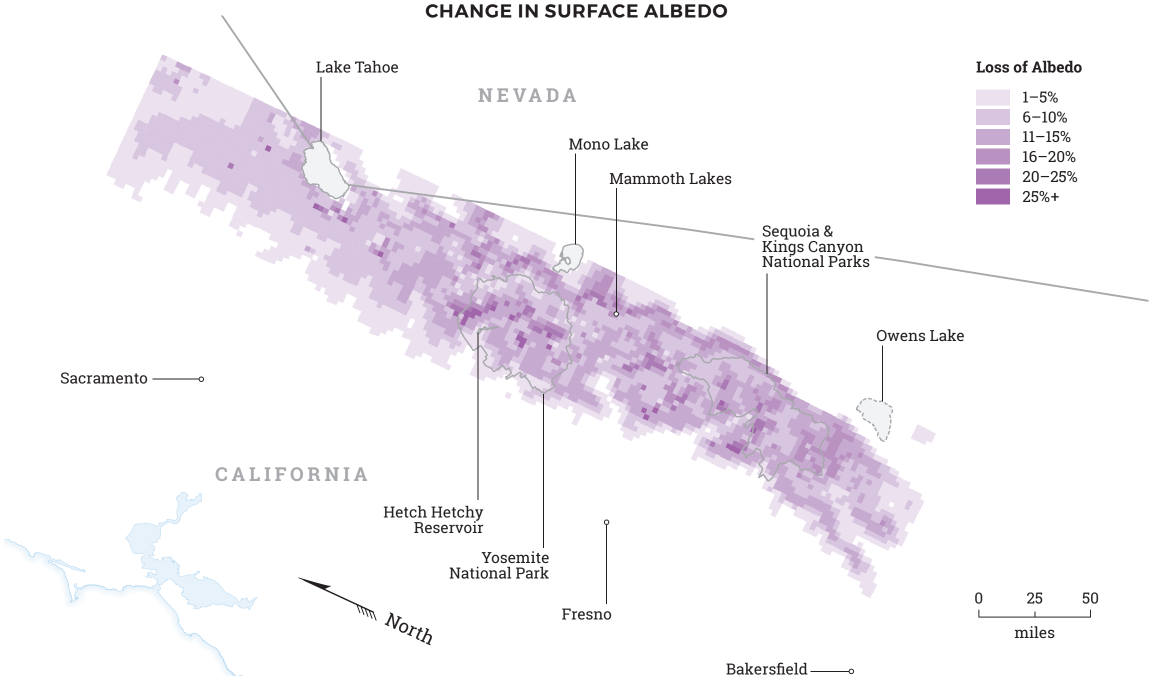


FIGURE 6

Business-as-Usual Reflectivity Loss, 2081–2100

This map shows where retreating snow cover causes a decrease in albedo, or a loss of the land surface's ability to reflect sunlight, during March–May at end-of-century under Business as Usual greenhouse gases. Decreases are greatest at 5,000–8,000 feet.



*Part of what makes our research on climate change in the Sierra unique is that our climate projection methods include a phenomenon called **snow albedo feedback**. Without accounting for this phenomenon, our projections would underestimate warming, snow, and runoff changes.*

What is snow albedo feedback, and why is it so important? Albedo is a measure of how much sunlight is reflected by a surface. Snow has a high albedo, meaning it reflects a lot more sunlight than it absorbs. Other land surfaces have lower albedos, meaning they absorb more sunlight than snow.

Snow albedo feedback occurs when warming causes snowpack to shrink at its margins. The ground that is uncovered loses albedo — it absorbs more sunlight than snow would have — and this enhances the warming at that location. The enhanced warming melts more snow, which exposes more sunlight-absorbing ground, which further enhances warming, and so on. In other words, snow albedo feedback is a feedback loop that leads to greater local warming than would be expected from atmospheric warming alone.

In our project, our initial dynamical downscaling simulations indicated that albedo decreases under climate change, especially at elevations of about 5,000–8,000 feet (see Figure 6). The albedo change corresponds to the warming seen in these simulations, indicating that snow albedo feedback is indeed leading to enhanced warming. From this information, we were able to build a statistical model that incorporated albedo change—and hence, enhanced warming—into our complete set of projections.

California measures Sierra snowpack each April 1 to assess the health of the water year. But under climate change, springtime snow could be on life support.

4

How will the snowpack change?

After examining warming across the Sierra under climate change, we turned our attention to changes in snow. Specifically, we wanted to understand how much less land would be covered by snow at points throughout the year. And even more central to our investigation of water resource changes, we wanted to understand how the total amount of snow would change as temperatures rose.

As we suspected, snow-covered area — that is, the land area that is blanketed with snow of any depth — decreases substantially by 2081–2100 under the Business as Usual scenario. For example, the total area covered by snow during the typical April decreases by 48%, compared with 1981–2000. At this time of year, snow cover loss is worst at elevations below 8,000 feet, whereas higher elevations remain relatively protected. During the snow season's shoulder months — October–November and May–July — all elevations are vulnerable to snow cover loss.

Looking at the loss of snow-covered area tells us just part of the story of snow changes under climate change — the part related to snow albedo feedback and enhanced warming. But to understand how water resources might be affected, we need to look also at how much snow volume is lost.

Since the density of snow can vary, snow depth isn't always a useful measure when you want to understand the water resource the snowpack can provide. Instead, you want to look at the amount of water in the snow. A metric often used by water managers is called ***snow water equivalent***. It's the depth of water that would occur if the snow were melted instantaneously, and it is often expressed in millimeters.

In this report, we focus on changes in the volume of snow at the average April 1 during our future periods. On the first day of each month during the snow season, water managers measure snow water equivalent in different locations throughout the Sierra to gauge the health of the snowpack. Historically, the April 1 measurement has captured the snowpack at its peak, and later measurements reflect snowmelt and runoff due to the spring thaw.

Our projections show a major loss of snow at April 1 by the end of the century under the Business as Usual scenario. As Figure 9 shows, in the average year between 2081–2100, April 1 snowpack across the entire Sierra domain will be just 36% of what it was during the average year in 1981–2000. The most snow is lost between 5,000 and 8,000 feet. This is where snow albedo feedback's vicious circle of warming, snow loss, and more warming and snow loss is occurring. Below 5,000 feet, April 1 snow disappears almost entirely.

This loss of snow occurs because warmer winter temperatures change the ratio of total precipitation that falls as rain versus snow. Because a smaller portion of precipitation falls as snow, the snowpack doesn't build up as much in the first place. It also melts faster under warmer temperatures and during wintertime rain events.

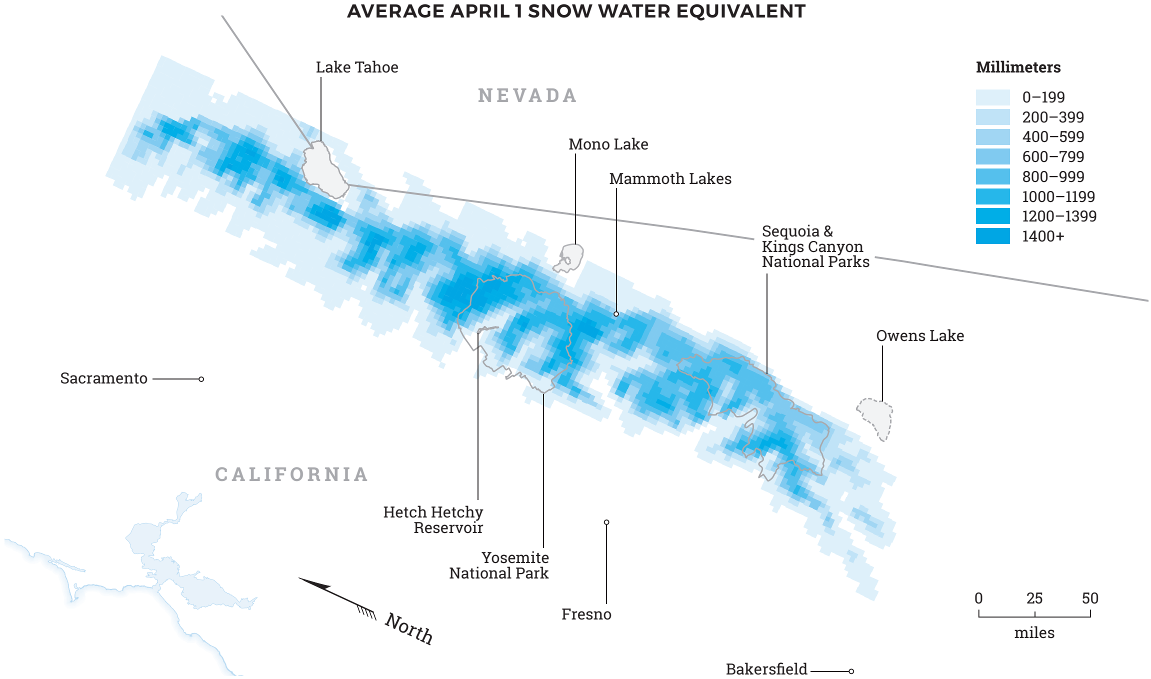
In many of the global climate model projections we assessed, total precipitation actually increases in the Sierra. At very high

FIGURE 7

Historical Springtime Snowpack, 1981–2000

This map shows average historical (1981–2000) values for snow water equivalent at April 1 across the Sierra. Measured in millimeters, snow water equivalent is the depth of water that would occur if snow melted instantaneously.

