

Empirical evidence for a recent slowdown in irrigation-induced cooling

Céline Bonfils^{*†} and David Lobell^{*}

^{*}School of Natural Sciences, University of California, Merced, CA 95344; and [†]Lawrence Livermore National Laboratory, Livermore, CA 94550

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Understanding the influence of past land use changes on climate is needed to improve regional projections of future climate change and inform debates about the tradeoffs associated with land use decisions. The effects of rapid expansion of irrigated area in the 20th century has remained unclear relative to other land use changes, such as urbanization, that affected a similar total land area. Using spatial and temporal variations in temperature and irrigation extent observed in California, we show that irrigation expansion has had a large cooling effect on summertime average daily daytime temperatures (-0.14°C to -0.25°C per decade), which corresponds to an estimated cooling of -1.8°C to -3.2°C since the introduction of irrigation practices. Irrigation has negligible effects on nighttime temperatures, leading to a net cooling effect of irrigation on climate (-0.06°C to -0.19°C per decade). Stabilization of irrigated area has occurred in California since 1980 and is expected in the near future for many irrigated regions. The suppression of past human-induced greenhouse warming by increased irrigation is therefore likely to slow in the future, and a potential decrease in irrigation may even contribute to a more rapid warming. Changes in irrigation alone are not expected to influence broad-scale temperatures, but they may introduce large uncertainties in climate projections for irrigated agricultural regions, which provide $\approx 40\%$ of global food production.

climate | irrigation effect | observations

Rapid changes in land use, including deforestation, urbanization, and irrigation, are widely acknowledged to influence regional scale climate (1–4). Urban areas occupy $\approx 2\%$ of the Earth's land surface (5), and considerable efforts have been devoted to estimating the contribution of urbanization to observed warming in certain regions (6). In contrast, although $\approx 2\%$ of global land surface is irrigated [$\approx 17\%$ of the $15 \times 10^6 \text{ km}^2$ of world's agricultural land (7)], the role of irrigation in observed temperature trends has been less a subject of investigation.

Because the surface cooling that accompanies evaporation of irrigation water seems negligible in comparison with global greenhouse warming, and because the positive radiative forcing associated with the increase in water vapor is small (8), influences of irrigation are often ignored in climate projections and often neglected in the process of detecting human-induced climate change (9). Yet, irrigated lands contribute to 40% of global food production, and uncertainties in regional climate projections and associated impact on crops depend on the future of irrigated agriculture and the magnitude of climate response to this land-use change (10). Moreover, modeling studies have identified the expansion of irrigation in regions with low rainfall, such as California, as a first-order climate influence (11) that can attenuate a greenhouse-gas-induced warming (10–12). Alternatively, stabilization or retraction of irrigation practice could accelerate greenhouse warming in agricultural regions.

Previous assessments of irrigation's impacts on climate, dating to at least 50 years ago (13) and including both modeling and observational studies, have produced conflicting results and provided limited insight into quantifying irrigation's climate effects because of several simplifying assumptions. Some

observational studies have highlighted a contrast between pre- and postirrigation temperature trends in irrigated regions (14–16), but most did not document the rate at which irrigation evolved, nor account for other potential climate forcings. Additional studies have compared temperatures in irrigated and nonirrigated sites, assuming that differences can be attributed to this disturbance (17–20). Part or all of the differences can, however, arise from variations in climate regimes or land characteristics [elevation, latitude, distance from sea (21)] and other external factors (such as urbanization, aerosols, or ozone) that can obfuscate the atmospheric signature of irrigation, especially when their spatial patterns correlate with irrigation patterns.

Modeling studies (10–11, 15, 22) have shown that, among other effects, irrigation causes large reductions in surface daytime temperatures. However, the amplitude of this change, as well as the sign of the change in nighttime temperature, often depend on the parameterization adopted to mimic irrigation and the climate model used (11). Moreover, some assumptions such as fixing a high value of soil moisture throughout the growing season, whereas moisture levels in actual irrigated fields are likely lower and more variable in time, can result in overestimating the effects of irrigation on temperatures.

