Possible Increase of Air Temperature by Irrigation

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Abstract

Irrigation cools near surface air temperature by increasing evapotranspiration from wetter soil. However, elevated evapotranspiration can also increase atmospheric albedo and enhance the local greenhouse effect via increased atmospheric water vapor. Their net effects on daily air temperature remains controversial. Here we show that in several considered regions, Northwest India and Central Valley of California, irrigation could result in warmer air temperature if night-time warming is stronger than daytime cooling by irrigation. During the daytime, air temperature reduces through evaporative cooling and reduced solar radiation from increased atmospheric albedo outweighing the local greenhouse effect. At night-time, the increased atmospheric water vapor by irrigation tends to make a stronger local greenhouse effect that increases night-time temperature. Our results highlight the possible increase of air temperature by irrigation and the importance of considering sub-daily processes when assessing the impact of irrigation on daily air temperature and temperature related socioeconomic phenomena.

Plain Language Summary

Irrigation can influence air temperature in two contrasting ways. Evaporative cooling from wetter soil can reduce air temperature. However, evaporated water is a greenhouse gas, which can increase air temperature. The impact of these two influences differs for daytime and night-time air temperature. Here, we examine the impact of irrigation on daytime and night-time air temperature under two different assumptions. Our simulations show that the warming influence of irrigation on night-time temperature could be greater than the cooling influence on daytime temperature in several considered regions, Northwest India and Central Valley of California. Our results underline that the impact of irrigation is a complex interplay of evaporative cooling and greenhouse warming and still needs to be further investigated.

1. Introduction

Global warming has accelerated dramatically in recent decades (Rogelj et al., 2012) and the significant contribution of human activities to climate change has become increasingly accepted (Kang & Eltahir, 2018; Milly et al., 2002). Irrigation is an important human activity that accounts for 70% of global total water demand (Shiklomanov, 1997; Wada et al., 2013) and plays an important role in changing regional-to-global climate and hydrological cycle (Fischer et al., 2007; Freydanck & Siebert, 2008; Kang & Eltahir, 2018; Wey et al., 2015).

Although the impact of irrigation on the global mean temperature is small (Wey et al., 2015), irrigation has a considerable impact on extreme temperatures, especially in areas with large volumes of irrigation (Chou et al., 2018; Thiery et al., 2020).

Irrigation can lead to two opposite effects on near surface temperature. Irrigation reduces near surface temperature over irrigated areas via increased evaporative cooling from wetter soil (Boucher et al., 2004; Haddeland et al., 2006; Thiery et al., 2017). On the other hand, increased atmospheric water vapor (as a primary greenhouse gas) from irrigation (Ozdogan et al., 2010) can also raise near surface air temperature by absorbing longwave radiation from the land surface (Kennedy & Hodzic, 2019). However, most current research argues that the impact of irrigation on surface temperature is dominated by evaporative cooling, rather than the local enhancing of the greenhouse effect (Boucher et al., 2004; Forster et al., 2007; Thiery et al., 2017).

Numerous observational studies (Bonfils & Lobell, 2007; Mahmood et al., 2006) and modeling studies (Haddeland et al., 2006) have shown the cooling effects of irrigation on annual mean and maximum temperature over irrigated areas (Chen & Dirmeyer, 2019; Haddeland et al., 2006; Kang & Eltahir, 2019). Irrigation has a significant effect on June–August average maximum temperature (decrease by ~2–3°C) (Bonfils et al., 2008; Lobell &
Bonfils, 2008), but no significant effects on minimum temperature over California (Kueppers et al., 2007). Similarly, irrigation-induced cooling on average temperature and average maximum temperature during the growing season has been found over Nebraska (Adegoke et al., 2003). On the other hand, a previous study pointed out that irrigation-induced cooling of near-surface temperature is mainly driven indirectly by increased cloud cover rather than direct evaporative cooling (Sacks et al., 2009).

