

Irrigation cooling effect reduced by water-saving practices

Corresponding Author: Dr Chao Zhang

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.

Version 0:

Decision Letter:

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Dear Dr Zhang,

Your manuscript titled "Unintended warming from water-saving irrigation" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised substantial concerns that must be addressed. In light of these comments, extensive revisions will be required before we can further consider the manuscript for publication. We would, however, be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. If additional work allows you to either incorporate or refute these criticisms, we will be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

Additionally, to be publishable in Communications Earth and Environment the following editorial thresholds need to be addressed.

*address dataset dependence and strengthen validation.

*improve structure and clarity of key definitions and assumptions.

*more convincingly frame the novelty of the work relative to prior publications.

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Please bear in mind that we will be reluctant to approach the reviewers again in the absence of substantial revisions.

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We are committed to providing a fair and constructive peer-review process. Please do not hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the reviewers' comments with a list of your changes to the manuscript text (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and any completed checklist:

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Please do not hesitate to contact us if you have any questions or would like to discuss the required revisions further. Thank you for the opportunity to review your work.

Best regards,

Srinivas Rallapalli, PhD
Editorial Board Member
Communications Earth & Environment
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(<https://www.nature.com/documents/commsj-phys-style-formatting-guide-accept.pdf>).

REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

The paper presents an analysis of the impact of irrigation in modulating climate. The phenomenon of irrigation providing a cooling effect has been studied in the past, but this study offers a novel perspective and approach at a large, country-wide scale. The paper is well written, and the results corroborate the discussions presented. At the scale at which the study is conducted—national (China)—the inherent uncertainty from the datasets and the approach itself could be a concern, but the authors provide a good discussion on the work's limitations. Nevertheless, the trends revealed through this high-level approach are real, novel, promising, and relevant for important policy decisions.

Reviewer #2 (Remarks to the Author):

Unintended warming from water saving irrigation

Zhang et al. present analysis of MODIS land surface temperature (LST) trends across China. They go on to identify irrigated and non-irrigated pixels and make a pair wise comparison to quantify the temperature trend over irrigated pixels relative to the non-irrigated pixels, which they find to be warming at a faster rate. They go on to consider the impact on the surface energy partitioning and implications for bowen ratio and near surface air temperatures.

This study provides a novel and interesting update on the role of irrigation and water saving technologies on modulating the surface energy balance, however the strength of the signal is reliant on observations from a single observation platform. The results would be strengthened with further validation e.g. in situ observations.

The main text could be structured a little more clearly (see specific comments below). The figures are on the whole clear and support the conclusions. This study will be of broad interest to those in the fields of land-atmosphere interactions and earth system sciences.

My main concern is that this study relies on a number of datasets which are derived from the MODIS Terra observation platform and therefore cannot be treated as truly independent. The most important of which are LST and EVI which together are used to infer the role of WSI technologies. The authors also use the MODIS ET product to validate the ET trends.

Analysis of dataset from an independent source e.g. flux sites, soil moisture datasets would provide additional validation of LST trends particularly in the humid region.

Minor comments

Title – Surely it is the cooling from irrigation that has been unintended perhaps the title should better capture that this. E.g.

Water saving irrigation reduces regional cooling.

L71 “While daytime surface cooling... -are less constrained” – it is not clear what the meaning of this sentence is.

Lines 86–96 this final paragraph presents findings and discussion and should be moved to the discussion section.

Instead it would help readers to mention how the analysis is conducted, introduce here the paper's key concept of “irrigation induced LST”, Δ LST and how it is derived referring to relevant section in the methods.

L90 “strongly regulates” – more explanation needed

L104–108 this section is ambiguous. Please clarify if this cooling effect is over irrigated pixels only, or the region as a whole. Probably the former but is not clear. It would also help to include a reference to methods section describing where the irrigated pixels are identified.

L123 “The spatial pattern of LST trends reinforces the role of declining IWU...,” – this sentence doesn't make sense. There is no irrigation adaptation to the trend in LST.

L126 Δ LST should be defined in the main text to help readers understand what is being compared.

L128 – “intensively irrigated agricultural zones” – it is not clear where these are – reference SIFig1?

L161 evapotranspiration dataset – is this the same dataset as the PML_V2 dataset described in the methods?

