The Effect of Irrigation on Regional Temperatures: A Spatial and Temporal Analysis of Trends in California, 1934–2002

DAVID B. LOBELL*

Lawrence Livermore National Laboratory, Livermore, California

CÉLINE BONFILS

University of California, Merced, Merced, California

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ABSTRACT

The response of air temperatures to widespread irrigation may represent an important component of past and/or future regional climate changes. The quantitative impact of irrigation on daily minimum and maximum temperatures ($T_{\min}$ and $T_{\max}$) in California was estimated using historical time series of county irrigated areas from agricultural censuses and daily climate observations from the U.S. Historical Climatology Network. Regression analysis of temperature and irrigation changes for stations within irrigated areas revealed a highly significant ($p < 0.01$) effect of irrigation on June–August average $T_{\max}$, with no significant effects on $T_{\min}$ ($p > 0.3$). The mean estimate for $T_{\max}$ was a substantial 5.0°C cooling for 100% irrigation cover, with a 95% confidence interval of 2.0°–7.9°C. As a result of small changes in $T_{\min}$ compared to $T_{\max}$, the diurnal temperature range (DTR) decreased significantly in both spring and summer months. Effects on percentiles of $T_{\max}$ within summer months were not statistically distinguishable, suggesting that irrigation's impact is similar on warm and cool days in California. Finally, average trends for stations within irrigated areas were compared to those from nonirrigated stations to evaluate the robustness of conclusions from previous studies based on pairwise comparisons of irrigated and nonirrigated sites. Stronger negative $T_{\max}$ trends in irrigated sites were consistent with the inferred effects of irrigation on $T_{\max}$. However, $T_{\min}$ trends were significantly more positive for nonirrigated sites despite the apparent lack of effects of irrigation on $T_{\min}$ from the analysis within irrigated sites. Together with evidence of increases in urban areas near nonirrigated sites, this finding indicates an important effect of urbanization on $T_{\min}$ in California that had previously been attributed to irrigation. The results therefore demonstrate that simple pairwise comparisons between stations in a complex region such as California can lead to misinterpretation of historical climate trends and the effects of land use changes.

1. Introduction

Land surface properties are widely acknowledged as an important control on local climate conditions (Bonan 1997; Chase et al. 2000; Bonan 2001; Pielke et al. 2002). The conversion of forests to croplands in temperate regions, for example, is known to exert significant cooling effects because of changes in surface albedo (Govindasamy et al. 2001). Changes in irrigation may also be expected to influence climate, because soil moisture affects surface albedo and evaporation and has been shown to influence regional temperature (Dai et al. 1999) and rainfall (Koster et al. 2004) variations. Quantification of irrigation's impact on climate is needed to better understand the causes of past climate changes and therefore anticipate the direction and magnitude of future changes in agricultural regions.

Quantitative understanding of how climate responds to irrigation, however, remains limited. Modeling studies in various regions have demonstrated that increased soil moisture from irrigation leads to significant local decreases in simulated average and maximum temperatures ($T_{\max}$), with mixed results for minimum tempera-

* Current affiliation: Program on Food, Security, and the Environment, Stanford University, Stanford, California.

Corresponding author address: David Lobell, Program on Food, Security, and the Environment, Stanford University, Stanford, CA 94305.
E-mail: dlobell@stanford.edu

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tures (T_{min}) (Chase et al. 1999; Adegoke et al. 2003; Snyder et al. 2006). A global modeling study showed that simulated cooling from irrigation is apparent for all agricultural regions regardless of their climate regime, although particularly strong cooling was observed in regions where irrigation caused increased cloud cover (Lobell et al. 2006). The relevance of these simulations to reality, however, depends on whether the appropriate amount of water is used to represent irrigation, as well as on the viability of several model simplifications, such as ignoring temporal changes in soil moisture throughout the growing season or irrigation-induced changes in vegetation characteristics. Kueppers et al. (2008) found that simulated effects of irrigation were model dependent, with even the sign of change for T_{min} varying between models.

Climate observations have also been widely used to study the effect of irrigation on temperature or rainfall (Fowler and Helvey 1974; Barnston and Schickedanz 1984; Mahmood et al. 2004, 2006). These studies have typically relied on pairwise comparisons of weather or climate trends between irrigated and nonirrigated locations. For example, Barnston and Schickedanz (1984) found that in the southern Great Plains, T_{max} was ~2°C lower over irrigated lands than adjacent lands on hot, dry days. Effects on T_{min} were insignificant. Mahmood et al. (2004) reported that T_{max} trends were significantly reduced for meteorological stations located at irrigated sites in Nebraska relative to dryland sites. Christy et al. (2006) reported greater warming of T_{min} in California's Central Valley relative to mountain stations and suggested that this reflected a positive effect of irrigation on T_{min}.

