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Irrigation in California's Central Valley strengthens the southwestern U.S. water cycle

Min-Hui Lo[1,2] and James S. Famiglietti[1,3]

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[1] Characterizing climatological and hydrological responses to agricultural irrigation continues to be an important challenge to understanding the full impact of water management on the Earth's environment and hydrological cycle. In this study, we use a global climate model, combined with realistic estimates of regional agricultural water use, to simulate the local and remote impacts of irrigation in California's Central Valley. We demonstrate a clear mechanism that the resulting increase in evapotranspiration and water vapor export significantly impacts the atmospheric circulation in the southwestern United States, including strengthening the regional hydrological cycle. We also identify that irrigation in the Central Valley initiates a previously unknown, anthropogenic loop in the regional hydrological cycle, in which summer precipitation is increased by 15%, causing a corresponding increase in Colorado River streamflow of ~30%. Ultimately, some of this additional streamflow is returned to California via managed diversions through the Colorado River aqueduct and the All-American Canal.

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1. Introduction

[2] California's Central Valley is the most productive agricultural region in the United States and one of the most productive in the world. It accounts for one sixth of the country's irrigated land [*Faunt*, 2009]. Because it is subject to intensive irrigation, the Central Valley is part of a unique and heavily managed hydrological system. A recent U.S. Geological Survey report on the water budget of the Central Valley showed that annual evapotranspiration (ET) exceeds annual precipitation by ~60% [*Faunt*, 2009]. This excess in ET, derived largely from irrigation, can have substantial effects on the local climate [*Lobell et al.*, 2009; *Sorooshian et al.*, 2011], including net land surface cooling [*Kueppers et al.*, 2008].

[3] Previous studies [*Kanamitsu and Mo*, 2003; *Mo*, 2008] have demonstrated that soil moisture can affect precipitation either by changes in local ET or by changes in lateral water vapor transport. Consequently, irrigation usually has a first-order effect on local surface energy and water budget partitioning [*Cook et al.*, 2011], because increased soil wetness leads to increased ET [*Pielke*, 2001; *Adegoke et al.*, 2003; *Bonfils and Lobell*, 2007; *Kueppers et al.*, 2007; *Lobell et al.*, 2009; *Sacks et al.*, 2009; *Ozdogan et al.*, 2010]. Irrigation also has a second-order effect on the atmospheric circulation, which is more uncertain and has potential impacts over a larger area [*Yeh et al.*, 1984; *DeAngelis et al.*, 2010; *Puma and Cook*, 2010].

[4] Regional climate models have been used to explore the impacts of irrigation in the Central Valley on local and regional climates [*Kueppers et al.*, 2008; *Sorooshian et al.*, 2011]. However, imposed lateral boundary conditions in regional climate models may limit simulated irrigation impacts by eliminating teleconnection effects through the atmosphere, making the second-order effects difficult or impossible to identify. Given the one-way nature of interactions simulated in regional models, as well as uncertainty in the imposed boundary forcing, global climate model simulations are an important step forward in understanding the full role of irrigation in climate system feedback, especially for characterizing the remote effects from a large, individual irrigated region.

[5] The Central Valley is one of the largest irrigated regions in the world, with 52,000 km^2 of irrigated area [*Famiglietti et al.*, 2011]. Irrigation in the Central Valley relies both on managed, surface water deliveries and on groundwater withdrawal from the underlying, regional aquifer system [*Faunt*, 2009; *Siebert et al.*, 2010]. How the excess in ET from irrigation affects the local and regional climate is thus of great interest and will help establish the human fingerprint of water management practices. In this study, we explore the importance of Central Valley irrigation in regional precipitation changes, including its role in enhancing land-atmosphere interactions in the southwestern United States.

2. Model and Data Sets

[6] We use the NCAR Community Atmosphere Model (CAM) version 3.5 [*Gent et al.*, 2009] combined with the Community Land Model (CLM) version 3.5 [*Oleson et al.*, 2008]. Two online experiments conducted with CAM version 3.5 are presented here: an Irrigation run and a Control run. In the Irrigation run, two extra anthropogenic fluxes, surface water deliveries and groundwater withdrawal, are represented in the CLM version 3.5 and only within the Central Valley. Specifically, the Irrigation run isolates only the impacts of irrigation without considering land-cover and land-use changes. As a result, the impacts of irrigation in the Central Valley on climate can be identified by differences (anomalies) between the two experiments.