L163 toward plant transpiration?

L202 Δ EVI - Is this the difference in EVI_ irrigated – EVI_non-irrigated ?

L226 – are the values calculated for all of China? But presumably dominated by the arid and semiarid areas, please clarify. The humid zone is more nuanced – it would be of interest to see regional versions of Fig5 in SI.

L319 – Are there other factors at play that lead to a reduction in EVI – it is less clear that there is a role of WSI in the humid region in contributing to the warming trend e.g. in SI Fig 10a changes in solar radiation are more important.

L 353 – it should be mentioned here also that the irrigation maps are assumed to be static in time – what are the implications of this assumption?

L357–358 The LST dataset is integral to the results and conclusions of the paper - these caveats should be expanded upon – are these assumptions going to lead to an overestimate/underestimate in the reported trends?

L369 Check the reference numbers

L434 I cannot find where the ground truth points are reported in the reference for this dataset. I presume these are a mixture of different land use types. How many have an irrigation classification? And over what time period were these made?

L436 “exclude changes in irrigation extent” - How does this assumption affect results in time. Presumably irrigation area is increasing in time so this leads to an overestimate of irrigation intensity?

L485 - “...during pairwise comparisons”. It is helpful to reference the relevant section. E.g (see section xx)

L782 summer – which months?

L783 I'm not so familiar with the growing seasons in China - is it the summer growing season. Which months?

Figures 2 and 3. It is difficult to see the black dots particularly on the darkest shading.

Fig3b Latitudinal mean upper bound looks truncated.

SI fig 13 The two lefthand plots on the top row have the same xaxis label – is this correct?

Discussion- Impact on humid heat stress is not discussed but could also be mentioned

Reviewer #3 (Remarks to the Author):

This manuscript by Zhang et al. investigates the biophysical climate impacts of water-saving irrigation (WSI) across China, drawing on two decades of satellite-based land surface temperature and energy flux observations. The authors show that widespread adoption of WSI has substantially weakened irrigation's daytime cooling effect while simultaneously intensifying nighttime cooling, with the balance of impacts varying by region and season. They attribute these changes primarily to shifts in irrigation water use (IWU) and altered surface energy partitioning. The study frames this as an emerging trade-off between improved water-use efficiency and reduced climate-mitigation capacity of irrigation, with implications for Earth system modelling and adaptation policy.

While the topic is timely and potentially relevant, the manuscript, in its current form, raises concerns regarding novelty, overlap with prior publications (notably Zhang et al., 2023), and the framing of WSI's climate implications. The key findings largely reiterate previously published results at a broader spatial scale, and some of the interpretive framing (particularly regarding the “negative” role of WSI) requires clarification and greater balance. Please refer to the accompanying document for major and specific comments.

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Version 1:

Decision Letter:

<*** REMEMBER TO ATTACH REVISIONS CHECKLIST (WORD)***>

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Zhang,

Your manuscript titled "Irrigation cooling effect reduced by water-saving practices" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The manuscript was already in great shape, and with the incorporation of the improvements suggested by the other reviewers, it is now ready for acceptance.

Reviewer #2 (Remarks to the Author):

I have reviewed the revised manuscript, and find it has been significantly improved, addressing most of my previous comments and recommend for publication. In particular, thank you for adding the additional regional plots of Fig5. Some final minor comments.

Line 58

'In China alone, per-hectare irrigation water use has declined by more than 30% since 2000' – reference needed

Lines 65 'For instance, drip irrigation is found to generate the least surface cooling' reference needed here too

L74-77. Consider shortening this sentence to clarify your point and L76 typo 'one' should read 'on'

'However, on one hand, these studies were restricted to a regional scale in arid regions and limits generalizations at broader scopes, especially across different climate backgrounds; one the other hand, the factors and mechanisms driving the changing cooling effects of irrigation over varied climate zones are still poorly investigated, impeding a deeper understanding of the shifting role of irrigation to mitigate climate warming.'

Lines 346-349 'However, this impact is partially offset by a decrease in incoming solar radiation due to higher surface albedo from "brighter" soils (Supplementary Fig. 8l, Supplementary Fig. 10e).'

This is not correct – perhaps you mean the signal is offset by both a reduction in incoming solar radiation and higher surface albedos – as mentioned in the responses.