AVERAGE APRIL 1 SNOW WATER EQUIVALENT



elevations that remain cold enough, snow is gained. But these gains are generally overwhelmed by large losses below 8,000 feet, resulting in substantial snowpack depletion. In other words, the increase in precipitation isn't nearly enough to counteract the loss of snow that's due to warming.

These findings suggest that in the future, snowpack will have peaked before April 1, and won't last nearly as long into the summer months. Changes to snowpack tell us that the water cycle in the Sierra is changing, but they don't give us the whole story. We need to understand how much water runs off from the mountains and enters streams, and when that occurs. These are the questions we turned to next.

Key Points

- At end-of-century under the Business as Usual scenario, the land area that is covered by any snow in April decreases by 48%.
- Snow water content decreases across the entire study domain, but losses are especially severe at elevations between 5,000 and 8,000 feet.
- On the average end-of-century April 1, the Sierra's total snowpack will be just 36% as large as it was in 1981–2000.
- Snow losses are due to warming and occur despite the precipitation increases shown by some climate models.

FIGURE 8

Business-as-Usual Snowpack, 2081–2100

This map depicts the percentage of average April 1 snow water equivalent projected to be lost by 2081–2100 under the Business as Usual scenario, compared with the historical period (1981–2000).

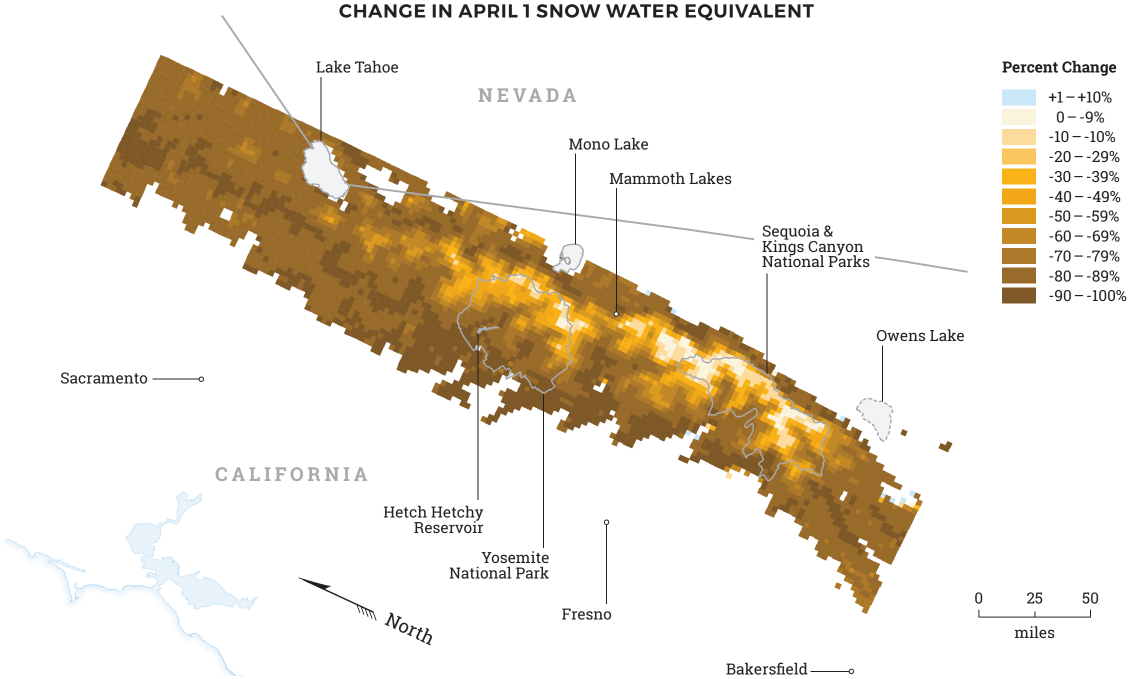
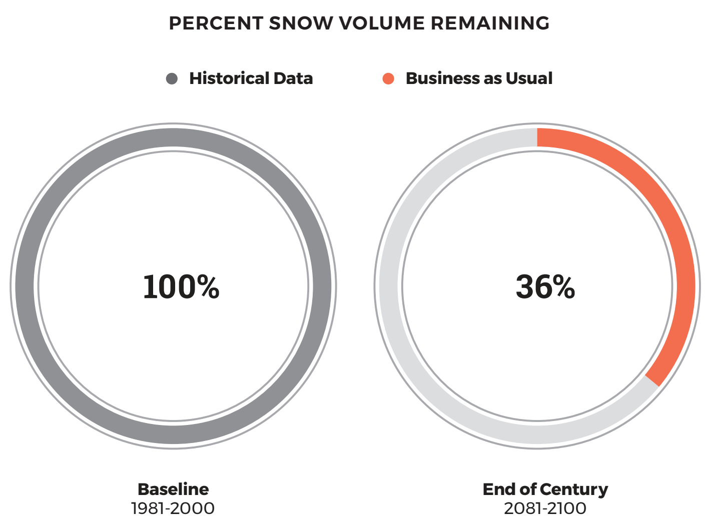


FIGURE 9

Snowpack Depletion, 2081–2100

This figure compares the total volume of the water stored snowpack across the study domain on the average April 1 during two time periods. In 2081–2100 under the Business as Usual scenario, snowpack is only 36% of what it was in 1981–2100.



Temperature and snow changes lead to an earlier shift in the timing of surface water runoff — which presents a major challenge to water management.

5

How will the water cycle change?

A big challenge to water management in California is that our wet season (November–March) is out of phase with when we use the most water (the hot summers). Historically, the Sierra snowpack has helped with this discrepancy: Snowmelt has typically run off from the mountains throughout the summer — timed just right to replenish manmade reservoirs and make supplies last until the next wet season.

But if climate change affects the timing of runoff in the future, water managers could have a big problem. And this is just what we expect to happen, because warming causes a greater share of precipitation to fall as rain instead of snow, and rain runs off immediately. Warming also causes snow to melt faster. Past studies have found that Sierra rivers already show earlier pulses of streamflow than they used to because of springtime warming. But to date, studies projecting changes to future Sierra runoff timing have been limited, especially at the level of spatial detail needed to plan for the future. In our project, we set out to close this knowledge gap.

We focused our analysis on a metric called the ***runoff midpoint***. This is the point in time by which half of the total water that runs off in a given year has done so. We compared the runoff midpoint in our future projections to that of the historical period, and found that in the future, it occurs much earlier.

Figure 10 illustrates the concept of a shift in the timing of runoff. The circles shown are sized according to the portion of total annual runoff that occurs, on average across the entire study domain, during each month. In the historical period (1981–2000), half the year's total runoff occurred by early May. At 2081–2100 under our Business as Usual scenario, the runoff midpoint shifts to early March. That's an advance of about 50 days.

In some locations, the advance is as great as 90 days. Figure 11 shows the change in runoff timing across the domain. The greatest timing shifts occur at elevations between 5,000 and 8,000 feet. These elevations have strong local warming, thanks to snow albedo feedback. Higher elevations remain cold enough that changes in runoff timing are relatively small.

Runoff timing matters because earlier runoff may be much more difficult to store. Manmade reservoirs serve two purposes: They not only store water for the summer but also hold back runoff that could otherwise flood downstream communities. To ensure reservoirs can serve this flood control purpose, water managers can't let them fill completely, or there would be no room to catch water from subsequent storms. If more runoff occurs earlier in the wet season, water managers may have to let the extra flow downstream rather than allow it to fill the reservoir. The question becomes: Where should that water go, and how can it be saved for summer?

Key Points

- Warming increases the ratio of rainfall to snowfall, and rain runs off right away.
- By 2081–2100 under the Business as Usual scenario, the midpoint of runoff occurs 50 days earlier, on average, than in 1981–2000.
- Earlier, flashier runoff is harder to capture and store than a steady, dependable flow from gradual snowmelt.

FIGURE 10

Earlier Shift in Runoff Timing

The size of the circles in this figure represents the percentage of total annual surface water runoff occurring each month in an average year. In 2081–2100 under the Business as Usual scenario, the midpoint of total runoff advances about 50 days.

