The Great 2006 Heat Wave over California and Nevada: Signal of an Increasing Trend

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ABSTRACT

Most of the great California–Nevada 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). Generally, there is a positive trend in heat wave activity over the entire region that is expressed most strongly and clearly in nighttime rather than daytime temperature extremes. This trend in nighttime heat wave activity has intensified markedly since the 1980s and especially since 2000. The two most recent nighttime heat waves were also strongly expressed in extreme daytime temperatures. Circulations associated with great regional heat waves advect hot air into the region. This air can be dry or moist, depending on whether a moisture source is available, causing heat waves to be expressed preferentially during day or night. A remote moisture source centered within a marine region west of Baja California has been increasing in prominence because of gradual sea surface warming and a related increase in atmospheric humidity. Adding to the very strong synoptic dynamics during the 2006 heat wave were a prolonged stream of moisture from this southwestern source and, despite the heightened humidity, an environment in which afternoon convection was suppressed, keeping cloudiness low and daytime temperatures high. The relative contributions of these factors and possible relations to global warming are discussed.

1. Introduction

In July 2006, California and Nevada were impacted by a heat wave that was unprecedented with respect to the magnitude and duration of high temperatures, especially high nighttime minima; great areal extent, as it simultaneously impacted both northern and Southern California; and very high humidity levels (Los Angeles Times, 25 July 2006). This heat wave stressed the delivery of water and energy resources and had significant morbidity and mortality impacts on humans and livestock (Knowlton et al. 2009; Ostro et al. 2009; Davis 2006; USAgNet, 31 July 2006). Here, we take a comprehensive retrospective look at the July 2006 heat wave in the context of the region’s climate over the past six decades.

Summer 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). Gershunov and Douville (2008) considered the spatial extent of summertime heat over Europe and North America in seasonal average temperature records and model projections, describing the increasing spatial scale of extreme continental summertime heat that is obviously
connected to heat wave activity and clearly tied to global climate change. Heat wave activity has received considerable attention lately, especially following the European heat waves in 2003 (e.g., Beniston and Diaz 2004; Schar et al. 2004; Stott et al. 2004; Meehl and Tebaldi 2004; Gershunov and Douville 2008). 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). However, heat waves are inherently regional phenomena 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.

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 society and nature 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 human and natural systems. Extreme daytime heat is known to endanger health most directly via heat stroke but health dangers are exacerbated by associated air pollution including near-surface ozone formation (e.g., Fischer et al. 2004; Stedman 2004; Gosling et al. 2008). 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; Grize et al. 2005; Gosling et al. 2008). Excess mortality across Switzerland due to the June and August 2003 European heat waves has been attributed to the compounding effect of elevated nighttime temperatures (Grize et al. 2005). 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 (Margolis et al. 2008). Perhaps they had turned off air conditioning in the evening expecting the strong nighttime cooling characteristic for this region, which did not materialize.

Physical mechanisms causing daytime and nighttime heat waves may differ. Observed warming trends are known to have been stronger at night than during the day (e.g., Easterling et al. 1997, 2000b) resulting in a decreased diurnal temperature range. Stronger nighttime heating trends have been observed at many locations around the globe and, in spite of modeling inconsistencies (Lobell et al. 2007) and recent observations that trends in diurnal temperature range may have ceased globally (Trenberth et al. 2007) or may be increasing over some regions (e.g., southern Mexico; Peralta-Hernandez et al. 2008), warmer nights are among the most widespread expectations from anthropogenic global climate change (e.g., Tebaldi et al. 2006). In this regard, the California region has been meeting expectations. The observed summertime average warming here has been largely due to minimum temperatures (not shown). In this topographically, environmentally, economically, and climatically complex region, global, regional, and local natural and anthropogenic effects abound (e.g., Duffy et al. 2007; Bonfils et al. 2008).

The purpose of this work is to describe the climatic behavior and regional causes of great heat waves over California and Nevada. Using this foundation, we investigate whether and to what extent the 2006 event may be considered an aberration or a manifestation of a long-term change. After describing the data, our approach to quantifying heat waves, and their general behavior (section 2), we illustrate the observed variability of regional daytime and nighttime heat waves (section 3), describe the synoptic characteristics of the greatest observed events in recent history (section 4), and explain the 2006 event in that context (section 5) as well as in the context of trends in daytime and nighttime heat waves (section 6).

2. Quantifying heat waves

There is no one objective and uniform definition of “heat wave.” Heat waves are typically defined locally with specific applications in mind. Mortality increases sharply when extreme heat persists (e.g., Sheridan and Kalkstein 2004). Consequently, health applications tend to stress duration and require that events last at least 2–3 days, but specific details vary regionally. Gosling et al. (2008) provide a useful summary of definitions. For example, in China, heat warnings are issued when maximum temperature is forecast to exceed 35°C on any one day, while in the United Kingdom, regionally varying thresholds of maximum and minimum temperature must be exceeded for two consecutive days and an intervening night. The Netherlands meteorological bureau issues warnings to health services when maximum temperatures are predicted to exceed 25°C for at least 5 days of which at least 3 days threaten temperatures above 30°C. In the United States, the National Weather Service suggests early warning when the daytime heat index (including adjustment for humidity) reaches 40.6°C and a nighttime minimum temperature of 26.7°C persists for at least 48 h. Various definitions are also adapted in the research literature. For example, Beniston (2004) defines a heat wave when local maximum temperature ($T_{\text{max}}$) exceeds the 90th percentile of local summertime climatology during 3 successive days. Gosling et al. (2007) require 3 days of excess above the 95th percentile, while Hajat et al. (2002)
require that a smoothed 3-day running mean of average temperature exceed the 97th percentile over at least 5 consecutive days. Local duration is obviously important for health applications, while for energy applications, spatial extent and regional as opposed to local duration could be more relevant.

