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Trends in 1970-2010 Southern California Surface Maximum Temperatures: Extremes and Heat Waves

Amanuel Tewolde Ghebreegziabher
San Jose State University

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TRENDS IN 1970-2010 SOUTHERN CALIFORNIA SURFACE MAXIMUM
TEMPERATURES: EXTREMES AND HEAT WAVES

A Thesis

Presented to

The Faculty of the Department of Meteorology and Climate Science

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Amanuel T. Ghebreegziabher

May 2013

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The Designated Thesis Committee Approves the Thesis Titled
TRENDS IN 1970-2010 SOUTHERN CALIFORNIA SURFACE MAXIMUM
TEMPERATURES: EXTREMES AND HEAT WAVES

by

Amanuel T. Ghebreegziabher

APPROVED FOR THE DEPARTMENT OF METEOROLOGY AND CLIMATE SCIENCE
SAN JOSÉ STATE UNIVERSITY

May 2013

Professor Eugene C. Cordero	Department of Meteorology and Climate Science
Professor Robert D. Bornstein	Department of Meteorology and Climate Science
Professor Jorge E. González	Department of Mechanical Engineering, CCNY/CUNY

ABSTRACT

TRENDS IN 1970-2010 SOUTHERN CALIFORNIA SURFACE MAXIMUM TEMPERATURES: EXTREMES AND HEAT WAVES

by Amanuel T. Ghebreegziabher

Daily maximum temperatures from 1970-2010 were obtained from the National Climatic Data Center (NCDC) for 28 South Coast Air Basin (SoCAB) Cooperative Network (COOP) sites. Analyses were carried out on the entire data set, as well as on the 1970-1974 and 2006-2010 sub-periods, including construction of spatial distributions and time-series trends of both summer-average and annual-maximum values and of the frequency of two and four consecutive “daytime” heat wave events. Spatial patterns of average and extreme values showed three areas consistent with climatological SoCAB flow patterns: cold coastal, warm inland low-elevation, and cool further-inland mountain top. Difference (2006-2010 minus 1970-1974) distributions of both average and extreme-value trends were consistent with the shorter period (1970-2005) study of previous study, as they showed the expected inland regional warming and a “reverse-reaction” cooling in low elevation coastal and inland areas open to increasing sea breeze flows. Annual-extreme trends generally showed cooling at sites below 600 m and warming at higher elevations. As the warming trends of the extremes were larger than those of the averages, regional warming thus impacts extremes more than averages. Spatial distributions of hot-day frequencies showed expected maximum at inland low-elevation sites. Regional warming again thus induced increases at both elevated-coastal areas, but low-elevation areas showed reverse-reaction decreases.

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1. INTRODUCTION

Mesoscale coastal flows are initiated by temperature gradients between land and ocean, which produce daytime sea breezes and nighttime land breezes. These flows, which result from differences in land versus sea thermal properties, impact diurnal-heating and cooling cycles. Sea surface temperatures (SSTs; acronyms and symbols are defined in Appendix) do not change much diurnally, mainly because of the large heat capacity of water; however, land areas heat rapidly during the day and cool rapidly at night.

Long-term observations confirm that US climates have changed rapidly since the 1970s due to global warming Intergovernmental Panel on Climate Change (IPCC, 2001). Average annual temperatures rose by almost 0.6°C during that period, and these changes were associated with even more rapidly increased extreme weather events with large regional differences in both of these effects.

a. Maximum Temperatures

A summary of 2-m summer temperature (herein synonymous with temperature) trends in coastal California during the last 100 years was given in Lebassi et al. (2009), herein referred to as L2009. Although they found a “mixed bag” of warming and cooling, the details are not summarized herein because their efforts (reviewed below) clarified the issue.

L2009 evaluated 1950-2005 San Francisco Bay Area (SFBA) and Southern California Air Basin (SoCAB) mean-summer (i.e., June to August, or JJA) maximum temperature ($T_{\max}$) values from 159 Cooperative Network (COOP) weather stations in

these two highly populated urban air basins. The results from the rapid post-1970 warming period for all sites together showed asymmetric warming, as minimum temperature ($T_{\min}$) values increased faster than $T_{\max}$ values. The spatial distribution of $T_{\max}$ values in both basins exhibited a complex pattern, with cooling in low elevation coastal areas open to marine air penetration and warming at inland areas and at higher elevation coastal sites. They thus hypothesized that the coastal cooling summer $T_{\max}$ values were due to a “reverse reaction” to global warming of inland areas, which results in increased sea breeze flow activity.

Cordero et al. (2011) evaluated 1970-2006 annual and seasonal daily $T_{\max}$ trends for 272 California COOP sites and also analyzed 1918-2006 monthly $T_{\max}$ trends for 58 California Historical Climatological Network Version 1 (HCN-1) sites. HCN sites are COOP sites that have undergone the series of filters and “corrections” described in Menne et al. (2009). About 60% of the COOP stations showed coastal cooling, but only one of the 58 HCN-1 stations (Santa Cruz) showed cooling.

The global IPCC (2001) 1976-2000 annual average temperature T_{ave} trend distribution, as well as the corresponding JJA distribution, in fact, both show a single overland California coastal-cooling data point (in addition to several similar SST points off the California coast); however, the corresponding 1901-2000 distribution does not show such a data point, as global warming throughout most of the pre-1976 period was stronger. These charts also show coastal-cooling data points over Chile, South Africa, and Australia (i.e., all west-coast areas [except Portugal] with Koëppen Csb Marine Mediterranean climates).

Coastal cooling has, in fact, also been observed in other parts of the world; for example, Falvey and Garreaud (2009) found coastal cooling along central and northern Chile. Their radiosonde data implied that the cooling was part of a larger-scale La Niña-like pattern that extended into the ocean mixed layer to depths of at least 500 m. Rouault et al. (2010) found a statistically significant negative trend in fall and winter (January to August) coastal SSTs along in the southwestern South African coast (near urban Benguela) and in winter (May to August) along the southern coast in the Port Elizabeth/Port Alfred region. They suggested that the cooling was from increased upwelling under southeasterly and easterly winds.

Lebassi et al. (2011) used the Regional Atmospheric Modeling System (RAMS) mesoscale meteorological numerical model, with a smallest horizontal grid resolution of 4 km, to reproduce the SoCAB observational $T_{\max}$ trends in L2009. Results for 1400 Local Standard Time (LST) showed a coastal cooling up of almost the exact magnitude as in the observed trend and a sea breeze acceleration of up to 1.5 m s^{-1} at the general location found in the observational study, thus supporting their original hypothesis of increased sea breeze activity.

Reanalysis of European Centre for Medium-Range Weather Forecasts (ECMWF) 40 modeled winds, as well as SSTs, by Gutiérrez et al. (2011) also showed coastal cooling since 1950 along Peru, which corresponds mainly due to intensified alongshore winds. These increases then intensify upwelling of cooler deep water during spring Gutiérrez et al. (2011).

b. Heat Waves

Heat waves are extreme weather phenomena that will increase in frequency, severity, duration, and/or areal extent due to global warming (IPCC 2001). Heat waves are defined by the National Weather Service (NWS) based on heat index (H_i) values, calculated by combining the effects of temperature and relative humidity (RH). Mid-latitude heat waves are generally associated with summer high pressure systems that produce subsidence (and hence adiabatic warming), light winds, and clear skies. They are most common in the southern US (Robinson 2001). In Southern California, offshore Santa Ana winds form when a branch of the summer Pacific High moves inland over Nevada, and coastal heat waves thus form via adiabatic warming as air descends to sea level (Gershunov and Guiguis 2012).

