

Future Climate, Hydrology, Vegetation, and Wildfire Projections for the Southern Sierra Nevada, California

**A climate change synthesis in support of Integrated
Regional Water Management Planning**

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GEOS
INSTITUTE

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Water Management Planning**

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EXECUTIVE SUMMARY

Broad scale changes in climate are already impacting local conditions across the West and are likely to continue and accelerate in the coming decades. Changes include the timing and availability of water, changes in tree and wildlife species, and changes in wildfire frequency and intensity.

Local communities will need to plan for such changes in order to continue to provide vital services to local residents and to support the economy. Integrating climate change science into water management planning is one step towards preparing people for climate change.

In support of Integrated Regional Water Management Planning for the Southern Sierra, we compiled climate change projections based on two global climate models, downscaled to reflect local conditions. We assumed the A2 “business-as-usual” emissions scenario. If emissions are reduced, mid-century projections may be stabilized. If emissions continue unabated, late-century projections become highly likely.

In this report, we provide a review of historic and future expected trends in temperature, precipitation, snowpack, water deficit, runoff, vegetation, wildfire, and carbon storage in vegetation. It is important to consider these model projections as two potential outcomes among many other possibilities. While one model is on

the warmer and drier end of the range of available models, and the other is on the less warm and wetter end of the range, there are still many other possible climate trends for the Southern Sierra. Unfortunately, continued historic climate conditions are highly unlikely.

Overall, managers in the Southern Sierra can expect warmer temperatures, declining snowpack, a dramatic shift in timing for runoff, and shifts in major types of vegetation. Changes in precipitation and wildfire patterns are also likely.



PROJECTIONS

Temperature – Average annual temperature in the Southern Sierra is expected to rise about 2° C (4° F) by mid-century and 3-4° C (5-7° F) by late century. Summer temperatures are expected to rise slightly more (4-6° C; 7-13° F) than winter temperatures (3-4° C; 5-7° F) by the end of the century.

Precipitation – Precipitation projections were more variable than temperature projections, with both increases and decreases in precipitation possible throughout the year. Even with increases, however, drier conditions are expected due to greater evaporation and evapotranspiration.

Runoff – The hydrograph for runoff is expected to change dramatically, with greater runoff Jan-April, as precipitation increasingly falls as rain instead of snow, and lower runoff May-September. Variation between the two models resulted in uncertainty in projections, with annual average precipitation that may increase, decrease, or remain similar to historic levels.

Snowpack – Snowpack is expected to decline, on average, by about 75% by mid-century and 85% by late century. Both climate models showed high agreement on snowpack declines.

Climate water deficit – Climate water deficit is expected to increase by about 20% by mid-century and 40-50% by late century as increased temperatures, shifts from snow to rain, and higher evaporation lead to overall

drier conditions across the Southern Sierra Nevada.

Vegetation – High elevation alpine zones are expected to become suitable for subalpine vegetation over the next century. As subalpine shifts to higher elevations, an expansion of temperate evergreen needleleaf forest is expected. Temperate grasslands at lower elevations could convert to subtropical grasslands and shrublands over time. A time lag between changes in climate and changes in vegetation is highly likely and not included in the model projections, making vegetation projections highly uncertain.

Wildfire – When compared to the historic period (1961-1990), biomass consumed by wildfire is expected to double or triple by mid-century and triple or quadruple by late century. The area burned, however, is only expected to increase 20-65% by late century. A time lag between changes in climate and changes in vegetation is highly likely and not included in the model projections, making wildfire projections highly uncertain.

Carbon storage in vegetation – The two models showed, overall, increasing carbon storage in vegetation across the Southern Sierra. By late century, however, declines in carbon storage are possible, as are increases.

VULNERABILITIES

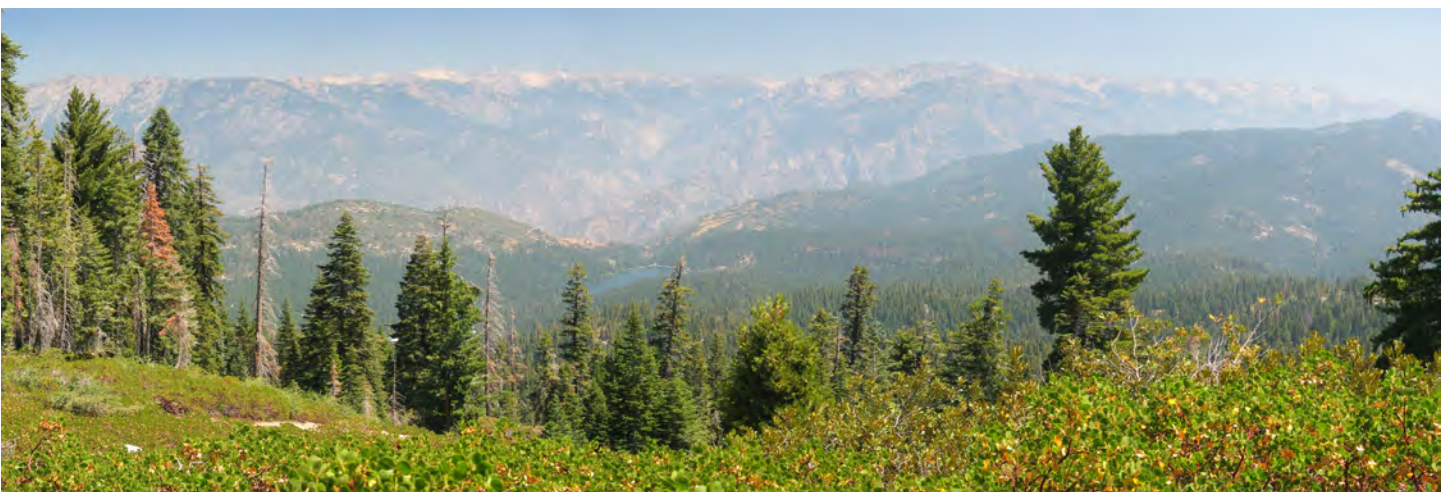
This climate science assessment provides information on potential climate change vulnerabilities for water-related resources of the Southern Sierra Nevada. Overall, the timing of water availability for storage and human consumption is highly vulnerable due to the projected seasonal changes in runoff. In addition, water quality is highly vulnerable based on the greater potential for drought, severe storms, wildfire, and lower late summer flows.

ADAPTATION STRATEGIES

Strategies that reduce the impacts of climate change by addressing specific goals and vulnerabilities will allow continued functioning of natural systems while also providing water resources for human populations. One of the primary impacts of climate change will be its exacerbating influence on existing stressors, which occur primarily through land management practices. As climate change progresses, reducing existing stressors will become increasingly necessary for retaining many of the services provided by functioning watersheds.

Some common adaptation strategies for reducing the vulnerabilities associated with water resources and watershed function include:

- Reduce water demand through conservation measures for residential and agricultural use;
- Reduce water demand by changing the types of crops grown in the region;
- Maintain late summer flow through wetland and meadow restoration at higher elevations;
- Increase water storage and flood abatement potential through watershed restoration activities, including, where appropriate, beaver reintroduction;
- Reconnect floodplains;
- Maintain water quality by reducing activities that lead to soils compaction and erosion, such as overgrazing, timber harvest, and roads;
- Diversify local economy to become more resilient in the face of drought and water insecurity.



INTRODUCTION

The state of California has committed to an integrated approach to managing its water resources. This approach, called Integrated Regional Water Management (IRWM) planning, brings together water-related interests to plan for sustainable water use, reliable supply, improved water quality, ecologically sound management, low use development, protection of agriculture, and a strong local economy.

This report was funded through the California Department of Water Resources (via Prop 84 funding) to provide basic climate change information for the Southern Sierra Integrated Regional Water Management Plan (SSIRWMP). The SSIRWMP boundaries include the foothills and headwaters of Kern, Poso, White River, Tule, Kaweah, Kings, and San Joaquin watersheds (Figure 1). Throughout this region, water flows from the crest of the Sierra Nevada range west towards Tulare Basin. Many dams and reservoirs store water throughout the region.

The ecology of the Southern Sierra Nevada is diverse and complex. Ecological zones range from annual grasslands, scrub and chaparral at lower elevations to subalpine forest and alpine meadows at higher elevations. The high mountains are dominated by coniferous forest.

Much of the land of the SSIRWMP area is in federal ownership. USFS manages the largest portion, with the National Park Service and BLM also managing significant amounts of land. The Tule

MITIGATION – Reducing the amount of greenhouse gases in the atmosphere in order to prevent rapid and irreversible climate change. Irreversible climate change occurs when positive feedbacks kick in to such an extent that emissions reductions are no longer effective.

ADAPTATION – Planning for expected and inevitable impacts of climate change and reducing our vulnerability to those impacts.

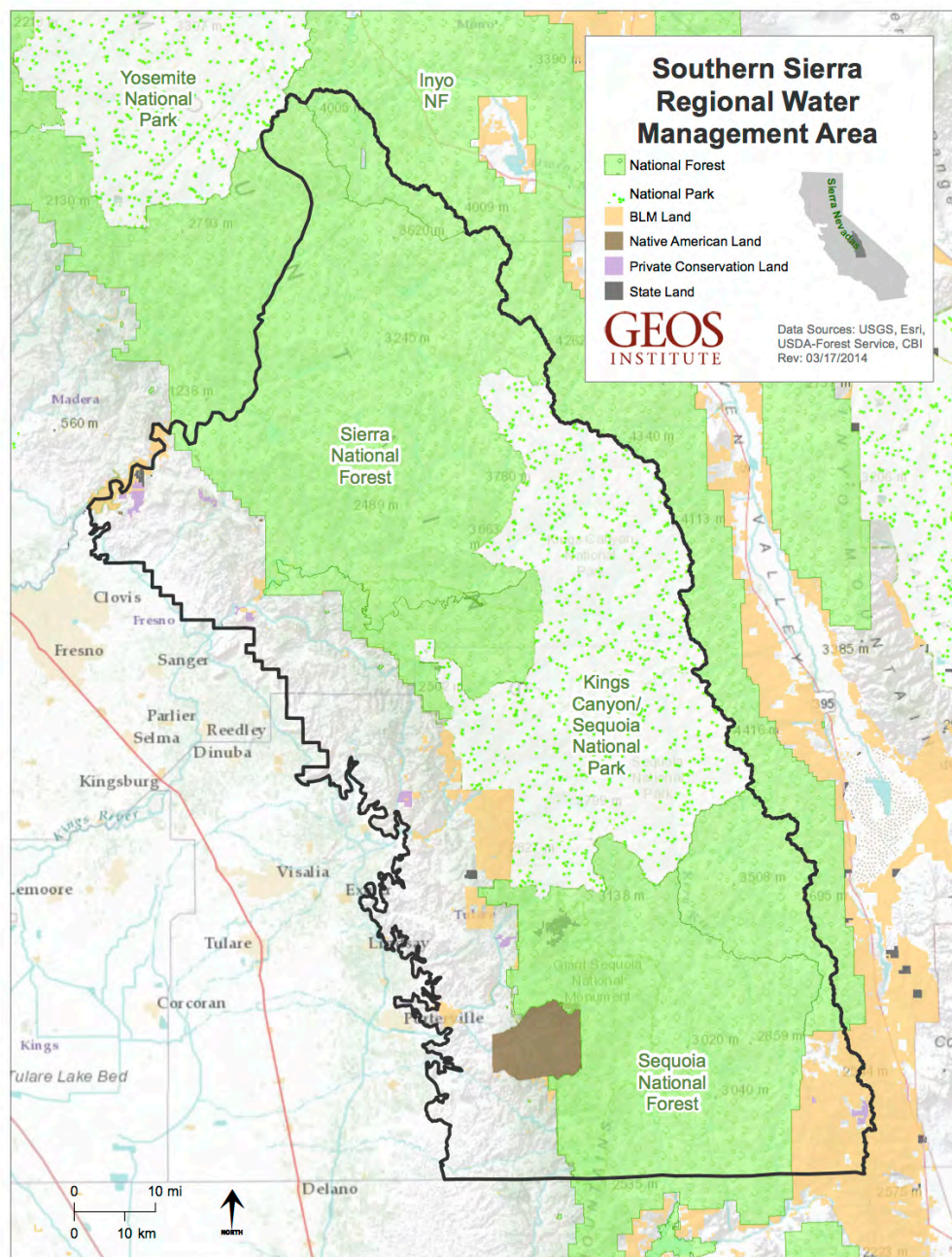
River Indian Reservation is located in the southern portion. Most of the western extent is in private ownership.

Broad scale changes in climate are already impacting local conditions across the West and are likely to continue and accelerate in the coming decades. Changes include the timing and availability of water, changes in tree and wildlife species, and changes in wildfire frequency and intensity. Local communities will need to plan for such changes in order to continue to provide vital services to local residents and to support the economy. Integrating climate change science into water management planning is one step towards preparing people for climate change.