All Supporting Information may be found in the online version of this article.

[1] UC Center for Hydrologic Modeling, University of California, Irvine, California, USA.

[2] Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan.

[3] Department of Earth System Science, University of California, Irvine, California, USA.

Corresponding author: J. S. Famiglietti, University of California, Irvine, CA 92697, USA. (jfamigli@uci.edu)

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[7] Simulations are performed at T85 resolution (~1.4° 1.4°) with 26 vertical hybrid coordinate levels. Initial conditions of water table depth and soil moisture profile are estimated by the fitting approach of *Lo and Famiglietti* [2010]. The simulation produces global monthly outputs over a 90-year period and is forced by climatological sea surface temperatures and sea ice concentrations [*Hurrell et al.*, 2008]. To remove the effects of uncertain initial and boundary conditions, the first 45 simulated years are treated as spin-up, and the latter 45 years are used for the analysis.

[8] We used the irrigation water demand from agriculture and climate data sets [*Wisser et al.*, 2008], in which the annual mean total irrigation water requirement in the Central Valley is ~350 mm and is supplied entirely by surface water deliveries and groundwater withdrawal. The groundwater contribution to total irrigation water in the Central Valley is 40% [*Siebert et al.*, 2010] based on the area equipped for irrigation use; hence, in this study, we assume surface water delivery of 210 mm $\mathrm{yr^{-1}}$ and groundwater withdrawal of 140 mm $\mathrm{yr^{-1}}$ in the model (see details in the Supplementary Information).

3. Results

[9] In simulations with irrigation, averaged total ET over the Central Valley increases significantly (149 mm or 100%) during the summer as indicated in Figure 1a, which shows the climatology of ET for the Control and Irrigation runs. Most of the increase in ET occurs between May and October, the months during which a total of 350 mm of irrigation water was applied. In the absence of irrigation, ET in the Central Valley is typically soil-water limited during the summer, that is, there is abundant solar radiation, but the lack of available soil-water significantly limits ET rates. However, when irrigation water is applied, ET can increase substantially as the land surface transitions to an energy-limited state, as shown by the Irrigation run in Figure 1a.

[10] Because of the prevailing atmospheric circulation in the lower troposphere during the summer, water vapor in the Central Valley is partially transported to the southwestern United States (Figures 1b and 1c). Tracer experiment simulations (see Figure S1 and Animation S1 in the Supporting Information) confirm this and indicate that the tracer mixing ratio has increased significantly throughout the southwestern United States. Furthermore, Figure 1b shows water vapor flux anomalies (Irrigation run - Control run), which demonstrate that water vapor from excess ET is transported to the southwestern United States.

[11] Figure 1c shows the changes in the spatial distribution of low-level (the first three atmospheric layers in the sigma vertical coordinate, which varies from 975 to 850 mb) water vapor due to irrigation for the 45-year average for June, July, and August. Only statistically significant differences are shown. Low-level water vapor increases the most over California, where the irrigation occurs. Although atmospheric water vapor increases due to enhanced ET during the summer, the Central Valley lies beneath the descending branch of the large-scale circulation, which inhibits the occurrence of precipitation there, as shown in Figure 1d.

[12] However, the remote effects of irrigation on precipitation can be clearly seen from Figure 1d. Figure 1c and Figure S1 suggest that the increased water vapor from irrigation-enhanced ET plays a role in triggering the positive precipitation anomalies observed in the southwestern United States. This study, therefore, will focus on the southwestern United States (the purple rectangular box in Figure 1b), where the precipitation changes are significant at the 90% level and have anomaly ratios [(Irrigation run - Control run) / Control run] ranging from 10% to 20%. This region covers most of the Colorado River Basin, a critically important river basin for water resources management in the southwestern United States and California, and also includes the southwestern U.S. monsoon area.