High temperatures increase the risk of human heat stress levels, with induced impacts on human health and mortality (Huynen et al. 2001). Persons with preexisting cardiovascular and respiratory diseases have increased risk of death associated with heat exposure, and that risk is higher for certain population groups, for example, the elderly, infants, and people of low socioeconomic status (Basu and Samet 2002); the 1996 northeast US heat wave produced 1181 excess deaths (Schuman 1972). Populations in urban environments are at increased risks for mortality from heat waves intensified by urban heat island (UHI); for example, the 1995 Chicago heat wave caused more than 700 excess deaths (Dematte et al. 1998).

Meehl and Tebaldi (2004) examined future heat waves with a global climate model, which predicted heat wave increases in the western and southern US in the second half of

the 21st century. Gershunov and Guiguis (2012) showed increasing frequency of day-time COOP heat waves during 1950-2012. They used a relative-threshold of $T_{\max}$ greater than the 95th percentile of all observations. Heat wave frequency was shown to increase in each California air basin, but their SoCAB basin was not divided into a cooling coastal area and a warming inland area, as was done in L2009.

Whereas L2009 attributed their observed decreased *summer-average* $T_{\max}$ values during 1970-2005 at coastal SoCAB COOP sites to increased sea breeze induced marine-air penetration, the current analysis calculates the analogous trends in *annual-maximum* $T_{\max}$ values and heat wave frequencies. The current study also lengthens the analysis period to 2010 for all three parameters.

2. DATA AND METHODOLOGY

Abatzoglou (2008) studied monthly-mean COOP temperature trends across California since 1970. Although they found that individual-station inhomogeneities can influence its trends, no wide-spread or geographically-coherent inhomogeneities were found. Daily and monthly $T_{\max}$ air temperatures from 1970-2010 (an extension of five years from that of L2009) were thus obtained from National Climate Data Center (NCDC) for the 28 SoCAB COOP sites (Fig. 1 and Table 1) used in L2009, as this start date is also supported by the IPCC (2001) global T_{ave} trends discussed in the introduction.

FIG. 1. Geographic distribution of all 28 SoCAB COOP sites, plus the four HCN (Green letters) and four (2006-2010) missing-data (yellow dots) sites; also shown are geographic sites (capitalized names) and topographic heights (m MSL, shading, adapted Lebassi et al. 2009).

Table 1. SoCAB COOP site: identifiers, locations, and elevations (MSL).

STATION NAME	CODE	ID	LON (°W)	LAT (°N)	MSL (m)
BEAUMONT	beau	40609	116.95	33.90	792.50
BIG BEAR LAKE	bibe	40741	116.92	34.30	2069.60
BURBANK VALLEY	burb	41194	118.35	34.20	374.90
CANOGA PARK	cano	41484	118.57	34.20	115.80
CULVER CITY	culv	42214	118.38	34.00	16.820
ELSINORE	elsi	42805	117.35	33.70	391.72
IDYLLWILD FIRE DEPT	idyl	44211	116.72	33.80	1642.87
LAGUNA BEACH	lagu	44647	117.75	33.50	10.70
LAKE ARROWHEAD	larr	44671	117.18	34.20	1586.50
LONG BEACH	long	45082	118.17	33.80	9.10
LOS ANGELES WSO ARPT	losa	45114	118.38	33.90	30.50
MONTEBELLO	mont	45790	118.10	34.00	73.00
MOUNT WILSON	mtwi	46006	118.07	34.20	1740.40
NEWPORT BEACH HARBOR	newp	46175	117.87	33.60	3.00
PASADENA	pasa	46719	118.13	34.10	263.30
POMONA CAL POLY	pomo	47050	117.85	34.10	731.50
REDLANDS	redl	47306	117.18	34.10	401.70
RIVERSIDE CITRUS	rvrc	47473	117.33	34.00	734.60
RIVERSIDE FIRE STN 3	rvrf	47470	117.40	34.00	734.60

SANTA ANA FIRE STN	sana	47888	117.87	33.80	213.40
SAN BERNARDINO	sanb	47723	117.27	34.10	342.90
SAN GABRIEL FIRE DEPT	sgfd	47785	118.10	34.10	137.20
SANTA MONICA PIER	smon	47953	118.50	34.00	4.30
SUN CITY	sunc	48655	117.20	33.70	432.80
TORRANCE	torr	48973	118.32	33.80	33.50
TUSTIN IRVINE RANCH	tust	49087	117.78	33.70	36.00
UCLA	ucla	49150	118.45	34.10	131.10
YORBA LINDA	yorb	49847	117.82	33.90	356.60

Although the SoCAB trend analyses of Cordero et al. (2011) include both the COOP and HCN-1 data at each site, all but one COOP coastal cooling sites in L2009 were converted to warming in their study. Discussions with the lead NCDC-author of Menne et al. (2009) indicated that the series of sequential corrections applied to the COOP data by NCDC to produce the HCN-1 and 2 data sets resulted in conversions of many of the original coastal cooling sites into warming, for reasons not totally clear (Ghebreegziabher et al. 2012). HCN data were thus not included in the current analysis, but discussions between SJSU and NCDC about these sequential corrections are ongoing.

Quality assurance (QA) procedures used by L2009 had previously eliminated incomplete data sets during the period of 1970-2005 as follows: (a) months with > 5 days of missing data, (b) years with < 2 months of data, and (c) sites with > 15 years of missing data. Note that four of the 28 L2009 sites (Fig. 1) had no data for 2006-2010,

and thus could not be used in some of the extended-period analyses. Daily $T_{\max}$ values at each site were used to produce summer-averaged (JJA) at each site for each year. To compare the 1970-2005 JJA SoCAB $T_{\max}$ trends in L2009 to the extended (1970-2010) trends of the current study, simple least-squares linear regression-slopes (b) and correlation-coefficients (r) were calculated for both periods for each of the 24 sites with data from 2006-2010, for all of the 24 sites together, as well for cooling-sites together and warming-sites together.

Although L2009 had used JJA $T_{\max}$ values, the current study mostly uses data from only the first two months, as more detailed analyses (not shown herein) showed a lack of either coastal cooling or warming during August. In addition, although the previous study had presented spatial distributions of average-summer $T_{\max}$ *trends*, it did not show such distributions of the corresponding distributions of the *actual* average-summer $T_{\max}$ values. Summer-average (only for June and July) $T_{\max}$ values for five-year *early* (1970-1974) and *current* (2006-2010) periods were thus determined, as was as the *change* in the averages from the early to the current period (and not the *trend* over the entire 40 year period) at each site.

L2009 showed if trends were started in 1950 (and not in 1970, as they did and as done herein), $T_{\max}$ cooling-slopes would be altered, as slopes were effectively zero from 1950-1970. In addition, actual end-point values carry no more weight than interior points, and do not thus significantly affect slope-values, unless they lie outside the normal range of interior values (which they do not in the current 1970-2010 cases).

The following statistical analyses (from Wigely et al. 2006) were performed separately on the cooling and warming-groups: correlation of yearly JJ warming and cooling rates (r_{wc}); linear-trend slope (b); mean square error (MSE); standard error (SE); variance (SE^2); and two-tail p value, determined from b/SE values in the Standard Normal table, in which p values decrease with increasing b/SE ratios. As L2009 stated that California COOP data have no significant autocorrelations, we also do not consider this effect. The following equations were used:

$$MSE = \sum e^2 / (n-2) \quad (1)$$

$$(SE)^2 = MSE / [n(n^2-1)/12] \quad (2)$$

A p value is defined as unity minus level-of-significance; hence low p values are more significant. The following arbitrary definitions are used herein, for p : ≤ 0.01 , extremely significant; > 0.01 to ≤ 0.05 , significant; > 0.05 to ≤ 0.10 , somewhat significant; and > 0.10 , less significant.

Isopleth-plots of the site-specific *early*-period, *current*-period, and *change* in T_{max} values were constructed. These plots can account for the known strong topographic-induced distortions of surface flows in coastal California, and thus subjective analyses were sometimes necessary (as was done in L2009), as interpolation-software cannot fully account for topographic distortions of most meteorological fields; no station values were “violated” in their construction.