Reviewer #3 (Remarks to the Author):

Summary

This manuscript by Zhang et al. investigates the biophysical climate impacts of water-saving irrigation (WSI) across China, drawing on two decades of satellite-based land surface temperature and energy flux observations. The authors show that widespread adoption of WSI has substantially weakened irrigation's daytime cooling effect while simultaneously intensifying nighttime cooling, with the balance of impacts varying by region and season. They attribute these changes primarily to shifts in irrigation water use (IWU) and altered surface energy partitioning. The study frames this as an emerging trade-off between improved water-use efficiency and reduced climate-mitigation capacity of irrigation, with implications for Earth system modelling and adaptation policy.

General Comments

Zhang et al. have taken previous comments, positing WSI in the negative, into consideration to improve the manuscript. The added clarifications show the authors made a good effort in responding to my comments to improve the draft. I believe the current version of the manuscript has been significantly improved. Therefore, I recommend its publication, pending some minor revisions raised in the comments below when addressed to the satisfaction of the handling editor.

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Response to Reviewer's Comments

We greatly thank the reviewers for the constructive feedback, which helped us to improve the quality and clarity of the manuscript. We have carefully considered each comment and revised the manuscript accordingly. Below are our detailed and point-by-point responses to all specific and general reviewer comments, detailing the changes made in the main text. Revised sections and sentences were provided in our responses for clarity. Please note that the comments from the reviewers are in black followed by our response in blue and revisions underlined.

Reviewer #1 (Remarks to the Author)

The paper presents an analysis of the impact of irrigation in modulating climate. The phenomenon of irrigation providing a cooling effect has been studied in the past, but this study offers a novel perspective and approach at a large, country-wide scale. The paper is well written, and the results corroborate the discussions presented. At the scale at which the study is conducted—national (China)—the inherent uncertainty from the datasets and the approach itself could be a concern, but the authors provide a good discussion on the work's limitations. Nevertheless, the trends revealed through this high-level approach are real, novel, promising, and relevant for important policy decisions.

Response: We sincerely thank you for your thoughtful and encouraging comments. We are pleased that you find our national-scale assessment to offer a novel perspective and appreciate the recognition of our efforts to acknowledge data-related uncertainties and clarify methodological limitations.

Reviewer #2 (Remarks to the Author):

Zhang et al. present analysis of MODIS land surface temperature (LST) trends across China. They go on to identify irrigated and non-irrigated pixels and make a pair wise comparison to quantify the temperature trend over irrigated pixels relative to the non-irrigated pixels, which

they find to be warming at a faster rate. They go on to consider the impact on the surface energy partitioning and implications for bowen ratio and near surface air temperatures.

This study provides a novel and interesting update on the role of irrigation and water saving technologies on modulating the surface energy balance, however the strength of the signal is reliant on observations from a single observation platform. The results would be strengthened with further validation, e.g. in situ observations.

The main text could be structured a little more clearly (see specific comments below). The figures are on the whole clear and support the conclusions. This study will be of broad interest to those in the fields of land-atmosphere interactions and earth system sciences.

My main concern is that this study relies on a number of datasets which are derived from the MODIS Terra observation platform and therefore cannot be treated as truly independent. The most important of which are LST and EVI which together are used to infer the role of WSI technologies. The authors also use the MODIS ET product to validate the ET trends. Analysis of dataset from an independent source e.g. flux sites, soil moisture datasets would provide additional validation of LST trends particularly in the humid region.

Response: We sincerely thank you for your insightful and constructive comments, and we truly appreciate your recognition of the novelty, clarity, and broader relevance of our study to the land-atmosphere and Earth system science communities.

(1) Structural clarification

As suggested, we have revised the structure of the Introduction to improve clarity and guide the readers more effectively. Specifically, we moved the final paragraph of the original Introduction, which previously included key findings, to the Discussion, and added a new paragraph describing our core analytical approach and definitions (e.g., ΔLST), along with references to the corresponding Methods sections. These changes are intended to better orient the readers before they reach the Results section. Details of the revision can be found in our response to your minor comments.