In the present study, we seek a straightforward measure that reflects an event’s characteristics known to be important in producing regional impacts on environment and society, including health, infrastructure, and economy. The desired measure would be simply computed from the available data. The resulting heat wave indices should include local components that can be aggregated to represent a heat wave’s regional magnitude and, therefore, reflect and quantify an event’s intensity, duration, and spatial extent. As we shall see below, regional duration is a quantity partly related to local duration but worth considering separately.

a. Observational data

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 nighttime temperatures ($T_{\text{max}}$ and $T_{\text{min}}$, respectively) recorded at 95 stations distributed more or less uniformly over the adjacent states of California and Nevada. 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 original set of 141 stations with daily $T_{\text{min}}$ and $T_{\text{max}}$ records going back to at least 1 January 1948 and running through August 2006 was selected for having no more than 15% of missing data at each station per summer. The choice of 1948 as the starting point was a reasonable compromise between record length and spatial completeness. All stations were purged of unnatural outliers. This original set of stations was characterized by a spatial sampling bias toward most populated areas. The 95 core stations were selected from this original set as representative of the region by keeping one best quality station (i.e., station with the least missing data) per locale of 30-km radius and thereby removing the urban density bias. 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 300 m per locale. The sparsely populated and observed areas of the southeastern California and Nevada deserts are, by necessity, underrepresented and downplayed by subsequent analyses. We computed local linear summertime $T_{\text{max}}$ and $T_{\text{min}}$ trends at all stations and visually examined trend maps for spatial outliers. Time series at several stations exhibiting conspicuous trends were examined for obvious discontinuities and outliers possibly exerting undue influence on the linear trends, but none were found. Although no formal homogenization procedure was performed, the use of many stations to characterize a region strongly reduces possible biases arising from occasional sporadic local glitches.

The seasonal focus here is on summer, June–August (JJA). The largest events tend to occur around the seasonal temperature maximum in mid–late July. Although intense heat waves do occasionally occur in September, they tend to be localized, resulting from rather different regional circulations than the extensive events considered here. Including a longer season would not significantly influence our results, but concentrating on JJA sharpens our focus on the largest events.

b. Quantifying regional summertime heat wave activity

Daytime and nighttime heat wave activity indices were derived to reflect the overall magnitude of extreme summertime heat consisting of intensity, frequency, duration, and spatial extent of daytime and nighttime heat waves. A local heat wave is defined to occur when temperature at a particular station ($j$) exceeds the 99th percentile of its local summertime climatology computed over the base period 1950–99 (Fig. 1) for duration of at least 1, 2, or 3 consecutive days or nights. On dates ($d^*$) when station temperatures exceeded these climatological values, we computed the local temperature excesses ($T_{\text{max}}^{j,d^*} - T_{\text{max}}^{j,99}, d^*$ marks the date when $T_{\text{max}}^{j,d^*} > T_{\text{max}}^{j,99}$ at station $j$; on all other dates, the quantity is defined as zero) and summed them over each summer ($s$), obtaining the local summertime degree-day index, $\text{DD}_{99}^j = \sum (T_{\text{max}}^{j,d} - T_{\text{max}}^{j,99})$, for $d$ ranging from 1 June to 31 August, the 92 days of summer ($d = 1, \ldots, 92$), resulting in an annually resolved time series at each station. Three versions of $\text{DD}_{99}^j[n]$ were computed given specific minimum durations of $n = 1, 2,$ and 3 consecutive days. The local summertime degree-night index ($\text{DN}_{99}^j$) is similarly defined from $T_{\text{min}}$. $\text{DD}_{99}^j$ and $\text{DN}_{99}^j$ represent the intensity and frequency of intense (the hottest one percent for $\text{DD}_{99}^j[1]$ and $\text{DN}_{99}^j[1]$ and progressively rarer given longer duration) local summer heat waves expressed during the day and night, respectively (Table 1).

Properties of $\text{DD}_{99}^j$ and $\text{DN}_{99}^j$ can be understood by plotting $T_{\text{min}}$ and $T_{\text{max}}$ at Sacramento (Weather Service

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1 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. Santa Ana is uncommon in spring and summer.
The distribution of $T_{\text{min}}$ is skewed, having a sharp lower limit and a more volatile upper bound; the well-defined lower threshold indicates that nighttime lowest values are limited, probably because cooling at night is predominantly radiative and is thus time limited, while large extremes on the hot side are not bounded by an equivalent threshold.

**TABLE 1. Overview of definitions for heat wave magnitude $M$ ($C^\circ$).** Locally (at station $j = 1, \ldots, N$), on a particular date ($d = 1, \ldots, 92$ or 1 June, ..., 31 August), and for a particular summer ($s = 1948, \ldots, 2006$), $M_{j,s,d}^{99\%}$ is exceedance over the local 99th percentile ($T_{j,s,d}^{99\%}$), computed over the base period of 50 summers, 1950–99. So, $M_{j,s,d}^{99\%} = (T_{j,s,d} - T_{j,s,d}^{99\%})$ if $T_{j,s,d} > T_{j,s,d}^{99\%}$, or zero otherwise. These local daily values are aggregated over space (all stations $j = 1, \ldots, N$) and time (all summer dates $d = 1, \ldots, 92$, or particular event durations: $s^*$, $d^*$) by summation ($\Sigma$) performed over the subscripted parameters. Asterisks (*) refer to the specific summer and days spanned by a particular event. In the text, we refer to $M$ computed for daytime or maximum temperatures ($T = T_{\text{max}}$) as degree-days (DD), while $M$ computed for nighttime or minimum temperatures ($T = T_{\text{min}}$) is referred to as degree-nights (DN). Regional magnitudes can be computed only using local magnitudes when the percentile threshold temperature is exceeded for at least $n$ consecutive dates, as is done in the text for $n = 1, 2,$ and 3 ($M[n] = \text{DD}[n]$ or $\text{DN}[n]$).

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Daily</th>
<th>Seasonal</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>$M_{j,s,d}^{99%} = T_{j,s,d} - T_{j,s,d}^{99%}$</td>
<td>$M_{99}^{\Sigma} = \sum_{d}(M_{j,s,d}^{99%})$</td>
<td>$M_{99}^{\Sigma} = \sum_{s}\sum_{d}(M_{j,s,d}^{99%})$</td>
</tr>
<tr>
<td>Regional</td>
<td>$M_{99}^{\Sigma} = \sum_{j}(M_{j,s,d}^{99%})/N$</td>
<td>$M_{99}^{\Sigma} = \sum_{j,d}(M_{j,s,d}^{99%})/N$</td>
<td>$M_{99}^{\Sigma} = \sum_{j,s,d}(M_{j,s,d}^{99%})/N$</td>
</tr>
</tbody>
</table>

**FIG. 1.** Observed (a) $T_{\text{max}}$ and (b) $T_{\text{min}}$ plotted in dots for every date of every summer on record with average (black circles) and 2006 observations (colored circles) for Sacramento [Weather Service office (WSO) city station]. The 99th percentile threshold (dashed line) was computed over the 1980–99 climatology. By definition, daytime or nighttime heat waves occur on days when $T_{\text{min}}$ or $T_{\text{max}}$ exceed this threshold over a given minimum duration ($n = 1, 2, 3$). They are quantified locally as sums of exceedances over the 99th percentile. The approximate (in bins) 99th percentiles of summertime (c) $T_{\text{max}}$ and (c) $T_{\text{min}}$ at each station. Regional heat waves are quantified as exceedances over the local 99th percentile, and given a specific minimum duration, summed over all stations. The “X” marks Sacramento.
physical process. Summer 2006, in late July, featured an extremely intense and persistent heat wave and is used here as an example. The 22–24 July $T_{\text{min}}$ at Sacramento was unprecedented over the historical record, reaching 29.8°C on July 23. The 99th percentile of 22.8°C was exceeded for seven (six consecutive) nights. $T_{\text{max}}$, meanwhile, although not unprecedented, exceeded the 99th percentile (42.2°C) for two straight days (23–24 July) and generally varied more symmetrically around the climatological mean values.