Linear-trend for the 1970-2010 June-July average T_{max} values were calculated separately for each site, combined *coastal-cooling* stations (i.e., those with negative trends), and combined *inland-warming* stations (i.e., with positive trends). To calculate

these combined-station trends, the mean value for each station over the period was determined, then the time series of deviation from this station mean for each year was determined, and finally the deviations were combined for the cooling and warming stations separately. Similar isopleth and trend analyses were then carried out for the *annual-extreme* monthly-average 1970-2010 $T_{\max}$ value at each site, but spatial plots are now of trends and not differences, as they were in the analyses for *summer-average* $T_{\max}$ values.

Similar analyses were carried out for trends in annual-extreme monthly values, where each value is from any site from the combined warming and cooling area, and then from the warming and cooling areas separately. The single-value for any year is thus from the station with the highest value, always from June to September in each of the 40 years of the study. These trends provide interesting information, even though data points are not at the same station each year.

The locations of the isopleth-boundaries (between warming and cooling areas, shown below in the Results section) generally agree with the known SoCAB flow patterns, even though the *exact* inland extent of the cooling areas could not be determined *a priori*. To further elucidate the relationship between the boundary between the cooling and warming regions, an elevation-view plot of station $T_{\max}$ trend values, as a function of inland distance and station elevation (MSL) was constructed, with these values extracted from the NCDC station inventory (Table 1).

Table 2. NWS heat wave definitions, as well as modifications and extensions (in italics) of Robinson (2001), where 80 and 105°F equal 26.7 and 40.6°C, respectively, and a difference of 10°F equals a difference of 5.6°C.

<p>Heat wave. A period at least 48 h during which, neither overnight low nor daytime H_i values fall below the thresholds of 80 and 105°F, respectively. <i>Where more than 1% of both high and low H_i observations exceed these thresholds, the 1% values are used as the thresholds.</i></p> <p>Intense heat wave. A period of at least 36 h during which, both daytime H_i values exceed the 105°F threshold by more than 10°F and overnight low values exceed the 80°F threshold.</p> <p>Hot spell. <i>A period of at least 48 h, during which both overnight low and day-time H_i values exceed those observed 1% of the time, but during which conditions fail to meet the criteria for heat waves. When the 1% values exceed the criteria, a hot spell is defined as an event with values above the criteria, but below the 1% values.</i></p> <p>Warm spell. <i>A period of at least 48 h during which, daytime H_i values exceed 80°F, and both the overnight low and daytime H_i values exceed those observed 2% of the time, but where conditions fail to meet the criteria for hot spells. When 2% of H_i values exceed both criteria, they are the minima for warm spells, but the 2% values are the minima for hot spells.</i></p> <p>Extended events. Occur when required conditions persist for 96 h or more.</p>
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NWS definitions of heat waves (for operational forecasts of watches and warnings) are based on specific absolute H_i value criteria over a specific consecutive day

and night-time period (regardless of starting time), and thus do not involve regional-differences in mean values. These criteria, however, are insufficient in climates in which these thresholds are frequently exceeded, and in cooler climates with extreme events, which although not life threatening, create socially disruptive hot spells (Robinson 2001). His study thus expanded the NWS criteria to include “relative-value” criteria (which thus allow for regional-differences) and to newly define associated events (Table 2). Other relative-value criteria exist; for example, the World Meteorological Organization (WMO) heat wave criterion that daily $T_{\max}$ values for five consecutive-days must be greater than those during the “normal-period” of 1961–1990 by at least 5°C (or 9°F). As NWS heat wave criteria are traditionally given in °F, the current discussion does not convert values to °C.

The “simple” NWS H_i (°F) value estimates human heat stress based on ambient temperature T (°F) and relative humidity RH (%), according to the following (from Rothfus 1990)

$$H_i = c_1 + c_2 \cdot T + c_3 \cdot RH + c_4 \cdot T \cdot RH + c_5 \cdot T^2 + c_6 \cdot RH^2 + c_7 \cdot T^2 \cdot RH + c_8 \cdot T \cdot RH^2 + c_9 \cdot T^2 \cdot RH^2,$$

where numerical values for constants c_{1-9} are given in the Appendix. H_i values produced from this equation, as a function of T and RH , are shown in Table 3 (from nws.noaa.gov/os/heat/images/heatindex.png). The dark-yellow shaded zone (values above 104°F) and beyond shows combinations that can cause increasingly severe heat disorders with continued exposure. More complex H_i formulations exist, in which meteorological variables in addition to T and RH are used to determine H_i values (see Kalkstein et al. 1996); for example, cloud free sunny skies increase human heat loads (Kalkstein and

Davis 1989), although high wind speeds remove body moisture that increases human heat loads (Steadman 1979). This study, however, uses only the simple NWS H_i definition.

Table 3. Heat Index H_i ($^{\circ}\text{F}$) as a function of T ($^{\circ}\text{F}$) and RH (%), where the black box is discussed in text (from a NOAA website).

RH values are not included in COOP data sets, but the link (ggweather.com/ccd/avgrh.htm) gives the average summer Los Angeles County RH at 1400 LST as just above 50%. The black box in Table 3 gives an interpolated H_i value of about 105°F (i.e., NWS day-time heat wave criteria) for an RH of about 50% and a T of 95°F . As the current analysis does not consider nighttime COOP $T_{\min}$ values, the following daytime-only criteria will be used herein for heat waves and extended heat waves (with “daytime” as a preceding modifying adjective): daytime $T_{\max}$ values $\geq 95^{\circ}\text{F}$ for two and four consecutive daytime periods, respectively. Spatial distributions of SoCAB two and four day “daytime” heat wave frequencies during 1970-1974 and 2006-2010, as well as their differences, were thus evaluated.

The current study does not correlate $T_{\max}$ with other parameters (e.g., precipitation, SSTs, Pacific Decadal Oscillation [PDO], or cloudiness), because SoCAB summers have no precipitation and L2009 and LaDochy et al. (2007) showed that only SoCAB $T_{\min}$ (and not $T_{\max}$) is correlated with PDO values. Although SST and cloud cover are important parameters for coastal-cooling trends, they are both not included in COOP observations and their observations by satellite are only available for periods shorter than that of the current study.

3. RESULTS

a. SoCAB Flow Pattern Climatology

The following summary of California summer climate appeared in L2009. It is dominated by oceanic and atmospheric General Circulation features, such as the continental thermal low, coastal ocean current system, and Pacific High. During spring and summer, the High generates alongshore wind stresses on the ocean surface, which results in upwelling cold water to the surface (Hickey 1979; Bakun 1990; Herbert and Schuffert 2001; McGregor et al. 2007). Gilliland (1980) suggested climate variability can modify these features; for example, Simpson (1983) showed upwelling diminishes and SSTs increase along California during El Niño years.

These features create strong coastal gradients of pressure, temperature, and moisture, as well as a nearly continuous summer daytime onshore cool moist marine air-flow along the coast (Williams and DeMandel 1966; Giorgis 1983; Miller and Schlegel 2006). An elevated inversion layer (a 250 m layer) is also created by subsidence from the High; the inversion caps a shallow marine boundary layer (MBL). Seaman et al. (1995) showed that the inversion base is lowest near the coast, where the MBL is cooled by upwelling water.

SoCAB flow-patterns are dominated by the same General Circulation features. The Basin is a plain with mountain ranges, which results in a widespread daytime onshore-directed marine-air intrusion. McElroy and Smith (1991) noted that the inland movement of the basin MBL was similar with that of a cold front. L2009 stated that the onshore marine-flow splits into the San Fernando Valley and to Chino, where it splits

towards the San Gabriel and San Bernardino Mountains and towards the Lakeview and Estelle Mountains. Boucouvala et al. (2003) also noted upper level easterly-flows, associated with mesoscale high pressure areas north of the gap between the San Gabriel and San Bernardino Mountains, sometimes prevent the marine-flow from exiting the basin.

