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Irrigation cooling effect: Regional climate forcing by land-use change

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[1] Regional detection of a greenhouse warming signal relies on extensive, long-term measurements of temperature. The potentially confounding impact of land-cover and land-use change on trends in temperature records has mostly focused on the influence of urban heat islands. Here we use a regional climate model to show that a regional irrigation cooling effect (ICE) exists, opposite in sign to urban heat island effects. The magnitude of the ICE has strong seasonal variability, causing large dry-season decreases in monthly mean and maximum temperatures, but little change in rainy-season temperatures. Our model produced a negligible effect on monthly minimum temperature. In California, the modeled regional ICE is of similar magnitude, but opposite sign, to predictions for future regional warming from greenhouse gases. Given our results for California and the global importance of irrigated agriculture, past expansion of irrigated land has likely affected observations of surface temperature, potentially masking the full warming signal caused by greenhouse gas increases. **Citation:** 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.

1. Introduction

[2] Biogeophysical changes associated with land-cover and land-use change are known to alter local, regional and global climate. For example, conversion of natural vegetation to croplands can increase or decrease temperature depending on whether conversion occurs in tropical or temperate areas, and can increase or decrease humidity depending on the type of natural vegetation replaced, and the type of crops established [*Bounoua et al.*, 2002]. Discussion of the impact of land-cover and land-use change on trends in observational climate records has mostly focused on the influence of urban heat islands [*Kalnay and Cai*, 2003; *Parker*, 2004; *Trenberth*, 2004]. However, irrigated agricultural land is more widespread than urban land, and has significant potential for altering climate. Irrigated land is particularly extensive in semi-arid regions, where lack of reliable rainfall has resulted in diversion of water to supplement soil moisture. Irrigation can alter climate by reducing soil albedo, increasing transpiration and evaporation, and enabling higher leaf areas than would otherwise be possible. Short-term model sensitivity tests [*Adegoke et al.*, 2003; *Segal et al.*, 1998; L. M. Kueppers et al., Seasonal temperature responses to land-use change in the western United States, submitted to *Global and Planetary Change*, 2007, hereinafter referred to as Kueppers et al., submitted manuscript, 2007] and observational analyses [*Barnston and Schickedanz*, 1984] suggest potentially significant impacts of irrigation on local clouds, precipitation and temperature. Few studies have focused on persistent multi-year climate effects of irrigated agriculture [*Boucher et al.*, 2004; *Lobell et al.*, 2006a, 2006b], and to date these have been global in scale.

[3] Irrigated land area has expanded rapidly over the last 200 years. In 1800, irrigation occupied ~8 million hectares globally, increasing to 40 million hectares in 1900, to 100 million hectares by 1950 [*Postel*, 1999], and to more than 270 million hectares in 2000 [*Siebert et al.*, 2005]. In the United States (U.S.), irrigation began with the settling of the western states. By 1900, irrigated area occupied 3.2 million hectares of the western U.S. [*Postel*, 1999], expanding to 14.8 million hectares by 1974 [*Frederick and Hanson*, 1982]. A large fraction of the West's irrigated land lies in California, where 81,000 hectares in 1878 expanded to more than 1.8 million hectares in 1928 [*Pisani*, 1984]. Irrigated area in California continued to grow through the mid-20th century, with an increase of 650,000 hectares between 1945 and 1974 [*Frederick and Hanson*, 1982], but has recently stabilized at ~3.3 million hectares (1974–1997 mean, $n = 7$ census estimates) [*National Agricultural Statistics Service*, 2004].

2. Experimental Design and Model Description

[4] We conducted a regional climate model (RCM) sensitivity experiment to quantify the climate effect of irrigated agriculture in California, reporting here the difference between two 20-year model runs differing only in the characteristics of the land surface. We took an RCM approach because local to regional climate impacts of land-use change are often pronounced, while globally averaged changes and remote climate effects due to atmospheric teleconnections are relatively small [*Bounoua et al.*, 2002; *Chase et al.*, 2000]. An RCM approach also allows land surface (including land use) heterogeneity to be better represented.