PERCENT OF TOTAL RUNOFF BY MONTH

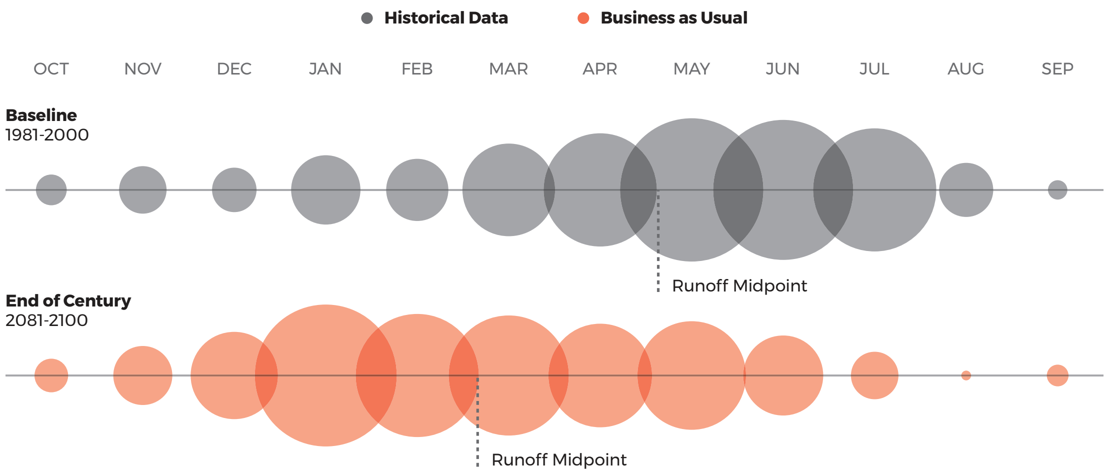
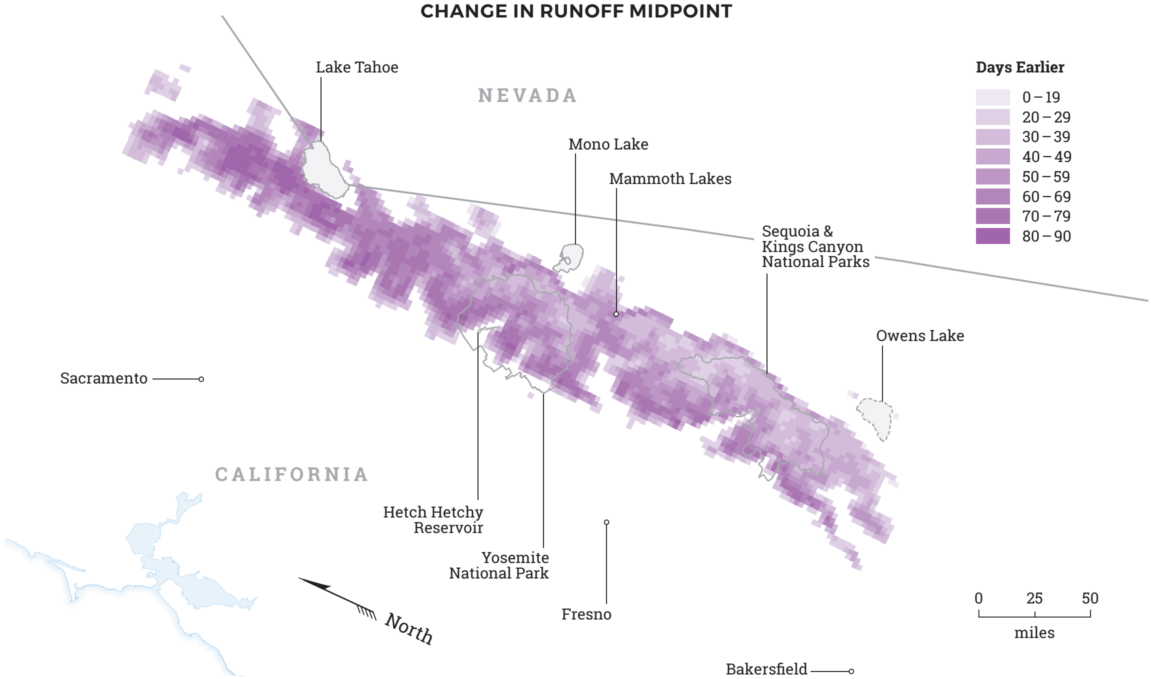


FIGURE 11

Business-as-Usual Runoff Advance, 2081–2100

This map shows the shift in runoff midpoint at 2081–2100 under Business as Usual, compared with 1981–2100. The unit shown is the number of days by which the timing shifts; for example, 50 days means the midpoint occurs 50 days earlier in the year.

CHANGE IN RUNOFF MIDPOINT



CASE STUDY

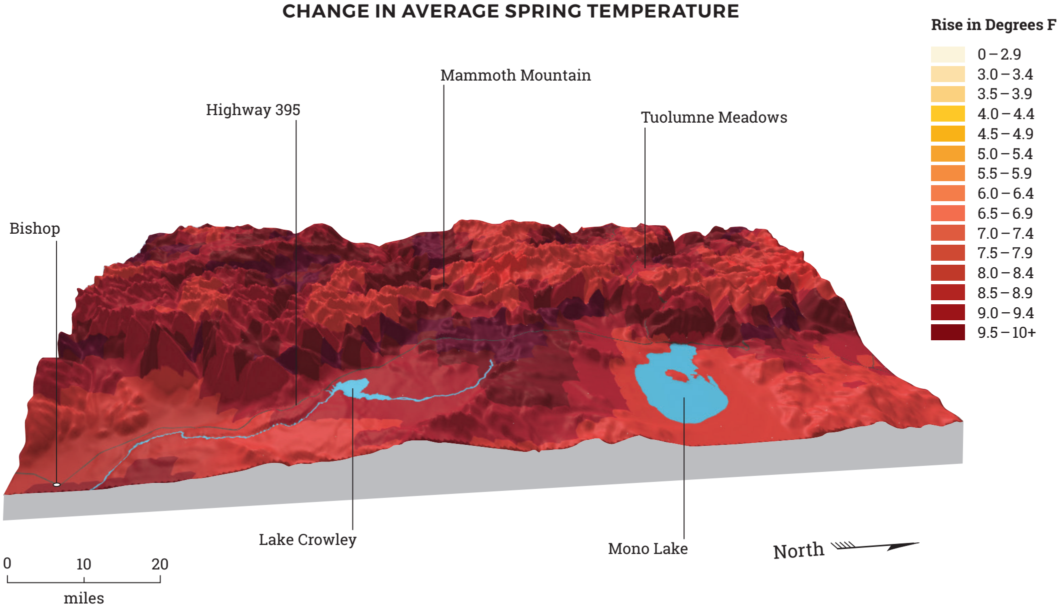
Eastern Sierra Watersheds

FIGURE 12

Business-as-Usual Warming, 2081–2100

This map shows the change in average 24-hour temperatures, in degrees Fahrenheit, for March–May at end-of-century. Warming is greatest at elevations between 5,000 and 8,000 feet, where snow albedo feedback is occurring.

CHANGE IN AVERAGE SPRING TEMPERATURE



In most of this report, we discuss our findings over our Sierra study domain as a whole. But one of the major advantages of high-resolution projections is that we can use them to understand climate change on even smaller scales. For many applications, it may be more useful to consider climate change impacts on a watershed-by-watershed basis. Looking at individual watersheds can help us understand how climate change could affect specific parts of our water resource infrastructure, such as a particular reservoir.

As an example of the kind of detail our projections can provide, here we zoom in on part of Eastern Sierra. In terms of water resources, Eastern Sierra watersheds are important because they:

- *Provide water to Mono Lake and communities throughout the Owens Valley.*
- *Are the source of the water that is used to control dust pollution in the Owens Valley, particularly in the mostly dry bed of Owens Lake.*
- *Feed the Los Angeles Aqueduct, which in an average year provides about one-third of Los Angeles's water.*

Quantifying the changes in Eastern Sierra watersheds can help water managers understand how much water from snowpack will be available in the future for these competing uses, and when in the year it will flow into manmade water infrastructure. Understanding these changes is the first step to adapting to a changing climate.

FIGURE 13

Business-as-Usual Snowpack, 2081–2100

This map depicts the percentage of average April 1 snow water equivalent projected to be lost by 2081–2100 under Business as Usual greenhouse gas emissions, compared with the historical period (1981–2000).

