Empirical evidence for a recent slowdown in irrigation-induced cooling

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Edited by Hans Joachim Schellnhuber, University of East Anglia, Norwich, United Kingdom, and approved July 16, 2007 (received for review January 6, 2007)

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 ≈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 ≈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 ≈2% of global land surface is irrigated [≈17% of the 15 × 10^6 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. 2*A*) 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.

Author contributions: C.B. and D.L. designed research, performed research, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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.

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This article contains supporting information online at www.pnas.org/cgi/content/full/0700144104/DC1.

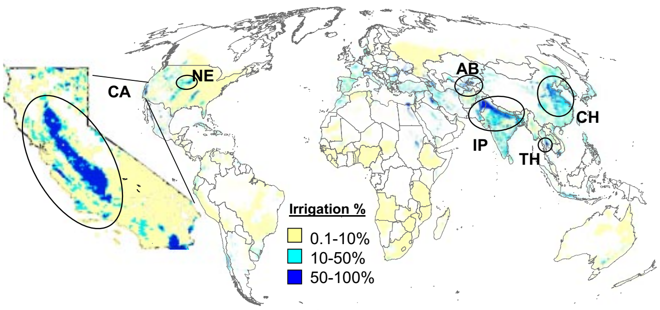

Fig. 1. Global map of the fraction of each 5′ × 5′ grid cell equipped for irrigation (percent, 37). Circles indicate major irrigation regions used in this study. AB, Aral Sea Basin; CA, California; CH, Eastern China; IP, Indo-Gangetic Plains of India and Pakistan; NE, Nebraska; TH, Thailand.

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. 2*A*). 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. 2*B*).

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. 3*A*). 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

§See *SI Text* and SI Fig. 7 for more details on the reference area.

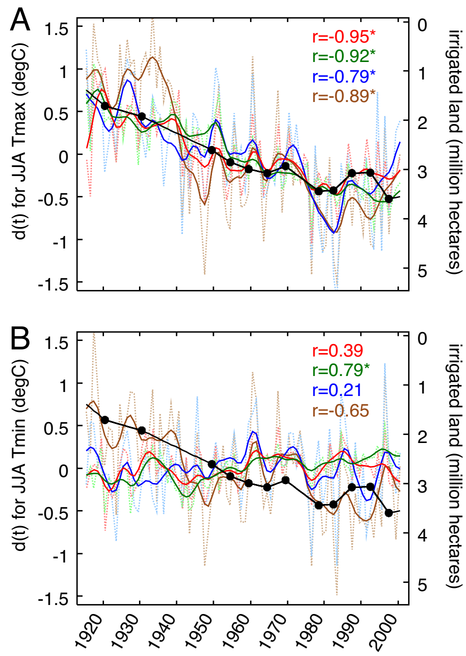

Fig. 2. Observed time-series of irrigated land cover in California and June–August temperature differences between intensively irrigated lands (CIF > 50%) and a reference area (0.1–10% CIF), both located in the Central Valley region (CV: 118.25–126.25°W, 34.75–40.25°N). $T_{\max}$ (*A*) and $T_{\min}$ (*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

¶To 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 *SI Text*).

Table 1. Climate least-squares linear trends (in °C·decade^{-1}) in heavily irrigated areas of the Central Valley (CIF > 50%) relative to the modestly irrigated reference region (CIF between 0.1% and 10%)

Data set	T_{max} 1915–1979	T_{min} 1915–1979	T_{ave} 1915–1979	DTR 1915–1979	T_{max} 1980–2000
UW	−0.136 ± 0.051***	+0.022 ± 0.037	−0.057 ± 0.036***	−0.157 ± 0.053***	0.099 ± 0.150
PRISM	−0.165 ± 0.032***	+0.037 ± 0.032**	−0.064 ± 0.021***	−0.202 ± 0.047***	−0.052 ± 0.112
CRU2.1	−0.157 ± 0.065***	+0.018 ± 0.059	−0.070 ± 0.055**	−0.176 ± 0.059***	0.409 ± 0.294**
CRU2.0	−0.249 ± 0.099***	−0.122 ± 0.079***	−0.186 ± 0.084***	−0.128 ± 0.066***	0.297 ± 0.227**

The 2σ trend confidence intervals are adjusted for temporal autocorrelation effects (see *SI Text*). **, $P < 0.05$; ***, $P < 0.01$.

expected, trends in wintertime T_{max} change modestly and often not significantly with increasing levels of irrigation (Fig. 3*A*).