In this study, we combined detailed spatial and temporal data sets to quantify the net impact of widespread irrigation on local and regional climate and to better understand recent observed temperature trends in irrigated regions. Analyses were first conducted for California, the top irrigating State in the U.S. (3.3 million hectares), and then for five other widespread irrigated regions of the world (Fig. 1).

Results and Discussion

Observed Irrigation and Temperature Time Series. Since the creation of irrigation districts in 1887, the development of irrigation (Fig. 24) has radically modified the landscape in California, particularly in the previously arid San Joaquin Central Valley that is now the mainstay of a multibillion-dollar agricultural economy. With a rapid expansion in the early decades of the 20th century (1.9 million hectares in 1930) and more moderate development until the 1980s (3.2 million hectares), irrigation is a time-varying climate forcing that we compared with temperature variations from four different observational data sets (UW, PRISM, CRU2.0, CRU2.1; Fig.

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Abbreviations: T_{ave} , daily average temperature; T_{min} , daily nighttime minimum temperature; T_{max} , daily daytime maximum temperature; DTR, diurnal temperature range; CIF, current irrigated fraction. UW, PRISM, CRU2.0, and CRU2.1 are acronyms for four observational data sets.

[†]To whom correspondence should be addressed. E-mail: bonfils2@llnl.gov.

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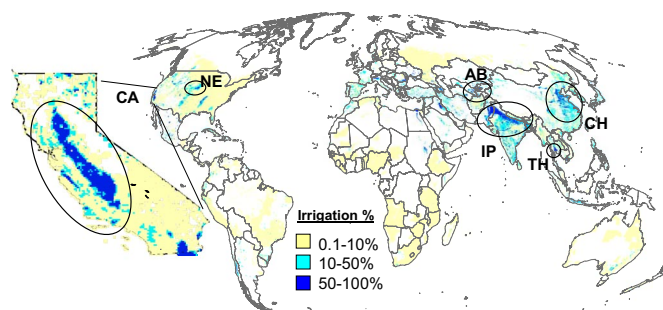


Fig. 1. Global map of the fraction of each $5' \times 5'$ grid cell equipped for irrigation (percent, 37). Circles indicate major irrigation regions used in this study. AB, Aral Sea Basin; CA, California; CH, Eastern China; IP, Indo-Gangetic Plains of India and Pakistan; NE, Nebraska; TH, Thailand.

2*A*; and see *Data and Methods*). Time-series of temperature differences [$d(t)$] were computed by subtracting spatially averaged summer (June–August) nighttime minimum temperature (T_{\min}) and daytime maximum temperature (T_{\max}) in a reference area [where current irrigated fraction (CIF) ranges between 0.1 and 10%][§] from spatially averaged values over intensively irrigated land (CIF >50%). Use of $d(t)$ aims at removing variability common to both time-series (23) while attempting to isolate the impact of irrigation from those of large-scale forcings.

A very close correspondence is evident between changes in irrigation and $d(t)$ for T_{\max} since 1915 (Fig. 2A). The temperature changes were gradual and concomitant with irrigation growth. The doubling of irrigated area from 1915 to 1979 was associated with a significant -0.14°C to -0.25°C per decade cooling relative to the modestly irrigated reference region (Table 1) or a total of 0.9°C – 1.6°C cooling over the 65 years [see also [supporting information \(SI\) Fig. 7](#)]. Assuming an equivalent amount of cooling associated with irrigation expansion before the study period, the total cooling since the introduction of irrigation practice was 1.8°C – 3.2°C . Moreover, periods with little change in irrigation cover (1959–1969 and 1978–1982) cooccurred with small $d(t)$ trends, and a recession of irrigation observed in 1982–1987 was associated with a warming of $d(t)$. In all data sets, the difference between 1915–1979 and the 1980–2000 T_{\max} trends (Table 1) were statistically significant (Student t test, $P < 0.001$). The large negative correlation ($r < -0.79$, $P < 0.01$) in all data sets suggests an effect of irrigation on T_{\max} . Such consistent correlation between irrigation and observed T_{\min} variations is not found across the four data sets (Fig. 2B).