Climate change presents us with a serious challenge as we plan for the future. Our current planning strategies at all scales (local, regional, and national) rely on historical data to anticipate future conditions. **Yet due to climate change and its associated impacts, the future is no longer expected to resemble the past.**

This report provides the Southern Sierra Integrated Regional Water Management planners with local climate change projections that can help them make educated planning decisions. We also provide supplementary information from the scientific literature. This report is intended to precede a vulnerability assessment and development of adaptation strategies for stakeholders

in the Southern Sierra Nevada. Many of the impacts of climate change are inevitable due to current levels of greenhouse gas emissions already in the atmosphere. Preparing for these impacts to reduce their severity is called “adaptation” (see box). Preventing even more severe impacts by reducing future emissions is called “mitigation.” Both are needed.



MODELS AND THEIR LIMITATIONS

To determine what conditions we might expect in the future, climatologists created models based on physical, chemical, and biological processes that form the earth's climate system. These models vary in their level of detail and assumptions, making output and future scenarios variable. Differences among models stem from differences in assumptions regarding what variables (and how many) are important to include in models to best represent conditions we care about. Differences also stem from different assumptions about greenhouse gas emissions. Because of the variation across models and assumptions, it is useful to look across numerous models to assess the full range of potential future conditions.

The Intergovernmental Panel on Climate Change (IPCC) uses numerous models to make global climate projections. The models are developed by different institutions and countries and have slightly different inputs or assumptions. Specific inputs to these models include such variables as greenhouse gas emissions, air and ocean currents, ice and snow cover, plant growth, particulate matter, and many others.¹

Most climate models project the future climate at global scales. Managers and decision makers, however, need information about how climate change will impact the local area. Global climate models can be adjusted to local scales using a variety of different methods for “downscaling.” Downscaling involves using locally

HIGH CERTAINTY:

Higher temperatures – Greater concentrations of greenhouse gases trap more heat. Measured warming tracks model projections.

Lower snowpack – Higher temperatures cause a shift from snow to rain at lower elevations and cause earlier snow melt at higher elevations.

Shifting distributions of plants & animals – Many species are limited in extent or number by climatic conditions that are expected to change.

MEDIUM CERTAINTY:

More severe storms – Changes in storm patterns will be regionally variable, but storms are generally expected to become more severe.

Changes in precipitation – Current models show wide disagreement on precipitation patterns, but the model projections converge in some locations.

Wildfire patterns – The relationship among fire, temperature, and available moisture has been well documented, but other components also play a role (such as vegetation, below).

LOW CERTAINTY:

Changes in vegetation – Vegetation may take decades or centuries to keep pace with changes in climate. While shifts are certain, what those shifts look like, and when will be highly variable.

specific data on historical temperature and precipitation variation over a landscape. The historical relationships between topography and climate variables are assumed to remain intact even as climate changes (a rainshadow, for example, is assumed to remain a rainshadow, even as overall levels of precipitation change over time).

The utility of the model results presented in this report is to help resource managers and other decision makers picture what the conditions and landscape might look like in the future and the magnitude and direction of change. Some model

outputs have greater certainty than others (see box on previous page). Information is provided here to explore the types of potential changes, but actual conditions may be quite different, especially if greenhouse gas emissions change substantially.

Uncertainty associated with projections of future conditions, however, should not be used as a reason for delaying action on climate change. The likelihood that future conditions will resemble historic conditions is very low, so **managers and policy makers are encouraged to begin to plan for an era of change, even if the precise trajectory or rate of such change is uncertain.**



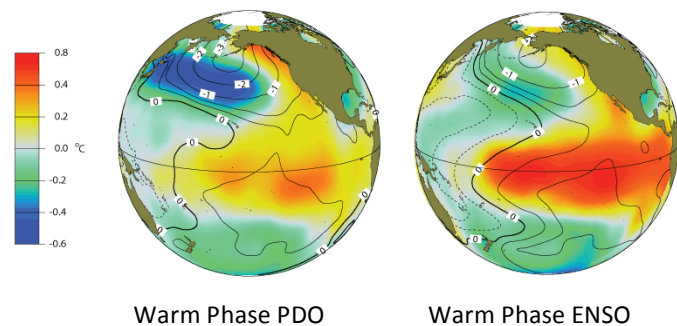
REGIONAL CLIMATE PATTERNS

The climate of the Western U.S. is heavily influenced by the Pacific Decadal Oscillation (PDO). The PDO influences surface ocean temperatures and cycles between a warm phase and a cool phase (Figure 2). Over the last century or more, these cycles have lasted about 20-30 years² (Figure 3).

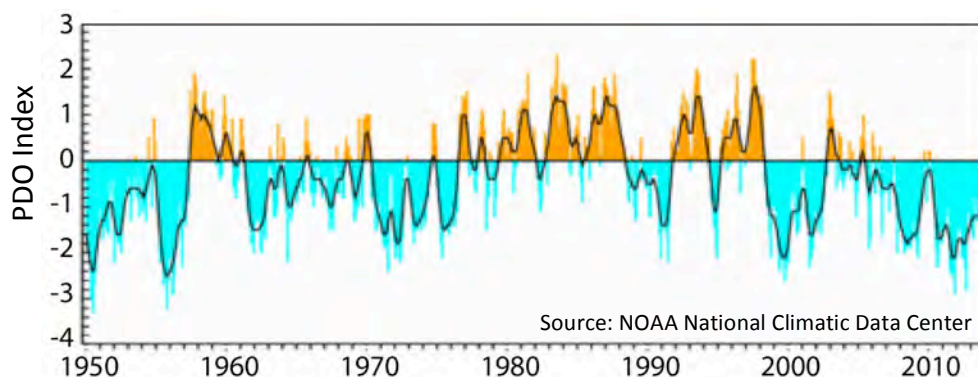
During the warm phase, the surface of the ocean along the coast of North America is unusually warm and low barometric pressure is enhanced over the central North Pacific. This results in warmer than average air temperatures across western North America, especially west of the Rocky Mountains. Some of the characteristics of the warm phase of the PDO are hot dry summers, warmer than average winters, and reduced snowpack. The warm phase of the PDO has been linked to increased wildfire and bark beetle outbreaks.³

Embedded within the decades long cycles of the PDO are the one- to two-year cycles known as El Niño-Southern Oscillation (ENSO). When the warm and dry cycle of the PDO coincides with the dry years brought by ENSO, extreme drought and wildfire can occur.

Unfortunately, the precise cause and duration of PDO cycles are not well understood. The PDO was recognized as recently as 1996, and the drivers of the system are still being investigated. While our understanding increases every year, predicting future patterns and, more specifically, understanding the relationship between PDO and climate change is limited at this time.



Source: Climate Impacts Group, University of Washington



Figures 2 (top) and 3 (bottom). Warm phase PDO (top left) and warm phase ENSO (top right) sea surface temperature anomalies. Lower graph shows Pacific Decadal Oscillation, based on the PDO index, since 1950.

CLIMATE PROJECTIONS FOR THE SOUTHERN SIERRA NEVADA

Climate change projections are provided here in two different formats – as averages (monthly and annual) in table format, and as maps that show variation across the region and over future time periods. We mapped climate, vegetation, hydrology, and wildfire variables for historical period (1961-1990 for all variables except hydrology variables, where the historical period was 1971-2000) and for three future periods (2010-39, 2040-69, and 2070-99).

The IPCC emission scenario used in this assessment was the “business-as-usual” trajectory (A2) that assumes that most nations fail to act to lower emissions.⁴ If the U.S. and other key nations drastically and immediately cut emissions, some of the more severe impacts, like irreversible climate change, may still be avoided. Due to climate system inertia, restabilization of atmospheric gases will take many decades even with drastic emissions reductions.⁴ Reducing emissions is vital to prevent the Earth’s climate system from reaching certain tipping points that will lead to sudden and irrevocable changes.

Throughout this report we present mid- and late-century model outputs.

We have more certainty in mid-century projections, due to greenhouse gases already released, but late-century projections may change, depending on future emission levels and natural feedback systems.

Historic trends are based on 4km PRISM data.⁵ PRISM data are compiled from climate observations from a wide range of monitoring networks.

All future climate projections were developed using the same two global coupled ocean-atmospheric climate models – GFDL (Geophysical Fluid Dynamics Laboratory)⁶, and Parallel Climate Model (PCM; National Center for Atmospheric Research, USA)⁷ based on the A2 emissions scenario.

Many other GCMs are available, but most have not been run with the Basin Characterization Model that provides detailed hydrology information for the region. Compared to projections from other models for the Southern Sierra, GFDL is warmer and drier than the average of all models, while PCM is cooler and wetter than average (climatewizard.org). These two models provide a reasonable range of potential future conditions, but many other outcomes are possible.

TEMPERATURE

On average, summer temperatures in the Southern Sierra are expected to rise more than winter temperatures (Figure 4; Table 1). This is a common trend throughout the Western U.S. Due to emissions already released, mid-century (2040-69) projections are highly likely to be realized while

late-century (2070-99) projections are less certain due to potential changes in emissions or positive feedbacks that could accelerate change. The projections presented in this report are for the A2 “business-as-usual” emissions scenario, using 2 GCMs: GFDL and PCM.

Figure 4. Average monthly temperature across the Southern Sierra Integrated Regional Water Management Planning area.

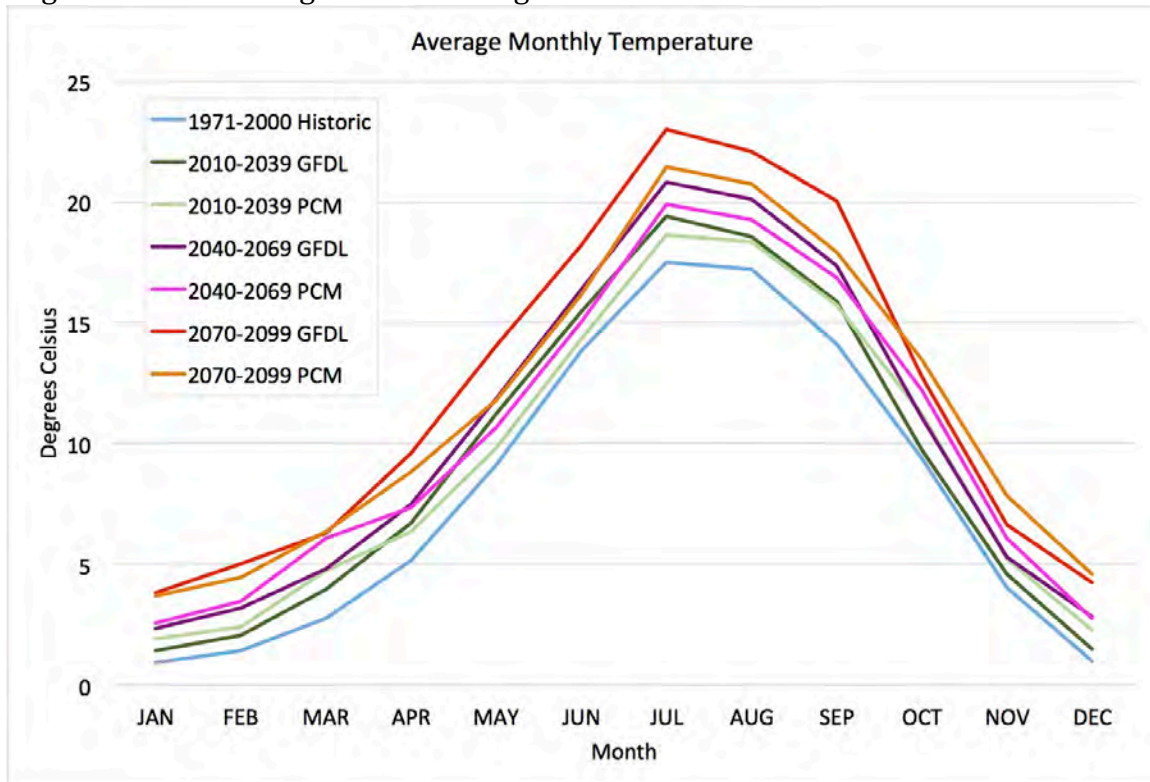
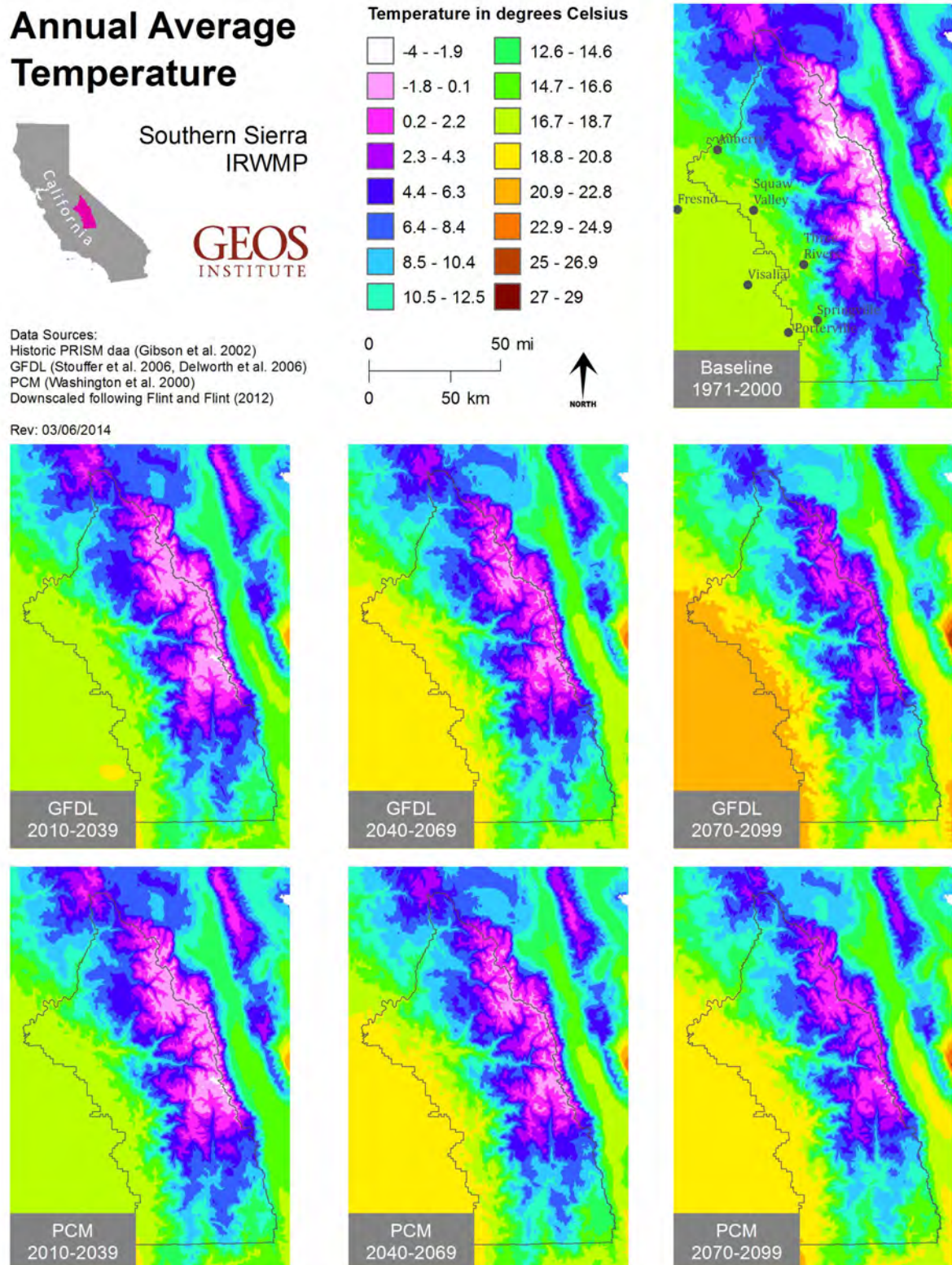


