California heat waves in the present and future

Alexander Gershunov[1] and Kristen Guirguis[1]

Received 6 July 2012; revised 10 August 2012; accepted 20 August 2012; published 27 September 2012.

[1] Current and projected heat waves are examined over California and its sub-regions in observations and downscaled global climate model (GCM) simulations. California heat wave activity falls into two distinct types: (1) typically dry daytime heat waves and (2) humid nighttime-accentuated events (Type I and Type II, respectively). The four GCMs considered project Type II heat waves to intensify more with climate change than the historically characteristic Type I events, although both types are projected to increase. This trend is already clearly observed and simulated to various degrees over all sub-regions of California. Part of the intensification in heat wave activity is due directly to mean warming. However, when one considers non-stationarity in daily temperature variance, desert heat waves are expected to become progressively and relatively less intense while coastal heat waves are projected to intensify even relative to the background warming. This result generally holds for both types of heat waves across models. Given the high coastal population density and low acclimatization to heat, especially humid heat, this trend bodes ill for coastal communities, jeopardizing public health and stressing energy resources. **Citation:** Gershunov, A., and K. Guirguis (2012), California heat waves in the present and future, *Geophys. Res. Lett.*, *39*, L18710, doi:10.1029/2012GL052979.

1. Introduction

[2] The flavor of California heat waves is changing: they are becoming more humid and therefore expressed with disproportionate intensity in nighttime rather than daytime temperatures [*Gershunov et al.*, 2009, hereinafter GCI'09]. If this trend continues, it will adversely affect California's biota acclimatized to the region's semi-arid Mediterranean climate with its warm dry summer days and cool nights. Such a trend translates into severe impacts on health, ecosystems, agriculture, water resources, energy demand and infrastructure, all with economic consequences. (For example, in late July 2006, extreme heat with high humidity impacted human mortality [*Ostro et al.*, 2009] as well as morbidity [*Knowlton et al.*, 2009; *Gershunov et al.*, 2011] and thus the healthcare industry.) It is imperative to develop a detailed understanding of the observed trend in regional heat wave activity if we are to effectively mitigate its escalating impacts.

[3] California's complex topography and proximity to the coast create distinct climate and ecological sub-regions within relatively close distances. In different locations, regional-scale heat waves may be expressed differently, or may respond to different mechanisms altogether. For example, offshore Santa Ana winds can cause coastal heat waves via adiabatic warming of air as it descends from high elevations to sea level. On the other hand, sea breeze and associated marine layer clouds can moderate coastal temperatures during inland heat waves. Furthermore, the non-uniform distribution of population and resources across the state make for non-uniform impacts. Although heat waves are synoptic phenomena with a regional footprint, these complexities make a sub-regional focus necessary.

[4] We will examine observations and downscaled model simulations to describe heat wave activity over six sub-regions of California spanning the last six decades as well as that projected for the 21st century. Before considering projections, however, we screen GCMs for their ability to simulate regional heat waves for the correct synoptic reasons. Stationary thresholds based on historical climate are used to quantify sub-regional heat wave magnitudes in a changing climate. This is the traditional approach often used in climate research [*Meehl et al.*, 2000; *Tebaldi et al.*, 2006; *Mastrandrea et al.*, 2009; *Diffenbaugh and Ashfaq*, 2010]. Also, because climate change is a long-term trend or non-stationarity in the daily temperature climatology, we examine regional heat wave activity relative to the contemporaneous climate, i.e., in a non-stationary framework, which is relevant to estimating contemporaneous impacts of weather extremes.

2. Data and Methods

2.1. Observations

[5] Observed data are daily maximum and minimum temperatures (Tmax and Tmin, respectively) interpolated onto a regular 12 × 12 km grid with temperature lapsed to grid cell center elevations [*Maurer et al.*, 2002]. The station source data are from the National Climatic Data Center (NCDC) first-order and cooperative observer summary of the day dataset [*National Climatic Data Center*, 2003]. Daily sea level pressure (SLP) and precipitable water (PRWTR) data are from NCEP/NCAR reanalysis.

2.2. Model Simulations and Downscaling

[6] Four GCMs were chosen (CNRM, GFDL, CCSM and PCM) from those participating in the Coupled Model Intercomparison Project Phase 3 (CMIP3) and Intergovernmental Panel on Climate Change 4th Assessment Report (AR4) for their ability to simulate seasonal features of California's Mediterranean-type climate and observed climate variability as well as for availability of requisite variables at daily temporal resolution (see Text S1 in the auxiliary material for details).[1] The spatially coarse GCM information from the historical and SRES A2 simulations

[1]Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California, USA.

Corresponding author: A. Gershunov, Scripps Institution of Oceanography, University of California, San Diego, 9500 Gilman Dr., La Jolla, CA 92093, USA. (sasha@ucsd.edu)

0094-8276/12/2012GL052979

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL052979.