An additional impact of irrigation on air temperature is through enhancing the local greenhouse effect via an increase in specific humidity, which can induce warming (Dessler & Sherwood, 2009; Hu et al., 2019). A previous study emphasized the important role of humidity and argued that irrigation could increase humid heat stress over irrigated areas in the North China Plain via locally increased humidity (Kang & Eltahir, 2018). The upward transfer of latent heat flux from near surface water vapor can also heat the troposphere (Cook et al., 2015; Sacks et al., 2009). Consequently, several studies argue that the possibility of irrigation having a net effect of warming (Kennedy & Hodzic, 2019) has been overlooked. However, the additional water vapor may not reach the upper troposphere to trigger greenhouse gas effect due to its short lifetime (Sherwood et al., 2018). Therefore, the magnitude of the irrigation related greenhouse gas effect on global warming is still unclear.

There exists a consensus that irrigation leads to a decreased daily maximum temperature (Chen & Jeong, 2018; Lobell et al., 2006; Sacks et al., 2009). However, studies report inconsistent conclusions for the impacts of irrigation on daily minimum temperature (Bonfils & Lobell, 2007; Christy et al., 2006; Kueppers et al., 2008). This is due in part to the lack of detailed analysis on how the radiative, evaporative cooling and greenhouse effects of irrigation interact toward their net effect on near surface temperature over diurnal cycles.

Furthermore, the influence of ongoing irrigation in the boundary regions on local surface temperature when local irrigation has ceased is also untested. To isolate from more complex remote effects and focus on the local land surface and atmospheric processes, particularly dynamic feedbacks via evaporative cooling, greenhouse effect, and radiative forcing, we used the Single Column Atmospheric Model (SCAM) in the Community Earth System Model (CESM) to examine the influence of local irrigation on sub-daily (daytime and night-time) air temperature over four major irrigated cropping areas: Northwest India (NI), East China (EC), Murray Darling Basin (MD), and California Central Valley (CV). We also conduct energy balance decomposition and sensitivity simulations by gradually reducing regional-scale irrigation (Kelly, 2014) to further explain the physical mechanisms. In this study, local time 10a.m.–5p.m. is used to represent daytime period, local time from 10p.m. to next day 5a.m. represents nighttime period.

2. Materials and Methods

2.1. CESM Model and Experiments

The Single Column Atmosphere Model (hereafter, SCAM), which is based on the Community Earth System Model (CESM2.1.0), is a single column model version of Community Atmosphere Model Version 6 (CAM6). Unlike the global model, SCAM does not have dynamic horizontal flux exchange with boundary columns at every time step. Its boundary environment has been prescribed by Intensive Observing Period (IOP) (hereafter, IOP) and initial conditions (hereafter, IC) files in advance (Gettelman et al., 2008). SCAM is an effective tool for developing, evaluating, and understanding the complex interactions and processes that are represented by physical parameterizations in the full model (Gettelman et al., 2019). Therefore, we choose SCAM to isolate from more complex remote effects and focus on the local land surface and atmospheric processes.

The IOP is needed to specify the locations and dates for a SCAM case set up and to provide the needed initial and boundary conditions for running a SCAM case (Zhang et al., 2016). There are several precomputed cases available with IOP forcing files in CAM6 (Gettelman et al., 2019). But if the user wants to run in an undefined area or time, an arbitrary IOP forcing can also be generated for any location and time by following instructions in the CAM6 users guide (https://ncar.github.io/CAM/doc/build/html/users_guide/). In this study, we are focusing on the four major irrigated cropping areas which are also located in different climate conditions (in NI (29.37°N, 75°E), EC (38.84°N, 115°E), MD Basin (35.05°S, 145°E), and California CV (36.95°N, 120°W)). Since they were not predefined in CAM6 IOP forcing files, specific IOP forcing files were generated manually. The locations of the selected irrigation areas are shown in Figure S1 in Supporting Information S1. Each experiment is conducted over the period 1980–2014 with an hourly output. The first 6 years were discarded as spin-up.
SCAM6 with its Eulerian dynamical core at resolution of T42 (2.8° × 2.8°) in the horizontal and 32 levels in the vertical is used in this study. The standard Community Land Model Version 5 (CLM5) without irrigation is used in the control simulation (referred to as CTR), whereas the irrigation module is enabled in CLM5 in the experimental simulation (referred to as IRR). All simulations are conducted on selected areas following different settings in Tables S1 and S2 in Supporting Information S1, with a timestep of 20 min. The prescribed land cover percentages over the selected regions are shown in Figure S2 in Supporting Information S1. In this study, we have two boundary condition assumptions, one assumes there is no irrigation in boundary areas, which is used in S1 and S2. This is the most popular assumption in previous studies when it comes to CTR simulation (Puma & Cook, 2010; Thiery et al., 2017; Wey et al., 2015). When we compare S1 and S2, it means only the selected area is irrigated. The other boundary condition assumes the boundary areas are irrigated as usual, which is used in S3 and S4. When S3 and S4 are compared, it means only the irrigation in the selected area is turned off. In other words, the horizontal diffusion in S1 and S2 is derived from the Global Climate Model (GCM) control simulation assuming no irrigation globally, and that in S3 and S4 from the GCM run with global irrigation.