(2) Clarifying the independence of MODIS products

We understand the concern regarding potential dependence between multiple MODIS-derived variables, as several of our core inputs (LST, EVI, ET) originate from the MODIS Terra platform. However, we would like to emphasize that these products are generated from distinct spectral bands—thermal infrared for LST and visible/NIR for EVI—and rely on independent retrieval algorithms (Wan et al. 2014 for LST; Huete et al. 2002 for EVI). The MODIS ET product is also generated via the Penman-Monteith algorithm and includes additional input data sources.

Importantly, the use of MODIS-based variables from a consistent satellite platform ensures co-located, synchronous, and spatially consistent observations, which is critical for robust inter-variable comparisons. This consistency is particularly valuable in our study of surface energy partitioning and vegetation-climate interactions. Indeed, MODIS products are widely trusted and commonly used in similar research on biophysical land-atmosphere feedbacks (Duveiller et al 2018; Li et al. 2023; Chen et al. 2024). We have now clarified this rationale in the revised manuscript.

(3) Addressing validation through independent data

We fully agree that independent validation using flux tower data or in situ soil moisture measurements would further strengthen the conclusions. However, due to the limited spatial coverage, coarse resolution (e.g., 10-25 km for satellite soil moisture), and the data access issues for flux towers across China, such validation was not feasible at the national scale. Instead, we drew upon findings from recent studies (Fu et al., 2022; Zhang et al., 2023) that used similar satellite methods and independently corroborate the attenuation of irrigation cooling effects, particularly in the arid Xinjiang region.

To acknowledge this limitation and reinforce our justification, we made the following updates.

1) In the Discussion, we added a more detailed paragraph summarizing the case of Xinjiang (as shown in Fu et al., 2022; Zhang et al., 2023), where satellite trends in IWU, LST, and ET were independently assessed and consistent with our national-scale findings.

“The climate impacts of WSI in China are spatially heterogeneous, with the most pronounced indirect warming occurring in arid zones. In arid regions, where agricultural production heavily relies on intensive irrigation, escalating water scarcity and cross-sectoral water competition have facilitated rapid WSI expansion, leading to significant attenuation of the biophysical

cooling¹⁶. Taking Xinjiang as an example, WSI techniques were imported in the late 1970s by the Xinjiang Production and Construction Corps and were gradually promoted to the whole of Xinjiang after 1998, leading to a 130% expansion of the WSI area and 26% reduction of IWU since the 21st century³⁸. As a result, significantly weakened irrigation cooling effects on surface air temperature (an average increase of 0.30 °C in growing-season temperature) and LST (daytime weakening trend: 0.21 °C/decade) were observed in Xinjiang in the last two decades^{20,21}. Specifically, the declining gaps of climatic factors (i.e., LST, ET, and VPD, etc.) between farms inside and outside Xinjiang Production and Construction Corps in our previous regional study²¹ stand as a good corroboration of the attenuated irrigation cooling effect in arid regions due to increasing WSI. However, semi-arid and semi-humid regions—where the original irrigation cooling effect was not as evident as in arid regions (Supplementary Fig. 2a)—exhibited muted thermal trends. This minimal change is largely attributed to vegetation greening, which enhances transpiration and offsets the indirect warming trend (Fig. 4c and Supplementary Fig. 9c)."

2) We also updated our limitations paragraph to explicitly state the lack of ground-based validation and call for future work integrating flux data, crop-specific biophysical models, and field-level irrigation metadata.

"In addition, due to data limitations, particularly at the national scale, we did not explicitly account for potential confounders such as crop type, management practices, or regional policy interventions, which may bring uncertainties to the attribution analysis. Future research that integrates ground-based measurements, crop-specific biophysical modeling, and more detailed irrigation metadata will be critical for improving the representation of WSI in climate models and enhancing the generalizability of our conclusions across diverse agroecological systems."

Together, these revisions clarify both the strengths of our data integration approach and the boundaries of inference, consistent with best practices in large-scale remote sensing studies.

References:

- Wan, Z. (2014). New refinements and validation of the collection-6 MODIS land-surface temperature/emissivity product. *Remote Sens. Environ.*, 140, 36-45
- Huete, A., (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens. Environ.*, 83, 195-213

Duveiller, G., et al. (2018). The mark of vegetation change on Earth's surface energy balance. Nat. Commun., 9, 679-690

Li, Y., et al. (2023). Biophysical impacts of Earth greening can substantially mitigate regional land surface temperature warming. Nat. Commun., 14, 121.