While intuitive, these pairwise comparisons have the potentially important pitfall that other climate forcings have coincided with irrigation changes in space or time (Small et al. 2001). For example, irrigated sites often differ from surrounding areas in elevation, aerosol concentrations, strength of sea breeze, or level of urbanization, all of which can influence climate. Another important consideration is that the distinction between irrigated and nonirrigated sites is often not clearly defined. Whether an "irrigated" site is surrounded by irrigated fields for several kilometers in all directions or adjacent to a single irrigated field would likely have an important effect on inferred effects on climate. Similarly, irrigated sites may differ in the types of crops grown (e.g., rice versus maize) or irrigation methods used (e.g., flood versus sprinkler).

A recent study (Bonfils and Lobell 2007) attempted to resolve some of these issues by using gridded datasets on temperature and irrigation extent (i.e., fraction of each $5' \times 5'$ grid cell that is irrigated) for California and other major irrigated regions of the world. Temperature trends were computed for grid cells with different levels of irrigation (e.g., 0%–10%, 10%–20%, etc.) in each region, and in nearly all regions T_{max} trends were increasingly negative with increasing levels of irrigation. Effects on T_{min} and diurnal temperature range (DTR = $T_{max} - T_{min}$) were less pronounced and varied for different climate datasets. Because other climate forcings such as urbanization, elevation, and CO_2 concentration were unlikely to have a spatial pattern identical to irrigation extent, the bias from these forcings was less than from a case comparing only two sites. (However, ozone concentrations were found to be correlated with irrigation in some regions.) While Bonfils and Lobell (2007) showed a clear correspondence between current irrigation levels and past temperature trends, the lack of temporal information on irrigation prevented firm conclusions about the incremental effect of irrigation. For example, it was unknown by how much irrigation had changed over the temperature record for each grid cell, or whether grid cells with the highest current levels of irrigation also had experienced the greater trends in irrigation since 1900 or 1950.

The current study aims to evaluate the effect of irrigation on trends in T_{min}, T_{max}, and DTR in California using a combination of daily station temperature data and county irrigation records since 1934. California provides a unique setting in which to examine irrigation's effects, because detailed records of both climate and irrigation practices are available at relatively fine spatial resolutions and for long time periods. By employing both spatial and temporal gradients in irrigation, the bias of other climate forcings is reduced, since these forcings are unlikely to be correlated both in space and time with irrigation. We first describe the datasets (section 2) and then the analysis methods used (section 3). Section 4 presents the main results and is followed by a discussion and some conclusions (section 5).

2. Datasets

a. USDA census irrigation data

The U.S. Department of Agriculture (USDA) has conducted a census of agriculture in California at least once per decade since the late nineteenth century. In addition to information on acreage and production of various crops in each county, data on the extent of irrigated and nonirrigated lands were collected for most census years. For this study, the area of harvested cropland from irrigated farms was obtained for each census year since 1934. (Data for years since 1978 were avail-

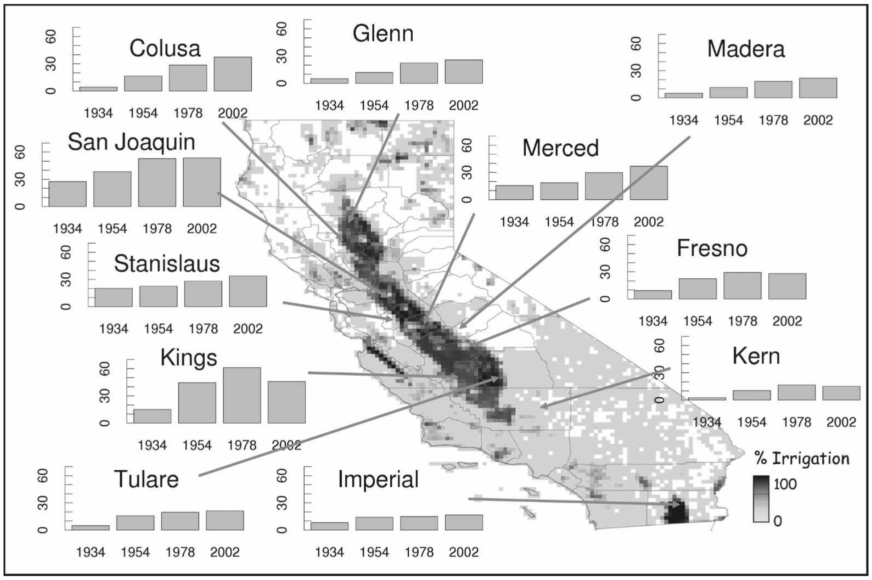

FIG. 1. Percent of land used for irrigated, harvested cropland for selected California counties in 1934, 1954, 1978, and 2002, according to USDA census records. Map shows percent of each 5′ × 5′ grid cell in California equipped for irrigation (from Doll and Siebert 2000).

able from http://www.nass.usda.gov/census/, while prior years' data were digitized from paper copies.)