Table 1. Projected average annual and monthly temperature (and change from historic), in degrees Celsius, across the Southern Sierra IRWMP region, based on output from two different global climate models (GFDL and PCM) and the A2 emissions scenario.

	Historic	2010-39	2040-69	2070-99
Annual	9.3°	9.2° to 9.3° (+1.2° to 1.2°)	10.2° to 10.3° (+2.1° to 2.2°)	11.5° to 12.2° (+3.4° to 4.1°)
January	0.9°	1.4° to 1.9° (+0.5° to 1.0°)	2.4° to 2.6° (+1.4° to 1.6°)	3.7° to 3.8° (+2.7° to 2.8°)
February	1.5°	2.1° to 2.4° (+0.6° to 1.0°)	3.2° to 3.5° (+1.7° to 2.0°)	4.4° to 5.0° (+3.0° to 3.6°)
March	2.8°	3.9° to 4.8° (+1.2° to 2.0°)	4.8° to 6.1° (+2.1° to 3.3°)	6.3° to 6.4° (+3.5° to 3.6°)
April	5.2°	6.4° to 6.7° (+1.2° to 1.5°)	7.4° to 7.5° (+2.2° to 2.3°)	8.8° to 9.6° (+3.7° to 4.5°)
May	9.1°	9.8° to 11.2° (+0.7° to 2.1°)	10.6° to 11.9° (+1.5° to 2.8°)	11.8° to 14.1° (+2.7° to 5.0°)
June	13.8°	14.3° to 15.5° (+0.5° to 1.6°)	15.0° to 16.4° (+1.2° to 2.5°)	16.2° to 18.2° (+2.3° to 4.4°)
July	17.5°	18.6° to 19.4° (+1.1° to 1.9°)	20.0° to 20.8° (+2.4° to 3.3°)	21.5° to 23.0° (+4.0° to 5.5°)
August	17.2°	18.5° to 18.4° (+1.2° to 1.3°)	19.3° to 20.1° (+2.0° to 2.9°)	20.8° to 22.1° (+3.5° to 4.9°)
September	14.1°	15.7° to 15.9° (+1.6° to 1.7°)	16.9° to 17.3° (+2.8° to 3.2°)	17.9° to 20.1° (+3.8° to 5.9°)
October	9.4°	9.8° to 11.2° (+0.4° to 1.8°)	11.1° to 12.2° (+1.7° to 2.8°)	12.8° to 13.5° (+3.3° to 4.1°)
November	4.0°	4.6° to 5.3° (+0.6° to 1.2°)	5.3° to 6.1° (+1.2° to 2.1°)	6.6° to 7.9° (+2.6° to 3.8°)
December	1.0°	1.5° to 2.3° (+0.4° to 1.2°)	2.8° to 2.9° (+1.7° to 1.8°)	4.3° to 4.6° (+3.3° to 3.6°)

Figure 5. Average annual temperature across the Southern Sierra Integrated Regional Water Management area in California, based on output from 2 different global climate models (GFDL and PCM) and the A2 emissions scenario.



PRECIPITATION

Projections for future precipitation varied (Fig. 18 and Table 2), with some months wetter than historic (Jan-Mar) and some slightly drier (Apr-Jun and Oct-Dec). Even with increased precipitation in the late

winter, overall drier conditions are expected to develop due to increases in temperature and evaporation. This can be seen in the water deficit projections (page 44).

Figure 6. Average monthly precipitation across the Southern Sierra Integrated Regional Water Management Planning area, for the historic period (1971-2000) and 3 future time periods (2010-2039, 2040-2069, and 2070-2099).

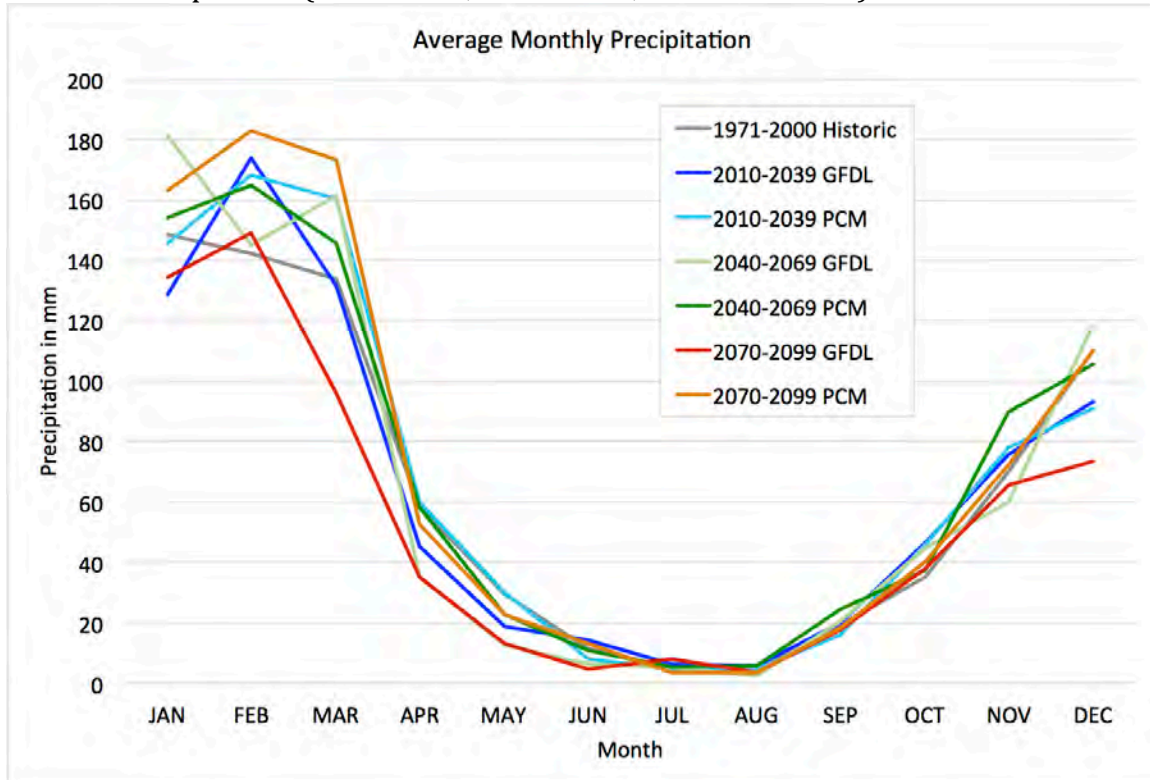
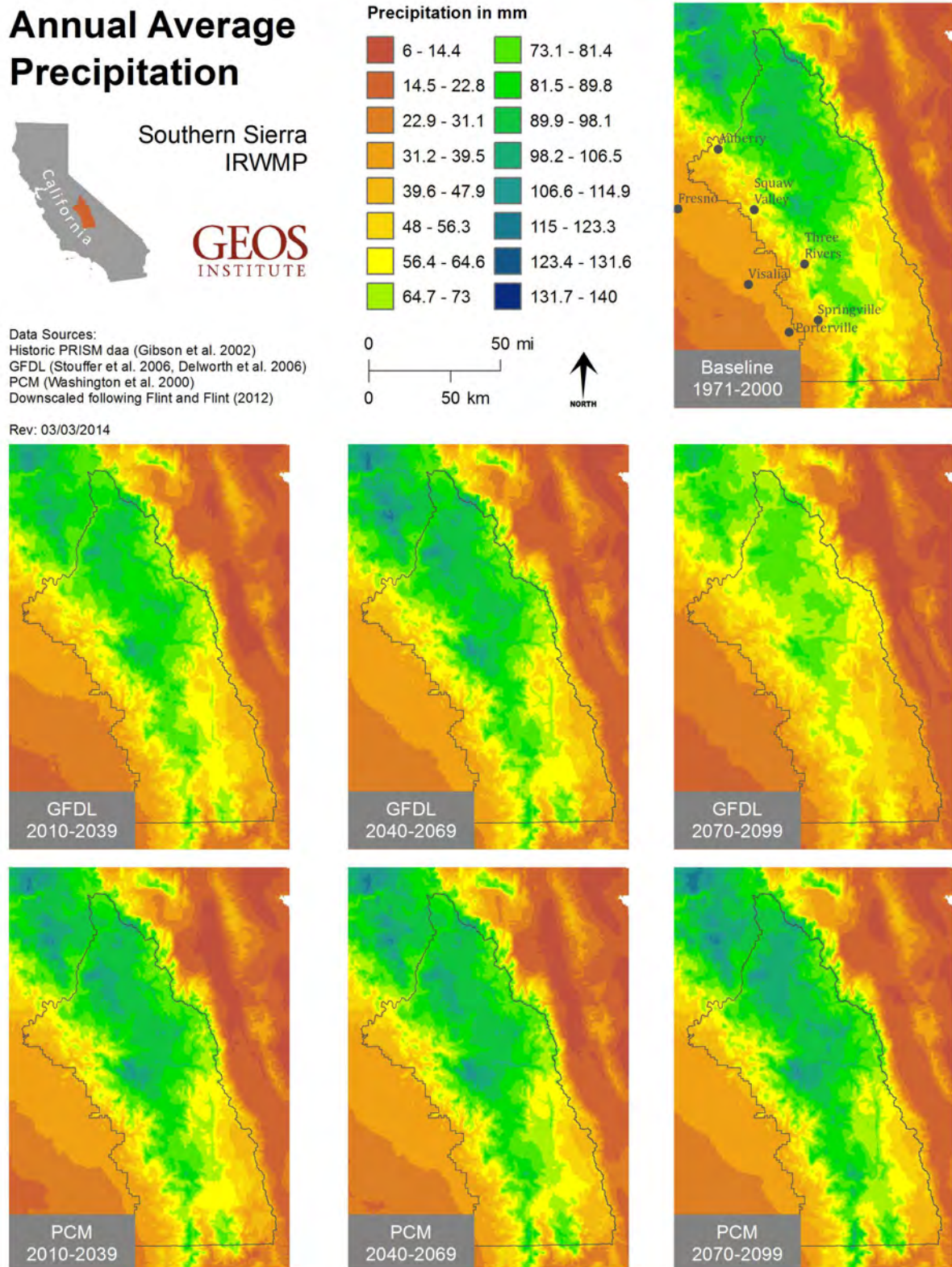


Table 2. Projected average annual and monthly precipitation (and percent change from historic) across the Southern Sierra IRWMP region, based on output from two different global climate models (GFDL and PCM) and the A2 emissions scenario. Precipitation projections include both rainfall and snow water equivalent, shown in millimeters.