In this study, we focused on simulations listed in Table S1 in Supporting Information S1 as CTR and IRR simulations, other experiments in Table S2 in Supporting Information S1 are mainly used to assess the sensitivity of our CTR (S3) and IRR (S4) simulation results. Soil matric potential and soil moisture threshold, two soil parameters in the model, are used to control irrigation water volume. With larger soil matric potential and smaller soil moisture threshold, a smaller irrigation amount will be applied to selected areas. In the IRR simulation, the model checks the soil moisture at 6a.m. UTC (Coordinated Universal Time) every day to determine whether to irrigate and how much to irrigate. Irrigation is triggered when soil moisture is below a specified threshold during a specific irrigation period. All water needed for irrigation is removed from river water storage (Lawrence et al., 2018).

2.2. Model Evaluation

To evaluate the performance of SCAM, the Climatic Research Unit (CRU TS v. 4.03) 0.5° × 0.5° observation-based monthly temperature datasets (Harris et al., 2014) are used to compare with simulated monthly average temperature in our experiments. Statistical methods Nash-Sutcliffe model efficiency coefficient (NSE) is also calculated to check whether SCAM is an appropriate tool to simulate near surface temperature. Before we start our comparison, the model results from S4 were evaluated. In general, the model performance is sufficient to simulate daily mean, minimum, and maximum temperature, and the NSE values for the four regions are mostly greater than 0.73 (Table S3 in Supporting Information S1). The irrigation scheme used in this study was also evaluated against the Food and Agricultural organization of the United Nations (FAO) census data used in previous studies (Sacks et al., 2009; Thiery et al., 2017; Wada et al., 2011).

3. Results

3.1. Case 1—Regional Irrigation Control With No Global Irrigation

Case 1 are baseline simulations, local irrigation (S2) versus no-irrigation (S1), with no global irrigation, which result in overall cooling of surface air temperature (Figure 1, Figures S3, S4, and S5 in Supporting Information S1) as reported in previous works, with warm semi-arid regions experiencing a more pronounced cooling effect (Cook et al., 2015; Thiery et al., 2017). As shown in the Methodology section, in S1 and S2 we assumed that there is no irrigation applied in the boundary areas, which is widely used in previous studies for control simulation (Chou et al., 2018; Lobell et al., 2009; Mishra et al., 2020; Wey et al., 2015). Irrigation is activated only in the selected area for S2. Under this assumption, the 2-m daily average air temperature decreased due to irrigation in all the four selected areas, which is consistent with most previous regional and global research (Haddeland et al., 2006; Thiery et al., 2017).