Figure 1 shows the irrigated area in 1934, 1954, 1978, and 2002 for 10 counties with substantial irrigated area. In some counties, such as Kern and Kings, irrigated area increased rapidly from 1934 to 1978 but decreased thereafter. In counties such as Merced and Stanislaus, irrigated area increased only slightly between 1934 and 1954 but grew more rapidly in the recent decades. Overall, both the current extent of irrigation and the pattern of irrigation development through time vary by county in California. This provides a gradient in irrigation levels in both space and time with which to evaluate temperature responses.

b. USHCN temperature data

Daily $T_{\min}$ and $T_{\max}$ data for 1934–2002 were obtained for all 50 California stations in the U.S. Historical Climatology Network (USHCN; Williams et al. 2004). USHCN stations are selected based on criteria such as minimal changes in measurement time and heat island effects over time, and the daily data used in this study have not been adjusted for these or any other effects. The vast majority of irrigated area in California occurs below 40°N and at relatively low elevations. For this study, therefore, only the 26 stations south of 40°N and below 500-m elevation were included in the analysis, to minimize differences in latitude and elevation between sites (Fig. 2).

Stations were then classified as irrigated or nonirrigated based on a map of irrigated areas (Doll and Siebert 2000), which designates the fraction of each 5′ × 5′ grid cell equipped for irrigation (5′ latitude × 5′ longitude corresponds to roughly 9 km × 7.5 km at this latitude). Stations within grid cells with at least 30% irrigation were deemed to be surrounded by a significant amount of irrigated land, and were thus classified as irrigated. Because the accuracy of the irrigation

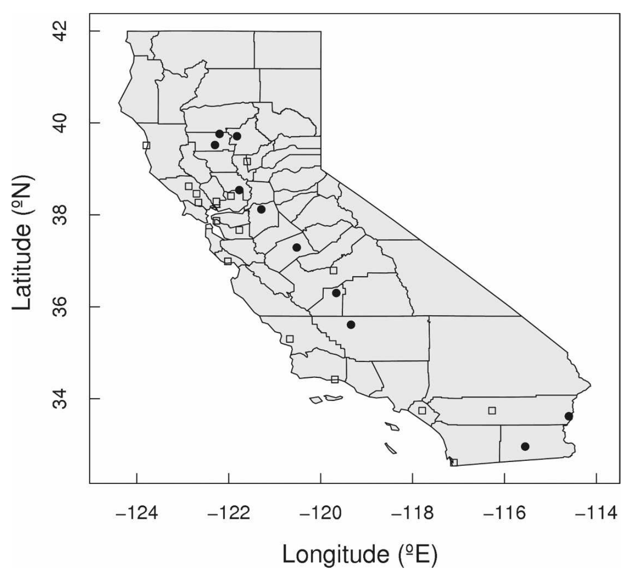

FIG. 2. Locations of irrigated (solid circles) and nonirrigated (open squares) USHCN stations used in this study.

map at 5′ × 5′ resolution is not well known (Doll and Siebert 2000), we supplemented this classification using the predominant land uses within 10 km of the station as detailed by Williams et al. (2005). One of the stations with more than 30% irrigation (Marysville in Yuba County) did not contain a designation of open farmland in the USHCN description and was therefore excluded from the irrigated class. In addition, one station (Tustin Irvine Ranch in Orange County) was excluded because it was within 10 km of a major city (area with buildings greater than 10 m or three stories tall). Both of these stations were therefore assigned to the nonirrigated class, although results were similar when these were excluded altogether from the analysis. In total, 10 stations were classified as irrigated and 16 as nonirrigated.

3. Methods

The USHCN daily temperature and irrigation records were used to compute trends for each station for three periods of roughly equal length: 1934–54, 1954–78, and 1978–2002. Trends in average T_{min}, T_{max}, and DTR were computed for each month. To investigate whether irrigation differentially affected warm and cool days (or nights), the trends in daily temperature percentiles from 0% to 100% in 5% increments were also computed (i.e., 100% for T_{max} corresponds to the warmest day of a month, with other percentiles computed based on interpolation of the empirical distribution of temperatures within each month.) Only 5 of the 10 irrigated stations and 8 of the 16 nonirrigated stations had sufficient temperature data for 1934–54 to compute trends over this time period.