Spatial Dependence of T_{\max} Trends. The fact that irrigation growth and T_{\max} are temporally correlated does not prove causality, because other factors correlated through time with irrigation extent could also be affecting T_{\max} . We therefore further analyzed the influence of irrigation on temperature by focusing on their spatial patterns. In particular, we have repeated the calculation of $d(t)$ using different levels of CIF (10–20%, 20–30%, up to 90–100%) and computed the trends of $d(t)$ for T_{\max} over 1915–1979, the period of irrigation growth (Fig. 3A). The trends are always shown relative to that of the reference region. By using the UW data set, the cooling effect for summertime T_{\max} was observed to increase incrementally with irrigation up to 80%. Most trends over intensively irrigated areas were significantly different from those found in the reference region at the

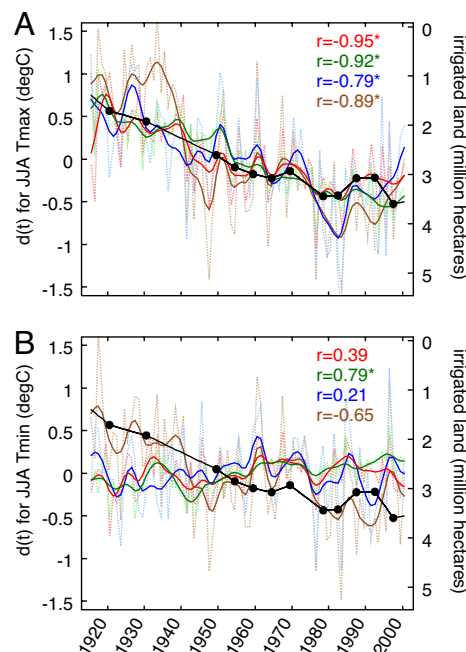


Fig. 2. Observed time-series of irrigated land cover in California and June–August temperature differences between intensively irrigated lands (CIF > 50%) and a reference area (0.1–10% CIF), both located in the Central Valley region (CV: 118.25–126.25°W, 34.75–40.25°N). T_{\max} (A) and T_{\min} (B) time-series are estimated by using UW (red), PRISM (green), CRU2.1 (blue), and CRU2.0 (brown) data below 500 m of elevation. Unfiltered (pale dotted lines) and low-pass-filtered averages (performed with a 11-point binomial filter, bright solid lines) are shown, both with climatology subtracted for clarity. Irrigation time-series (black line, right, vertical scale is reversed) is interpolated from data collected in a total of 12 U.S. Department of Agriculture censuses (represented by black dots). r numbers show correlation coefficients between irrigation and each filtered temperature time-series using the 12 paired observations. An asterisk indicates that temperature and irrigation are highly correlated ($P < 0.01$).

1% level[†]. These results corroborate the hypothesis that enhanced evaporative cooling associated with an increase of soil moisture (and vegetation cover) causes a decrease in sensible heat flux during daytime. In comparison, we found no clear effect of irrigation fraction on T_{\max} over 1980–2000, a period with no net growth of irrigation (data not shown).

Very similar patterns were found when analyzing PRISM, CRU2.0, and CRU2.1 data sets, suggesting that results are not qualitatively very sensitive to the choice of the data set. For the CRU2.0 and CRU2.1 data sets, there were no grid cells falling in the highest levels of irrigation (CIF >80%) and only one grid cell falling in the 20–30% CIF class, but T_{\max} consistently declined at a faster rate as the degree of irrigation increases from 30% to 80%. These results are, by construction, independent of the choice of reference region and of potential factors influencing it (fog, stratus, sea breeze, or urbanization). They further support the notion that greater irrigated area causes cooling of summertime T_{\max} , because other climate forcings were unlikely to vary both temporally and spatially with irrigation. Irrigation practice in California peaks in summer and is significant in spring but is rather sparse during the fall and winter seasons (24). As

[§]See [SI Text](#) and [SI Fig. 7](#) for more details on the reference area.

