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Development, delivery, and application of data on climate extremes for the southwestern United States

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Principal investigator: Erica Fleishman, University of California, Davis and Colorado State University, efleishman@ucdavis.edu

Co-principal investigators: Dan Cayan, Scripps Institution of Oceanography, University of California, San Diego; Alexander Gershunov, Scripps Institution of Oceanography, University of California, San Diego; Kelly Redmond, Desert Research Institute (through 2016); Tamara Wall, Desert Research Institute (after 2016)

Other project personnel
  - Britta Daudert, Desert Research Institute
  - Kristen Guirguis, Scripps Institution of Oceanography
  - Ben Hatchett, Desert Research Institute
  - David Pierce, Scripps Institution of Oceanography
  - Mary Tyree, Scripps Institution of Oceanography

Graduate student researchers
  - Frank Fogarty, University of California, Davis
  - Martha Wohlfeil, University of California, Davis

Other collaborators
  - Tim Brown, Desert Research Institute
  - Ana Davidson, Colorado State University
  - Jordan Goodrich, Scripps Institution of Oceanography
  - Janin Guzman Morales, Scripps Institution of Oceanography
  - David Lightfoot, University of New Mexico
  - Tom Miller, Rice University
  - Jennifer Rudgers, University of New Mexico
  - Kristen VanderMolen, Desert Research Institute

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PURPOSE AND OBJECTIVES

We aimed to improve the scientific capacity to estimate climate extremes, evaluate their effects on natural resources, and enhance a platform for derivation of and access to customized climate information for the full extent of the Southwest. Extreme climate can have substantial effects on species, ecological and evolutionary processes, and the health of visitors to public lands. Researchers generally can specify the climate-extreme metrics, and the extents and resolutions of those metrics, most relevant to their scientific objectives and the practical applications of their work. However, such application-specific data rarely are available.

We screened global climate models (GCMs) on the basis of their realism in representing natural regional patterns and extremes of temperature and precipitation, including those driven by El Niño and La Niña. We provided qualitative assessments of the extent to which each GCM represented different climate elements. We delivered gridded observations and downscaled model projections, at daily and 6 km resolution, on past and future extreme temperature and precipitation. Additionally, we used downscaled data on temperature and precipitation to drive a hydrologic model and derive probabilistic estimates of water availability, flood, and drought. Simultaneously, we worked with research and management groups in the Southwest that either are making decisions about management of natural resources given climate extremes, or working directly with federal decision-makers to project biological responses to climate extremes.

METHODS AND RESULTS

Regional screening and selection of global climate models

David Pierce used other sources of funds to apply the localized analog statistical downscaling method (LOCA) to more than 30 global climate models and two representative concentration pathways (RCPs), 4.5 and 8.5. Temperature and precipitation from the GCM simulations have been downscaled for the conterminous United States, southern Canada, and much of Mexico. Pierce and colleagues screened these models on the basis of their ability to replicate climate variables at global, regional, and California-wide extents. They used the LOCA data for the 10 models that were retained following the screening process as inputs to a variable infiltration capacity model (6 km resolution across California and Nevada), which they used to simulate surface water and energy balances.

In 2016, Pierce resolved a modest temporal discontinuity in the LOCA runs for 2000–2005 period. It was necessary to bias-correct the data for this period to the 30 years before and after. The resolution improved the way that the bias correction is implemented across the transition between the historical training period (1950–2005) and the future period (2006–2100). After making the corrections, he reimplemented the downscaling and released the final LOCA data.

Temperature extremes

Guirguis, Gershunov, and Cayan studied winter temperature variability in the southwestern United States. They quantified variation across space and time in the shape of probability density functions (PDFs) of daily temperatures that were resolved at 6 km over the southwestern United

States, and the contribution of daily extreme temperatures to that shape during a season (Guirguis et al. 2015). They investigated the relation between changes in central tendency and extreme probability by fitting a skew-normal distribution to daily temperature PDFs at each location. The skew-normal is specified by three parameters: location, scale, and shape. Location is a measure of central tendency, scale is a measure of variation, and shape is a measure of skew.

The team found that in some parts of the western United States, especially the Front Range and Great Plains, cold extremes differentiate a cold winter from a warm winter. A cold winter is defined on the basis of the location parameter, which represents the central tendency of the distribution, or typical temperatures, but has relatively low sensitivity to extremes. For example, in eastern New Mexico, anomalously cold winters are characterized by a relative absence of warm extremes, whereas cold extremes occur during most winters. By contrast, in coastal California, cold winters are characterized by a relatively high number of cold extremes, whereas warm extremes occur during most winters; warm winters are characterized by a relative absence of cold extremes. Warm extremes during winter in coastal California also are characterized by Santa Ana winds. It may be possible to project the frequency of cold and warm extremes (e.g., the probability of exceeding a certain temperature, or the number of days above freezing) in addition to seasonal means.

When the investigators applied the skew normal distribution to LOCA data for summer, they found little difference in the ability of different downscaled models to reproduce observed distributions of climate variables. The distribution was a relatively good fit to data on maximum temperature, but not to data on minimum temperature. Topographic heterogeneity in the southwestern United States can lead to considerable variation in local climate at relatively fine spatial resolution. Minimum temperatures tend to be idiosyncratic and locally determined, especially in montane areas; differences between minimum temperatures in valleys and mountains are more pronounced than those between maximum temperatures. Across the western United States, minimum temperatures during the summer are more strongly connected to the Pacific Ocean sea surface temperatures than are maximum temperatures, which are more closely related to soil moisture.

Heat extremes. Guirguis et al. (2018) found that variation in maximum summer temperature decreased from north to south. The strongest negative skew in the PDF (longer cold tails and shorter warm tails) occurred over the Rocky Mountains and Intermountain West. Weak negative skew occurred over southern Arizona and New Mexico, and positive skew (longer warm tails and shorter cold tails) occurred over coastal California. Minimum summer temperature was less variable than maximum summer temperature. Guirguis et al. observed greater variation in minimum temperature over the Intermountain West than along the California coast or locations with a maritime climate affected by the Gulf of Mexico. Near the coast, heat waves (defined as temperatures exceeding the historical [1961–1990] 95th percentile) were extremely hot relative to typical temperatures.