For each irrigated station, trends in irrigated area were computed for the same three time periods as temperature. As census records of irrigated area were only available at the county scale, irrigation trends for station j in time period t ($\Delta\mathrm{Irr}_{j,t}$) were computed from the following equation:

$$\Delta\mathrm{Irr}_{j,t} = \Delta\mathrm{Irr}_{C_{j,t}} * \frac{\mathrm{Irr}_{j,\sim 2000}}{\mathrm{Irr}_{C_j,2002}}, \qquad (1)$$

where $\Delta\mathrm{Irr}_{C_{j,t}}$ corresponds to the trend in irrigated area in time period t (percentage change over time period) for the county with station j, Irr_j is the current (circa 2000) percentage of irrigated area for the grid cell with station j (from Doll and Siebert 2000), and Irr_{C_j} is the percent of the county with station j irrigated according to the 2002 census. This equation assumes that changes in irrigated area within each 5′ × 5′ grid cell were proportional to their current area of irrigation. For example, Wasco station in Kern County lies within a grid cell with 75% irrigated area, whereas the 2002 census irrigated area in Kern was 15%. Historical values of county irrigated area were therefore multiplied by 5.0 (75/15) to obtain estimates of irrigated area surrounding the station for each census year. This assumption likely introduced some error into the estimate of irrigated area change, but unfortunately the lack of subcounty data on irrigation changes prevented a thorough analysis of this uncertainty.

A total of 25 joint observations of temperature and irrigated area trends for irrigated sites were obtained from the above procedure, with 5 irrigated sites with temperature trends for 1934–54 and 10 sites for 1954–78 and 1978–2002. These data were then used to estimate the effect of irrigation on temperature using a linear regression model

$$\Delta T_{j,t} = \alpha_0 + \beta_{\mathrm{Irr}} * \Delta\mathrm{Irr}_{j,t} + \varepsilon, \qquad (2)$$

where $\Delta T_{C_{j,t}}$ and $\Delta\mathrm{Irr}_{C_{j,t}}$ represent the temperature and irrigated area trends, respectively, for station j in time period t, α_0 and β_{Irr} are the model intercept and slope, and ε is the model error assumed to follow a Gaussian distribution. This equation assumes that the effect of irrigated area on temperature is linear, and therefore does not depend on the initial level of irrigation. Moreover, by expressing temperature change only as a function of local irrigated area changes, Eq. (2) ignores a potential influence of advection from nearby irrigated areas (Kueppers et al. 2007).

As discussed above, the use of trends from different time periods and locations was an attempt to minimize possible confounding of irrigation with other climate forcings. For example, some counties had their greatest irrigated area increases in 1934–54, while others increased more for 1954–78. Overall, however, there was still a tendency for $\Delta\mathrm{Irr}_{j,t}$ to be higher for 1934–54 than for later time periods (see Fig. 1), introducing the possibility that differences in trends between time periods could be attributed to irrigation changes when, in fact, they arose from a different time-dependent forcing, such as atmospheric greenhouse gas concentrations.

To evaluate the sensitivity of results to other potential forcings, the effect of irrigated area was also evaluated using the equation

$$(\Delta T_{j,t} - \Delta T_{R,t}) = \alpha_0 + \beta_{\mathrm{Irr}}\Delta\mathrm{Irr}_{j,t} + \varepsilon, \qquad (3)$$

where $\Delta T_{R,t}$ represents the average regional temperature trend for time period t that arose from factors unrelated to irrigation. For this equation, $\Delta T_{R,t}$ was computed as the average trend for the 16 nonirrigated stations in each time period. This formulation is similar to the study of Small et al. (2001), who subtracted from

