The Role of Irrigation Expansion in Past and Future Temperature Trends

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ABSTRACT: Expansion of irrigated land can cause local cooling of daytime temperatures by up to several degrees Celsius. Here the authors compare the expected cooling associated with rates of irrigation expansion in developing countries for historical (1961–2000) and future (2000–30) periods with climate model predictions of temperature changes from other forcings, most notably increased atmospheric greenhouse gas levels, over the same periods. Indirect effects of irrigation on climate, via methane production in paddy rice systems, were not considered. In regions of rapid irrigation growth over the past 40 yr, such as northwestern India and northeastern China, irrigation's expected cooling effects have been similar in magnitude to climate model predictions of warming from greenhouse gases. A masking effect of irrigation can therefore explain the lack of significant increases in observed growing season maximum temperatures in these regions and the apparent discrepancy between observa-

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tions and climate model simulations. Projections of irrigation for 2000–30 indicate a slowing of expansion rates, and therefore cooling from irrigation expansion over this time period will very likely be smaller than in recent decades. At the same time, warming from greenhouse gases will likely accelerate, and irrigation will play a relatively smaller role in agricultural climate trends. In many irrigated regions, therefore, temperature projections from climate models, which generally ignore irrigation, may be more accurate in predicting future temperature trends than their performance in reproducing past observed trends in irrigated regions would suggest.

KEYWORDS: Land use; Climate

1. Introduction

Efforts to anticipate the impacts of climate change on crop production and food security depend critically on projections of future climate in agricultural regions. General circulation models (GCMs) commonly used to make these projections consider changes in atmospheric concentrations of carbon dioxide (CO_2) and other well-mixed greenhouse gases, and many also consider changes in anthropogenic aerosol levels. However, few consider climate forcing from land-use changes, which may be especially important in the small fraction (~12%) of land surface on which crops are grown.

Several studies have evaluated the sensitivity of climate to land-cover changes, such as conversion of forests to croplands (Feddema et al. 2005; Sitch et al. 2005), while a smaller number have evaluated the influence of management changes within existing agricultural lands, such as introduction of irrigation or adoption of reduced till practices (Lobell et al. 2006). Of these changes, increased irrigation appears to represent one of the strongest potential climate forcings, with both observational and modeling studies suggesting a local cooling of daily maximum temperature by as much as 8°C following the introduction of irrigation (Haddeland et al. 2006; Lobell et al. 2006; Bonfils and Lobell 2007; Kueppers et al. 2007). These studies have led several researchers to suggest that irrigation may have masked the warming effects of greenhouse gas increases in heavily irrigated regions (Bonfils et al. 2007; Kueppers et al. 2007). The regional warming observed upon the desiccation of the Aral Sea (Small et al. 2001) also underscores the potential importance of hydrological changes for regional climate.

For the purpose of modeling future climate change, however, the key question is not whether irrigation will have some effect, but whether this effect will be large relative to other forcings and, therefore, whether improved treatment of irrigation in climate projections is warranted. A secondary issue relevant to future projections is the relative role that irrigation has played in climate changes over the past 50–100 yr. For example, can irrigation explain mismatches between observed and simulated historical climate trends in agricultural regions? Such information on the sources of past model errors is useful in evaluating the reliability of future model projections (e.g., Tebaldi et al. 2005).

Whether the inclusion of a particular land-use change would substantially alter model projections generally depends on 1) the amount of land-use change that occurs; 2) the sensitivity of climate to this change; and 3) the climate impact of forcings already included in the model, such as elevated CO_2. As mentioned, several studies have focused on the second of these criteria, but without placing the sensitivity in the context of other climate forcings. Here, we compare the climate effects of irrigation with other forcings for both past and future climates, utilizing data on 1961–2000 irrigation trends by country, projections of 2000–30 irrigation trends, and simulations of twentieth- and twenty-first-century climate from a suite of climate models used in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). We do not consider biogeochemical effects of irrigation, namely, the production of methane from paddy rice fields, which contribute to global warming but have small local effects.

