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Irrigation cooling effect on temperature and heat index extremes

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[1] Previous studies of the long-term climate effects of irrigation have focused on average monthly temperatures. Given the importance of temperature (T) extremes to agriculture and human health, we evaluated irrigation induced changes in various metrics of T extremes using daily observations in California and Nebraska. In addition, simulations from a regional climate model were used to evaluate irrigation effects on T and heat index (HI; also known as the discomfort index) extremes in California, with the latter representing a combined measure of T and humidity. Contrary to our expectation that irrigation would have larger effects on hot days when sensible heat fluxes are higher, both observations and a regional climate model indicate that irrigation cools T on the hottest days of the year by a similar magnitude as on an average summer day. The HI is also reduced by irrigation, but by a much smaller magnitude than T because of the higher humidity above irrigated surfaces. Interestingly, HI is influenced less on the most extreme days than on average days, because of the nonlinear effect of humidity on HI at high T.
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1. Introduction

[2] The impacts of climate change on agriculture will depend, in part, on changes in the frequency and intensity of extreme events. While most impact assessments have focused on changes in monthly or growing season averages, a small but growing number of studies have begun to quantify the response of cropping systems to temperature and precipitation extremes [*Rosenzweig et al.*, 2002; *Schlenker and Roberts*, 2006; *White et al.*, 2006]. A current challenge to these efforts is the reliability of climate model projections of extreme temperatures in agricultural areas. More specifically, climate models have relatively simple treatments of land use that may ignore important processes affecting extreme events.

[3] For example, soil moisture is an important control on heat and water transfer between the land and atmosphere, which in turn affects the development of extreme heat events [*Ferranti and Viterbo*, 2006]. While roughly 17% of global croplands are irrigated, none of the climate models included in the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) includes a representation of soil moisture changes due to irrigation. Meteorological studies have demonstrated effects of irrigation on surface temperatures, cloud formation and precipitation at local to continental scales [*Adegoke et al.*, 2003; *Segal et al.*, 1998]. Analysis of long-term observations [*Bonfils and Lobell*, 2007; *Mahmood et al.*, 2006] and climate or land surface modeling [*Haddeland et al.*, 2006; *Kueppers et al.*, 2007] efforts have also shown that irrigation can consistently reduce maximum daily temperatures by up to 7.5°C upon irrigation. However, most of these studies have not explicitly considered extreme temperatures. *Barnston and Schickedanz* [1984] argued that the cooling effect of irrigation in Texas would be significantly larger on the hottest days because of reduced humidity relative to cool days. However, in an analysis of USHCN station data, *Lobell and Bonfils* [2008] found similar effects of irrigation on average and very hot summer days in California.

[4] The main goal of this paper is to evaluate the long-term climatological effect of irrigation on extreme temperatures, using two independent approaches. First, we conduct an empirical analysis based on gridded daily temperature data sets in both California and Nebraska. Second, we utilize simulations from a previously published regional climate model (RCM) experiment in California. A secondary goal is to evaluate effects of irrigation on extremes in the heat index (HI), which is a measure of discomfort that combines temperature and relative humidity (RH) [*Schoen*, 2005]. We consider the HI because it is often a more useful predictor of human health effects and mortality than temperature itself, and provides a basis for heat advisories in the United States [*Davis et al.*, 2003]. For the HI analysis we focus only on the RCM simulations, as long-term spatially complete gridded data sets of daily RH observations are currently unavailable.

2. Methods and Models

2.1. Temperature

[5] Our analysis of historical observations followed the method of *Bonfils and Lobell* [2007] by comparing historical temperature trends in areas with high levels of irrigation (>50% of area equipped for irrigation) with trends from a nearby "reference" area with 0.1–10% irrigation. Analyses were conducted for the Central Valley of California (CA) and the irrigated plains of Nebraska (NE), which represent the two regions in the United States with the most amount of land that is intensively (>50% of area) irrigated. In both regions, only grid cells below an elevation of 500 m were used to avoid bias from comparing cells in low-lying irrigated areas to higher elevations. A 1/12° × 1/12° resolution map of area equipped for irrigation [*Siebert et*