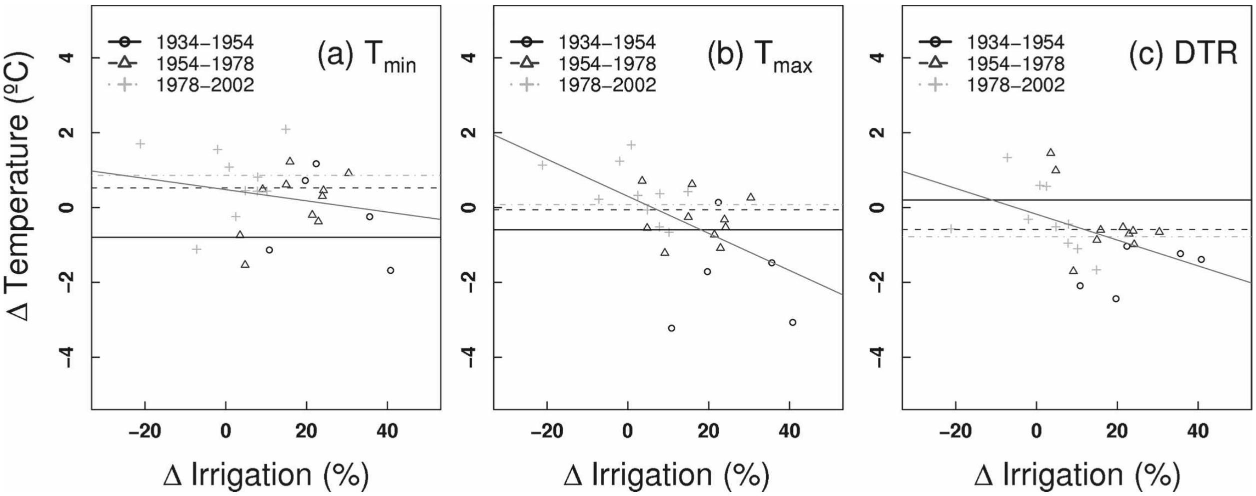

FIG. 3. Irrigated area and (a) JJA T_{min}, (b) JJA T_{max}, and (c) JJA DTR changes for three different time periods for irrigated USHCN sites. Horizontal lines indicate average trends for nonirrigated sites in each time period. Best-fit linear regression line is also shown.

local stations the average temperatures for stations neighboring the "analysis region" to identify local changes attributable to desiccation of the Aral Sea.

By subtracting the regional trend from each station trend, we assume that trends at "nonirrigated" stations were unaffected by irrigation in nearby regions. This assumption is supported to some extent by modeling studies (Kueppers et al. 2007) that suggest the effects of irrigation in California are localized and do not greatly influence areas outside of the Central Valley. However, given that several nonirrigated sites, such as Fresno Airport, are less than 10 km from areas with high irrigation levels, it is unlikely that their temperature trends are entirely independent of irrigation. Subtraction of average trends from nonirrigated sites could therefore lead to an underestimate of irrigation's effect using Eq. (3).

We therefore consider both Eq. (2), which assumes that differences in temperature trends between time periods were due solely to irrigation changes, and Eq. (3), which assumes that nonirrigated sites represent an accurate estimate of temperature changes from all factors other than irrigation, to be imperfect models for estimating β_{Irr}, the effect of irrigation on temperature. Instead, we focus on cases where estimates of β_{Irr} are similar for the two models, indicating that the results are fairly insensitive to the assumptions discussed above. Equations (2) and (3) were applied for each climate variable (average T_{min}, T_{max}, and DTR, and percentiles of T_{min} and T_{max}) and for each of four seasons: December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). Irrigation in California peaks in JJA and is also significant in MAM, while relatively small amounts of water are applied during SON and DJF (Salas et al. 2006).

4. Results

a. *The effect of irrigation on mean T_{max}, T_{min}, and DTR*

The irrigated area and temperature changes for all sites and time periods for JJA are shown in Fig. 3 as an example of the data used in the regression analysis. For T_{max}, there was a tendency for the larger irrigated area trends to be associated with more negative T_{max} trends, indicating that irrigation has a cooling effect on T_{max} (Fig. 3b, $p < 0.05$). No significant effect of irrigation was apparent for T_{min} (Fig. 3a), while irrigation appeared to cause a reduction in DTR (Fig. 3c).

The horizontal lines on Fig. 3 show the mean trends for the nonirrigated sites for the three time periods. These lines indicate that, for JJA, the apparent effect of irrigation was unlikely to result from temporal changes in other climate forcings. For example, T_{max} trends were more negative in irrigated sites for 1934–54, the period of largest irrigation increases, than other time periods. However, T_{max} trends in nonirrigated sites were only slightly (<0.5°C) more negative in 1934–54 than the other time periods. Similarly, while the period of most negative DTR trends in the irrigated sites (1934–54) coincided with the period of most rapid increase in irrigated area, the DTR trends in nonirrigated sites were actually more positive in 1934–54 than in the other time periods.

Estimates of β_{Irr} along with their uncertainties (Fig. 4) confirmed that the effect of irrigation was sta-