2. Data and methods

The Food and Agriculture Organization (FAO) of the United Nations maintains records on annual irrigated area in each country since 1961. In collaboration with others (Doll and Siebert 1999; Siebert et al. 2005), FAO has also developed a dataset on the spatial distribution of percent land area equipped for irrigation circa 2000, with global extent and 1/12th degree resolution (~10 km at the equator). For this study, a map of 1961 irrigated area was produced by multiplying the percent irrigation in each grid cell by the ratio of 1961 to 2000 irrigated area for the country containing the grid cell.

As part of a recent FAO assessment of agriculture trends (Bruinsma 2003), Faurès et al. (Faurès et al. 2002) developed projections of irrigated area in 2015 and 2030 for 93 developing countries. These projections were based on consideration of many factors, including availability of suitable land and water resources, expectations for food demand, and productivity growth rates. Here, the ratio of projected area in 2030 to irrigated area in 2000 was used to derive an estimate of 2030 irrigated area for each grid cell. For grid cells where the result exceeded 100%, the excess above 100% was instead allocated to the next highest grid cell within the country. This was done iteratively until all grid cells were between 0% and 100% irrigation. The resulting maps of irrigation for the three years were combined to produce difference maps for 1961–2000 and 2000–30.

Estimates of temperature responses to irrigation exist from both modeling and empirical studies. Unfortunately, some modeling studies consider only extreme irrigation treatments (e.g., constant soil saturation) that could result in overestimates of temperature responses (Lobell et al. 2006), while many observational studies are based on station data from regions that are only partially irrigated (Barnston and Schickedanz 1984; Mahmood et al. 2006), thus likely underestimating the temperature response to 100% irrigation. Studies that utilize more realistic model treatments or attempt to empirically determine the effect of full irrigation have been limited mainly to the western United States, particularly California (Table 1). In this region, estimates range from ~2° to 8°C cooling of daily maximum temperatures (Tmax) for 100% irrigation, with small and often nonsignificant effects on minimum temperatures (Tmin). It is worth noting that, although the modeling studies assume constant soil moisture, the simulated effects agree reasonably well with empirical estimates.

To quantify the effect of past or future irrigation changes on growing season Tmax, the irrigation changes from above were multiplied by 2°, 5°, and 8°C to provide low, medium, and high estimates, respectively, of irrigation's impact. This

Table 1. The estimated impacts of irrigation on maximum and minimum surface temperatures reported in previous studies. (n/s is no statistically significant effect was found.)

Location	Observational (O) or modeling (M) study	Month(s)	Tmax change for 100% irrigation	Tmin change for 100% irrigation	Reference
Central Valley, California (CA)	O (Gridded data)	June–August	−4.3 to −2.4	n/s	Bonfils and Lobell 2007
CA	O (Station data)	June–August	−5.0 ± −2.9	n/s	Lobell and Bonfils 2008
CA	M (One regional climate model, 20-yr simulation)	June–August	−7.0 ± 0.2	−0.9 ± 0.2	Kueppers et al. 2007
CA	M (Three regional climate models, 1-yr simulation)	August	−8.2 to −4.7	−0.8 to 2.5	Kueppers et al. 2008
Western United States	M (Three regional climate models, 1-yr simulation)	August	−6.1 to −2.9	−0.8 to 2.0	Kueppers et al. 2008

approach assumes that the range of irrigation effects inferred from studies in California include the true effects in irrigated areas worldwide. In a global modeling study, Lobell et al. (Lobell et al. 2006) found similar effects of irrigation on growing season Tmax in the major irrigated regions, with the exception of China where impacts were roughly half as large because of greater growing season rainfall relative to other irrigated regions. The global modeling study of Boucher et al. (Boucher et al. 2004), which prescribed evaporative fluxes based on estimated water withdrawals, similarly indicated comparable changes in annual average temperature for California and other major irrigated regions. Haddeland et al. (Haddeland et al. 2006) reported similar effects of irrigation on surface temperatures in the Colorado and Mekong river basins, with a magnitude consistent with the California studies. Therefore, the wide range of effects considered in the current study (2°–8°C) likely includes the actual impacts for most irrigated regions.