Across the southwestern United States, heat waves are likely to become more humid, and to be expressed via nighttime rather than daytime temperatures. This pattern likely is related to warming of the oceans, which is intensified west of Baja California. Warming of the ocean surface over a region from which air is advected during strong heat waves in California increases the humidity of the circulation patterns that drive the heat waves. About half of the ten GCMs did not effectively represent synoptic circulation patterns that are responsible for heat waves over California and the southwestern United States.

With respect to maximum temperature, the probability of heat waves increased dramatically over the Great Basin, inland California, and some parts of Texas. With respect to minimum temperature, the greatest increases in the probability of heat waves occurred along the Gulf Coast and coastal California. Increases in the number of heat waves were more likely in locations with short warm tails than long warm tails. As tail length and variance in the PDF increased, the probability of heat waves decreased.

Although climate models suggest that increases in temperature are likely to be greater in the northern than the southern part of the southwestern United States (e.g., the Four Corners region), the probability of future heat waves in the north was somewhat reduced by the region's relatively long warm tails. By contrast, the probability of future heat waves in the south was increased by that area's short-tailed PDFs. Across most of the Southwest, projected increases in future maximum temperature were greater than increases in future minimum temperature. However, the probability of extremely high minimum temperatures increased more quickly than the probability of extremely high maximum temperatures.

Cold extremes. The work of Guirguis et al. suggested that the speed of decreases in the number of extreme cold events during winter is negatively correlated with the length of cold tails in the temperature PDF. They found that the number of cold spells in coastal areas of California and California's interior valleys may increase in response to poleward migration of the storm track, which in turn reflects uneven warming across the globe.

To evaluate historical and potential future cold extremes in the western United States, Daudert, Guirguis, Gershunov, and Hatchett conducted a principal component analysis of daily minimum and maximum temperatures during winter (December–February) with nine downscaled global climate models and a historical gridded temperature product (Livneh et al. 2013)[1]. These GCMs previously were identified as the most appropriate for climate assessments in the western United States (California Department of Water Resources 2015)[2].

For each grid point, the team defined a cold index as the number of degrees below the 5th percentile (based on the 1951–2005) observed at that location on a given day. When aggregated across the western United States, they found that the increase in minimum temperature, about

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[1] Livneh, B., E.A. Rosenberg, C. Lin, B. Nijssen, V. Mishra, K.M. Andreadis, E.P. Maurer, and D.P. Lettenmaier. 2013. A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States: update and extensions. Journal of Climate 26:9384–9392.

[2] California Department of Water Resources. 2015. Perspectives and guidance for climate change analysis. California Department of Water Resources Climate Change Technical Advisory Group. Available at http://www.water.ca.gov/climatechange/docs/2015/Perspectives_Guidance_Climate_Change_Analysis.pdf

0.1° per decade, was not statistically significant ($p = 0.22$). The trend in the summed cold index was statistically significant ($p < 0.05$); cold extremes are becoming less frequent. Extremes of minimum temperature were most common in the lee of the Cascades, the panhandle region of Idaho, western Montana, and east of the Rockies in Wyoming. Minimum-temperature cold extremes also were noticeable in southwestern Utah, central and eastern Montana, eastern Colorado, and the northern Great Basin. Maximum-temperature cold extremes most frequently occurred throughout Montana, east of the Rockies in Wyoming and Colorado, and in north-central Oregon and south-central Washington. The principal component analysis of minimum-temperature cold extremes indicated a dipole in cold extremes between the Pacific Northwest and the Four Corners region. The analysis also indicated that the Four Corners region was distinct from the Pacific Northwest and the eastern Montana / High Plains region. The results generally were consistent with the physical mechanisms that produce cold outbreaks in winter.

The analysis of downscaled GCMs indicated that cold extremes will become warmer and less frequent. Several models produced spatial patterns of variance in the principal component analysis that were similar to those in the historical period, indicating that these models effectively simulated the global processes that create cold extremes.

Temperature extremes and wind

Janin Guzman Morales and Gershunov explored Santa Ana winds, which not only affect the severity of wildfires in southern California, but can produce coastal heat waves in seasons other than summer. Guzman Morales found that Santa Ana winds typically begin in early autumn and may continue through late spring, peaking in December and January. The highest temperatures along the coast generally are associated with Santa Ana winds that occur early (September – October) or quite late in the season (April – May). Guzman Morales and Gershunov developed a novel, 65-year database of Santa Ana winds at 10 km spatial and hourly temporal resolution on the basis of a dynamical downscale of the NCEP / NCAR Reanalysis, validated these modeled winds with observations from Remote Automated Weather Stations and Automated Surface Observing Stations, and examined their response to El Niño Southern Oscillations and Pacific Decadal Oscillations that were not apparent in the shorter time series previously available (Guzman-Morales et al. 2016).

Analysis of warm-season temperatures from 1999–2013 indicated that along the San Diego coast, nearly 50% of hot days (> 85°F) that occurred in May were attributable to Santa Ana events. In October, more than 70% of hot days were attributable to Santa Ana events. Early season heat waves strongly affect human health because they generally occur before the population has acclimated to summer warm weather. In related work, Guirguis et al. (2014)[3] found that many of the recent heat waves in California that had adverse effects on human health occurred in May.

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[3] Guirguis, K., A. Gershunov, A. Tardy, and R. Basu. 2014. The impact of recent heat waves on human health in California. Journal of Applied Meteorology and Climate 53:3–19.

Automated method for detection of atmospheric rivers

Gershunov and colleagues developed a novel method to automatically detect atmospheric rivers. Atmospheric rivers are detected on the basis of integrated vapor transport (vertically integrated, wind-driven movement of water vapor through the atmospheric column) rather than by precipitation.

