

## Southwest Climate Science Center – Final Project Report # G13AC00336

1. **USGS Grant/Cooperative Agreement # : G13AC00336**
2. **PROJECT TITLE: Natural variability in the changing climate: Interaction of Interannual, decadal, and century timescales with daily weather and a focus on extreme events**
3. **PRINCIPAL INVESTIGATOR EMAIL: sasha@ucsd.edu**
4. **CO-PRINCIPAL INVESTIGATOR(S) EMAIL: dcayan@ucsd.edu**
5. **PERSONNEL: Use N/A for lines that do not apply.**
  - a. Principal Investigator (Name and institution) Alexander Gershunov, Scripps Institution of Oceanography (SIO)/UCSD
  - b. Co-Investigators (Name and institutions) Dan Cayan, SIO/UCSD and USGS
  - c. Undergraduate Students (Names and institutions) None
  - d. Graduate Students – MS or MA (Names and institutions) None
  - e. Graduate Students – Ph.D. (Names and institutions) None
  - f. Postdoctoral Researchers (Names and institution(s)) Suraj Polade, SIO/UCSD
  - g. Other 1 (please specify) Kristen Guirguis, Assistant Project Scientist, SIO/UCSD
6. **PROJECT START DATE: (MM/YYYY) 09/2013**
7. **EXPECTED COMPLETION DATE: (MM/YYYY): 09/2016**
8. **PURPOSE AND OBJECTIVES:** Describe the project goals and objectives, with particular emphasis on any changes made to the objectives as stated in the original proposal. If the objectives have been added to, eliminated, or modified, please explain why these changes have been made.

Natural climate variability can strongly temporarily enhance or obscure long-term trends in regional weather due to global climate change. We planned to explore (from our original proposal):

(1) The influence of low frequency climate variability (interannual and decadal) on the seasonal probability distributions of daily weather (temperature and precipitation) within the Southwest, with a view on how natural variability modulates regional trends due to global warming. We explored natural climate variability and its impacts on extreme temperatures in Guirguis et al. (2015). We also explored natural climate variability and its impacts on precipitation extremes in Cavanaugh et al. (2015), Cavanaugh and Gershunov (2015) and Gershunov et al. (in review).

(2) Quantify the teleconnections/relationships traditionally important for seasonal climate prediction to quantify the predictable natural interannual to decadal variability of daily weather statistics. We have explored natural climate variability responsible for seasonal predictability of precipitation in Gershunov et al. (in review) as well as for temperature extremes (Guirguis et al. 2015).

(3) Investigate the projected effects of climate change on the stability of these teleconnections/relationships. We have come to the realization that the natural climate forcings (ENSO, PDO) and their teleconnections are not adequately enough represented in GCMs, nor robustly enough projected, for a meaningful investigation of projected changes in natural climate variability in the current (CMIP5) version of climate models. We are pursuing elements of this work by focusing on mechanistic analysis of projected precipitation changes by examining Atmospheric Rivers as causes of many of the regional precipitation extremes. Work by Guirguis et al. (in review) and Polade et al. (2014) and Polade et al. (in review) focuses more broadly on now natural

variability in precipitation is affected by projected climate change, i.e. via increased natural variability of annual precipitation in the Southwest. We plan to investigate the implications of these changes to water resources in our region where water resources are already highly volatile.

We focused on entire seasonal distributions of daily weather, especially on high-impact extreme events, to quantify their variability in past climate (Guirguis et al. 2015, Cavanaugh et al. 2015, Cavanaugh and Gershunov 2015) and related it to known natural climate forcings using multivariate statistical techniques (Gershunov et al. in review). We investigated the impact of natural variability on climate change trends (Guirguis et al. in review) and, conversely, the impact of climate change on these natural modes of regional variability in weather and climate over the Southwest (Polade et al. 2015 and Polade et al. in review). We quantified the associations between multi-year changes and the seasonal PDFs of daily weather, quantifying uncertainty, and identifying predictable signals in temperature extremes (Guirguis et al, in review).

We were also planning to investigate the impact of natural variability and anthropogenic trends on peak streamflow, particularly its impact on California's Bay-Delta. This last element we were not able to address as the original version of LOCA downscaling, that was to be used to drive the VIC hydrologic model, was flawed and the entire LOCA downscaling exercise had to be re-run for all GCMs. This unfortunate development hampered our progress on projected streamflow/runoff analysis and this is something that we are still planning to pursue in the future with our USGS partner Noah Knowles.

9. **ORGANIZATION AND APPROACH:** Explain how each research task is being conducted. Briefly list which research methods are being used to achieve results, including any new methods that were not described in the original proposal. Please also discuss any problems or delays encountered in conducting the research during the reporting period.

We have examined skew-normal distributions to summarize seasonal behavior of daily temperatures over the Southwest at 6km resolution. This approach has proven to be successful and powerful in the assessment of natural variability and trends in the seasonal statistics of daily weather. In particular, it has highlighted the preferential importance of cold and warm extremes in determining the average seasonal temperatures over the complex Southwestern landscape (Guirguis et al. 2015). In an extension of this work, we have investigated the extent to which projected changes in the temperature regime can be thought of as rigid shifts versus elastic changes in the shape of the probability density function of daily temperature with implications for the role of extreme events in projected changes (Guirguis et al. in review).

In precipitation research, we have taken a non-parametric approach to assess the climate change fingerprint in projected daily precipitation trends as a function of precipitation intensity organized in quantile ranges. Here, we have first addressed regional precipitation produced by GCMs in preparation for considering downscaled results. A clear precipitation regime change signature has emerged. Recognizing the relevance of atmospheric rivers (ARs) to the projected changes in precipitation regime over the Southwest, we have begun to investigate the climate behavior of these synoptic features directly. In this vein, we have developed an automated detection schemes for ARs and created a catalog of ARs affecting the Western US back from 1948 to the present (Gershunov et al. in review). We have analyzed historical behavior of ARs and have begun to apply the automated detection scheme to GCM simulations and projections.

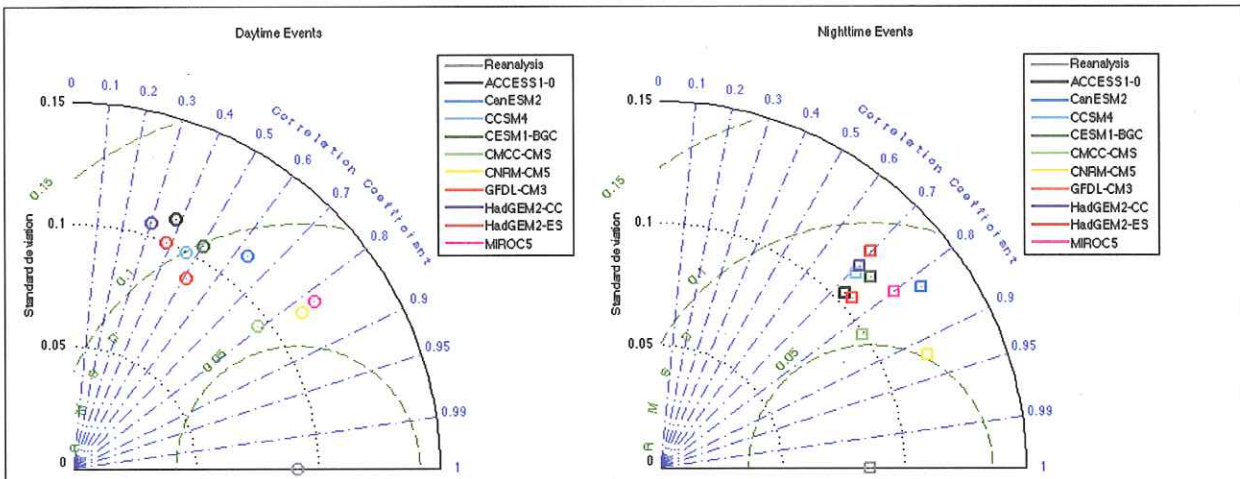
We have also studied projected changes in precipitation regime from daily data over California and made head way towards understanding these changes in the context of climate change projections in other Mediterranean climate regions around the world (Polade et al. in review).