Chen, C., et al. (2024). Biophysical effects of croplands on land surface temperature. Nat. Commun., 15, 10901.

Fu, J. et al. (2022). Amplified warming induced by large-scale application of water-saving techniques. Environ. Res. Lett. 17, 034018.

Zhang, C. et al. (2023). Attenuated cooling effects with increasing water-saving irrigation: Satellite evidence from Xinjiang, China. Agric. For. Meteorol. 333, 109397-109409

Minor comments

Title – Surely it is the cooling from irrigation that has been unintended perhaps the title should better capture that this. E.g. Water saving irrigation reduces regional cooling.

Response: Thanks for this thoughtful advice. We modified the Title to “Irrigation cooling effect reduced by water-saving practices”.

L71 “While daytime surface cooling... -are less constrained” – it is not clear what the meaning of this sentence is.

Response: We deleted this elusive sentence as it seems to be redundant to the front sentence.

Lines 86 –96 this final paragraph presents findings and discussion and should be moved to the discussion section. Instead, it would help readers to mention how the analysis is conducted, introduce here the papers key concept of “irrigation induced LST”, Δ LST and how it is derived referring to relevant section in the methods.

Response: Very good suggestion! Accordingly, we merged this paragraph into the first paragraph of the Discussion, considering that both are conclusive paragraphs. The new paragraph is as follows:

“This study provides the first large-scale observational evidence that widespread adoption of water-saving irrigation can weaken irrigation's biophysical climate benefits, most notably its

daytime cooling effect. Over the past two decades, irrigation water use per hectare has declined significantly across China, coinciding with attenuated daytime land surface cooling and strengthened nighttime cooling. These contrasting diurnal responses, which are most pronounced in arid regions, stem from shifts in surface energy partitioning and thermal storage: increased sensible heat flux drives daytime warming, while reduced soil moisture and longwave insulation accelerate nighttime cooling. These diurnal contrasts are most pronounced in arid zones, where irrigation strongly regulates surface climate. Although vegetation greening associated with improved crop management partly sustains transpiration and offsets warming³³, it cannot fully compensate for the loss of latent heat under lower water inputs. These findings reveal a critical and underrecognized trade-off between improved water-use efficiency and the land surface's capacity to buffer climate warming. While our study centers on China, the insights are broadly applicable to other intensively irrigated regions undergoing similar transitions under mounting water stress."

Furthermore, we supplemented in the Introduction how our analysis was conducted, introduced here the paper's key concept of "irrigation induced LST", Δ LST, and how it was derived, referring to the relevant section in the methods. Below is the revised paragraph.

"This study addresses key empirical and modeling gaps by providing the first large-scale observational assessment of how WSI alters irrigation-induced climatic effects. Focusing on China—a region experiencing rapid WSI expansion and high spatial heterogeneity—as a high-resolution natural laboratory, we test two hypotheses: (1) that widespread WSI implementation has attenuated irrigation's cooling effect, thereby contributing to regional warming; and (2) that the direction and magnitude of these effects vary across space and time, depending on WSI intensity and local climatic conditions. To investigate, here we use the declining irrigation water use per unit cropland area in China¹⁴ as a proxy for the expanding water-saving irrigation (WSI) technologies—the shift from traditional flood irrigation to more efficient irrigation practices. We first extract the changes in satellite-observed LST from MODIS (difference in LST between irrigated and nearby non-irrigated areas, denoted as Δ LST hereafter) and concurrent changes in energy fluxes caused by irrigation at the 1-km pixel scale. We then quantify their temporal trends at various temporal (annual, seasonal, and diurnal) and spatial (national, climate zone, and provincial) scales. Last, we explore the underlying mechanisms by examining the relationship between temporal trends in Δ LST and irrigation water consumption, as well as the background climatic and environmental factors (see Methods). Our findings about the varying irrigation cooling trends across climate zones and the underlying mechanisms due to increasing

water-saving practices highlight the importance of considering land management changes in models for projecting future climate changes.”