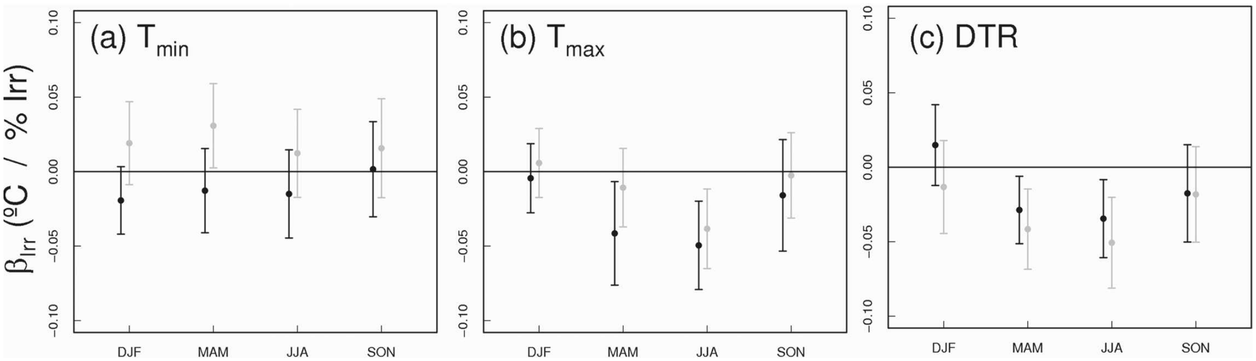

FIG. 4. Estimated values of β_{Irr} for (a) T_{min}, (b) T_{max}, and (c) DTR for different seasons using Eq. (2) (black) or (3) (gray). Dots show mean estimate and error bars indicate 95% confidence interval.

tistically significant ($p < 0.05$) for JJA T_{max} and DTR, using either Eq. (2) or (3). Negative effects on T_{max} were also significant for spring (MAM) using Eq. (2) but not for Eq. (3), indicating that the effect of irrigation on T_{max} in this season is not clearly distinguishable from other possible forcings. However, effects on MAM DTR were significant using both approaches. It was found that β_{Irr} was not statistically significant for T_{min} using either approach in JJA, and only marginally significant for MAM using Eq. (3). Estimates of β_{Irr} were not statistically significant for any variable in DJF and SON using either equation. This was expected since most irrigation water is applied during spring and summer months in California, with rainfall providing the bulk of soil moisture in other months (Salas et al. 2006).

The data therefore indicate a highly significant, negative effect of irrigation on average T_{max} and DTR during summer months, with minimal effects on T_{min}. These findings are qualitatively consistent with several of the modeling and observational studies discussed in the introduction, with the exception of Christy et al. (2006), who inferred a positive effect of irrigation on T_{min} (discussed below). Unfortunately, the quantitative estimates of irrigation's impact in the current study (β_{Irr}) are characterized by relatively large uncertainties. For example, the 95% confidence interval for β_{Irr} for JJA T_{max} was -0.079 to -0.020°C %irr^{-1}, with a mean estimate of -0.050°C %irr^{-1} using Eq. (2). Corresponding values for Eq. (3) were -0.065 to -0.012°C %irr^{-1}, with a mean estimate of -0.038°C %irr^{-1}. These uncertainties likely reflect the combined influence of many factors, including (i) errors in the estimation of irrigation changes surrounding the meteorological stations; (ii) variations in other climate forcings, such as urbanization, aerosols, or sea breeze between different stations and time periods; and (iii) variations in the response of temperature to irrigation changes, for instance because of local differences in wind direction, boundary layer heights, or initial irrigation levels.

b. *Effects on temperature extremes*

Estimates of β_{Irr} for different temperature percentiles revealed only slight and insignificant differences between effects on low and high temperature extremes [Fig. 5; values shown are from Eq. (2)]. For T_{max}, mean estimates of β_{Irr} were very consistent for percentiles in JJA and increased slightly for the highest percentiles in MAM. The latter result is likely explained by the fact that cooler days in MAM occur mainly in early spring, before the onset of most irrigation. For T_{min}, β_{Irr} was significantly different than zero only for the 95th–100th percentiles in JJA. The similar response of T_{max} to irrigation for cool and warm days is in contrast to the conclusion of Barnston and Schickedanz (1984) that irrigation lowered temperatures in north Texas more on hot, dry days. However, their conclusion was based on measurements only from hot spells with average relative humidity (RH) of 35%, and theoretical arguments that effects would be 50% smaller during damp, cool days, with RH of 60%, because of reduced evaporation rates with higher humidity.

In California, RH during summer months is not highly correlated with average or maximum temperatures. For example, we compared daily measurements of T_{max} and RH from Shafter station in Kern County, which is part of the California Irrigation Management Information System (CIMIS; additional data are available online at http://wwwcimis.water.ca.gov). The correlation between T_{max} and RH for JJA measurements from 1990 to 2006 was fairly low ($r = -0.30$), and the best-fit regression line indicated an average RH difference between the coolest and warmest days of less than 15%. Correlation between T_{max} and reference evapotranspiration was similarly low ($r = 0.39$). Thus, a weak correspondence between RH and T_{max} may explain the