FIG. 2. Average June-July $T_{\max}$ ($^{\circ}\text{C}$) values for (a) 1970-1974 and (b) 2006-2010; green lines demarcate sub-regions.

b. Summer-Average $T_{\max}$ - Values and Trends

L2009 showed only summer $T_{\max}$ *trend* distributions, and not actual $T_{\max}$ distributions, in the SoCAB air basin, and thus Fig. 2 shows both the 1970-1974 and 2006-2010 distributions of average June-July SoCAB $T_{\max}$ values. The distribution during the earlier period shows the expected three sub-areas, with a subjectively-determined 29°C boundary temperature between two adjacent sub-areas and with the following temperature ranges: cold coastal, $21\text{-}29^{\circ}\text{C}$; inland low-elevation warm-area, $29\text{-}34^{\circ}\text{C}$; and cool (due to elevation) further inland mountain-top region, $26\text{-}29^{\circ}\text{C}$.

FIG. 3. Average June-July $T_{\max}$ ($^{\circ}\text{C}$) difference (2006-2010 minus 1970-1974) values (increment of 0.5°C); blue and red colors indicate cooling and warming isopleths and station locations, respectively.

The pattern is similar for the latter period, except that the subjectively-determined boundary-temperature is now lower at 28°C . Changes from the earlier to the later period are best seen in the differences shown in Fig. 3. Differences (2006-2010 minus 1970-1974) between the two average June-July $T_{\max}$ distributions (Fig. 2) shows that over 36 years, values have generally increased (due to regional warming) in three sub-areas (again defined by the early-period 29°C boundary) of Fig. 2: higher elevation coastal area, core inland low-elevation warm area, and far-inland mountain-top area. Values have cooled, however, in the low elevation “reverse-cooling” coastal and inland areas open to sea breeze flows. This *pattern* is similar to the 1970-2005 *trends* in L2009 (Fig. 4), with both warming and cooling areas comparably located.

FIG. 4. June to August 1970-2005 $T_{\max}$ ($^{\circ}\text{C}$) trends ($^{\circ}\text{C decade}^{-1}$, increment of 0.2°C); where arrows indicate predominant summer daytime flow-patterns; isopleth color is as in Fig. 3; dashed isopleths are extrapolated; and statistical p values of ≤ 0.01 , 0.01 to ≤ 0.05 , 0.05 to ≤ 0.1 , and > 0.1 are represented, respectively, by full-colored, half-colored, plus sign, and open circles (from Lebassi et al. 2009).

Accurate comparison of the new JJ 1970-2010 $T_{\max}$ differences ($^{\circ}\text{C}$, Fig. 3) with the L2009 JJA 1970-2005 trends ($^{\circ}\text{C decade}^{-1}$, Fig. 4) at each of the 24 SoCAB sites requires that the former values be divided by 3.5 and be extended to the JJA period. Comparison (Fig. 5) thus shows an overall high correlation ($r = 0.9$) between the 35 and 40-year values. It also shows that, of the nine shorter-period warming sites (all to right of dashed vertical line), a majority of seven warm at a slightly higher rate in the longer period (data points also above 1:1 dashed line). Of the remaining two, one warms at only a slightly lower rate in the longer period (data point also below 1:1 dashed line, but in upper right quadrant) and one now cools (data point also in lower right quadrant). Of the 15 shorter-period “reverse-reaction” cooling sites (all to left of dashed vertical line), eight cool at a higher rate (data points also below 1:1 dashed line). Of the remaining seven, three cool at a slightly lower rate in the longer period (data points also

above 1:1 dashed line, and in lower left quadrant) and four now warm during this period (data points also in upper left quadrant).

FIG. 5. Comparison of 1970-2005 vs. 1970-2010 JJA- $T_{\max}$ trends ($^{\circ}\text{C decade}^{-1}$) at each of 24 sites; also shown are 1:1 (dashed) and trend (red) lines.

The combined average JJ $T_{\max}$ trend-line during 1970-2010 for all 24 SoCAB sites (Fig. 6a) shows a small decrease of $-0.065^{\circ}\text{C decade}^{-1}$. The seven warming sites (Fig. 6b) show a larger combined average increase of $0.15^{\circ}\text{C decade}^{-1}$, with a large p value of 0.32 (Table 4), which represents a 32% probability that this trend occurred by chance. The 17 coastal cooling sites show an even larger decrease of $-0.28^{\circ}\text{C decade}^{-1}$, and because this is larger than the trend at the warming sites, the trend for all sites (Fig. 6a) shows a slight cooling. The cooling sites also show a smaller p value of 0.06, which represents only a 6% probability that this trend occurred by chance. Even though the

cooling and warming-site SEs are almost the same, the larger absolute magnitude of the cooling slope b makes its p value more significant.

FIG. 6. Average June-July 1970-2010 $T_{\max}$ trend-lines ($^{\circ}\text{C decade}^{-1}$) for: (a) combined warming and cooling area and (b) warming (red) and cooling (blue) areas.

FIG. 7. Annual extreme monthly-average $T_{\max}$ values at each site, where the value at each site is determined during any month during 1970-2010 ($^{\circ}\text{C}$, increment of 1°C); green line demarcates sub-regions.

Table 4. Statistical significance for JJ-average $T_{\max}$ trends for 1970-2010, where all symbols are defined in Appendix.

	Slope	Mean Sq. Error	Variance	Standard Error		
	b (K yr^{-1})	MSE ($\text{K}^2 \text{ yr}^{-2}$)	(SE) 2 ($\text{K}^2 \text{ yr}^{-2}$)	SE (K yr^{-1})	b/SE	<i>p</i> value
Warming	0.015	1.28	0.00022	0.015	1.00	0.32
Cooling	-0.028	1.32	0.00023	0.015	-1.85	0.06

The L2009 JJA warming and cooling trends (for all their SFBA and SoCAB sites combined) were 0.32 and $-0.30^{\circ}\text{C decade}^{-1}$ (i.e., twice the warming and about the same cooling as the current JJ SoCAB rates). Elimination of August (slight warming) values in the current study implies that its JJ coastal-cooling trend should be even greater than what

it is now, although its corresponding inland-warming rate should have been reduced from its current value, but inclusion of SFBA data in L2009 invalidates such simple comparisons without additional reanalysis. In summary, the above trends are consistent with the SoCAB results of L2009; moderate inland warming rates of mean summer $T_{\max}$ values produces a faster coastal-cooling of these values.

FIG. 8. Same as Fig. 7, but for annual extreme monthly-average $T_{\max}$ trends ($^{\circ}\text{C decade}^{-1}$, increment of $0.2^{\circ}\text{C decade}^{-1}$), where the annual value is determined from the value at the extreme site.

c. *Extreme $T_{\max}$ - Values and Trends*

As many climate impacts depend on annual *extreme monthly-average $T_{\max}$ values*, and not on just the *average JJ $T_{\max}$* values of Fig. 2, the distribution of the highest $T_{\max}$ (i.e., heat wave) value at each site (at any month) during the 1970-2010 period is shown in Fig. 7. The three sub-areas of Fig. 2 are again seen, but with an obviously higher (again subjectively-determined) boundary-temperature of 34°C and with the following new ranges: cold coastal, $27\text{-}34^{\circ}\text{C}$; inland low-elevation warm-area, $34\text{-}40^{\circ}\text{C}$; and cool

(due to elevation) further inland mountain-top region, 28-34°C. All three heat wave upper-bound $T_{\max}$ values are thus each higher (by 5-7°C) than the corresponding values of Fig. 2, although the three lower-bound values are higher by only 1-6°C.