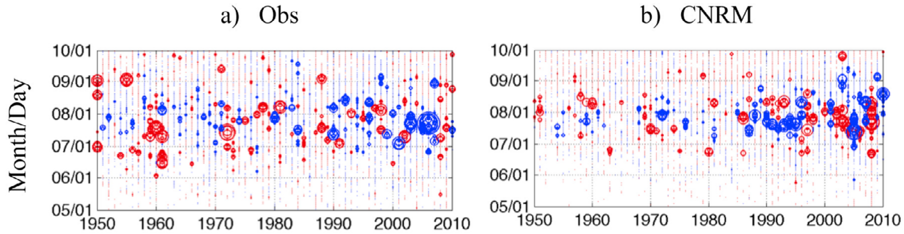

Figure 1. Spatially-averaged state-wide heat wave index (HWI) derived independently from Tmax and Tmin (see text) for (a) observations and (b) the CNRM model. An individual heat wave is defined as a group of consecutive days in which either Tmin or Tmax exceeded the p95 threshold. A Type I heat wave (red) is one when the HWI sum for Tmax exceeded that for Tmin. For Type II heat waves the Tmin HWI sum was greater (blue).

was statistically downscaled onto the 12 × 12 km grid according to the methodology of *Maurer et al.* [2010], which is based on a constructed analogues approach (CA) of *Maurer and Hidalgo* [2008] matching modeled and observed daily large-scale anomalies with a quantile-mapping bias correction on the large-scale data prior to the CA approach. We use this statistical downscaling approach with awareness of the implicit assumption that the observed relationships between large-scale and fine-scale weather are stationary under climate change.

2.3. Heat Wave Definition

[7] Heat waves were defined as in GCI'09 and *Guirguis et al.* [2011] as daily temperature excesses over a threshold. We use daily Tmax and Tmin exceeding their respective 95th percentile (p95) thresholds computed from the local daily climatologies over the May through September warm season spanning the years 1950–1999. The heat wave index (HWI) so defined captures the frequency, intensity and duration of heat waves. The HWI is calculated daily and locally for each 12 km grid box. We obtain regional and/or seasonal heat wave indices by aggregating daily values over a region or season, respectively. The observed daily HWI values averaged over the entire state are shown in Figure 1a.

2.4. Model Validation

[8] As with most extremes, the rare nature of regional heat waves requires that GCMs be validated for their ability to realistically simulate them for the correct dynamical/synoptic reasons. Validation of the four GCMs followed the synoptic analysis of GCI'09 to diagnose SLP anomalies that produce extensive heat waves in California (Figure S1). Only one of the models (CNRM) performed realistically – prominently exhibiting both a surface High over the Great Plains and a Pacific Low that together produce southerly advection over California State. Other models are deficient in this regard displaying an overly extensive Pacific Low that extends over California and an underdeveloped Great Plains High. Daily PRWTR data (uniquely available from the CNRM model) was further verified to exhibit a perfectly realistic differentiation between Type I and II heat waves – increased PRWTR over the region during the more humid Type II heat waves (not shown). This CNRM version 3 GCM (CNRM [*Salas-Mélia et al.*, 2005]) boasts a good overall performance in simulating southwestern regional climate features [e.g., *Favre and Gershunov*, 2009; *Das et al.*, 2011; *Cayan et al.*, 2010]. We further focus on the downscaled past (1950–2010) and future (2011–2099) CNRM model runs, but also include results from the other models in the auxiliary material for completeness. The "past" period was selected as a concatenation of the historical and projected model simulations that is consistent with the observational period.

2.5. California Regionalization

[9] Unique California climate regions (Figure 2a, also referred to as "sub-regions") were identified using rotated principal components analysis (PCA) to isolate spatially cohesive regions experiencing similar temporal variability. Numerous studies have used PCA for regionalization purposes [e.g., *Richman and Lamb*, 1985; *Ehrendorfer*, 1987; *Comrie and Glenn*, 1998; *Guirguis and Avissar*, 2008]. We applied PCA to the local daytime HWI over the 1950–1999 base period to identify the primary patterns of summertime heat wave variability. Six PCs representing 65% of the overall variance were varimax rotated and regions were identified following the maximum loading method [*Comrie and Glenn*, 1998]. The results were stable to choice of base period and orthogonal versus oblique rotation as well as to whether the daytime or nighttime HWI was used. We tested the ability of the models to represent California's sub-regional climatology by repeating the regionalization using downscaled data and the results were very similar, especially for CNRM, to observed (not shown). Accordingly, the grid coordinates of observed climate sub-regions were used for the regional analyses.

3. Results

3.1. State-Wide Heat Wave Activity

[10] Figure 1 (Figure S2) shows the daily HWI averaged over California in observations and the CNRM model (all models). Strong interannual and decadal variability in heat wave activity is evident in all data. In earlier decades, Type I events dominated in frequency and intensity, but Type II events have become more dominant in the last couple of decades. Observations and model simulations are comparable in this regard, although models tend to show a higher recent propensity towards both types of events. Although CNRM simulates the most realistic heat waves in terms of synoptic forcing (Text S1), its HWI trend is overestimated compared to observations and other models (Table 1). We will not discuss the absolute magnitudes of these trends, but rather concentrate on their qualitative manifestations, noting that all models show significant increases in heat wave activity of both types, although with a consistently disproportionate increase in Type II heat waves in future projections (Table 1).