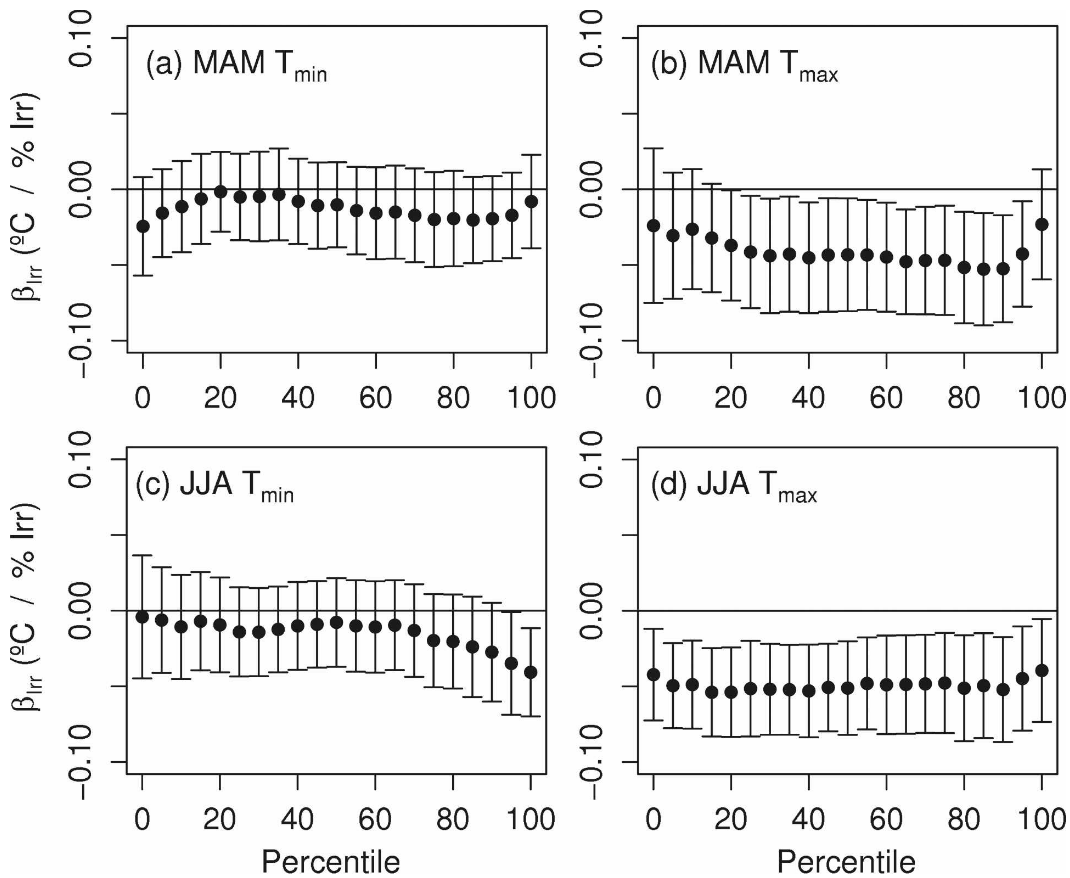

FIG. 5. Estimated values of β_{Irr} for each percentile of (a) MAM T_{min}, (b) MAM $T_{max,}$ (c) JJA T_{min}, and (d) JJA T_{max}, using Eq. (2).

lack of evidence for stronger effects of irrigation on T_{max} for warmer days. In regions with greater variations in RH, such as north Texas, effects of irrigation may indeed vary by temperature percentile.

c. *Temperature trends in irrigated versus nonirrigated sites*

For comparison with the analysis above, which relied mainly on differences among the irrigated sites, we also compared average trends for the 10 irrigated sites for 1934–2002 with average trends for the 16 nonirrigated sites (Table 1). This analysis revealed statistically significant differences in JJA trends for both T_{max} and T_{min}, with irrigated sites exhibiting trends in both that were roughly 0.3°C decade^{-1} cooler than the nonirrigated sites. For the 68-yr time period, this corresponds to a substantial 2.0°C change in the difference between irrigated and nonirrigated site average temperatures.

As a result of the similar differences in T_{min} and T_{max} trends, changes in DTR were nearly identical for the two groups of sites (Table 1). Thus, if the comparison of trends over irrigated and nonirrigated sites were used to infer the effect of irrigation, the conclusions would be quite different than those discussed in the previous sections. In particular, one would infer that irrigation causes a decrease in both T_{max} and T_{min}, whereas the analysis using only irrigated sites showed a cooling effect on T_{max} but no effect on T_{min}. This disparity appears to arise from the fact that all but one of the 16 nonirrigated sites are within 10 km of a city, as defined by the USHCN land use classification (Williams et al. 2005). The exception is the coastal Fort Bragg station,

TABLE 1. Trends (°C decade^{-1}) for T_{max}, T_{min}, and DTR for 1934–2002 averaged for 10 irrigated sites and 16 nonirrigated sites. Values in bold are significant at $p < 0.05$.