To quantify temperature changes due to forcings other than irrigation, such as greenhouse gas and aerosol changes, simulations of Tmax from GCMs involved in the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) that contributed to the AR4 were used (Table 2; data and model descriptions available online at http://www-pcmdi.llnl.gov). Average monthly Tmax was available for eight and seven models for the twentieth- and twenty-first-century simulations, respectively. Simulations for three emission scenarios [Special Report on Emissions Scenarios (SRES) A1b, A2, and B1] were used for analysis of twenty-first-century trends, with a total of 18 model-scenario combinations. For models with multiple realizations, only the first realization was used in our analysis, so that results were not biased to any single model with a large number of realizations. The intermodel range therefore includes uncertainty due both to structural model differences and differences in initial conditions, the latter of which were not reduced as commonly achieved by using ensemble averages.

Table 2. Climate model simulations of monthly average maximum temperatures used in this study. See PCMDI Web site (http://www-pcmdi.llnl.gov) for more details on individual models. Scenarios with available simulations are marked with an x.

Model name	Originating group(s)	Twentieth century	SRES B1	SRES A1b	SRES A2
Bjerknes Centre for Climate Research Bergen Climate Model version 2.0 (BCCR-BCM2.0)	Bjerknes Centre for Climate Research, Norway	x	x		x
Community Climate System Model version 3 (CCSM3)	National Center for Atmospheric Research, United States	x	x	x	x
Commonwealth Scientific and Industrial Research Organisation Mark version 3.0 (CSIRO-Mk3.0)	CSIRO Atmospheric Research, Australia	x	x	x	x
Goddard Institute for Space Studies Atmosphere–Ocean Model (GISS-AOM)	National Aeronautics and Space Administration (NASA) Goddard Institutes for Space Studies, United States	x	x	x	
Institute for Numerical Mathematics Climate Model version 3.0 (INM-CM3.0)	Institute for Numerical Mathematics, Russia	x	x	x	x
Model for Interdisciplinary Research on Climate 3.2, medium-resolution version [MIROC3.2 (medres)]	Center for Climate Systems Research/National Institute for Environmental Studies/Frontier Research Center for Global Change (CCSR/NIES/FRCGC), Japan	x	x	x	x
Model for Interdisciplinary Research on Climate 3.2, high-resolution version [MIROC3.2 (hires)]	CCSR/NIES/FRCGC, Japan	x	x	x	
Parallel Climate Model (PCM)	National Center for Atmospheric Research, United States	x			

For comparison with effects of irrigation changes, linear trends in winter [December–February (DJF)] and summer [June–August (JJA)] Tmax were computed for 1961–99 in the twentieth-century simulations, and for 2001–30 in the twenty-first-century simulations. All trends were computed using ordinary least squares linear regression. Data for year 2000 were omitted, as some models did not provide data for all months in this transition year between "historical" and "future" runs. All climate and irrigation datasets were resampled to a 0.5° × 0.5° grid to facilitate comparison. In addition, linear trends in observed temperatures for 1961–99 were computed from the Climatic Research Unit (CRU) TS2.1 dataset (Mitchell and Jones 2005).