**RESULTS:** Present your preliminary project results if possible. Both quantitative and qualitative results (descriptions of how well or poorly something worked) are useful. Of particular interest are major discoveries, innovative approaches and solutions, and accomplishments made by the project team to date.

## I. Temperature Extremes in the Southwest US

### A. Climate model evaluation

We have screened ten global climate models (GCMs) on the basis of their ability to simulate regional heat waves adequately. The analysis showed that while the observations clearly show a difference between synoptic conditions yielding dry daytime-accentuated heat waves (measured by daily maximum temperatures, Tmax) versus humid nighttime-accentuated heatwaves (measured by daily minimum temperatures, Tmin), most models do not capture this difference. The observations show daytime-accentuated heatwaves as resulting from northeasterly flow from the continental interior while nighttime-accentuated heatwaves are due to southwesterly flow from the Gulf of California region. This makes physical sense since nighttime-accentuated events are more humid owing to the influx of marine moisture from the Gulf. The anatomy of observed dry daytime-accentuated and humid nighttime-accentuated heat waves was described in detail for California and Nevada by Gershunov et al. (2009). In general, the models simulate nighttime-accentuated events well. However, most models (seven of ten) do not adequately represent the synoptic conditions associated with daytime-accentuated heat waves. Three models were superior at representing the observed synoptic conditions associated with heat waves in the Southwest, and these were uniquely able to simulate both dry and humid heat wave varieties well (Figure 1).

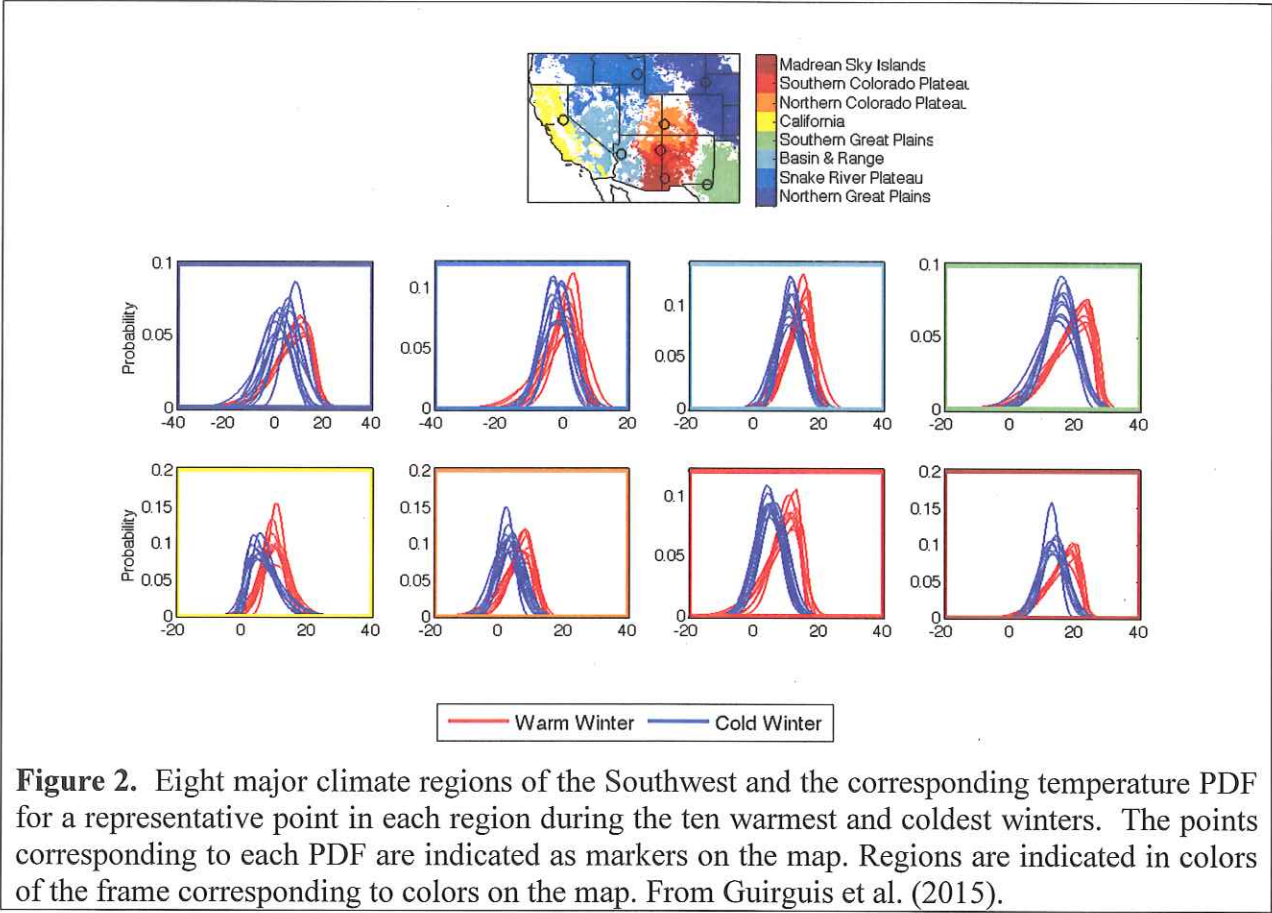


**Figure 1.** Taylor Diagrams as a measure of skill for ten GCMs in their ability to simulate SLP conditions associated with Southwest heat waves for dry daytime-accentuated (left) and humid nighttime-accentuated (right) events. Here, GCMs closest to observations (Reanalysis, gray) are the better performers. In general, nighttime-accentuated events are simulated better than daytime-accentuated events and two GCMs (CNRM-CM5 and CMCC-CMS) show the best performance for both types of heat waves.