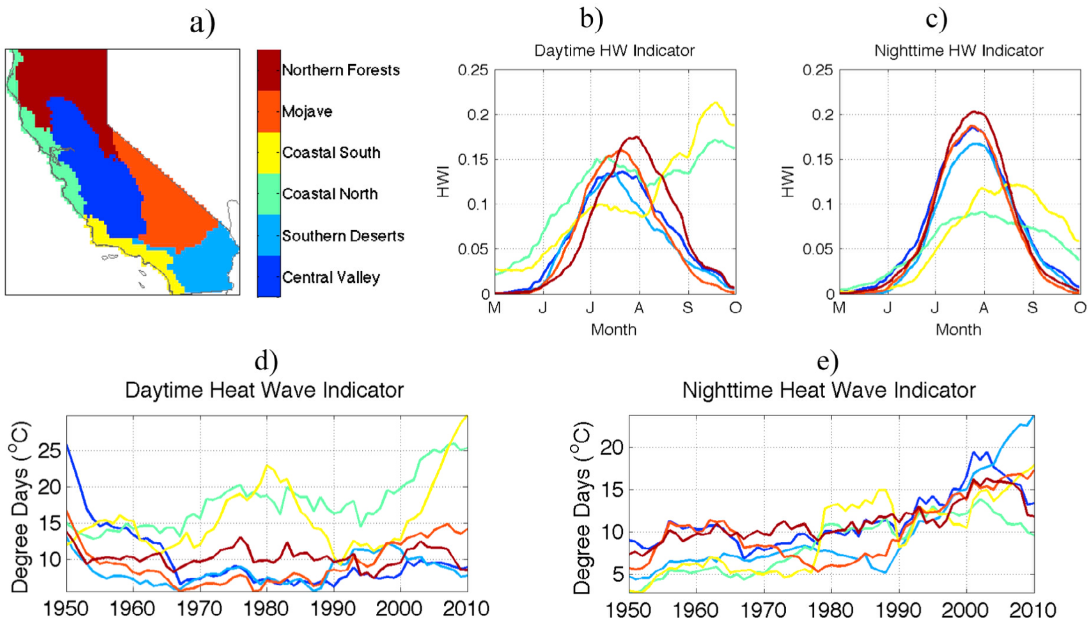

Figure 2. (a) California sub-regions derived from daily HWI variability, (b, c) seasonality of observed daytime and nighttime heat waves for each California sub-region and (d, e) time series of the seasonal daytime and nighttime HWI shown smoothed with a 5-point running mean. The colors in Figures 2b–2e correspond to the sub-regions in Figure 2a.

3.2. Regional Heat Wave Activity

[11] The peak of the heat wave season typically occurs at the seasonal temperature peak in late July for all inland regions (Figures 2b and 2c). Coastal regions present an exception to this rule, however, particularly for Type I heat waves, with a bi-modal distribution and the primary peak in September (also seen in Figures 3b and 3c). When inland temperatures are at their seasonal maximum, the sea breeze and associated marine layer clouds tend to cool the coastal regions. The 95th percentile thresholds are therefore cooler in coastal regions and are more readily exceeded early and especially late in the season. In September, a regional katabatic offshore wind, known in Southern California as the *Santa Ana* [*Raphael*, 2003; *Hughes and Hall*, 2010], causes dry coastally trapped heat waves as high desert air descends from the Great Basin (~1000 m above sea level) and over the coastal ranges, warming adiabatically and drying on its way down to the coast. The historical GCM simulations reproduce these late-season, predominantly Type I, coastal heat waves, albeit with underestimated intensity (Figures 3e and 3f). The observed coastal heat wave season is therefore somewhat broader with more frequent and intense late-season predominantly Type I events (Figures 3b and 3c; also true for the other models, not shown).

[12] Observed nighttime heat waves are seen to be significantly increasing in all regions (Table 1 and Figure 2e). In coastal regions, midsummer nighttime heat waves have shown a marked increase beginning in the 1980s (Figures 2e, 3b, and 3c). This coastal trend in midsummer nighttime heat waves is due to an increase in spatial extent of inland-centered heat events causing them to encroach upon coastal areas (Figure 4), a development perhaps facilitated by greater atmospheric stability at night and associated land-breeze circulation. Modeled Type II heat waves are increasing more than Type I for most regions, except along the coast where both types tend to be comparably on the rise, broadly consistent with observations (Table 1).