3. Results

From 1961 to 2000, the largest irrigation increases occurred in the Indo-Gangetic plains of northern India and Pakistan, where more than 25% of land area was estimated as converted to irrigated agriculture over the four decades

(Figure 1). Substantial increases of more than 10% also occurred in northeastern China, Turkey, and central Mexico. For comparison with other climate forcings, we focus on averages over four spatial domains: 1) northwestern India (NW India; 28°–32°N, 74°–79°E; outlined in Figure 1c); 2) northeastern China (NE China; 31°–38°N, 113°–118°E); 3) all land in developing countries with more than 10% irrigated land in 2000 (DV_{Irr}); and 4) all land in developing countries (DV_{All}). The first two represent areas with the most rapid irrigation trends since 1960, where the relative impact of irrigation on climate should be greatest. DV_{Irr} provides a measure of how important irrigation changes are to irrigated agricultural areas in general (i.e., including regions with less rapid land-use changes), while DV_{All} measures the overall importance of irrigation trends at very broad scales.

The estimated impact of irrigation trends on Tmax in these regions range from a maximum cooling effect of −0.73°C $decade^{-1}$ in NW India (or 2.9°C of total cooling over four decades) to a negligible cooling of −0.01 $decade^{-1}$ for DV_{All} (Figure 2a). Figure 2 also presents the average and range of climate model simulated trends in Tmax for the relevant growing seasons in these regions, as well as the observed trend for 1961–99. Averages for DJF were used in NW India because irrigation is most prevalent during the winter wheat season (FAO 2007), while averages for JJA were used for the other three regions.

Tmax trends from increasing greenhouse gases and other forcings included in climate models were mainly positive for 1961–99, with all but three simulations in NE China indicating a warming trend (Figure 2a). Interestingly, however, Tmax trends computed from the CRU dataset were below the minimum simulated trends for NW India and NE China. In both cases, the lack of irrigation forcing in the climate models can explain this disparity, as the observed trends lie within or above the range of estimated impacts of irrigation. This result highlights the potential masking effect that irrigation expansion has had in recent decades, as suggested by recent studies (Bonfils and Lobell 2007; Kueppers et al. 2007).

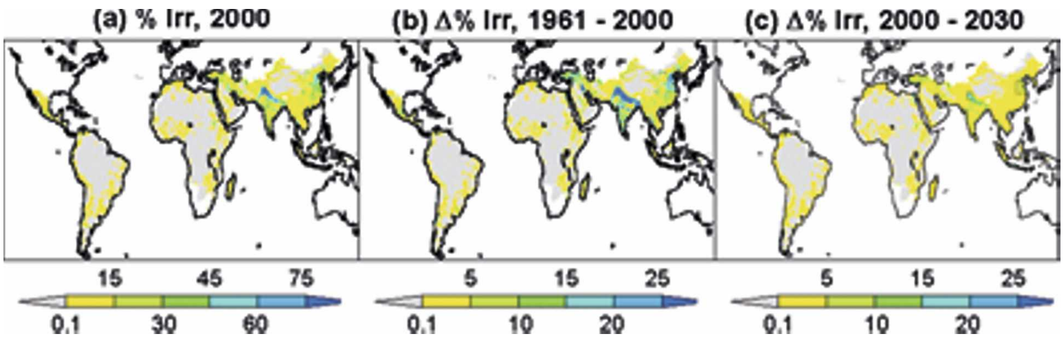

Figure 1. (a) Percent of each 0.5° × 0.5° grid cell equipped for irrigation in 2000 (Siebert et al. 2005). (b) Change in percent irrigation from 1961 to 2000 based on historical country data (FAO 2006). (c) Projected change in percent irrigation from 2000 to 2030 based on FAO country projections (Faurès et al. 2002). Countries shown in white were not considered in this study. Boxes in (c) outline NW India and NE China regions used in this study.

