Arnold Schwarzenegger
Governor

RECENT INCREASE IN CALIFORNIA HEAT WAVES: JULY 2006 AND THE LAST SIX DECADES

PIER PROJECT REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

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Abstract

Summertime heat waves in California vary from event to event in their daytime and nighttime temperatures. Various factors, including timing, large-scale atmospheric circulation, and humidity, determine the magnitude, that is, the intensity, duration, and area, of any particular event. Most of the great California heat waves can be classified into primarily daytime or nighttime events depending on whether atmospheric conditions are dry or humid. A rash of nighttime-accentuated events in the last decade was punctuated by an unusually intense case in July 2006, which was the largest heat wave on record (1948–2006). Although daytime temperatures during the July 2006 event were comparable to those in some prior great heat waves, the duration of the event was exceptionally long, and its nighttime temperatures were unprecedented. Its astonishing magnitude was caused by a combination of factors, the most unusual of which was a very early and intense moisture anomaly transferred into the region by a weaker heat wave circulation that preceded the main event. To describe the spatial extent, duration, and daytime and nighttime characteristics of heat waves in California, researchers obtained temperature measurements from 95 weather stations around California and Nevada and performed a variety of statistical and mapping functions upon the data. Generally, there is a growing trend in heat wave activity over the entire region that is expressed more strongly and clearly in nighttime rather than daytime temperature extremes. Daytime heat wave activity has been intensifying more rapidly over the elevated interior compared to the lowland valleys. The intensification of nighttime heat wave activity since 2000 appears to be part of a longer-term smooth and steadily increasing trend that is fully consistent with the observed overall warming trend in minimum temperatures. Circulations associated with great regional heat waves draw hot air from the south. This air can be dry or moist, depending on whether an appropriately positioned moisture source is available, causing heat waves to be expressed preferentially during day or night. A particular source is a marine region west of Baja California that has been experiencing significant sea surface warming and atmospheric moistening. The correlation between heat wave occurrences over California and unusually warm sea surface temperatures in the region west of Baja California is intriguing because the sea surface temperature warming there appears to be part of a global pattern of sea surface temperature warming during the last six decades.

Keywords: Heat waves, California climate change, synoptic circulation, sea surface temperature

Executive Summary

Introduction

Regional heat waves stress ecosystems and society. In particular, they pose important challenges to agriculture, energy supply, and health care. Heat waves are traditionally driven by regional weather patterns, but they are also sensitive to global climate change.

Purpose

This report investigates the causes of observed variability and long-term changes in California heat waves to better reduce their impacts.

Project Objectives

This research began by defining local heat waves from daily maximum and minimum temperature observations at weather stations. Using data from almost 100 weather stations from 1948 to 2006, the data was used to construct indices of heat wave activity that reflect a heat wave's temperature intensity, duration and spatial extent — all components of heat waves related to their impacts. Noting important differences in the behavior of daytime versus nighttime temperature variability and trends, the researchers define daytime and nighttime heat waves separately from the available maximum and minimum temperature observations, respectively.

Having defined and described regional heat wave activity, this research investigated the drivers of synoptic weather (weather conditions over a broad area) for major California heat waves, focusing specifically on the causes of daytime and nighttime heat waves. Having described the regional weather drivers of great heat waves, the researchers attempted to describe the likely causes of observed long-term trends, specifically in nighttime heat waves.

Project Outcomes

Most of the great California heat waves can be classified into primarily daytime or nighttime events depending on whether atmospheric conditions are dry or humid. A rash of nighttime-accentuated events in the last decade was punctuated by an unusually intense case in July 2006, which was the largest heat wave on record (1948–2006). The next largest event occurred in July 2003, and it also far exceeded previous events on record. The astonishing magnitude of these two events was caused by a combination of factors, the most unusual of which was a very moist air mass that moved into the region from the south by the typical heat wave atmospheric circulation. Both events were nighttime-dominated heatwaves.

Generally, there is a positive trend in heat wave activity over the entire region that is expressed more strongly and clearly in nighttime rather than daytime temperature extremes. Daytime heat wave activity has been intensifying preferentially over the elevated interior compared to the lowland valleys. Nighttime heat wave activity shows a strong positive trend over the entire region and record. This trend has intensified markedly since 2000.

Circulations associated with great Californian heat waves bring hot air from the south. This air can be dry or moist, depending on whether an appropriately positioned moisture source is available. If the source region contains abundant moisture, the heatwaves will be expressed preferentially during the night (high nighttime temperatures). One particular source in this case is a marine region west of Baja California that has been experiencing significant atmospheric moisture. This is intriguing because this increase in moisture appears to be related to a global sea surface temperature warming pattern.

Conclusions

California heat waves are changing — they are becoming more humid and expressed more strongly at night. The hotter nighttime temperatures also encourage hotter daytime temperatures (as the day starts out hotter) as well as increased heat wave duration and area. This change is consistent with climate change globally and therefore can be expected to continue for the long term. However, the specific regional mechanism of this change, the strongly increasing sea surface temperatures and associated moisture source directly to the south of California, west of Baja California, must be understood and explained more fully before skillful seasonal predictions and more detailed long-range projections will become possible.

Recommendations

Traditionally, low humidity and strong nighttime cooling have characterized heat waves in California, giving humans, animals, and plants needed respite from daytime heat. Due to the observed and expected further increase in humid heat waves expressed more strongly at night, specific recommendations can be made for farmers, energy producers, health care providers, and the public. For example, increased *nighttime* energy demand can be expected during current and future heat waves. Targeted warnings can also be issued with this changing character of heat waves in mind, for example, the use of fans may be ill-advised during hot *and humid* conditions. Specific changes to the energy infrastructure as well as to routine and emergency cooling methods may be recommended.

Benefits to California

A better, more detailed understanding of current and expected future changes in regional climate and adverse weather extremes benefits California by illuminating more targeted and effective strategies for societal adaptation and impact reduction.

1.0 Introduction

According to anecdotal evidence, the July 2006 California heat wave was unprecedented in several respects. Many local records for duration of above-threshold temperatures were broken. The heat wave affected Northern and Southern California simultaneously. Nightfall did not provide the expected relief from daytime heat. Unusually high humidity levels exacerbated the stressful effects and probably contributed to maintaining high nighttime temperatures (*Los Angeles Times* 2006). Enormous demands were placed on water and energy resources (Davis 2006). Californians, human and cattle alike, suffered, some expired[1], and most noticed that something highly unusual was underway. Now that weather data is available for most observing stations, we take a comprehensive retrospective look at the July 2006 California heat wave in the context of the region's climate over the past six decades: the temporal extent of sufficient data and the experience of a human lifetime.

Summertime heat waves top the list of stressful weather extremes that are most commonly linked with global anthropogenic climate change (e.g. Easterling et al. 2000a, Meehl and Tebaldi 2004, Tebaldi et al. 2006). Heat wave activity has received considerable attention lately, especially following the European heat waves in 2003 (e.g. Beniston and Diaz 2004, Schar 2004, Stott et al. 2004, Meehl and Tebaldi 2004, Gershunov and Douville 2007). Most studies have focused on local extreme temperature magnitudes and durations associated with heat waves (e.g. Beniston 2004, Beniston and Diaz 2004, Schar et al. 2004). Heat waves are inherently regional phenomena, however, with regional impacts. The spatial scale of heat waves amplifies the event's stressful effects by spreading them over broader sectors of ecosystems, society and infrastructure. Gershunov and Douville (2007) considered the spatial extent of summertime heat over Europe and North America in seasonal average temperature records and model projections. Although the increasing spatial scale of extreme continental summertime heat is obviously connected to heat-wave activity and clearly tied to global climate change, the explicit behavior of individual heat waves as well as their diurnal properties could not be considered in seasonally or daily averaged data.

A more precise and useful description of heat wave activity should include an explicit and separate quantification of daily and nightly temperature extremes. During a persistent daytime heat wave, cool nights provide respite from the stressful effects of heat on the health and general well-being of plants and animals, as well as for the energy sector, and prepare nature and society to face another day of scorching heat. Heat waves strongly manifested at night eliminate this badly needed opportunity for rejuvenation and increase the chances for catastrophic failure in natural and human systems. Extreme daytime heat is known to endanger health most directly via heat stroke as well as impact air pollution including ozone formation and thereby amplify heat wave related mortality (e.g. Fischer et al. 2004, Stedman 2004). Health impacts of nighttime heat are less well known, but there are indications that high minimum temperatures during heat waves enhance morbidity and mortality (Hemon and Jougla 2003,

[1] Over 140 human and 25000 cattle mortalities were attributed to the July 2006 heat wave in California (Munoz 2006, USAgNet 2006).

Grize et al. 2005). Analyzing excess mortality across Switzerland due to the June and August 2003 European heat waves, Grize et al. (2005) attributed local spikes in mortality to the compounding effect of elevated nighttime temperatures. During the July 2006 California event, a significant number of victims, most of whom were elderly and living alone, had not used their functioning air conditioning (Helene Margolis, personal communication). Perhaps they had turned off air conditioning in the evening expecting the strong nighttime cooling characteristic for this region, which did not materialize.

The physical mechanisms of day and nighttime heat waves may differ. Recent warming trends are known to have been stronger at night than during the day (e.g. Easterling et al. 1997, 2000b) resulting in a generally decreased diurnal temperature range. Stronger nighttime heating trends have been observed consistently at most locations around the globe and, in spite of modeling inconsistencies (Lobell et al. 2007), are among the most reliable and widespread expectations from anthropogenic global climate change (e.g. Tebaldi et al. 2006). In this regard, the California region is no exception as the observed summer warming here has been largely due to minimum temperatures (Figure 1). In this topographically, environmentally, economically and climatically complex region, global, regional and local, natural and anthropogenic effects abound (e.g. Duffy et al. 2007). Clear connections between regional extreme weather and global climate are generally elusive. Where they exist, they provide extremely useful opportunities to understand and skillfully anticipate the stressful local effects of global climate change. Weather extremes, however, must first be understood regionally, typically on the synoptic level.

The following sections describe the data including average summertime temperature variability and trends, as well as our approach to quantifying heat waves and their general behavior (Section 2), illustrate the observed variability of regional day and nighttime heat waves (3), describe the synoptic dynamics leading to the greatest observed events in recent history (4), explain the 2006 event in that context (5), and finally focus on trends in day and nighttime heat waves (6). Summary and conclusions are presented in Section 7.

2.0 Average Summer Temperature and Heat Wave Activity

There is no one objective and uniform definition of "heat wave." In the present study, we seek a regional measure that reflects an event's impacts (on regional health, infrastructure, economy, etc.) and that can be easily quantified in indices that are clear and simply computed from the available data. We want these indices to plainly reflect important aspects of regional heat wave activity and to be straightforward, flexible and easily adaptable for relevant applications. The resulting heat wave indices should include components that add up to a heat wave's regional magnitude and result in numerous impacts on specific sectors of society and environment, and therefore, reflect and quantify an event's intensity, duration and spatial extent.

2.1. Observational Data

In order to describe the spatial extent of heat waves affecting the California region, their duration, and differential symptoms during day and night, we start with day- and night-time temperatures (Tmax and Tmin, respectively) recorded at ninety-five stations distributed more-or-less uniformly over the adjacent states of California and Nevada. These ninety-five stations (CA_{95}) are a subset of a larger set of 141 stations with premium quality daily Tmin and Tmax records going back to at least January 1, 1948 and running through August 2006 (Figure 1a,b, circles). The original set of 141 stations is characterized by a spatial weighting bias towards most populated areas (Figure 1a,b, black dots). The 95 core stations (CA_{95}) were selected as representative of the region by keeping one best quality station per *locale* of 30km radius and thereby removing the urban density bias[2]. Stations with the most complete records are typically found at lower elevations. To retain the effects of mountain climate diversity important in this topographically complex region, the highest elevation station, in addition to the best quality station, was retained wherever the elevation range exceeded 300m per *locale*. All stations were required to have at least 85% of the data present for the entire 59-year period. The sparsely populated and observed areas of the southeastern California and Nevada deserts are, by necessity, underrepresented and downplayed by subsequent analyses. All station data were selected from the updated National Climatic Data Center (NCDC) first order and cooperative observer summary of the day dataset, known as DSI-3200 (NCDC, 2003).