[13] The increase of water vapor in the lower troposphere results in positive atmospheric moist static energy (MSE) anomalies (Figure 1e), which is defined as

$$MSE = C_p T + L_v q + gz, \qquad (1)$$

where C_p is the specific heat at constant pressure ($\mathrm{J\,kg^{-1}\,K^{-1}}$), T is temperature (K), L_v is the latent heat of vaporization at 0 °C ($\mathrm{J\,kg^{-1}}$), q is the specific humidity ($\mathrm{kg\,kg^{-1}}$), g is the gravitational acceleration ($\mathrm{m\,s^{-2}}$), and z is height (m). Figure 1f (the vertical profile of changes in MSE averaged inside the rectangular box) shows that higher MSE in the lower troposphere reduces moist static stability, which increases convective instability [*Eltahir*, 1998] in the Irrigation run. This instability leads to an initial increase in precipitation in the southwestern United States shown in Figure 1d.

[14] The vertically integrated atmospheric moisture budget equation is also used to explore precipitation anomalies in Figure 1d:

$$\left\langle \frac{\partial q}{\partial t} \right\rangle = ET - P - \langle \nabla \cdot (vq) \rangle, \qquad (2)$$

where q is water vapor, ET is evapotranspiration, P is precipitation, $\mathbf{v}$ is horizontal velocity, and $\langle\rangle$ denotes a mass integration throughout the troposphere (i.e., $\frac{1}{g}\int_{p_s}^{p_t} ()dp$, where g is gravity ($\mathrm{m\,s^{-2}}$), p_1 is the pressure at the top of troposphere (hpa), and p_s is surface pressure (hpa). Therefore, precipitation anomalies (P') shown in Figure 1d are decomposed into evapotranspiration anomalies (ET'), water vapor convergence ($-\langle \nabla \cdot (vq) \rangle'$), and water vapor changes with time ($-\left\langle \frac{\partial q}{\partial t} \right\rangle'$) as shown in Figure 2. The spatial distribution and magnitude of ET' are similar to those of P' in most of the southwestern United States (Figures 2a and 2b). Water vapor convergence contributes to positive precipitation anomalies in the east of the study domain (Figure 2d). The combined effects of local ET enhancement and water vapor convergence are associated with maximum positive water vapor and precipitation anomalies seen in the eastern area in Figure 1d.

[15] The similarity between the patterns of ET' and P' indicates the importance of land-atmosphere interactions in the southwestern United States. Previous studies [*Kurc and Small*, 2007; *Vivoni et al.*, 2009] also show that this region is regarded as a zone where the land and atmosphere are tightly coupled; therefore, we hypothesize that positive soil moisture feedback may yield higher local precipitation. We confirm this by conducting another simulation in which land-atmosphere interaction over the southwestern United States is inhibited (No Land-Atmosphere Interaction run). This No Land-Atmosphere Interaction run has the same model configuration as the Irrigation run, except that