CHANGE IN APRIL 1 SNOW WATER EQUIVALENT

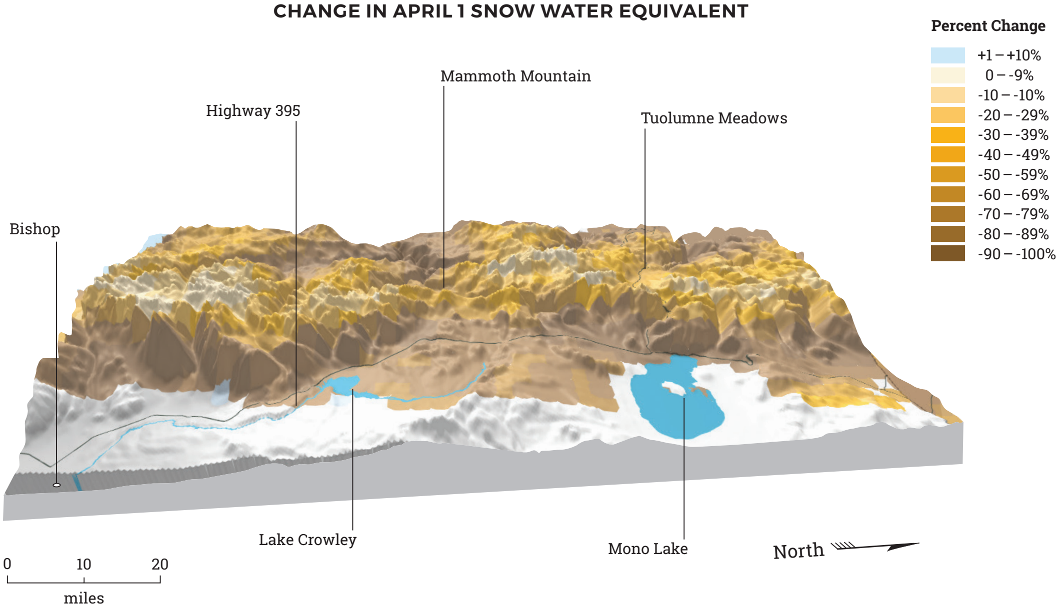
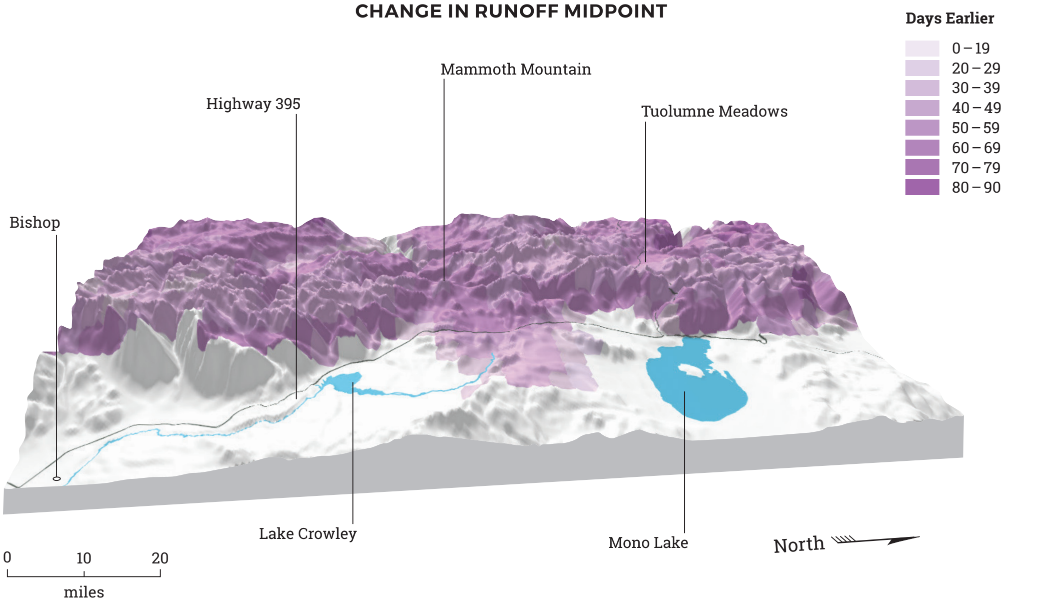


FIGURE 14

Business-as-Usual Runoff Advance, 2081–2100

This map shows the shift in runoff midpoint at 2081–2100 under Business as Usual, compared with 1981–2000. The unit shown is the number of days by which the timing shifts; for example, 50 days means the midpoint occurs 50 days earlier in the year.

CHANGE IN RUNOFF MIDPOINT



Business as Usual is the path we're on, but it isn't a foregone conclusion. Cutting greenhouse gas emissions can mitigate end-of-century impacts.

6

How much could mitigation help?

So far in this report, we've focused on the Business as Usual scenario, in which greenhouse gas concentrations keep rising throughout the century. Although this is the path the world is currently on, it's only one of many possible futures. Under the United Nations Framework Convention on Climate Change, most countries are working to reduce their greenhouse gas emissions.

For this reason, we also wanted to look at a scenario in which greenhouse gas concentrations were substantially reduced. By comparing such a scenario to Business as Usual, we can measure the benefits of global efforts to reduce greenhouse gas emissions. We nicknamed our lower-emissions scenario "Mitigation," hypothesizing that it would mitigate climate change impacts. (For more about what the Mitigation scenario entails, see page 29.)

Across all the climate change impacts we assessed, we confirmed this hypothesis. At end-of-century under Mitigation, warming still occurs, but is less severe. Figure 15 compares the change in average springtime (March–May) temperature between the two scenarios. Under Business as Usual, the average springtime is more than 7 degrees hotter than in the historical period. Under Mitigation, it is only about 4 degrees hotter.

Another way to look at future averages is to compare them with the full range of springtime averages from the historical period, which is shown in Figure 15 with gray shading. During that period's warmest springtime, temperatures averaged 53 degrees. In the Mitigation scenario, the average end-of-century springtime is just under 52 degrees, within the range of historical variability. But under Business as Usual, the average springtime, at more than 55 degrees, is warmer than the warmest springtime in the historical period, marking a pronounced change in overall climate.

As with temperature, snow loss still occurs under Mitigation, but is less severe. At end-of-century under Mitigation, the reduction in snow-covered area is about half that under Business as Usual. In addition, less total snow volume is lost. As shown in Figure 16, at end-of-century under Mitigation, snowpack volume at April 1 is 70% of what it was during 1981–2000 — a great improvement over the 36% left in the Business as Usual scenario.

Finally, runoff timing doesn't shift as much under Mitigation as under Business as Usual. Under Mitigation at end-of-century, the date of the runoff midpoint advances an average of 25 days, compared with 50 days under Business as Usual.

The differences between Mitigation and Business as Usual at the end of the century are substantial, and they indicate that cutting global greenhouse gas emissions can lessen the impacts of climate change in the Sierra.

Key Points

- At 2081–2100, marked differences are seen between Business as Usual and a Mitigation scenario of global greenhouse gas emissions cuts.
- In the Mitigation scenario, changes to temperature, snowpack, and runoff timing are half of what they are under Business as Usual.

FIGURE 15

Future Warming Scenarios

By 2081–2100, average March–May temperatures rise substantially more under Business as Usual than under Mitigation. Baseline shading shows full range of historical average spring temperatures; future error bars show range of outcomes across global climate model projections.

AVERAGE SPRING TEMPERATURE

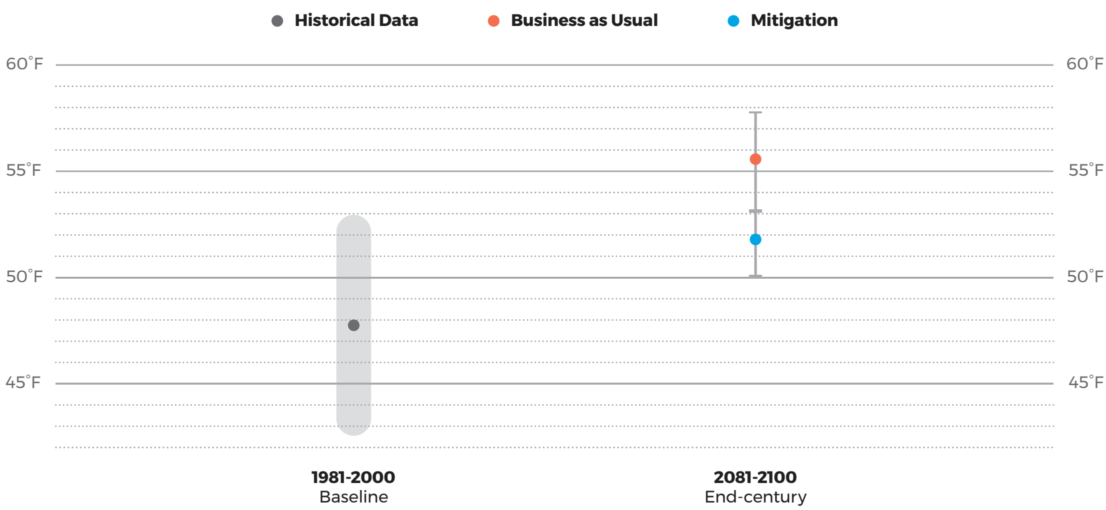
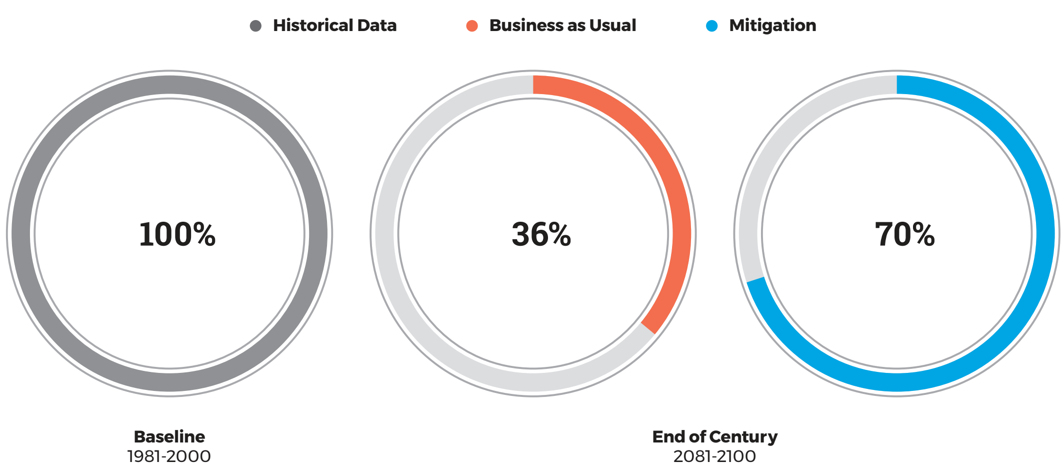


FIGURE 16

Snowpack Depletion Scenarios

At end-of-century, snowpack losses are less severe in the Mitigation scenario than in Business as Usual. In the average year during 2081–2100 under Mitigation, snowpack volume on the average April 1 is 70% of what it was during 1981–2000.

