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Short Communications

Global assessment of the impact of irrigation on land surface temperature

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A comprehensive and quantitative understanding of the climatic feedbacks of irrigation is of paramount importance for current and future food security. The impact of irrigation on climate, especially temperature, has been assessed by various Earth system models, which have demonstrated that, despite a slight decrease in surface albedo, the net biophysical effect of irrigation is to cool surface temperature through the increase in evapotranspiration (ET) [1,2]. Modeling results are effective in presenting mechanistic understandings of the effects of irrigation on climate, but show high uncertainties in the sign, magnitude, and spatial distribution of the predicted effects, due to their heavy dependence on the model's structure and parameterization [3,4]. Observations from *in-situ* measurements (e.g., weather stations and field experiments) can provide local reliable evidence to verify the model results [5]. However, the previous observational studies have been mostly restricted to local regions [6–8], because of the insufficient coverage of *in-situ* measurements, and it is still unclear as to what extent this observed local evidence can be extrapolated to larger areas. High-quality and spatially continuous land surface temperature (LST) observations from satellites such as the Moderate Resolution Imaging Spectroradiometer (MODIS) have provided a new perspective for understanding the impact of irrigation on temperature. In this study, based on MODIS LST data and other satellite-derived observations (Text S1 and Fig. S1 online), we provide a global-scale quantitative assessment of the impact of irrigation on LST, and explore the possible controlling factors (i.e. albedo and ET) underlying its spatiotemporal variations.

The impact of irrigation on LST is expressed as the LST difference (ΔLST) between irrigated areas and adjacent non-irrigated areas (Fig. S2 online), because of their similar climatic and geographic conditions. The ΔLST was calculated in nearly 5000 valid windows across the globe (Fig. S3 online) based on a window searching strategy (Text S2 online). The results show that almost all the irrigated areas have a lower LST than their adjacent non-irrigated areas (negative ΔLST) across the globe, signifying the prevalent cooling effect of irrigation (Fig. 1). This cooling effect shows an evident diurnal difference. During daytime, irrigation reduces LST in most irrigated regions of the world (Fig. 1a), leading to an annual average cooling effect of 0.96 ± 1.66 K across the globe (Fig. 1d). In the nighttime, cooling is still the dominant effect in the majority of the irrigated areas relative to non-irrigated areas (Fig. 1b), but with a much weaker magnitude (global annual nighttime mean ΔLST, −0.34 ± 0.71 K, Fig. 1e). In fact, this diurnal asymmetry of the impact of irrigation on LST mainly appears in areas with low precipitation (i.e. arid regions), where irrigation has a much stronger cooling effect on the land surface during daytime than during nighttime (Fig. 1d, e and Table S1 online). However, in areas with high precipitation (i.e. humid regions), the impact of irrigation on LST is consistently weak, regardless of day or night (Fig. 1d, e and Table S1 online). The combination of the strong daytime cooling effect and the weak nighttime cooling effect results in an annual daily net cooling benefit of about 0.65 ± 0.99 K across global irrigated regions (Fig. 1f). The spatial distribution of the daily ΔLST is largely determined by the daytime result, due to its greater magnitude, with a clear difference between arid (e.g., Western America and Northwestern China) and humid regions (e.g., most parts of India, Fig. 1c).

The impact of irrigation on LST shows seasonal variations, and the seasonal pattern is very much dependent on precipitation (Fig. 1g–i, and Tables S2, S3 online). In the warm season (i.e. mostly the growing season), the daytime cooling effect peaks in