	Historic	2010-39	2040-69	2070-99
Annual	768.8	759.5 to 812.0 (-1.2 to +5.6%)	792.6 to 825.1 (+3.1 to +7.3%)	637.6 to 855.4 (-17.1 to +11.3%)
Jan	148.5	128.7 to 145.9 (-13.4 to -1.8%)	154.2 to 181.3 (+3.8 to +22.1%)	134.1 to 163.1 (-9.7 to +9.8%)
Feb	142.1	168.1 to 173.7 (+18.3 to +22.2%)	145.3 to 165.7 (+2.3 to +15.9%)	148.9 to 182.9 (+4.8 to +28.7%)
Mar	134.0	131.5 to 160.5 (-19.7 to -1.9%)	145.5. to 161.4 (+8.6 to +20.5%)	96.0 to 173.5 (-28.3 to +29.4%)
Apr	58.5	45.4 to 60.0 (-22.3 to +2.7%)	35.0 to 58.1 (-40.2 to -0.6%)	35.1 to 52.5 (-39.9 to -10.1%)
May	29.4	19.0 to 29.9 (-35.5 to +1.7%)	12.6 to 22.7 (-57.3 to -23.0%)	12.9 to 22.6 (-56.3 to -23.2%)
Jun	11.6	14.1 to 8.1 (-29.9 to +21.4%)	6.2 to 10.9 (-46.7 to -5.6%)	4.8 to 13.3 (-58.6 to +14.4%)
Jul	5.5	6.1 to 4.8 (-12.4 to +12.6%)	5.3 to 5.4 (-2.6 to -1.1%)	3.8 to 7.9 (-30.4 to +45.6%)
Aug	4.6	4.7 to 5.6 (20.1 to 0.7%)	2.4 to 5.9 (-47.5 to +27.1%)	3.5 to 3.6 (-24.7 to -23.1%)
Sep	19.4	15.7 to 20.2 (-19.1 to +3.8%)	20.4 to 24.6 (+5.1 to +26.6%)	17.5 to 18.2 (-9.8 to -6.1%)
Oct	34.9	45.6 to 46.6 (+30.8 to 33.6%)	37.6 to 44.6 (+7.8 to +27.8%)	37.9 to 39.9 (+8.7 to +14.6%)
Nov	70.3	75.6 to 77.9 (+7.5 to +10.8%)	59.7 to 89.8 (-15.1 to +27.7%)	65.3 to 72.2 (-7.1 to +2.7%)
Dec	110.1	90.9 to 93.1 (-15.4 to -7.4%)	105.8 to 115.4 (-3.9 to +7.6%)	73.6 to 109.9 (-33.1 to -0.2%)

Figure 7. Average annual precipitation across the Southern Sierra Integrated Regional Water Management area in California, based on output from 2 different global climate models (GFDL and PCM) and the A2 emissions scenario.



HYDROLOGY

In the Sierra Nevada, surface runoff and hydrology is controlled largely by the snow water equivalent (SWE) of winter snowpack.

Many changes to the hydrology of the Western U.S. have been well documented. These include:

Changes in flow

- 15.8% declines in SWE⁹
- Declines in streamflow^{10,11}
- Diminished recharge of subsurface aquifers that support summer baseflows¹²
- Declining summer low flows¹³

Changes in temperature

- Stream temperatures have increased in many areas¹⁴
- Increased wildfire leads to even more water temperature increase¹⁵

Changes in storm intensity

- 16% increase in frequency and intensity of very heavy precipitation¹⁶
- Increased probability of 20-year flood from 1915 to 2003¹⁷

Changes in seasonal timing

- Rivers and lakes freeze over, on average, 5.8 days later each century¹⁰
- The ice breakup date is, on average, 6.5 days earlier each century¹⁰

- Snowmelt and snowmelt-driven runoff also is occurring earlier¹⁸
- Spring runoff has advanced steadily during the latter half of the twentieth century and now occurs 1 to 3 weeks earlier^{7,19}
- Observed streamflow has increased in March and declined in June¹¹
- Shifts towards more rainfall, less snowfall²⁰

Changes in minimum temperature, declines in SWE, and changes in streamflow timing were all attributed to increased greenhouse gas concentrations in the atmosphere.¹⁸ More extreme downpours are expected to worsen during the coming century.^{16,21}

As temperature increase leads to more rain and less snow, the flood risk is expected to increase in the Sierra Nevada.²² Decreases in snow pack and in the length of the snow season could have serious repercussions to winter recreation and water storage alike.

As temperatures and evapo-transpiration increase, summer low flows are expected to become more severe, with longer and lower low flows.¹²

Basin Characterization Model

Projections of hydrological variables, including average annual and monthly runoff, water deficit, and snowpack, were provided via the Basin Characterization Model (BCM). Below is the abstract from a paper published on the model in 2012. The full paper can be downloaded from the following link:

<http://climate.calcommons.org/bib/development-and-application-downscaled-hydroclimatic-predictor-variables-use-climate>

Citation:

Thorne, J., R. Boynton, L. Flint, A. Flint, and T.-N. Le. 2012. **Development and Application of Downscaled Hydroclimatic Predictor Variables for Use in Climate Vulnerability and Assessment Studies.** California Energy Commission Report #500-2010-010.²³

Abstract:

This paper outlines the production of 270m grid-scale maps for 14 climate and derivative hydrologic variables for a region that encompasses the State of California and all the streams that flow into it. The paper describes the Basin Characterization Model (BCM), a map-based, mechanistic model used to process the hydrological variables. Three historic and three future time periods of 30 years (1911–1940, 1941–1970, 1971–2000, 2010–2039, 2040–2069, and 2070–2099) were developed that summarize 180 years of monthly historic and future climate values. These comprise a standardized set of fine-scale climate data that were

shared with 14 research groups, including the U.S. National Park Service and several University of California groups as part of this project. The paper presents three analyses done with the outputs from the Basin Characterization Model: trends in hydrologic variables over baseline, the most recent 30-year period; a calibration and validation effort that uses measured discharge values from 139 stream gages and compares those to Basin Characterization Model-derived projections of discharge for the same basins; and an assessment of the trends of specific hydrological variables that links historical trend to projected future change under four future climate projections. Overall, increases in potential evapotranspiration dominate other influences in future hydrologic cycles. Increased potential evapotranspiration drives decreasing runoff even under forecasts with increased precipitation, and drives increased climatic water deficit, which may lead to conversion of dominant vegetation types across large parts of the study region, as well as have implications for rain-fed agriculture. The potential evapotranspiration is driven by air temperatures, and the Basin Characterization Model permits it to be integrated with a water balance model that can be derived for landscapes and summarized by watershed. These results show the utility of using a process-based model with modules representing different hydrological pathways that can be interlinked.

Figure 8. Mean projected runoff (top), snowpack (middle), and water deficit (bottom) across the Southern Sierra Integrated Regional Water Management Planning area based on output from the Basin Characterization Model, run with 2 global climate models (GFDL and PCM) and the A2 emissions scenario.

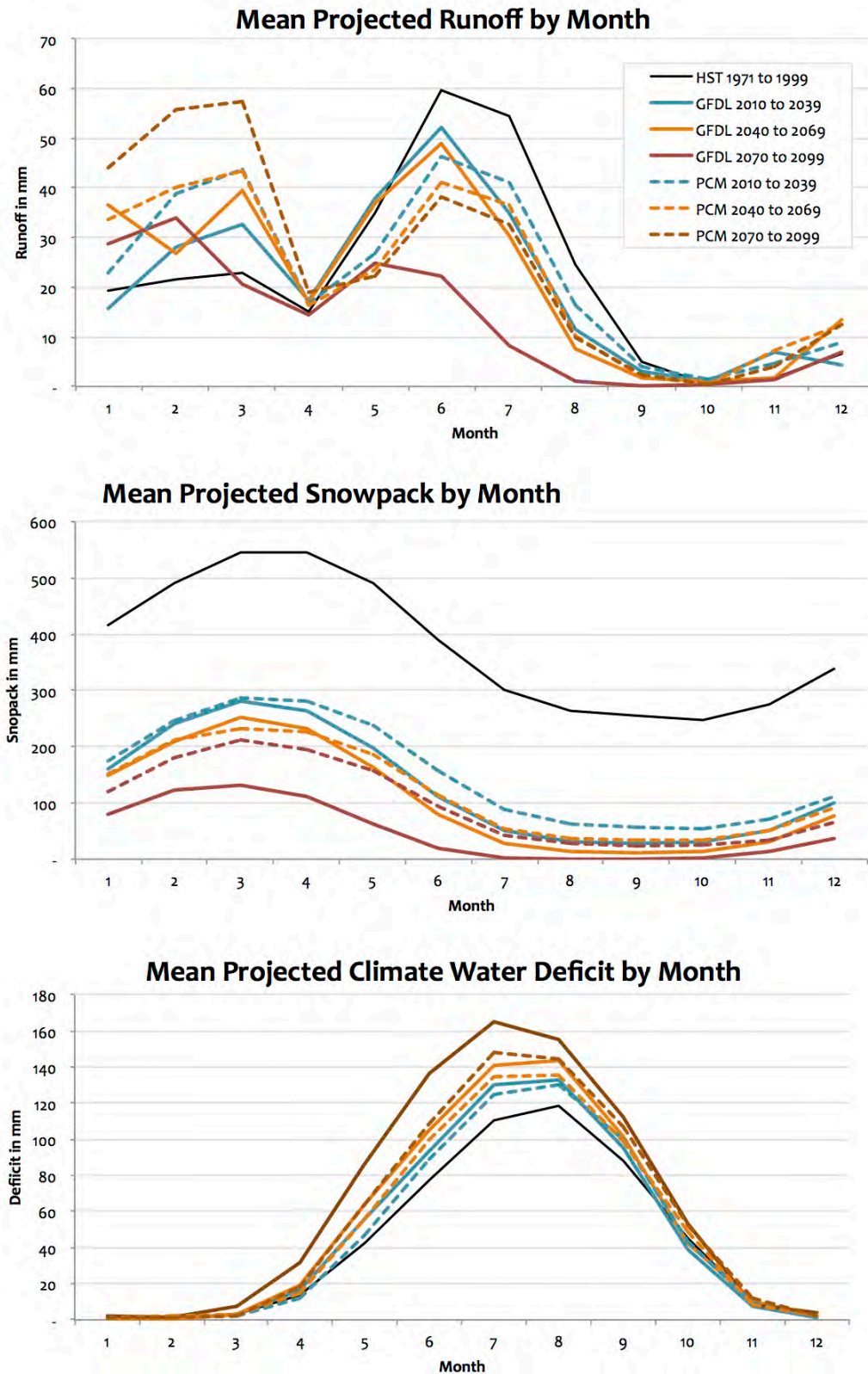


Table 3. Projected annual and monthly runoff (and percent change from historic) across the Southern Sierra IRWMP region, based on output from two different global climate models (GFDL and PCM), shown in millimeters.