Spatial Dependence of T_{min}, T_{ave}, and Diurnal Temperature Range (DTR) Trends. Here, we analyze the effect of irrigation fraction on T_{min}, daily average temperature (T_{ave}) and DTR trends, relative to those observed in the reference region (Fig. 3 *B*–*D*). In using the UW, PRISM, and CRU2.1 data sets, it appears that effects on June–August T_{min} were positive but very small, indicating that the warming in summertime nights occurring in California since 1915 (20) is unlikely the result of irrigation. However, CRU2.0 indicates that increasing levels of irrigation are associated with reduction of nighttime temperatures in both summer and winter seasons. These results are questionable because irrigation practice in California is very modest in wintertime (24), and trends in T_{min} should not be sensitive to the level of irrigation during this season (as seen in UW, PRISM and CRU2.1). The disagreement between CRU2.0 and the more recent CRU2.1 data set reflects changes in the gridding algorithms, how elevation and/or missing data are allowed for, and the underlying observational data.

The net impact of widespread irrigation (in regions where CIF >50%) is a significant cooling in T_{ave} (between −0.06°C and −0.19°C per decade) and a significant decline in DTR (−0.13°C to −0.20°C per decade) at the 1% level (Table 1). The results show strong consistency across data sets, at least in the sign of those effects. The surplus of energy at the surface to partition into latent and sensible heat fluxes and the active transpiration of plants in daytime can partly explain why the impact of irrigation is asymmetrical at the diurnal timescale (large during the day and minimal at night).

Analyses in Other Regions. India, China, U.S., and Pakistan contain the largest areas of irrigated land (Food and Agriculture Organization of the United Nations; Fig. 4*A*) and have all undergone significant expansion of irrigation since 1961 (+1.4 to +2.9% per year on average). Similarly, irrigated areas in the Aral Sea region increased by 60% in 20 years (3% per year) after Soviet policy assigned Central Asia the role of raw material supplier in the 1960s. Although irrigation generally slowed in the former Soviet Union after its dissolution (Fig. 4*B*), irrigation development has continued at a slower rate along the Amu Darya and Syr Darya Rivers, shrinking the Aral Sea at a concerning rate (25). Another region of interest is Thailand, which includes a substantial area of intensively (>50% CIF) irrigated land. Thailand experienced a major growth of irrigation in the 1950s (+13% per year during 10 years) and a rapid expansion since 1960 (+4.9% per year on average) (26).

We evaluated the effect of irrigation on climate for the period 1950–2000 in Nebraska (NE; second to California in irrigated area in the U.S.) using the PRISM data set, and in Eastern China (CH), the Indo-Gangetic Plains of India and Pakistan (IP), the Aral Sea Basin (AB) and Thailand (TH) using the CRU2.1 data set (Fig. 5).

In most regions, as seen in California, a cooling effect in daytime maximum temperature (T_{max}) was associated with increasing irrigation fraction in the summer season. In Thailand and in the Aral Sea basin, where irrigation has developed rapidly, the amplitude of the effect is estimated at −0.129°C and −0.077°C per decade, respectively ($P < 0.05$). In Nebraska, our results corroborate those of previous findings (16, 27) showing that mean maximum temperatures decreased over time in irri-