The seasonal focus here is on the summer period, June – August (JJA). The largest events tend to occur around the seasonal temperature maximum in mid-late July. Although intense heat waves occasionally occur in May and September, they tend to be localized resulting from rather different regional circulations than the extensive events considered here[3]. Including those months would not significantly influence our results, but concentrating on JJA sharpens the researchers' focus on the largest events. The authors further limit the temporal extent of this

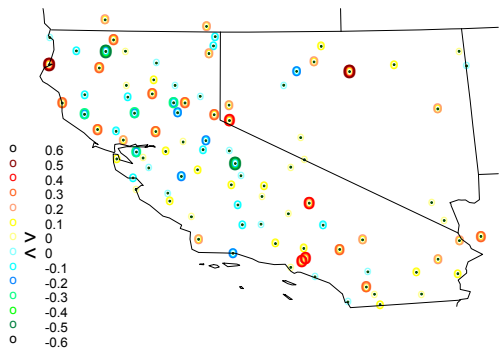
[2] The analysis performed on the entire set of 141 stations predictably resulted in somewhat larger regional trends in both day and nighttime temperatures, but these differences were statistically insignificant.

[3] The September 1978 daytime heat wave expressed along the south and central coast was one such example that resulted from an intense Santa Ana condition.

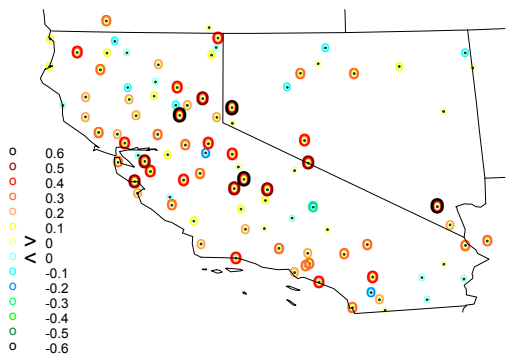
study to the 59 summers between 1948 and 2006. This choice was dictated by compromising record length for spatial completeness and detail.

As a prelude to studying heat wave activity, we first describe the observed trends in summer average temperature. Figure 1 shows local JJA Tmax and Tmin trends in addition to region-wide average temperatures and trends.

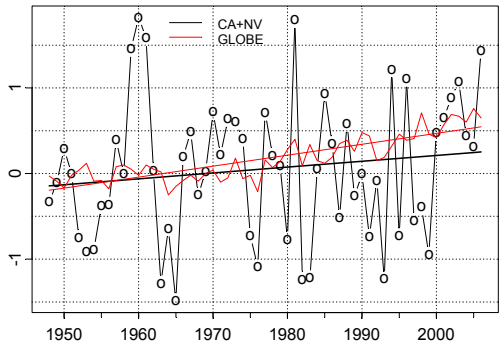
a) JJA Tmax linear trend (°C/decade)



b) JJA Tmin linear trend (°C/decade)



c) JJA Tmax averaged over 95 stations



d) JJA Tmin averaged over 95 stations

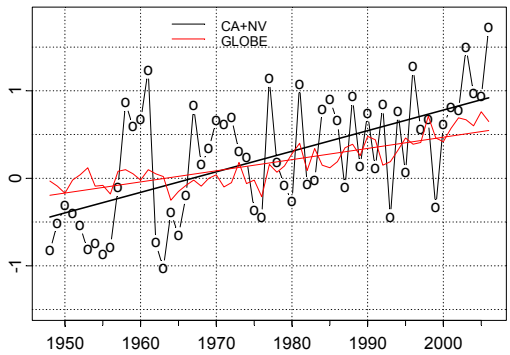


Figure 1. Linear trend in ambient JJA Tmax (a) and Tmin (b) by station. Red dots mark the 95 stations analyzed, while black dots mark urban-sprawl stations not used. Colored circles around the analyzed stations represent the sign and magnitude of local trends according to the legend in °C/decade. Larger circles depict greater trends. Panels (c) and (d) show regional anomalies and trends averaged over the 95 chosen stations and fitted regression line. Global *annual average mean* temperature anomalies and trend computed from the global meteorological station network updated from Hansen et al. (2001) are shown in red for reference. Anomalies are plotted with respect to the 1951-1980 period in this figure. Region-averaged Tmax/Tmin trend is 0.07/0.24°C per decade (0.4/1.4°C over the 59-yr record, compared to the global average of 0.13°C per decade or 0.76°C global warming recorded at land stations over the same period). The linear trends account for 2% and 35% of the variance of JJA mean Tmax and Tmin, respectively.

Both daytime and nighttime temperatures have exhibited warming trends, but those for nighttime are considerably larger (Figures 1 a-d). Some stations showing the largest Tmin trends are urban (Reno WSFO Airport is second with a Tmin warming trend of 1.25°C/decade, Las Vegas WSO Airport is fourth with 0.68°C/decade). A priori, we expect the urban heat island effect to be especially strong for Tmin data (e.g. Cayan and Douglas 1984). Our data set includes a representative sample of urban points. These are, of course, also the places most at risk due to the compounded effects of heat waves on society, e.g. more people potentially exposed, power failure risk, etc. So, it is important to have the heat island effect represented here, but, as will be shown, it does not explain the bulk of the nighttime warming observed over the region. Rural stations are also warming considerably at night. Nevada City, a gold rush town in the low Sierra Nevada of California records the largest Tmin trend of 1.34°C/decade and Auberry, California, located in the Sierra Nevada foothills between Fresno and South Yosemite Entrance comes in third with 0.99°C/decade. Many other rural stations are warming at about 0.4°C/decade at night and the average trend of 1.4 degrees over the 59-yr period of record is impressive. Maximum temperatures are not warming as much or as consistently throughout the state, but the overall trend of 0.4ºC/six decades is noteworthy. As noted by Alfaro et al., (2006), day-to-day, Tmax is more variable than Tmin. This intraseasonal observation obviously translates to interannual timescales further confounding trend detection in Tmax, especially at individual stations. Nevertheless, the summertime regional warming observed here over California and Nevada is fully consistent with the annual average global warming observed over land areas in worldwide station records (Figure 1 c,d). This is the average seasonal picture. The authors' primary interest below is to study the punctuation of the regional mean summer climate by outbreaks of extreme heat.

2.2. Quantifying Regional Summertime Heat Wave Activity

Daytime and nighttime heat-wave activity indices were derived to reflect the overall magnitude of extreme summertime (JJA) heat[4] consisting of intensity, frequency, duration and spatial extent of day and nighttime heat waves. At a particular station, a heat wave is defined to occur when temperature exceeds the 99th percentile of its local summertime climatology[5] (Figure 2). On days and nights when station temperatures exceeded these climatological values, researchers computed the local temperature excesses ($T_{i,j} - T_{99,j}$, i marks days/nights such that $T_{i,j} > T_{99,j}$, at station j) and summed them over each summer, obtaining the *local summertime* Degree Day index, $DD_{99}^{j,s} = \Sigma_i(Tmax_{i,j} - Tmax_{99,j})$, for *i* ranging from June 1 to August 31, the 92 days of summer, resulting in an annually resolved time series at each station. The Degree Night index (DN) is similarly defined for Tmin. By definition, $DD_{99}^{j,s}$ and $DN_{99}^{j,s}$ represent the intensity and frequency of intense (the hottest one percent of) local summer heat waves expressed during the day and night, respectively.

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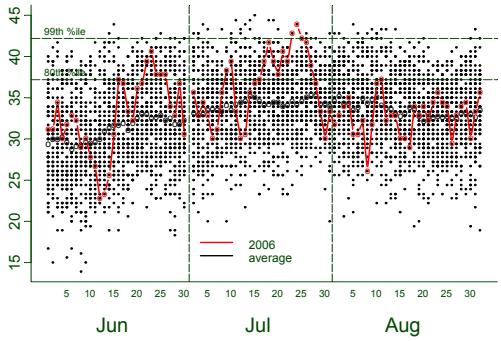
[4] The authors consider individual events as well, below.

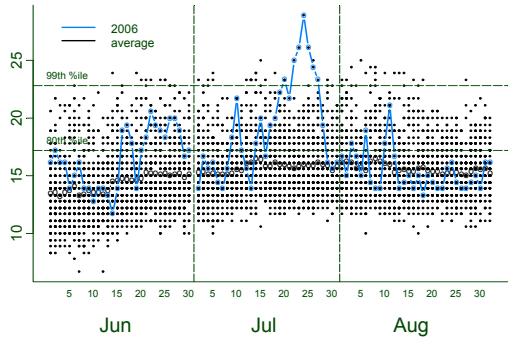
[5] The 99th percentile of June through August daily Tmax and Tmin for the base period 1950 – 1999. By definition, only the 1% hottest days and nights exceed these values during the base period. The authors define these events as local heat waves.

99th PERCENTILE OF SUMMER DAILY AND NIGHTLY TEMPERATURES

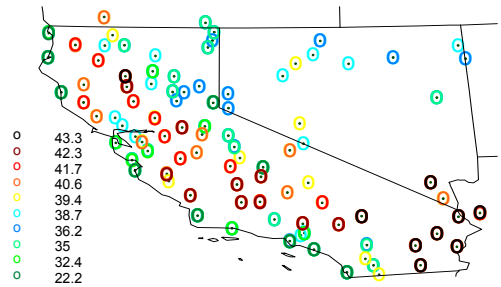
a) Sacramento Tmax



b) Sacramento Tmin



c) Tmax 99th percentile



d) Tmin 99th percentile

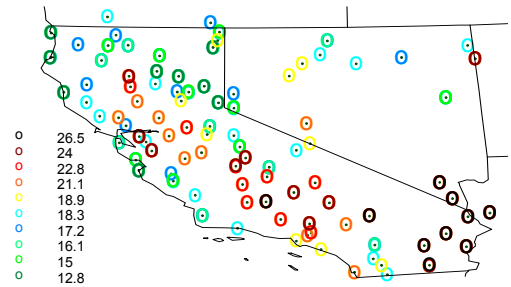
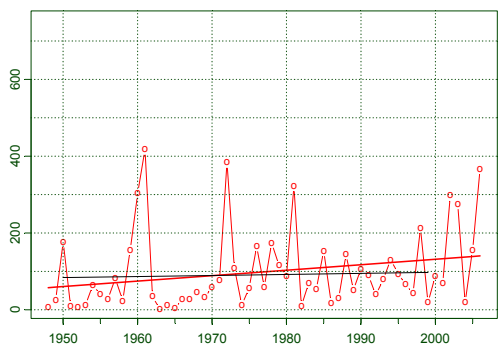


Figure 2. The spread of observed Tmax (a) and Tmin (b) plotted in °C in dots for every day of the summer with average (black circles) and 2006 observations (colored curve) as well as the 99th percentile (dashed line) computed over the 1950 – 1999 climatology for Sacramento (WSO City station). By definition, daytime or nighttime heat waves occur on days when Tmin or Tmax exceed this line. They are quantified locally as sums of exceedances over the 99th percentile. Panels (c) and (d) depict the approximate (in bins) 99th percentiles of summertime Tmax and Tmin, respectively, at all stations. Regional heat waves are quantified as exceedances over the local 99th percentile summed over all stations. At Sacramento (WSO City station), the larger variance of summertime daily Tmax compared to Tmin variance is apparent in the different scales of Figure 2, panels a and b. The distribution of Tmin is skewed, having a sharp lower limit and a more volatile upper bound; the well-defined lower threshold indicates that nighttime cold extremes are limited, probably because radiative cooling is time-limited, while large extremes tend to occur on the hot side. Summer 2006, especially late July, featured an extremely intense and persistent heat wave and is used here as an example. July 2006 featured warm Tmin excursions (5–10+ °C above the climatological mean) and cold extremes just 1-2 °C below the mean (Figure 3b). July 22-24 saw Tmin unprecedented on this record with 29°C (84°F). The 99th percentile of 22.8°C (73°F) was exceeded for seven (six consecutive) nights. Tmax, meanwhile, although not unprecedented, exceeded the 99th percentile (42.2°C/108°F) for two straight days (July 23-24) and generally varied more symmetrically around the climatological mean values.