[5] The first run (MOD) used a modern vegetation distribution (circa 1990) that included both irrigated and non-irrigated agriculture, as well as urban land. Because irrigated area did not change systematically during the time period of our study, we held irrigated area constant in the MOD case. The second run (NAT) used potential natural vegetation, and did not include any agricultural or urban land cover types. To characterize modern land cover we used the Global Land Cover Characteristics database, version 2.0, which determines land use and land cover categories for each 1-km pixel based on 1992–1993 AVHRR data [*Loveland et al.*, 2000]. To characterize

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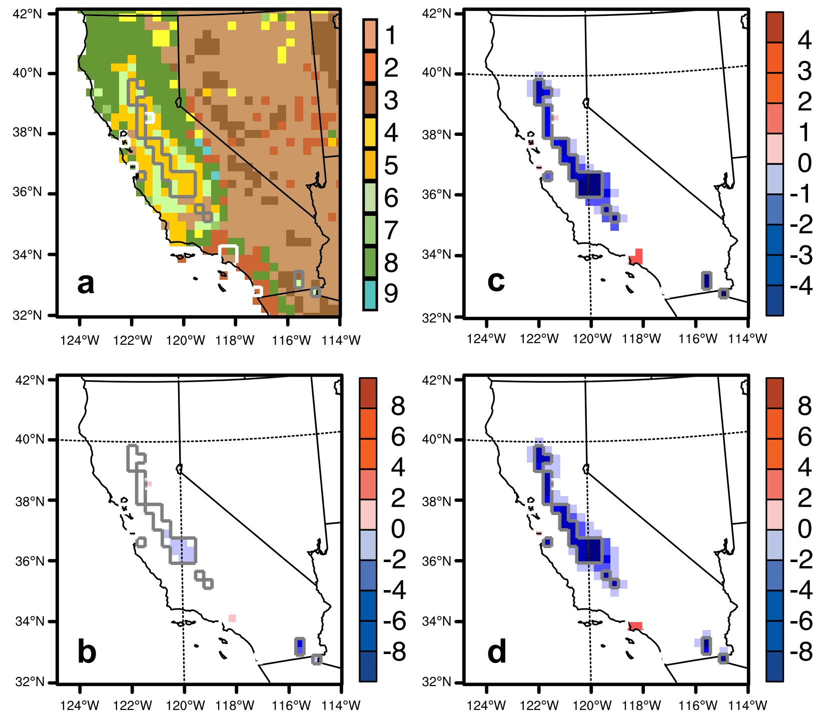

Figure 1. (a) Potential natural vegetation used in the NAT case, with grid cells replaced by irrigated agriculture in MOD outlined in gray, and grid cells replaced by urban areas in MOD outlined in white. Vegetation types are 1) semi-desert, 2) evergreen shrub, 3) desert, 4) short grass, 5) tall grass, 6) mixed woodland, 7) deciduous broadleaf trees, 8) evergreen needleleaf trees, and 9) tundra. Difference (MOD-NAT) in August (b) Tmin, (c) Tmean, and (d) Tmax (°C), with outlines as in Figure 1a and with only statistically significant ($p < 0.05$, $n = 20$ years) differences shown.

potential natural vegetation we used the natural land cover described by Kueppers et al. (submitted manuscript, 2007), which assigned modern agricultural and urban pixels to natural types based on a nearest-natural-neighbor approach. We compared the result to the potential natural vegetation map by *Ramankutty and Foley* [1999], to ensure consistency.

[6] We used the International Center for Theoretical Physics (ICTP) Regional Climate Model, RegCM3 [*Pal et al.*, 2007]. RegCM3 is a third-generation regional-scale climate model derived from the National Center for Atmospheric Research-Pennsylvania State (NCAR-PSU) MM5 mesoscale model. RegCM3 has the same dynamical core as MM5, the CCM3 radiative transfer package, and the Biosphere-Atmosphere Transfer Scheme (BATS) land surface model. Improvements to RegCM3 over previous versions include a new large-scale cloud and precipitation scheme, SUBEX, a new ocean flux parameterization, and the availability of a new cumulus convection scheme. RegCM has been validated against observations of modern-day climate in the domain studied here, and does a good job of simulating spatial and temporal climate features [*Bell et al.*, 2004; *Snyder et al.*, 2002].