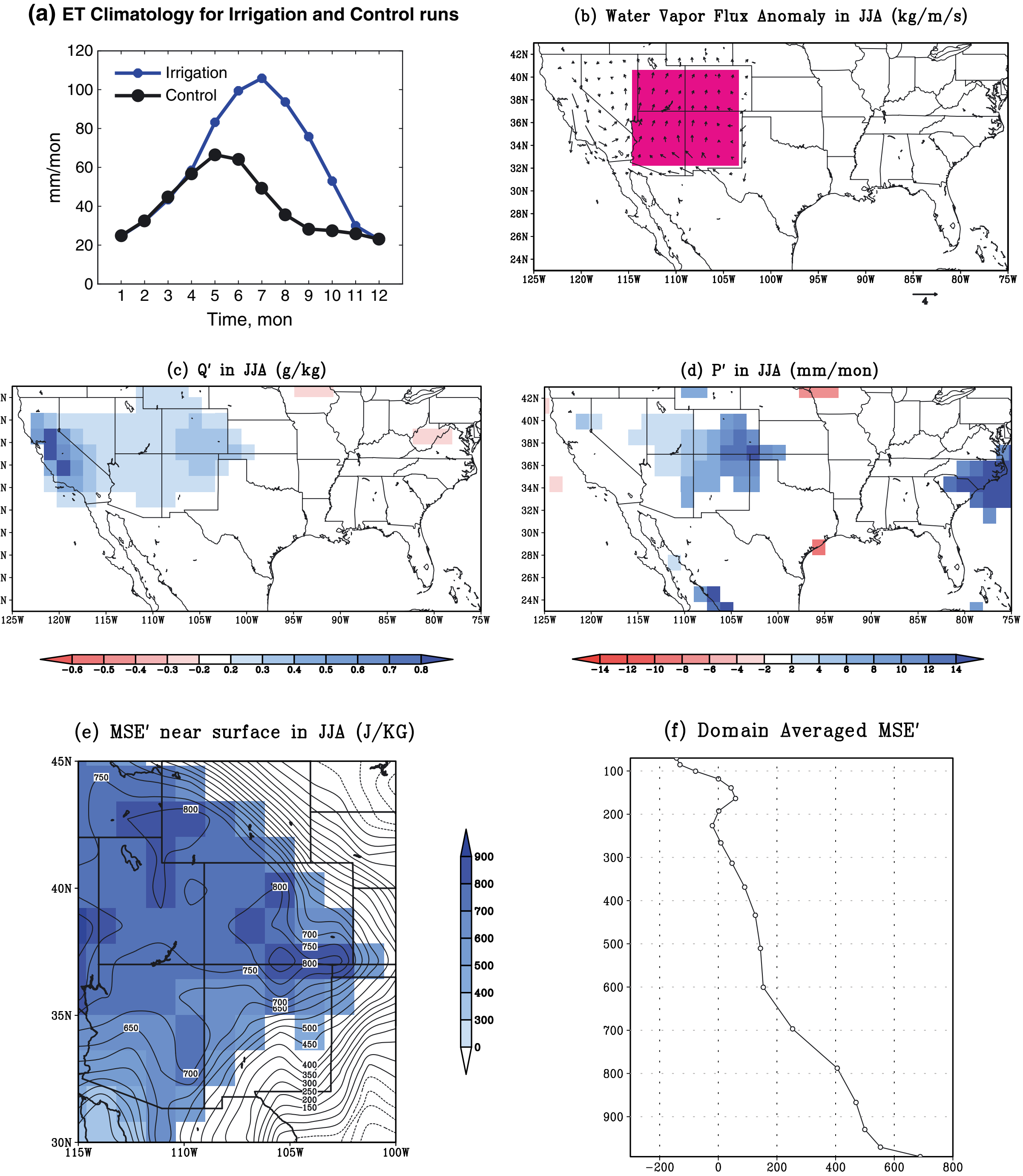

Figure 1. (a) Climatology (45-year average) of ET (mm mo^{-1}) averaged over the Central Valley for the Control and Irrigation runs. Irrigation-induced changes in the spatial distribution of (b) low-level water vapor flux (kg m^{-1} s^{-1}), (c) low-level water vapor (g kg^{-1}), (d) precipitation (mm mo^{-1}), and (e) MSE (J kg^{-1}). Only differences greater than the 90% significance level are shown for water vapor, precipitation, and MSE. (f) Vertical profile of change in MSE over the rectangular box in (b). All figures show the average during the summer.

soil moisture content inside the boxed region of Figure 1b was prescribed at climatological values (from the Control run) to isolate it from the effects of the precipitation anomalies. Figure 3 shows the difference in precipitation between this No Land-Atmosphere Interaction run and the Irrigation run and demonstrates that precipitation decreases after positive land-atmosphere interaction is inhibited. Therefore, positive soil moisture feedback plays an important role in driving precipitation over this region when irrigation water is applied in the Central Valley. In fact, Figure 3 also shows that the precipitation anomalies shift to the east where the land and atmosphere interactions are still active, indicating that having active land and atmosphere interactions is the key to maintaining the positive precipitation anomalies.