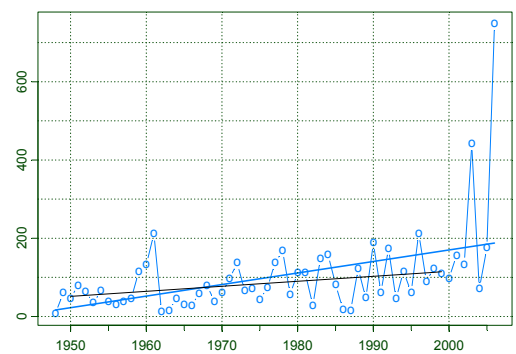
To define heat wave activity and individual events over the region, the authors first compute the 99th percentiles at all stations (Figure 2c,d). This result indicates that the highest temperature extremes during both day and night typically occur in the southeastern low deserts and interior valley regions, while the coolest hot extremes occur in the high Sierra Nevada and along the coast and coastal ranges. Extremes of both Tmax and Tmin display a very similar spatial distribution with few local exceptions, e.g. the Southern California coast exhibits relatively hot extremes at night while the northern coastal hills are relatively more prone to intense daytime heat. These percentiles are used to quantify regional heat wave activity simply by summing threshold exceedances (departures over these local thresholds) over each summer and all stations (Figure 3).

REGIONAL SEASONAL HEAT WAVE MAGNITUDE

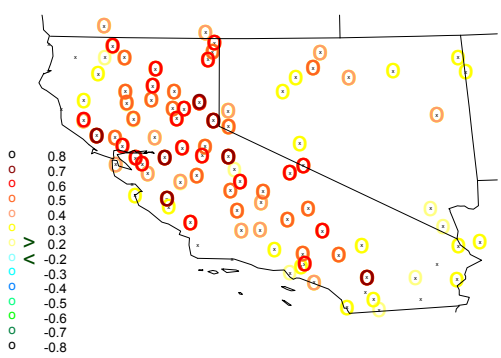
a) DD_{99}: overall daytime magnitude



b) DN_{99}: overall nighttime magnitude



c) Spatial expression (cor) of DD_{99}



d) Spatial expression (cor) of DN_{99}

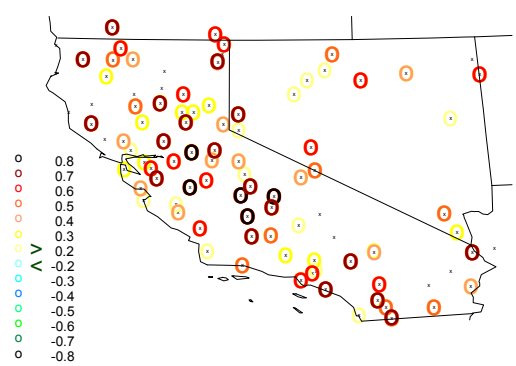


Figure 3. Degree days (DD_{99}, a) and nights (DN_{99}, b) defined as exceedances over local climatological 99th percentiles summed over each summer and all stations, i.e. $DD_{99}=\Sigma_j(DD_{99}^{j,s})$, j = 1,…,95 stations. Linear regression lines are shown for the entire record (1948-2006, colors) and over the base period (1950-1999, black). The spatial expressions of these region-wide indices are shown as correlations with local DD_{99} (c) and DN_{99} (d).

These indices, DD_{99} and DN_{99} (ρ=.60), reflect region-wide summertime heat wave activity, i.e. intensity, frequency, duration, and spatial extent of individual heat waves aggregated over each summer (Figure 3a,b). Although the first half of the record saw intermittent intense *daytime* heat wave activity notably in the summers of 1960, 1961 and 1972, these occurred over a background of low activity (Figure 3a). There was a shift to generally higher activity in the mid 1970s that is consistent with warmer average temperatures (Figure 1c), that is in turn related to the North Pacific Decadal Oscillation (NPO) shift that is known to affect California summer temperature, including cooling degree days and frequencies of Tmax extremes (Alfaro et al. 2004). However, the slight trend in daytime heat wave activity is mostly due to enhancement at the very end of the record. In contrast, the increasing trend in *nighttime* heat wave activity is a feature of the entire record that seems to have gotten a boost during the most recent summers 2003 and 2006, each unprecedented (Figure 3b).

The statewide nature of the most intense heat wave activity is apparent from the correlations of regional DD_{99} and DN_{99} with local values (Figure 3c,d). Principal components analysis (performed on the correlation matrix) reveals leading modes (PC1s) that are practically identical to region-wide DD_{99} (ρ=.954) and DN_{99} (ρ=.987). This is not surprising, given the large-scale nature of intense heat wave activity, and especially of the DN_{99} trend (Figure 3c,d). However, a strong and spatially coherent trend[6] is expressed in PC2 of DD_{99} (Figure 4a). This trend is towards a relative intensification of daytime heat wave activity in the elevated interior relative to the lowlands. The spatial pattern of this relative trend in daytime heat wave activity (Figure 4b) is strongly correlated with station elevation (ρ=.52). The elevational dependence of this relative trend is visually apparent to anyone familiar with the topography of the region by visual examination of Figure 4b. Although PC2 modifies the spatial footprint of large daytime heat waves, it is, by definition, uncorrelated with PC1 (Figure 3a) over the entire record. Rather, it shows that heat waves affected the 'heartland' valleys more than the interior hills in the earlier part of the record and the hills more than the valleys in the more recent summers, i.e. (anti-) correlated over the (early) late part of the record (compare Figures 4a and 3a). Moreover, the change from negative to positive correlations took place in the form of a clear linear trend in addition to a discrete shift in the late 1970s, indicating a progressive and coherent change in the spatial patterns of large daytime heat waves.

Although a detailed analysis of this geographic trend is beyond the scope and focus of this paper, it appears likely that the highlands, which are drying in summer due to progressively decreasing snow/rain ratio (Knowles et al. 2006), earlier spring snowmelt and runoff (Cayan et al. 2001, Stewart et al. 2005) and generally decreasing snowpack (Mote et al. 2005), are becoming relatively more prone to intensified daytime heat wave activity compared to the irrigated farmland of the Central Valley and the coastal valleys, e.g. the wine growing regions of Napa and Sonoma counties, where the trend in heat wave activity appears to have been progressively suppressed. Summertime Tmax, but not Tmin, is inversely related to natural soil moisture

[6] EOF2 (Figure 4b) reflects the trend pattern seen when trends are computed for each station's DD_{99} separately (not shown). The latter, of course, is noisier, while the former emerges because of the inherent spatial coherence in heat wave activity trends.

variability (e.g. Alfaro et al. 2006). Moreover, irrigation is known to suppress summertime daytime heat in California while leaving nighttime temperatures unaffected (Bonfils and Lobell 2007, Lobell and Bonfils 2007). Agricultural and urban aerosols, more concentrated in the valleys, may also be limiting lowland Tmax extremes. Low deserts circa southeastern California, evidently, are exempt from this daytime heat suppression (Figure 4b).

a) PC2 of DD_{99} explains 12% of variance b) EOF2 as correlation with DD_{99}

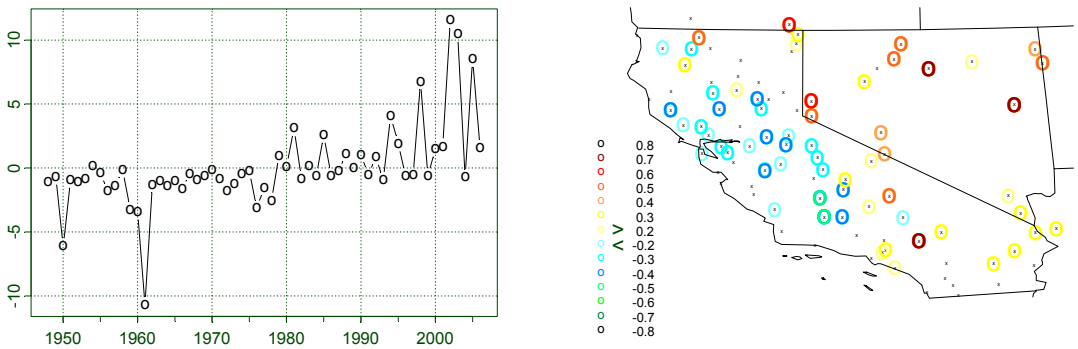


Figure 4. Second principle component of DD_{99} (PC2, a) and its corresponding spatial pattern (EOF2) expressed as temporal correlation coefficient of PC2 with DD_{99} at each station (b). PC2 explains 12% of total variance in DD99, compared with 27% for PC1 (similar to DD_{99}, Figure 4a,c). The spatial correlation of EOF2 with station elevation is 0.52.

In summary, regional heat wave activity is on the rise especially as expressed in Tmin and most prominently and increasingly since the 1970s. The observed trend is not explicitly focused on population centers and is apparently occurring on spatial scales involving at least California and Nevada. The early part of this rise is related to the mid-seventies NPO shift (Alfaro et al. 2004). This shift is best expressed in daytime heat waves, but the trend, especially in nighttime heat wave activity, continued and intensified since then in sync with regional average temperatures and observed large scale warming. Increasing daytime heat wave activity trend is strongest in the elevated interior of the region but suppressed in the lowland valleys. Following this general seasonal quantification and discussion of summertime heat wave *activity*, the authors focus on the magnitude of individual heat wave events and describe the intensity, spatial extent and duration of the largest observed extremes. The authors will then describe the synoptic causes of these events.

2.3. Definitions

The terminology adapted in this article to describe heat wave ***magnitude*** should be clarified. *Local* and *daily* (or *nightly*) magnitudes are the Tmax (or Tmin) threshold exceedances recorded at a specific station on a specific day or night. These can be aggregated (summed) over space and time into *seasonal regional magnitude* (Figure 3a,b); *daily regional magnitude* summed over all stations representing a region on a particular day or night (Figures 5, 8); *local cumulative heat wave magnitude* at a single location summed over the duration of a heat wave (Figure 10). Local

(or regional) heat wave *duration* is defined as the number of consecutive days when local threshold(s) is (are) exceeded, while *spatial extent* is defined as the percentage of representative stations where local thresholds are exceeded. *Peak* seasonal (or event) magnitude and spatial extent are defined as the maximum daily value over a season, e.g. Figure 6a-d (or over the duration of a particular heat wave, e.g. Table 2). The authors sometimes apply the terms "total" or "overall" to mean aggregated measures over space and/or time, e.g. Figure 9.