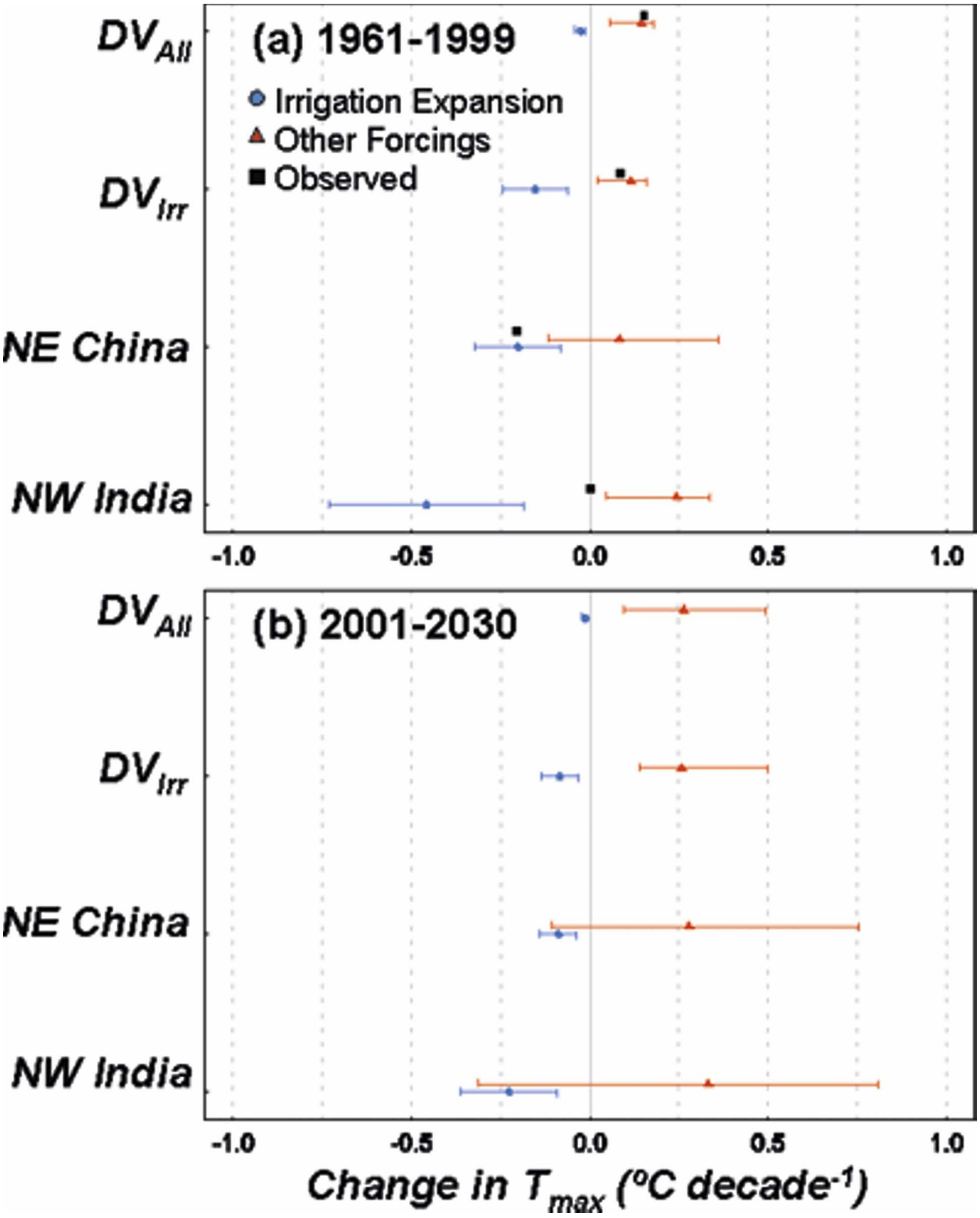

Figure 2. (a) Estimated change in growing season average maximum temperature (°C decade^{-1}) for 1961–99 in four regions due to irrigation expansion (circles) and nonirrigation forcings included in the CMIP3 models (triangles). Bars show range (min to max) of estimated impacts. Squares indicate the observed trend for the same time period, based on CRU TS2.1. (b) Same as in (a), but for projected changes for 2001–30.