¹To assess whether increasing the irrigation level has a significant effect on temperature trends, we need to assess whether the temperature trend over low-irrigated areas is significantly different than that over more intensively irrigated areas. To distinguish small trend differences, we used a statistical test (23) that computes the least square linear trend of $d(t)$ and tests the null hypothesis that the trend is not different from zero at 1% significance level, accounting for data temporal autocorrelation effects (see [S1 Text](#)).

30), but in the Central Valley, summertime cloudiness is too low to be implicated in explaining differential T_{\min} and T_{\max} trends.

One hypothesis, stating that irrigation development can explain the large increase in T_{\min} , is an object of controversy (e.g., 11, 20, 31, 32). Although there is no consensus among modeling studies, two observational studies (32, 20) have reported this result. In the first study, in comparing surface temperature trends estimated from reanalyses with those registered at the weather stations, Kalnay and Cai (32) found rapid increase in T_{\min} (and T_{\max}) in the Central Valley region that they attribute to changes in land use (including both irrigation and urbanization effect). In the second, based on an apparent contrast in summer T_{\min} trends in the Central Valley and the adjacent Sierra mountains, Christy *et al.* (20) attributed the nighttime warming in the Valley ($>0.3^{\circ}\text{C}$ per decade) to expanding irrigation. This attribution has been previously questioned because strong positive trends in nighttime temperature are a common feature throughout the Western U.S. and not only in irrigated regions (31). The lack of consistent variations in T_{\min} trends among the different irrigation classes found in Fig. 3 also refutes this interpretation and indicates that irrigation cannot explain the large nighttime warming observed in California.

A more credible hypothesis to explain the differential in T_{\min} and T_{\max} trends is that irrigation-induced cooling has counteracted a greenhouse gas-induced warming during the day but not during the night. Taking the T_{\max} trends for the grid cells that are on average 75% irrigated as a guide (-0.14°C to -0.25°C per decade; Table 1), we estimate the statewide effects of irrigation by linearly scaling from 75% to 100% the CIF- $d(t)$ trend relationship and multiplying it by the irrigated area represented by each CIF (SI Table 2). We estimate a regional effect of irrigation on summer T_{\max} trends of -0.021°C to -0.037°C per decade. This is smaller in magnitude than the observed trend for the state ($-0.048 \pm 0.06^{\circ}\text{C}$ per decade, from UW), and thus insufficient to entirely explain the summer T_{\max} cooling between 1915 and 1979. However, the effect of irrigation is likely underestimated. First, our analysis ignored the fact that meteorological stations in irrigated areas may influence the interpolated temperatures for nonirrigated cells in the gridded data sets. Second, the regions of reference from which our trends are computed may have also been influenced by irrigation. Indeed, it has been shown that, through advection of moisture from evapotranspiration and cloudiness feedbacks, effects of irrigation are probably not limited to regions of direct forcing but can impact broader-scale climate (18, 22), up to 75 km away (11). Accounting for such effects would involve trend analyses comparing the UW data set and a new version of the data set in which effects of irrigation are adjusted at the station level. Third, the estimate of irrigation's effect on T_{\max} may also be affected by on-shore breezes, which may have intensified in response to enhanced land-sea temperature contrast (33) and caused a cooling of coastal grid points in the reference region relative to inland, irrigated sites.