Gershunov et al. (2017) applied the method to the National Center for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) 69-year reanalysis product, yielding a catalog of atmospheric rivers that reached the west coast of North America (20–60°N) from 1948–2016. They evaluated the catalog in two ways. First, they compared it to an existing catalog that was based on special sensor microwave imager (SSM / I) satellite observations of long, narrow plumes of enhanced, vertically integrated water vapor from 1997–2015 (Neiman et al. 2008)[4]. Second, they compared the contribution of atmospheric rivers from both catalogs to precipitation resolved over the western United States at daily, 6-km resolution (Livneh et al. 2013).

Identification of the strongest atmospheric rivers by the two catalogs was similar. Relative to the SSM / I-based catalog, the Gershunov et al. catalog contained a greater number of atmospheric rivers during winter and fewer atmospheric rivers during summer, which is less windy but more humid than winter. The Gershunov et al. catalog reflected a greater amount of accumulated precipitation and more-intense storms, reflecting atmospheric rivers associated with heavy orographic precipitation over the coastal ranges and, to some extent, inland mountain ranges. Additionally, the latter catalog accounted for heavy precipitation over the interior mountains and deserts, which are associated with atmospheric rivers that reach Baja California, more effectively than the SSM / I-based catalog.

Gershunov et al. (2017) found that the seasonality in the intensity and frequency of atmospheric rivers differed significantly along the west coast of North America. Pacific decadal variability and warm sea surface temperatures off the coast of British Columbia were associated strongly with the activity of atmospheric rivers that made landfall. Furthermore, they detected an increase in atmospheric river activity associated with a long-term warming trend in Pacific sea surface temperatures. These results provided additional motivation for evaluating the attributes of atmospheric rivers in GCM projections.

Accordingly, Gershunov applied the method for detection of atmospheric rivers to projections of GCMs. They evaluated 16 models on the basis of their ability to realistically simulate the seasonal cycle of atmospheric river landfalls along the West Coast, and the contribution of atmospheric river-related precipitation to total precipitation. Their results were consistent with those from Polade et al. (2017), which projected that precipitation will become less frequent, but more intense. The results of the current work indicate that precipitation from storms that are not

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[4] Neiman, P.J., F.M. Ralph, G.A. Wick, J.D. Lundquist, and M.D. Dettinger. 2008. Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the west coast of North America based on eight years of SSM/I satellite observations. Journal of Hydrometeorology 9:22–47.

produced by atmospheric rivers will decrease, whereas extreme precipitation associated with atmospheric rivers will increase. All 16 of the models projected an increase in atmospheric river activity. The most realistic models suggested that the amount of precipitation delivered by atmospheric rivers will increase by 20–30%. Gershunov et al. projected that thermodynamic changes will lead atmospheric rivers to become wetter, wider, and longer as temperatures increase as a result of increased moisture in the atmosphere. Additionally, they projected that the flow direction of future atmospheric rivers will be more southwesterly at landfall, resulting in a more effective delivery of moisture onshore. These changes likely will affect hazards such as flood and debris flow, particularly on the Transverse Ranges of southern California.

Gershunov and Guirguis also examined the extent to which atmospheric rivers can be predicted at seasonal to subseasonal resolution. They found that precipitation associated with atmospheric rivers was less predictable than precipitation that was not associated with atmospheric rivers. Additionally, they discovered that the predictability of seasonal precipitation has decreased since the 20th century. The El Niño Southern Oscillation (ENSO) traditionally has been used as the main predictor of winter precipitation in the western United States. Recently, however, ENSO has not predicted the amount of precipitation effectively. Accordingly, Gershunov et al. are using simulations from GCMs to examine the extent to which the decadal modulation of ENSO in the early 20th century can be explained by natural sampling variability and, if warranted, to identify additional physical drivers of this modulation.

Moreover, with the goal of improving subseasonal to seasonal predictions of water availability in the western United States, Guirguis and Gershunov investigated relations between spatially extensive climate variability and atmospheric rivers that make landfall. They identified dominant circulation patterns associated with atmospheric rivers that make landfall and explained how seasonal variation in the prevalence of certain circulation features modulates the frequency of landfalls at different latitudes in a given year (Guirguis et al. in press). Recent wet and dry years in California were related to the relative frequency of favorable versus unfavorable atmospheric states. The majority of atmospheric river landfalls along the west coast were associated with a small number of circulation features, which may improve predictive capacity.

Focusing on northern California, Guirguis et al. (unpublished manuscript) examined the effects of different phases of spatially extensive climate modes on the characteristics of atmospheric rivers, including their ability to drive westerly versus southwesterly landfall orientations and relations between orientation and variability in moisture transport and precipitation over California. The results suggested that the ENSO, which they previously discovered did not affect the number of atmospheric river landfalls, has substantial effects on landfall orientation, which affects inland vapor transport and precipitation patterns in California and across the western United States. Regional connections among the Arctic Oscillation, Western Pacific Oscillation, and Eastern Pacific Oscillation also strongly affect characteristics of atmospheric rivers that make landfall in northern California. The work of Guirguis et al. suggested that regional climate modes have a greater effect on atmospheric-river related variability of precipitation in California than does ENSO.

Hydrologic model simulations and applications

We completed hydrologic model simulations across the full extent of the Southwest for GCMs that were retained after the regional screening process. Management partners, including the US Bureau of Reclamation, are evaluating the outputs of these models and their applicability to meeting management objectives.

We examined projected spatial and temporal changes in precipitation in the Colorado Basin on the basis of the CMIP5 GCM simulations, assuming either RCP 4.5 or RCP 8.5. Our projections included changes in temperature and VIC-simulated changes in runoff and soil moisture. We examined how different temperature and pressure patterns are associated with changes in Colorado River flow. With primary support from the US Bureau of Reclamation and supplementary support from this grant, we evaluated representation of climate mean and variability in the Colorado River Basin by CMIP3 and CMIP5. We ranked the GCMs on the basis of their fidelity in reproducing observed climate patterns. This work included several novel elements. For example, because in practice, bias correction is applied to model results before they are used, we ranked the GCMs after conducting a simple bias correction. We also examined streamflow bias correction in the Colorado River Basin and determined that a commonly used method, quantile mapping, systematically makes projections of future streamflow in the Colorado River Basin that are too wet.