In NI, the average 2-m air temperature decreased by 3.18°C ± 0.09°C after being irrigated during peak irrigation season (March–June). We also see a lower minimum and maximum temperature after irrigation in March–June (Figure 1). Our simulations show that increasing evapotranspiration cooling and decreasing shortwave radiation are the dominant factors reducing 2-m average air temperature, minimum temperature, and maximum temperature in NI. However, the decreased surface albedo during March–June due to increased irrigation and soil moisture (Figure 1) can partly counteract the local cooling effect (Cheng et al., 2017). Equivalent results are also seen in
the CV, California. The average 2-m air temperature decreased by 2.82°C ± 0.06°C due to irrigation during peak irrigation season (May–September) and the drop in daytime temperature (4.36°C ± 0.08°C) is larger than that at night-time (1.77°C ± 0.05°C) during May–September (Figure S5 in Supporting Information S1). The surface albedo also decreased during May–September due to irrigation, which contributes to the local warming effect. In EC and MD Basin, irrigation cooled near surface temperature to a lesser extent (Figures S3 and S4 in Supporting Information S1). The diurnal temperature variations and surface albedo had minor differences as well. The average 2-m air temperature decreased by 0.40°C ± 0.02°C and 0.21°C ± 0.03°C respectively after being irrigated during peak irrigation season (April–September, October–March). The drop in daytime temperature (0.49°C ± 0.03°C and 0.26°C ± 0.03°C) is slightly larger than that at night-time (0.36°C ± 0.02°C and 0.17°C ± 0.03°C).

3.2. Case 2—Regional Irrigation Control With Global Irrigation

Case 2 simulations, local irrigation (S4) versus no-irrigation (S3), with global irrigation, seek to understand the effect of stopping local irrigation while irrigation continues around that location. The boundary assumption in S3 and S4 is that the boundary areas are irrigated, which means only the study area is not irrigated in the control simulation (S3). Overall, the average daily temperature during the peak irrigation season increased by 0.60°C ± 0.10°C in March-June because of irrigation in NI (Figure 1). Over NI, the average night-time temperature, 2-m relative humidity, evapotranspiration, downward longwave radiation, latent heat flux, and soil moisture all increased after irrigation, while average maximum temperature, diurnal temperature range, sensible

Figure 1. The 1986–2013 monthly average simulated data in NI. Hereafter, T2m: 2-m air temperature, Tmin: daily minimum temperature, Tmax: daily maximum temperature, ΔT: diurnal temperature range, SM10: soil water in top 10 cm of soil, RH2m: 2-m relative humidity, Atm Albedo: atmospheric albedo, IRR: irrigation amount, Rain: atmospheric rain, LE: latent heat flux, SH: sensible heat flux, Surf Albedo: surface albedo, LWdown: downwelling longwave radiation, SWdown: downwelling shortwave radiation. The gray background areas indicate months with intense irrigation. Different lines reflect results from different simulations. Details about simulations S1 to S4 are shown in Table S1 in Supporting Information S1.
heat flux, downward shortwave radiation, and surface albedo all decreased due to irrigation. Seasonally, the irrigation-induced climatic changes during the peak irrigation season in March to June are always higher than the change during July to February (Bonfils & Lobell, 2007). Comparing control (S3) and irrigation (S4) simulations, the average maximum temperature decreased by 3.33°C ± 0.09°C and the average minimum temperature increased by 5.09°C ± 0.15°C due to irrigation during March to June in NI (Figure 1). Therefore, the average daily temperature increased during the peak irrigation season in NI because the night-time warming effect is stronger than the daytime cooling effect by irrigation. The diurnal temperature range decreased after irrigation, which is consistent with previous study (De Ridder & Gallée, 1998; Lobell et al., 2006).

In the model experiments, evapotranspiration, and latent heat flux all increased because of irrigation both in S1 and S3, which led to increased evapotranspiration cooling and decreased maximum temperature. On the other hand, we also found that downward longwave radiation increased due to irrigation in S3, which in turn contributed to increasing the near-surface temperature. The changes in average daytime temperature are dominated by evaporative cooling during daytime (Figure S10 in Supporting Information S1). However, due to the limited solar energy, night-time evapotranspiration was very small, longwave radiation from clouds and water vapor exerted greater influence on the night-time temperature. At the same time, we also found a similar increase in downward longwave radiation after irrigation due to the increased atmospheric water content. These are all possible factors contributing to night-time warming after irrigation. Moreover, compared to S3, the additional water vapor in the irrigation case (S4) results in a higher dew-point temperature, which limits night-time cooling and smooths diurnal fluctuations in temperature.