The *trend* in annual extreme $T_{\max}$ values at each site (again at any month) over 1970-2010 (Fig. 8) shows: decreases up to $-0.8^{\circ}\text{C decade}^{-1}$ in the low-elevation coastal cooling-area, increases up to $0.4^{\circ}\text{C decade}^{-1}$ in the higher-elevation coastal warming-area, and (larger) increases up to $0.6^{\circ}\text{C decade}^{-1}$ in the high-elevation mountain areas. Of the 16 warming sites, four had $p \leq 0.01$ (i.e., highest significance level), one was > 0.01 to ≤ 0.05 , one was > 0.05 to ≤ 0.10 , and ten were > 0.10 (i.e., lowest significance level). Of the 12 cooling sites, the number of sites were four, three, one, and four, respectively (i.e., a higher fraction of sites at the two most significant levels).

As compared to the JJA-averaged $T_{\max}$ trends of L2009 (Fig. 3), current maxima in Fig. 8 are equal ($0.4^{\circ}\text{C decade}^{-1}$) in the higher-elevation coastal-warming area, but larger in the coastal cooling (-0.8 vs. $-0.6^{\circ}\text{C decade}^{-1}$) and mountain warming (0.6 vs. $0.4^{\circ}\text{C decade}^{-1}$) areas, implying that regional warming effects extreme peak temperatures (and thus their reverse-reaction cooling values) even more than it effects average values.

The inland-mountain warming area of Fig. 3 is split in Fig.8 into eastern and western parts by a deeper-penetration of marine-air into the mountain pass on the northern SoCAB edge. This extended penetration is expected, as the heat wave related warmer-inland extreme $T_{\max}$ values of Fig. 7 thus trigger a more intense coastal-cooling reverse-reaction. The inland low-elevation warming-core of Fig. 3 is now, however, combined with the western inland mountain-warming area, due to the just described

increased northward marine flow, and to its thus decreased flow around the Lakeview-Estelle higher elevation area of Fig. 1.

FIG. 9. Annual extreme monthly average 1970-2010 T_{max} trend-lines ($^{\circ}\text{C decade}^{-1}$), where (a) annual values are determined from the extreme site and where (b) deviations are averages for the warming (red) and cooling (blue) sub-areas.

Table 5. Same as Table 4, but for annual-extreme $T_{\max}$ trends, where the annual value is determined from the value at the extreme site.

	Slope	Mean Sq. Error	Variance	Standard Error		
	b (K yr ⁻¹)	MSE (K ⁻² yr ⁻²)	(SE) ² (K ⁻² yr ⁻²)	SE (K yr ⁻¹)	b/SE	<i>p</i> value
Warming	0.027	38.8	0.00685	0.080	0.21	0.83
Cooling	-0.104	4.70	0.00082	0.030	-3.64	0.001

The 1970-2010 extreme monthly-averaged $T_{\max}$ trend-line (Fig. 9a) for all (combined warming and cooling) sites, with the value for a given year determined from the extreme maximum monthly-average at any site, shows a cooling of $-0.38^{\circ}\text{C decade}^{-1}$. The 16 warming sites (Fig. 9b) show an increase of $0.27^{\circ}\text{C decade}^{-1}$, with a large *p* value of 0.83 (Table 5) (i.e., 83% probability that this trend occurred by chance). The 12 coastal cooling sites show an even larger decrease of $-1.04^{\circ}\text{C decade}^{-1}$, and because its absolute magnitude is larger than the warming trend, the overall trend (Fig. 9a) showed cooling. The cooling sites thus show a *p* value of 0.001, a low probability that this trend occurred by chance. Even though not much difference exists between the SE values at the cooling and warming-site (Table 5), the larger absolute magnitude of the cooling slope *b* is what makes its *p* value more significant. The reverse-reaction cooling-trend may be larger than the regional warming (forcing) trend because the warming sites are not far enough inland to be completely free of marine influences.

The corresponding $T_{\max}$ trend-line, but with the value for a given year determined from the average (not the extreme) at all sites, shows cooling for all (combined warming

and cooling) sites (Fig. 10a) at almost the same rate ($-0.35^{\circ}\text{C decade}^{-1}$) as seen in Fig. 9a ($-0.40^{\circ}\text{C decade}^{-1}$). The 16 warming sites alone (Fig. 10b), however, show a much smaller increase (almost $0.001^{\circ}\text{C decade}^{-1}$), with a high (79%) probability (Table 6) that this trend occurred by chance; this trend is also smaller than the warming trend ($0.27^{\circ}\text{C decade}^{-1}$) in Fig. 9b. Both these results are expected, as Fig. 10 is based on average values and not the maximum values of Fig. 9.

FIG. 10. Same as Fig. 9, but for the annual value determined from the average of the values at all sites. '23

Table 6. Same as Table 5, but for annual-extreme $T_{\max}$ trends, with annual value determined from the average of the values at all sites.

	Slope	Mean Sq. Error	Variance	Standard Error		
	B (K yr ⁻¹)	MSE (K ⁻² yr ⁻²)	(SE) ² (K ⁻² yr ⁻²)	SE (K yr ⁻¹)	b/SE	<i>p</i> value
Warming	0.001	1.18	0.00021	0.014	0.27	0.79
Cooling	-0.70	1.54	0.00027	0.016	-4.30	0.001

The 12 coastal-cooling sites had a decrease of $-0.70^{\circ}\text{C decade}^{-1}$, a 0.001% probability that it occurred by chance. Because the absolute magnitude of this value (-0.70°C) is larger than the corresponding warming trend (Fig. 10b), thus the overall trend showed cooling (-0.35°C). Also, the trend in Fig. 10b less than the corresponding cooling trend in Fig. 9b, again as expected the trend is based on average and not maximum values. Even though the cooling and warming-site SEs are not much different, the larger absolute magnitude of the cooling slope *b* again makes its *p* value more significant.

Figure 11a shows the 1970-2010 annual-extreme $T_{\max}$ trends of Fig. 8 as a function of station perpendicular-distance to the coast (all 28 sites are within 110 km inland) and MSL-elevation, along with the *p* values for each site. The isopleth analysis of these trends (Fig. 11b) showed all but one marine-influenced cooling site at elevations < 600 m. The one outlier, Lake Arrowhead (larr in Fig. 1), is a 90 km inland higher-elevation (1600 m) valley site. Its daytime cooling could arise from lake-breeze effects from nearby Lake Arrowhead. All sites > 600 m showed warming, with elevations that

generally increase with inland distance. Note that the 600 m maximum station-elevation for coastal-cooling is the same coastal-cooling depth found in the SoCAB modeling study of Lebassi et al. (2011).

FIG. 11. Values of Fig. 8 $T_{\max}$ trends ($^{\circ}\text{C decade}^{-1}$) as a function of perpendicular inland-distance and station-elevation (m, MSL), where blue and red colors indicate cooling and warming stations, respectively, and where (a) shows significance levels as in Fig.4 and (b) gives isopleth distribution.

FIG. 12. Spatial distribution of 1970-1974 (days year⁻¹, increment varies) days with daily $T_{\max} \geq 85, 90$, and 95°F ; green line demarcates sub-regions.

FIG. 13. Same as Fig. 12, but for 2006-2010 and with different increments.

d. Heat Waves

The spatial-distribution (Fig. 12) of the number of 1970-1974 days with high daily- $T_{\max}$ values shows both (i.e., coastal and inland-mountain) cold areas with < 10 days year⁻¹ above 85°F and only < 5 days year⁻¹ above 95°F. Inland low-elevation warm-areas, of course, have more hot days (i.e., up to 130 days year⁻¹ above 85°F and up to 80 days year⁻¹ above 95°F).

FIG. 14. Spatial-distribution of Fig. 13 minus Fig. 12 values (days year⁻¹, but with different increments).