	JJA			DJF		
	T_{max}	T_{min}	DTR	T_{max}	T_{min}	DTR
Irrigated	**−0.32**	**−0.11**	**−0.22**	**−0.15**	0.04	**−0.19**
Nonirrigated	0.03	**0.21**	**−0.24**	−0.09	**0.21**	**−0.30**
Difference	**−0.30**	**−0.32**	0.03	**−0.06**	**−0.18**	**0.12**

and removing this station had little effect on the values in Table 1.

Therefore, the "irrigated" and "nonirrigated" sites may be more accurately characterized as "irrigated, nonurban" and "nonirrigated, urban." In California, very few stations below 500-m elevation do not fall into one of these two categories. A comparison of the two categories therefore reveals the combined effects of irrigation and urbanization, as opposed to either one alone. In an analysis of urban and rural USHCN stations, Karl et al. (1988) concluded that urbanization causes a significant increase in T_{min} and an order of magnitude smaller cooling effect on T_{max}. More recent studies also support the notion that urbanization has its greatest impact on T_{min} (Gallo et al. 1996; Zhou et al. 2004).

The greater warming of T_{min} in nonirrigated sites may therefore be the consequence of more rapid urbanization in these areas rather than of irrigation-induced cooling in the irrigated sites. Interestingly, the warming effects of urbanization on JJA T_{min} for urban stations in California have apparently been very similar in magnitude to the cooling effects of irrigation on JJA T_{max} for irrigated stations (~0.3°C decade^{-1}; Table 1). In DJF, differences in T_{min} are greater than in T_{max}, reflecting the relatively small role of irrigation in the winter. These results provide a clear example of the pitfalls of comparing trends from two regions to infer the effects of a single climate forcing, and, conversely, demonstrate the value of comparing temperature trends among multiple sites that have different levels of a single forcing (such as for irrigation in this study).

5. Discussion and conclusions

The mean estimate of 5.0°C cooling for 100% relative to 0% irrigated area agrees well with Kueppers et al. (2008), who simulated 4.7°–8.2°C cooling of August T_{max} from 100% irrigation in California's Central Valley. In contrast, 5.0°C is more than twice the 2°C difference in T_{max} between irrigated and nonirrigated regions reported in Barnston and Schickedanz (1984), although the latter value is within the (broad) 95% confidence interval of 2.0°–7.9°C. Bonfils and Lobell (2007) estimated a 2.4°–4.3°C cooling for 100% irrigation, which is within the range estimated in the current study.

For the irrigated stations in this study, average JJA T_{max} decreased by 2.0°C relative to nonirrigated sites from 1934 to 2002, while average irrigation for the 10 sites increased from 22.4% to 62.6%. Based on the mean estimate of 5.0°C cooling for 100% irrigation, the expected cooling from a 40.2% increase in irrigation was roughly 2.0°C. Therefore, the difference between T_{max} trends in irrigated and nonirrigated sites (2.0°C) was consistent with the estimated effect of irrigation on T_{max}, as estimated using variability among the irrigated sites. In contrast, we found that differences between irrigated and nonirrigated sites for T_{min} trends were large, while differences among irrigated sites appeared unrelated to irrigation.

This disagreement demonstrated the value of using differences among irrigated sites, rather than simple comparisons between regional averages that are easily affected by other climate forcings. Specifically, urbanization in nonirrigated lands has likely caused significant warming of T_{min}. Urbanization also provides an explanation for the observation in Christy et al. (2006) that Central Valley T_{min} was warming more than adjacent Sierra stations. While the authors inferred a positive effect of irrigation on Valley T_{min}, many of their Valley stations were located in or near urban centers (e.g., one station is labeled "Fresno downtown"). Given the results presented here and in previous studies, showing that irrigation does not significantly affect T_{min} while urbanization does, it is likely that the positive T_{min} trend anomaly for Valley stations in their study was driven by the urban subset of the Valley stations.

Several caveats apply to the quantitative conclusions of the current study. Irrigated area changes for each site were estimated from county level historical data and 5′ × 5′ maps of current irrigation, and therefore these estimates almost certainly contain some random error. However, we find no reason to believe that our estimation procedure would result in systematic error that would introduce bias in the estimate of β_{Irr}. In addition, our study did not consider spatial or temporal differences in the types of crops grown or irrigation methods used, both of which may have influenced evapotranspiration rates and temperature responses (Hsiao and Xu 2005; Orang et al. 2005). Finally, the large uncertainties associated with the estimates of β_{Irr} reflect the relatively small sample size of the USHCN irrigated sites ($n = 10$). Future studies that incorporate data from additional station networks may result in more precise estimates. These studies may also wish to consider other climate variables when available, such as changes in relative and specific humidity that result from enhanced evapotranspiration in irrigated lands.

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