Clouds, humidity and precipitable water also increased after irrigation over NI (Figure S12 in Supporting Information S1). Clouds appeared especially important during the dry season in India (Lobell et al., 2009). Our results also indicate that differences between control and irrigation simulations in mid-level and total clouds are the largest during peak irrigation season (March–June) and much smaller during the lesser irrigation season (July–October). Moreover, compared to the irrigation simulation, the planetary boundary layer height is slightly higher in the control simulation due to the lower near surface humidity.

In order to evaluate the sensitivity of our control (S3) and irrigation (S4) simulation results, we conducted a series of simulations with different irrigation volumes (Table S2 in Supporting Information S1). From the results of our six experiments in NI, gradually increasing the amount of irrigation has less impact on the daily maximum temperature but has a relatively greater impact on the daily minimum temperature, diurnal temperature range, humidity, surface evapotranspiration and surface energy exchange during March–June. Our results showing that net shortwave radiation and net longwave radiation gradually decreased, while net radiation gradually increased with increasing irrigation amount, which is also associated with increasing night-time temperature and 2-m air temperature (Figure 1). Moreover, the decreased net shortwave and net longwave radiation is also consistent with increased humidity and cloud fraction in the atmosphere after irrigation. Changes in longwave radiation are much larger than those in shortwave radiation, which corresponds to the increases in net radiation. However, the surface temperature changes in S3 implies that the temperature drop caused by the reduction of longwave radiation can be offset or even exceed the temperature rise caused by the reduction of evapotranspiration under the condition of turning off irrigation.

For EC and MD regions, the changes in near-surface temperature, relative humidity, evapotranspiration, and downward longwave radiation after irrigation are small. An explanation is that there is too little irrigation amount in these two selected areas within the model (Thiery et al., 2017), only 26.5 mm/month average irrigation in EC and 6.9 mm/month in MD respectively.

For the selected area in the CV, California (Figure S9 in Supporting Information S1), we could see a similar pattern with NI, but to a lesser magnitude. The average minimum temperature, 2-m relative humidity, evapotranspiration, downward longwave radiation, latent heat flux, and soil moisture all increased with the increased irrigation amount over CV. From a seasonal perspective, the irrigation-induced changes in sensible heat flux, evapotranspiration, and downward longwave radiation during peak irrigation season (May–September) are always higher than those during October to April over CV (Figure S11 in Supporting Information S1). Moreover, the seasonal effects of irrigation on average daily temperature and daytime temperature are quite different. From May to September, the average daily temperature and daytime temperature all decreased after irrigation (Bonfils & Lobell, 2007). However, from October to April, the daily average temperature and night-time temperature all increased due to irrigation. One possible explanation for the different seasonal response is that in the wet season (from October to
April), the irrigation amount is very small, and it has negligible impact on daytime temperature. In addition, the seasonal difference of irrigation-induced night-time temperature change is very small in the CV. The night-time temperature always increases due to irrigation throughout the year (Kalnay & Cai, 2003). Moreover, the changes in evapotranspiration, and sensible heat flux caused by irrigation are much higher during the day than at night.

3.3. The Differences in Boundary Condition

Figure S13 in Supporting Information S1 illustrates the vertical profile of the two different boundary conditions used in this study during March–June in NI. Overall, the boundary condition temperature in S3/S4 is slightly lower than that of S1/S2, while the specific humidity of S3/S4 is higher than that of S1/S2, which is consistent with the boundary settings shown in Table S1 in Supporting Information S1. In general, the specific humidity tendency (could be understood as gradient) and meridional water transport in S3/S4 is lower than that in S1/S2 (Figure S14 in Supporting Information S1). On the contrary, the temperature tendency in S3/S4 is much higher than that in S1/S2 especially in the vertical level between 600 and 986 hPa. In other words, with a higher specific humidity boundary condition, the specific humidity tendency of S3/S4 is much lower than that of S1/S2. Therefore, there is less water vapor and cloud cover in the atmosphere of S3/S4, so more solar radiation reaches the surface and more longwave radiation is lost as shown in Figure 1. Furthermore, the vertical velocity in S3/S4 is also larger than that of S1/S2, which tends to decrease low-cloud cover when turning off irrigation in S3.