The corresponding 2006-2010 distribution (Fig. 13) shows similar patterns, with the changes from the earlier period (Fig. 12) best seen in Fig. 14, the difference (2006-2010 minus 1970-1974) values. The inland low elevated area shows a moderate number of regional warming induced increases (i.e., up to 18, 8, and 4 days year⁻¹, respectively, for the 85, 90, and 95°F thresholds), although the elevated coastal area shows smaller increases. The western inland mountain-area shows the largest increases (i.e., to 28, 20, and 12 days year⁻¹, respectively), but the eastern mountain area unexpectedly has either small increases or decreases (i.e., up to only 4 days year⁻¹). Coastal low-elevation areas, however, show large reverse-reaction decreases (i.e., up to -32, -24, and -16 days year⁻¹,

respectively, for the three thresholds), with maximum decreases (again) somewhat inland, as sea breeze effects were always frequently at the coast.

FIG. 15. Spatial distribution of exactly two-day long daytime heat wave events (days 5-years⁻¹, increment varies) with $T_{\max} \geq 95^{\circ}\text{F}$ in 1970-1974 (top-left) and 2006-2010 (top-right), and 2006-2010 minus 1970-1974 values (lower); color code same as in Fig. 3.

FIG. 16. Same as in Fig. 15, but for exactly four-day long daytime heat wave events, and with different increments.

The spatial distribution of the number of “daytime” heat waves of exactly two successive-days in duration during 1970-1974 with $T_{\max}$ values $\geq 95^{\circ}\text{F}$ at a given site (Fig. 15) shows an expected maximum (22 events per five years) at inland low elevation sites, with none at both low-elevation coastal and inland high-elevation mountain areas. The corresponding 2006-2010 distribution shows a similar pattern, with changes best seen in the difference (2006-2010 minus 1970-1974) plot, which shows the elevated coastal area with a regional warming induced increase (up to four events per five years). Although the western inland mountain-area shows no change, the eastern mountain area shows a decrease of three events per five-years. Coastal low-elevation and inland low-

elevation areas, however, show large decreases (up to eleven and five events per five-years, respectively), with maximum decreases (again) somewhat inland. These coastal decreases are again a reverse-reaction to inland regional warming induced more-frequent daytime heat waves.

The corresponding spatial distributions of “daytime” heat waves of exactly four successive days in duration during 1970-1974 at a given site (Fig. 16) shows that these frequencies are all smaller (as expected) than those of the two-day events. The four day events again show an expected maximum (six events per five years) at inland low elevation sites, with none again found at both low-elevation coastal and inland high-elevation mountain areas. The corresponding 2006-2010 distribution also shows a similar pattern, with changes also best seen in the difference (2006-2010 minus 1970-1974) plot, which again shows the elevated coastal area with a regional warming induced increase (up to two events per five years).

The western and eastern inland mountain-areas again show no change. Coastal low-elevation and inland low-elevation areas, however, show reverse-reaction decreases (up to three and five events per five-years, respectively), with maximum decreases (again) somewhat inland.

4. CONCLUSION

Daily $T_{\max}$ 2-m air temperatures from 1970-2010 were obtained from NCDC for the 28 South Coast Air Basin (SoCAB) COOP sites in L2009. The 1970-2010 period has been shown by IPCC (2001) global T_{ave} trends as the current global warming period, and the period is also a five-year extension from that in L2009. Analysis of HCN-1 and 2 data sets showed that NCDC-corrections converted erroneously all but one of the seven original L2009 coastal-cooling sites into warming sites; thus HCN data were not included in the current analysis.

Daily $T_{\max}$ values at each site were used to produce summer (JJA)-averaged values at each site for each year. Most analyses (except for comparisons with L2009 results) in the current study use data from only the first two months, as analysis showed neither significant cooling nor warming during August. In addition, although L2009 presented spatial distributions of average-summer $T_{\max}$ *trends*, they did not show distributions of actual average-summer $T_{\max}$ *values*, and so such an analysis was carried out. An elevation view-plot of station $T_{\max}$ trend values, as a function of inland distance and station elevation (MSL), was also constructed.

Similar analyses were then carried out for the SoCAB *annual maximum* $T_{\max}$ values from 1970-2010 at the SoCAB sites, in which time-series slopes were evaluated (separately for the cooling and warming-groups) for the trends in *basin-wide* extreme $T_{\max}$ values (regardless of the site at which it occurred in a given year) and for *basin-wide average* (at all sites within each group) $T_{\max}$ values.

NWS heat wave definitions are based on specific absolute H_i value criteria over specific consecutive day and night-time periods, with its “simple” H_i used to estimate human heat stress levels from ambient T and RH values. More complex H_i formulations exist, in which meteorological variables in addition to T and RH are used to determine H_i values, but this study only used the simple NWS definition.

RH values are not included in COOP data sets, but the average summer SoCAB 1400 LST RH is just above 50%. As an interpolated H_i value of about 105°F (i.e., NWS daytime heat wave criteria) results from a RH of about 50% and a T of 95°F, that latter T value was thus used in the current analysis to defined “daytime” heat waves. In fact, as a uniform RH was applied to all sites, plots of 105°F H_i heat wave days would have the same pattern as would plots of 95°F T_{max} days; that is, the number of days at each site would not change from one plot to another.

As the current analysis also does not consider nighttime COOP T_{min} values, the following daytime-only criteria was used herein for heat waves and extended heat waves: daytime T_{max} values $\geq 95^\circ\text{F}$ for two and four consecutive-daytime periods, respectively. Spatial distributions of SoCAB two and four day “daytime” heat wave frequencies during 1970-74 and 2006-10, as well as their differences, were thus evaluated.

Results showed that the 1970-1974 and 2006-2010 computed spatial-distribution patterns of JJ-average T_{max} values were both consistent with climatological SoCAB summer flow patterns, as they showed three areas (i.e., cold coastal, warm inland low-elevation, and cool [due to elevation] further inland mountain top). The difference (2006-2010 minus 1970-1974) distribution was also consistent with that of (the five-year

shorter period) L2009, as it showed generally increased $T_{\max}$ values over the 36 years (due to regional warming) in three sub-areas: higher-elevation coastal, inland low-elevation warm, and far-inland mountain-top. Values again cooled, however, in the low elevation “reverse-cooling” (coastal and inland) areas of L2009 open to sea breeze flows.

Comparison of these new JJA-averaged 1970-2010 $T_{\max}$ trends with the L2009 1970-2005 $T_{\max}$ trends at each of the 24 SoCAB sites showed an overall high correlation of 0.9 between the 35 and 40-year values. Of the nine L2009 warming sites, most (i.e., seven warmed) at a slightly higher rate over the longer period, although of the 15 L2009 “reverse-reaction” cooling sites, most (i.e., eight) cooled at a higher rate. These faster warming rates imply that over the 2006-2010 period, regional SoCAB inland-warming has accelerated, and thus the reverse-reaction coastal-cooling has also accelerated. The combined average JJ $T_{\max}$ trend-line during 1970-2010 for all seven SoCAB inland-warming sites showed an average increase of $0.15^{\circ}\text{C decade}^{-1}$, although the 17 coastal-cooling sites showed a larger (and thus dominant) decrease of $-0.28^{\circ}\text{C decade}^{-1}$, which produced (an overall) small decrease of $-0.065^{\circ}\text{C decade}^{-1}$.

The distribution of the *extreme* monthly-average $T_{\max}$ values at each site (at any month) during the 1970-2010 periods showed again the same three areas in the JJ-average $T_{\max}$ distribution. All upper-bound $T_{\max}$ values in those areas were thus also higher (by $5\text{-}7^{\circ}\text{C}$), although all three lower-bounds were only higher by $1\text{-}6^{\circ}\text{C}$. The corresponding extreme $T_{\max}$ trends showed cooling in the low-elevation coastal areas, warming in the higher-elevation coastal areas, and (faster) warming in the high-elevation mountain areas.