[7] RegCM3 represents vegetation as a single layer canopy with irrigated crops having fairly low roughness length, low stomatal resistance, leaf area similar to grassland and forest, and albedo similar to deciduous broadleaf trees. To mimic the effects of irrigation, RegCM3 forces root zone (top 1 m for irrigated crops) soil moisture to field capacity at every time step, year round. This assumes that irrigated agricultural land is managed to have high water availability at all times of year, independent of crop cycles. In the absence of spatially and temporally explicit data, we believe this to be a reasonable approximation since much of the study region supports a year round growing season. Where there is no irrigation, the land surface model determines soil moisture as a function of precipitation, evapotranspiration, and soil properties, allowing drainage and runoff.

[8] For both MOD and NAT model runs, we used a domain centered at 37.5°N/121.5°W, spanning 28.5°N to 47.0°N and 110.5°W to 132.0°W with a horizontal resolution of 30 km, used NCEP/DOE Reanalysis II [*Kanamitsu et al.*, 2002] as lateral boundary condition data, and used National Oceanic and Atmospheric Administration Optimally Interpolated Sea Surface Temperatures [*Reynolds et al.*, 2002]. We held atmospheric CO_2 concentrations constant at 355 ppm. We discarded the first two years of the January 1979 – December 2000 model runs as equilibration time, and report results from the final 20 years (January 1981 – December 2000) as differences between the two cases (MOD-NAT).

3. Results

[9] Over the 20-year time period of the RCM sensitivity experiment, August mean and maximum temperatures were, on average, 3.7 ± 0.2 and 7.5 ± 0.3°C lower, respectively, where natural vegetation was converted to irrigated agriculture (Figure 1 and Table 1). August minimum temperatures were 0.9 ± 0.2°C lower, although this effect was less geographically consistent; in most grid cells, minimum

Table 1. Climate Differences Between Model Cases in Irrigated Areas[a]

	Tmean, °C		Tmin, °C		Tmax, °C		SMT, mm		LHFS, W/m^2		SHFS, W/m^2		RH, %	
	Mean	s.e.m.	Mean	s.e.m.	Mean	s.e.m.	Mean	s.e.m.	Mean	s.e.m.	Mean	s.e.m.	Mean	s.e.m.
Jan	0.02	0.07	0.25	0.05	−0.4	0.1	3.8	0.8	5	2	−3	1	0.01	0.01
Feb	−0.07	0.09	0.18	0.06	−0.5	0.2	3.8	0.9	9	4	−6	3	0.02	0.01
Mar	−0.27	0.13	0.10	0.09	−1.0	0.2	**5.8**	0.9	20	6	−15	5	0.04	0.01
Apr	−1.13	0.16	−0.07	0.13	−3.0	0.2	**13.1**	0.6	**63**	7	**−48**	6	**0.11**	0.01
May	−2.07	0.16	−0.40	0.14	**−4.6**	0.2	**17.7**	0.4	**108**	7	**−86**	5	**0.17**	0.01
Jun	**−3.09**	0.17	−0.78	0.16	**−6.1**	0.2	**20.9**	0.3	**147**	6	**−116**	5	**0.22**	0.01
Jul	**−3.78**	0.18	−0.96	0.16	**−7.3**	0.2	**22.5**	0.2	**163**	5	**−127**	4	**0.25**	0.01
Aug	**−3.69**	0.19	−0.86	0.16	**−7.5**	0.3	**22.7**	0.3	**147**	4	**−114**	4	**0.25**	0.01
Sep	**−3.02**	0.15	−0.65	0.13	**−6.7**	0.2	**21.3**	0.2	**108**	4	**−81**	3	**0.23**	0.01
Oct	**−1.85**	0.13	−0.31	0.08	**−4.4**	0.2	**17.7**	0.3	**58**	4	**−42**	3	**0.17**	0.01
Nov	−0.38	0.11	0.10	0.06	−1.3	0.2	8.8	0.8	14	3	−10	2	0.05	0.01
Dec	0.01	0.07	0.27	0.06	−0.5	0.1	5.4	0.8	6	2	−3	1	0.02	0.01