At broader scales (DV_{Irr} and DV_{All}), the expected temperature effect of irrigation is smaller, and observed trends in Tmax lie within the range of climate model simulations. Thus, the masking effect of irrigation becomes less important at broader spatial scales, as expected since average irrigation extent is reduced when including areas outside of India and China.

For future projections, irrigation trends are anticipated to decelerate in most developing countries, though increases of more than 10% land area are still expected in several regions (Figure 1c). The estimated cooling effects of these trends are correspondingly smaller than for the historical period (Figure 2b). For example, the cooling from irrigation in NW India and NE China for 2001–30 is projected to be roughly half of the historical rate for 1961–99.

At the same time, net warming from other climate forcings is expected to be more rapid for 2001–30 than in the previous decades (Figure 2). As a consequence of diminished cooling from irrigation and enhanced warming from other forcings, irrigation will play a smaller role in future Tmax trends than in the past. In fact, the expected combined impact of irrigation and other forcings is projected to switch from a net cooling for 1961–99 to a net warming for 2001–30 (Figure 3).

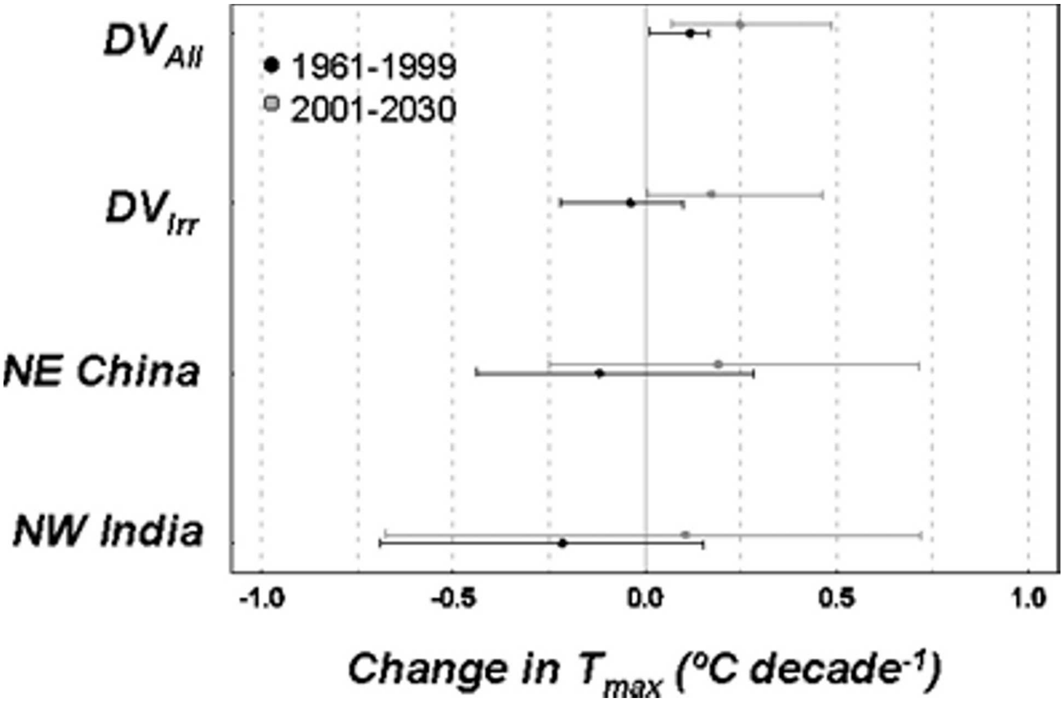

Figure 3. Estimated net impact of irrigation expansion and other climate forcings on growing season average maximum temperature (°C decade^{-1}) for 1961–99 (black) and 2001–30 (gray) in four regions. Bars show range of estimated impacts. Relatively strong effects of irrigation results in expected net cooling for many irrigated regions in the historical period, but future warming trends from greenhouse gas increases are expected to dominate in the future.