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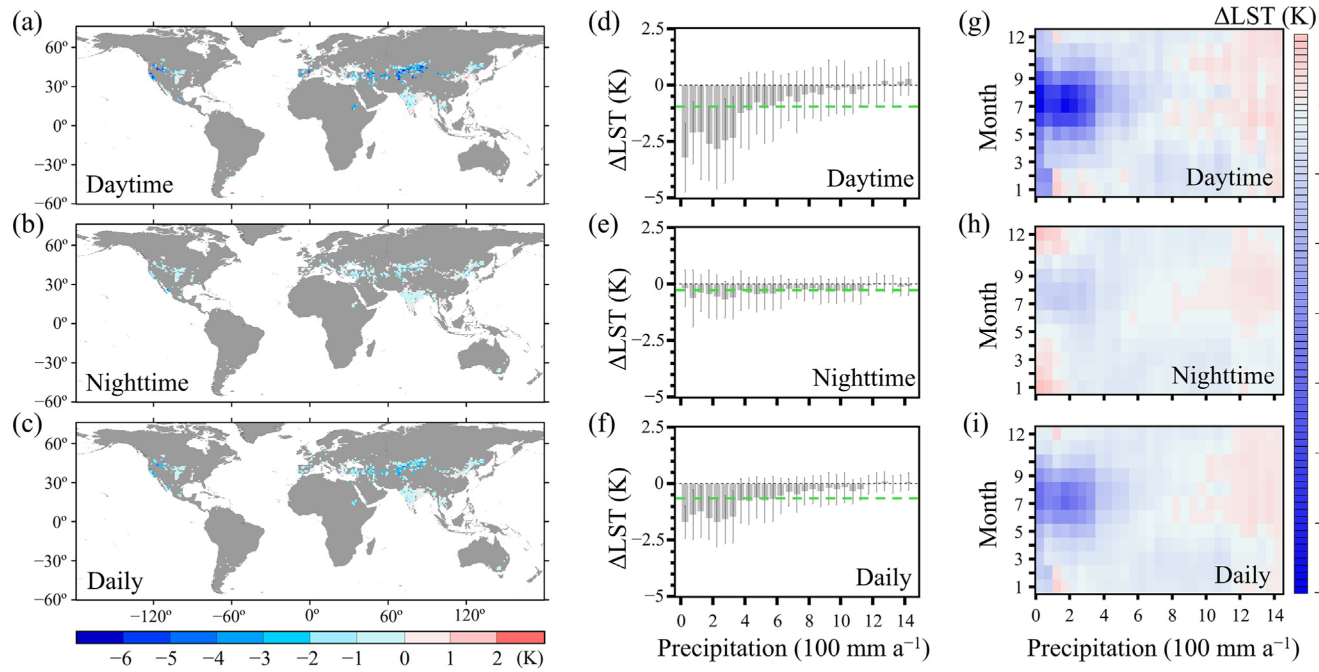

Fig. 1. Spatiotemporal patterns of the impact of irrigation on LST (ΔLST) across the globe. (a)–(c) Spatial patterns (averaged on 1° × 1° grids for visualization) of annual average ΔLST. (d)–(f) Precipitation dependence of annual average ΔLST. (g)–(i) Seasonal variation of ΔLST in the Northern Hemisphere. ΔLST is calculated as the LST difference of irrigated areas minus adjacent non-irrigated areas, and negative (positive) ΔLST indicates a cooling (warming) effect of irrigation. The vertical lines around the bars denote the standard deviation, and the dashed green lines represent the global mean values.

magnitude in the relatively arid regions, which, coupled with the weak nighttime cooling, leads to a strong net daily cooling effect. Meanwhile, with the increase in precipitation, both the daytime and nighttime cooling effects can weaken, disappear, or even reverse. For example, in the Northern Hemisphere, the irrigation-induced summertime daily cooling effect reaches 2.72 ± 1.71 K, on average, in areas with precipitation of less than 400 mm a^{-1}, which is much stronger than in other areas with high precipitation (e.g., precipitation >1200 mm a^{-1}, summertime daily mean ΔLST = 0.17 ± 0.47 K; Table S2 online). In the cold season (i.e. the mostly dormant season), the magnitude of the nighttime effect is comparable to that of the daytime, and their combination generates a slight cooling effect on local surfaces, except for some humid regions. In general, irrigation has a stronger cooling effect in the warm season than in the cold season, and this seasonal pattern is consistent in both hemispheres and across different continents (Fig. S4 online).

The direct impact of irrigation on the land surface is to enhance soil moisture, which in turn changes the surface albedo, and can have a subsequent influence on the solar radiation absorption (Rn). On the other side of the coin, irrigation has an indirect impact on vegetation, which can affect ET, and further repartition sensible and latent heat fluxes (LE). As Rn and LE are two important components of the surface energy process [9], irrigation can be expected to offer feedback to the surface climate, especially LST. This underlying mechanism is supported by the existing models [1,2] and our spatiotemporal analyses of satellite observations (Figs. 2, S5, S6 online).