Snow level rise and snow droughts in the Sierra Nevada

As the climate warms, precipitation in the Sierra Nevada is likely to shift from snow to rain. To address anecdotal evidence suggesting an increase in winter rainfall over the past decade, we capitalized on an existing observational network of vertically oriented radars along the western slope of the northern Sierra Nevada. The snow-level radars provide an hourly estimate of the brightband elevation, the elevation of the transition between snow and rain. We found that in over the past 10 years, the average brightband elevation in the northern Sierra Nevada increased by 72 m per year (Hatchett et al. 2017). During the same period, hourly weather stations indicated a decrease of about 3% per year in the percentage of precipitation falling as snow (the snow fraction). Daily data from weather stations indicated that the recent ten-year trend also was the steepest decline in snow fraction from 1951–2017. Much of the increase in brightband elevation appeared to be attributable to atmospheric rivers, which tend to deliver a greater proportion of precipitation as rain than winter storms that are not driven by atmospheric rivers. The correlation between winter snow fraction and sea surface temperature was negative and statistically significant, suggesting that continued regional ocean warming will contribute to further temperature increases that increase brightband elevation (lower snow fractions) and, ultimately, decrease the proportion of precipitation falling as snow.

Snow droughts are periods of below-normal snowpack. There are two primary classes of snow drought, dry and warm. A dry snow drought occurs when both snowpack and precipitation are below normal. A warm snow drought is characterized by below-normal snowpack but near-normal or above-normal precipitation—a winter in which more precipitation falls as rain than snow. Hatchett and McEvoy (2018) examined the origins and evolution of northern Sierra Nevada snow droughts. They found that the drivers of warm snow droughts are diverse. Warm snow droughts result from extreme precipitation events that contribute substantial rainfall and from early spring melting. Thus, snow water equivalent on 1 April may be well below normal whereas accumulated precipitation is above normal. A case of

warm snow occurred during April 2018, when an atmospheric river that originated as an early season western Pacific typhoon was entrained into the midlatitude flow and ultimately made landfall on the California coast. The snow levels during this storm were the highest observed (> 4000 m) since installation of the snow-level radar network. Hatchett (2018) documented numerous effects of the storm, such as avalanches, debris flows, and high elevation flooding (including the tenth greatest all-time and greatest April flow observed on the Merced River in Yosemite Valley). This event produced heavy precipitation and led to near-normal water year precipitation following an extremely dry winter and wet March. However, the event did not contribute to snowpack accumulation. Therefore, classifying the snow drought during water year 2018 in the Sierra Nevada, and characterizing its effects, is challenging given that the majority of the winter was classified as dry snow drought but the water year ended with wet snow drought. The snow level and snow drought work highlights the value of weather and climate data with high temporal resolution (hourly to monthly) and of a historical perspective on the causes and effects of snow drought. Hatchett and McEvoy are working with the National Oceanic and Atmospheric Administration's National Integrated Drought Information System group to build and improve a web page on snow drought conditions.

Responses of southern California birds to climate variability and change

Much research has examined whether long-term changes in phenology are associated with climate change. In temperate ecosystems, birds often are a focus of such work. They are relatively easy to observe, spatially extensive observational networks such as the North American Breeding Bird Survey (BBS) exist (albeit with caveats about data quality or applications), their natural history is relatively well known, and a number of aspects of their ecology or life history are known or reasonably can be hypothesized to be associated with changes in climate. Research also has capitalized on long-term observational records (again with caveats) to identify trends in distribution, and to associate those trends with changes in land use, land cover, or climate.

By comparison, relatively little work has examined whether long-term variation in abundance of birds is associated with long-term variation in weather or climate. Abundance and variation are more relevant to drawing inference to long-term viability than distribution data. Fogarty, Cayan, and Fleishman assessed whether variation in abundance of passerine birds in southern California at different temporal extents and resolutions, from annual to decadal, are associated with regional variation in temperature and precipitation, and with atmospheric circulation patterns that are more spatially extensive. BBS data for southern California include about 60 routes, some of which have been sampled for many decades. Additionally, the density of weather stations in southern California is fairly high, increasing confidence in modeled values of climate variables. We examined whether changes in the estimated abundances of birds at different temporal extents and resolutions, from annual to decadal, were consistent with changes in climate. We selected 41 taxa with relatively high abundances and that collectively represented diverse life histories, land-cover associations, and nesting strata. We derived variables for two hypothesized drivers of abundance (precipitation and surface air temperature) for three seasons: June-August (summer) of the previous year, the season during which the potential for juvenile mortality is high and the driest and warmest months; December-February (winter) prior to the surveys, the season during which most precipitation occurs in the region and therefore the period with the greatest effect on primary productivity; and March-May (spring), the season during which most species are establishing breeding territories and high primary productivity likely continues.

Abundances of 33 of 41 species were significantly associated with either temperature or precipitation in winter or spring. Abundances of an additional 5 species were significantly associated with temperature or precipitation in the previous summer. Of the climate variables we examined, winter precipitation, winter temperature, and spring temperature appeared to be the most consistently associated with abundances of breeding birds. Most (6 of 7) of the largest magnitude associations on abundance were for either winter precipitation or spring temperature. This may reflect that winter had the highest average precipitation and the most annual variation among routes, and spring temperature was the most varied among routes

Abundances of species grouped by land-cover associations, nesting strata, or migration were not consistently associated with previous-summer precipitation, maximum previous-summer temperature, or spring precipitation. The lack of association between abundance and previous-summer variables may be due to the lag between the effects and observations. Abundances of a limited number of species (11) were associated with spring precipitation, and responses were both negative (6 species) and positive (5 species). Much of the spring precipitation may fall after breeding birds have established territories and begun breeding. Also, BBS sampling is conducted before most species fledge, so the counts do not reflect any effects of spring precipitation on reproductive output.