4. Discussion and conclusions

The results indicate a significant role for irrigation changes in recent decades (1961–2000) in determining net changes of Tmax in heavily irrigated regions of the developing world, such as NW India and NE China. While most climate models, which do not include irrigation changes, simulate a warming in these regions, observed growing season trends have exhibited either no change or a cooling (Figure 2). The cooling effect of Tmax can therefore explain the discrepancy between modeled and observed trends, with irrigation essentially masking greenhouse warming. However, these results are suggestive rather than conclusive, as other regional forcings may have influenced Tmax in ways not well simulated by the current suite of models. For example, Menon et al. (Menon et al. 2002) simulated a significant cooling effect of black carbon on summer temperatures in NE China, suggesting that increased black carbon emissions in this region, in part the result of biomass burning in agricultural areas, may explain some or all of the observed cooling.

Projections of irrigation in developing countries anticipate further expansion in most regions to meet growing food demand, but at a rate substantially slower than in recent decades (Figure 1). As a result of this trend and the enhanced greenhouse warming simulated by climate models, we estimate a diminished role for irrigation in future agricultural climate change. While irrigation expansion will continue to exert an important cooling effect in some locations, Tmax trends over most agricultural regions will be increasingly dominated by greenhouse warming. Temperature projections from climate models may therefore be more accurate in predicting future temperature trends than their performance in reproducing past trends over heavily irrigated areas would suggest.

Several caveats apply to these conclusions. Our estimates of irrigation effects on Tmax relied mainly on studies from California, which has a Mediterranean climate with a hot, dry growing season. The DJF season in India is similarly dry, but growing seasons in regions such as China are more humid and therefore the impact of irrigation is likely less than in California. Additionally, the effects of low albedo for standing surface water in flooded rice paddies have not been considered in most modeling studies but may be important throughout Asia. Unfortunately, studies of irrigation impacts in developing countries have been limited, due in part to data availability and complications from aerosol forcings (Bonfils and Lobell 2007). While the broad range considered in this study is likely to include the true effect of irrigation in most regions, more study is needed to discern the spatial dependence of irrigation effects.

Another important issue is the spatial scale of irrigation’s influence. Kueppers et al. (Kueppers et al. 2007) simulated cooling effects several kilometers beyond irrigated land in California because of advection. In general, though, the extent to which irrigation influences the climate of neighboring agricultural land, and therefore the heterogeneity of effects within the 0.5° × 0.5° grid cells considered here, remain unclear. For example, will expansion of irrigation in northern India affect climate over the millions of fields that are already irrigated, or only over the newly irrigated fields? Similarly, does the effect of irrigation scale linearly with amount of irrigated land, as assumed in the current study? Questions such as these could not be addressed here given the coarse scale of available data and models, but are deserving of future work.

Finally, we have evaluated the impacts of irrigation using only a single projection of irrigation changes at the national level. The actual evolution of irrigated land area will almost certainly deviate from these projections, but a thorough uncertainty analysis that considers the assumptions underlying these projections has yet to be performed. Similarly, the sensitivity of Tmax to irrigation has been approximated by a best guess (5°C cooling for 100% irrigation) and range (2°–8°C) rather than with a more probabilistic treatment of uncertainty. Despite these limitations, this is the first study to integrate data and projections of irrigation land use with simulations of climate change from other forcings. We believe the general conclusion that irrigation has played a relatively important role in local Tmax changes in the past, and that this role will diminish in the future, is likely to be robust to the various assumptions noted above.

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References

Barnston, A. G., and P. T. Schickedanz, 1984: The effect of irrigation on warm season precipitation in the southern Great Plains. *J. Climate Appl. Meteor.*, **23,** 865–888.

Bonfils, C., and D. Lobell, 2007: Empirical evidence for a recent slowdown in irrigation-induced cooling. *Proc. Natl. Acad. Sci. USA*, **104,** 13 582–13 587.

——, P. Duffy, B. Santer, T. Wigley, D. Lobell, T. Phillips, and C. Doutriaux, 2007: Identification of external influences on temperatures in California. *Climatic Change*, in press.