To define regional heat wave activity, we first compute the 99th percentiles at all stations (Figs. 1c,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 lowest hot extremes occur in the high Sierra Nevada and along the coast and coastal ranges. Extremes of both $T_{\text{max}}$ and $T_{\text{min}}$ display a very similar spatial distribution with few local exceptions, for example, the Southern California coast exhibits relatively hot extremes at night while the northern coastal hills are relatively more prone to intense daytime heat.

The 99th percentile temperatures are used to quantify regional heat wave activity simply by summing threshold exceedances (departures over these local thresholds) over each summer and all stations given three minimum local durations (Fig. 2). These indices, $DD_{99}$ and $DN_{99}$, reflect region-wide summertime heat wave activity, that...
is, intensity, frequency, duration, and spatial extent of individual heat waves aggregated over each summer (Figs. 2a,b). The significant trend in daytime heat wave activity for local durations of at least 3 days \((n = 3)\) is mostly due to enhancement toward the end of the record. In contrast, the increasing trend in nighttime heat wave activity is a feature of the entire record that holds regardless of local duration, although it is accentuated by the most recent summers 2003 and 2006, each unprecedented (Fig. 2b). The broad coherent patterns of entirely positive correlations of regional DD\(_{99}\) and DN\(_{99}\) with local values (a median correlation of 0.50/0.48 for DD\(_{99}/\)DN\(_{99}\) for \(n = 1\)) indicate the widespread nature of intense heat waves (Figs. 2c,d).

The observed trend includes California’s major population centers around the Bay Area and Southern California but operates at broader scales involving most of California and Nevada and likely larger areas. A correlation analysis (Figs. 2c,d) demonstrates that the regional daytime and nighttime heat wave indices are appropriate measures that capture the summertime heat wave activity in California–Nevada.

c. Overview of definitions

The terminology adapted in this article to describe heat wave magnitude \(M\) is summarized in Table 1. Local (daily and nightly), seasonal, and regional magnitudes, as well as magnitudes of specific events, are described below. Regional duration is defined as the number of consecutive days or nights when local thresholds are exceeded. 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 or over the duration of a particular heat wave as appropriate. Regional duration, as well as spatial extent and magnitude, certainly depend on local duration, but local-scale meteorology complicates this scaling-up process to the regional level. We sometimes apply the terms “total” or “overall” to mean aggregated measures over space and/or time. Regional magnitudes are displayed as averages over all stations, that is, in locally meaningful temperature exceedance (i.e., degree-days/degree-nights) units. “Daytime” and “nighttime” events refer to heat wave types, not the diurnal character of the data used to describe them; for example, either type of event has a signature in both \(T_{\text{max}}\) and \(T_{\text{min}}\).

3. Hot summer days and nights

We 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 3a documents the magnitude of extreme heat waves of unspecified local duration \((n = 1)\) for each day and night on our 59-year record. Figure 3b shows the same information for heat waves of 3 or more days/night local duration \((n = 3)\). Timing and duration of strong heat waves can be visually identified on these plots. Regionally,

- heat waves tend to cluster between late June and mid-August;
- daytime heat waves occurred sporadically throughout the 59-yr period;
- nighttime heat waves have markedly increased in occurrence since the 1970s;
- heat wave activity in both \(T_{\text{min}}\) and \(T_{\text{max}}\) has increased considerably since 2000;
- the largest \(T_{\text{max}}\) events nearly always have some expression in \(T_{\text{min}}\) and vice versa.

These observations hold for regional heat waves, regardless of their minimum local duration. Detailed comparisons between the red and blue bubbles (DD\(_{99}\) and DN\(_{99}\)) in Fig. 3, as well as the intraseasonal temporal correlations between them (Fig. 4), suggest a temporal coupling between hot \(T_{\text{min}}\) and \(T_{\text{max}}\) extremes that is strong during active summers and has strengthened as heat wave activity has increased.

While overall summertime magnitude of regional heat wave activity was summarized in Figs. 2 and 3, each summer’s peak regional heat waves can be summarized by their maximum intensity (Figs. 5a,b), spatial extent (Figs. 5c,d), and duration (Figs. 5e,f) components.

The regional components of daytime heat waves and their positive trends (Figs. 5a,c,e and Table 2) suggest that the weak positive trend, especially in locally persistent daytime heat wave activity (Fig. 2a and Table 3), can be attributed mainly to increasing regional duration (Fig. 5e), somewhat less to spatial extent (Fig. 5c), and least of all to maximum magnitude (Fig. 5a). Nighttime heat waves have undergone acceleration toward higher levels of activity in all their regional components.

4. Anatomy of great heat waves

Before considering synoptic characteristics of July 2006 compared to other large events, we describe the timing and canonical features of a handful of the largest daytime

\(^2\) Both Figs. 3a and 3b represent regional heat waves, whether locally persistent or not. Figure 3b may be more relevant to health professionals, while Fig. 3a may be of greater relevance to energy providers. We do not display the intermediary figure based on local durations of at least 2 consecutive dates \((n = 2)\).
FIG. 3. The daily level magnitude of regional heat wave activity as defined in Table 1: DD_{99} (red ovals) and DN_{99} (blue ovals). The x axis corresponds to each year on record, while the y axis corresponds to each summer date. (a) Regional magnitude for unspecified local duration \( n = 1 \), and (b) local duration of at least 3 consecutive dates. The larger the oval, the greater the magnitude. The scale is given by the maximum magnitude recorded each summer and shown at the top of each panel and again in Figs. 5a,b. The overall magnitude for each summer is shown in Figs. 2a,b.
and nighttime events on record, which we call the “great” heat waves. Below, only results computed for events of unspecified local duration \((n = 1)\) are presented for brevity and because they are largely representative of all regional heat waves.

a. The greatest events: Case studies

To illustrate the general appearance of great day- and nighttime heat waves, we identify six of the most extensive and intense daytime and nighttime heat wave episodes on record. Figure 6 presents the timing and magnitude of the largest events chosen according to results presented in Figs. 2, 3, and 5 and emphasizing the greatest magnitude, events defined without regard to local duration. Statistics for these events, moreover, are presented in Table 4.