As seen from the energy budgets in Figure 2 under two different irrigation practices in boundary areas, evapotranspiration and shortwave radiation are the dominant factors influencing surface temperature in S1/S2 (no boundary irrigation), while evapotranspiration and longwave radiation are the dominant factors in S3/S4 (with boundary irrigation). Overall, the differences between S1 and S2 are mostly larger than those of S3 and S4. In NI, there is a 2.96°C ± 0.13°C increase in night-time temperature in S4 compared to S3 during March–June, while about 2.55°C ± 0.09°C decrease in daytime temperature because of irrigation. The increase in night-time temperature is slightly larger than the decrease in daytime temperature, which is consistent with the increase (0.60°C ± 0.10°C) in averaged temperature due to irrigation in S3/S4 over NI. The diurnal temperature range also increased more in S3/S4 relative to S1/S2 (Figure 1).

In EC and the MD Basin the differences are smaller when we compare the temperature differences of S3/S4 with those of S1/S2. In CV, there is a 0.64°C ± 0.03°C increase in night-time temperature in S4 compared to S3 during May–September, while a 1.04°C ± 0.03°C decrease in daytime temperature because of irrigation. The increase in night-time temperature is a bit smaller than the decrease in daytime temperature during May–September, which is consistent with the slightly decreased daily temperature during peak irrigation season May–September.

Overall, the slightly increased daily temperature for NI is mostly during the peak irrigation season (March–June), while the slightly increased daily temperature for CV is mostly during the lesser irrigation season (October–April). Based on our results, we would assume that the night-time warming over NI is mostly affected by local irrigation, while the night-time warming over CV is probably caused by both local and remote irrigation. Furthermore, geographical location, climatic cycles, boundary conditions and other factors may also play a role, but at least our results show the possibility of night-time warming due to irrigation in the considered regions of NI and CV of California. In our results, night-time temperature has a stronger response to irrigation than daytime temperature during peak irrigation season March–June in NI. However, daytime temperature has a stronger response to irrigation than night-time temperature during peak irrigation season May–September in CV, while increased night-time temperature contributes to the increased daily temperature in the lesser irrigation season of October–April.