[a]Mean differences between cases (MOD-NAT) and standard error of the mean differences (s.e.m.) were calculated from 20-yr averages in grid cells irrigated in MOD (n = 30 grid cells). Bold values indicate months when all 30 grid cells had statistically significant ($p < 0.05$) changes between cases (n = 20 years for each grid cell). Tmean, mean temperature; Tmin, minimum temperature; Tmax, maximum temperature; SMT, top layer (0–10 cm) soil moisture; LHFS, latent heat flux; SHFS, sensible heat flux; and RH, relative humidity.

temperature did not change significantly (Figure 1 and Table 1). There was a latitudinal trend in the size of the effect; southern irrigated areas generally had larger temperature decreases, relative to northern areas (Figure 1). This trend corresponds with general trends in temperature and precipitation, with southern areas being warmer and drier than northern areas. The modeled decreases in temperature were accompanied by large increases in relative humidity (25 ± 1%, absolute change), as well as a shift away from sensible and toward latent heat fluxes (Table 1).

[10] The irrigation cooling effect (ICE) was not confined to the near-surface atmosphere in irrigated grid cells, but spread to adjacent grid cells and the lower troposphere via advection of the relatively cooler, moister air (note statistically significant differences in unmodified grid cells in Figures 1 and 2). For California as a whole, the model produced a net decrease of 0.38 ± 0.05°C in August mean temperature due to land-use change.

[11] The ICE also led to changes in regional circulation. During the warm summer months in California's Central Valley, daytime heating of the surface typically results in unstable conditions; the rising air draws in cooler air from western coastal areas. The decrease in surface temperatures stabilized the atmosphere, reducing the strength of the westerly land-sea breeze by 25 to 75 cm/s (−20 to −40%) along the western margin of the Central Valley. The presence of irrigation in the Central Valley also generated inland breezes [*Seth and Giorgi*, 1996] due to the contrast between the relatively cool, moist irrigated areas and adjacent warm, dry natural vegetation. Inland airflow of up to 50 cm/s (+10 to +20%) appeared in the southern part of the Central Valley, where the temperature and humidity effects of irrigated agriculture were most pronounced (Figure 2). No significant changes in precipitation or clouds were detected.

[12] While the RCM produced the most widespread climate changes in the month of August, statistically significant changes occurred year round for maximum temperature, relative humidity, and sensible and latent heat flux, primarily in southern California's Imperial Valley. The temporal pattern of the ICE in this Mediterranean-like region is most pronounced in the warm, dry summer months, minimal in the cool, wet winter months, and intermediate, but still significant in many areas, in spring and fall (Table 1). From year to year, variation in large-scale atmospheric flow can influence the magnitude of cooling produced by the model, since the size of the ICE is partially dependent on the difference in soil moisture available for evapotranspiration between the two cases. Summers following relatively wet winters (defined as total Dec–Mar precipitation >1σ above mean 1981–2000 levels) tend to have less pronounced cooling from irrigation than other summers (i.e., the maximum drop in temperature from NAT to MOD model cases is smaller following wetter winters) (Figure 3). Over all years, the maximum cooling is positively related to Dec–Mar precipitation ($r = 0.77$), with drier years having a larger cooling effect. Thus, the ICE is most pronounced

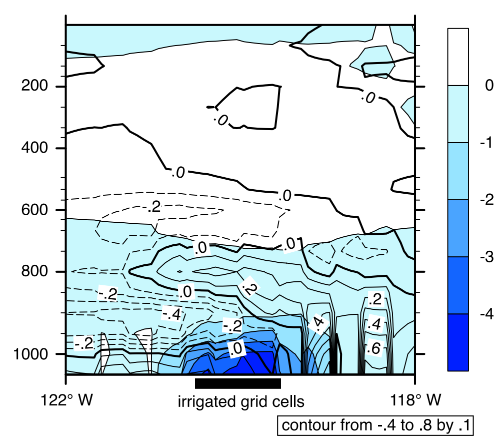

Figure 2. Vertical cross-section of modeled atmospheric temperature difference (color fill; °C), and difference in wind velocity (black contours; m/s) between model cases (MOD-NAT) along a line of constant latitude (36.4 deg N). Decreases in wind velocity are shown with dashed contours, and increases are shown with solid contours. RegCM3 has 18 vertical levels in the atmosphere that were interpolated to pressure levels (mb) for plotting. The longitudinal extent of the irrigated region is shown with the black box below the x-axis.