With the exception of 2006 and 2003, the greatest daytime heat waves have been larger overall than the greatest nighttime events. Extreme nighttime heat accompanied the great daytime heat waves to some degree and vice versa. Regional durations are generally about a week for most great heat waves, but they can persist for 2–3 weeks, for example, in 1961, 2003, and 2006. Each great event has a well-defined peak date or two. As far as spatial extent (Table 4), all six of the great daytime heat waves were of comparable scale, with about 40% of the stations registering extreme \(T_{\text{max}}\) on the peak day. In contrast, during the great nocturnal heat wave of 2006, 74% of our stations recorded extreme \(T_{\text{min}}\) values on 23 July 2006, an event without recorded parallel in the 59-year record (Table 4).

In the first five decades on record, nighttime heat waves were 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 increasing markedly, not in magnitude but in the fact that the most recent great daytime events were daytime expressions of huge nighttime events, for example, 2003 and 2006. During the day, July 2006 is fourth in terms of daytime peak intensity, but its impressive regional duration and spatial extent makes it first among daytime events in terms of overall \(T_{\text{max}}\) magnitude.

b. Synoptic aspects of great daytime and nighttime heat waves: A canonical view

Here, we are specifically interested in comparing synoptic characteristics of great daytime and nighttime heat waves and understanding the unprecedented 2006 anomaly. We start by describing synoptic features for the canonical peak date of regional heat waves and then examine the temporal evolution of their most salient features with the intent to understand causal relationships. Circulation and precipitable water data are from
FIG. 5. Seasonal maxima of regional heat wave components: total magnitude on the peak (a) day and (b) night of the greatest events, maximum spatial extent in % of stations by (c) day and (d) night, and maximum continuous regional duration of (e) daytime and (f) nighttime heat waves. All variables were computed for each summer on record from data presented in Fig. 3. Components were computed given local durations of at least 1, 2, and 3 consecutive days/nights ($n = 1, 2, 3$) and delineated in progressively darker shades of gray. Correlations between these indices and trends are given in Table 3.
TABLE 2. Correlation coefficient between, and trends within, the heat wave component indices displayed in Fig. 5 for regional daytime (Roman font) and nighttime (italic font) heat waves. Correlations between daytime and nighttime heat wave components are displayed along the main diagonal (Roman bold font). All correlations are significant at the 99% level after adjusting for autocorrelation. Trends are in appropriate units decade$^{-1}$ (in local DD for maximum magnitude, i.e., per average station, % stations for spatial extent, and days for regional duration) are displayed along the bottom row with significance (*90%, **95%, ***99%, under a two-tailed test). For brevity, all results are shown for heat waves of unspecified local duration (n = 1 day or night).

<table>
<thead>
<tr>
<th>Maximal components</th>
<th>Magnitude</th>
<th>Spatial extent</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude</td>
<td>0.46</td>
<td>0.96</td>
<td>0.58</td>
</tr>
<tr>
<td>Spatial extent</td>
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<td>0.46</td>
<td>0.65</td>
</tr>
<tr>
<td>Duration</td>
<td>0.67</td>
<td>0.70</td>
<td>0.60</td>
</tr>
<tr>
<td>Trends 1948:2006</td>
<td>0.03**:0.07***</td>
<td>2.1**:3.4***:</td>
<td>0.8***:1.0***</td>
</tr>
<tr>
<td>Trends 1950:1999</td>
<td>0.01**:0.03***</td>
<td>0.9**:1.0***:</td>
<td>0.6**:0.4***</td>
</tr>
</tbody>
</table>

National Centers for Environmental Prediction—National Center for Atmospheric Research (NCEP–NCAR) reanalysis representing 24-h averages. “Daytime” and “nighttime” refers to heat wave event type, not the diurnal character of the reanalysis data.

Synoptic features of great heat waves can be identified by compositing circulation anomalies at the surface [mean sea level pressure (MSLP) and wind at sigma level 995] and the free atmosphere [500-mb geopotential height (Z500)] as well as precipitable water (PRWTR) on the peak day of the five largest daytime and nighttime events (Fig. 7). These dates are listed in Table 4. The two largest daytime and nighttime events (July 1972$^3$ and 2006) are considered separately.

Great heat waves are associated with a baroclinic structure in the atmospheric circulation involving horizontal and vertical motions conducive to hot regional weather (Figs. 7a–d). The day- and nighttime heat wave surface circulation composites (Figs. 7a,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 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 the Washington coast. During peak daytime events, these features bring convergent surface winds into California, particularly from the south (see below). 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 (to the point of being insignificant$^5$ in this case), making for reduced anomalous convergence, especially from the Great Basin, that is, from the high Nevada desert. The circulation aloft (Figs. 7c,d) consists of a broad and intense high centered above Washington State. Slight differences between daytime and nighttime canonical event circulation composites are not significant; they are within the range of variability of each of the two samples of five intense day- and nighttime events.

While circulation at the surface as well as aloft appears rather similar for peak dates of both daytime and nighttime events, atmospheric moisture content presents a sharp contrast (Figs. 7e,f). Nocturnal events are about twice as moist as climatological normals (PRWTR anomaly twice the normal of about 18 kg m$^{-2}$ for JJA averaged over this arid region). For daytime events, the average anomaly is slightly (insignificantly) drier than normal over the California and Nevada box. It is generally (i.e., climatologically) not cloudy and, aside from occasional mountain and desert thunderstorms, does not rain over this arid region in summer. However, available moisture levels during the great heat waves of the humid nocturnal variety may be enough to briefly modify this general picture and depress daytime temperatures. We will examine precipitation and cloudiness in section 5d below. At this point, however, evidence clearly indicates that the enhanced greenhouse effect of water vapor is what mainly upholds nighttime temperatures during nocturnal heat waves. Fig. 7f shows elevated moisture levels, especially in Southern California as well as to the north.

$^3$ The 1972 heat wave was the largest purely daytime event, but it differed considerably in its circulation from the other great heat waves. The event featured a surface high over British Columbia with a southeastern branch extending into the Great Basin together with a pronounced surface low over the central California coast, creating a statewide 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.

$^4$ Dynamic cartoons of these maps spanning the evolution of events clearly show this development but cannot be fully reproduced in this static format.