This distribution also showed the inland-mountain warming area split into eastern and western parts by the deeper-penetration of marine-air through the mountain pass on the northern SoCAB edge. This extended penetration is expected, as inland extreme $T_{\max}$ values trigger more intense coastal-cooling reverse-reaction flows. This also shows that regional warming impacts extreme $T_{\max}$ values (and thus their reverse-reaction cooling values) even more than it impacts summer-average $T_{\max}$ values.

The average slope of these extreme $T_{\max}$ values for all 16 warming sites showed an increase of $0.27^{\circ}\text{C decade}^{-1}$, although the 12 coastal-cooling sites showed a larger (and thus dominant) decrease of $-1.04^{\circ}\text{C decade}^{-1}$; the overall trend was $-0.38^{\circ}\text{C decade}^{-1}$. The corresponding trend-line for the annual- $T_{\max}$ trend-line for all warming sites showed a small increase of almost $0.00^{\circ}\text{C decade}^{-1}$, although the 12 coastal-cooling sites showed a larger (and thus again dominant) decrease of $-0.70^{\circ}\text{C decade}^{-1}$; the overall trend was $-0.35^{\circ}\text{C decade}^{-1}$. As expected each of the three basin-average- $T_{\max}$ trends are thus smaller than the corresponding basin-maximum trends.

Annual 1970-2010 basin-average $T_{\max}$ trends of as a function of both inland station distance and MSL-elevation generally showed marine-influenced cooling at sites with elevations < 600 m. Sites with elevations > 600 m generally showed warming, with elevations that generally increased with inland distance. This maximum station-elevation depth for coastal-cooling agrees well with the corresponding value found in a SoCAB modeling study.

The spatial-distribution of the frequency of 1970-1974 days with high daily- $T_{\max}$ values above 95°F showed a maximum at the inland low-elevation areas (up to 80 days

per year) and equal maxima at both the coastal and inland-mountain areas (up to 15 days per year); the corresponding 2006-2010 distribution showed a similar pattern. The largest regional warming induced increases (over the 35 years) occurred at inland areas (up to an additional 12 days per year), although coastal areas showed a similar-magnitude reverse-reaction decreases (up to 16 days per year), again somewhat inland.

The spatial distribution of the number of “daytime” heat waves, herein defined as exactly two successive-days with $T_{\max}$ values $\geq 95^{\circ}\text{F}$, at a given site during 1970-1974 showed an expected maximum of 22 events per five-years at inland low-elevation sites, with none at both low-elevation coastal and inland high-elevation mountain areas. The corresponding 2006-2010 distribution again showed a similar pattern, with the largest regional warming induced increases (over the 35 years) at both the elevated-coastal area and a high-elevation inland area (up to an additional 4 events per 5-years). Low-elevation areas again showed large decreases, with maximum decreases (up to an additional -11 events per five-years), again somewhat inland.

The corresponding spatial distribution of the number of exactly four day daytime heat waves during 1970-1974 showed an expected maximum of six events per five-years at inland low-elevation sites, again with none at both low-elevation coastal and inland high-elevation mountain areas. The corresponding 2006-2010 distribution again showed a similar pattern, with the largest regional warming induced increases (over the 35 years) at high-elevation inland area (up to an additional four events per 5-years). Low-elevation areas again showed decreases, with maximum decreases (up to an additional five events per five-years), once again somewhat inland.

The current heat wave trend results are in contrast to those of Gershunov and Guiguís (2012) because of several methodological differences. First they studied the 1950-2012 period, the first 20 years of which L2009 showed to have a near-zero daytime $T_{\max}$ trend. More importantly, like Cordero et al. (2011), their SoCAB basin was not divided into a cooling coastal area and warming inland area, as was done in L2009 and herein.

Previous studies have suggested that the decrease of JJA $T_{\max}$ values in coastal California were due to increased irrigation, coastal upwelling, or cloud cover, although the current hypothesis (as in L2009) is that coastal-cooling arises from regional warming of inland areas of California, which results in increased sea breeze flow activity, which overwhelms the warming in coastal areas. This is consistent with reported increases of upwelling, which increases coastal temperature gradients, sea breeze flows, and thus coastal stratus.

A significant result from the current calculation of trends in *annual-maximum* temperatures and heat wave frequencies is to show that some extreme environmental occurrences; for example, energy brown-outs, ozone episodes, wild-fire intensity and frequencies, and heat stress events should have increased during the period of study, as their occurrences depend on extreme (and not average) $T_{\max}$ values. The current results thus should be useful to planners in these fields.

Although coastal-cooling has been found in observational and modeling studies of summer-average $T_{\max}$ trends at other west-coast low-elevation mid-latitude areas with Marine Mediterranean climates, future efforts should focus on extreme temperatures and

should employ observational or dynamically downscaled numerical regional climate models. Also recommended is that future SoCAB heat wave studies use relative-value thresholds (i.e., different thresholds for coastal, inland, and mountain areas). These efforts should also involve analyses of links between coastal cooling and spatial-temporal variations of SSTs and coastal stratus. This would allow for the separation of cold air advection effects from increased sea breeze penetration versus that from cooling SST temperatures, as well non-advective effects from increased cloud-top reflection of solar energy.

Finally, work has begun at SJSU and NCDC to determine the precise steps during the NCDC procedures for the conversion of COOP to HCN-1 and 2 data (Ghebreegziabher et al. 2012; Menne et al. 2012; Bornstein et al. 2013). This will allow for a better understanding of the conversion of many SoCAB coastal-cooling trends to warming values, as currently occurs during these conversions.

REFERENCES

- Abatzoglou, J. T., K. T. Redmond, and L. E. Edwards, 2008: Classification of regional climate variability in the state of California. *J. Appl. Met. Climatol.*, **48**, 1527-41.
- Boucouvala, D., R. Bornstein, J. Wilkinson, and D. Miller, 2003: MM5 simulations a SCOS97-NARSTO episode. *Atmos. Environ.*, **37**, S95–S117.
- Bakun, A., 1990: Global climate change and intensification of coastal ocean upwelling. *Science*, **247**, 198–201.
- Basu, R., and J. M. Samet, 2002: An Exposure assessment study of ambient heat exposure in an elderly population in Baltimore, Maryland. *Environ. Health Persp.*, **110**, 1219-1224.
- Bornstein, R. D., A. T. Ghebreegziabher, M. J. Menne, J. González, and B. Lebassi, 2013: A case study on the impact of homogenizing monthly temperature-series along coastal-California. Presented, 93rd AMS Annual Meeting, Austin, TX, Amer. Meteor. Soc., <https://ams.confex.com/ams/93Annual/flvgateway.cgi/id/-24202?recordingid=24202>.
- Cordero, E. C.; W. Kessomkiat, J. Abatzoglou, and S. Mauget, 2011: Identification of distinct patterns in California temperature trends. *J. Clim. Change*, **108**, 357-382.
- Dematte, J. E., K. O'Mara, J. Buescher, C. G. Whitney, S. Forsythe, T. McNamee, R. B. Adiga, and I. M. Ndukwu, 1998: Near-fatal heat stroke during the 1995 heat wave in Chicago. *Ann. Intern. Med.*, **129**, 173-181.