	Historic	2010-39	2040-69	2070-99
Annual	267.1	245.8 to 272.3 (-8.0 to +1.9%)	262.5 to 268.1 (-1.7 to +0.4%)	163.6 to 299.3 (-38.8 to +12.0%)
Jan	19.4	15.8 to 22.8 (-18.6 to +17.7%)	33.7 to 36.6 (+73.8 to +88.6%)	28.7 to 44.0 (+48.1 to +126.6%)
Feb	21.7	28.2 to 38.7 (+29.6 to +78.1%)	26.9 to 40.2 (+23.8 to +85.0%)	34.1 to 55.8 (+56.8 to +156.8%)
Mar	22.8	32.6 to 43.7 (+43.5 to 92.0%)	39.7 to 43.5 (+74.3 to +91.0%)	20.6 to 57.3 (-9.4 to +151.9%)
Apr	15.2	16.6 to 17.4 (+8.8 to +14.0%)	16.5 to 17.2 (+8.5 to +12.7%)	14.5 to 19.1 (-4.7 to +25.3%)
May	35.0	26.9 to 37.8 (-23.1 to +8.1%)	23.4 to 36.9 (-33.2 to +5.5%)	22.3 to 24.7 (-36.2 to -29.3%)
Jun	59.7	46.4 to 52.1 (-22.2 to -12.7%)	41.2 to 48.9 (-30.9 to -18.0%)	22.2 to 38.2 (-62.8 to -36.1%)
Jul	54.4	34.8 to 41.2 (-35.9 to -24.2%)	30.5 to 36.6 (-43.9 to -32.6%)	8.3 to 32.5 (-84.7 to -40.2%)
Aug	24.6	11.7 to 16.3 (-52.6 to -33.8%)	7.7 to 10.1 (-68.6 to -58.8%)	1.2 to 9.9 (-95.1 to -59.7%)
Sep	5.1	3.0 to 4.0 (-41.11 to -20.6%)	1.6 to 2.2 (-68.0 to -57.7%)	0.1 to 2.5 (-97.4 to -51.2%)
Oct	0.4	1.1 to 1.5 (+162.9 to 255.1%)	0.4 to 0.9 (-11.9 to +123.3%)	0.3 to 0.4 (-26.0 to +0.9%)
Nov	1.7	4.7 to 6.9 (+177.8 to +309.2%)	1.8 to 7.3 (-7.1 to +336.6%)	1.5 to 4.1 (-10.3 to +146.4%)
Dec	6.8	4.3 to 9.1 (-36.7 to +33.7%)	12.6 to 13.4 (+85.9 to +98.2%)	7.0 to 12.6 (+3.8 to +86.6%)

Table 4. Projected annual and monthly average snowpack (and percent change from historic) across the Southern Sierra IRWMP region, based on output from two different global climate models (GFDL and PCM), shown in millimeters.

	Historic	2010-39	2040-69	2070-99
Annual	4151.3	1390.6 to 1662.3 (-66.5 to -60.0%)	977.6 to 1204.7 (-76.5 to -71.0%)	582.6 to 731.2 (-86.0 to -82.4%)
Jan	416.11	159.0 to 173.2 (-61.8 to -58.4%)	148.9 to 150.5 (-64.2 to -63.8%)	80.3 to 119.2 (-80.7 to -71.4%)
Feb	490.9	241.5 to 246.4 (-50.8 to -49.8%)	208.6 to 210.7 (-57.5 to -57.1%)	121.6 to 179.4 (-75.2 to -63.5%)
Mar	546.1	280.2 to 285.7 (-48.7 to -47.7%)	233.5 to 251.2 (-57.25 to -54.0%)	132.8 to 212.4 (-75.7 to -61.1%)
Apr	546.0	264.9 to 280.6 (-51.5 to -48.6%)	225.5 to 230.9 (-58.7 to -57.7%)	110.8 to 195.7 (-79.7 to -64.2%)
May	490.3	197.9 to 238.1 (-59.6 to -51.4%)	164.0 to 185.7 (-66.5 to -62.1%)	63.7 to 157.6 (-87.0 to -67.9%)
Jun	389.4	110.5 to 157.2 (-71.6 to -59.6%)	80.6 to 115.6 (-79.3 to -70.3%)	20.2 to 95.6 (-94.8 to -75.5%)
Jul	301.7	50.8 to 88.9 (-83.2 to -70.6%)	27.4 to 54.5 (-90.9 to -81.9%)	2.9 to 43.7 (-99.0 to -85.5%)
Aug	262.9	31.7 to 63.0 (-87.9 to -76.0%)	13.9 to 36.5 (-94.7 to -86.1%)	0.4 to 27.4 (-99.9 to -89.6%)
Sep	254.4	27.3 to 56.2 (-89.3 to -77.9%)	11.4 to 33.4 (-95.5 to -86.9%)	0.1 to 23.6 (-100.0 to -90.7%)
Oct	247.3	30.4 to 54.1 (-87.7 to -78.1%)	14.1 to 34.1 (-94.3 to -86.2%)	0.9 to 24.5 (-99.7 to -90.1%)
Nov	273.9	51.9 to 72.3 (-81.1 to -73.6%)	29.7 to 50.1 (-89.2 to -81.7%)	14.0 to 34.5 (-94.9 to -87.4%)
Dec	339.0	100.4 to 110.5 (-70.4 to -67.4%)	76.1 to 92.4 (-77.6 to -72.7%)	48.8 to 98.3 (-88.9 to -80.5%)

Table 5. Projected annual and monthly average water deficit (and percent change from historic) across the Southern Sierra IRWMP region, based on output from two different global climate models (GFDL and PCM), shown in millimeters.

	Historic	2010-39	2040-69	2070-99
Annual	502.4	553.2 to 567.6 (+10.1 to +13.0%)	597.3 to 625.1 (+18.9 to +24.4%)	654.8 to 755.2 (+30.3 to 50.3%)
Jan	0.9	0.7 to 0.9 (-19.34 to +5.1%)	0.9 to 1.9 (-0.1 to +124.7%)	1.1 to 1.2 (+31.1 to +38.7%)
Feb	1.1	0.4 to 0.7 (-63.4 to -34.3%)	1.5 to 2.1 (+31.1 to +88.8%)	1.5 to 2.1 (+38.9 to +89.0%)
Mar	3.1	2.7 to 3.0 (-12.9 to -2.3%)	2.4 to 7.3 (-21.9 to +135.3%)	2.4 to 3.0 (-24.1 to -3.8%)
Apr	13.7	16.8 to 19.1 (+23.2 to +39.4%)	12.0 to 31.7 (-12.4 to +132.1%)	14.6 to 18.1 (+6.9 to +32.5%)
May	42.4	56.0 to 63.8 (+32.0 to +50.6%)	47.2 to 86.4 (+11.4 to +103.9%)	56.3 to 63.8 (+32.9 to +50.5%)
Jun	77.4	93.4 to 105.3 (+20.6 to +36.1%)	88.9 to 136.3 (+76.1 to +14.8%)	99.8 to 109.0 (+28.4 to +40.8%)
Jul	110.2	129.9 to 141.3 (+18.0 to +28.3%)	165.4 to 124.8 (+13.3 to +50.1%)	135.2 to 147.9 (+22.7 to +34.2%)
Aug	118.3	132.6 to 143.9 (+12.0 to +21.6%)	129.9 to 155.8 (+9.8 to +31.7%)	135.8 to 144.8 (+14.8 to +22.4%)
Sep	87.8	95.1 to 101.2 (+8.3 to +15.2%)	99.4 to 111.9 (+13.2 to +27.4%)	98.5 to 106.9 (+12.2 to +21.7%)
Oct	44.8	38.6 to 42.5 (-13.8 to -5.2%)	43.2 to 52.8 (-3.7 to +17.9%)	48.4 to 52.4 (+8.1 to +16.9%)
Nov	9.0	7.4 to 10.1 (-18.4 to +12.4%)	8.6 to 9.2 (-4.9 to +1.4%)	8.7 to 12.3 (-3.7 to +36.8%)
Dec	2.4	1.7 to 2.6 (-28.9 to +8.0%)	1.7 to 4.2 (-30.1 to +75.5%)	1.9 to 2.4 (-20.3 to +1.8%)

Figure 9. March runoff across the Southern Sierra Integrated Regional Water Management area in California, based on output from 2 different global climate models (GFDL and PCM) and the A2 emissions scenario.

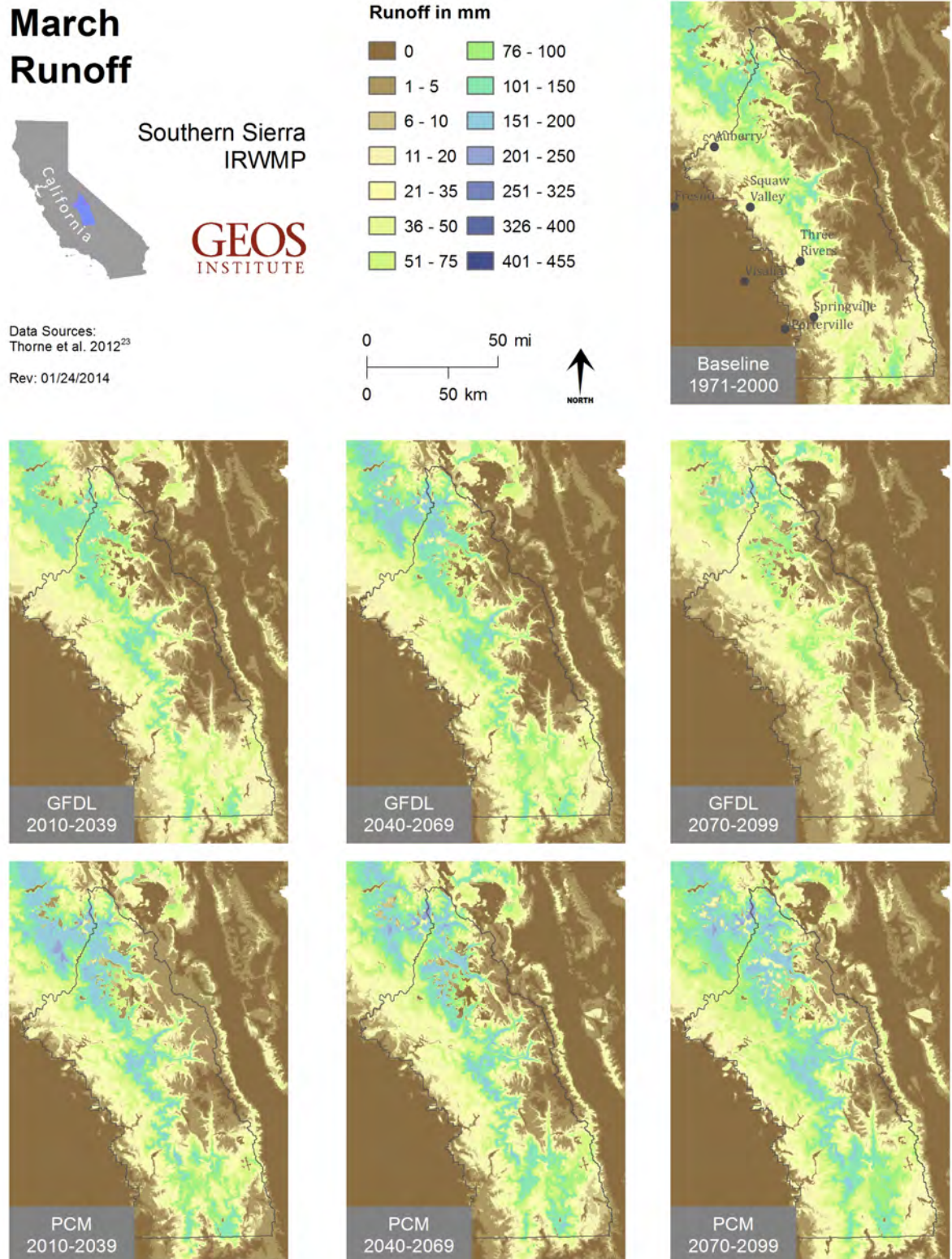


Figure 10. June runoff across the Southern Sierra Integrated Regional Water Management area in California, based on output from 2 different global climate models (GFDL and PCM) and the A2 emissions scenario.