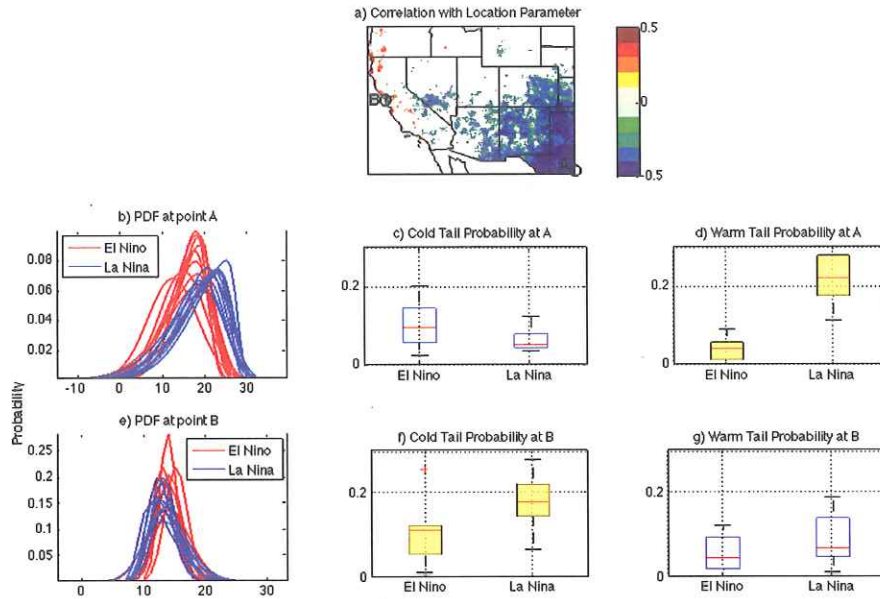
### B. Interannual variability of daily wintertime temperature probability distribution functions

We investigated temperature variability in the Southwest U.S. using skew-normal probability distribution functions (SN PDFs) fitted to observed wintertime daily maximum temperature records. Our goal

was to study how natural variability affects the shape of the temperature PDF and ultimately the probability of wintertime cold and warm extremes. We found dramatic variation in the shape of PDFs from year-to-year, with important geographical differences in the relationship between the central tendency and tails (Figure 2). Interestingly, we found that the warmest and coldest extremes do not necessarily follow the distribution center. For example, in California the cold tail is more variable while the warm tail remains relatively stable, so warm years are associated with fewer cold extremes but not necessarily more warm extremes. The opposite relationship is seen in the Great Plains. We also demonstrated how changes in temperature PDFs are conditioned by different phases of El Niño-La Niña (ENSO) and the Pacific Decadal Oscillation (PDO). For example, in the Southern Great Plains, La Niña and/or negative PDO are associated with generally warmer conditions (Figure 3 shows ENSO results). However, in terms of extremes, while the warm tails become thicker and longer, the cool tails are not impacted—extremely warm days become more frequent but extremely cool days are not less frequent. These results could have implications for global warming. For example, if a rigid shift of the whole range occurs, then warm years are not necessarily a good analogue for a warmer climate. These results were published in Guirguis et al. (2015), and were featured in the 2015 ‘Environmental Research Round-Up’, which is a news digest highlighting selected recent *Environmental Research Letters* articles.



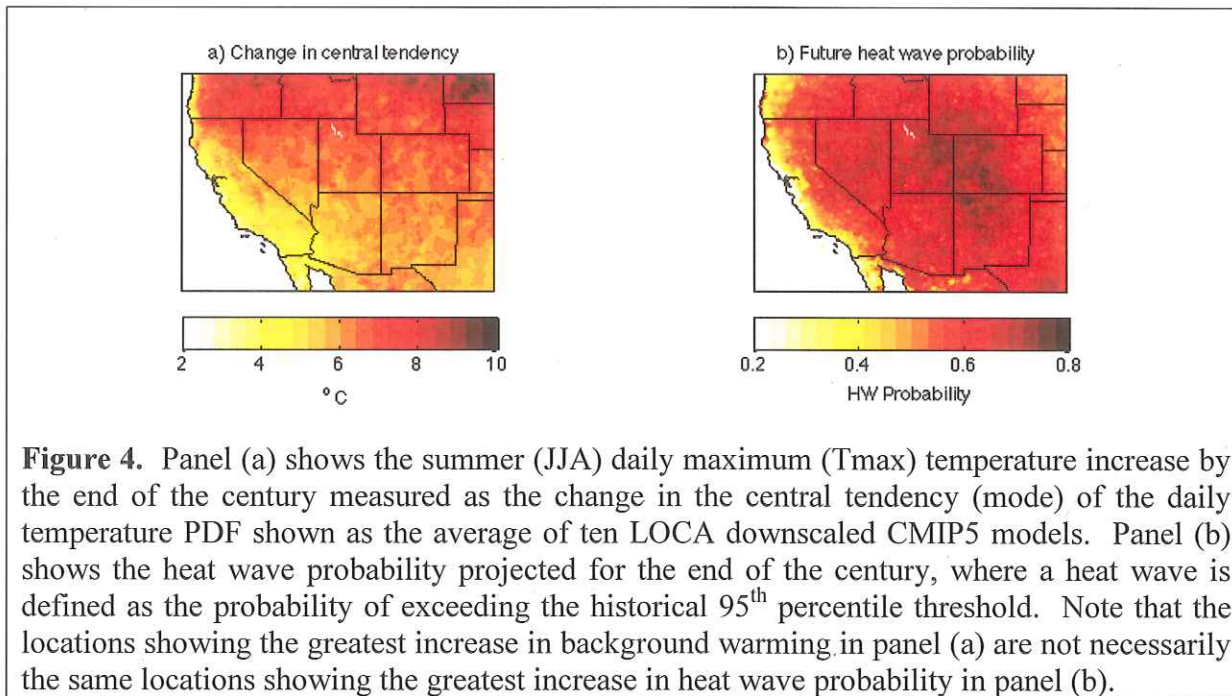
**Figure 2.** Eight major climate regions of the Southwest and the corresponding temperature PDF for a representative point in each region during the ten warmest and coldest winters. The points corresponding to each PDF are indicated as markers on the map. Regions are indicated in colors of the frame corresponding to colors on the map. From Guirguis et al. (2015).



**Figure 3.** Panel (a) shows a map of the correlation between the Niño3.4 index and the location parameter, where shading indicates significance at the 95% level. Points A and B marked on the map are two points selected for having a strong correlation with ENSO ( $r=0.55$  and  $r=-0.60$ , respectively). Panels (b)-(d) show the temperature PDFs at point A along with box plots showing cold and warm tail probability during the top 10 cases of El Niño and La Niña as measured from the Niño3.4 index. Shaded boxplots indicate the difference is significant at the 95% level using a t-test for unequal means. From Guirguis et al. (2015).