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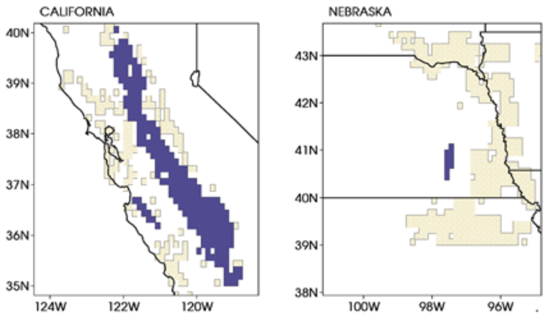

Figure 1. The (left) California (CA) and (right) Nebraska (NE) study regions. Dark blue cells indicate the irrigated region where greater than 50% of the grid cell area is equipped for irrigation. Light brown indicates the associated reference region with 0.1–10% area equipped for irrigation, according to the maps of *Siebert et al.* [2005]. Both regions were restricted to grid cells with mean elevation below 500m.

al., 2005] was used to delineate the irrigated and reference regions, which are illustrated in Figure 1.

[6] For gridded temperatures, we used 1/8° × 1/8° resolution grids of historical daily minimum (T_{min}) and maximum (T_{max}) temperatures, obtained from the Surface Water Modeling group at the University of Washington (http://www.hydro.washington.edu/Lettenmaier/Data/gridded/). Two versions of this data set exist, an earlier one that covers the entire the United States for January 1949–July 2000 [*Maurer et al.*, 2002], and a more recent one that corrects for temporal inhomogeneities in station data and extends from January 1915–December 2003 but covers only selected western states [*Hamlet and Lettenmaier*, 2005]. In this study, we use the newer version (UW2) for CA but rely on the first version (UW1) for NE, which is beyond the current spatial extent of UW2.

[7] The irrigation map was re-sampled to the slightly coarser resolution of the temperature data sets, and spatial averages of daily T_{max} were computed for both the irrigated and reference regions for the relevant study periods (n_{CA_irr} = 227 grid cells; n_{CA_ref} = 147; n_{NE_irr} = 9; n_{NE_ref} = 428). In CA, we used the period 1915–1980, as this represents the period of most rapid irrigation expansion during which irrigated land area doubled [*Bonfils and Lobell*, 2007]. In NE, the coverage of the UW1 data set limited the analysis to 1950–1999, a period in which irrigated area increased by a factor of more than eight (http://www.ers.usda.gov/Data/MajorLandUses/).

[8] We then computed several metrics of temperature extremes using daily T_{max}. Following *Hegerl et al.* [2004], we computed average T_{max} on the hottest 1, 5, 10, and 30 days of each year, and also the average T_{max} for June–August (JJA) for comparison. An index of heat wave duration was computed using the warm spell duration index (WSDI), which is one of the extreme indices defined by the Expert Team on Climate Change Detection and Indices (ETCCDI, http://cccma.seos.uvic.ca/ETCCDI/list_27_indices.shtml.) The WSDI is defined as the annual count of days with at least six consecutive days when T_{max} exceeds the 90th percentile of the climatology. The climatology was defined for each day using values from 1961–1990 for a five day window centered on that day (giving a total of 150 values for each day). Linear trends in all extremes were computed using ordinary least squares regression for the entire study period, 1915–1980 in CA and 1950–1999 in NE, and are reported in °C decade^{-1}. To estimate the effects of irrigation, we calculated trends in the differences of extremes between irrigated and reference regions. In this manner, climate variations or trends (ascribable to natural modes of climate variability or resulting from other forcing agents) that are common to both irrigated and reference regions do not affect the analysis [*Bonfils and Lobell*, 2007]. The 95% confidence interval was computed non-parametrically via bootstrap resampling (n = 50) of the original time series. The different data sets and time periods used in the two regions caution against direct comparison of the values derived in each region, and instead we focus on a qualitative comparison of results in each region.