PERCENT OF SNOW VOLUME REMAINING



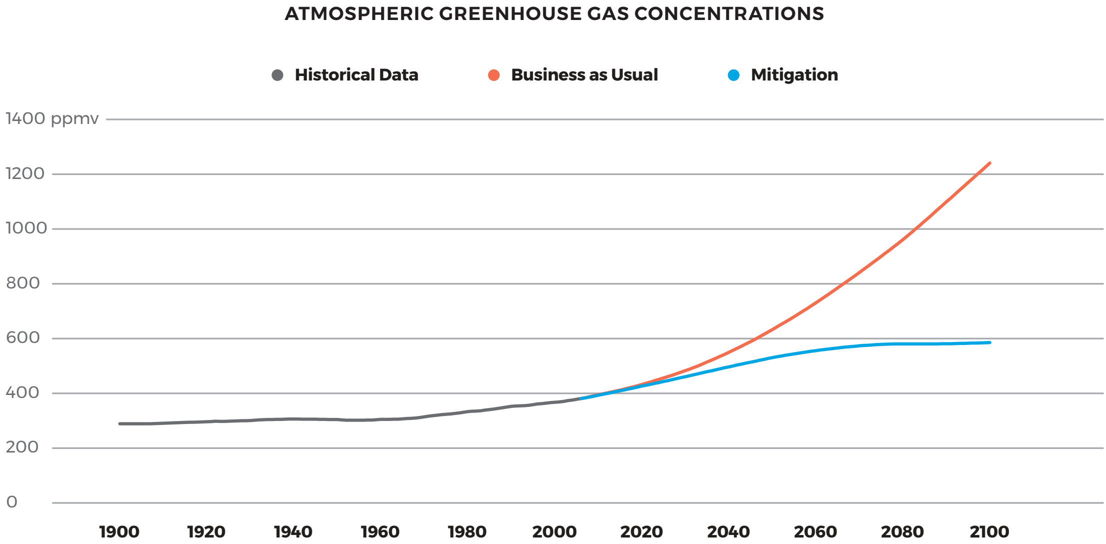
CONCEPT SPOTLIGHT

The Meaning of "Mitigation"

FIGURE 17

Possible Climate Futures

In our Business as Usual scenario, atmospheric greenhouse gas concentrations (shown here in parts per million) keep rising. In Mitigation, which approximates the goals of the 2015 Paris Agreement, concentrations keep rising through mid-century, then level off.



We highlight the difference that a Mitigation pathway could make in curbing climate change impacts. But what is "Mitigation"?

When it comes to cutting global greenhouse gas emissions, there are so many different possible outcomes, it's difficult to predict how it will all play out. For this reason, climate researchers develop standardized scenarios of greenhouse gas concentrations over time so that results can be compared across studies.

We used scenarios created for the United Nations (UN) Intergovernmental Panel on Climate Change's 5th Assessment Report. Called Representative Concentration Pathways (RCPs), these scenarios are assigned numbers based on how much extra radiative energy accumulates in the atmosphere due to greenhouse gas buildup.

There are four RCPs, and we assessed all of them. In this report, we focus on two. RCP8.5 is our Business as Usual scenario, and it is the path the world is currently on. RCP4.5 is our Mitigation scenario; it's the most aggressive scenario of greenhouse gas reductions that we deem at all likely.

RCP4.5 also comes close to matching the goals of the 2015 Paris Agreement — in which all 195 parties to the UN Framework Convention on Climate Change agreed to set greenhouse gas reductions targets. The Paris Agreement's goal is to keep the rise in average global temperatures under 3.6 degrees Fahrenheit, and the estimated global warming under RCP4.5 ranges from 2 to 4.7 degrees. It isn't an exact match, but it's close enough that we think of Mitigation as a rough equivalent to a successful implementation of the Paris Agreement.

An investigation of how recent extreme events would have played out under different scenarios shows that climate change is already affecting Sierra snowpack.

7

What's different in extreme years?

In most of our project, we focused on changes in climate averages: average springtime temperatures, snowpack at April 1st, and timing of runoff. Looking at future averages is a useful way to measure overall change. But some of the most important climate change adaptation questions are related to extremes, such as very dry and wet years. Extremes pose great challenges to water managers: In times of drought, they must try to make water supplies last, and during very wet years, they must try to prevent flooding.

Our research design did not allow us to assess whether droughts and wet extremes would become more common in the future (although that is the focus of another Center project; see page 47). But we realized we could look at recent examples of extreme periods to see how climate change affected them and will affect events like them in the future. In other words, we could run a set of climate model experiments to ask a series of hypothetical questions:

- How would these events have played out if there were no such thing as human-caused climate change?
- How would they play out if they occurred at end-of-century under Business as Usual? Or under Mitigation?

We ran just such a set of experiments for two recent extreme periods: the drought years of 2011–2015 and the wet year of 2016–2017.

Our findings on the 2011–2015 drought are shown in Figure 18. When we compared the snowpack that actually occurred (gray line) to a "natural" simulation with no human-caused warming (purple line), we found the actual snowpack was 25% smaller than it would have been without climate change. The same exercise for the 2016–2017, shown in Figure 19, tells a similar story: 2016–2017 snowpack levels were 20% lower than they would have been with no human-caused warming. In addition, early season runoff was 30% greater than it would have been (not pictured). These results tell us that climate change is already affecting the Sierra snowpack. Warmer temperatures are turning snow events to rain events and melting snow faster.

We also found that climate change's effect on snow during extreme years will intensify in the future. As shown in Figure 18, if a drought like 2011–2015's occurred at end-of-century under Business as Usual warming, snowpack would be reduced by 85%. If it occurred under Mitigation-level warming, the decrease would be 60%. Figure 19 shows that if a wet year like 2016–2017 occurred at end-of-century, snowpack would be reduced by two-thirds under Business as Usual and one-third under Mitigation.

Key Points

- Climate change is already affecting Sierra snow. Snowpack during 2011–2015 was 25% smaller than it would have been without human-caused warming. 2016–2017 snowpack was 20% smaller.
- Future climate change will cause even greater reductions in snowpack in extreme years. Under end-of-century Business as Usual warming, a period like the 2011–2015 drought loses 85% of its snow, and a wet year like 2016–2017 loses two-thirds of its snow.

FIGURE 18

Impact of Climate Change on Drought Snowpack

This graph shows average Sierra snowpack during 2011–2015 as it actually occurred (gray line), as it would have occurred without climate change (purple line), and as it would occur at 2081–2100 under Business as Usual (red line) and Mitigation (blue line).