Our results reveal that the irrigated areas generally have a lower albedo (negative ΔAlbedo) but a higher ET (positive ΔET) than their adjacent non-irrigated areas across the globe (Fig. S5 online). Hence, we can say that irrigation increases the absorbed solar radiation (positive ΔRn, ΔRn = − 1 × ΔAlbedo × incoming solar radiation) and, meanwhile, enhances the heat dissipation into the latent heat fluxes (positive ΔLE, ΔLE = $\lambda \times$ ΔET, λ = 2.451 MJ m^{-2}/mm) at the global scale (Fig. 2a, b). The net effect of irrigation on LST can be regarded as the result of the competition between the potential warming effect caused by the lower albedo and the consequent cooling effect of the higher ET. In relatively arid regions (e.g., precipitation <400 mm a^{-1}), both ΔAlbedo and ΔET peak in magnitude, which leads to substantial differences in Rn (annual daily mean ΔRn, 0.24 ± 0.35 MJ m^{-2} d^{-1}) and LE (annual daily mean ΔLE, 0.51 ± 0.36 MJ m^{-2} d^{-1}) between the irrigated and non-irrigated areas (Fig. 2a, b and Table S4 online). Evidently, the enhanced heat loss through higher ET in the irrigated regions exceeds the extra energy gain induced by the lower albedo (negative ΔRnLE, ΔRnLE = ΔRn − ΔLE, Fig. 2c), which provides an explanation for the strong cooling effect of irrigation in arid regions. With the increase of precipitation, the magnitudes of ΔAlbedo and ΔET, along with their corresponding energy factors (ΔRn and ΔLE), become smaller (Fig. 2a, b), indicating the limited influence of irrigation on the surface energy budgets in humid regions. Consequently, the difference in energy residual (ΔRnLE) between the irrigated and non-irrigated areas is small and almost zero in humid regions (Fig. 2c and Table S4 online), which is the most plausible reason for the negligible impact of irrigation on LST in areas with abundant precipitation. With regard to the seasonal variations, the irrigation-induced change in LE during the warm season is obviously higher than that during the cold season (Fig. 2e and Tables S5, S6 online). For example, in the arid regions (e.g., precipitation <400 mm a^{-1}) of the Northern Hemisphere, the summertime ΔLE is more than 1.00 MJ m^{-2} d^{-1}, on average, whereas the wintertime ΔLE is <0.05 MJ m^{-2} d^{-1}, on average (Table S5 online). However, the effect of irrigation on Rn seems to be consistently low in the different seasons (Fig. 2d and Tables S5, S6 online). Accordingly, the irrigation-induced change in surface energy (i.e. ΔRnLE) shows a remarkable seasonal difference between the warm and cold seasons (Fig. 2f and Tables S5, S6 online), which is the underlying reason for the clear seasonal variation of ΔLST in arid regions.

Our analysis of the correlation between ΔLST and ΔRnLE further reinforces the above understandings. The results indicate that

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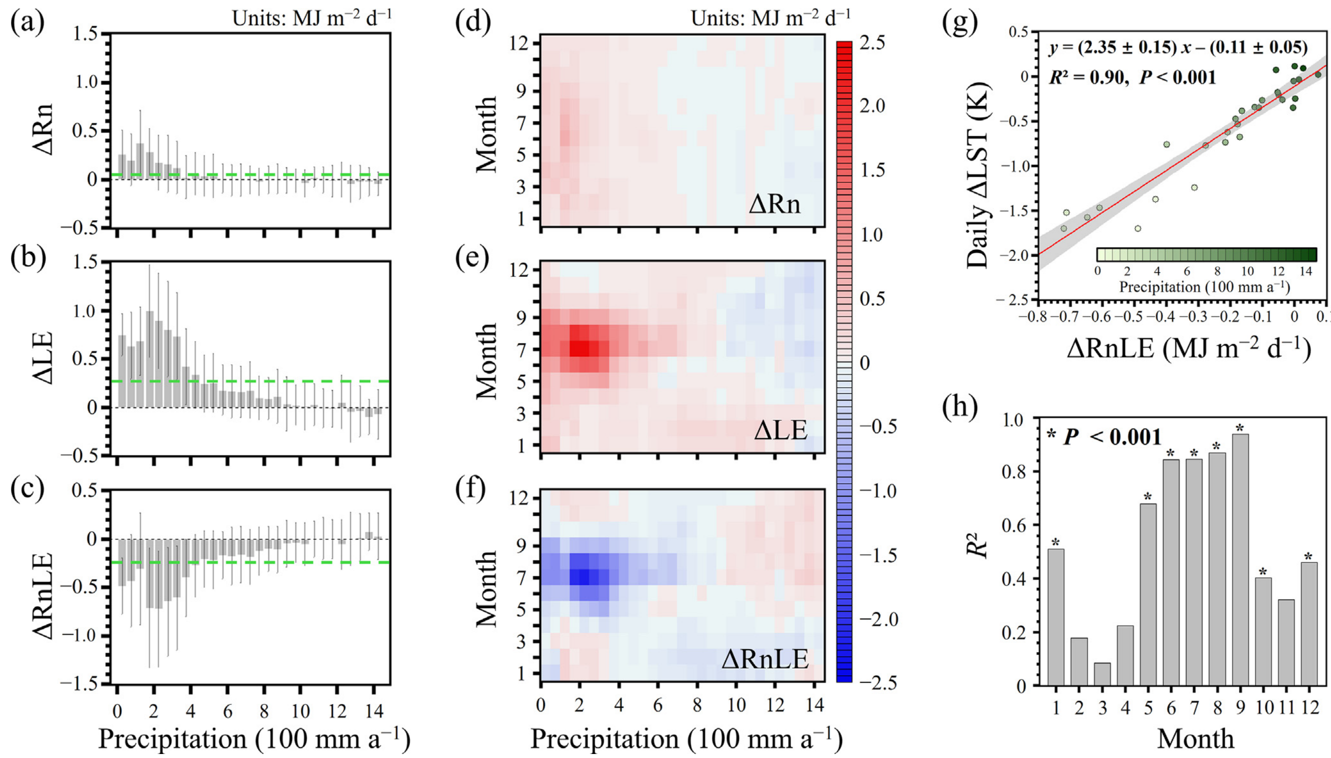