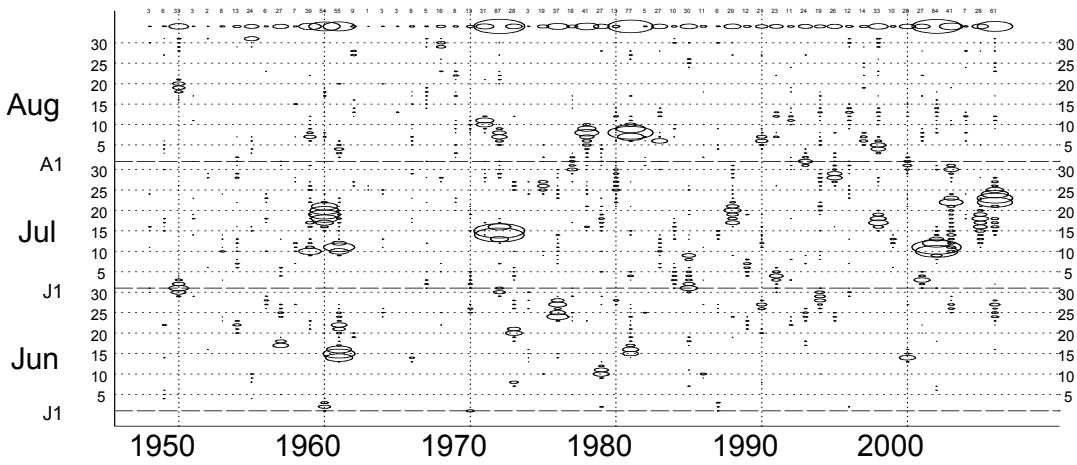
3.0 Hot Summer Days and Nights

The authors next examine the frequency and magnitude (i.e., duration, intensity and spatial extent) of regional heat waves more closely at daily and nightly resolution. Figure 5a,b documents the magnitude of extreme ($T > T_{99}$) heat waves for each day and night on our 59-year record. Since spatial extent of heat waves strongly determines their regional magnitude, magnitude strongly reflects spatial extent (ρ=.95 for both day and nighttime events). Individual heat waves are visible on these plots. In general,

- Heat waves tend to occur between late June and mid-August.
- Heat waves tend to last for a few to several consecutive days.
- Daytime heat waves occurred sporadically throughout the 59-yr period.
- Nighttime heat waves have markedly increased in occurrence since the 1970s.
- Heat wave activity during both day and night has been remarkable since 2000.

Detailed comparisons between the two panels of Figure 5, as well as intraseasonal temporal correlations (Table 1) of DD_{99} and DN_{99} regional magnitude and spatial extent (Figure 6), suggest that day and nighttime events are often, but not nearly always, coincidental. However, also from close examination of Figure 5, and as seen below, the largest Tmax events nearly always have *some* expression in Tmin and visa versa. Summers with notable types of extensive heat-wave activity can be identified, e.g.: 1960 with extensive and durable *daytime* heat wave in mid-July; 1961 with two separate large primarily *daytime* events in June and July; 1972 with a short and intense heat wave in mid-July primarily extensive *during the day* and a couple of separate minor episodes; 1981 with an extensive *daytime* event in early August; 2001 with a large *nighttime* event in early July and modest daytime expression; 2002 with a short and extensive primarily *daytime* event in early July; 2003 with a durable heat wave spanning a large portion of July *during night and day*; 2005 had a less extensive but durable *day and nighttime* event in the middle of July; 2006 with a durable and tremendously extensive July heat wave**.** In terms of the overall *nightly* magnitude the most recent period (since 2000) appears to have been without precedent on this record and July 2006 stands far out from even the enhanced nighttime heat wave activity of this most recent period.

a) Daily regional magnitude



b) Nightly regional magnitude

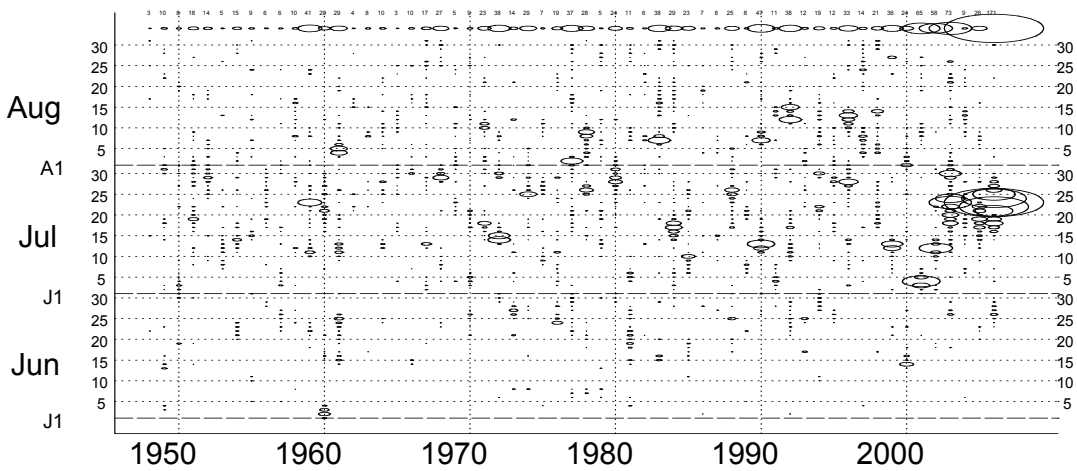


Figure 5. The daily-level magnitude of heat wave activity defined by DD_{99} (a) and DN_{99} (b) summed over all stations on the record. The x-axis corresponds to each year on record, while the y-axis corresponds to each summer day (a) and night (b). The scale is given by the maximum magnitude recorded each summer shown at the top of the plot and again in Figure 7a,b. The overall magnitude for each summer is shown in Figure 4a,b.

While overall summertime magnitude of heat wave activity was summarized in Figure 3, each summer's peak regional heat waves can be summarized, by their maximum intensity (Figure 6a,b), spatial extent (Figure 6c,d) and duration (Figure 6e,f).

3.1. Peak Magnitude, Spatial Extent, and Maximum Duration: Co-Variability and Trends

Both the mean summer (Figure 3) and maximum daily spatial extent of heat-wave activity summarized for each summer on record (Figure 6a,b) suggest that, occasionally large heat waves notwithstanding, the general (background) level of heat-wave activity has increased as a step-function (a shift) in the 1970s for daytime heat waves, reflecting the known relationship between springtime NPO and JJA temperatures over the region (Alfaro et al. 2004). The same cannot be said for nighttime heat waves, which show a rather continuously accelerating increasing trend. When diurnal mean (Tmin + Tmax) regional heat waves are considered, the distinction between climate shift and trend could be more difficult to make out. The same can be said for peak spatial extent and duration.

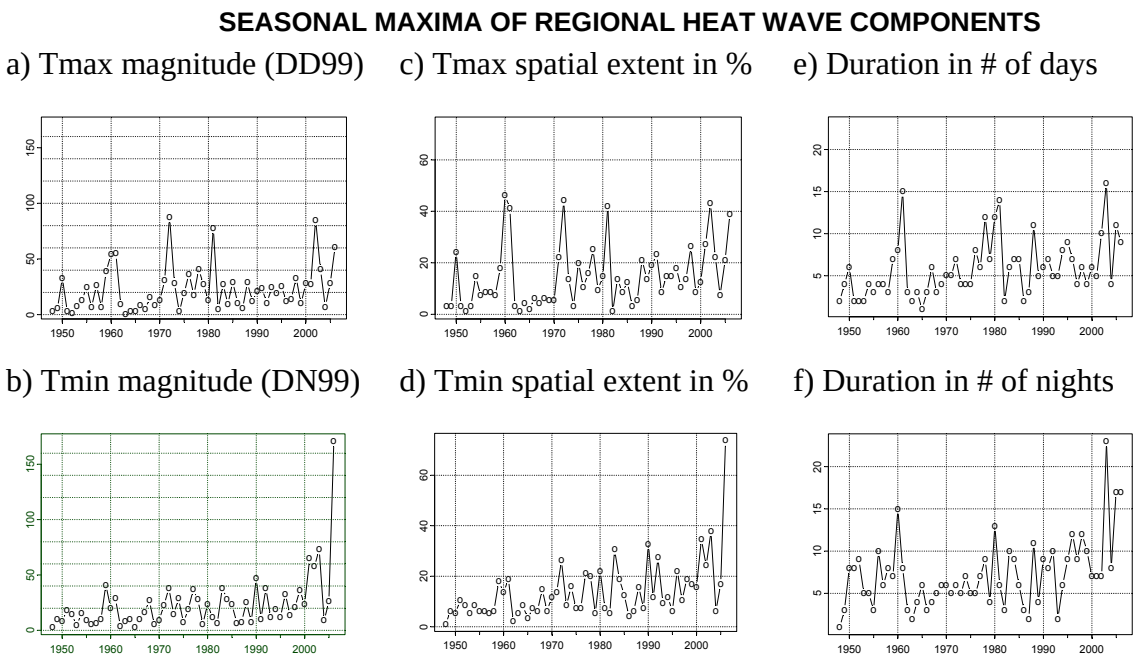


Figure 6. Seasonal maxima of heat wave components: total regional magnitude on the peak day (a) and night (b) of the greatest events, maximum spatial extent in % of stations by day (c) and night (d); and maximum continuous duration of daytime (e) and nighttime (f) heat waves. All variables were computed for each summer on record from data presented in Figure 5. Note that the maximal components of day and nighttime heat wave activity do not always refer to the same events. Also, the greatest one-day (or night) magnitude or spatial extent is not always, i.e. not in every summer, associated with the longest duration. Correlations between these indices are given in Table 1.

CORRELATION BETWEEN MAXIMAL HEAT WAVE COMPONENTS

Maximal components	MAGNITUDE	SP EXTENT	DURATION
MAGNITUDE	0.46	0.96	0.58
SP EXTENT	0.91	0.46	0.65
DURATION	0.67	0.70	0.60
TRENDS 1948:2006	3.0* : 6.6***	2.1** : 3.4***	0.8*** : 1.0***
TRENDS 1950:1999	0.7 : 2.5**	0.9 : 1.9***	0.6** : 0.4

Table 1. Correlation coefficient between, and trends within, the heat wave component indices displayed in Figure 6 for regional daytime (red) and nighttime (blue) heat waves. Correlations between daytime and nighttime heat wave components are displayed along the main diagonal. All correlations of 0.4 and above are significant at the 99.9% level. Trends in appropriate units per decade (degree days for magnitude, % stations for spatial extent, days for duration) are displayed along the bottom row with significance (*90%, **95%, ***99%)

Table 1 confirms that peak spatial extent and magnitude are very closely correlated for both daytime and nocturnal events. They almost always refer to the same extreme days or nights. Duration and peak spatial extent are also closely related for both types of heat waves, although there are exceptionally active summers when the most extensive event is not the most durable (e.g. 1981). The somewhat weaker positive correlations between duration and peak magnitude suggest that heat wave duration is related to peak magnitude via a more direct relationship with spatial extent. Peak spatial extent (and magnitude) of daytime and nighttime heat wave activity are weakly (although, at ρ=0.46, certainly significantly) related; seasonal maximum duration of the two types of events is more strongly related (36% of interannual variance in common). It is likely that the more durable events tend to be those expressed robustly during day and night. Ranked (Spearman) correlations between daily-scale DD_{99} and DN_{99} (Figure 7) are highly variable from summer-to-summer but always positive and notably strong in years with strong heat wave activity during day and/or night (Figures 3a,b and 5). This coupling between day and nighttime heat wave timing has been persistently strong during the recent summers of enhanced heat wave activity.

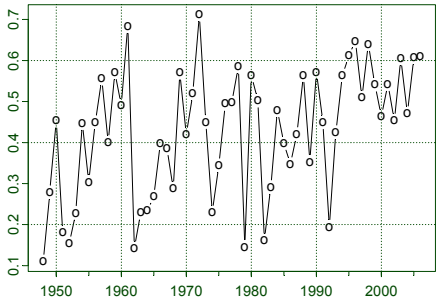


Figure 7. Ranked (Spearman's) correlations between each summer's daily and nightly heat wave magnitude. This reflects the degree to which day- and nighttime heat waves are coincident.