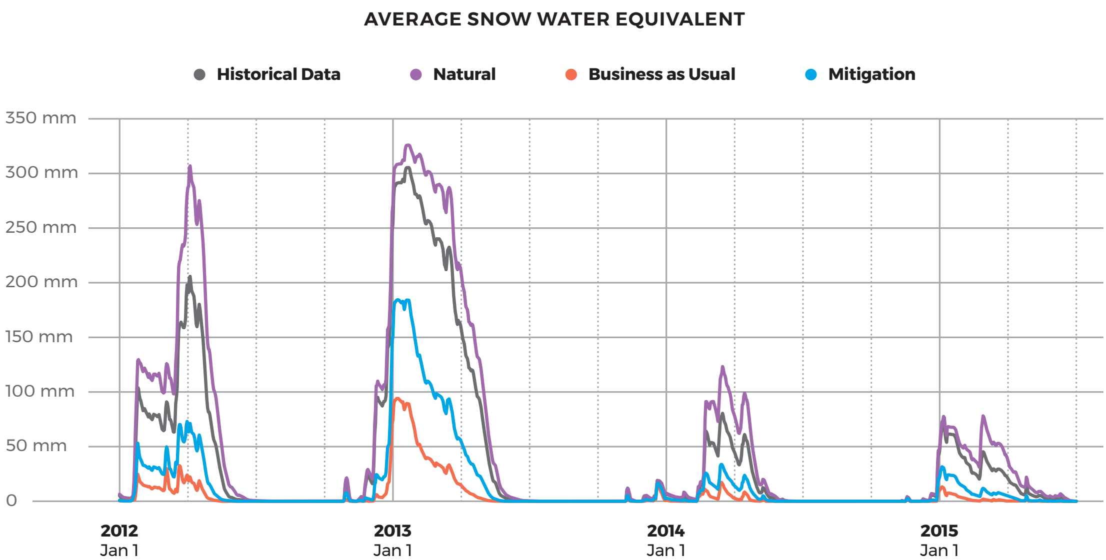
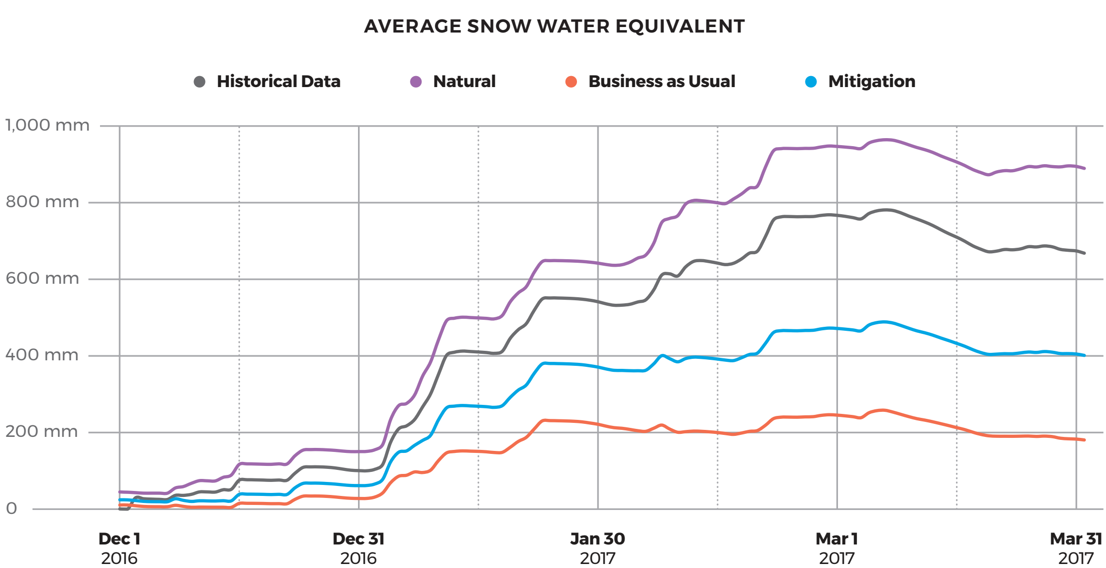


FIGURE 19

Impact of Climate Change on Wet Year Snowpack

This graph shows average Sierra snowpack during 2016–2017 as it actually occurred (gray line), as it would have occurred without climate change (purple line), and as it would occur at 2081–2100 under Business as Usual (red line) and Mitigation (blue line).



We don’t have to wait for the end of the century to feel climate impacts. Climate change is affecting Sierra snow now, and these effects will increase in coming decades.

8

When will we feel the effects?

Throughout this report so far, we have focused on future climate at the end of this century. That can seem awfully far away, and it's true that many of the readers (and writers) of this report may not live to see that time period. However, our children, grandchildren, or succeeding generations will. And although the distance between now and 2100 feels long in human terms, it's quite short in climate terms. The climate system takes time to respond to changes in emissions of greenhouse gases, and if we want to change our path and protect future generations from the worst impacts of climate change, the time to act is now.

But our focus on end-of-century doesn't mean we won't feel climate change impacts sooner. In fact, as we've shown in our analysis of extreme years on pages 31–33, climate change is already affecting Sierra snowpack. Hypothesizing that influence will become greater over the next few decades, we looked at a second future period of 2041–2060 to see what changes are in store in the relatively near term.

Our findings on warming are summarized in Figure 20. At mid-century, average springtime temperatures over the Sierra rise by about 4 degrees Fahrenheit under the Business as Usual scenario. In the Mitigation scenario reflecting global greenhouse gas emissions cuts, average springtime temperatures increase by about 3 degrees. The similarity of the two scenarios at mid-century reflects the fact that there are lags in the climate system; it takes some time for previous greenhouse gas emissions to take effect.

A similar story is told in our findings on snowpack change, as shown in Figure 21. At mid-century under the Business as Usual scenario, April 1 snowpack is just 70% of what it was in 1981–2000. Under the Mitigation scenario, 80% of the snowpack remains. That's an improvement over Business as Usual, but it still represents a significant change that California will have to figure out how to address.

That the two scenarios are similar at mid-century but diverge greatly at the end of the century gives us a clear message: Both mitigation and adaptation are necessary. We still have the ability to avoid the worst projected climate change impacts if we choose the Mitigation pathway. But in the meantime, there are some climate change impacts to which we are committed and must adapt. Cutting greenhouse gas emissions and adapting to climate change are not mutually exclusive. We need to do both.

Key Points

- At 2041–2060 under Business as Usual, the Sierra will warm by 4 degrees on average and lose 30% of its April 1 snowpack.
- The Mitigation scenario is only slightly better: the region warms by 3 degrees and 20% of April 1 snowpack is lost.
- We are committed to some climate change impacts no matter what greenhouse gas emissions pathway the world chooses, and we need to adapt.

FIGURE 20

Future Warming Scenarios, Mid- and End-of-Century

This graph shows springtime (March–May) warming averaged over the study domain. At mid-century, Business as Usual and Mitigation show similar degrees of warming. At end-of-century, the outcomes diverge.

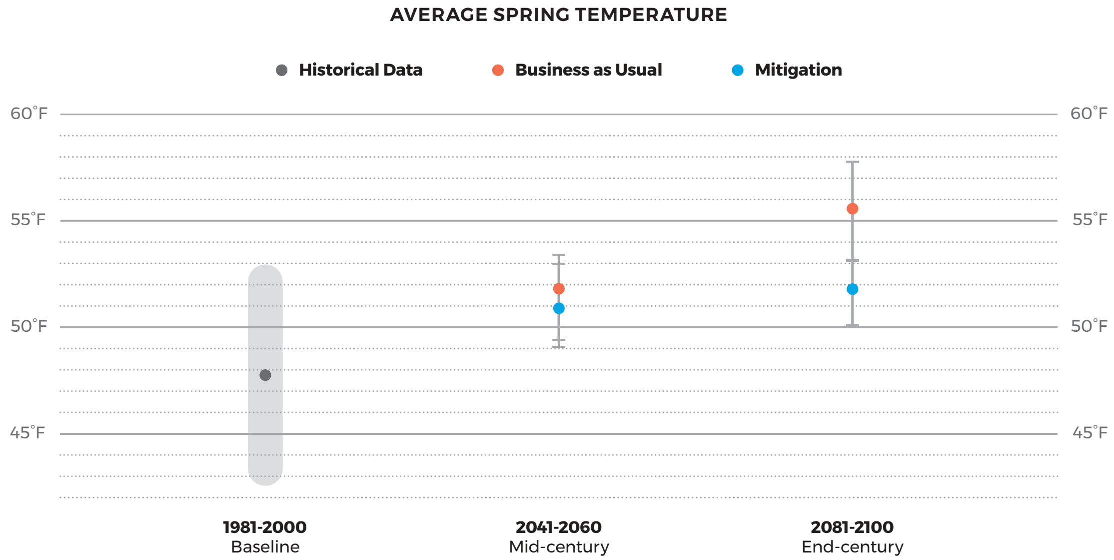
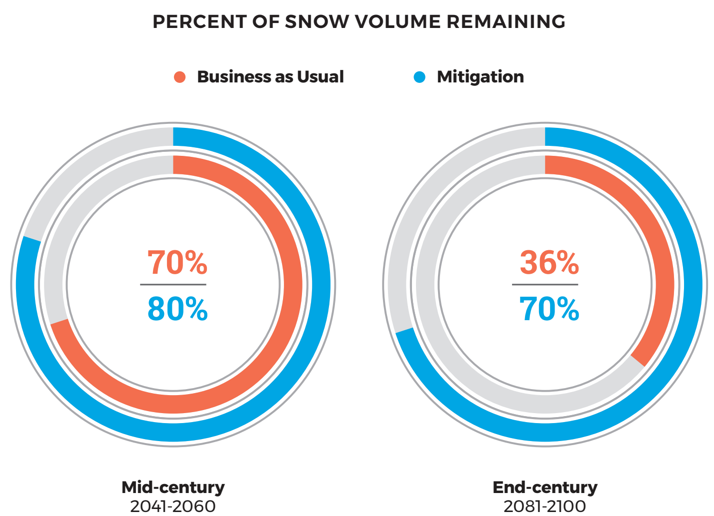


FIGURE 21

Snowpack Depletion Scenarios, Mid- and End-of-Century

These rings show the volume of baseline (1981–2000) April 1 snowpack that remains in our two future periods and under our two different greenhouse gas scenarios. At end-of-century, the scenarios differ markedly. At mid-century, they are similar.



Climate change can feel like an insurmountable problem. But there is a lot we can do now to make a big difference.

9

What can California do?

Our findings about the future of Sierra Nevada snowpack give us two main messages. First, we must contribute to a global effort to reduce greenhouse gas emissions so that we can avoid the most dramatic changes projected. Second, some climate change impacts are inevitable, and we must adapt to them. As climate scientists, we don't have all the answers about the best ways to accomplish these goals. But we do have some basic ideas that can get the conversation about our climate future started — and get you thinking about ways to pitch in.