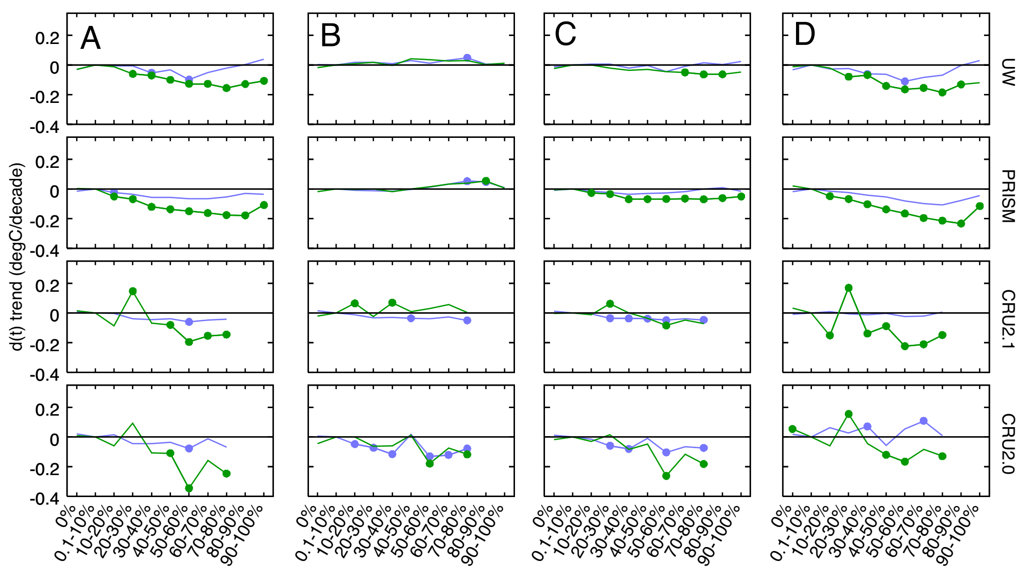

Fig. 3. Observed 1915–1979 trends in June–August (green) and December–February (blue). (*A*) T_{max} in regions of the Central Valley partitioned by CIF classes, relative to the trend in the reference class. Filled circles indicate that trend of $d(t)$ is statistically significant at $P < 0.01$. The same analyses were conducted for T_{min} (*B*), T_{ave} (*C*), and DTR (*D*).

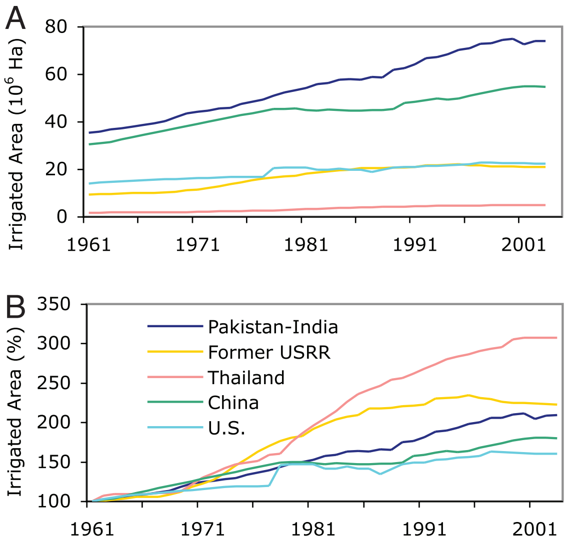

Fig. 4. Irrigated area expressed in 10^6 ha (*A*) and in percent relative to 1961 (*B*) for six different regions of the World.

gated agriculture sites and increased over adjacent natural grass sites. Also consistent with a previous study (27), we found a significant cooling effect of irrigation from 1950 to 2000 in regions of Nebraska where the current irrigation level exceeds 50% (−0.102°C per decade, $P < 0.01$) but no effect over the period 1915–1950 (0.049°C per decade, $P > 0.5$), i.e., prior the development of irrigation.

In India–Pakistan and Eastern China, the attribution of the temperature change to irrigation alone is unclear. In these regions, the 1979–1992 average in aerosol optical depth from the Total Ozone Mapping Spectrometer data set (Nimbus7-TOMS, 28) covaries with the level of irrigation (Fig. 6). In comparison, the distribution in aerosol is spatially homogeneous over the other regions. By reflecting a fraction of sunlight to space or by absorbing it, aerosols contribute to the observed cooling and obfuscate a change in temperature attributable to irrigation. Aerosols, such as black carbon, might be of particular concern, being largely emitted in rural areas (household burning of biofuels and coal, biomass burning). In India, temperature trends decrease with increased CIF in summer (the peak of the agricultural cycle in India), but we cannot determine how much of this cooling is due to irrigation alone. In China, T_{max} responds modestly to the level of irrigation in summer but increases significantly over irrigated soils in winter. A possible explanation for this finding is that a factor whose effects raise T_{max}, such as urbanization, is correlated spatially with irrigation and thus canceled out the effects of irrigation in summer. This is likely because most Chinese stations are located in or near cities (6). Additionally, in CRU2.1, the underlying station network is considerably sparser in China than, for example, in the U.S., and this considerably complicates the correction for spatial and temporal inhomogeneities (6). Overall, our methodology appears less suitable for detecting the influence of irrigation over large regions, where other climate forcings can exhibit substantial spatial variability.