$^5$ The relevant noise distribution consisted of 1000 5-day composite anomaly maps that were resampled (bootstrapped) from the data using the base period (1950–99). By design, and for realism’s sake, the resampling scheme selected July dates with twice the probability of either June or August.
south-southwest of the region during regional nocturnal heat waves.

5. The July 2006 heat wave compared to other great events

a. Synoptic characteristics on peak date

The peak of the 2006 event was characterized by circulation rather similar to other great heat waves, especially those of the daytime variety (cf. Figs. 8a,b and 7a–d). In this case, the surface low off the California coast was particularly strongly developed. Strong teleconnections were present upstream and downstream of the regional MSLP anomalies. At the 500-mb level, the geopotential height over Washington State was impressive, with a positive anomaly of 206 m. There was enhanced moisture over the entire region, with a significant positive anomaly over Nevada. On 23 July 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 causes requires a view of its time evolution rather than just a static snapshot of the peak date.

b. Magnitude evolution of 2006 and other great heat waves

The evolution of the 2006 event regional magnitude compared to the canonical daytime and nighttime events is presented in Fig. 9. Notably, daytime ($T_{max}$) expressions of nighttime events typically peak one day prior to the main (i.e., nighttime) peak (blue envelope in Fig. 9a), and nighttime peaks associated with primarily daytime events tend to occur just after the main (i.e., daytime) peak at date zero (red envelope in Fig. 9b).

The evolution of 2006 daytime ($T_{max}$) expression is fully consistent with the average of the largest daytime heat waves, except that strong anomalous regional heating took place 7–5 days prior to the main event and daytime heat subsided more slowly than expected (Fig. 9a). Its nighttime expression was unprecedented among all other nighttime events; more intense at the peak and more persistent at unprecedented levels. The sizeable warming that occurred over several nights and days before the onset of the main event was of magnitude and duration comparable to our canonical great nighttime heat waves. This prelude may have played an important role in setting the stage for the main event that peaked on 23 July.

c. Synoptic dynamics

Figure 10 displays the evolution of circulation and moisture anomalies during the 2006 heat wave compared to the canonical daytime and nighttime events. We show the temporal evolution of key circulation and moisture indices of day- and nighttime heat wave activity, for example, surface pressure gradient expressed as difference of MSLP anomalies over the central–southern Great Plains and coastal California waters, circulation aloft ($Z_{500}$ over Washington State), and precipitable water averaged over California and Nevada. Low-level

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6 Compared to noise distribution resampled as described in footnote 5 but using 1-day random maps.
convergence and temperature advection into the California and Nevada box are also displayed in Figs. 10d,e. Vertical velocity (omega at 850 hPa) averaged over the box is displayed in Fig. 10f. Averaging was done in boxes displayed in Figs. 7 and 8, while the time frame is identical to that of Fig. 9 for convenient comparison: temporal evolution over 31 days centered on the peak date of heat waves.

The salient results of Fig. 10 can be summarized as follows: The July 2006 low-level circulation evolution described by the mean sea level pressure gradient across the region (Fig. 10a) is not significantly different up to the peak date between daytime and nighttime events. The gradient observed in 2006, although building up unusually early, was not unprecedented. However, the geopotential ridge aloft was unprecedented in its strength and early development preceded the surface pressure gradient anomalies by at least one day (Fig. 10b, and cross-correlation functions, not shown). For canonical events, temperature anomalies tend to reach the peak within 2 days of the initial warming (Fig. 9), approximately in sync with surface pressure gradient anomalies (Fig. 10a), while the upper-level ridge ramps up at least one day earlier (Fig. 10b, and cross-correlation functions, not shown). This earlier development of the ridge aloft, typical of canonical events, suggests that the large-scale circulation aloft precedes and drives surface pressure anomalies as well as advection of heat and humidity, when available, leading to different flavors of regional heat waves.

The separation of precipitable water accumulation into and past the peak dates of great daytime and nighttime heat waves is clearly visible in Fig. 10c. The magnitude of moisture accumulation in July 2006 was unprecedented. The buildup of moisture started early, in unison with the circulation anomalies, and continued up to one day past the event’s peak, suggesting that a strong moisture source was present nearby for advection. Other differences between evolutions of daytime and nighttime events are not nearly as consistent. Low-level convergence (Fig. 10d) is similar for day- and nighttime heat waves. Warming by advection (Fig. 10e), however, tends to start earlier for canonical nighttime compared to daytime events. In both cases, it is mainly from the south with contributions from the east and west (directional detail not shown). On the other hand, daytime events tend to be characterized by anomalous subsidence several days prior to the peak (Fig. 10f). The stronger subsidence can create and exacerbate the hot and dry atmospheric conditions leading up to the daytime event peak (Figs. 9a and 10c).

In July 2006, heat advection started early and with unprecedented strength, weakening into the main peak and recovering afterward, prolonging this unprecedented event. We note that delayed convergence of heat and moisture (Figs. 10d,c) is typical of day- and nighttime events and does not seem to be driven simply by the large-scale circulation anomalies, which tend to be on the decline after the peak heat wave date. It may be that regional heat and moisture start driving surface

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7 In this arid region dominated in the summertime by subtropical high pressure, moisture is advected.

### Table 4. Peak dates of the greatest regional heat waves on record listed in order of largest magnitude. Only events listed in bold font were not used for composite results in Figs. 8 and 10–12. Overall magnitude, defined as $DD_{99}^s = \sum_{s,t,d} (DD_{99}^{s,t,d})$ and $DN_{99}^s = \sum_{s,t,d} (DN_{99}^{s,t,d})$, where asterisk (*) refers to the particular summer and days spanned by the specific event, i.e., the overall magnitude over the entire duration of the event and over all stations associated with each event. Here $DD_{99}$ and $DN_{99}$ are given in Roman and italic font, respectively, as are the peak spatial extent and regional duration. Results are for unspecified local durations ($n = 1$).