Since its introduction, we estimated that the local impact of irrigation has been 1.8°C – 3.2°C in regions that are, on average, 75% irrigated, which roughly corresponds, by linear interpolation, to a 2.4°C – 4.3°C cooling for a total conversion from potential to irrigated land. These values are smaller than those inferred from modeling studies [4.7°C – 8.2°C (11)]. This could be attributed to the limits of our method, but also to the fact that soil moisture depends on irrigation technique and crop. Whereas flood irrigation was practiced on $>80\%$ of irrigated land in California before 1970, sprinkler and drip irrigation systems are now more widely used to optimize water use and yield production (34). In consequence, observed soil moisture is likely often well below values assumed in models, such as field capacity.

Current and Future Evolution of Irrigation. Our results suggest that the rate at which irrigation developed rather than the presence of irrigation is at the origin of net cooling effect in several regions of the planet, possibly masking the effects of greenhouse-induced warming. In California, the end of irrigation expansion since 1980 is likely to persist in the future, as urban areas and water demand continue to expand (35) and irrigation water sources decline (either by overdrafting existing groundwater systems and rivers or by potential shifts in stream-flow timing or rainfall patterns). A recession in irrigation-induced cooling associated with projected future greenhouse-induced warming would result in substantial warming in the Central Valley, which could have strong, negative effects on agriculture. In most other intensively irrigated regions of the world, such as Asia, growth in irrigation has recently decelerated and is projected to slow even more in the future (36). In the U.S., with less irrigated farms, irrigation has decreased for the first time by 2% between 1998 and 2003. In consequence, throughout the major irrigated regions of the world, the cooling influence of irrigation on T_{\max} will therefore likely be much smaller in the next 50 years than in the past century.

Data and Methods

Irrigation Data Sets. Time-series of irrigated area in California were documented from 20 U.S. Department of Agriculture censuses available since 1889 and linearly interpolated between available censuses. The spatial distribution of current irrigation fraction (Fig. 1) was provided by a high-resolution ($5' \times 5'$) gridded data set of percent land area equipped for current irrigation (37).

Temperature Data Sets. Spatial and temporal climate variations in T_{ave} , T_{\min} , and T_{\max} and in DTR ($\text{DTR} = T_{\max} - T_{\min}$) over California are documented by four observational gridded data sets (UW, PRISM, CRU2.0, and CRU2.1) for the 1915–2000 period (the longest common period covered by the data sets). All observational products include some form of adjustment for nonclimatic influences (e.g., changes in instrumentation, observation time, and station location) and are suitable for long-term trend analysis. With a good station coverage over California [including both the U.S. Historical Climatology Network (HCN) and Cooperative network observations (COOP)], a high $1/8^{\circ} \times 1/8^{\circ}$ resolution and adjustment for urbanization effects, the UW data set (38) represents our best candidate to study the contribution of irrigation to temperature variations in California. PRISM is also a high-quality, high-resolution, and topographically sensitive ($4 \text{ km} \times 4 \text{ km}$) data set for the U.S., based on HCN and COOP stations but also on SNOTEL and agricultural climate data (39). The CRU2.0 (40) and CRU2.1 (41) data sets have $1/2^{\circ} \times 1/2^{\circ}$ resolution, mainly rely for California on adjusted HCN records, and were not adjusted for urbanization effects. However, their addition allowed the robustness of results to observational uncertainty over California to be tested. In all cases, the stations cover well both high and low irrigated areas (SI Fig. 8). In addition, the CRU2.1 data set enabled analyses in other regions that are not documented by the UW and the PRISM data sets. Trends in T_{\min} , T_{\max} , and T_{ave} from UW and CRU data sets agree well with those computed from individual U.S. HCN stations data in California for all seasons (12).

Regridding and Elevation Criterion. In all analyses, irrigation and elevation data sets are regridded to the resolution of each temperature data set, and all calculations are executed after masking data that do not represent California. To avoid any climate bias generated by elevation, our study focused only on irrigated and nonirrigated areas located at low elevation: any grid cells $>500 \text{ m}$ of altitude were excluded from analysis.

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