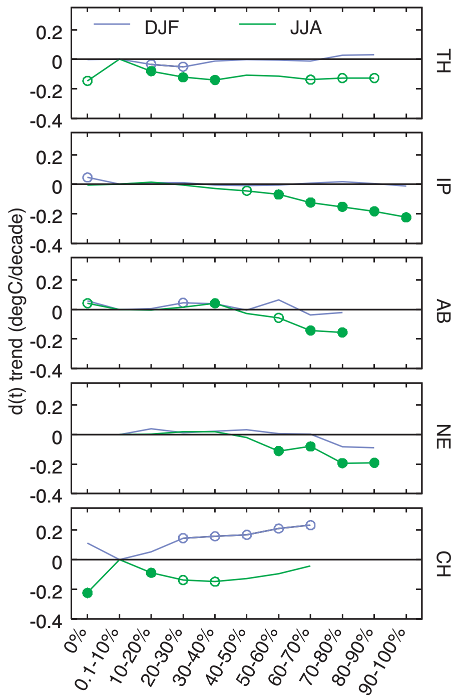

Fig. 5. Observed 1950–2000 June–August (JJA) and December–February (DJF) T_{max} trends in regions partitioned by CIF classes, relative to a reference class (0.1–10% CIF) for five irrigated regions, by using the PRISM data set for the Nebraska (NE) region and CRU2.1 for the four other regions. Filled/open circles indicate that the trend of $d(t)$ is statistically significant at $P < 0.01/0.05$. TH, Thailand; IP, Indo-Gangetic Plains of India and Pakistan; AB, Aral Sea Basin; CH, Eastern China.

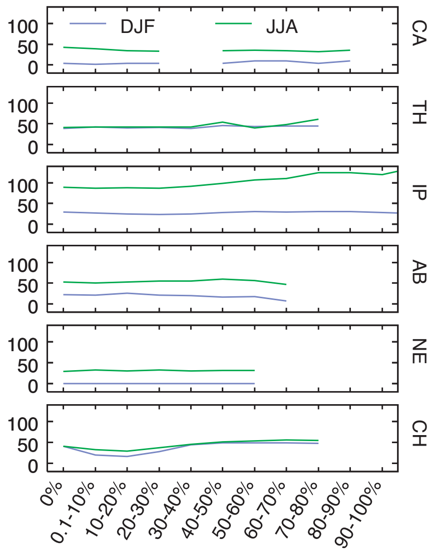

Fig. 6. Observed 1979–1992 June–August (JJA) and December–February (DJF) average in aerosol optical depth (AOD, unitless) from the Total Ozone Mapping Spectrometer data set (Nimbus7-TOMS, 28) in six regions partitioned by CIF classes. CA, California, TH, Thailand; IP, Indo-Gangetic Plains of India and Pakistan; AB, Aral Sea Basin; NE, Nebraska; CH, Eastern China.

Relative Importance of Irrigation for Observed Trends in California. In California, between 1915 and 2000, both T_{min} and T_{max} have increased in winter at a rate exceeding those possible from natural climate variability alone (12). Contributions from external factors, such as increase in greenhouse gases, are thus required to explain such trends. In summer however, although T_{min} has increased significantly, there has been no significant trend for T_{max} (results that are not sensitive to the inclusion of adjustments for urbanization effects). The observed worldwide decline in DTR in the latter part of the 20th century is often associated with increase in cloud cover and soil moisture (29–

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°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 ± 0.06°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′ × 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 (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° × 1/8° 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 km × 4 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° × 1/2° 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 m of altitude were excluded from analysis.

We warmly thank P. Duffy and B. Santer for their constructive comments, P. Jones and A. Hamlet for the list of underlying stations and helpful discussions, and our three reviewers for their suggestions to improve the manuscript. C.B. was supported by the State of California through the Public Interest Energy Research Program, and D.L. was supported by a Lawrence Fellowship from Lawrence Livermore National Laboratory under Contract W-7405-Eng-48. Data sets were provided by the Surface Water Modeling group at the University of Washington (Seattle, WA) via the web site at www.hydro.washington.edu/Lettenmaier/gridded_data), by the Climatic Research Unit (CRUTS2.0, CRUTS2.1, www.cru.uea.ac.uk/cru/data/), and by the PRISM Group, Oregon State University (Corvallis, OR), www.prismclimate.org.

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