4. Conclusions and Discussion

In this study, we use SCAM to assess local climatic changes (mostly daytime and night-time temperature and humidity) and energy budgets under two different irrigation practices in boundary areas. Regional scale impact of irrigation on surface air temperature and the contributions of evaporative cooling, greenhouse effect, and atmospheric albedo changes are investigated over major irrigated cropping areas located in different climatic conditions (areas in NI, EC, MD Basin, and California CV). Under two different irrigation conditions in boundary areas, evapotranspiration and shortwave radiation are the possible dominant factors on irrigation-induced surface temperature change in Case 1 (only the selected area is irrigated), while evapotranspiration and longwave radiation are the possible dominant factors in Case 2 (only the irrigation in the selected area is turned off).
Overall, under the first boundary assumption, when irrigation is only applied at the selected area, while there is no irrigation in boundary areas, the cooling effect of irrigation is mainly due to the evaporative cooling of daytime temperature, which is consistent with previous regional and global research (Haddeland et al., 2006; Thiery et al., 2017). However, in another scenario where boundary regions are irrigated “as usual,” the night-time warming by irrigation in NI is mainly due to enhancing of the water vapor greenhouse effect. As known in previous study, cloud is a very important factor for the dry season in India when it comes to irrigation response (Lobell et al., 2009). We saw larger meridional water transport in S1/S2 than in S3/S4, due to larger humidity tendency (Figures S13 and S14 in Supporting Information S1), causing more cloud in low and mid-level, which in turn enhancing the greenhouse effect. For both Case 1 and Case 2, a decrease in surface albedo after irrigation over NI (Figure 1) and CV, especially during peak irrigation season (March–June, May–September, respectively),
contributed to surface warming. Overall, the average daily temperature in NI increased by 0.60°C ± 0.10°C in March–June after irrigation (S3 vs. S4), while the average daily temperature in the other three regions all showed different degrees of decrease (0.36°C ± 0.02°C, 0.14°C ± 0.02°C, 0.13°C ± 0.02°C, respectively). The greater the amount of regional irrigation, the greater the magnitude of increase in relative humidity and soil moisture. Our simulations show that the increased daily temperature after irrigation under Case 2 conditions in NI is mainly due to the influence of irrigation on night-time temperature being significantly greater than its influence on daytime temperature (Figure 1). In other words, the difference in maximum temperature between model runs with and without irrigation was much less than the difference in minimum temperature. Hence, any decrease in daytime temperature due to irrigation could be overset by night-time warming under Case 2 conditions, which is different from most previous studies (Thiery et al., 2017). However, irrigation-induced temperature increases in some parts over India (Boucher et al., 2004; Chen & Dirmeyer, 2019; Puma & Cook, 2010; Thiery et al., 2017) and North China Plain (Chen & Jeong, 2018) had been reported in previous studies, although the seemingly counter-intuitive effect was not the focus of the studies. Some authors noted the irrigation-induced warming, possibly originating from the enhanced downward longwave radiation due to increased humidity (Puma & Cook, 2010), which can also support the important role of water vapor on surface temperature (Kennedy & Hodzic, 2019). From our results under Case 2, the increased atmospheric water vapor by irrigation tends to be kept in the region, which makes a stronger local greenhouse effect that increases night-time temperature. The decrease of night-time temperature when local irrigation is turned off is mainly due to the energy dissipation caused by the decreased water vapor and clouds in the atmosphere (Figure S12 in Supporting Information S1). Moreover, the additional water vapor in the irrigation case (S4) results in a higher dew-point temperature, which limits night-time cooling and smooths diurnal fluctuations in temperature over NI (Figure 1) and CV (Figure S5 in Supporting Information S1) especially during peak irrigation season (March-June, May-September respectively). For EC and MD regions, the changes in near-surface temperature, relative humidity, evapotranspiration, and downward longwave radiation after irrigation are small in both Case 1 and Case 2, which is also associated with less irrigation amount.

The higher the usual irrigation volume in a certain area, the greater the impact of irrigation on the average temperature and daily minimum temperature of the area. As shown in the sensitivity test of S3/S4 over NI, we can see that relative humidity and downward longwave radiation are most sensitive to changes in irrigation volume, followed by surface albedo, minimum daily temperature and maximum daily temperature, and 2-m air temperature is the least sensitive to changes in irrigation volume (Figure S6 in Supporting Information S1).

While many studies have used fully coupled GCMs, this study uses SCAM to explore the importance of irrigation practices in boundary areas with the advantage of isolating from more complex remote effects and understanding the complex interactions and vertical feedbacks in water and energy exchange of a single specific column, which is not shown previously in those fully coupled GCM studies. Our results highlight the possible increase of air temperature by irrigation and the importance of considering sub-daily processes when assessing the impact of irrigation on daily air temperature and temperature related socioeconomic phenomena. Whether this situation is a characteristic of a specific area or a common phenomenon in NI and CV, needs to be further verified with a fully coupled model under irrigated boundary areas as shown in this study.

However, there are several uncertainties that need to be considered in this study. Unlike the global coupled model, SCAM does not have dynamic horizontal flux exchange with boundary columns at every time step. With the fixed horizontal exchange, the local climate response to irrigation could be overestimated due to extra vapor kept in the study region. Irrigation time and volume used in this study is calculated based on modeled soil moisture status due to the lack of observational data set, which could cause a slight underestimation or overestimation of local temperature changes. Furthermore, different regions with different climates might have different temperature response to irrigation, which could also increase the uncertainty of regional study and need to be considered in future studies.

**Conflict of Interest**

The authors declare no conflicts of interest relevant to this study.
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Data Availability Statement
Community Earth System Model (CESM2.1.0) used for state-of-the-art computer simulations is available via https://www.cesm.ucar.edu/models/cesm2/release_download.html and developed openly at https://github.com/escom/cesm.
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