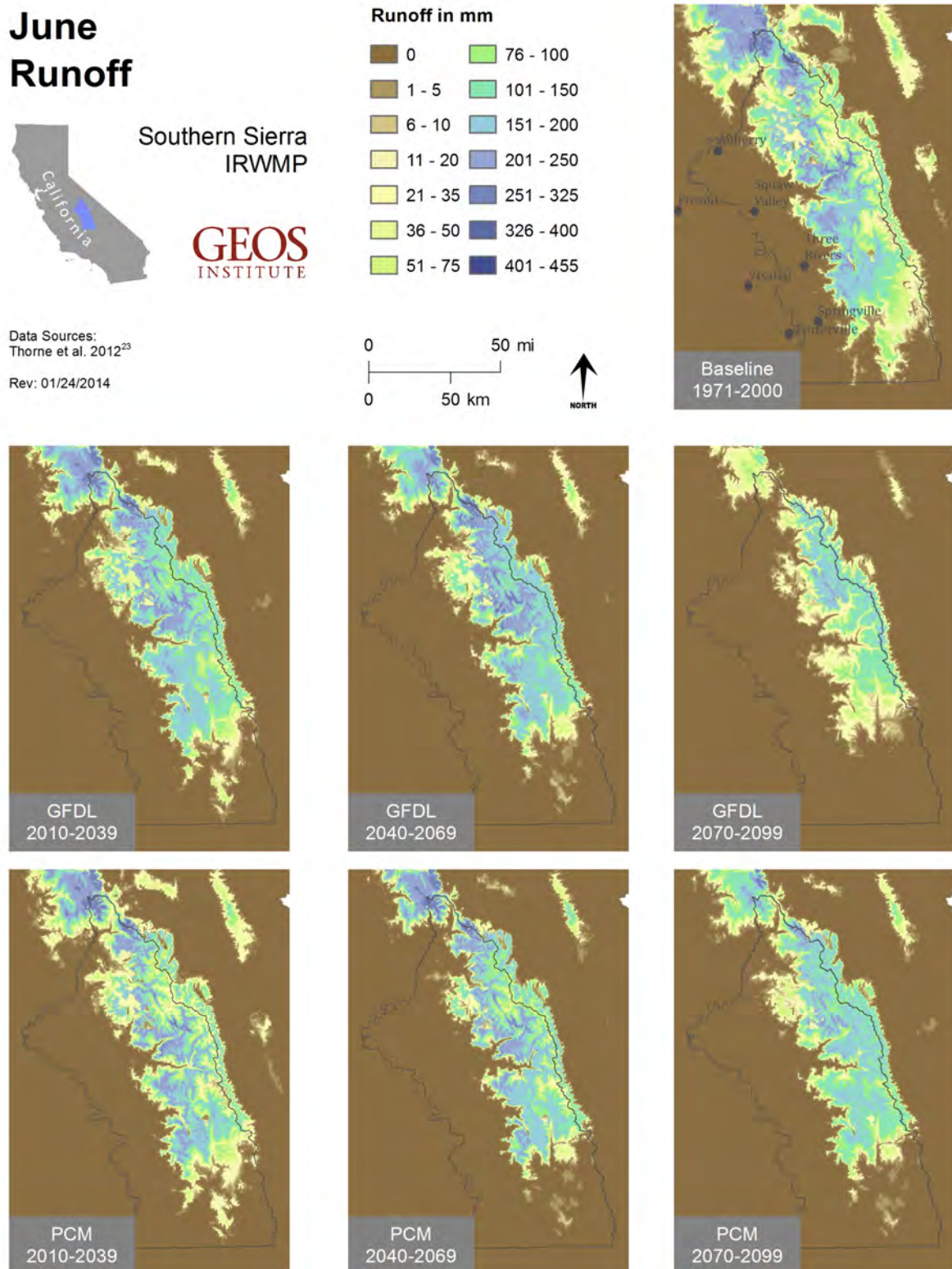


Figure 11. April snowpack across the Southern Sierra Integrated Regional Water Management area in California, based on output from 2 different global climate models (GFDL and PCM) and the A2 emissions scenario.

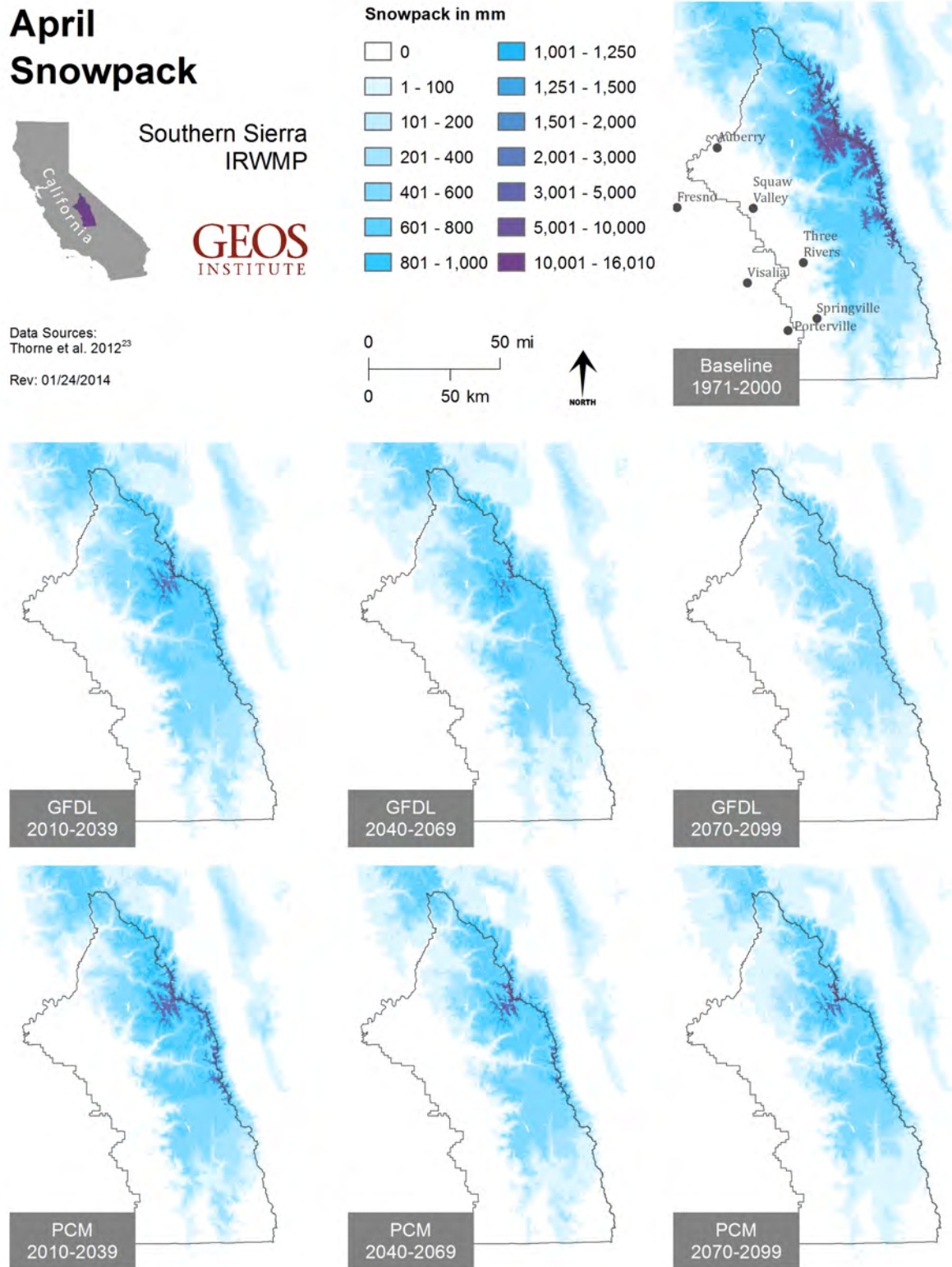


Figure 12. July climate water deficit across the Southern Sierra Integrated Regional Water Management area in California, based on output from 2 different global climate models (GFDL and PCM) and the A2 emissions scenario.

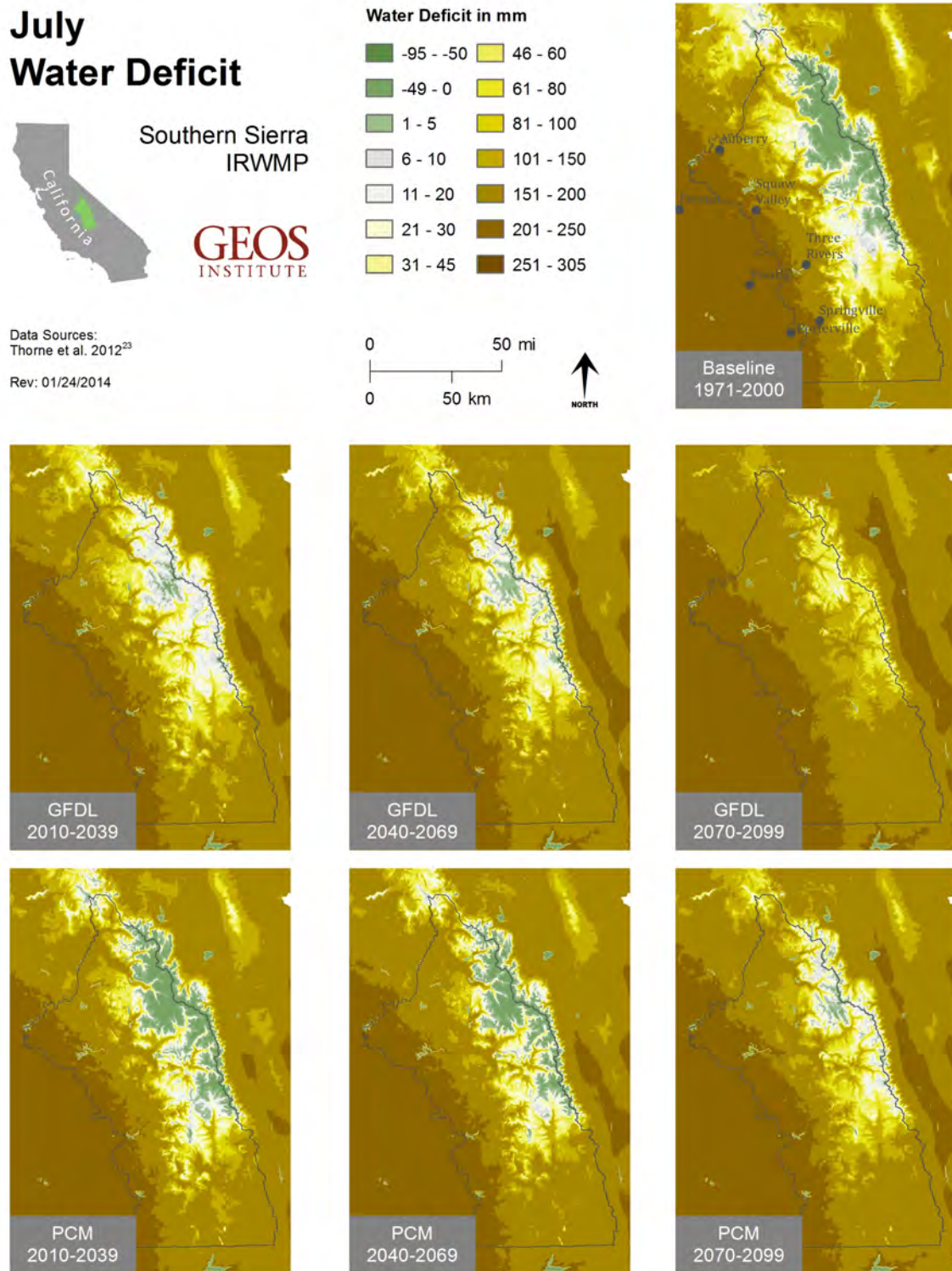


Figure 13. August climate water deficit across the Southern Sierra Integrated Regional Water Management area in California, based on output from 2 different global climate models (GFDL and PCM) and the A2 emissions scenario.