[16] Moreover, the tracer concentration in Figure S1 (Supporting Information) shows different spatial patterns than those of water vapor anomalies in Figure 1c, especially for the local maximum water vapor concentration over eastern

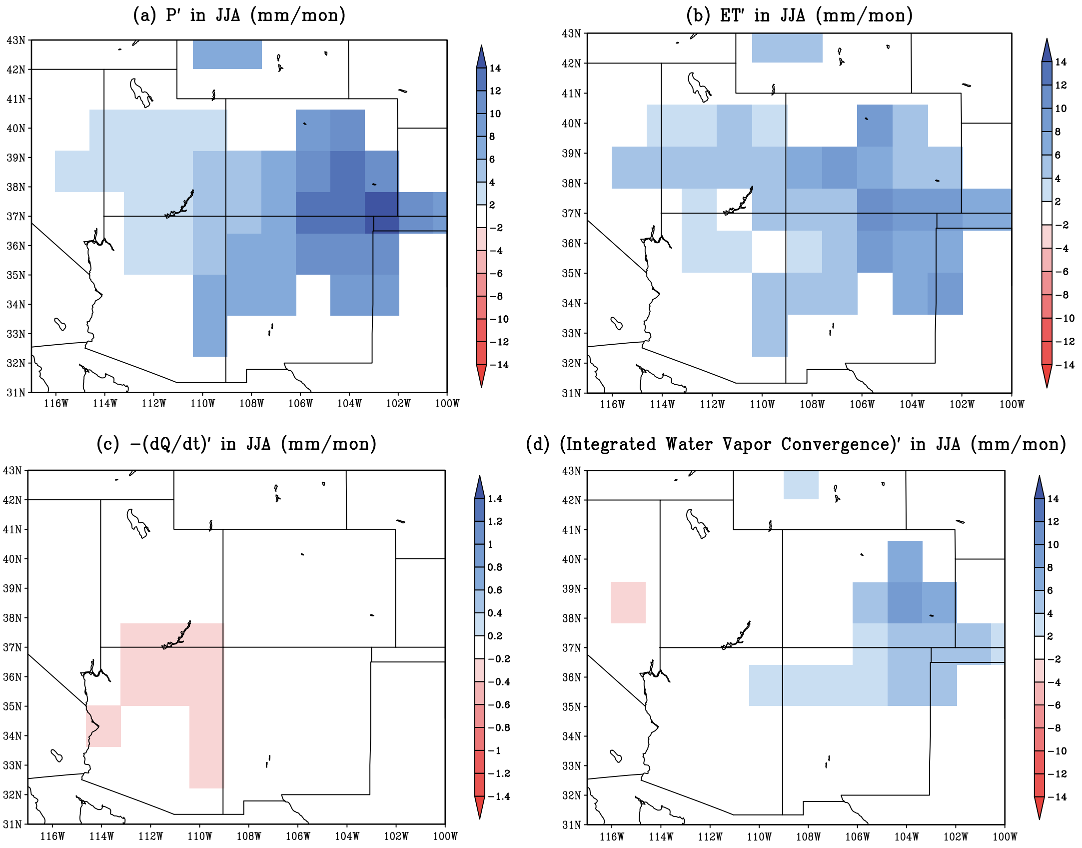

Figure 2. Spatial distributions of the four terms in Eq. (2) during the summer (a) P', (b) ET', (c) $-\left\langle \frac{\partial q}{\partial t} \right\rangle'$, and (d) $-\langle \nabla \cdot (vq) \rangle'$. All the terms are in units of mm mo^{-1}. Only differences greater than the 90% significance level (based on P') are shown.