### C. Heat wave probability in the changing climate of the Southwest US

We investigated and quantified the implications of a changing climate on extreme temperature probabilities in the Southwest US by considering the full PDF of daily maximum and minimum daily temperatures during summer using observations and downscaled climate model projections from ten CMIP5 models. The results of our analyses of observed non-Gaussian daily temperature probability distribution functions (PDFs) in the Southwest US highlight the importance of tail length and variance in determining future heat wave probability. Even if no PDF shape change occurs with climate change, locations with shorter tails/smaller variance will see a greater increase in heat wave probability, defined as exceedances above the historical 95<sup>th</sup> percentile threshold, than will long tailed/larger variance distributions. Projections from ten downscaled CMIP5 models show important geospatial differences in the amount of warming expected for a location (Figure 4a). However, changes in heat wave probability do not directly follow changes in background warming (Figure 4b). In some areas of the Southwest where stronger warming is projected, future heat wave probability is buffered somewhat by longer PDF tails. In other areas where less warming is projected, heat wave probability is enhanced because of shorter tailed PDFs. To understand changes in heat wave probability in future climate, we considered the effects of a rigid shift in the temperature PDF versus a change in shape. We found that projected changes in heat wave probability are largely explained by a rigid shift of the distribution. Any effects of PDF shape changes are generally small by comparison, and fall within the range of uncertainty among models in the amount of warming expected by the end of the century. A manuscript describing these results (Guirguis et al. 2016) entitled *Heat wave probability in the changing climate of the Southwest US* has been submitted and is in peer-review in *Climate Dynamics*.



**Figure 4.** Panel (a) shows the summer (JJA) daily maximum (Tmax) temperature increase by the end of the century measured as the change in the central tendency (mode) of the daily temperature PDF shown as the average of ten LOCA downscaled CMIP5 models. Panel (b) shows the heat wave probability projected for the end of the century, where a heat wave is defined as the probability of exceeding the historical 95<sup>th</sup> percentile threshold. Note that the locations showing the greatest increase in background warming in panel (a) are not necessarily the same locations showing the greatest increase in heat wave probability in panel (b).

#### D. Heat waves and their health impacts

Guirguis et al. (2014) have examined the health impacts of recent heat waves statewide and for six subregions of California: the north and south coasts, the Central Valley, the Mojave Desert, southern deserts, and northern forests. By using canonical correlation analysis applied to daily maximum temperatures and morbidity data in the form of unscheduled hospitalizations from 1999 to 2009, 19 heat waves spanning 3–15 days in duration that had a significant impact on health were identified. On average, hospital admissions were found to increase by 7% on the peak heat-wave day, with a significant impact seen for several disease categories, including cardio-vascular disease, respiratory disease, dehydration, acute renal failure, heat illness, and mental health. Statewide, there were 11,000 excess hospitalizations that were due to extreme heat over the period, yet the majority of impactful events were not accompanied by a heat advisory or warning from the National Weather Service (NWS). On a regional basis, the strongest health impacts are seen in the Central Valley and the north and south coasts. The north coast contributes disproportionately to the statewide health impact during heat waves, with a 10.5% increase in daily morbidity at heat-wave peak as compared with 8.1% for the Central Valley and 5.6% for the south coast. The temperature threshold at which an impact is seen varies by subregion and timing within the season. These results suggest that heat-warning criteria should consider local percentile thresholds to account for acclimation to local climatological conditions as well as the seasonal timing of a forecast heat wave.

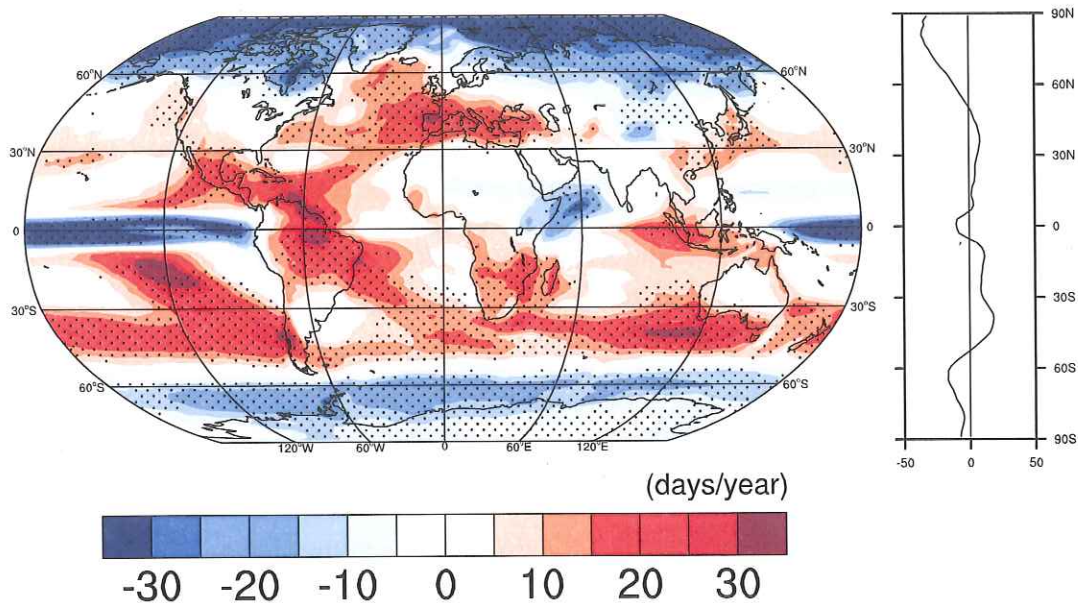
Guirguis et al. (2014) is a seminal research paper presenting results of an interdisciplinary collaboration between climatologists, an epidemiologist and a NWS warning coordination meteorologist. It helped motivate a new funded NOAA project titled *Interplay of marine layer clouds and heat waves along the California coast: Impacts on human health*. This project involves a novel line of research on marine layer dynamics being carried out in our group by postdoctoral researcher Rachel Clemesha. In addition, the results of Guirguis et al. (2014) have recently been applied to improve the NWS heat warnings system by taking local climatology into account along with weather forecasts (<http://www.wrh.noaa.gov/wrh/hil/?id=1yHbjQJfR8TAqBMvK-bA6uR3MEYv0R69VaFIWFL8dcq8&wfo=SGX>). This applied work continues with a finer focus on San Diego County via our involvement with a new UCSD Institute of Public Health–funded project titled *Heat waves, human health, and disparities in San Diego County*, where we are working with epidemiologists and students at

the UCSD School of Medicine to quantify health impacts of heat waves on a highly diverse population of our climatically-diverse region.

## II. Precipitation extremes

### A. Precipitation regime change as projected by global climate models (GCMs)

Realizing that the current (CMIP5) GCMs do not project clear tendencies for total annual precipitation in California and the Southwest, Polade et al. (2014) took a global view of projected precipitation change focusing on daily precipitation regimes. The results showed clear changes projected for the frequency and intensity of precipitation that cancel each other out and give a semblance of no projected change specifically for California when total annual precipitation is considered. Future changes in days with precipitation per year can either reinforce or counteract projected increases in daily precipitation intensity as the climate warms. We analyzed climate model projected changes in daily precipitation frequency using 28 coupled global climate models from the Coupled Model Intercomparison Project, version 5 (CMIP5). We find that the Mediterranean Sea region, parts of Central and South America, and western Indonesia could experience up to 30 fewer days with precipitation per year by the end of this century. We illustrate how changes in the number of wet days and the precipitation intensity on precipitating days combine to produce changes in annual precipitation, and show that over much of the subtropics the change in number of wet days dominates the annual changes in precipitation and accounts for a large part of the change in interannual (i.e. natural) precipitation variability. The Southwest, for example, is projected to experience more year-to-year variability of precipitation translating to more volatile water resources in this region where water resources are already uncertain.