These observations reflect the fact that the timing of regional daytime and nighttime heat waves is usually coincidental; as we shall see below, they are nearly always produced by the same or similar synoptic atmospheric circulation features. However, their relative intensities as expressed during night and day vary a great deal. The most intense and extensive heat waves expressed primarily in Tmin or Tmax may therefore respond to profoundly different synoptic forcing features. This is addressed below. The authors will also see more clearly that the July 2006 heat wave, although consistent with increasing heat wave activity trends and shifts, cannot be entirely explained by these factors, especially where night-time temperatures are concerned. A closer look at the synoptic setting is required.

4.0 Anatomy of Great Heat Waves

Before considering synoptic causes of July 2006 compared to other large events, the authors describe the timing and canonical features of a handful of the largest day and nighttime events on record, which are called the "great" heat waves.

To illustrate the general appearance of and concurrence between great day- and nighttime heat waves, the authors identify these most extensive and intense day and nighttime heat wave episodes on record. Figure 8 presents the largest events for five most active summers, besides 2006, ranked according to results presented in Figures 5 and 6 and emphasizing instantaneously the largest (i.e. greatest peak magnitude), not necessarily the most durable, events.

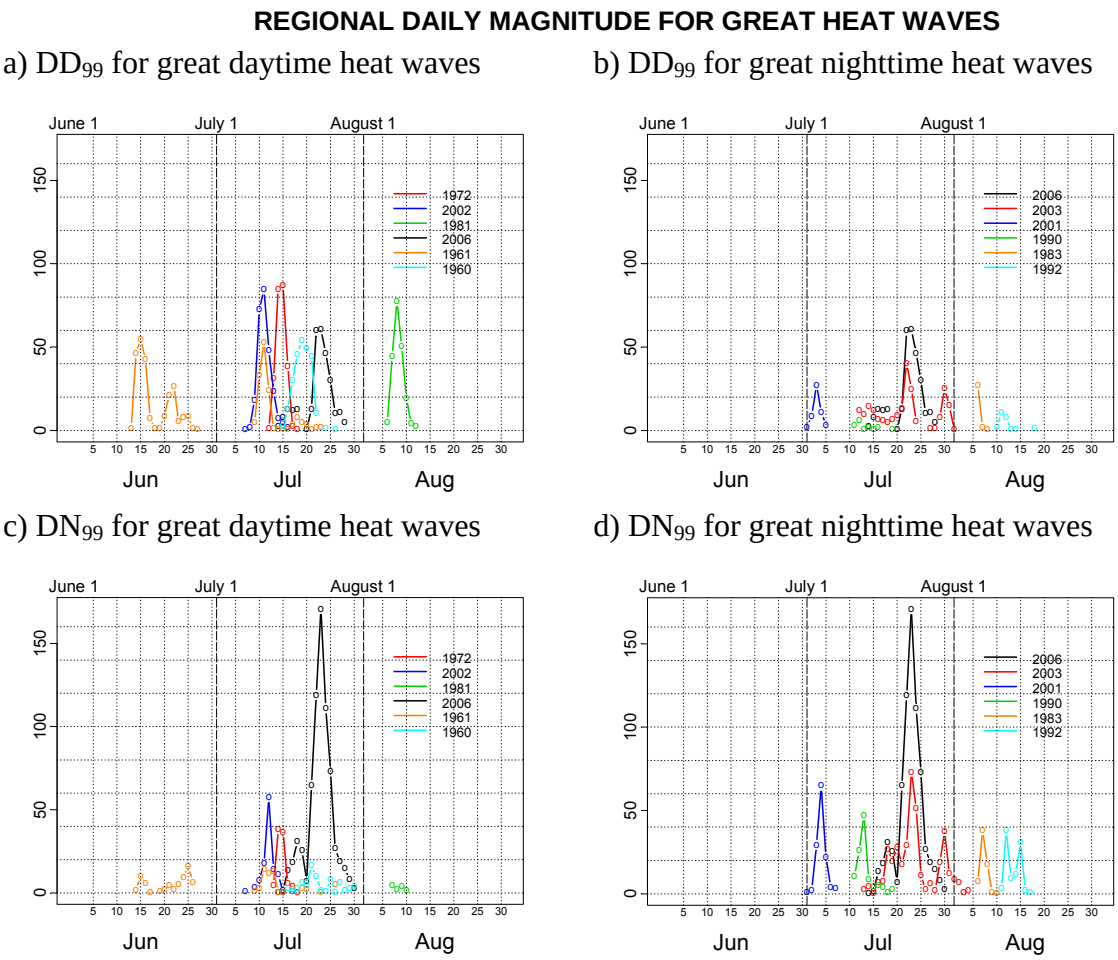


Figure 8. Regional degree days (DD_{99}: a,b) and nights (DN_{99}: c,d) associated with the greatest daytime (a,c) and nighttime (b,d) heat waves. Events (colors) are arranged in order of decreasing peak magnitude. Only the main events for each of the chosen summers are shown. Note that the same colors refer to the same (different) events on the vertical (horizontal) panels.

Figure 8 shows the magnitude of the largest events, which is closely related to spatial extent (Table 1). The entire seasons' activity can be seen on Figure 5. Statistics for these events, moreover, are presented in Table 2 and discussed below. With the exception of July 2006, the largest daytime heat waves have been more extensive than the largest nighttime events (Table 2). Extreme nighttime heat accompanied the greatest and most extensive daytime heat waves to some degree (Figure 8a,c) and visa versa (Figure 8d,b); thus the moderate temporal correlations observed in Figure 7. Durations are generally about a week for most great heat waves, but can drag on for 2-3 weeks as occurred in 1961 and also in 2003 and 2006. Each great event has a well-defined peak date or two. Nighttime heat waves display a stronger preference for July than do their daytime counterparts (this is also confirmed by Figure 5 as well as other results based on lower thresholds, not shown). As far as spatial extent (Table 2), all six of the great heat waves were of comparable scale, with about 40% of the stations registering extreme Tmax on the peak day. *In contrast, during the great nocturnal heat wave of 2006, 74% of researchers' stations recorded extreme Tmin values on July 23, 2006, an event without recorded parallel on the 59-year record (Table 2).* Notably, a hot prelude preceded the peak night (and day) of the event on July 23.

GREAT DAYTIME HEAT WAVES

Peak Date	Overall Magnitude	Peak Sp Extent	Duration
1972, 7, 14	273/120 (°C)	44/26 (%)	7/6 (days)
2002, 7, 11*	264/115	43/24	10/7
1960, 7, 19*	251/72	46/14	9/15
1961, 6, 15*	236/65	41/12	15/8
1981, 8, 8*	204/12	42/7	7/4
1961, 7, 11*	145/58	40/14	15/8

GREAT NIGHTTIME HEAT WAVES

Peak Date	Overall Magnitude	Peak Sp Extent	Duration
2006, 7, 23	**709/286 (°C)**	**74/39 (%)**	**17/9 (days)**
2003, 7, 23*	384/249	38/22	23/16
2001, 7, 4*	128/54	35/27	7/5
1990, 7, 13*	116/14	33/19	9/6
1983, 8, 7*	103/44	31/14	5/3
1992, 8, 12*	100/27	27/8	7/5

Table 2. Peak dates of the greatest regional heat waves on record listed in order of largest one-day and one-night magnitude (see Figure 5). The events marked by an asterisk (*) are used for composite results in Figure 11. The great 2006 and 1972 events (bold) are treated separately. Overall magnitude, defined as the sum of DD_{99} and DN_{99} over the entire duration of the event and over all stations, associated with each event is given in red and blue font, as are peak spatial extent and duration. The station-by-station values of DD_{99} and DN_{99} are plotted for the 3 largest overall events (2006, 2003, and 1972) in Figure 10. The overall daytime and nighttime magnitudes are plotted in Figure 9.

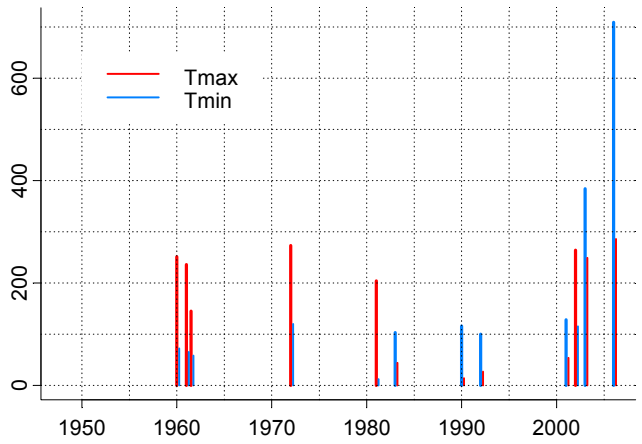


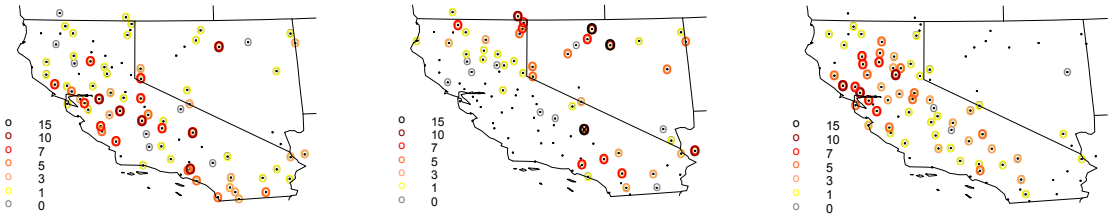
Figure 9. Overall magnitude [cumulative temperature departures (°C) in excess of 99th percentile of each station] of the six daytime (red) and nighttime (blue) great heat waves in California region. Thick (thin) lines delineate the heat wave's primary (secondary) expression, i.e. daytime or nighttime.

Overall heat-wave magnitude (Figure 9) better separates the largest events than duration or spatial extent alone. Nighttime heat waves used to be of smaller magnitude than daytime events, but this has lately changed. Nighttime events of 2001, 2003 and 2006 have each set successive magnitude records. Daytime heat wave activity is changing, not in magnitude but in the fact that the most recent great daytime heat waves were daytime components of even greater nighttime events, e.g. 2003, 2006. The order of the most intense heat waves is modified somewhat with respect to the merely most spatially extensive with the greatest events tending to occur towards the latter part of the record, especially at night (Figure 9). The 2006 event was by a large measure unprecedented in overall magnitude, again, specifically at night. During the day, July 2006 is fourth in terms of daytime peak intensity, but its rather impressive duration makes it number 1 among *daytime* events in terms of overall magnitude.

The spatial patterns of overall day and nighttime magnitude are shown for three of the largest events on record (2006, 2003 and 1972) in Figure 10.

CUMULATIVE MAGNITUDE FOR THE THREE LARGEST HEAT WAVES

a) Tmax (July, 2006) c) Tmax (July-Aug 2003) e) Tmax (July 1972)



b) Tmin (July, 2006) d) Tmin (July-Aug, 2003) f) Tmin (July, 1972)

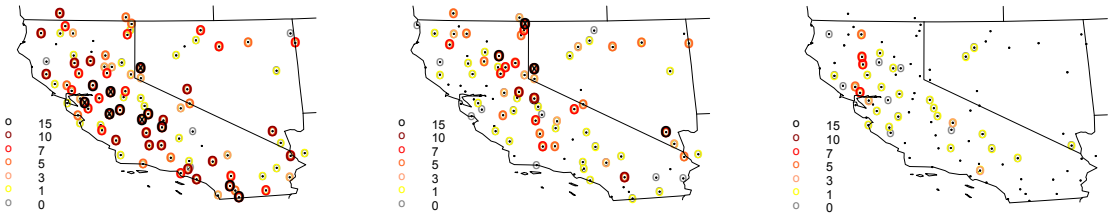


Figure 10. Local overall daytime (top panels) and nighttime (bottom panels) magnitude [cumulative °C] of the July 2006 event and the two next largest events. Station-level Degree Days (DD_{99}: a) and Nights (DN_{99}: b) are integrated over the duration of the 2006 event (July 15-30). Comparable results for July 12-August 4, 2003 (c,d) and July 12-18, 1972 (e,f). Black dots are the 95 core stations. Colored circles correspond to values exceeding those given in the legend, black "X"s mark values in excess of 20 degrees. Overall regional magnitude, aggregated over all stations, for each event is given in Table 2 and Figure 9.