Differences in the ecology of groups of birds that are associated with different land-cover types, nesting strata, or migration patterns might explain their distinct associations with climate. For example, the patterns we observed generally were consistent with hypotheses that increases in aridity will negatively affect desert or semidesert shrubland species. However, our results suggested that the abundances of bird species in forests and oak woodlands may not be limited by precipitation. Although our results indicated that some forest and woodland bird species may benefit from increases in temperature, it is unclear how the trees themselves will respond.

Responses of Sevilleta grasshoppers to climate variability and change

The densities of grasshoppers (Hexapoda: Orthoptera: Acridomorpha) fluctuate substantially over time in response to variation in temperature and precipitation, which has both direct physiological effects and effects on their food sources, competitors, predators, parasitoids, and disease. Changes in climate means and variances almost certainly will affect grasshoppers and other invertebrates across the southwestern United States.

We are working with David Lightfoot and Jennifer Rudgers (University of New Mexico), Ana Davidson (Colorado State University), and Tom Miller (Rice University) to apply climate sensitivity function analyses to grasshoppers. Linear and nonlinear climate sensitivity models allow one to evaluate the effects of both mean climate and climate variance on animal and plant populations (Rudgers et al. 2018)[5].

Rudgers et al. (2018) used the standardized precipitation evapotranspiration index (SPEI) as a measure of water availability over four to five years. They found that the response of above-ground plant production differed among ecosystems in the same semi-arid region over the same period of time. Our colleagues surveyed grasshoppers in the same locations and over the same time period in which Rudgers et al. measured above-ground plant production. We are evaluating whether the responses of grasshoppers and plants to mean climate and variation in climate are similar.

Data on weather, vegetation, and grasshoppers were collected at the Sevilleta National Wildlife Refuge (Sevilleta) in central New Mexico as part of the Sevilleta Long-Term Ecological Research (LTER) program. Three major ecoregions converge in the Sevilleta: Chihuahuan Desert (grasslands dominated by black grama grass [*Bouteloua eriopoda*] and creosote bush [*Larrea tridentata*]), Arizona / New Mexico Plateau (dominated by blue grama grass [*Bouteloua gracilis*] and sacaton grasses [*Sporobolous* spp.]), and southwestern tablelands (woodlands dominated by one-seed juniper [*Juniperus monosperma*], pinyon pine [*Pinus edulis*]), and blue grama grass). Grasshoppers were sampled at four locations from 1992–2016, with some differences in which locations were sampled when. Sampling targeted species that are adults in late summer. Response variables were individual species of grasshoppers, groups that use similar substrates, and all species.

Scripts Institution of Oceanography is developing a proxy for SPEI from variable infiltration capacity model outputs. We anticipate that they will project SPEI to 2100 given RCP 4.5 and RCP 8.5. In the meantime, the team is using data on humidity, precipitation, temperature, and soil moisture and temperature that were collected from three meteorological stations near the study sites. They also are using data on precipitation from a nearby National Weather Service station.

Preliminary results suggested that densities of the full assemblage and of different groups were not associated strongly with short-term variation in climate. However, associations for some individual species were strong. For example, density of *Trimerotropis pallidipennis*, was significantly and positively related to temperature and aridity. This ongoing work will elucidate variation among species in potential adaptive capacity, and may allow projections of cascading effects through the food chain.

Information access through the SCENIC

Britta Daudert led integration of LOCA data, and then reintegration of updated LOCA data, into the Applied Climate Information System (ACIS). Users of the Southwest Climate and Environmental Information Collaborative (SCENIC) can access the outputs of ten GCMs (i.e.,

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[5] Rudgers, J.A., Y.A. Chung, G.E. Maurer, D.I. Moore, E.H. Muldavin, M.E. Litvak, and S.L. Collins. 2018. Climate sensitivity functions and net primary production: a framework for incorporating climate mean and variability. Ecology 99:576–582.

ensemble members), each linked with two RCP and providing data from 1950 through 2100 on maximum temperature, minimum temperature, and precipitation across the conterminous United States, Canada, and Mexico. We incorporated into SCENIC a primer on climate data, GCMs, downscaling methods, and selection of data for different applications, which was developed by graduate student researcher Frank Fogarty and Daudert.

From 2015 through 2017, we discussed with the Southwest Climate Science Center's director, Steve Jackson, the feasibility of serving not only data on temperature and precipitation but an additional ten variables derived from runs of the VIC model: evaporation, surface runoff, base flow, soil moisture (3 layers), snow water equivalent, snowfall rate, snow melt rate, snow sublimation, potential evapotranspiration (PET) for short crops, PET for tall crops, and PET for natural vegetation. These variables also are available for the full conterminous United States, Canada, and Mexico, and associated with the two RCPs and ten GCMs already stored and served. The utility of these data to stakeholders is diverse and extensive. The data are applicable to estimates of water availability to flora, fauna, and human uses, both currently and given alternative scenarios of climate change, climate extremes, and water allocation. The data are applicable to management of the probability of fire and flood, both directly (especially in the case of flood) and as mediated by vegetation. Additionally, the data are useful the US Department of Agriculture, university extension programs, and the agricultural communities they serve. Ultimately, it was not possible to access additional funds to support serving these data through SCENIC.

In 2017, the Western Regional Climate Center evaluated the content and usability of SCENIC on the basis of responses from end-users. They conducted semi-structured interviews with 11 end-users and three members of the Western Regional Climate Center technical team (WRCCT2) in April and May 2017. They also used web analytics to obtain information from March 2014 through May 2017, and collected testimonials from four end-users from 2016 through 2018.