[13] Although observed long-term trends in Type I heat wave activity are positive for all regions, except the heavily irrigated Central Valley, only the Coastal North shows a significant trend in daytime heat waves (Table 1). Modeled trends are also shown in Table 1 for the simulated past and future climate periods. There is a significant modeled trend

Table 1. Table of Daytime and Nighttime Seasonal HWI Trends for Observations (Obs) and Downscaled GCMs Given in °C per Decade[a]

	Obs		CNRM		GFDL		CCSM		PCM	
	Daytime	Nighttime	Daytime	Nighttime	Daytime	Nighttime	Daytime	Nighttime	Daytime	Nighttime
CA	0.4	**1.6**	**3.7 (33.0)**	**3.9 (43.2)**	**2.5 (19.6)**	**2.3 (21.2)**	**1.1 (17.9)**	**1.2 (21.6)**	**1.5 (9.2)**	**1.3 (10.0)**
Central Valley	−0.9	**1.6**	**3.8 (32.2)**	**4.3 (43.6)**	**2.4 (16.8)**	**2.4 (19.0)**	**0.9 (16.6)**	**1.1 (19.4)**	**1.6 (9.7)**	**1.5 (10.3)**
Southern Deserts	0.6	**2.5**	**3.1 (31.8)**	**3.4 (36.4)**	**2.1 (24.3)**	**2.6 (23.1)**	**1.8 (22.4)**	**1.2 (21.9)**	**1.2 (9.3)**	**1.4 (9.4)**
Coastal North	**2.0**	**1.7**	**4.5 (54.4)**	**3.6 (58.2)**	**2.1 (19.0)**	**1.5 (26.1)**	**1.5 (16.9)**	**1.5 (28.1)**	**2.1 (9.1)**	**1.3 (11.7)**
Coastal South	1.1	**2.3**	**3.7 (53.4)**	**3.6 (55.3)**	**2.1 (23.3)**	**1.7 (20.9)**	**1.6 (20.2)**	**1.3 (24.0)**	**2.1 (8.9)**	**2.0 (10.3)**
Mojave	0.9	**1.4**	**3.4 (25.5)**	**4.0 (38.0)**	**2.5 (23.0)**	**2.7 (21.7)**	**1.5 (21.1)**	**1.1 (22.1)**	**1.2 (9.4)**	**1.1 (10.1)**
Northern Forests	0.3	**1.2**	**3.7 (26.4)**	**3.9 (41.2)**	**3.1 (16.6)**	**2.3 (20.1)**	0.5 **(13.9)**	**1.1 (20.2)**	**1.2 (8.5)**	0.8 **(9.4)**

[a]Bold font indicates trends are significant at the 95% level. Trends for the historical period (1950–2010) and future (2011–2099) are provided for the GCMs, with the future trends shown in parentheses.

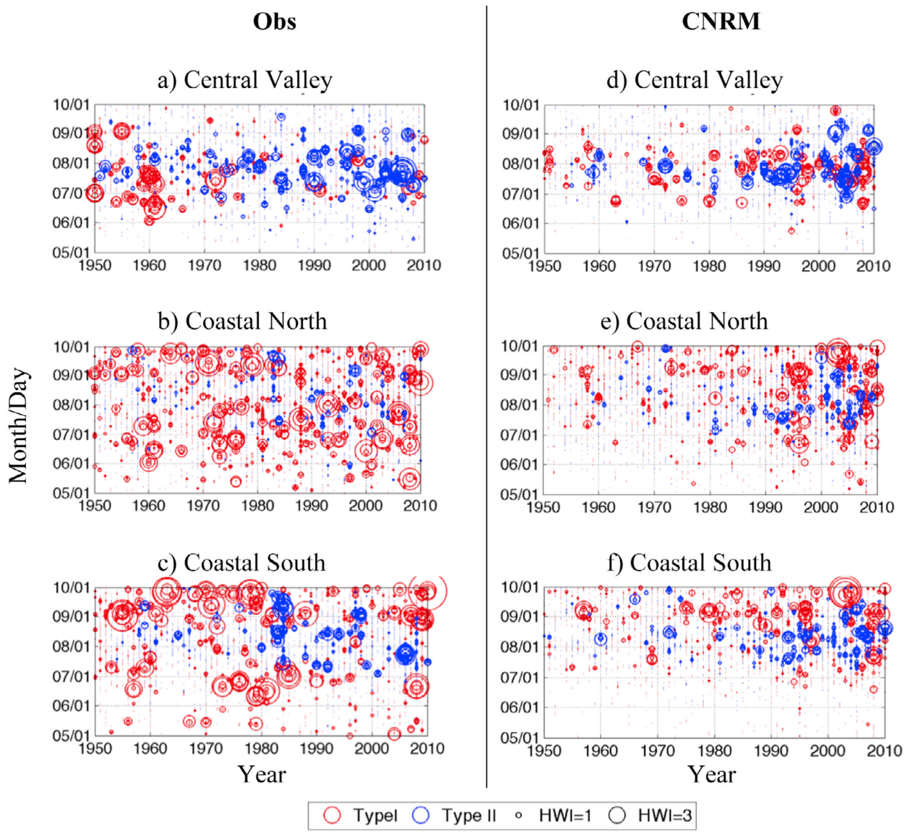

Figure 3. As in Figure 1 but for selected California sub-regions.

for the past period in both daytime and nighttime heat waves. Excepting the coastal regions, past nighttime trends tend to be greater for most models. Future climate shows intensified increasing trends, with trends in Type II heat waves exceeding those of Type I for the vast majority of regions and models (Table 1). Moreover, most models project both the North and South Coasts to experience the largest increase in Type II heat wave magnitude.