[9] To complement the observational study, we analyzed RCM simulations from the experiment described by *Kueppers et al.* [2007]. Briefly, we performed two simulations with RegCM3 [*Pal et al.*, 2007] at a horizontal resolution of 30km, using NCEP/DOE Reanalysis II as lateral boundary conditions for the period 1979–2000. One simulation used California land cover defined as potential natural vegetation (NAT) and one used modern day land cover that included irrigated cropland (MOD), where soil moisture for irrigated land is maintained at field capacity all year round. For the current study, we spatially averaged daily T_{max} for all grid cells converted to irrigated agriculture in the Central Valley (between 24–30°N and 118–124°W; n = 27 grid cells) in the MOD run for each simulation, and computed temperature extremes for the final 20 years of the simulation. Heat wave extremes in MOD were computed using the climatology from NAT. We calculated differences between MOD and NAT 20-year averages for each T and HI metric to estimate the effect of irrigation on extremes in the RCM.

2.2. Heat Index

[10] As described by *Kueppers et al.* [2007], the simulated cooling of average monthly T_{max} is largely driven by higher latent heat fluxes, which also leads to substantial increases in RH. A relevant issue is therefore the net effect on HI, which decreases with lower T but increases with higher RH. We computed the daily maximum HI (HI_{max}) for the MOD and NAT runs using the definition of *Schoen* [2005], which is an empirical fit to a data table generated from a model of human physiology:

$$\mathrm{HI} = \mathrm{T} - 1.0799\ \mathrm{e}^{0.03755\mathrm{T}}\left[1 - \mathrm{e}^{0.0801(\mathrm{D}-14)}\right] \tag{1}$$

where T is temperature and D is dewpoint, which varies with RH and T. Figure 2 illustrates the relationship between HI and RH for different levels of T, demonstrating that RH has a stronger effect on HI on warmer days.

3. Results and Discussion

3.1. Temperature

[11] Observed trends in T_{max} were negative for irrigated grid cells in both CA and NE over the study periods, and slightly positive for the reference region in CA but negative for the reference region in NE (Figure 3). The time series of

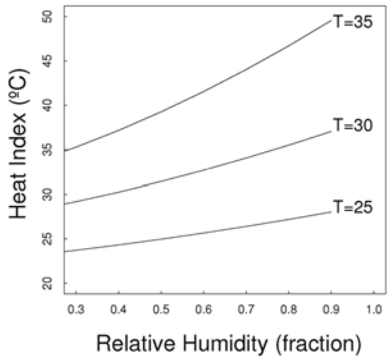

Figure 2. The relationship between heat index (HI) and relative humidity (RH) for different values of temperature (T), according to the equations of *Schoen* [2005].

differences between the irrigated and reference regions exhibited significant negative trends for both states.

[12] The cooling effect on the hottest days, although slightly larger, was indistinguishable from that on the average summer day. We therefore find little evidence that irrigation has a larger or smaller effect on particularly hot days.

[13] Trends in WSDI were not significantly different from zero for the irrigated and reference regions, or for the difference between the two (Figure 3). A significant effect of irrigation was observed for the number of heat waves in CA (the number of times per year that six or more consecutive days had T_{max} above the 90th percentile), but not in NE (not shown). Overall, there was therefore no clear signal of changes in heat waves resulting from irrigation, despite significant effects of irrigation on T_{max} extremes. A possible explanation is that WSDI has many years with a value of zero (e.g., 25 out of 66 years in CA reference region), which leads to an odd statistical distribution with several values of zero and all other values greater than five. Trend detection in time series of WSDI is therefore difficult as the values can appear quite noisy, which has led some to exclude heat wave indices altogether from their analysis [*Kiktev et al.*, 2003]. Others, however, have found significant trends in WSDI for many regions, although not CA or NE [*Alexander et al.*, 2006].