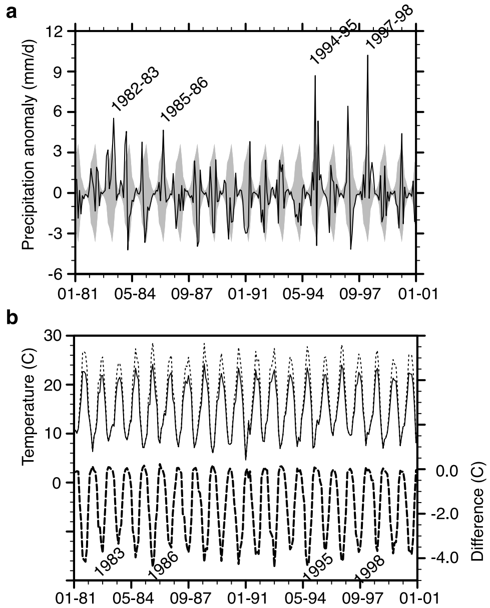

Figure 3. From January 1981 to December 2000, (a) mean monthly precipitation deviations from 1981–2000 monthly means (solid line), with the shaded area representing one standard deviation from the monthly means; and (b) monthly temperature in the MOD case (solid) and NAT case (short-dash), with the difference between cases (MOD-NAT) shown below (heavy long-dash). All monthly values are spatial averages over grid cells that are irrigated in the MOD case (n = 30). Individual years with relatively high December–March precipitation and small maximum temperature differences are noted (see text).

during warm, dry times of the year, and during relatively warm, dry years, and vice versa.

4. Discussion and Conclusions

[13] The actual magnitude of the ICE for this region or the many other agricultural regions around the world is not known. This study used a single RCM to estimate the climate effects of irrigated agriculture. Like all climate models, RCMs have differing sensitivity to climate forcings. In a 1-year RCM intercomparison study, using the same land surface cases as in the current study, we found that RegCM3 had relatively high sensitivity to irrigation, and underestimated temperatures in irrigated regions compared to a global gridded observational dataset (Kueppers et al., submitted manuscript, 2007). The experiment reported here used an idealized representation of irrigation, forcing soil moisture to field capacity at all times. Finally, we focused our study on a single region – California – where mechanized irrigation has resulted in a large area that is intensely irrigated. Irrigation in other regions is likely a mix of mechanized sprinklers, flooded fields, ditch irrigation, and drip irrigation. The amount of water added to the soil, and period of elevated soil moisture, varies considerably around the world. In spite of these caveats, we believe that the ICE portrayed here is qualitatively correct.

[14] As with the urban heat island effect, understanding the spatial and temporal "fingerprint" of the ICE may be critical for detecting greenhouse gas-driven climate change. In California, 626 (76%) of the National Oceanic and Atmospheric Administration Cooperate Observer Program climate stations (73% of total stations) are located in areas with some irrigated agriculture [*Siebert et al.*, 2005]