**Figure 5.** CMIP5 28-model ensemble average mean change in frequency of dry days or days without precipitation (days/year) by 2060–2089, relative to the historical period 1960–1989, using the RCP8.5 forcing scenario. Stippling indicates areas where at least 70% of the models agree on the sign of the change. Graph to the right: zonal means values. From Polade et al. (2014).

In the U.S. Southwest, the projected decrease in precipitation frequency is more robust and consistent across models than the annual precipitation trend, since the latter reflects a competition between fewer days with precipitation and greater precipitation intensity on wet days. Such anthropogenic trends in the daily precipitation regime suggest increasing regional probabilities of drought as well as flood, but are obscured by

temporal aggregation to multi-year averages. Given the complex, spatially varied interplay of the influence of dry and wet extremes in shaping annual precipitation volumes and their variability, we next focused more regionally.

### *B. Precipitation regime change in Mediterranean climate regions, focusing on California*

Realizing that a better mechanistic understanding of dry-day occurrences and their geographic shifts requires regionally focused investigation, we next focused on Mediterranean climate regions around the globe, which are mostly projected to dry (Polade et al. 2014) particularly trying to understand why California is projected to become so different (not clearly dry) as the other four regions. In most Mediterranean climate regions around the world, CMIP5 models consistently project drier futures. In California, however, projections of changes in total annual precipitation amount are not consistent. Polade et al. (in review) analyzed wintertime precipitation projections at daily resolution from 30 CMIP5 global climate models (GCMs) focusing on the five Mediterranean climate (MedClim) regions globally. Our aim was to understand regional differences and similarities in future hydrometeorology expectations and to disentangle the causes of uncertainty in projections over California.

We investigated the dynamical vs. thermodynamic drivers of regional precipitation regime change and found that most MedClim regions are expected to dry via decreased frequency of precipitation driven mainly by dynamically stronger semi-permanent subtropical high-pressure systems. This drying effect is lacking in California where projected increases in frequency of heavy and extreme precipitation (99<sup>th</sup> percentile events), along with an increase in intensity offsets the decrease in overall precipitation frequency. In multi-model mean, California is projected to have 5-7 fewer wet days and a two-fold increase in heavy precipitation events (2 instead of 1 P99 events) per winter.

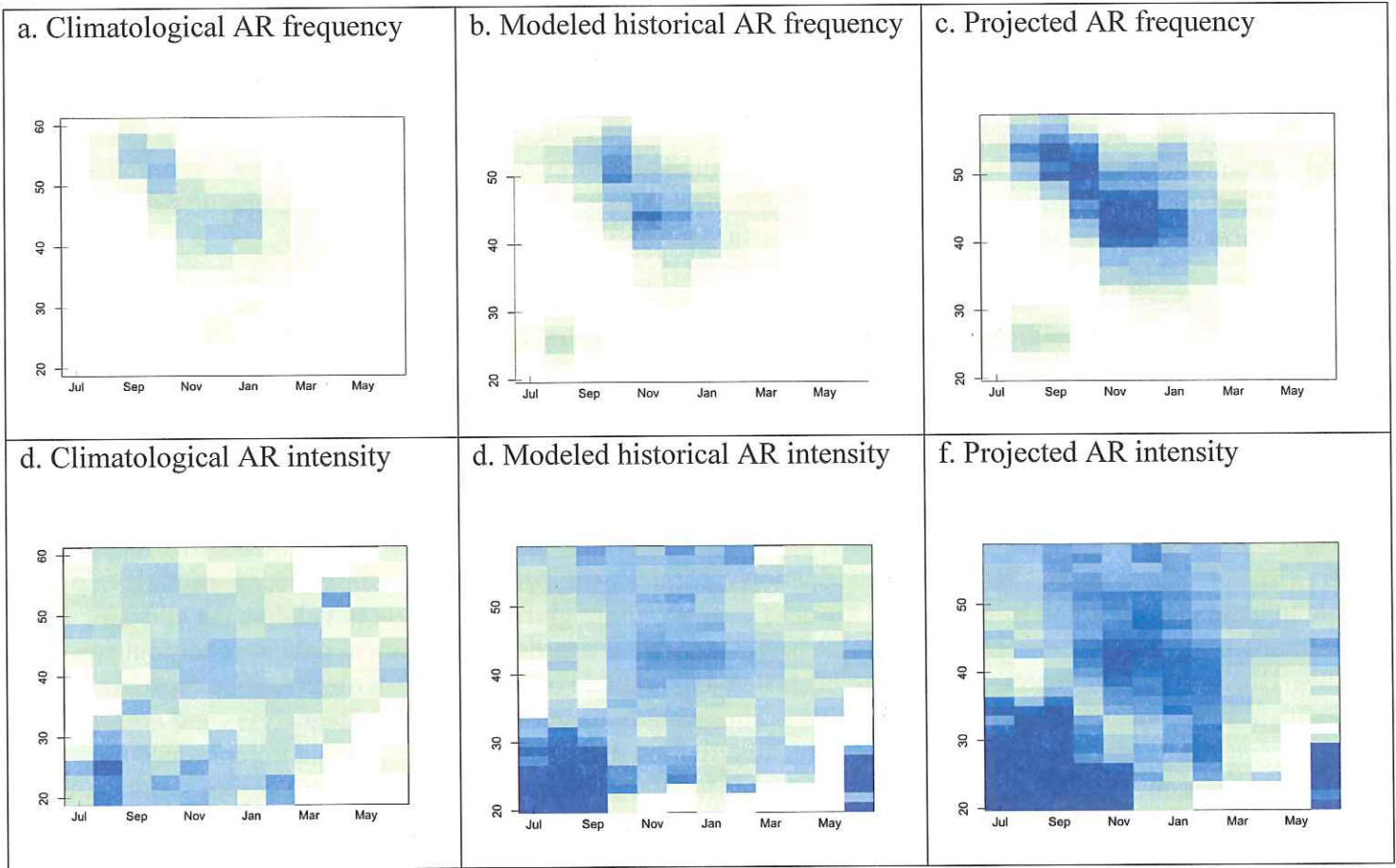
Specifically, the weaker dynamically-driven decrease in low and moderate intensity daily precipitation over California together with a significant thermodynamically-driven strengthening of extremes, compared to other MedClim regions, are attributed to the deepening and south-eastward extension of the Aleutian low pressure system, which bolsters the increased horizontal water vapor transport that occurs in a warmer climate.