[14] The results of the RCM simulations were generally consistent with those from the observational analysis. Namely, T_{max} extremes were reduced by irrigation, but by an amount that differed little from the effect on an average summer day (Figure 4a). The primary mechanism responsible for this cooling was an increase in latent heat flux and corresponding reduction in sensible heat flux, as described in detail by *Kueppers et al.* [2007]. That the increase in latent heat flux was the same on average and very hot days indicates that evapotranspiration in RegCM3 for conditions typical of California summer is limited by a factor other than temperature, such as solar radiation, stomatal conductance, or wind speed. Indeed, there is little day-to-day correlation between evapotranspiration and daily temperature in the model, both for MOD and NAT experiments (not shown). The WSDI was reduced in the RCM from an average of 8.9 days per year in NAT to 1.7 days per year in MOD, a decrease equivalent to roughly one heat wave per year.

[15] The magnitude of T_{max} decreases in the RCM from irrigation, for example 7.0°C for JJA, was substantially larger than the 0.13°C per decade (or roughly 1.0°C over the 1915–1980 period) in the UW analysis for CA. These observed and simulated changes are however not directly comparable. One obvious reason for this is that of the ~75% of land area that is currently irrigated in the irrigated region, half was already irrigated by 1915. Thus, irrigation was introduced in only ~38% of the land area in the irrigated region over 1915–1980 [*Bonfils and Lobell*, 2007]. If one assumes that the regional effect of irrigation scales linearly with irrigated area, this implies a roughly 2.5°C cooling for 100% irrigation, still well below the RCM value. Other possible reasons for the discrepancy include

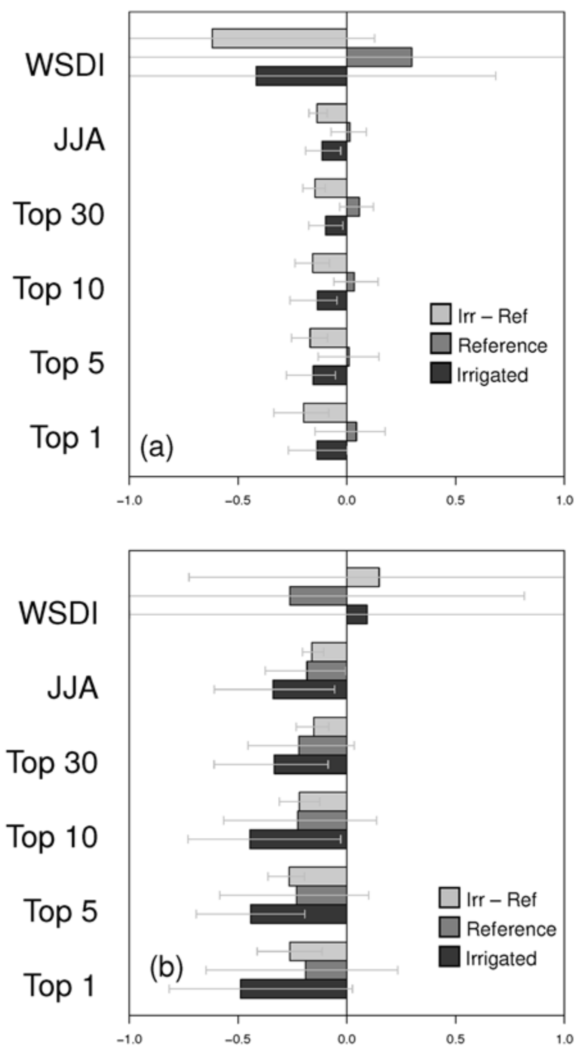

Figure 3. Decadal trends in the average of the 1, 5, 10, and 30 highest daily T_{max} values per year, along with the average June–August (JJA) T_{max} and warm spell duration index (WSDI) for (a) California and (b) Nebraska. Error bars indicate 95% confidence interval based on bootstrap resampling. Units are °C decade^{-1} for all indices except WSDI, which is expressed as day decade^{-1}. Irr-Ref represents the trends in the difference between values in the irrigated and reference regions, used as a measure of the effect of irrigation.