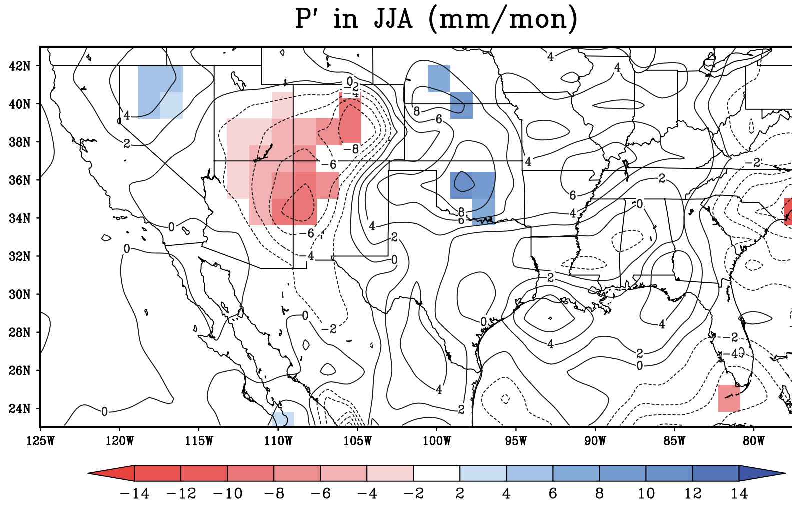

Figure 3. Changes in the spatial distribution of precipitation (mm mo^{-1}) during the summer due to land-atmosphere interactions. Results are the summer differences between the No Land-Atmosphere Interaction and the Irrigation runs for the 45-year simulations analyzed. Note that the No Land-Atmosphere Interaction experiment includes irrigation and that only differences greater than the 90% significance level are shown.

Colorado and eastern New Mexico. This is because the tracer experiment only shows the water vapor transport from the irrigation-induced ET without contributions from soil moisture feedback and lateral water vapor transport. Hence, the additional water vapor transported from Central Valley irrigation acts as a trigger for enhancing precipitation, and then the soil moisture and ET over the southwestern United States, or more generally for accelerating the water cycle in this region. Figure 1b shows that the enhanced water cycle dynamics in the southwestern U.S. region result in an increase of the water vapor flux into this region from the south and the east as well as from the west. This is broadly consistent with other studies, which have shown that enhanced ET in the southwestern United States can introduce more lateral moisture flux into the region [e.g., *Kanamitsu and Mo*, 2003; *Xu et al.*, 2004; *Anderson et al.*, 2006]. This primarily occurs because changes in ET can modify surface temperature and pressure systems, resulting in an increase of low-level water vapor transport/fluxes.

4. Discussion

[17] Whereas the first-order effect of Central Valley irrigation results in a net land surface cooling and increases atmospheric water vapor locally in California, the second-order effect of Central Valley irrigation results in higher precipitation rates over the southwestern United States, including enhancing summer monsoon rainfall and strengthening the regional water cycle. We demonstrate in a model a clear mechanism that the water vapor transport resulting from irrigation initiates atmospheric instabilities over the southwestern United States, where soil moisture feedback and lateral water vapor convergence also play an important role in increasing precipitation in the region. In addition to increasing precipitation, the additional rainfall results in increased runoff in the southwestern U.S. region. Summer runoff in this region increases by $2.6\,\mathrm{km}^3$ (56%) and $0.4\,\mathrm{km}^3$ (28%) over the Colorado River Basin. The Colorado River aqueduct and All-American Canal transport $\sim 5\,\mathrm{km}^3$ of water from the Colorado River to Southern California annually (data from U.S. Bureau of Reclamation). When the return flows of streamflow in the southwestern U.S. region are considered, it is apparent that irrigation in the Central Valley initiates a regional, anthropogenic loop of the hydrological cycle, as shown in Figure S3 in the Supporting Information. Although the Central Valley does not use water from the Colorado River for irrigation, part of the irrigated water applied in the Central Valley ultimately flows back to Southern California because of teleconnection effects (increased remote precipitation and runoff) and the regional water management system (Colorado River Basin allocations to Southern California). Table S1 in the Supporting Information quantifies the anomalies and the corresponding estimated uncertainties in summer flux rates for the main branches of the anthropogenic loop.

[18] This study highlights the importance of human-driven impacts on the hydrological cycle and regional climate and for water resources management in California and the southwestern United States. Ultimately, our results show that Central Valley irrigation has led to a strengthening of the southwestern U.S. hydrological cycle and forms an anthropogenic loop within the hydrological cycle of the southwestern United States and California. Given that the future of Central Valley irrigation is uncertain due to unsustainable rates of groundwater depletion [*Famiglietti et al.*, 2011] and that water deliveries from Colorado River will also become unsustainable toward the end of this century [*Barnett and Pierce*, 2009; *Cayan et al.*, 2010] due to declining snowpack in the western United States, a better understanding of how irrigation impacts local-to-remote climate and water availability is essential for informed resource management. Therefore, this study underscores the importance of including water management practices in current climate models, including observed irrigation rates, to more realistically simulate regional water cycle dynamics.

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