<table>
<thead>
<tr>
<th>Peak date</th>
<th>Overall magnitude (°C)</th>
<th>Peak spatial extent (%)</th>
<th>Regional duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 Jul 1972</td>
<td>2.87/1.26</td>
<td>44/26</td>
<td>7/6</td>
</tr>
<tr>
<td>11 Jul 2002</td>
<td>2.78/1.21</td>
<td>43/24</td>
<td>10/7</td>
</tr>
<tr>
<td>19 Jul 1960</td>
<td>2.64/0.76</td>
<td>46/14</td>
<td>9/15</td>
</tr>
<tr>
<td>15 Jun 1961</td>
<td>2.48/0.68</td>
<td>41/12</td>
<td>15/8</td>
</tr>
<tr>
<td>8 Aug 1981</td>
<td>2.15/0.13</td>
<td>42/7</td>
<td>7/4</td>
</tr>
<tr>
<td>11 Jul 1961</td>
<td>1.53/0.61</td>
<td>40/14</td>
<td>15/8</td>
</tr>
</tbody>
</table>

Great nighttime heat waves

<table>
<thead>
<tr>
<th>Peak date</th>
<th>Overall magnitude (°C)</th>
<th>Peak spatial extent (%)</th>
<th>Regional duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>23 Jul 2006</td>
<td>7.46/3.01</td>
<td>74/39</td>
<td>179</td>
</tr>
<tr>
<td>23 Jul 2003</td>
<td>4.04/2.62</td>
<td>38/22</td>
<td>23/16</td>
</tr>
<tr>
<td>4 Jul 2001</td>
<td>1.35/0.57</td>
<td>35/27</td>
<td>7/5</td>
</tr>
<tr>
<td>13 Jul 1990</td>
<td>1.22/0.15</td>
<td>33/19</td>
<td>9/6</td>
</tr>
<tr>
<td>7 Aug 1983</td>
<td>1.08/0.46</td>
<td>31/14</td>
<td>5/3</td>
</tr>
<tr>
<td>12 Aug 1992</td>
<td>1.05/0.28</td>
<td>27/8</td>
<td>7/5</td>
</tr>
</tbody>
</table>
FIG. 7. Composite anomalies of (a),(b) surface circulation (wind at sigma level 995, arrows in m s$^{-1}$) and mean sea level pressure in millibars; (c),(d) 500-mb geopotential height in meters; and (e),(f) precipitable water kg m$^{-2}$ 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 4 for exact dates). The data are from the NCEP–NCAR reanalysis I (Kistler et al. 2001). Black rectangles outline regions used for evolution plots presented in Fig. 10. Contours and colors represent the same anomalies, but only values statistically significant with 95% confidence (two-tailed test) determined via bootstrap resampling (performed with 1000 resampled 5-date composite anomaly maps) are plotted in color. Low-level wind vectors are colored blue where significant according to similar resampling test performed for the $u$ and $v$ components separately. Significance is everywhere a function of magnitude and location. The reference period for computing anomalies is 1950–99, as elsewhere. The anomalies are computed from 24-h averaged fields.
convergence via hot air expansion and convective processes following the peak of nighttime events in particular. If this is the case, it could explain (together with somewhat stronger temperature advection past the peaks of daytime events) why nighttime heat waves cool faster than daytime events (Fig. 9) and, although this was not the case in 2006, why daytime temperatures tend to be depressed during humid nighttime heat waves.

d. Precipitation, cloudiness, and maximum daytime temperatures

Precipitation data are available daily at all 95 stations used in this analysis (NCDC 2003). Figure 11 shows daily accumulations of area-averaged precipitation following convention established in Figs. 9 and 10. Although precipitation is a noisy variable, we can plainly see that all nighttime heat wave peaks are followed by significant precipitation for four days after the peak date with median rainfall up to 1 mm per station on day 3. While this may not seem like much rain, it is a significant amount for this predominantly arid Mediterranean climate region during the dry season. In July, it rains on average 1.2 days a median of 1.5 mm per rainy day for a monthly total of 4.8 mm (3.8 mm) per mean (median) station. June and August are somewhat rainier (9.8 and 6.9 mm monthly total per mean station, respectively), so that, in an average summer month, there are 1.6 rainy days (including trace amounts); it rains a median of 2 mm per rainy day, a mean (median) monthly total of 7.1 (6.1) mm per station. Any amount of precipitation is highly unusual at a vast majority of stations on any summer day, especially in July. There has been recorded rain over the region on each of the several days of and following the peaks of each of the great nighttime heat waves on our record (Fig. 11). The rainfall amount accumulated over the one-week period from day −1 to day 5 surrounding the peak date (day 0) of a canonical (i.e., average of five) nighttime heat wave amounted to exactly the average monthly total for the month of July (4.8 mm per station). During nighttime heat waves, it obviously does not rain at all stations but rainy stations may experience downpours. Besides local soil moisture effects, the associated cloudiness may be widespread enough to strongly depress
maximum temperatures via increased albedo. The great humid event of 2006, however, was, in terms of rainfall, in line with seasonal climatology and close to dry daytime events, suggesting a radiative explanation, involving reduced cloud cover and albedo, for the unusually large T\textsubscript{max} magnitude of this predominantly nighttime event (see below).

Figure 12 presents the T\textsubscript{max} expression of four heat waves: 2006, 2003, 2002, and 2001. Obviously, the T\textsubscript{min} expressions of 2006, 2003, and 2001 are more substantial, but we do not show them here. Superimposed on temperature exceedances accumulated over the duration of each event (DD\textsubscript{99}), we show local precipitation accumulation over exactly one week starting 1 day prior to peak date and ending 5 days after the peak. During this week, cloudiness and soil moisture should be important in suppressing daytime maximum temperatures associated with the peak and its eventual decline. We note that the great 2006 event, in spite of its unprecedented precipitable water accumulation, was characterized by low precipitation amounts at few stations compared to the other nighttime events, specifically the two recent ones: 2003 and 2001 (cf. Fig. 12a to Figs. 12b,d). Precipitation accumulated over the region during the 2003 event was below the nighttime event median. The 2001 event was typical of great nighttime heat waves: it was very wet in terms of both spatial extent and precipitation amount, which must have strongly reduced its temperature expression during the day. The 2002 event was typical of dry daytime heat waves: it featured low precipitation amounts and that only over a few mountain and desert stations. The great 2006 event with 26\% of stations recording precipitation with average weekly accumulations of 3.4 mm per station was only slightly wetter than 2002. Specifically, precipitation did not materialize over the Central Valley where temperatures and humidity were at record-breaking levels at most stations.