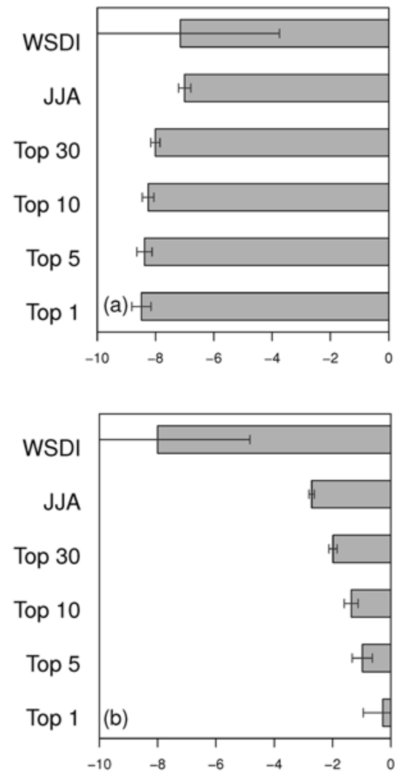

Figure 4. (a) Average differences between the final 20 years of the MOD and NAT simulations (MOD−NAT) for the 1, 5, 10, and 30 highest daily T_{max} values per year, along with the average June–August (JJA) T_{max} and warm spell duration index (WSDI). Units are °C for all indices except WSDI, which is expressed as days. (b) Same as in Figure 4a except using HI_{max} instead of T_{max}. Averages are taken over all 27 grid cells converted to irrigated agriculture in MOD. Error bars indicate ± 2 standard errors.

artificial smoothness in the gridded data sets that arises from the interpolation of station data and obscures the full effect of irrigation, downwind effects of irrigation on the nearby reference region grid cells, and unrealistically high and stable soil moisture in the RCM simulation [*Bonfils and Lobell*, 2007].

3.2. Heat Index

[16] Values of the extreme indices and JJA averages computed from HI_{max} rather than T_{max} reveal some interesting differences between the two variables (Figure 4b). First, the irrigation-induced decrease in average summer HI_{max} was just 2.7°C, less than half the value for T_{max}. This result is driven by the increase in summer RH from an average 0.45 in NAT to 0.69 in MOD, which counters but does not completely balance the effect of reduced T on HI. More interestingly, the most extreme HI_{max} values were affected much less by irrigation than the average summer day, with the highest value of HI_{max} not statistically different between the NAT and MOD simulations.

[17] The diminished response of extreme heat days to irrigation is explained by the temperature dependence of the relationship between HI and RH (Figure 2). For example, an increase in RH from 0.45 to 0.69 leads to an increase in HI of 3.1°C, 5.6°C, and 10.1°C at T equal to 30°C, 35°C, and 40°C, respectively. In the NAT simulation, T_{max} averages roughly 36°C in JJA and reaches above 40°C on the hottest days. A cooling of ~7°C in T_{max} from irrigation is therefore larger than the effect of RH increases on an average summer day, but not on the hottest days of the year. The level of discomfort to humans is accordingly diminished by irrigation for average summer days, but the increase of humidity on the hottest days makes these days just as uncomfortable as they would be without irrigation.

4. Summary and Conclusions

[18] The results of both the long-term observational and modeling studies presented here indicate that maximum temperatures for two major irrigated regions in the United States are similarly reduced by irrigation on average and hot summer days. While this conclusion implies that the frequency and length of heat waves should also be diminished by irrigation, we observed a significant effect only in the modeling study. The lack of a detectable trend in WSDI in the observations likely results from the high percentage of years in the current data sets with WSDI equal to zero.

[19] Values of the maximum daily heat index, HI_{max}, in the RCM simulations were reduced much less by irrigation than T_{max}, as a result of substantial increases in RH. Values on extremely uncomfortable days (highest HI_{max} of the year) were particularly unaffected by irrigation because HI is more sensitive to RH at higher temperatures. Future work to synthesize observations of relative humidity in relation to land cover and land use change–perhaps by pursuing a similar effort to that for temperature by digitizing, quality checking, and interpolating data to fine mesh grids–will be useful for further understanding extreme values of HI beyond the modeling results presented here. Overall, we conclude that irrigation has a similar cooling effect on relatively average and hot summer days in terms of T_{max}, but that cooling effects on HI_{max} are more pronounced on average days.

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