L90 “strongly regulates” – more explanation needed

Response: We adjusted the total paragraph and merged it into the first paragraph in the Discussion. A relevant explanation can be found in the new paragraph in the revised version, which is also pasted here:

“These contrasting diurnal responses, which are most pronounced in arid regions, stem from shifts in surface energy partitioning and thermal storage: increased sensible heat flux drives daytime warming, while reduced soil moisture and longwave insulation accelerate nighttime cooling.”

L104 -108 this section is ambiguous. Please clarify if this cooling effect is over irrigated pixels only, or the region as a whole. Probably the former but is not clear. It would also help to include a reference to methods section describing where the irrigated pixels are identified.

Response: Thanks, we agree with this ambiguity and that the cooling effect is over irrigated pixels only. We modified the sentence as follows:

“On average, irrigation produced a daytime cooling effect of -0.34 ± 0.04 K across continuously irrigated croplands (see Methods) in China during 2001–2020 (Supplementary Fig. 2; Supplementary Text 1).”

L123 “The spatial pattern of LST trends reinforces the role of declining IWU.., “ – this sentence doesn’t make sense. There is no irrigation adaptation to the trend in LST.

Response: We deleted this sentence according to your comment.

L126 Δ LST should be defined in the main text to help readers understand what is being compared.

Response: Thanks, as you see in our response to the previous comment, we defined Δ LST in the new ending paragraph of the Introduction, also shown below:

“To investigate, here we use the declining irrigation water use per unit cropland area in China¹⁵ as a proxy for the expanding water-saving irrigation (WSI) technologies—the shift from traditional flood irrigation to more efficient irrigation practices. We first extract the changes in satellite-observed LST from MODIS (difference in LST between irrigated and nearby non-irrigated areas, denoted as Δ LST hereafter) and concurrent changes in energy fluxes caused by irrigation at the 1-km pixel scale.”

L128 – “intensively irrigated agricultural zones” – it is not clear where these are – reference SIFig1?

Response: Thanks, we deleted this sentence and pointed out the positions with prominent signals in the front sentence, which is linked to Fig. 2.

“Spatially, 58% of irrigated grid cells (at 0.5° resolution) exhibited statistically significant daytime LST trends over the 2001–2020 period (Fig. 2a). Among these, two-thirds showed a positive trend, meaning either a weakening of daytime cooling (in areas with initially negative Δ LST like Northwest China) or an intensification of surface warming (where Δ LST was already positive like Southern China, Fig. S2c).”

L161 evapotranspiration dataset – is this the same dataset as the PML_V2 dataset described in the methods?

Response: Yes, we specified this dataset in the revised manuscript:

“Moreover, leveraging a high-resolution evapotranspiration dataset (PML_V2²⁸, see Methods), we observe a consistent trend of rising transpiration and declining soil evaporation (Supplementary Fig. 6).”

L163 toward plant transpiration?

Response: Yes, we updated the sentence accordingly: “These findings suggest that WSI shifts the source of evapotranspiration away from bare soil and toward plant transpiration, maintaining or even enhancing plant water use despite constrained irrigation inputs.”

L202 Δ EVI - Is this the difference in EVI_{irrigated} – EVI_{non-irrigated} ?

Response: Yes, we explained this index in the updated manuscript:

“To disentangle the drivers of observed changes in irrigation-induced LST effects, we conducted a multi-factor attribution analysis incorporating irrigation water use (IWU), background climate conditions (precipitation, solar radiation, air temperature, and wind speed), and vegetation greening (Δ EVI, the difference in EVI between irrigated and non-irrigated croplands).

L226 – are the values calculated for all of China? But presumably dominated by the arid and semiarid areas, please clarify. The humid zone is more nuanced – it would be of interest to see regional versions of Fig5 in SI.

Response: Thanks for your meticulous observation. All the values in Fig. 5 are calculated at the national scale. In the revised manuscript, we updated this point and provided the regional versions in Supplementary Fig. 12, which are also shown as follows.