Fig. 2. Irrigation-induced changes in surface energy factors (ΔRn, ΔLE, and ΔRnLE) and their relationships with ΔLST. (a)–(c) Precipitation dependence of annual average ΔRn, ΔLE, and ΔRnLE. (d)–(f) Seasonal variation of ΔRn, ΔLE, and ΔRnLE in the Northern Hemisphere. (g), (h) Relationship between daily ΔLST and ΔRnLE: (g) annual averages; (h) seasonal results in the Northern Hemisphere. ΔRn indicates the difference in absorbed solar radiation between irrigated and non-irrigated areas. ΔLE indicates the difference in surface heat loss by evapotranspiration between irrigated and non-irrigated areas. ΔRnLE indicates the energy residual of irrigated areas minus non-irrigated areas, reflecting how much absorbed energy is offset by evapotranspiration (ΔRnLE = ΔRn − ΔLE). The vertical lines around the bars denote the standard deviation, and the dashed green lines represent the global mean values.

annual daily ΔLST is significantly and positively correlated to annual daily ΔRnLE (R^2 = 0.90, P < 0.001, Fig. 2g). As ΔRnLE is determined by ΔAlbedo and ΔET, we can conclude that albedo and ET are the two important biophysical controls on the impact of irrigation on LST. Furthermore, the relationship between ΔLST and ΔRnLE differs greatly among the seasons (higher R^2 in the warm season, Fig. 2h), which is probably due to the fact that plants usually grow rapidly in the warm season.

In summary, our results show that irrigation decreases both daytime and nighttime LST, leading to a daily average cooling effect of about 0.65 K across the global irrigated regions. The cooling effect of irrigation is substantial in arid regions (such as Western America and Northwestern China) during the warm season, but is negligible in humid regions (e.g., most parts of India) throughout the year. This spatiotemporal pattern of the impact of irrigation on LST is closely related to the biophysical effects mediated by albedo and evapotranspiration. These results are robust against parameters of the window search strategy and different data sources (Text S3 and Figs. S7–S11 online). Our findings highlight the broad range of the impact of irrigation on local climate across the globe, especially in arid regions, where the irrigation-induced cooling benefits may surpass the warming pressure caused by urbanization [10–12] and/or greenhouse gas emissions [5,6,8]. However, besides local climate, irrigation may also have an impact on remote regions through land–atmosphere interactions [13,14], which needs to be further investigated by combining multi-source datasets and coupling observational and modeling methods. Overall, our results underscore the warming reduction benefits that accompany irrigation expansion, and indicate the potential trade-offs or synergies between temperature benefits and water security in arid regions.

Conflict of interest

The authors decare that they have no conflict of interest.

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Author contributions

Xin Huang conceived the work; Qiquan Yang and Xin Huang designed the method and analyzed the data; all authors contributed to the writing of this paper.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2020.04.005.

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