### *C. Automated detection of Atmospheric Rivers land-falling on the west coast of the North America and their natural climate-scale variability*

Atmospheric rivers are responsible for most of the precipitation extremes in California and a sizeable number of cold season extremes in the Southwest. We have developed a novel method for automatic detection of atmospheric rivers (ARs) and applied it to a 68-year atmospheric reanalysis, yielding an extensive catalog of ARs that made landfall along the west coast of North America during 1948-2015. This catalog provides a large array of variables that can be used to examine AR cases and their climate-scale variability in exceptional detail. The new record of AR activity, as presented, validated and examined here, provides a perspective on the seasonal cycle and the natural interannual-interdecadal variability of AR activity affecting the hydroclimate of western North America. Strong links to hydroclimate are demonstrated using a high-resolution precipitation data set. We describe the seasonal progression of AR landfalls from the Gulf of Alaska coastline in late summer-early fall to California by the late fall-early winter. Importantly, AR intensity does not exactly follow the climatological pattern of AR frequency. Many of the precipitation extremes in the Southwest are found to be produced by ARs making landfall in Baja California and able to bring moisture deep into the mountainous Southwest. We also diagnose linkages between seasonal AR activity and climate variability expressed in Pacific sea surface temperatures, revealing links to Pacific decadal variability, recent regional anomalies, and long-term ocean warming. This catalog provides new opportunities to study the climate-scale behavior and predictability of ARs affecting western North America in unprecedented detail.

### *D. Developing a further mechanistic understanding of increasing precipitation extremes in a changing*

Seeing that the projected increase in extreme precipitation event frequency and intensity in California (Polade et al., in review), is driven by thermodynamically increasing moisture transport in a warmer climate (Lavers et al. 2015), we are most recently focusing on Atmospheric Rivers (ARs) in climate projections as the meteorological mechanism responsible for much of the moisture transport into our region as well as for most of the precipitation extremes in California and many in the Southwest. Using the automated AR detection methodology developed by Gershunov et al. (in review, see section IIC above), we are now examining ARs in GCM projections. Our preliminary results show that, at least according to the first model we examined, the frequency and intensity of land-falling ARs is clearly projected to increase (Figure 6).



**Figure 6.** Climatological, 1948-2015, AR frequency (a) and intensity (d) measured in integrated vapor transport (IVT) of ARs at landfall are shown by month (x-axis) and land-falling latitude (y-axis) as in Gershunov et al. (in review). Panels b and d show modeled historical, 1970-1999, (b) and end of century, 2070-2099, projected (c) frequency as well as modeled historical (d) and projected (f) intensity in units of IVT at landfall (kg/m/s). The GCM used here is the CNRM-CM5 GCM that is a consistently quality performer for our region.

Figure 6 shows that, at least in the CNRM-CM5 model, the seasonal cycle of AR land-falling behavior is well simulated, although the frequency and intensity are overestimated, and that future frequency and intensity of land-falling ARs is projected to clearly increase as we suspected from thermodynamic considerations, i.e. warmer air holds more moisture (e.g. Lavers et al. 2015). We are now producing similar results for other GCMs and we plan on using projected behavior of land-falling ARs to understand projected changes in precipitation extremes by matching AR landfalls and their spatial footprints with LOCA-downscaled daily precipitation. This work is in progress and is a direct continuation of this project. Any publication that results will clearly acknowledge USGS/DOI support.

### *E. Probability distribution of extreme precipitation*

In addition to the abovementioned studies, we have, in parallel, carried out two studies of the probability distribution of precipitation and particularly extremes in observed and modeled contexts. Brief descriptions of results from these two papers (Cavanaugh et al. 2015 and Cavanaugh and Gershunov 2015) follow:

Cavanaugh et al. (2015) examined the probability tail structure of over 22,000 weather stations globally in order to identify the physically and mathematically consistent distribution type for modeling the probability of intense daily precipitation and extremes. Results indicate that when aggregating data annually, most locations are to be considered heavy tailed with statistical significance. When aggregating data by season, it becomes evident that the thickness of the probability tail is related to the variability in precipitation causing events and thus that the fundamental cause of precipitation volatility is weather diversity. These results have both theoretical and practical implications for the modeling of high-frequency climate variability worldwide. In particular, they show that the traditionally applied exponentially-tailed distribution functions are inadequate for modeling extremes, their probabilities and return periods and that the relevant models for estimating extreme precipitation probabilities are heavy-tailed. It is particularly important to use the correct probability models in the changing climate as the traditional models will underestimate the probabilities of extremes, as extremes become more extreme in the future, than they do in a stationary historical climate.

Cavanaugh and Gershunov (2015) continued to examine the probability structure of daily precipitation, particularly how this structure depends on spatio-temporal averaging and using results to understand modeled precipitation extremes. Daily precipitation variability as observed from weather stations is heavy tailed at most locations around the world (Cavanaugh et al. 2015). It is thought that diversity in precipitation-causing weather events is fundamental in producing heavy-tailed distributions, and it arises from theory that at least one of the precipitation types contributing to a heavy-tailed climatological record must also be heavy-tailed. Precipitation is a multi-scale phenomenon with a rich spatial structure and short de-correlation length and timescales; the spatiotemporal scale at which precipitation is observed is thus an important factor when considering its statistics and extremes. In this study, we examine the spatiotemporal scaling behavior of intense precipitation from point-scale to large grid cells and from 1 day to 4 weeks over the entire globe. We go on to validate the current generation of historically-forced climate models and reanalyses against observational data at consistent spatial scales. Our results demonstrate that the prevalence and magnitude of heavy tails in observations decrease when moving to lower spatiotemporal resolutions, as is consistent with stochastic theory. Reanalyses and climate models generally reproduce large, synoptic scale distribution classifications, but struggle to reproduce the statistics in regions that are strongly affected by mesoscale phenomena, such as the Southwest in summer. We discuss these results in relation to physically consistent atmospheric regimes.

Importantly, at the scale of several days, many regions that can be considered exponential at higher-temporal resolutions become heavy-tailed (e.g., in the South West), pointing to the influence of diverse larger-scale precipitation regimes on extremes in these locations. Specific to the southwest coastal United States, this result may be attributable to the effect of atmospheric rivers that produce peak precipitation rates over relatively large areas at roughly three-day accumulations. At high spatial resolution (i.e., point-scale or  $0.25^\circ$ ), the degree of exponentiality monotonically increases when moving toward lower temporal resolutions (Fig. 3). Areas that retain their heavy-tailed behavior at low temporal resolutions tend to be regions that experience extremely heavy and large-scale precipitation events, for example, tropical cyclones along the Gulf and Atlantic coasts and heavy orographic frontal precipitation in the mountains, such as from atmospheric rivers along the windward slopes of west-coast mountain ranges. These same regions retain their heavy-tailed behavior at the lowest spatiotemporal resolutions. This result provides more impetus to continue our investigation into the mechanistic Atmospheric River-caused precipitation extremes in the changing climate of the Southwest.

**NEXT STEPS:** State and describe the next steps in the research, including an updated project timeline and anticipated completion date.

This project is now over, but we plan to continue the research thrust started here as follows:

- By using projected behavior of land-falling ARs to understand projected changes in precipitation extremes by matching AR landfalls and their spatial footprints with LOCA-downscaled daily precipitation. This work is now in progress and is a direct continuation of this project.
- By applying the results of Cavanaugh et al. (2015) and Cavanaugh and Gershunov (2015) to estimate the probabilities of precipitation extremes and their return periods in a non-stationary changing climate.
- By considering heat waves and cold spells from the probabilistic point of view in a changing non-stationary climate and investigating their impacts by also considering acclimation of ecosystems and people to the background climate change. This will require further collaboration with ecologists and epidemiologists.