5.0 Synoptic Aspects of Great Daytime and Nighttime Heat Waves

5.1. A Canonical View

The authors next describe mechanistic causes of great heat waves by compositing circulation anomalies at the surface (mean sea level pressure or MSLP and wind at sigma level 995) and the free atmosphere (500mb geopotential height) as well as precipitable water (PRWTR) on the peak day of the five largest daytime and nighttime events (Figure 11). These dates are marked with asterisks in Table 2. The two largest day and nighttime events (July 1972 and 2006) are treated separately below. Although including these events would not noticeably change the composites presented in Figure 11, these two events were rather different from the other great day and nighttime heat waves in several important aspects.

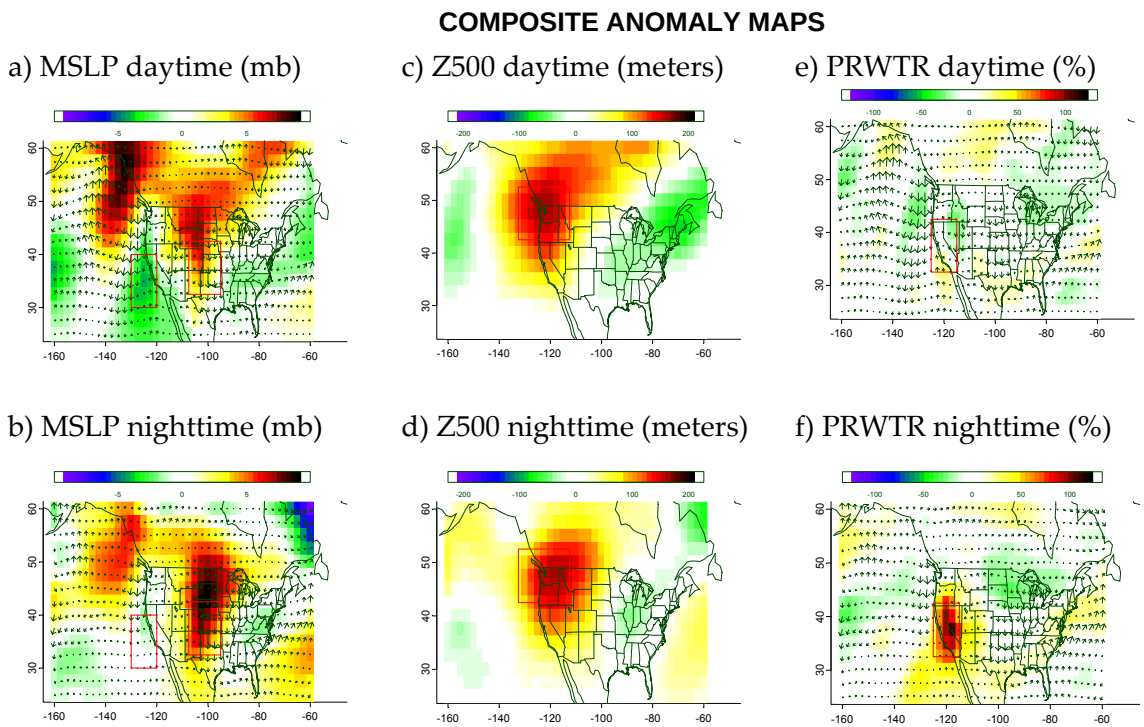


Figure 11. Surface circulation (wind at sigma level 995) and mean sea level pressure in millibars (a,b), 500mb geopotential height in meters (c,d), and precipitable water in percent of normal content (e,f) anomalies with respect to JJA mean. Anomalies are composited for the peak days of the largest five daytime events (a,c,e) and the largest five nighttime events (b,d,f) excluding 2006 and 1972 (see Table 2 for exact dates). The data are from the NCEP/NCAR Reanalysis I (Kistler et al. 2001). Red rectangles outline regions used for evolution plots presented in Figure 14.

Great heat waves are set up by a baroclinic structure in the atmospheric circulation involving horizontal and vertical motions conducive to hot regional weather (Figure 11a-d). The day and nighttime heat wave surface circulation composites (Figure 11a,b) show an anomalous surface pressure gradient sloping southwestward from the Great Plains to the Pacific Coast causing anomalous surface convergence into California. Regional circulation during the peak day in daytime events is characterized by an anomalous surface High that has moved[7] southward along the Front Range of the Rockies into the central and southern Great Plains, a surface Low off the California coast and a broad High several degrees longitude west of Washington coast. During peak daytime events, these features bring strong convergent surface winds into California from practically all directions. During peak nighttime events, the Great Plains High tends to be stronger and more extensive while the other features, including the California Coastal Low, are weaker making for a reduced anomalous convergence, especially from the Great Basin, i.e. from the high Nevada desert. The circulation aloft (Figure 11c,d) consists of a broad and intense High centered above Washington state. During the two types of events, the anomalous high intensity is similar (about 160 geopotential meters), but the center of the High tends to be displaced zonally by a couple of degrees so that during daytime (nighttime) events it is centered over western (eastern) Washington. It is difficult to assess the absolute significance of these slight differences since they may be due to small sample size as well as to differences in the timing with respect to circulation of the most intense day and nighttime events. These differences between the two types of canonical events are certainly within the range of variability of the two five-day samples. In any case, the circulation at the surface as well as aloft appears rather similar for both day and nighttime event peaks.

The observations indicate that it is the atmospheric moisture content, rather than circulation that determines whether a heat wave is predominantly a daytime or nighttime event (Figure 11e,f). Nocturnal events are about twice as moist (PRWTR anomaly of more than twice the normal ~18 kg/m2 for JJA averaged over this arid region). For daytime events, the anomaly is slightly drier than normal over California and Nevada. It is not generally cloudy and, aside from occasional mountain and desert thunderstorms, does not rain over this arid region in summer even during the hot spells of the humid nocturnal variety. It seems clear that the enhanced greenhouse effect of water vapor is what mainly elevates nighttime temperatures during nocturnal heat waves. This regionally enhanced greenhouse operates during the day as well, to be sure, but the moisture also tends to reduce somewhat the incident solar radiation, particularly over topography where convective cloudiness develops in hot moist conditions. Compared to humid heat waves, in dry heat waves the daytime temperatures heat up due to stronger surface absorption of direct sunlight, while at night the surface cools more efficiently by emitting long-wave radiation. Slight differences in circulation may play a minor role, but those differences are likely also related to moisture advection. As the heat wave circulation develops, the existence of a moisture source to the south and/or east of Southern California appears to make the difference between a primarily day or nighttime event. The intensity of the

[7] Dynamic cartoons of these maps spanning the evolution of events clearly show this development but cannot be fully reproduced in this static format.

southwest monsoon, for example, can play an important role in this regard. As will be shown, there is also evidence for a warm sea surface temperature-associated moisture source directly to the south of the region. The atmospheric moisture content and its role in regulating the surface energy balance is the main reason why all large Californian heat waves can be classified into *primarily* daytime and nighttime events.

5.2. July 1972

The 1972 heat wave was the largest purely daytime event, but it differed considerably in its circulation from the other great heat waves. The associated spatial pattern of intense heat can be seen on Figure 10e,f. The 1972 event featured a surface High over British Columbia with a southeastern branch extending into the Great Basin. Together with a pronounced Low over the Central California coast, creating a state-wide version of a Santa Ana condition, i.e. strong northeasterly flow from the high deserts down into the low valleys of interior and coastal California. This produced subsidence, drying and adiabatic heating. The upper-level anticyclonic circulation was displaced southwestward of its canonical location and moisture levels were below normal over California. For brevity, these results are not shown, but because this event was, in terms of synoptic circulation, so different from the rest, we exclude it from daytime event composites.

5.3. July 2006

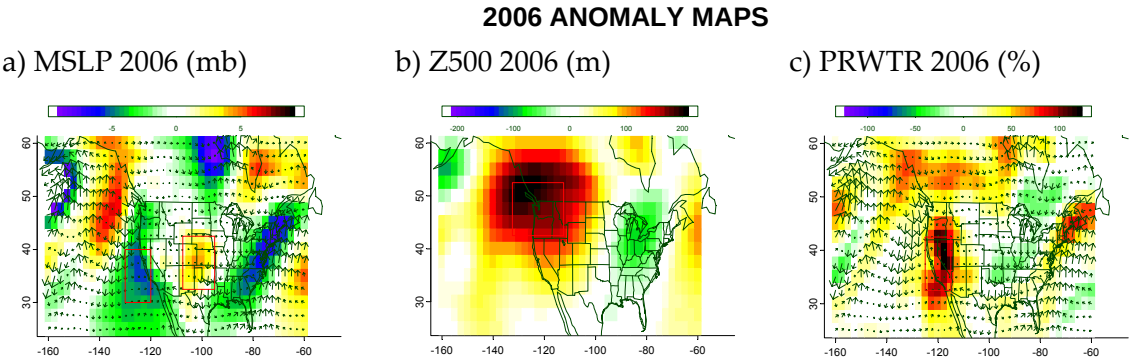


Figure 12. July 23 2006 anomalies of MSLP and wind at 995 sigma level (a), 500m geopotential height (b), and precipitable water (c). Units are the same as in Figure 11.

The peak of the 2006 event was characterized by surface circulation rather similar to other great heat waves, especially those of the daytime variety. In this case, the anomalous high over the central and southern Great Plains was somewhat weaker and the surface Low off the California coast was unusually strongly developed. Strong teleconnections were present upstream and downstream of these regional MSLP anomalies. At the 500mb level, the geopotential height over Washington state was impressive with a positive anomaly of 206 meters. There was enhanced moisture over the region, with a positive anomaly over Nevada reaching 121% of

normal summertime moisture content there[8]. On July 23 2006, moisture over most of California reached levels that were comparable with other great nocturnal heat waves. While these values are impressive, they are only one component explaining why the July 2006 heat wave was so exceptional in its magnitude. To better understand its enormity requires a view of its time evolution rather than just a static snapshot of the peak date.

5.4. Synoptic Evolution of Great Heat Waves

Figure 13 more precisely compares the evolution of the 2006 event regional magnitude to the canonical day and nighttime event. Apparently, the moderate nighttime event peaks tend to precede large daytime event peaks. 2006 trumped all other nighttime events, it was more durable than most other intense heat waves, day or night, and it was also noteworthy in the fact that it was preceded by a sizeable day and nighttime warming occurring over several days and 3-5 days before the onset of the main event that peaked on July 23.

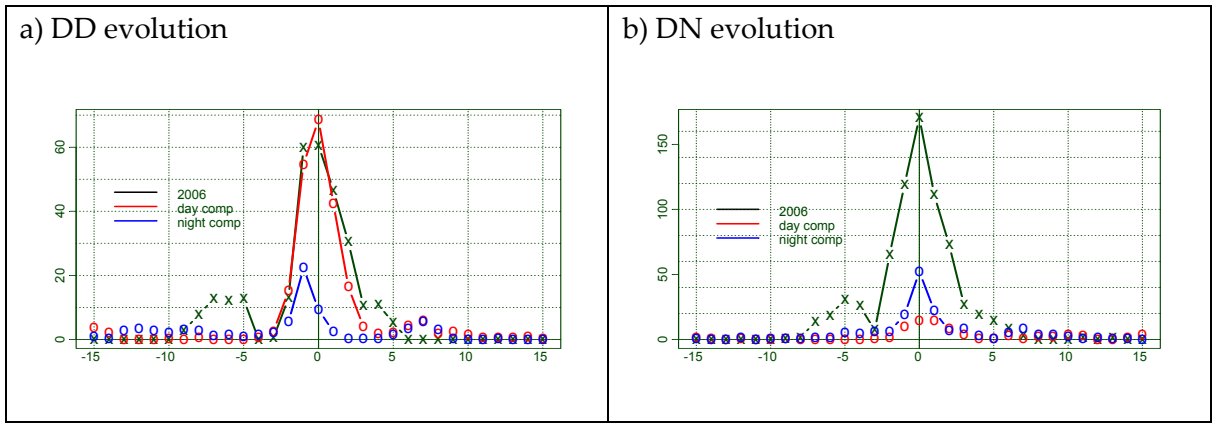


Figure 13. Evolution July 2006 regional DD_{99} (a) and DN_{99} (b) magnitude compared to composite evolution of 6 other major day and 5 nighttime events from 15 days before to 15 days after the peak magnitude of events. Degree Day (a) and Degree Night (b) evolution.