Geostationary satellite imagery\textsuperscript{8} covers the four events displayed in Fig. 12. Figure 13 shows albedo averaged over California and Nevada from 8 days before to 8 days after peak dates of the 2006, 2003, 2002, and 2001 events. These composites are displayed for 10, 12, 14, and 16 h local time. The spatial cloud patterns (not shown) are consistent with station rainfall. The wet 2001 event (Fig. 13d) shows a strong peak in regional albedo for days ~1 to 3 around peak date with a maximum of almost 50\% at 16 h on day 2 after peak date. Strong diurnal enhancement of albedo with a late afternoon peak on cloudy days is clearly characteristic of convection. Convective cloudiness was also present during other events, but it was progressively more spatially limited in 2003, 2006, and 2002. In mid-July 2006, convective clouds and precipitation reduced the daytime expression of the “prelude” to the main event on days ~3 and ~4 but then abated, allowing maximum temperatures to rise sharply into the main peak (Fig. 9). Specifically, the peak day did not generally see convective cloudiness in 2006 (albedo did not peak at 16 h),

\textsuperscript{8} Albedo data were obtained from Geostationary Operational Environmental Satellite (GOES)-10 (2000–03 events) and GOES-11 (2006 event) satellite imager visible channel measurements. Horizontal resolution of the albedo measurements is approximately 1 km. Postlaunch sensor calibrations were performed using the algorithm of Nguyen et al. (2004). Visible channel pixels over the land regions of California and Nevada were used to compute average albedo values.
FIG. 10. Evolution July 2006 compared to composite evolution of 5 other major daytime 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 black over relevant panels in Figs. 7 and 8 and anomalies computed relative to JJA climatology. (a) MSLP anomaly gradient (Great Plains box–California shore box), (b) Z500 averaged over the Washington box, (c) PRWTR anomaly averaged over the California–Nevada box or region (42.5°–32.5°N, 125°–115°W), (d) low-level (995 sigma) wind convergence, (e) warming due to low-level temperature advection into the region, and (f) vertical velocity (omega, negative = upward) at 850 hPa over the region. Circles with thick red and blue lines are composite average daytime and nighttime event evolutions. Envelopes are drawn around composite maxima and minima. Black lines punctuated with X’s represent evolutions of the 2006 event. For ease of interpretation, smoothing was performed via weighted means of running medians (Tukey 1977). To illustrate the mild effect of this smoothing, the raw time series for 2006 is also drawn in the thin black line. A strict comparison requires that the smoothed version (thick black line with X’s) be compared to the colored envelopes.
allowing record-breaking daytime temperatures, while the high humidity prevented nighttime cooling. The persistent 2003 event was most strongly expressed over the mountains and deserts. Its peak was almost as convective as that in 2001 but was then followed by a lull in convection.

The 2002 and 2001 events were typical of dry daytime and humid nighttime heat waves, respectively, in terms of atmospheric humidity (i.e., precipitable water) and precipitation. Although satellite data are not long enough to verify this directly, the link with precipitation allows us to infer that these events were also typical of their type in terms of cloudiness. The 2006 and, to a lesser extent, 2003 events were atypical—there was plenty of atmospheric humidity to make them predominantly nighttime events; however, widespread cloudiness and precipitation did not materialize, allowing daytime temperatures to rise to levels typically associated with the greatest daytime heat waves.

The reasons for this weak convection observed during the most recent two great heat waves (especially 2006) in the presence of so much heat and moisture are beyond the scope of this article. On the one hand, it is surprising to see so much convection depressing daytime temperatures during “typical” great nighttime heat waves in this normally arid Mediterranean climate. On the other, convective suppression during such events is even more surprising and could be detrimental were it to reoccur during future humid heat waves.

6. 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 is the observed trend in the probability of more intense, larger, and more persistent nighttime heat waves (Tables 2 and 3). As the 2006 and 2003 events suggest, humid heat waves with suppressed convective cloudiness can result in intense daytime heat associated with primarily nighttime events. This, together with the positive trend observed in the coupling between $T_{\text{max}}$ and $T_{\text{min}}$ expressions of heat waves (Fig. 5), 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 associated with primarily nighttime events. In the final part of this work, we 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, expressed in both minimum and maximum temperatures. For nocturnal heat waves especially, the trend toward 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 summertime average precipitable water from reanalysis (Fig. 14a) and sparse in situ dewpoint and radiosonde records (not shown) are not characterized by coherent or significant regional trends over California and Nevada. There is a possibility that the relevant regional humidity changes are episodic, for example, 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?

Although we cannot see a moistening over California and Nevada, Figs. 14a,b show a strong and significant moistening trend centered over the marine region west of Baja California and more generally to the west-southwest of California State. This is a region where a strong positive trend in summertime sea surface temperature (SST) is observed (e.g., Pierce et al. 2006, their Fig. 20) and linked to global warming via a cloud feedback mechanism (Clement et al. 2009). 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 offshore and to the south prior to the event’s development and through its peak, while daytime events are typically preceded by a dry anomaly there (Fig. 14c). Heat wave circulations advect air northeastward from this region into California (Fig. 14d). The anomalous advection via the southwestern and southern borders of our focus region does not typically take place until the peak date of both daytime and nighttime events. Different humid events must tap different available moisture sources (associated with the southwest monsoon, for example). In 2006, however, advection from the southwestern marine region started strongly five days before the peak and continued for the entire duration of the event. This southwesterly advection was unprecedented; it strongly contributed to the buildup of moisture over the region (Fig. 10c and 14d) and preconditioned that great heat wave to be expressed most strongly at night. This coincidence of the moisture anomaly with southwesterly advection was clearly a rare event, but it is made more likely by the strong moistening trend present in this marine source region. Other peaks in the summer PRWTR time series there (Fig. 14b) can be identified to correspond to summers with large nocturnal heat waves, for example, 1990, 1992, etc. The correlation coefficient between this time series (Fig. 14b) and overall nighttime regional heat wave activity, $DN_{99}$, is 0.48 (Fig. 2b), 0.52 with maximal spatial extent (Fig. 5d), 0.44 with maximum regional duration (Fig. 5f), and 0.52 with maximum one-day magnitude (Fig. 5b)—all highly significant.

The regional moistening by advection observed during nighttime heat waves does not occur frequently enough to make for clearly detectable summertime moisture trends over California and Nevada, but its episodic

Fig. 12. Local overall daytime binned magnitude $[DD_{99}^W = \sum_{s,d} (DD_{99}^{s,d})]$, where $s^*$ and $d^*$ refer to the particular summer and dates spanned by the event; circle colors correspond to the lowest $DD_{99}^{s,d}$ of the bin] accumulated over the duration of each of four selected events and rainfall (arrows) accumulated over the period from 1 date prior to 5 dates following the peak date. Blue (green) arrows signify local amounts in excess of summer (average summer month) totals. Overall regional magnitude, aggregated over all stations, for each event is given in Table 4 and Fig. 6. Titles for each panel give the year of the event, % of stations with measurable rainfall, total accumulated rainfall, and average accumulated rainfall per wet station.
effect on $T_{\text{min}}$ extremes may be strong enough to be partially reflected in average summertime $T_{\text{min}}$ over the region.