- Falvey, M., and R. D. Garreaud, 2009: Regional cooling in a warming world: Recent temperature trends in the southeast Pacific and along the west coast of subtropical South America (1979-2006). *J. Geophys. Res.*, **114**, doi: 10.1029/2008JD01519.
- Gershunov, A., and K. Guirguis, 2012: California heat waves in present and future. *Geophys. Res. Lett.*, **39**, doi: 10.1029/2010GL046324.
- Ghebreegziabher, A. T., R. D. Bornstein, B. Lebassi, and J. E. González, 2012: Trends in 1970-2010 summertime coastal California air temperatures: How HCN-corrections to COOP-data eliminated coastal-cooling. Presented, 92nd AMS Annual Meeting, New Orleans, LA, Amer. Meteor. Soc., <https://ams.confex.com/ams/92Annual/webprogram/Paper202103.html>.
- Gilliland, R. P., 1980: The structure and development of the California heat trough. M.S. Thesis, Department of Meteorology, San Jose State University, 90 pp.
- Giorgis, R. B., 1983: Meteorological influence on oxidant distribution and transport in the Sacramento Valley. Ph.D thesis, University of California at Davis, 124 pp.
- Gutiérrez, D. I. Bouloubassi, L. Méjanelle, A. Lorre, A. Sifeddine, S. Purca, K. Goubanova, B. Dewitte, M. Graco, D. Field, F. Velazco, R. Salvattecí, D. Quispe, G. Vargas, and L. Ortlieb, 2011: Coastal cooling and marine productivity increasing off Peru. *Geophys. Res. Lett.*, **38**, doi:10.1029/2010GL046324.
- Herbert, T. D., and J. D. Schuffert, 2001: Collapse of the California current during glacial maxima linked to climate change on land. *Science*, **293**, 71-76.
- Hickey, B. M., 1979: The California current system- hypotheses and facts. *Prog. Oceanogr.*, **8**, 191-279.

- Huynen, M. P. Martens, D. Schram, M. Weijenberg, and A. Kunst, 2001: The impact of heat waves and cold spells on mortality rates in the Dutch population. *Environ. Health Perspect.*, **109**, 463-470.
- IPCC 2001: Impacts, adaptation, and vulnerability. *Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. J. J. McCarthy, Ed., Cambridge University Press, Cambridge, 267 pp.
- Kalkstein, L. S., P. F. Jamason, J. S. Greene, J. Libby, and L. Robinson, 1996: The Philadelphia hot weather-heat watch/warning system: Development and application, summer 1995. *Bull. Amer. Meteor. Soc.*, **77**, 1519-1528.
- _____, and R. E. Davis, 1989: Weather and human mortality: An evaluation demographic and inter-regional responses in the U.S. *Annals Assoc. Amer. Geogr.*, **79**, 44–64.
- LaDochy, S., R. Medina, and W. Patzert, 2007: Recent California climate variability: spatial and temporal patterns in temperature trends. *Climate Research*, **CR 33**, 159–169.
- Lebassi, B. H., J. E. González, D. Fabris, E. Maurer, N. L. Miller, C. Milesi, and R. D. Bornstein, 2009: 1970-2005 Cooling of Summer daytime temperatures in coastal California. *J. Clim.*, **22**, 3558-3573.
- _____, _____, and R. Bornstein, 2011: Modeled large-scale warming impacts on summer California Coastal cooling trends. *J. Geophys. Res.*, **116**, doi:10.1029/2011JD5759.

- McElroy, J., and T. Smith, 1991: Lidar descriptions of mixing-layer thickness characteristics in a complex terrain/coastal environment. *J. Appl. Meteor.*, **30**, 585–597.
- McGregor, H. V., M. Dima, H. W. Fischer, and S. Mulitzal, 2007: Rapid 20th-century increase in coastal upwelling off Northwest Africa. *Science*, **315**, 637–639.
- Meehl, G., and C. Tebaldi, 2004: More intense, more frequent, and longer lasting heat waves in the 21st century. *Science*, **35**, 994–997.
- Menne, Jr., M. J., C. N. Williams, and R. S. Vose, 2009: The US historical climatology network monthly data, version 2. *Bull. Amer. Meteor. Soc.*, **10**, 993–1007.
- _____, M. J., R. D. Bornstein, A. T. Ghebreegziabher, J. González, and B. Lebassi, 2012: A case study on the impact of homogenizing monthly temperature series along coastal California. Presented, *AGU Fall Meeting*, San Francisco, CA, Amer. Geophys. Uni., <http://fallmeeting.agu.org/2012/eposters/eposter/a43b-0135/>.
- Miller, N. L., and N. J. Schlegel, 2006: Climate change projected fire weather sensitivity: California Santa Ana wind occurrence. *Geophys. Res. Lett.*, **33**, L15711.
- Robinson, P., 2001: On the definition of a heat wave. *J. Appl. Meteor.*, **40**, 762–775.
- Rothfusz, L. P., 1990: The heat index equation (or, more than you ever wanted to know about heat index). *NWS Southern Region Technical Attachment, SR/SSD 90-23*, Fort Worth, TX., 2pp, http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&ved=0CDkQFjAB&url=http%3A%2F%2Fwww.srh.noaa.gov%2Fimages%2Fffc%2Fpdf%2Fta_htindx.PDF&ei=w_heUemvJOa40gHYtYC4

Bg&usg=AFQjCNH8Q7Id81Qrmu6dQ39ez_xej2G88g&bvm=bv.44770516,d.dm
Q.

- Rouault, M., B. Pohl, and P. Penven, 2010: Coastal oceanic climate change and variability from 1982 to 2009 around South Africa. *African J. Marine Sci.*, **32**, 237-46.
- Schuman, S. H., 1972: Patterns of urban heat wave deaths and implications for prevention: Data from NY and St. Louis during July, 1966. *Environ. Res.*, **5**, 59-75.
- Seaman, N. L., D. R. Stauffer, and A. M. Lario-Gibbs, 1995: A multiscale four dimensional data assimilation system applied in the San Joaquin Valley during SARMAP. Part I: modeling design and basic performance characteristics. *J. Appl. Meteor.*, **34**, 1739–1761.
- Simpson, J. J., 1983: Large-scale thermal anomalies in the California Current during the 1982-1983 El Niño. *Geophys. Res. Lett.*, **10**, 917-940.
- Steadman, R. G., 1979: The assessment of sultriness: Part I: A temperature-humidity index based on human physiology and clothing science. *J. Appl. Meteor.*, **18**, 861-873.
- Wigely, T. M. L., B. D. Santer, and J. R. Lanzante, 2006: Temperature trends in the lower atmosphere, Appendix A: Statistical issues regarding trends.
- Williams, W., and R. DeMandel, 1966: Land-sea boundary effects on small scale circulations. SJSU Res. Rep., Meteor. Dept., 97 pp.

APPENDIX: List of Acronyms and Symbols

Acronyms

Csb	Köppen Marine-Mediterranean Climates
COOP	Cooperative Network
ECMWF	European Centre for Medium-Range Weather Forecasts
HCN	Historical Climatology Network
HCN-1, 2	Historical Climatology Network Versions-1 and 2
IPCC	Intergovernmental Panel on Climate Change
JJA	June, July, and August
L2009	Lebassi et al. (2009)
Lat	Latitude
Lon	Longitude
LST	Local Standard Time
MBL	Marine Boundary Layer
MSL	Mean Sea Level
NCDC	National Climatic Data Center
NSF	National Science Foundation
NWS	National Weather Service
QA	Quality Assurance
RAMS	Regional Atmospheric Modeling System
SST	Sea Surface Temperature
SoCAB	South Coast Air Basin
UHI	Urban Heat Island

WMO World Meteorological Organization

Symbols

b	Slope
c ₁₋₉	Constants in H _i -equation = -42.379 (°F), 2.04901523, 10.14333127 (°F), -0.22475541, -6.83783×10 ⁻³ (°F ⁻¹), -5.481717×10 ⁻² (°F), 1.22874×10 ⁻³ (°F ⁻¹), 8.5282×10 ⁻⁴ , -1.99×10 ⁻⁶ (°F ⁻¹)
e	Actual-data minus estimated-value
H _i	Heat Index
MSE	Means Square Error
n	Total number of data for MSE calculation
r	Correlation coefficient
RH	Relative Humidity
SE	Standard Error
T _{avg}	Average Temperature
T _{max}	Maximum Temperature
T _{min}	Minimum Temperature