10. **PRODUCTS:** The terms and conditions of this award (C.5 Publications) addressed how to acknowledge and provide a disclaimer statement in all publications, web pages and orally during all news media interviews (SEE ATTACHED GUIDANCE SHEET). **Suggested copy:**

**This material is based upon work supported by the U.S. Geological Survey under Grant Agreement No G \_\_\_\_\_ from the Southwest Climate Science Center.** The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Geological Survey. Mention of trade name or commercial products do not constitute their endorsement by the US Geological Survey.

- a. Please list any **peer-reviewed publications** that have resulted from this project (full citations). Please include articles in preparation, in review, accepted, or published.

Polade, S.D., A. Gershunov, D. Cayan, M.D. Dettinger and D. Pierce, 2016: Precipitation in a warming world: Assessing projected hydro-climate of California and other Mediterranean climate regions. *Nature Scientific Reports*, in review.

Guirguis, K., A. Gershunov, D.R. Cayan and D. Pierce, 2016: Heat wave probability in the changing climate of the Southwest US. *Climate Dynamics*, in review.

Gershunov A., T.M. Shulgina, F.M. Ralph, D. Lavers and J.J. Rutz, 2016: Assessing climate-scale behavior of Atmospheric Rivers affecting western North America. *Geophysical Research Letters*, in review.

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.

Cavanaugh, N.R., A. Gershunov, 2015: Probabilistic Tail Dependence of Intense Precipitation on Spatiotemporal Scale in Observations, Reanalyses, and GCMs. *Climate Dynamics*, 45, 2965-2975, DOI:10.1007/s00382-015-2517-1.

Cavanaugh, N.R., A. Gershunov, A.K. Panorska, and T.J. Kozubowski, 2015: The Probability Distribution of Intense Daily Precipitation. *Geophysical Research Letters*, 42, 1560–1567. doi: [10.1002/2015GL063238](https://doi.org/10.1002/2015GL063238).

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, doi:[10.1002/2015GL064672](https://doi.org/10.1002/2015GL064672).

Polade, S.D., Pierce, D.W., Cayan, D.R., Gershunov, A. & Dettinger, M.D. 2014: The key role of dry days in changing regional climate and precipitation regimes. *Nature Scientific Reports* 4, 4364; DOI:10.1038/srep04364.

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 Climatology*, 53, 3-19.

b. **Non-peer-reviewed publications** (full citations).

California Heat Waves. A two-pager for stakeholders and the public. 2015. Gershunov, Cayan, and Guirguis contributed. [http://cnap.ucsd.edu/pdf/CNAP\\_CA\\_heat\\_waves.pdf](http://cnap.ucsd.edu/pdf/CNAP_CA_heat_waves.pdf)

El Niño in California and Nevada. A two-pager for stakeholders and the public. 2015. Cayan and Gershunov contributed. [http://cnap.ucsd.edu/pdf/CNAP\\_EINino\\_Dec2015.pdf](http://cnap.ucsd.edu/pdf/CNAP_EINino_Dec2015.pdf)

Sierra Nevada Snowpack. A two-pager for stakeholders and the public. 2016. Cayan contributed. [http://cnap.ucsd.edu/pdf/CNAP\\_Snowpack.pdf](http://cnap.ucsd.edu/pdf/CNAP_Snowpack.pdf)

California Department of Water Resources, Climate Change Technical Advisory Group (CCTAG) Report: “Perspectives and Guidance for Climate Change Analysis”, August 2015. Cayan was principal author of Chapter 2 “Climate Model Selection”.

California Energy Commission [Integrated Energy Policy Report \(IEPR\)](#) White Paper: Creating Probabilistic Sea Level Rise Projections to support the 4<sup>th</sup> California Climate Assessment, by D. Cayan, J. Kalansky, S. Iacobellis, D. Pierce, 22pp. June 2016.

California Energy Commission [Integrated Energy Policy Report \(IEPR\)](#) White Paper: Creating Climate projections to support the 4<sup>th</sup> California Climate Assessment, by D. W. Pierce, Cayan, L. DeHann

c. Please list any **conference talks** you have given based on this project (conference title, date, and location).

April 25, 2014, State Capitol, Sacramento, CA. California Drought Summit, University of California sponsored. Cayan gave invited talk.

May 15, 2014, Sacramento. California Drought Forum, NIDIS and NOAA sponsors. Cayan gave invited talk.

June 16-17 2014, Sacramento. CalFire/California State University Workshop on Wildfire in the Wildland-Urban Interface. Cayan gave talk.

August 15, 2014, SIO/UCSD. Resilient San Diego Symposium, Gershunov gave invited talk.

October 15, 2014, Sacramento. EPA Region 9 Tribal Conference, Gershunov gave invited talk and participated in panel discussion. Guirguis gave talk.

August 14, 2015, Baltimore. Ecological Society of America. Gershunov gave invited talk.

Nov, 2015 Southwest Climate Summit. Gershunov gave invited talk on “downscaling and understanding weather extremes in a changing climate”.

Mar 3, 2016 Nevada Water Resources Association Annual Mtg Cayan gave invited talk and participated in “forecasting” panel; talk title: “The multiple atmospheric patterns that deliver wetness (or dryness) to

California and Nevada--how well are they predicted?"

- d. Please list any **data outputs, maps, decision-support or other informational tools** developed as part of this project and provide: 1) a very brief description of the product 2) Internet links if applicable.

We have prepared decision support documents for SWCSC stakeholders for communication through SCENIC (<http://www.wrcc.dri.edu/csc/scenic/>) in the form of two short reports on the topics of (1) heat wave probability in the Southwest US and (2) the thermal tolerance of the California Spotted Owl in the Central Sierras.

The first short report demonstrates how changes in heat wave probability do not directly follow changes in background warming. This is because local temperature PDFs are different across the Southwest and those locations with shorter warm tails experience a greater increase in heat wave probability even under comparable or less background warming. For example, Badlands National Park in South Dakota is projected to experience a larger increase in daily maximum temperatures than is projected for the Colorado National Monument. However, in terms of heat wave probability, Colorado National Monument is projected to experience more heat waves.

The second short report provides analysis of the thermal tolerance of the California Spotted Owl in the context of climate change. The US Forest Service and others involved in natural resource management are interested in identifying climate extremes relative to thermal tolerances of select species that are targets of management. For spotted owls, at temperatures above 35.2°C the resting metabolic rate increases substantially and behavioral responses to heat stress have been observed at temperatures from 30–34°C. We show that the lower elevations will exceed the critical threshold for the majority of summer days while some higher elevations could be more habitable for the owl species. While there may be locations within the territory that remain cool enough for the owl species, the amount of space will be limited. For example, if we assume that the Spotted Owl species can tolerate a few critically hot days in a summer (say 5% of summer days), then historically 84% of the domain would support the Owl based on these criteria. Projections for the end of the 21<sup>st</sup> century suggest this space will reduce to 8-32%, depending on model. We expect these short reports to be disseminated to stakeholders through SCENIC in early January 2017.