What our State and local governments can do

Fortunately, California is tremendously engaged when it comes to preventing and preparing for climate change impacts. The state has set a goal to reduce greenhouse gas emissions by 2030 to 40% below 1990 levels, and is achieving these cuts through a cap-and-trade program that provides financial incentives for emitters to cut back.

When it comes to water-related adaptation issues, however, there's more work to be done. California's highly engineered water system, with its more than 1,400 dams, unfortunately isn't very nimble; it takes time and a lot of money to build new infrastructure. And it's highly questionable whether building new dams to make up for some fraction of the surface storage lost with snowpack would make environmental or economic sense. For one thing, dams cause a lot of environmental damage; for other, there aren't many spots left to put them. In the Western Sierra, for example, every river but one is already dammed. Remaining potential sites are where it's more expensive to build, relative to how much water could be gained.

But underground storage is another possibility. One idea is to divert Sierra storm water to open fields where it can infiltrate into groundwater aquifers. An approach like this could have multiple benefits, recharging groundwater that's been unsustainably overdrawn and restoring some of the vast wetland area that has been lost in the Central Valley. There are currently many challenges to such an approach, including water rights issues, but it has the potential to yield more storage capacity than new surface reservoirs.

For the far-flung coastal communities that currently depend on Sierra water, another common-sense approach is to make better use of local water supplies. In Los Angeles, for example, most local rainfall — enough to meet up to half of the city's water demand — washes out to the ocean, unused. Local storm water capture, water recycling, and conservation would lessen cities' dependence on Sierra water and thus increase their resilience to changes to snowpack.

What we can do in our communities

Since climate change is occurring on a global scale, it can seem as though individual actions wouldn't make much difference. But actions taken by large numbers of individuals do add up. And by modeling climate-friendly practices, you can influence your family, friends, and neighbors in a positive direction. Here are some suggestions to get you started.

Learn where your water comes from. Before reading this report, you may not have given much thought to the origin of your tap water. But chances are, it was some part of the Sierra. San Franciscans get much of their water from the Tuolumne River. Central Valley cities get Sierra water via the Central Valley Project. Sierra water comes to Los Angeles via the State Water Project and the Los Angeles Aqueduct. Realizing your connection to your water sources is the first step toward becoming a better advocate for your water future. Visit www.watereducation.org/aquapedia and click on "Where does my water come from?"

Save water and energy at home. By making your home more water- and energy-efficient, you can contribute to better water resilience in your community, lower your carbon footprint, and save on utility bills. Check with your local utility about energy efficiency upgrade programs and rebates on efficient appliances. Consider installing a rainfall capture and/or gray water system to provide water for outdoor uses. And, importantly, consider a switch to native, drought-tolerant landscaping. In Los Angeles, more than half of residential water use goes toward outdoor watering, mainly of lawns. Turf grass is not adapted to our hot summers, so it needs a lot of water. Native gardens not only save water, but they also provide habitat for local wildlife. A great resource for learning more about native plants is the Theodore Payne Foundation: www.theodorepayne.org.

Take advantage of transportation alternatives. The biggest chunk of California's greenhouse gas emissions comes from our cars. A simple way to emit less is to drive less. When possible, take public transit, and for shorter trips, consider walking or biking. If you're in the market for a new car, consider going electric.

Talk about climate change. According to research from the Yale Program on Climate Change Communication, more than 60% of Americans think climate change is important, but only 30% talk about it with people they know. It's difficult to solve climate change problems if people aren't talking about them. Your government representatives need to hear from you as well. Politicians track calls to their local offices to gauge what issues are important to voters. Signal your support for climate change mitigation and adaptation measures in your community via phone, social media, and your votes.

New knowledge needed

In this project, we focused on climate change impacts in the Sierra from a water resources perspective. We chose to look through this lens because Sierra water is used by so many people and industries across California. But water resource challenges are far from the only impact that changes to Sierra snowpack will have. Ecosystems that depend on snowpack are likely to be harmed by the changes. For example, earlier snowmelt and warming-enhanced evaporation can dry soils, which could lead to vegetation changes. Hotter, drier conditions can contribute to tree death and increase wildfire risk. In addition, snow loss could threaten skiing, fishing, and other recreation in the Sierra, as well as the local economy that depends on it. All of these areas merit further study to understand future impacts and what can be done about them.

Our research method has the advantage of incorporating physical climate processes that other methods of downscaling miss.

10

What went into this research?

In this report, we've described future Sierra Nevada climate projections that we created using a special technique we developed called hybrid downscaling. Here, we want to provide some more information about our project methodology's advantages and caveats. For more detail, please refer to our scientific papers, listed on page 50.

Advantages

With most downscaling techniques, researchers have to make a choice between physical credibility — that is, the ability of the model to capture important regional climate phenomena that are not well represented by global climate models — and comprehensiveness. If they use dynamical downscaling for physical realism, they cannot practically downscale more than a few of the three dozen global climate models available. But if they choose a technique that allows them to look at many global climate models in the same study, it's often because they are using statistical downscaling methods that don't take physical phenomena into account.

In hybrid downscaling, we combined both dynamical and statistical downscaling so that we would not have to choose between physical realism and comprehensiveness — we could have both. First, we ran a limited set of dynamical climate projections using a high-resolution regional climate model, and then using the relationships we observed between the coarse-resolution data and the fine-resolution data, we developed a statistical model that could mimic the regional climate model. We then used that statistical model to downscale the remaining global climate models.

An important strength of our statistical model is that it explicitly accounts for snow albedo feedback, a cycle of warming and snow cover loss that can greatly affect projections of snowmelt. (For more about snow albedo feedback, see page 14.) Incorporating this feedback allowed us to capture enhanced warming between the elevations of 5,000 and 8,000 feet, and as a result, enhanced changes to snow volume and runoff timing at the same elevations.

This is detail that other downscaling methods can miss. In Figure 22, we compare our results on the change in runoff timing to two statistical downscaling methods: Bias Correction and Spatial Disaggregation (BCSD) and Bias Correction Constructed Analogs (BCCA). Because hybrid downscaling incorporates snow albedo feedback, it shows greater changes in runoff timing between 5,000 and 8,000 feet. BCSD and BCCA miss the extra warming at these elevations and therefore underestimate the resulting enhanced shift in runoff timing.

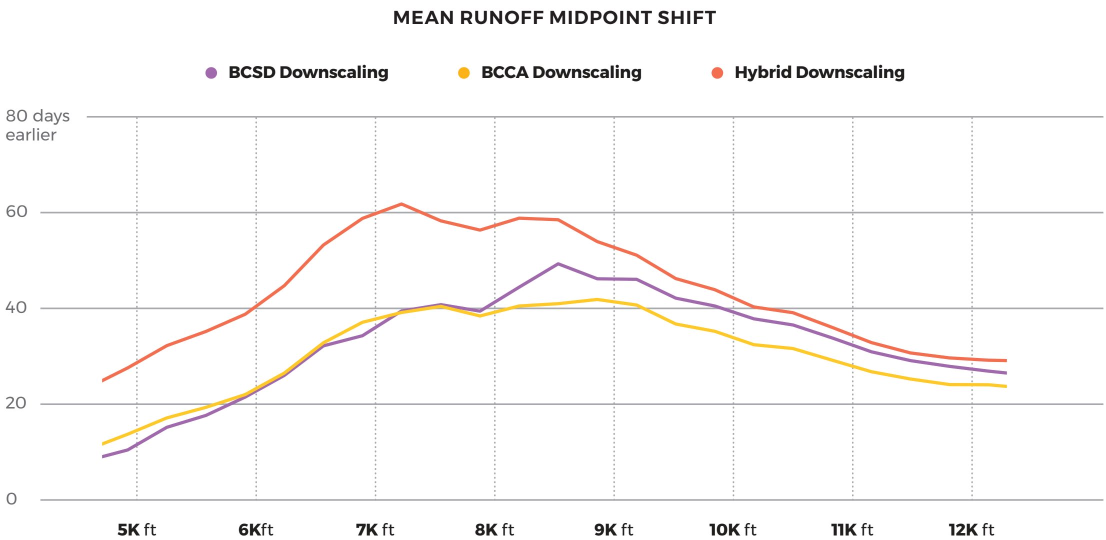
Caveats

One potential downside of any downscaling study is that the results are only as credible as the global climate model outcomes used in the downscaling exercise. Different global climate models have different ways of representing certain climate phenomena, and therefore produce a range of outcomes in their projections. To account for the full outcome range, we downscaled all available latest-generation global climate models. The climate change values that we show in this report are the average of all these outcomes, a value called the ensemble-mean.

FIGURE 22

Measures of Runoff Timing by Elevation, End-of-Century

This figure compares our hybrid downscaling method's projections of 2081–2100 Business as Usual runoff timing change to those shown by two other methods. Since hybrid downscaling captures snow albedo feedback, it shows greater shifts at elevations of 5,000–8,000 feet.