The WRCC used grounded theory to analyze the data from the interviews and testimonials. They found that diverse end-users were satisfied with using SCENIC for a wide range of applications, and requested some additional content and enhancements. On the basis of their results and additional input from the WRCCT2, the WRCC recommend four ways to continued developing and engaging stakeholders with SCENIC. First, refine usability on the basis of feedback from current end-users. Second, augment sources of data with feedback from individuals affiliated with the former Landscape Conservation Cooperatives. Third, examine integration of additional data (e.g., snowpack telemetry [SNOTEL] Remote Automated Weather Stations {RAWS], California Data Exchange Center) on the basis of current and anticipated feedback from end-users. Fourth, improve the performance of SCENIC on the basis of current and anticipated feedback from end-users.

The WRCC aims to use developmental evaluation to investigate how stakeholders might use SCENIC and iteratively provide feedback. This work would facilitate expansion of SCENIC's user base, integrate SCENIC more fully into research under the auspices of the Southwest Climate Science Center, and enable the Center to become a leader in evaluation of climate tools. The WRCC also hopes to demonstrate use of climate data in research, planning, and products by governmental and private entities.

Collaborations with end-users

Sudden oak death. We applied data on climate extremes to research on *Phytophthora ramorum*, the aquatic pathogen that causes sudden oak death, and on mortality of tanoak and oak trees from this pathogen. Sudden oak death increases forest fuel loads, has killed millions of tanoak and oak trees, and can incur substantial costs through quarantine of the nursery trade. Temperature and precipitation affect the sporulation rate and frequency of infection of *P. ramorum*, and these relations are the basis of regional models of the likelihood of disease and its spread. Our partners in this work were Susan Frankel (USDA Forest Service, Pacific Southwest Research Station), Richard Cobb (Department of Plant Pathology, University of California, Davis), and Francesco Tonini and Ross Meentemeyer (North Carolina State University).

Our partners found that annual changes in the area of mortality from sudden oak death were most strongly associated with precipitation two years previous (i.e., a two-year time lag in response of mortality to precipitation). The relation between mortality and precipitation in the previous year was not statistically significant, and the relation between mortality and current-year precipitation was negative. When two-year lag precipitation was > 1200 mm, survival times of tanoak trees infected with *P. ramorum* were about two years. By contrast, when two-year lag precipitation was < 800 mm, survival times of tanoak trees infected with *P. ramorum* were three to four years.

Devils Postpile. Devils Postpile National Monument's location on the middle fork of the San Joaquin River, with high ridges on either side, is conducive to radiational pooling. The monument believes that cold-air pooling may provide a local microclimate refugium as the climate warms. Before the climate extremes project was launched, Cayan and colleagues assisted the monument in characterizing the data for each sensor or location and developing vertical and horizontal distributions of cold air.

Following a series of telephone conversations that included the full investigative team, Daudert and Fleishman traveled to Devils Postpile National Monument in July, 2015, where they met with the superintendent and the manager of the natural resource program. The monument was interested in learning whether the locations, timing (at any resolution), and environmental attributes associated with cold-air pooling or nighttime inversions are predictable.

It was unclear whether GCMs are suited to evaluating cold-air pooling that occurs at fine resolution and within a fairly small geographic extent (e.g., within one or two 6-km grid cells). Therefore, the project team and monument staff agreed that as a first step, the project team would assist the monument in exploring their many years of field data (gathered with thermal sensors) on daily temperature in greater detail. We agreed that if a reasonably strong pattern emerged, we will investigate whether the regionally screened GCMs could create the observed pattern if one included an area somewhat larger than Devils Postpile. Cayan is examining diurnal variation in temperature and the incidence of extremely cool temperatures in low-lying areas. Cayan and postdoctoral researcher Jordan Goodrich also aim to delineate where cold air pools occur across the river canyon.

Riparian restoration. Following an initial meeting at the Southwest Climate Science Summit in autumn 2015, we began collaborating with River Partners (www.riverpartners.org), a non-profit corporation based in Chico, California, on their restoration efforts near Stillwater National Wildlife Refuge near Fallon, Nevada. River Partners was interested in obtaining downscaled climate data for the Stillwater National Wildlife Refuge and Carson Sink. In the riparian areas in which they are trying to restore native vegetation, understory regeneration in spring and in late summer may be associated positively with soil moisture. Flows in the Truckee and Carson Rivers also likely are relevant to the potential success of restoration efforts. These flows affect water supply within the Newlands Project and Stillwater National Wildlife Refuge. Additionally, River Partners wished to identify the week or month in each year (observed and projected) that includes the hottest period. We discussed alternative ways to define heat waves, including differences between daytime and nighttime temperatures. Furthermore, we discussed whether future climate might affect water rights and efforts to purchase water or water rights. We worked with River Partners to match their focus areas to the available downscaled data. However, River Partner's focus area was quite small—one or two 6-km cells—and model uncertainty at that level of resolution is high. Also, the individual at River Partners who was most eager to work with the project team left the organization. As a result of these technical and personnel challenges, it was not feasible to sustain this collaboration.

Central Sierra Province, USDA Forest Service. In summer 2015, we began working with the USDA Forest Service to integrate climate extremes with forest planning for the Central Sierra Province. The Forest Service hoped to use data on climate extremes to inform upcoming forest plan revisions for the Eldorado, Tahoe, and Stanislaus National Forests. The planning rule emphasizes restoration of the function, structure, composition, and connectivity of ecosystems and watersheds to adapt to climate change and other ecosystem drivers and stressors. The planning cycle is about 15 years. However, projections at other temporal extents (e.g., 50 years) are relevant to planning.

The Forest Service was interested in identifying climate extremes relative to the thermal or hydrologic tolerances of individual species that are targets of management. For example, at temperatures above 35.2˚C, the resting metabolic rate of adult California Spotted Owls (*Strix occidentalis occidentalis*) increases substantially. Behavioral responses to heat stress have been observed at temperatures from 30–34˚C. Daudert provided the Forest Service with LOCA data on the location and duration of exceedances of 30˚C, 34˚C, and 35.2˚C within the portion of the species' range that falls within the Central Sierra Province. The Forest Service used the data in an internal report on California Spotted Owls to illustrate the mean number of days from May through September during which the daily maximum temperature exceeded 30˚C and 35.2˚C in 1985 and 2025 (assuming RCP 4.5), and the difference between those years.