[14] Because exceedances over local temperature thresholds are accumulated over space (region) and time (season) a general warming resulting in stronger and more persistent exceedances over once-extreme thresholds leads to enormous trends as these thresholds are rendered less and less extreme and are exceeded on a more and more regular basis in a warming climate. In other words, the inflated HWI trends in future climate are due to stationary thresholds applied in a non-stationary climate.

3.3. Non-stationary Variance Structure of Daily Temperature

[15] The magnitude of trends in heat wave activity, although everywhere positive, varies by region (Table 1). These regional variations of trends may be due to varying magnitudes of heat waves relative to the regional background warming. To consider this possibility, we define rare extremes relative to the typical values making up most of the

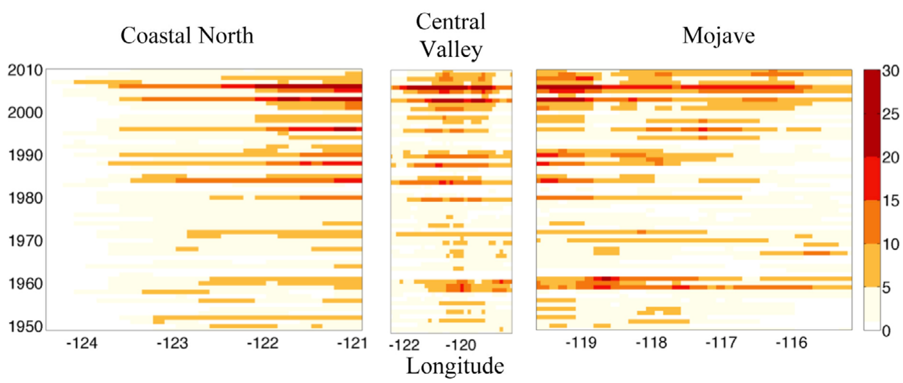

Figure 4. Longitudinal averages of the July nighttime HWI for three neighboring regions showing how the spatial extent of Type II heat waves is increasing and their influence is spreading to coastal regions in July, the peak of the inland heat wave season.