7. Summary, discussion, and conclusions

We have quantified heat wave activity over California and Nevada during summers 1948–2006 in terms of regional magnitude (relative to local intensity and duration thresholds) and its components: intensity, spatial extent, and duration. Heat waves typically impose a regional footprint and can be classified into primarily dry daytime and humid nighttime events, those with the greatest regional magnitudes expressed in $T_{\text{max}}$ or $T_{\text{min}}$, respectively. Daytime (nighttime) events typically have sizeable but far smaller expressions in $T_{\text{min}}$ ($T_{\text{max}}$).
The atmospheric circulation anomalies responsible for most great daytime- and nighttime-type California heat waves are remarkably similar, consisting of a prominent anticyclone aloft above Washington State. This feature reinforces a strong surface pressure gradient between a high pressure anomaly over the Great Plains and a low off the California coast. This synoptic pattern produces low-level heat advection into California and Nevada. The main feature that distinguishes nighttime from daytime heat waves is the anomalously moist atmosphere during nighttime events. The moisture advected over California and Nevada can reach twice its normal levels and help maintain exceptionally high nighttime temperatures via the elevated greenhouse effect of a moist atmosphere. Elevated moisture and temperature also typically result in convective cloudiness and precipitation that depress daytime maximum temperatures. This tends to limit nighttime temperatures and keep anomalous $T_{\text{min}}$ and $T_{\text{max}}$ magnitudes lower during most nighttime heat waves compared to the $T_{\text{max}}$ magnitudes of dry daytime events. Dry daytime heat waves are characterized by soaring $T_{\text{max}}$ while radiative cooling efficiently reduces $T_{\text{min}}$. Thus, the presence of humidity during heat waves normally suppresses daytime temperatures, but its absence diminishes nighttime temperatures, both via radiative effects. The expected positive feedback between $T_{\text{min}}$ and $T_{\text{max}}$, therefore, may be weakened during either type of California heat waves.

This general picture has been changing, however. Regional magnitudes, as well as their components (intensity, spatial extent, and duration) are increasing, particularly for humid nocturnal heat waves, which have tended to cluster and amplify toward the end of the
record. These changes in regional heat wave activity are related in part to the presence of an increasing Pacific moisture source to the southwest of California State, west of Baja California. The coupling between daytime and nighttime temperature expressions of heat waves has also been strengthening significantly throughout the 59-year record. The most recent great heat waves on record, namely 2003\(^9\) and 2006, were primarily nighttime events. These events lasted over two weeks each and far exceeded previous highest nighttime magnitudes. Furthermore, they have had overall daytime expressions to match or exceed, in the case of 2006, the greatest observed daytime heat waves.

In mid-July 2006, beginning early (15–20 July)\(^{10}\) in advance of the peak of the great heat wave that occurred on 23 July, the large-scale upper-level circulation pattern and regional humidity anomalies over California and Nevada were remarkably strong. Humidity, which exceeded previous heat waves, was advected particularly from the southwest. Strong and persistent baroclinic circulation resulting in steady low-level convergence kept pumping moisture and heat into the region until unprecedented levels of more than twice the normal summertime atmospheric precipitable water collected over California and Nevada. For reasons not yet understood, convection was suppressed and the overall daytime temperature expression of the 2006 event surpassed all daytime heat waves on record. This conspicuous relative absence of convection in the presence of so much moisture led to intense daytime warming, which in turn promoted more intense and extensive nighttime heat, without any observed precedent. The positive feedback between \(T_{\text{max}}\) and \(T_{\text{min}}\) strengthened and made the heat wave more intense, widespread, and persistent.

Mechanisms that support the positive feedback between high nighttime and high daytime temperatures seem particularly crucial to understand, in view of the dangerous effects on human health and other biological impacts. Although controls on convective cloudiness and rainfall in the presence of heat and moisture are beyond the scope of this paper, it is noteworthy that 1) aerosol production does, in a complex way, depend on humidity and temperature (e.g., Jamriska et al. 2008), and 2) aerosols can have multiple effects on cloudiness and precipitation (e.g., Ramanathan et al. 2001; Givati and Rosenfeld 2004; Rosenfeld and Givati 2006). Convection, rare for this Mediterranean climate in summer, has not, to our knowledge, been studied with respect to aerosol effects. It is possible, however, that elevated summertime heat and moisture, especially under convergent surface wind conditions, may promote higher concentrations of aerosol pollutants that could have multiple effects on clouds and precipitation affecting daytime temperatures. Aerosols might, for example, hamper convection by altering the vertical tropospheric temperature structure. Aerosols are known to impact health risks associated with heat exposure (e.g., Fischer et al. 2004; Stedman 2004; Gosling et al. 2008) and further study is warranted to determine their net direct and indirect effects on maximum temperatures during humid heat wave conditions.

Is the climb in nocturnal heat wave activity that we are witnessing now over California and Nevada simply a regional process? Evidently not. The unusual magnitudes of the most recent California heat waves seem to be partially rooted in the long-term trend of nighttime heat wave activity and \(T_{\text{max}} - T_{\text{min}}\) coupling. This trend is related to the availability of an anomalous and increasing moisture source west of Baja California. This moisture source is coincident with a warming SST trend, which appears to be part of the global ocean warming pattern known to be due to anthropogenic climate change (Barnett et al. 2001, 2005; Pierce et al. 2006) and regionally exacerbated by a cloud feedback mechanism (Clement et al. 2009). To elucidate this process will require an augmented set of tools including dynamical models and their detailed synoptic-level verification. For now we simply note that the recent upturn in California–Nevada heat waves appears consistent with the regional symptoms of global warming. This suggests a plausible scenario for future summertime heat wave activity in California: more frequent, hotter, more extensive, and more persistent humid nighttime heat waves with a growing daytime signature.

Thus, it seems that heat waves should be investigated in a much larger geospatial context. Although most severely impacting California, the July 2006 heat wave extended across the contiguous United States as well as into adjacent parts of Canada and Mexico. At the same time, a heat wave also affected most of Europe, although it was not as severe as the great European heat wave of summer 2003. So, while heat waves in California may be unique in their regional causes and details, their observed changes may be largely emblematic in terms of heat wave activity globally. 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 2008). Together

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\(^9\) The event of 10 July–2 August 2003 was the most intense and extensive nighttime event up to that time; 3 times greater in overall magnitude than the previous record (2001). It was characterized by relatively low convection and a strong daytime expression, placing it third on the list of daytime events.

\(^{10}\) The seventh greatest one-night spatial extent of extreme heat on the 59-summer record occurred on 19 July 2006.
with our more focused regional results, this further suggests a direct and increasing link between regional heat waves and global climate change.

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