The Forest Service also was interested in applying Hatchett's work on changes in the distribution of the elevation at which snow transitions to rain throughout the Sierra Nevada to their management planning. He will provide the agency with a time series of raster data on observed median snow levels over the past 15 years and raster data on changes in timing of the onset and termination of selected snow depth / water equivalent thresholds. The latter are based on a novel, 100-m resolution, daily snow water equivalent reanalysis product (Margulis et al. 2016)[6] for 1985–2016.

Snow depth and snow cover. Hatchett is working with the Winter Wildlands Alliance (WWA), a nonprofit organization that focuses on preserving winter-season, human-powered recreation in montane regions of the United States. The WWA is interested in changes in the location and timing of sufficient snow depth for various recreational uses, particularly over-snow vehicle use. As a result of a 2015 federal ruling, the Forest Service is required to engage in winter travel management planning and to develop plans for over-snow vehicle use. The work with the WWA is taking advantage of Natural Resource Conservation Service Snowpack Telemetry (SNOTEL) data and the snow water equivalent reanalysis product to examine trends in snow depth and snow water equivalent at over-snow vehicle trailheads and potential causes of these trends. The period during which snow depth at trailheads is sufficient for various recreational uses (over-snow vehicles and human-powered) has decreased by approximately two weeks in the past three decades, and appears to be related to increases in both rainfall and the frequency of dry days during early winter (Hatchett and Eisen unpublished). These results generally are consistent across the independent data from SNOTEL and the reanalysis product. The information generated by this project is being provided to Region 5 Forest Service offices that are conducting travel management planning, including the Lassen, Tahoe, and Eldorado National Forests. The project also is teaching people how to measure snow and enter the data into an app on their mobile telephone. As a result, data on snow depth are being collected from locations at which historical data are few or absent. Hatchett is working to link these citizen-collected data with near-real-time spatial snow depth products such as the snow data assimilation system (SNODAS). He also is exploring potential links with the Moderate Resolution Imaging Spectroradiometer and the Terra polar-orbiting satellite, which measure the normalized difference snow index on the basis of reflectivity; it may be possible to examine correlations between the spatial extent and depth of snow. These remote sensing products were used to demonstrate the elevational distribution of warm snow drought conditions by Hatchett and McEvoy (2018). Hatchett also is investigating relations between the remote sensing products and snow depth and snow cover.

Climate resilience for Reno, Nevada. Hatchett and Kristen VanderMolen worked with the City of Reno to inform development of the city's first sustainability report. Through a comprehensive literature review, they summarized data on the primary weather and climate hazards to which Reno is susceptible, such as flooding, fire, air quality, heat extremes, and drought. VanderMolen conducted interviews to collect information directly from city, state, and federal managers about the effects of different types of hazards, and individual events, on their ability to function. This information was condensed into a ten-page brief that was provided to about 200 city officials and other local and regional stakeholders at an inaugural city sustainability meeting in May 2018. The City of Reno is using the information provided by Hatchett and VanderMolen to develop a climate adaptation and resilience plan aligned with NOAA's Climate Resilience Toolkit.

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[6] Margulis, S.A., G. Cortés, M. Girotto, and M. Durand. 2016. A Landsat-era Sierra Nevada (USA) snow reanalysis (1985–2015). Journal of Hydrometeorology 17:1203–1221.

Hatchett also worked with the City of Reno sustainability manager's office and the University of Nevada Office of Undergraduate Research to produce two requests for proposals for undergraduate research on Truckee River flooding and urban heat extremes. The awards supported two undergraduates during the autumn and spring semesters of 2017–2018. Cory Rogaczewski explored how floods have changed over time, and how Reno has adapted via changes in policy and infrastructure. Adora Shortridge focused on historical heat extremes in Reno. Results indicated the nighttime temperatures are increasing substantially, which likely will affect public health given stress on vulnerable populations such as the young, elderly, or low income, or those with preexisting illnesses.

Klamath National Forest. The Klamath National Forest expressed interest in learning about projections of high runoff that may affect infrastructure (e.g., roads) and watershed ecology within their jurisdiction. Cayan engaged in several discussions with the Forest's hydrologist, who was enthusiastic about collaboration. However, it appeared that the hydrologist was unable to obtain interest and support from their regional office. As a result, collaboration was limited.

OUTPUTS

Peer-reviewed publications

Clemesha, R.E., A. Gershunov, S.F. Iacobellis and D.R. Cayan. 2017. Daily variability of California coastal low cloudiness: a balancing act between stability and subsidence. Geophysical Research Letters 44:3330–3338.

Clemesha, R.E., A. Gershunov, S.F. Iacobellis, D.R. Cayan, and A.P. Williams. 2016. The northward march of summer low cloudiness along the California coast. Geophysical Research Letters 43. doi: 10.1002/2015GL067081.

Gershunov A., T.M. Shulgina, F.M. Ralph, D. Lavers, and J.J. Rutz. 2017. Assessing the climate-scale variability of atmospheric rivers affecting western North America. Geophysical Research Letters 44:7900–7908.

Guirguis, K., A. Gershunov, and D. Cayan. 2015. Interannual variability in associations between seasonal climate, weather and extremes: wintertime temperature over the Southwestern United States. Environmental Research Letters 10:124023. doi: 10.1088/1748-9326/10/12/124023.

Guirguis, K., A. Gershunov, T. Shulgina, R.E.S. Clemesha, and F.M. Ralph. In press. Atmospheric Rivers impacting Northern California and their modulation by a variable climate. Climate Dynamics.

Guzman Morales, J., A. Gershunov, J. Theiss, H. Li, and D. Cayan. 2016. Santa Ana winds of southern California: their climatology, extremes, and behavior spanning six and a half decades. Geophysical Research Letters 43. doi: 10.1002/2016GL067887.

Hatchett, B.J. 2018. Snow level characteristics and impacts of a spring typhoon-originating atmospheric river in the Sierra Nevada, USA. Atmosphere 9:233. doi: 10.3390/atmos9060233.