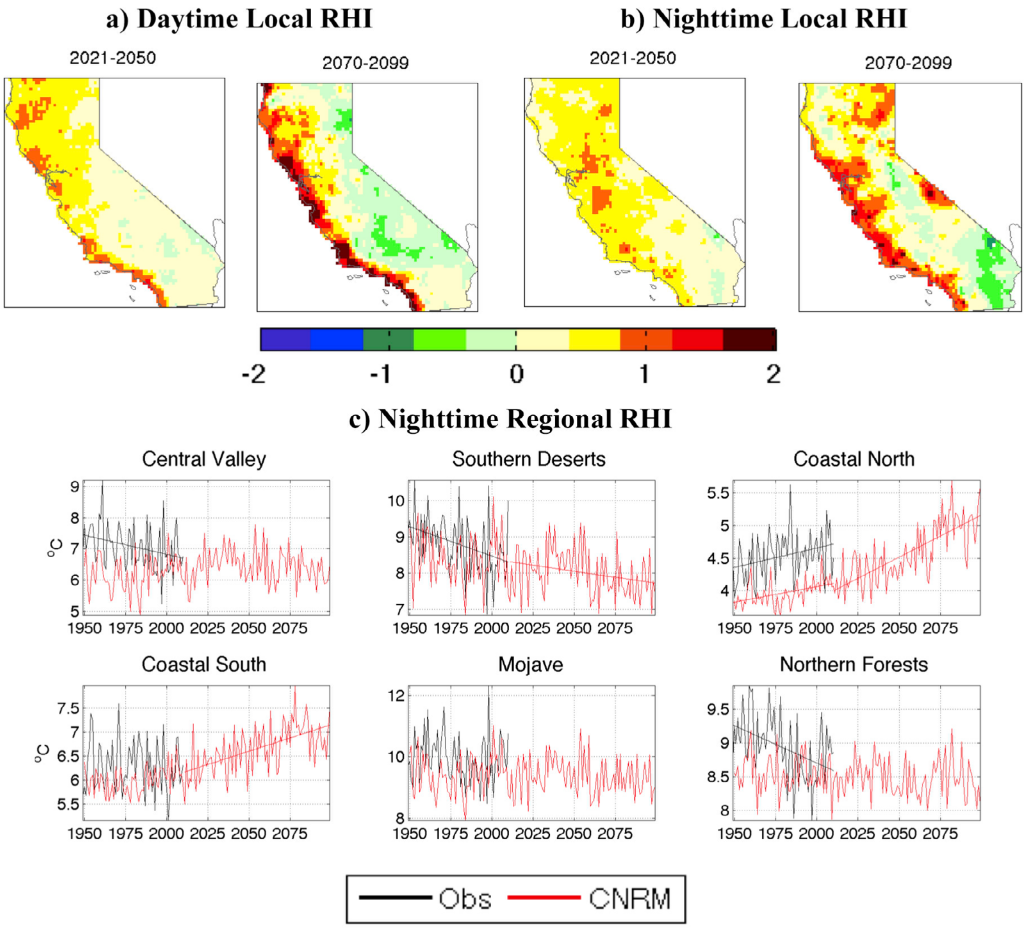

Figure 5. The relative heat index (RHI) index calculated at each grid cell from CNRM (a) maximum and (b) minimum temperatures and shown as the difference between the mean RHI for a given climate period (2021–2050 or 2070–2099) and (c) the mean RHI over the historical period (1950–2010) and the RHI index calculated from regionally aggregated minimum temperatures according to observations (black) and CNRM simulations (red). Solid lines show linear trends significant at the 95th confidence level calculated separately for the past (1950–2010) and future (2011–2100) periods.

contemporary probability density function (PDF), i.e., temperatures to which biota can potentially acclimate with time. Thus, we next consider extremes relative to a changing climatology.

[16] To evaluate the intensity of extremes in this non-stationary framework, we examine the ratio of p95 to the median (p50) of daily Tmax and Tmin PDF in each summer season. Maps and time series of p95-p50 (Figure 5) reflect the magnitude of sub-regional heat waves relative to median seasonal temperatures and therefore the severity of heat waves relative to a non-stationary climate. Let us call this index the *relative heat index* or RHI.

[17] Although Type II heat wave activity increased and was simulated and projected to increase in all sub-regions (Table 1 and Figure 3e), observations show decreasing heat wave magnitude relative to seasonal median warming (i.e., decreasing RHI) in the inland regions (Figure 5c). The Southern and Mojave Deserts are the only regions where RHI, for either type of heat waves, is projected by the CNRM to significantly decrease relative to continuing median warming (Figures 5 and S4). In these hottest of the six regions, the change in the magnitude of heat waves seems limited by that of seasonal warming. Observations and projections, as well as from the other models, seem to broadly agree on this point (Figures 5 as well as Figures S3 and S4).

[18] At the same time, we observe increasing heat wave magnitude relative to seasonal median warming (i.e., increasing RHI) only along the North Coast. This is the only region where CNRM simulates significant change over the observational period – an increase consistent with the observed. The model furthermore projects increasing RHI exclusively for both coastal regions (see Figures 5a–5c for Type II and Figure S4 for Type I). Other models tend to agree (Figure S3). Summertime coastal seasonal warming is expected to be modulated by cool coastal waters and is projected to be much weaker than inland warming [*Cayan et al.*, 2008, 2009]. Increasing frequency, intensity, duration and especially spatial extent of large inland Type II heat waves (GCI'09), however, result in humid nighttime-accentuated heat encroaching more and more into coastal regions, particularly at night when the sea breeze weakens. This effect is already visible in the observations over the northern part of the state (Figure 4). This intensification of coastal heat waves relative to the slower average warming explains the stronger projected coastal HWI

trends relative to other regions (Table 1). The models projecting strong intensification of heat wave activity along the coast relative to inland regions broadly agree on this point.

4. Discussion and Conclusions

[19] We examined observed and modeled heat wave activity over California and its sub-regions. Four downscaled GCM simulations were validated against observations for their ability to reproduce heat waves in terms of realistic synoptic forcings. The most realistic model was found to also best reproduce the most important feature of the observed regional trend – the stronger relative trend in Type II (humid, Tmin-accentuated) versus Type I (dry, Tmax-accentuated) regional heat waves. This differential trend was most coherent for the inland regions in observations and in most models. Projected heat wave activity was examined in the context of observed trends using stationary thresholds as well as in a non-stationary context.

[20] The analysis of heat waves involving stationary thresholds, the 95th percentile of the local historical summertime climatology of daily temperatures, is relevant to examining how current acclimatization and existing infrastructure might perform in future heat waves. This conventional approach suggests that, according to the GCMs, the trend towards stronger and more frequent Type II relative to Type I heat waves is a signal of anthropogenic climate change that is expected to continue and accelerate through the 21st century. However, much of this change in extremes may be produced simply by the trend in the mean summertime temperature also observed to have been strongest in Tmin rather than Tmax over this region [*Gershunov and Cayan*, 2008] as well as over many other regions around the globe [e.g., *Easterling et al.*, 1997].