In Figure 14, the authors address the evolution of circulation and moisture anomalies in July 2006 compared to the canonical daytime and nighttime events. The authors show the temporal evolution of key circulation and moisture indices of day and nighttime heat wave activity, e.g. surface pressure gradient expressed as difference of MSLP anomalies over the central/southern Great Plains and coastal California waters, circulation aloft (Z500 over Washington, and precipitable water averaged over California and Nevada. Simultaneous examination of Figures 13 and 14 shows how typical intense events develop and how the 2006 event developed differently from most intense heat waves on record.

[8] The main thrust of the event, however, was over California, especially intense over the central part of the state at night (Figure 10a,b).

EVOLUTION OF CIRCULATION ANOMALIES

a) (MSLP GP – CA shore) b) Z500 over the northwest c) PRWTR over CA/NV

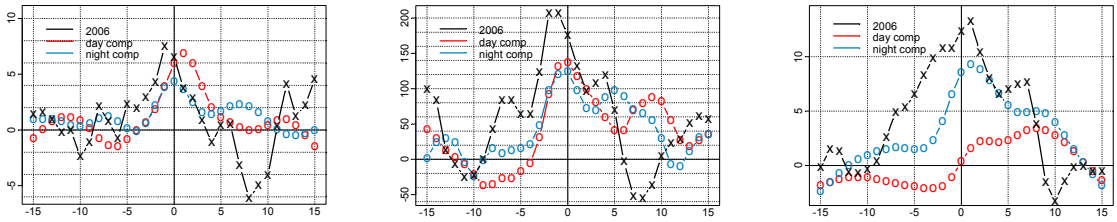


Figure 14. Evolution July 2006 compared to composite evolution of 5 other major day and 5 nighttime events from 15 days before to 15 days after the peak magnitude of events. All indices were averaged over rectangles outlined in red over relevant plates on Figures 12 and 13 and anomalies computed relative to JJA climatology. MSLP gradient (Great Plains box – California Shore box: a), Z500 averaged over the Washington box (b), and PRWTR anomaly averaged over the California/Nevada box (125 – 115W, 42.5 – 32.5N, c). Thick red and blue lines with O's are canonical average daytime and nighttime event evolutions. Thick black and yellow lines punctuated with X's represent evolutions of the 2006 event.

Once the circulation associated with the typical day or nighttime event ramps up, Tmax heats up fast, and if the moisture source is available, moisture is advected over the region very quickly, which intensifies the nighttime magnitude while putting a cap on daytime warming. Daytime events apparently tend to be preceded by a low pressure aloft over the northwest and a quick build-up of the High. The circulation build-up to the nighttime events is more variable over this region and depends much more on moisture availability and a surface circulation conducive to advecting it over the region sometimes ahead of the developing heat wave. The 2006 event is an example of this early moisture advection coupled with an early development of the surface pressure gradient and the high pressure aloft. The circulation associated with the 2006 event set in very early and strong, especially aloft, where the timing was the earliest and the magnitude of the Z500 anomaly was also the largest of any other event on record. In 2006, moisture was available early and kept accumulating over the region throughout the event and also apparently to unprecedented levels compared to other events on record. This anomalous moisture was consistently pumped into the region from a Pacific source to the south of southern California (animation result cannot be shown). The early development of the heat wave circulation and the tremendous and early availability of moisture apparently gave rise to the hot and moist "prelude" that, after a short lull in the circulation, intensified into the heat wave of July 2006. The unprecedented moisture available so early coupled with a primer of hot temperatures and a suddenly intensifying circulation gave rise to a nighttime heat wave of enormous magnitude. Daytime temperatures were able to rise to remarkable levels and over an impressive space-time scale, much more so than during any other large nighttime event, largely because early mornings were so hot already before the solar heating set in. Tmin and Tmax interacted constructively and persistently to sear California over the last two weeks of July 2006.

6.0 Trends

From the above account, it is clear that the causes of heat waves over California and Nevada are complex and that numerous conditions coincided to create the unprecedented heat of July 2006. One of these conditions, touched on in the beginning of this article, is the trend especially in nighttime temperatures which intensified greatly since 2000 and must be related to the increased probability of larger nighttime heat waves. As the 2006 and 2003 events suggest, such events can spill over into, or prime the environment for, greater daytime heat associated with primarily nighttime events. This may account for part of the trend observed in daytime heat wave activity as well. In any case, the strongest trend and the best possibility for its physical explanation are shrouded in the hot and humid darkness of the night. In this last part of this article, the authors will try to shed some light on this matter by focusing on long-term changes in heat wave activity over this region.

The yet incomplete final decade on our record (1998 – 2006) has already produced much stronger heat wave activity than any of the previous five decades, during both day and night. For nocturnal heat waves especially, the trend towards greater heat wave activity is apparent as an orderly progression from one decade to the next (result not shown). The increasing relative magnitude of nighttime versus daytime heat waves is also apparent. This raises the obvious question: Is humidity increasing over the region? Our results, based on the available Reanalysis and sparse *in situ* dew point and radiosonde records, are inconclusive on this point[9]. There is a possibility that the relevant regional humidity changes are episodic, e.g. triggered by the synoptic nature of the heat wave circulations and therefore not clearly manifested except during heat waves. But what mechanism could possibly account for such a trend?

Let us now consider the connections between regional summer climate and large-scale Pacific sea surface temperature (PSST) patterns. Summertime Tmax and Tmin (Figure 1 c and d, respectively) should be differently related to PSST. Summertime Tmin over the western and central U.S. is more strongly related to and can be more skillfully predicted by Pacific SST, while Tmax is more strongly related to local soil moisture (Alfaro et al. 2006). Thus, it is not surprising that JJA average Tmin over California and Nevada is more strongly related to PSST than is Tmax (Figure 15a,b).

As noted by Alfaro et al. (2004), California summer temperature is clearly related to the North Pacific decadal Oscillation (NPO). It is curious, however, that the strongest correlations between regional average Tmin and Pacific SST are found not off the California coast, but rather directly to the south, just west of Baja California, Mexico. This is a region where a strong positive trend

[9] Warm humid nights are becoming more frequent, but apparently not more humid, while warm dry days are becoming a little more humid since the 1970s – although the overall trend is not significant due to an apparent moist bias in the reanalysis in the very early part of the record. Average seasonal and July PRWTR amounts are also on the rise since the 1970s but not significantly so, again because of the moist early 1950s in the Reanalysis. The in situ data do not support this moist anomaly in the 1950s, but these data, which are only available from a small number of airport stations, do not show clear and consistent trends either.

in SST is observed (Figure 15c,d). Others have detected this regional trend as well, and it appears to be a prominent part of the global ocean warming observed in conjunction with anthropogenic climate change (e.g. Pierce et al. 2006, their Figure 20). The question arises, then, whether the moisture content of the air mass advected into the California region during heat wave circulations is affected by the underlying SST trend from this region off Baja California?

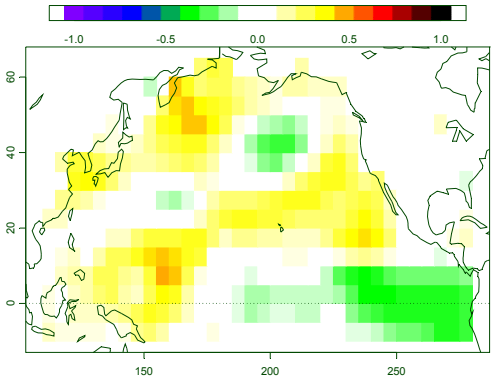
The spatial pattern of the trend in precipitable water is presented in Figure 16. Although the authors cannot see a moistening over California[10] and Nevada, Figure 16 (a,b) clearly shows a moistening over the region of warming SST east of Baja California (BSST, Figure 15c) where a strong correlation between SST and average Tmin was observed (Figure 15b). This trend makes anomalous moisture more readily available for California heat wave circulations to advect and more frequently and preferentially intensify the nocturnal expression of California heat waves. Great nocturnal heat waves are characterized by enhanced moisture availability east of Baja California for about 10 days before and after the peak of the event (Figure 16c). Heat wave circulations advect air northward from this region to California (Figure 16d). This is exactly what happened in 2006, but that time, the anomalous moisture was available earlier and advection occurred days before the onset of the main event (Figures 16c,d, 14c), preconditioning this great heat wave to be expressed most strongly at night.

The strong and trendy relationship between regional average summertime Tmin and BSST (Figure 15b) appears, therefore to be partially explained by the effect of BSST via atmospheric moisture that is advected into the California region by heat wave circulations. This moistening does not occur frequently enough to make for clearly detectable summertime moisture trends over California and Nevada, but its episodic effect on Tmin extremes is apparently strong enough to be partially reflected in average summertime Tmin over the region. This link seems to contribute to the relationship between average Tmin and BSST (Figure 15b) as well as to the observed trend in summertime average Tmin via enhanced nocturnal heat wave activity.

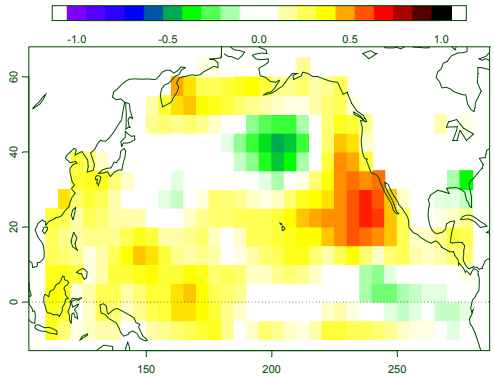
[10] There is a curious localized drying trend over southern California/Northern Baja (Figure 16a) that may be related to the moist early 1950s in the Reanalysis. This local issue is tangential to the current focus.

CORRELATIONS WITH SEA SURFACE TEMPERATURE

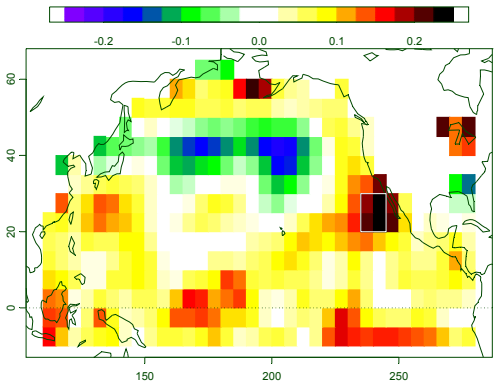
a) With average Tmax from Figure 1c



b) With average Tmin from Figure 1d



c) Linear trends in °C



d) SST and trend off Baja California

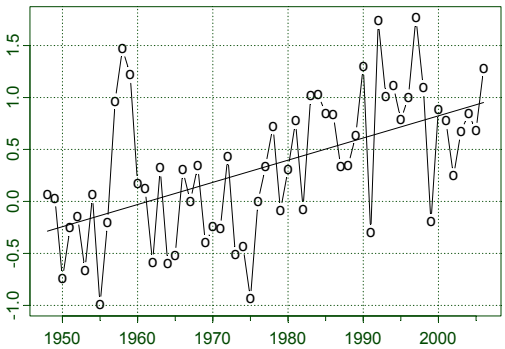
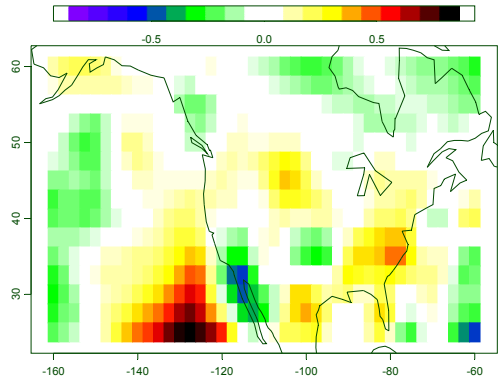


Figure 15. Correlation coefficient between June-August averaged SST[11] and contemporaneous region-averaged Tmax (a) and Tmin (b) as shown in Figure 1c,d. Linear trends (c) in SST are predominantly positive. The time series of SST averaged in the white box off of Baja California (BSST) is shown with linear trend (d). The linear trend accounts for 33% of BSST variance. The correlation coefficient between BSST and average Tmin (Tmax) is 0.63 (0.32). Much of this correlation is due to the similar trend in the regional Tmin time series. Interannual correlations (with trends removed) are lower, but also significant at 0.44 (0.29).