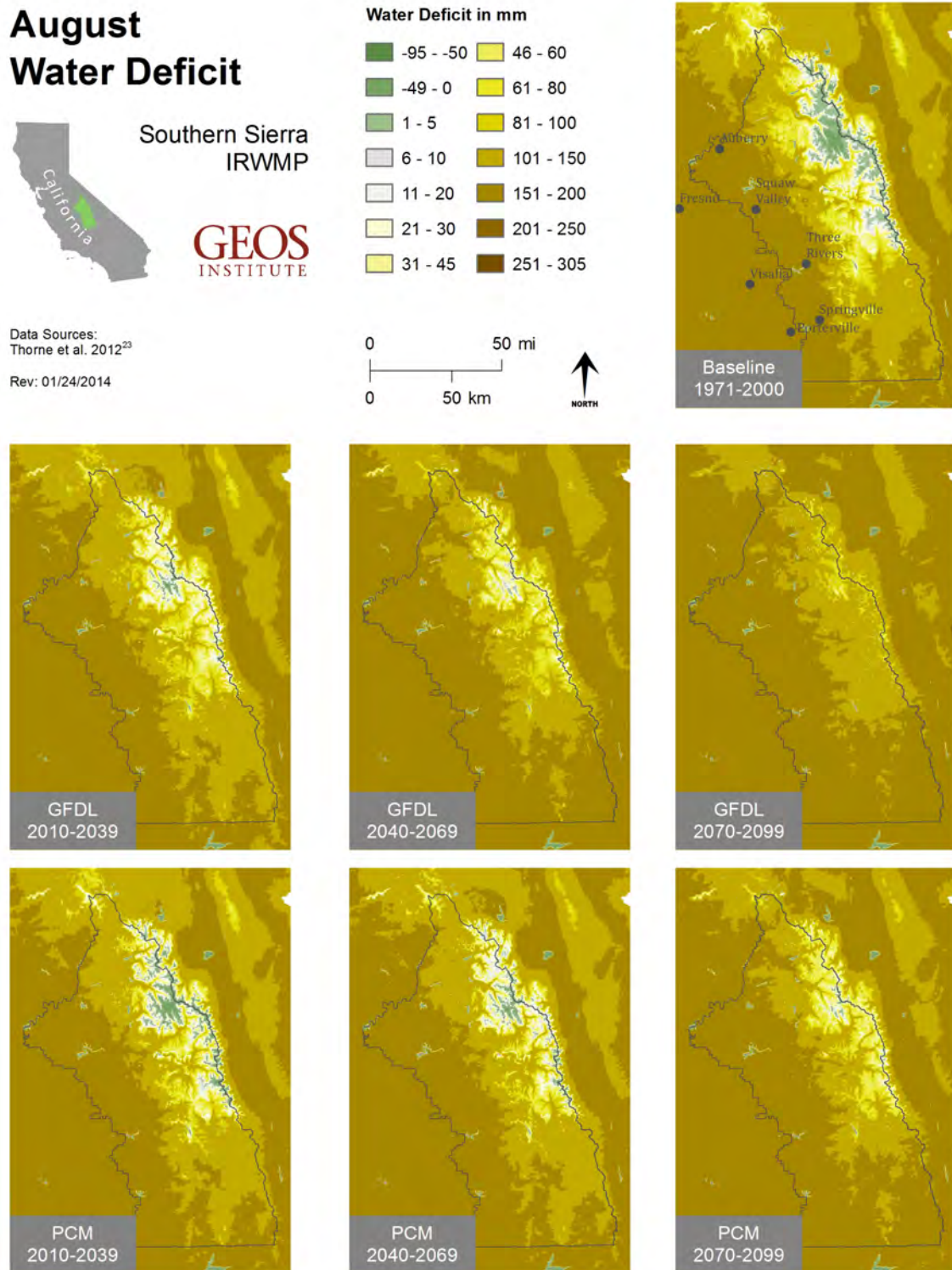
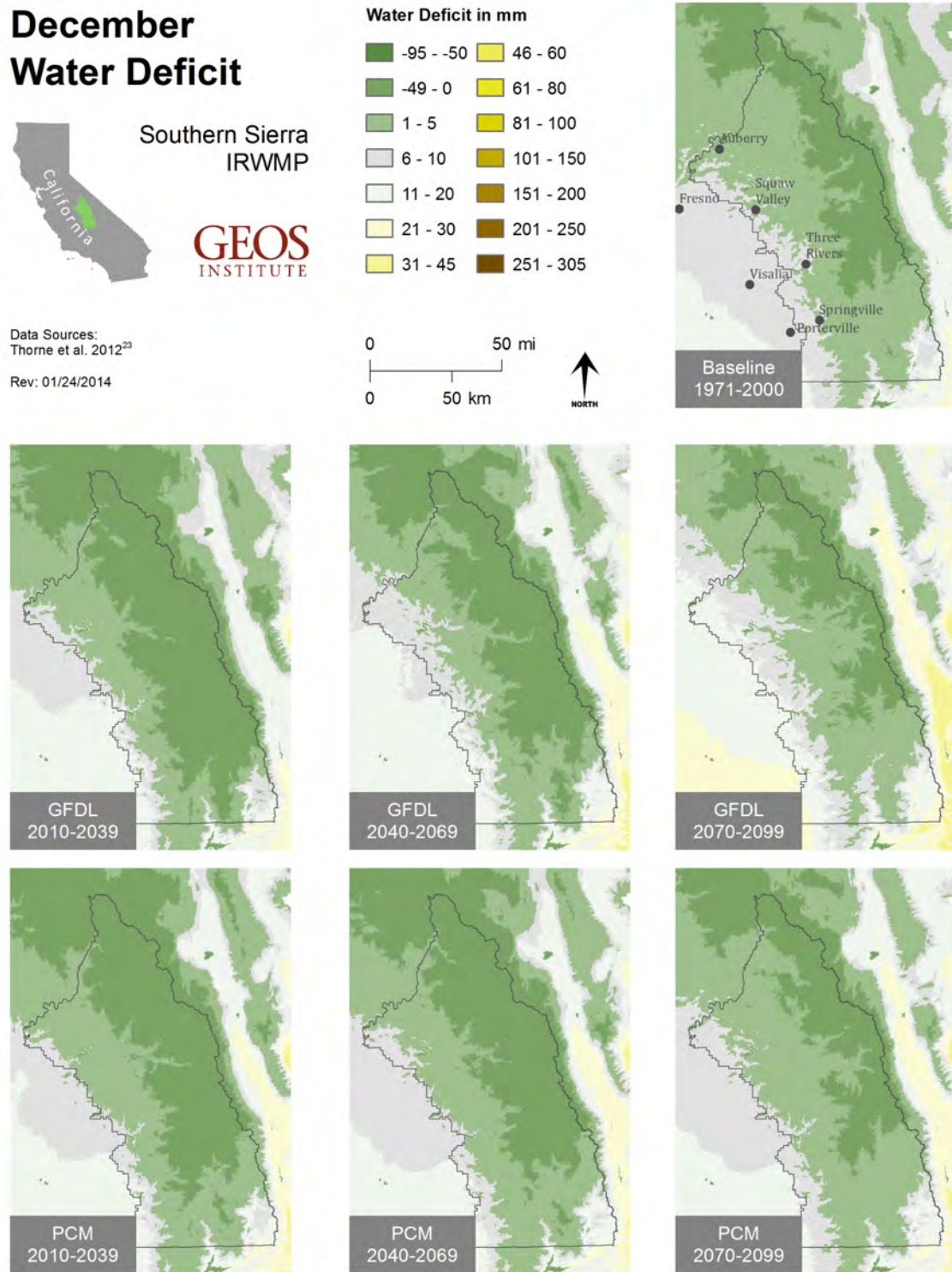


Figure 14. December climate water deficit across the Southern Sierra Integrated Regional Water Management area in California, based on output from 2 different global climate models (GFDL and PCM) and the A2 emissions scenario.



VEGETATION CHANGE AND WILDFIRE

Vegetation composition throughout the Sierra Nevada has changed over time.²⁴ Most changes are due to harvest, natural succession, fire, and insect or disease outbreaks, some of which may be linked to climate change. Overall, U.S. forests have become more productive in the last 55 years,²⁵ likely due to a longer growing season and higher CO₂ levels. Treeline has advanced up slope. As conditions become warmer and drier in the summer, forests in many areas are expected to become less productive due to lower soil moisture during the growing season, temperature stress, insect and disease outbreaks, invasive species prevalence, and wildfire.

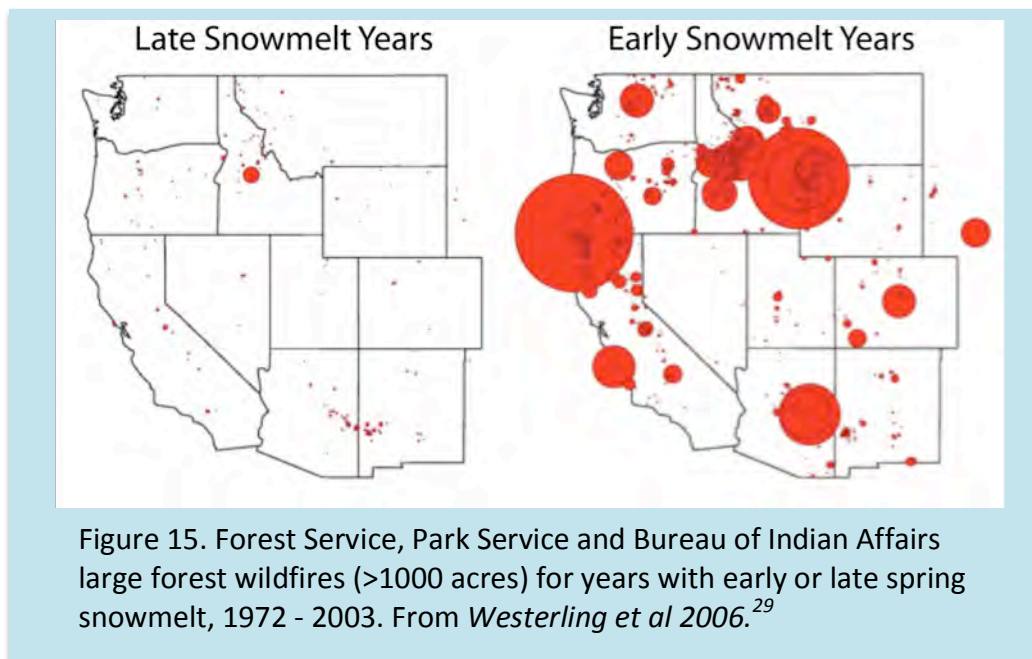
In the western United States, wildfire is driven by a number of natural factors, temperature, precipitation, wind, humidity, lightning strikes, and anthropogenic factors, including human-caused fire starts. The natural factors are significantly affected by climate.²⁸ Wildfire is also closely

associated with large scale climate patterns such as El Niño.²⁸

Years with early arrival of spring account for most of the forest wildfires in the western United States (Figure 3). Wildfire activity increases during warm years, with relatively little activity in cool years. Since the mid-1980s the incidence of wildfire, extent of area burned, and length of season all have increased. The frequency of large wildfires in western U.S. forests, on average, is four times greater today than it was in 1970-1986.²⁹ Obviously, there is substantial variation from region to region.

The average length of fire season (the time between the first wildfire discovery date and the last wildfire control date) has increased by 78 days (64%) since 1970. The wildfire season is expanding its reach earlier into spring and later into fall.²⁸

There is much debate over whether fire severity has already increased,



compared to early historical times.³⁰ Fire severity throughout the Western U.S. can be expected to increase given warmer and drier conditions.³¹ An assessment of climate change and forest fires over North America projected 10-50% increases in seasonal severity rating (SSR) over most of the U.S.³² Regional variation, however, means that not all areas will see such increases, and forest management will need to be based on local and regionally-specific information.

Lightning strikes are also expected to increase with increasing CO₂ in the atmosphere³³, potentially affecting fire frequency.³¹

Of note is the fact that the potential drivers of wildfire extent and severity throughout the western U.S. are primarily climatically driven. Whether future wildfire risk can or should be abated through fuels treatment remains unclear.³⁰ Most western forests are highly adapted to wildfire, and even the most severe fires have been shown to (1) have been common across pre-settlement landscapes, and (2) have positive long-term benefits for forests and biological diversity.³⁵

MC1 Dynamic Vegetation Model

In this section we present the results of the MC1 dynamic vegetation model.²⁷ MC1 is a widely used dynamic global vegetation model (DGVM) that simulates vegetation types, ecosystem fluxes of carbon, nitrogen, and water, as well as wildfire occurrence and impacts. MC1 is routinely implemented on spatial data grids of varying resolution (i.e., grid cell sizes ranging from 900 m² to 2500 km²). The MAPSS Team (Mapped

Atmosphere-Plant-Soil System) at the USFS Pacific Northwest Research Station used two global climate models (GFDL and PCM) and the A2 emissions scenario to provide input variables to MC1.

The model reads climate data at a monthly time step and calls interacting modules that simulate biogeography, biogeochemistry and fire disturbance.

Most climate models project the future climate at global scales. Managers and decision makers, however, need information about how climate change will impact the local area. The MAPSS Team adjusted global model output to local and regional scales (800 m). This process increases the precision of the projections, but not the accuracy; they are still associated with high uncertainty and variation, especially because they are based on only 2 global climate models.

The MC1 model provides projections for suitable climate for predominant vegetation types rather than individual species. It only makes projections for native vegetation and does not account for land use change (i.e. agriculture and development), introduced species (i.e. non-native grasses), or human ignition.

Finally, the MC1 model assumes immediate shifts from one type of mature vegetation to another, without consideration of dispersal, establishment or succession. A lag time, which is not considered in the model, is expected between changes in climate conditions and establishment and maturation of new vegetation types on the ground – this lag time could be decades or even centuries.

MC1 Results

MC1 vegetation projections indicate an expansion of temperate evergreen needleleaf forest at higher elevations and a concomitant decline in alpine areas (listed as “tundra”; Fig. 73). Subalpine forest is expected to shift to higher elevations. Similar patterns were projected for much of the Sierra Nevada range.³⁶

At lower elevations, temperate grassland is expected to be replaced by subtropical grassland and a mid-elevation band of subtropical shrubland.

The results from MC1 showed an increase in biomass consumed by wildfire over time – doubling by mid-century and tripling or quadrupling by late-century (Table 6; Fig. 74). The area burned, however, is not expected

to increase to the same degree (Table 6; Fig. 75). This indicates that wildfires could become more severe, as compared to the historic period of 1961-1990, and/or that changes in vegetation type and condition could cause more biomass to be consumed.

The MC1 projections show an overall increase in carbon storage in vegetation over time, although a slight decrease is also possible (Table 6; Fig. 76).

Important to note is that MC1 projects the vegetation that the future climate is most suitable for, but transitions in vegetation are highly uncertain and can take decades to centuries to occur. Also, MC1 does not account for non-native species or vegetation altered by people.

Table 6. Modeled historic (1961-1990) and future wildfire trends across the Southern Sierra Nevada, based on the MC1 dynamic vegetation model and 2 global climate models, GFDL and PCM. Variables include annual average biomass consumed by wildfire (measured in grams of carbon per m²), percent of grid cell burned by wildfire, and maximum carbon storage in vegetation (measured in grams of carbon per m²).