Boucher, O., G. Myhre, and A. Myhre, 2004: Direct human influence of irrigation on atmospheric water vapour and climate. *Climate Dyn.*, **22,** 597–603.

Bruinsma, J., Ed., 2003: *World Agriculture: Towards 2015/2030: An FAO Perspective*. Earthscan Publications, 432 pp.

Doll, P., and S. Siebert, 1999: A digital global map of irrigated areas. Center for Environmental Systems Research, University of Kassel, Kassel, Germany, Rep. A9901, 45 pp.

FAO, 2006: World agriculture towards 2030/2050. Interim Rep., Food and Agricultural Organization of the United Nations, 78 pp.

——, cited 2007: Irrigation cropping calendar per country. [Available online at http://www.fao.org/nr/water/aquastat/water_use/index.stm.]

Faurès, J., J. Hoogeveen, and J. Bruinsma, 2002: The FAO irrigated area forecast for 2030. Food and Agriculture Organization of the United Nations, 14 pp.

Feddema, J. J., K. W. Oleson, G. B. Bonan, L. O. Mearns, L. E. Buja, G. A. Meehl, and W. M. Washington, 2005: The importance of land-cover change in simulating future climates. *Science*, **310,** 1674–1678.

Haddeland, I., D. P. Lettenmaier, and T. Skaugen, 2006: Effects of irrigation on the water and energy balances of the Colorado and Mekong river basins. *J. Hydrol.*, **324,** 210–223.

Kueppers, L. M., M. A. Snyder, and L. C. Sloan, 2007: Irrigation cooling effect: Regional climate forcing by land-use change. *Geophys. Res. Lett.*, **34,** L03703, doi:10.1029/2006GL028679.

——, and Coauthors, 2008: Seasonal temperature responses to land-use change in the western United States. *Global Planet. Change,* **60,** 250–264.

Lobell, D. B., and C. Bonfils, 2008: The effect of irrigation on regional temperatures: A spatial and temporal analysis of trends in California, 1934–2002. *J. Climate,* in press.

——, G. Bala, and P. B. Duffy, 2006: Biogeophysical impacts of cropland management changes on climate. *Geophys. Res. Lett.,* **33,** L06708, doi:10.1029/2005GL025492.

Mahmood, R., S. A. Foster, T. Keeling, K. G. Hubbard, C. Carlson, and R. Leeper, 2006: Impacts of irrigation on 20th century temperature in the northern Great Plains. *Global Planet. Change,* **54,** 1–18.

Menon, S., J. Hansen, L. Nazarenko, and Y. Luo, 2002: Climate effects of black carbon aerosols in China and India. *Science,* **297,** 2250–2253.

Mitchell, T. D., and P. D. Jones, 2005: An improved method of constructing a database of monthly climate observations and associated high-resolution grids. *Int. J. Climatol.,* **25,** 693–712.

Siebert, S., P. Doll, J. Hoogeveen, J. M. Faures, K. Frenken, and S. Feick, 2005: Development and validation of the global map of irrigation areas. *Hydrol. Earth Syst. Sci.,* **9,** 535–547.

Sitch, S., V. Brovkin, W. von Bloh, D. van Vuuren, B. Eickhout, and A. Ganopolski, 2005: Impacts of future land cover changes on atmospheric CO_2 and climate. *Global Biogeochem. Cycles,* **19,** GB2013, doi:10.1029/2004GB002311.

Small, E. E., L. C. Sloan, and D. Nychka, 2001: Changes in surface air temperature caused by desiccation of the Aral Sea. *J. Climate,* **14,** 284–299.

Tebaldi, C., R. L. Smith, D. Nychka, and L. O. Mearns, 2005: Quantifying uncertainty in projections of regional climate change: A Bayesian approach to the analysis of multi-model ensembles. *J. Climate,* **18,** 1524–1540.