Guirguis et al. (2014) was co-produced with a NWS warming coordination meteorologist (Mr. Alex Tardy). Results of Guirguis et al. (2014) have recently been applied to improve the NWS heat warnings system by taking local climatology into account along with weather forecasts (<http://www.wrh.noaa.gov/wrh/hil/?id=1yHbjQJfR8TAqBMvK-bA6uR3MEYv0R69VaFIWFL8dcq8&wfo=SGX>).

11. **OUTREACH AND ENGAGEMENT:** Describe all project-related outreach opportunities to date.
  - a. Please list any **presentations, seminars, webinars, or workshops** made to stakeholders, the public at large, or any other group outside the research community.

April 25, 2014, State Capitol, Sacramento, CA. California Drought Summit, University of California sponsored. Cayan gave invited talk.

May 15, 2014, Sacramento. California Drought Forum, NIDIS and NOAA sponsors. Cayan gave invited talk.

June 16-17 2014, Sacramento. CalFire/California State University Workshop on Wildfire in the Wildland-Urban Interface. Cayan gave talk.

August 15, 2014, SIO/UCSD. Resilient San Diego Symposium, Gershunov gave invited talk.

October 15, 2014, Sacramento. EPA Region 9 Tribal Conference, Gershunov gave invited talk and participated in panel discussion. Guirguis gave talk.

November 18, 2015, Camp Pendleton, Oceanside CA. Camp Pendleton Marine Base, Climate Informed Monitoring Workshop. Cayan gave invited talk.

November 20, 2014, Sacramento. Delta Stewardship Council November Meeting, Cayan gave briefing.

December 11, 2014 Los Angeles. National Hydropower Association, California Regional Mtg.

Oct 1, 2015 Camp Pendleton US Marine Corps General John Simpson and staff Cayan gave El Nino 2015-16 briefing.

Oct 7, 2015 San Diego City Council El Nino outlook public outreach Cayan gave Winter Weather briefing

Nov, 2015 Southwest Climate Summit. Gershunov gave invited talk on “downscaling and understanding weather extremes in a changing climate”.

Dec, 2015: California heat waves in the present and future with implications for human health. Institute of Public Health, UCSD. Invited presentation. Guirguis presented.

Mar 3, 2016 Nevada Water Resources Association Annual Mtg Cayan gave invited talk and participated in “forecasting” panel; talk title: “The multiple atmospheric patterns that deliver wetness (or dryness) to California and Nevada--how well are they predicted?”

Mar 10, 2016 South Coast Climate Science Alliance, Forum and Networking Event at Cabrillo National Monument in San Diego. Cayan made brief remarks scoping climate science aspects of the Climate Alliance and networked with attendees.

Apr 27, 2016 Regents Point Continuing Care Community, Cayan gave Invited Presentation "California's Climate--Expected Changes on Top of Already High Variability"

July 14, 2016 Sacramento/San Joaquin Delta Independent Science Board Cayan gave Invited Presentation on Sea Level Rise, Coastal Storms, Sea Level Extremes

- b. **Communications with decision-makers**, including their name and agency and the date(s) and frequency of your communications. Information on whether the decision-makers were involved in the design of the project plan or if the research has been tailored to address a specifically stated management need is also helpful.

We are in regular communication with Dr. Rupa Basu, epidemiologist at Cal/EPA, Office of Environmental Health Hazard Assessment (OEHHA) who provided health data and participated in the design of the project plan that resulted in the publication by Guirguis et al. (2014). We are also in regular communication with Mr. Alex Tardy, Warnings Coordination Meteorologist at the NWS. Guirguis et al. (2014) was co-produced with Dr. Basu and Mr. Tardy and resulted in an improved tool for generating heat warnings at the NWS. This tool can be accessed online: <http://www.wrh.noaa.gov/wrh/hil/?id=1yHbjQJfR8TAqBMvK-bA6uR3MEYv0R69VaFIWFL8dcq8&wfo=sgx>

We have been in intermittent communication with Susan Fankel (USFS) on a Sudden Oak Death collaboration project spearheaded by Erica Fleishman. We are providing data/result for this project.

We have been in intermittent communication with Shana Gross of USFS on Spotted Owl habitat collaboration project spearheaded by Erica Fleishman. See section 10d above.

We have been in occasional communication with Michael Rogner of River Partners (NGO) on a riparian restoration collaboration project spearheaded by Erica Fleishman.

- c. Are you aware of any **resource management decisions** that have come out of this project? If so, please provide a brief description.

12. **OTHER:** project impacts, outcomes, or communications not discussed above.

Guirguis et al. (2014) helped motivate a new funded NOAA project titled *Interplay of marine layer clouds and heat waves along the California coast: Impacts on human health*. This project involves a novel line of research on marine layer dynamics being carried out in our group with the participation of postdoctoral researcher, Dr. Rachel Clemesha.

This heat waves and public health work (Guirguis et al. 2014) also continues with a finer focus on San Diego County via our involvement with a new UCSD Institute of Public Health-funded project titled *Heat waves, human health, and disparities in San Diego County*, where we are working with epidemiologists and students at the UCSD School of Medicine to quantify health impacts of heat waves on a highly diverse population of our climatically-diverse region.

Acquaintances made in connection with this project included Dr. Dawn Lawson, Ecologist at the Environmental Sciences and Applied Systems Branch of SPAWARSYSCEN Pacific (DOD). We are now collaborating with Dr. Lawson and her colleague, Dr. Sula Vanderplank at the Botanical Research Institute of Texas, on a proposal to SERDP (DOD) to develop a new project to study *weather extremes and climate change effects on vegetation dynamics*.

13. **BUDGET:** Briefly describe the budget, with particular emphasis on changes to the budget that was submitted in the original proposal. **Please discuss reasons for substantial budget modifications or why funds have not been spent as expected.**

Budget has been spent approximately as expected, with the caveat that the project was extended at no cost for one year.

**Need help?** Anita Govert, SW CSC Grants Administrator is happy to answer any budget questions you may have about what's needed if you need to make changes in the budget, [agovert@email.arizona.edu](mailto:agovert@email.arizona.edu), 520-626-8524.

Submitted by: ALEXANDER GERSHUNOV

(Project PI name)

 111 / 23 / 16

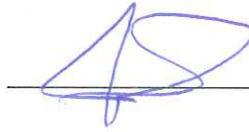
DAN CAYAN

(Project Co-Principal name(s))

 111 / 23 / 16

Reviewed by:

Jonathan T. Overpeck  
SW CSC University Director



12/14/16

Reviewed by:

Stephen T. Jackson,  
SW CSC Director, USGS



1 / 1 / 16

- ❖ **Please send the Word version and signed PDF** of your Final Report to Anita Govert, SW CSC Grants Administrator, agovert@ email.arizona.edu. Anita will route it to the Directors for their review.