First, we specified that the values are calculated for China in the first paragraph of Section *Causal pathways from IWU to LST*:

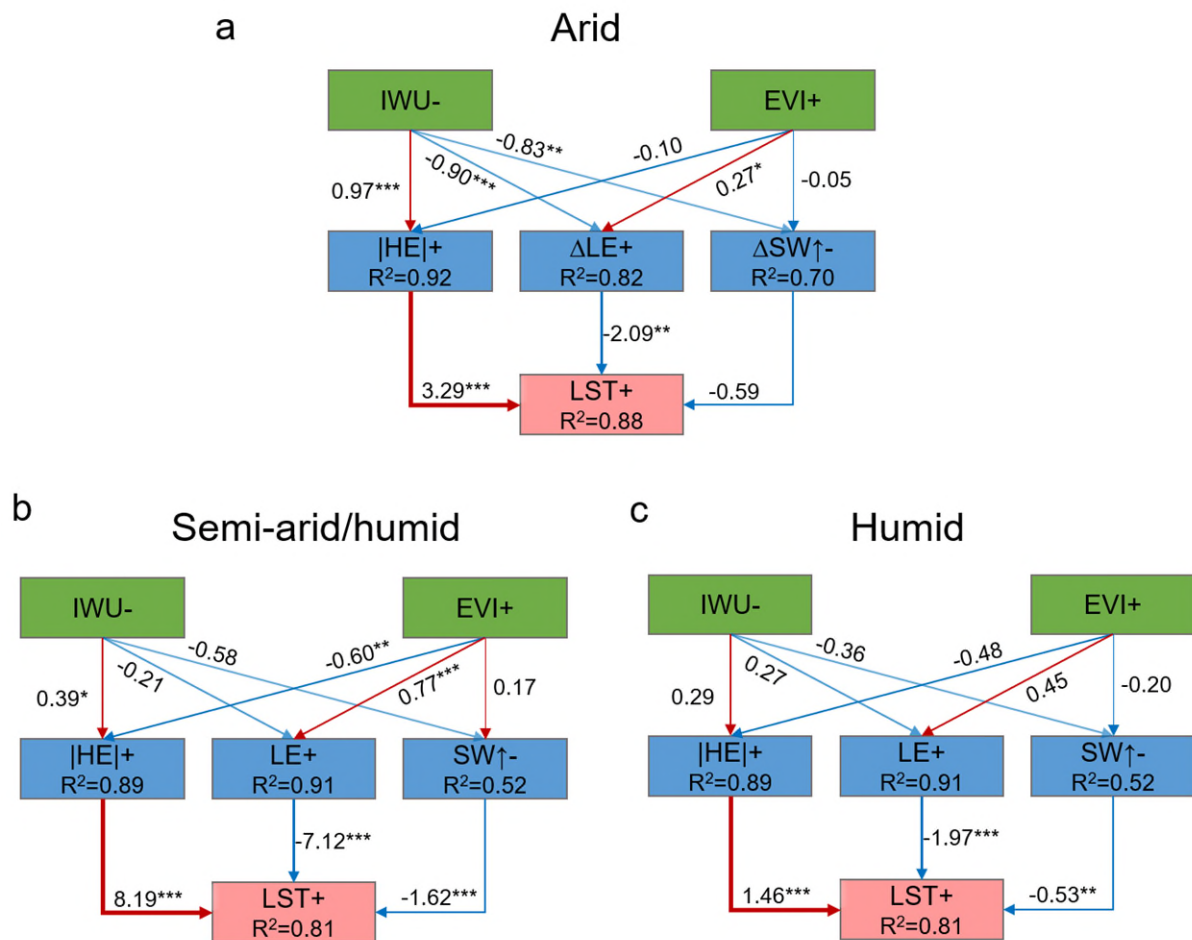
“To elucidate the causal relationships among IWU, vegetation greenness (Δ EVI), surface energy fluxes, and LST, we applied a structural equation modeling approach both at the national and climate zone scales. We find that both IWU and Δ EVI significantly affect LST across China, albeit via different mechanisms and magnitudes (Fig. 5a).”