Hatchett, B.J., B. Daudert, N.S. Oakley, C.B. Garner, A.E. Putnam, and A.B. White. 2017. Recent winter snow level rise in the Sierra Nevada, California, 2008–2017. Water 9:899. doi:10.3390/w9110899.

Hatchett, B.J. and D.J. McEvoy. 2018. Exploring the origins of snow drought in the northern Sierra Nevada, California. Earth Interactions 22(2):1–13. doi: 10.1175/EI-D-17-0027.1.

Lavers, D.A., F.M. Ralph, D.E. Waliser, A. Gershunov, and M.D. Dettinger. 2015. Climate change intensification of horizontal water vapor transport in CMIP5. Geophysical Research Letters 42:5617–5625.

Polade, S.D., A. Gershunov, D.R. Cayan, M.D. Dettinger, and D.W. Pierce. 2017. Precipitation in a warming world: assessing projected hydro-climate changes in California and other Mediterranean climate regions. Scientific Reports 7:10783. doi:10.1038/s41598-017-11285-y.

Invited presentations

2015 (April). Cayan, D. Causes and monitoring of drought. Plenary presentation, Chapman Conference on California Drought, University of California, Irvine.

2015 (August). Frankel, S.J. and R.C. Cobb. Risk of forest diseases given climate change: case study of *Phytophthora ramorum*. American Phytopathology Society, Pasadena, California.

2015 (September). Fleishman, E., D. Cayan, B. Daudert, A. Gershunov, and K. Redmond. Development, delivery, and application of data on climate extremes for the southwestern United States. Session on Extreme Tahoe—droughts, floods, and other natural experiments. Tahoe Science Conference, Reno, Nevada.

2015 (October). Fleishman, E. and D.S. Dobkin. Responses of wildlife habitat to climate variability and fire in sagebrush shrubsteppe and pinyon and juniper woodlands. Symposium on implications of "hotter drought" for forest ecosystems and their management in the southwestern United States. Biennial Conference of Science and Management on the Colorado Plateau and Southwest Region, Flagstaff, Arizona.

2015 (October). Fleishman, E. Reconciling statistical rigor and biological inference in occupancy models. University of Connecticut, Storrs.

2015 (November). Gershunov, A. Downscaling and understanding weather extremes in a changing climate. Southwest Climate Summit, Sacramento, California.

2016 (April). Fleishman, E., R. Scherer, M. Leu, and D.T. Pavlik. Reconciling statistical rigor and biological inference in models of butterfly occupancy. Symposium on current insect conservation: research and theory. Pacific Branch, Entomological Society of America, Honolulu, Hawaii.

2016 (April). Fleishman, E. Reconciling statistical rigor and biological inference in models of occupancy. Department of Fisheries and Wildlife, Oregon State University, Corvallis.

2016 (June). Fleishman, E. Climate change and management of endangered species. Continuing legal education conference on Endangered Species in California. Long Beach, California.

2016 (November). Fleishman, E. Natural history and land management in the western United States. National Taiwan University, Taipei.

2017 (January). Fleishman, E. Reconciling rhetoric, statistical rigor, and ecological inference in the Great Basin. Department of Fish, Wildlife and Conservation Biology, Colorado State University, Fort Collins.

2017 (March). Fleishman, E. Measuring and interpreting faunal responses to climate in the Intermountain West. Department of Atmospheric Science, Colorado State University, Fort Collins.

2017 (October). Hatchett, B.J., et al. Recent abrupt winter snow level rise in the northern Sierra Nevada. Gary Comer Conference on Abrupt Climate Change, Madison, Wisconsin.

2017 (October). McEvoy, D. and B.J. Hatchett. The hydrometeorological origins of snow droughts. Yosemite Hydroclimate Conference, Yosemite Valley, California.

2018 (March). Hatchett, B., N.S. Oakley, B. Daudert, C.B. Garner, and A.E. Putnam. Recent snow level rise in the northern Sierra Nevada: proximal causes and potential implications. Carson Water Subconservancy District 2018 Water Summit, Carson City, Nevada.

2018 (April). Hatchett, B., N.S. Oakley, B. Daudert, C.B. Garner, and A.E. Putnam. Sierra Nevada snow drought and snow level rise. Bill Foster Sierra Avalanche Center Professional Workshop, Squaw Valley, California.

Contributed poster

2015. Fleishman, E., D. Cayan, B. Daudert, S. Gershunov, and K. Redmond. Application of data on climate extremes for the southwestern United States (poster). American Geophysical Union, San Francisco, California.

OUTREACH AND ENGAGEMENT

In January 2015, our climate extremes group was included as collaborators in a preproposal to the National Estuarine Research Reserve System Science Collaborative by Karen Thorne (USGS). The project team also includes a research ecologist at the USGS Patuxent Wildlife Research Center and a research coordinator at a national estuarine research reserve in Imperial Beach, California. The proposed work would focus not only on estuaries in the San Francisco Bay and San Diego Bay but on estuaries in the Chesapeake Bay (Jug Bay and Monie Bay). Collaborative participants and end users named in the proposal include managers and biologists at national estuarine research reserves, US Fish and Wildlife Service wildlife refuges, and state and local refuges along the east and west coasts.

As an outgrowth of this project, Fleishman, Cayan, Pierce, Leroy Westerling (University of California, Merced), and others collaborated on development of wildfire scenarios for California’s fourth climate change assessment, an effort funded by the California Energy Commission via an award to Scripps. Our climate extremes group also collaborated on the project “Planning tools for new hydrology, changing lake conditions and new lake levels under extremes of climate,” which is led by Geoff Schladow, Director of the University of California, Davis’s Tahoe Environmental Science Center, and funded by the California Tahoe Conservancy. Additionally, Fleishman, Cayan, and Daudert, along with T. Creech, E. Rubin, S. Sesnie, and M. Williamson, are the investigators of “Forecasting resource availability for wildlife populations in desert grasslands under future climate extremes,” a project funded by the Southwest Climate Science Center in 2017.