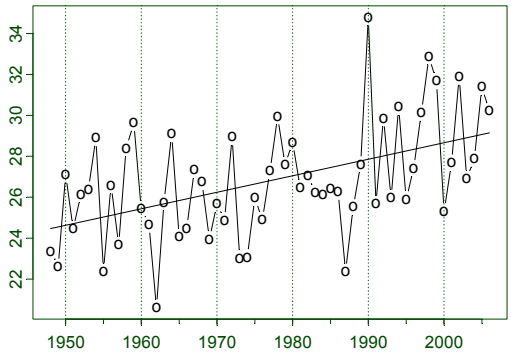
11 Monthly SST anomalies from KAPLAN EXTENDED v2: Statistically homogenous concatenation of Kaplan et al. (1998) OS SST, Reynolds and Smith (1994), Smith and Reynolds (2004) NCEP OI analyses.

http://ingrid.ldeo.columbia.edu/SOURCES/.KAPLAN/.EXTENDED/.v2/.ssta

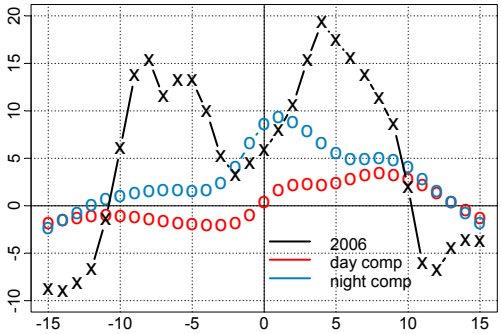
a) Trend in July average PRWTR



b) July trend in 130-117.5W, 25-27.5N



c) PRWTR anomaly off Baja California



d) VWIND in 125-117.5W, 32.5-25N

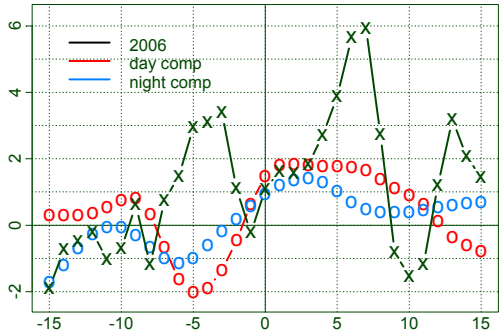


Figure 16. (a) Linear trend computed at each pixel of the PRWTR averaged for July. (b) July PRWTR in a box 130-117.5W, 25-27.5N and linear trend. The trend explains 24% of the variance and the time series is correlated at ρ=0.4 with regional average Tmin (Figure 1d), ρ= 0.15 without the trends. (c) Daily anomaly of PRWTR in the same box for 15 days around the peak of great daytime and nighttime heat waves as well as the 2006 event (as in Figure 14). (d) Daily anomaly of the v-component of the surface-level wind in a box 125-117.5W, 32.5-25N, representing the northward advection from the region west of Baja California to California state.

7.0 Summary, Discussion, and Conclusions

The authors have quantified heat waves over the California region in terms of their overall regional seasonal magnitude (relative to local climatology) as well as their components; intensity, spatial extent and duration; down to local and daily scales. Great Californian heat waves can be classified into primarily dry daytime and humid nighttime events, those with the greatest regional magnitudes expressed in Tmax or Tmin, respectively. Daytime (nighttime) events typically have significant but far smaller expressions in Tmin (Tmax). Heat waves can occur anytime in summer, but show a preference for late July, near the climatological peak in the seasonal cycle of regional temperature. Nighttime heat wave magnitude and all its components display a clear and increasing regional trend. Daytime heat wave activity is more variable and sporadic. It is also increasing, but a large part of this daytime increase has occurred as a shift in the 1970s. Interestingly, interior highlands have tended to experience progressively stronger daytime heat waves relative to the lowland valleys throughout the 59-year record. Extreme heat waves typically last about a week where temperatures exceed the threshold (the hottest one percent of climatological Tmax or Tmin) over a large part of the region and, during their peak date, these events can affect vast parts of the region. The most recent great heat waves on the researchers' record, namely 2003 and 2006, were primarily nighttime events. These events lasted over two weeks each, far exceeded previously set nighttime magnitude records, and have had overall daytime expressions to match or exceed, in the case of 2006, the greatest observed daytime events on record.

The atmospheric circulation anomalies responsible for most great day and nighttime California heat waves are remarkably similar consisting mainly of a strong surface pressure gradient across the region set up between a high pressure anomaly over the Great Plains and a Low off the California coast. The circulation anomaly aloft contains a massive anticyclone above Washington state, resulting in low-level convergence into California, especially from the south and east. The main difference between day and nighttime heat waves is the presence of a moisture source that may sometimes be associated with an active southwest monsoon, but more typically is a moist marine air mass to the south. If available, this moisture source is advected northward over the region by the heat wave circulation. The moisture thus advected over California and Nevada typically reaches twice the normal levels for this arid region and maintains exceptionally high nighttime temperatures mainly via the elevated greenhouse effect of a moist atmosphere. When the moisture source is unavailable, nighttime surface temperatures cool off efficiently by radiation as is normal for this arid region. A moisture source to the south of California, west of Baja California has been growing in association with a warming SST trend in this region.

The frequency and magnitude of nighttime heat waves has clearly and steadily been on the rise and the trend appears to be accelerating. Out of the largest 6 nighttime (daytime) events occurring over almost six decades between 1948 and 2006, 3 (1) have occurred in the last six years [12]. The heat wave that spanned the second half of July 2006 reached a nighttime spatial

[12] However, the daytime expression of these most recent nighttime heat waves has been on par with the greatest daytime events on record. This observation is alarming. Health impacts of daytime temperature

extent to include almost 75% of the stations in the region, at its peak on July 23. Its overall nighttime magnitude was roughly twice that of the next largest recorded nighttime event (July 2003[13]) and its overall daytime magnitude was also unprecedented, due particularly to the unusual combination of its duration and intensity.

What made the 2006 event so intense and long lasting? Circulation and humidity anomalies were remarkably strong and early without precedent. Humidity in excess of previous events was advected from the south and was already present in the area during the prelude (July 15-20)[14] to the onset of the most intense and extensive temperature anomalies. During this prelude, a local surface low developed just off the California coast advecting moisture from the south (Figures 14 and 16, and animation, not shown), collecting more than twice the normal summertime levels of atmospheric precipitable water over California and Nevada and setting the stage for the greatest nighttime (and daytime) heat wave on record. When the broad surface High spilled into the Great Plains (July 20– 22), the coastal Low persisted, it intensified as the High came down the Great Plains and dissipated, while the anomalous coastal Low kept pumping moisture and heat from the south into California keeping temperatures high, especially at night[15]. The persistent coastal Low and moisture availability upstream, i.e. south of the Low, led to a moisture build-up that nocturnalized and "super-sized" what would have otherwise been merely another very large daytime event. As it happened, its overall daytime expression surpassed all *daytime* heat waves on record. Intense and extensive nighttime heat without observed precedent, helped to intensify daytime warming and make the heat wave more intense and durable via the positive feedback between Tmax and Tmin.

While coincident and persistent key circulation anomalies of late July 2006 and the availability of a great moisture source played their pivotal roles in making the greatest heat wave on record, the strong and accelerating trend in regional nocturnal heat wave activity suggests that the probabilities are mounting for synoptic conditions to combine more often in ways conducive to the occurrence of nighttime heat waves. The summertime average Tmax and Tmin trends (Figure 1) go hand-in-hand with heat wave occurrences expressed in day and nighttime temperature extremes, which these average trends partially reflect and partially determine via association to large-scale teleconnections. As we pointed out before, the main factor that determines whether a heat wave will be primarily expressed in day or nighttime temperatures is the availability of an anomalous moisture source upwind of the synoptic circulation that

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expressions of humid nighttime events are expected to be larger since humidity can exacerbate heat stress, i.e. humid heat feels worse than dry heat as reflected in apparent temperature.

[13] July10 – August 2, 2003, was the most intense and extensive nighttime event to date, 3 times greater in overall magnitude than the previous record (2001). It had a strong daytime expression as well, placing it third on the list of *daytime* events.

[14] July 19th, 2006, saw the seventh greatest one-night spatial extent of extreme heat on the 59-summer record.

[15] The extremely strong and persistent upper-level circulation with the blocking high over the Northwest, must have encouraged the persistence of the low-level circulation.

converges hot surface air into the region. A warming SST trend east of Baja California appears to have been instrumental in making this moisture source more readily available. This SST trend is part of the global ocean surface and subsurface warming known to be due to anthropogenic climate change (Barnett et al., 2001, 2005, Pierce et al. 2006). Important questions to be addressed by future studies emerge. How much of the trend in BSST is caused by global warming? How strongly can it be expected to continue? How much of the climb in nocturnal heat wave activity that we are witnessing now over California and Nevada partly a regional expression of a global process? These questions take the authors beyond the scope of this study and will require an augmented set of tools including dynamical modeling. For now the authors simply note that the results presented here appear consistent with the regional symptoms of global warming. They intuit a plausible scenario for future summertime heat wave activity in California: more, hotter, more extensive and durable humid nighttime heat waves with a growing daytime signature.

Although most severely impacting California, the July 2006 heat wave extended across the conterminous United States as well as into adjacent parts of Canada and Mexico. A contemporaneous heat wave also affected most of Europe, although it was not as severe as the great European heat wave of summer 2003. Some heat waves may be viewed in a much larger geo-spatial context and a broader viewpoint may provide greater insight. Global climate warming is becoming and is expected to increasingly become more apparent in the mounting spatial scale of regional summertime heat (Gershunov and Douville 2007). Together with our more focused regional results, this further suggests a direct and increasing link between regional heat waves and global climate change. It suggests that a smooth global warming trend consists to some extent of regional extremes. Heat waves in California may be unique in their specific regional causes, but may not be unique in terms of the rise that is apparent in nighttime heat wave activity. Fortunately, the likely antropogenic forcing behind the observed trend, if verified, will provide an excellent basis for longer-term regional projection. Towards this goal, regional coupling mechanisms (e.g. between day and nighttime temperatures under various humidity conditions) should be explored in detail and especially in dynamical models which can then be used to explore causal mechanisms for the observed trends in regional heat wave activity. Regional climate change, especially as manifested in extreme events, must be better understood via examination of synoptic dynamics (and hydro-dynamics) typical for a region. To dynamically validate regional manifestations of global climate change and project them in their extreme detail, climate models should be scrutinized for their ability to simulate the salient dynamical features for the region of interest and then used selectively to project these features into the future.

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