[21] The past and future regional trends are positive as can be expected, because, following convention, we have first defined heat waves relative to stationary local thresholds in a warming non-stationary climate. In other words, exceedance of stationary historical thresholds is bound to increase over time due simply to a trend in the mean of the daily temperature distribution, so that a long-term mean warming will eventually make historical heat waves commonplace. This does not mean that heat wave activity per se is expected to change relative to the changing mean climate. And it does not explain why coastal heat waves are projected to change relative to stationary thresholds more than their inland counterparts while coastal mean seasonal warming is projected to be less than that inland [*Cayan et al.*, 2008, 2009].

[22] The non-stationary analysis provides insight into how heat waves may change relative to seasonal warming, or how the shape of the daily summertime Tmax and Tmin PDFs and especially their tails may change relative to the warming mean state. Non-stationary analysis suggests that heat waves in hot desert regions will likely become less intense relative to strong inland warming, especially at night, while coastal heat waves will become more intense relative to the milder warming modulated by the cool ocean's proximity. This projected coastal trend is enhanced for Type II heat waves in July and it is already observed in coastal Northern California. It largely represents coastal penetration of expanding Type II midsummer inland heat waves.

[23] This trend is particularly distressing for coastal regions where population density is the highest, while physiological acclimatization and air conditioning penetration are the lowest for the state [*Sailor and Pavlova*, 2003]. The non-stationary view is relevant for estimating future impacts on health, ecosystems and agriculture as it implicitly incorporates the effects of adaptation (e.g., via physiological or technological acclimatization) to the evolving climate state. The strong and coherent impact on public health, as measured by emergency department visits, can already be detected most clearly along the north-central coast when considering the unprecedented heat wave of July 2006 [*Knowlton et al.*, 2009; *Gershunov et al.*, 2011]. Given results presented here, that unprecedented Type II event can be considered a harbinger of sub-regional impacts to come. In the future, little acclimatization to warmer temperatures can be expected due to the relatively weak warming projected along the highly populated California coast compared to inland areas [*Cayan et al.*, 2008, 2009]. Therefore, a disproportionate coastal increase in heat wave activity is bound to be impactful. Coastal areas will be the subject of more in-depth future research. In particular, the interaction of nighttime land-breeze and late-summer Santa Ana winds on the one hand with sea-breeze-related coastal marine layer cloud influences on the other, will need to be examined in detail to develop a refined and rigorous physical understanding of coastal heat wave trends.

[24] **Acknowledgments.** This work was supported by DOI via the Southwest Climate Science Center, by NOAA via the RISA program through the California and Nevada Applications Center, and by the National Institute of Environmental Health Sciences grant RC1ES019073 ("Projected heat wave magnitudes and public health impacts"; PI Margolis, H.G.). Kristen Guirguis was supported via a UCAR PACE fellowship. We thank Mary Tyree for data retrieval, downscaling and handling. The order of authorship was determined by a coin toss.

[25] The Editor thanks the two anonymous reviewers for assisting in the evaluation of this paper.

References

Cayan, D. R., E. P. Maurer, M. D. Dettinger, M. Tyree, and K. Hayhoe (2008), Climate change scenarios for the California region, *Clim. Change*, *87*, 21–42, doi:10.1007/s10584-007-9377-6.

Cayan, D., M. Tyree, M. Dettinger, H. Hidalgo, T. Das, E. Maurer, P. Bromirski, N. Graham, and R. Flick (2009), Climate change scenarios and sea level rise estimates for the California 2009 Climate Change Scenarios Assessment, *Publ. CEC-500-2009-014-F*, 64 pp., Clim. Change Cent., La Jolla, Calif.

Cayan, D. R., T. Das, D. W. Pierce, T. P. Barnett, M. Tyree, and A. Gershunov (2010), Future dryness in the southwest US and the hydrology of the early 21st century drought, *Proc. Natl. Acad. Sci. U. S. A.*, *107*, 21,271–21,276, doi:10.1073/pnas.0912391107.

Comrie, A. C., and E. C. Glenn (1998), Principal components based regionalization of precipitation regimes across the southwest United States and northern Mexico, with an application to monsoon precipitation variability, *Clim. Res.*, *10*, 201–215, doi:10.3354/cr010201.

Das, T., M. D. Dettinger, D. R. Cayan, H. G. Hidalgo (2011), Potential increase in floods in California's Sierra Nevada under future climate projections. *Climatic Change*, *109*, S71–S94, doi:10.1007/s10584-011-0298-z.

Diffenbaugh, N. S., and M. Ashfaq (2010), Intensification of hot extremes in the United States, *Geophys. Res. Lett.*, *37*, L15701, doi:10.1029/2010GL043888.

Easterling, D. R., et al. (1997), Maximum and minimum temperature trends for the globe, *Science*, *277*, 364–367, doi:10.1126/science.277.5324.364.

Ehrendorfer, M. (1987), A regionalization of Austria's precipitation climate using principal component analysis, *Int. J. Climatol.*, *7*, 71–89, doi:10.1002/joc.3370070107.

Favre, A., and A. Gershunov (2009), North Pacific cyclonic and anticyclonic transients in a global warming context: possible consequences for western North American daily precipitation and temperature extremes, *Clim. Dyn.*, *32*, 969–987, doi:10.1007/s00382-008-0417-3.