	Historic	2010-39	2040-69	2070-99
BCW	99	171 to 203 (+73 to +105%)	183 to 263 (+84 to +166%)	282 to 374 (+185 to 277%)
PB	3.2%	3.4 to 3.8% (+6.6 to +20.1%)	3.0 to 4.0% (-6.6 to +25.8%)	3.8 to 5.3% (+20.1 to +65.4%)
CS	12,577	13,150 to 13,174 (+4.6 to +4.7%)	13,164 to 14,542 (+4.7 to +15.6%)	12,508 to 16,292 (-0.6 to +29.5%)

Figure 16. Modeled current and future vegetation type across the Southern Sierra Integrated Regional Water Management area in California, based on output from 2 different global climate models (GFDL and PCM), the A2 emissions scenario, and the MC1 dynamic vegetation model. Note that the MC1 model does not consider current vegetation or land use change.

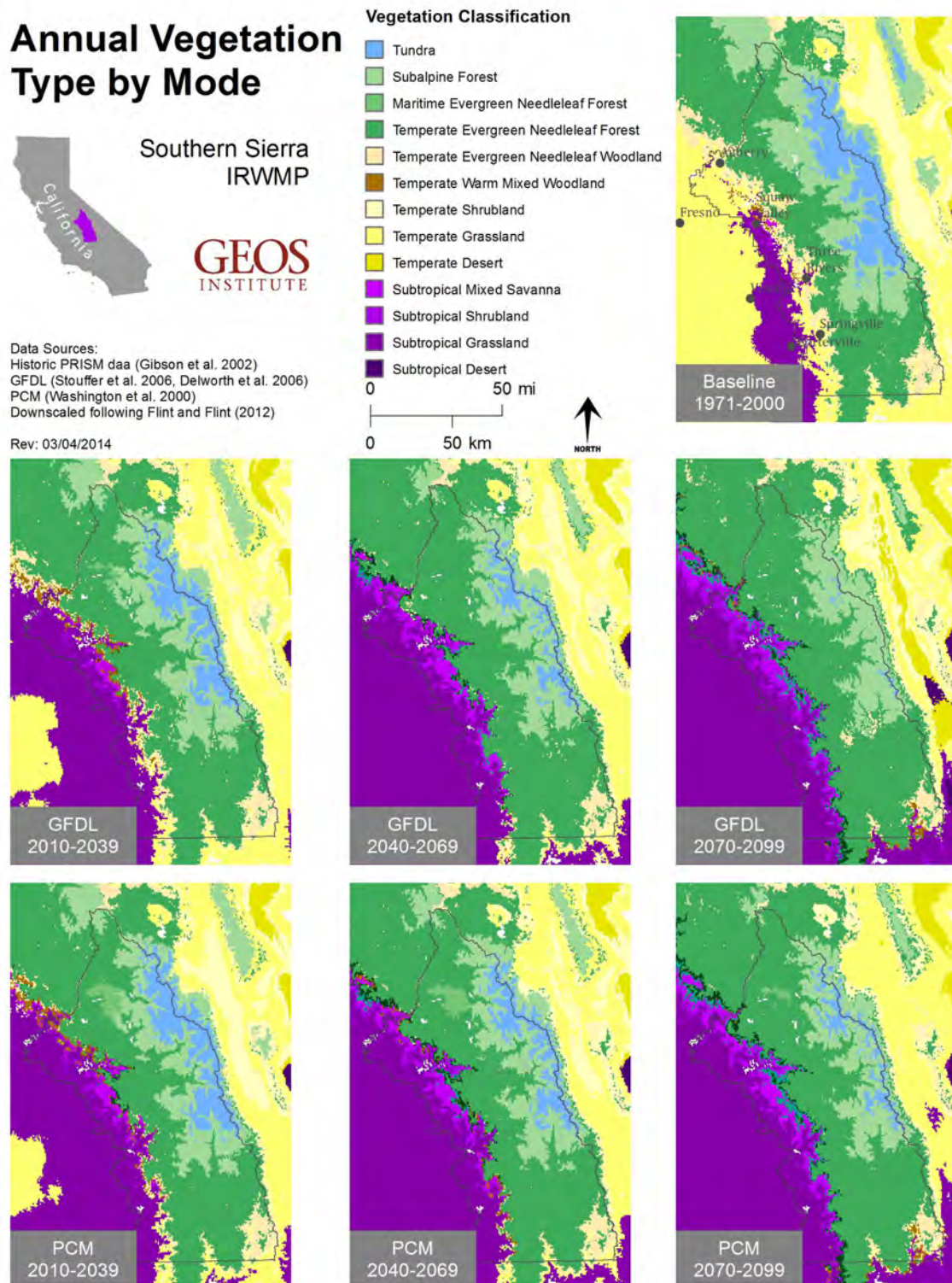


Figure 17. Modeled current and future biomass consumed by fire across the Southern Sierra Integrated Regional Water Management area in California, based on output from 2 different global climate models (GFDL and PCM), the A2 emissions scenario, and the MC1 dynamic vegetation model. Note that the MC1 model does not consider current (actual) vegetation or human influence.

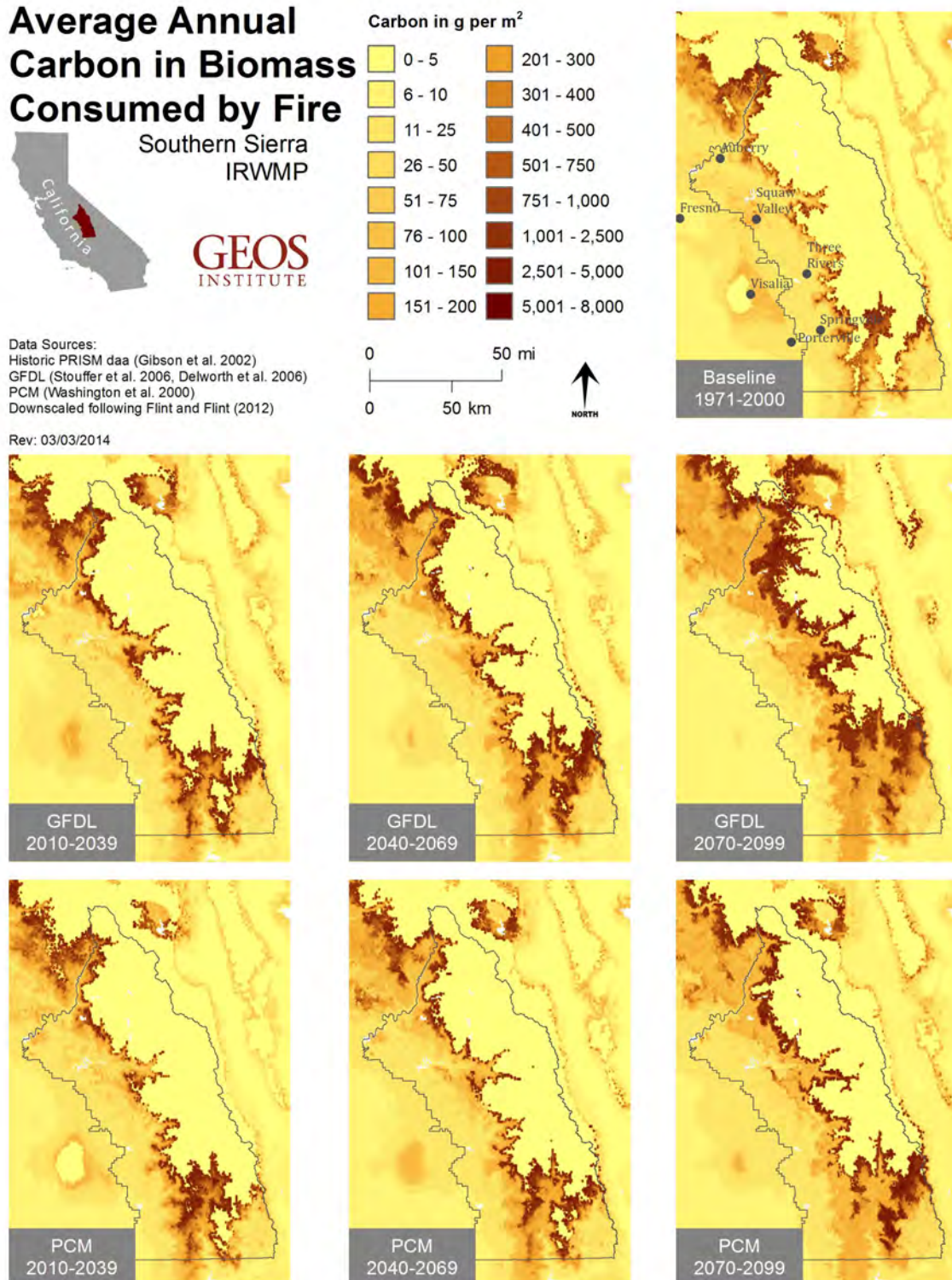
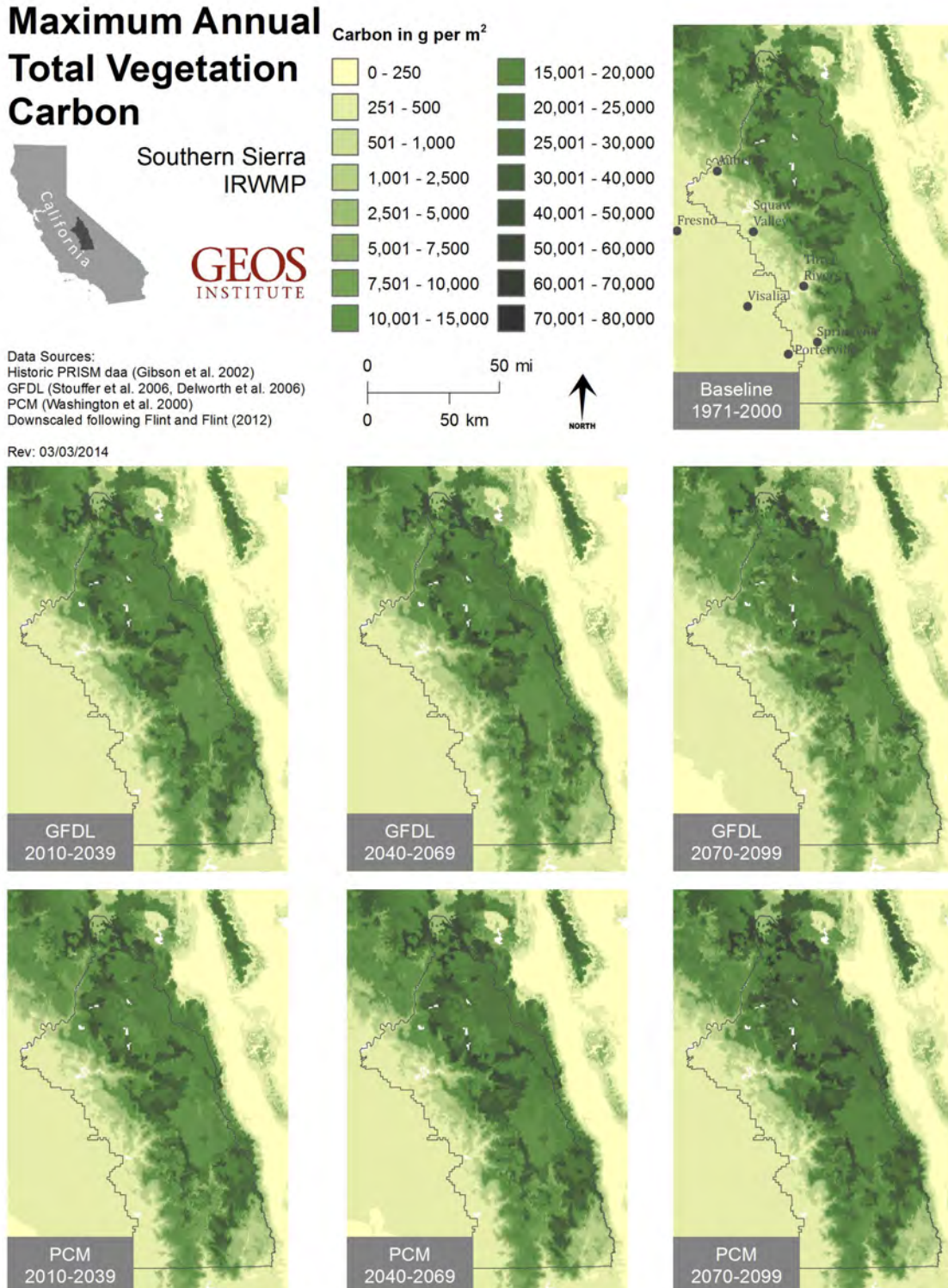


Figure 18. Modeled current and future annual vegetation carbon across the Southern Sierra Integrated Regional Water Management area in California, based on output from 2 different global climate models (GFDL and PCM), the A2 emissions scenario, and the MC1 dynamic vegetation model. Note that the MC1 model does not consider current (actual) vegetation or human influence.



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