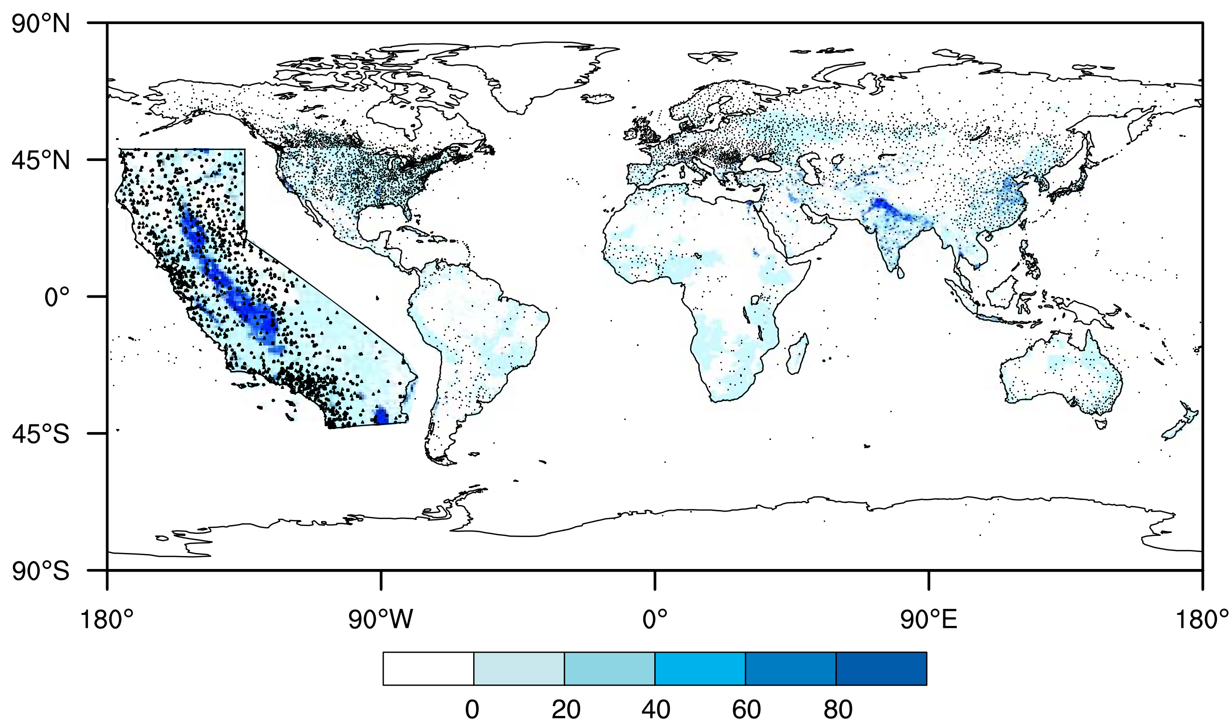

Figure 4. Global irrigation intensity [*Siebert et al.*, 2005] represented by the percent of irrigated area in each grid cell, plotted together with the locations of climate stations used by a global observational dataset [*Willmott and Matsuura*, 2001]. California climate stations active between 1995 and 2000 are shown in the inset.

(Figure 4, inset). A recent analysis across multiple observational datasets detected consistent positive trends (1950–2000) in winter through summer minimum temperatures, and in winter mean and maximum temperatures in California (C. Bonfils et al., Identification of external influences on temperatures in California, submitted to *Climatic Change*, 2007). Consistent trends in mean and maximum temperature were absent spring through autumn. We found mean and maximum temperatures between the months of May and October to be most influenced by the ICE in irrigated areas, and found few significant changes in minimum temperatures at any time of year. Based on our findings, one interpretation of Bonfils et al. is that over the 50 year period of their study, and where irrigation extent was increasing concurrently with greenhouse gas concentrations, land-use change provided a seasonally variable regional climate forcing opposite to greenhouse forcing.

[15] Greenhouse gas increases coincided with the expansion of irrigation in California from the late 19th century to the late 20th century, a longer period than the 50 years of the Bonfils et al. study. While increasing greenhouse gas concentrations may have increased temperatures over the last 150 years [*Intergovernmental Panel on Climate Change*, 2001], expanding irrigation may have introduced a countervailing temperature effect over at least part of the same time period, limiting detection of a global (greenhouse) warming signal in observations of temperature. Finally, in California, the modeled regional ICE is of similar magnitude, but opposite sign, to predictions for future regional warming from greenhouse gases [*Snyder et al.*, 2002; *Snyder and Sloan*, 2005]. Irrigated area has currently stabilized, but if it declines due to lack of sufficient water supply or conversion of irrigated agriculture to urban land, greenhouse gas-driven warming may be reinforced by regional land-use change.

[16] In addition to California, India, China, the Black Sea region, and the Great Plains of the United States have large areas under irrigation, with 53% of stations in one global observational dataset occurring in irrigated areas [*Siebert et al.*, 2005; *Willmott and Matsuura*, 2001] (Figure 4). Our results suggest that the climatic effects of irrigation can be relatively large on a regional scale. We hypothesize that past expansion of irrigation may have masked regional increases in temperature due to greenhouse gas increases. As a result, the true impact of greenhouse gas increases may have been underrepresented by temperature observations. Without accurate time-series data on the historic extent and amount of irrigation, it is impossible to estimate how the ICE may have changed over longer time periods, and in other regions. Development of such datasets is critical for quantifying the global influence of irrigation on trends in climate.

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