When it comes to precipitation changes over California, some global climate models are thought to represent relevant climate phenomena better than others. We did not rule out global climate models deemed to perform less well or give extra weight to those deemed to perform better. Researchers preparing downscaled climate data for the upcoming California 4th Climate Change Assessment selected a subset of global climate models because they were found to simulate aspects of California precipitation best. We compared the mean values from this subset to our ensemble-mean, and found them to be similar.

A limitation of our project is that our methodology does not allow us to assess changes in the frequency of precipitation extremes. Our regional climate model simulations are representations of how the historical period would have been different if the background climate were altered to reflect the climate change signals shown in the global climate model projections. As a result, year-to-year variability in our future simulations is similar to that in our baseline simulation; we do not capture changes in this variability. In other words, from this work we cannot say whether droughts and floods will become more common in the future. However, this is the subject of an ongoing Center project. (See page 47 for more on this.)

Finally, we should note there is great uncertainty about future greenhouse gas emissions. The Business as Usual and Mitigation scenarios are two possible futures, and Business as Usual is the path we're currently on. Whether countries meet their commitments under the Paris Agreement will determine whether we stay on the Business as Usual path, move to Mitigation, or land somewhere in between.

Project Team

Alex Hall, PhD

Director
UCLA Center for Climate Science,
Institute of the Environment
and Sustainability

Neil Berg, PhD

Associate Director, Science
UCLA Center for Climate Science,
Institute of the Environment
and Sustainability

Fengpeng Sun, PhD

Assistant Professor
Department of Geosciences,
University of Missouri–Kansas City

Xingying Huang, PhD

Postdoctoral Scholar
UCLA Center for Climate Science,
Institute of the Environment
and Sustainability

Daniel Walton, PhD

Postdoctoral Scholar
UCLA Center for Climate Science,
Institute of the Environment
and Sustainability

Marla Schwartz, PhD

Atmospheric Perils Specialist
Swiss Re

Katharine Davis Reich, MA

Associate Director, Strategic Planning and Communications
UCLA Center for Climate Science,
Institute of the Environment
and Sustainability

Ongoing Center projects are answering critical questions about fire, extreme precipitation, and other aspects of our climate future.

11

What's next for the Center?

Our Center at UCLA focuses on building interdisciplinary research collaborations to answer societally relevant questions about climate change. We also engage the public and other stakeholders so we can take charge of our climate future. Described below are some of the exciting projects we currently have under way.

To learn more about our work and stay up to date on our research progress and findings, visit our website at www.ioes.ucla.edu/climate. To sign up for our mailing list, click on "Get Involved."

The Future of California Drought, Fire, and Forest Dieback

From 2011 to 2015, California experienced a drought of historic severity. It was bracketed by two very wet years in 2010 and 2016, and accompanied by unprecedented tree death and wildfire in California's wildlands. As a result, the 2017 fire season was one of the worst in modern history. The potential for climate change to make such conditions more common raises critical questions: Are the recent extreme forest dieback and fire conditions a harbinger of even greater future changes? What do future changes mean for California's unique ecosystems, forest and fire management practices, and economy?

To study these questions, we recently won a large grant from the University of California Laboratory Fees Research Program and are leading a large collaboration that includes UC Berkeley, UC Davis, UC Irvine, UC Division of Agriculture and Natural Resources, Los Alamos National Laboratory, and Lawrence Berkeley National Laboratory. We're using climate, vegetation, and fire observations and models to explore the impact of climate change on drought, forests, and fire risk, how these changes interact with and exacerbate one another, and what can we do to prepare.

The project will produce first-of-their-kind climate, vegetation, and fire simulations that will deepen our understanding of the complex interactions within California's wild lands, as well as a modeling framework that can be easily applied to other regions. The results will help stakeholders plan effective climate change adaptation and mitigation, and our outreach efforts will educate the public about climate change impacts on the treasured lands and resources they depend on.

The Future of Extreme Precipitation in California

In this project, funded by the UCLA's Sustainable LA Grand Challenge, the Nature Conservancy's NatureNet Science Fellows program, and the US Department of Energy, we are investigating the effects of climate change on heavy precipitation events in the state. Specifically, we're focusing on ***atmospheric rivers***, moisture-laden filaments of air that move across oceans and can produce heavy precipitation when they make landfall. California's atmospheric rivers are responsible for most of the state's heavy rains and mountain snowfall.

Managing water resources in California's feast-or-famine climate is already challenging, but climate change promises to make it even more so. Projections from global climate models — the computer simulation tools that inform the Intergovernmental Panel on

Climate Change's scientific assessments — lead us to expect that future precipitation in California will change. However, it's unlikely the biggest change will be in overall ***amount*** of precipitation the state gets. Instead, it's thought the ***character*** of precipitation will change, with more intense atmospheric rivers and longer dry spells between them.

For water managers to be able to plan for these changes, we need to better understand how they will play out in California. That starts with answering questions about how climate change will affect the intensity, frequency, and seasonality of atmospheric rivers. With a powerful combination of expertise in global and regional climate modeling, the global hydrologic cycle, and regional atmospheric dynamics, our team is uniquely equipped to analyze atmospheric rivers in global climate model simulations — and importantly, to understand the physical reasons for changes in atmospheric rivers. In addition, we've pioneered techniques for creating highly detailed, physically realistic climate change projections from global climate model output. We'll use that expertise to quantify changes to heavy precipitation on the local scales that are most relevant to water resource managers.

Los Angeles Regional Climate Change Assessment

Since 2006, the State of California has undertaken periodic scientific assessments with the goal of understanding future climate change impacts on the state. For the first three such assessments, released in 2006, 2009, and 2012, a portfolio of research projects investigated climate change impacts, and the assessment report described the results of these studies. The upcoming 4th California Climate Change Assessment, due out in summer 2018, will include a new element: regionally focused assessments that survey the scientific literature and summarize the state of knowledge about climate change impacts in the region.

Our Center is honored to be leading the Los Angeles Region chapter of the regional assessments. Coordinating lead author Alex Hall is convening an expert author panel to report on climate impacts to water, energy, transportation, public health, environmental justice, agriculture, ecosystems, and a host of other sectors. With regional stakeholder input, the authors will summarize the state of the science on observed and modeled climate change, what it means for people and natural systems, and what is being done to adapt. The report will also identify knowledge gaps and opportunities for further research to answer critical questions.

12

References and Acknowledgements

References

More detail about the research described in this report can be found in the following scientific journal articles.

Berg N and A Hall, 2017: Anthropogenic warming impacts on California snowpack during drought. *Geophysical Research Letters*, 44(5), 2511–2518. DOI: 10.1002/2016GL072104

Huang, X, A Hall, and N Berg, 2018: Anthropogenic warming impacts on today's Sierra Nevada snowpack and flood risk, *Geophysical Research Letters*, under review.

Schwartz M, A Hall, F Sun, DB Walton, and N Berg, 2017: Significant and inevitable end-of-21st-century advances in surface runoff timing in California's Sierra Nevada. *Journal of Hydrometeorology*, 18(12): 3181–3197. DOI: 10.1175/JHM-D-16-0257.1

Sun F, A Hall, M Schwartz, N Berg, and DB Walton, 2018: Almost inevitable end-of-century loss of spring snowpack over California's Sierra Nevada. *Geophysical Research Letters*, conditionally accepted.

Walton DB, A Hall, N Berg, M Schwartz, and F Sun, 2017: Incorporating snow albedo feedback into downscaled temperature and snow cover projections for California's Sierra Nevada. *Journal of Climate*, 30(4): 1417-1438. DOI: 10.1175/JCLI-D-16-0168.1

Funding Acknowledgements

Funding support for this project was provided primarily by the Metabolic Studio in partnership with the Annenberg Foundation (Grant 12-469; "Climate Change Projections in the Sierra Nevada"). Additional support was provided by the National Science Foundation (Grant EF-1065853, "Collaborative Research: Do Microenvironments Govern Macroecology?") and the US Department of Energy (Grant DE-SC0014061, "Developing Metrics to Evaluate the Skill and Credibility of Downscaling," and Grant DE-SC0016605, "An Integrated Evaluation of the Simulated Hydroclimate System of the Continental US"). Funding for the design of the graphics contained in this report and public talks conducted by Dr. Alex Hall about this work was provided by the 2015 UC Climate Action Champion Award, part of the University of California Office of the President's Carbon Neutrality Initiative.

Special Thanks

We would like to thank Lauren Bon of the Metabolic Studio for providing the initial funding that made this project possible, and Jonathan Parfrey for early conversations that established the need for and direction of this work.

We wish to express our gratitude to our supporters for believing in our Center's mission and contributing to our day-to-day operations.

Finally, we would like to acknowledge the work of our talented graphic designers: Rebecca Hume, who created the infographics and report design, and Bart Wright of Lohnes + Wright, who created the geospatial visualizations. See more of their work at www.rebeccaaviva.com and www.lohneswright.com.

Photo credits:

pages 4–5: Snow Margin at White Mountain Research Center, ©UCLA

page 48: FEMA Photo Library, Photo by Andrea Booher

UCLA Center for Climate Science

www.ioes.ucla.edu/climate