Gershunov, A., and D. Cayan (2008), Recent increase in California heat waves: July 2006 and the last six decades, PIER Project report, Calif. Energy Comm., Sacramento. [Available at http://www.energy.ca.gov/2008publications/CEC-500-2008-088/CEC-500-2008-088.PDF.]

Gershunov, A., D. Cayan, and S. Iacobellis (2009), The great 2006 heat wave over California and Nevada: Signal of an increasing trend, *J. Clim.*, *22*, 6181–6203, doi:10.1175/2009JCLI2465.1.

Gershunov, A., Z. Johnston, H. G. Margolis, and K. Guirguis (2011), The California heat wave 2006 with impacts on statewide medical emergency, *Geogr. Res. Forum*, *31*, 53–69.

Guirguis, K. J., and R. Avissar (2008), A precipitation climatology and dataset intercomparison for the western United States, *J. Hydrometeorol.*, *9*, 825–841, doi:10.1175/2008JHM832.1.

Guirguis, K., A. Gershunov, R. Schwartz, and S. Bennett (2011), Recent warm and cold daily winter temperature extremes in the Northern Hemisphere, *Geophys. Res. Lett.*, *38*, L17701, doi:10.1029/2011GL048762.

Hughes, M., and A. Hall (2010), Local and synoptic mechanisms causing Southern California's Santa Ana winds. *Climate Dynamics*, *34*, 847–857.

Knowlton, K., M. Rotkin-Ellman, G. King, H. G. Margolis, D. Smith, G. Solomon, R. Trent, and P. English (2009), The 2006 California heat wave: Impacts on hospitalizations and emergency department visits, *Environ. Health Perspect.*, *117*, 61–67.

Mastrandrea, M. D., C. Tebaldi, C. P. Snyder, and S. H. Schneider (2009), Current and future impacts of extreme events in California, *PIER Tech. Rep. CEC-500-2009-026-D*, Calif. Energy Comm., Sacramento.

Maurer, E. P., and H. G. Hidalgo (2008), Utility of daily vs. monthly large-scale climate data: An intercomparison of two statistical downscaling methods, *Hydrol. Earth Syst. Sci.*, *12*, 551–563, doi:10.5194/hess-12-551-2008.

Maurer, E. P., A. W. Wood, J. C. Adam, D. P. Lettenmaier, and B. Nijssen (2002), A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States, *J. Clim.*, *15*, 3237–3251, doi:10.1175/1520-0442(2002)015<3237:ALTHBD>2.0.CO;2.

Maurer, E. P., H. G. Hidalgo, T. Das, M. D. Dettinger, and D. R. Cayan (2010), The utility of daily large-scale climate data in the assessment of climate change impacts on daily streamflow in California, *Hydrol. Earth Syst. Sci.*, *14*, 1125–1138, doi:10.5194/hess-14-1125-2010.

Meehl, G. A., et al. (2000), An introduction to trends in extreme weather and climate events: Observations, socioeconomic impacts, terrestrial ecological impacts, and model projections, *Bull. Am. Meteorol. Soc.*, *81*, 413–416, doi:10.1175/1520-0477(2000)081<0413:AITTIE>2.3.CO;2.

National Climatic Date Center (2003), Data documentation for data set 3200 (DSI-3200): Surface land daily cooperative summary of the day, report, Asheville, N. C. [Available at http://www.ncdc.noaa.gov/pub/data/documentlibrary/tddoc/td3200.pdf.]

Ostro, B. D., L. A. Roth, R. S. Green, and R. Basu (2009), Estimating the mortality effect of the July 2006 California heat wave. *Environ. Res.*, *109*, 614–619.

Raphael M. N. (2003), The Santa Ana winds of California. *Earth Interactions*, *7*, 1–13.

Richman, M. B., and P. J. Lamb (1985), Climatic pattern analysis of three- and seven-day summer rainfall in the central United States: Some methodological considerations and a regionalization, *J. Clim. Appl. Meteorol.*, *24*, 1325–1343, doi:10.1175/1520-0450(1985)024<1325:CPAOTA>2.0.CO;2.

Sailor, D., and A. Pavlova (2003), Air conditioning market saturation and long-term response of residential cooling energy demand to climate change, *Energy*, *28*, 941–951, doi:10.1016/S0360-5442(03)00033-1.

Salas-Mélia, D., F. Chauvin, M. Déqué, H. Douville, J. F. Guérémy, P. Marquet, S. Planton, J. F. Royer, and S. Tyteca (2005), Description and validation of the CNRM-CM3 global coupled model, *CNRM Work. Note 103*, Cent. Natl. de Rech. Meteorol., Toulouse, France.

Tebaldi, C., K. Hayhoe, and J. M. Arblaster (2006), Going to the extremes: an intercomparison of model-simulated historical and future changes in extreme events, *Clim. Change*, *79*, 185–211, doi:10.1007/s10584-006-9051-4.