Second, we pointed out that spatial heterogeneity in the second paragraph of this Section:

“Importantly, the path coefficient from Δ HE to LST (+4.65) was substantially larger in magnitude than that from Δ LE to LST (−3.32), suggesting that the warming effect of enhanced sensible heat outweighs the cooling effect of latent heat under reduced water availability. While improved vegetation conditions partly buffer against thermal stress through increased transpiration, this effect is insufficient to offset the dominant warming pathway mediated by Δ HE. Additionally, IWU exerts a minor influence on net shortwave radiation through changes in albedo, likely due to shifts in surface reflectivity as soils become drier and brighter. However, this radiative pathway plays a minimal role in the overall LST response. Notably, the strength of these influencing mechanisms varies spatially (Supplementary Fig. 12), for example, the largest path coefficient from IWU to LE appears in arid regions, while EVI to LE dominates in

semi-arid and semi-humid regions. In contrast, the effect is negligible in humid areas. Together, these results underscore a robust causal chain from reduced IWU to daytime warming, driven primarily by increased sensible heat flux and only partially mitigated by vegetation feedbacks. This mechanistic understanding reinforces earlier findings and emphasizes that while WSI promotes agricultural water savings, it alters the surface energy budget in a way that diminishes irrigation's climate mitigation capacity.”

Third, we added Supplementary Fig. 12 to show the regional results.



Supplementary Fig. 12 | Same as Fig. 5a in the main text, but for regional statistics including arid (a), semi-arid/humid (b), and humid (c) climate zones.

L319 – Are there other factors at play that lead to a reduction in EVI – it is less clear that there is a role of WSI in the humid region in contributing to the warming trend e.g. in SI Fig 10a changes in solar radiation are more important.

Response: Thank you for this thoughtful comment. We believe you are referring to Line 309 in the original manuscript. We agree that the contribution of WSI to the warming trend in humid regions appears less pronounced compared to arid and semi-arid zones. This is likely due to several overlapping factors. In particular, we observe a lagged greening trend across irrigated areas in the humid zone, potentially driven by shifts in cropping patterns—such as the transition from double to single rice systems—which lowers the annual mean EVI. In addition, while WSI may reduce soil evaporation, its warming influence in this region may be partially masked by concurrent reductions in incoming solar radiation and increased surface albedo from exposed or “brighter” soils.

Based on your observation and suggestion, we have revised the paragraph describing the warming mechanisms in humid regions as follows:

“In contrast, the contribution of WSI to the warming trend in humid regions appears relatively limited, likely due to a weakened trend in vegetation greening within irrigated areas (Supplementary Fig. 5d). This lag in greening, closely associated with reduced evaporative cooling (Supplementary Fig. 5l) may be linked to a decline in cropping intensity, such as the shift from double to single rice cultivation³¹. Meanwhile, the promotion of WSI has further reduced soil-driven evaporative cooling (Supplementary Fig. 6l), thereby exacerbating the warming effect. However, this impact is partially offset by a decrease in incoming solar radiation due to higher surface albedo from “brighter” soils (Supplementary Fig. 8l, Supplementary Fig. 10e).”

L353 – it should be mentioned here also that the irrigation maps are assumed to be static in time – what are the implications of this assumption?

Response: Thank you for this important observation. You are absolutely right, the use of a static irrigation map is a methodological choice intended to isolate the trend in irrigation-induced cooling, free from the confounding effects of expanding irrigation area. By focusing on persistently irrigated areas, we aim to attribute LST changes more directly to evolving irrigation practices (e.g., WSI adoption) rather than spatial changes in irrigation extent.

However, we fully acknowledge that this approach may lead to an underestimation of the overall weakening of the cooling effect, as newly irrigated areas, particularly those equipped

with water-saving technologies, are excluded from the analysis. These newly added irrigated pixels might exhibit stronger reductions in cooling due to their more efficient irrigation methods.

In line with your suggestion, we have revised the limitations paragraph to explicitly acknowledge this uncertainty as follows:

“Despite the robustness of our findings, several limitations warrant consideration. First, the irrigation maps used in this study, while independently validated, can not fully capture intra-seasonal variability or field-level irrigation practices such as rotation, deficit irrigation, or timing of water application. Moreover, the irrigation cooling trends assessed here are confined to persistently irrigated areas over the past two decades. As a result, they may represent a conservative estimate of the actual trend magnitude, since newly irrigated regions adopting water-saving technologies were not included. Second, while we use per-hectare IWU as a proxy for WSI intensity, ...”.

L357-358 The LST dataset is integral to the results and conclusions of the paper - these caveats should be expanded upon – are these assumptions going to lead to an overestimate/underestimate in the reported trends?

Response: Thank you for the comment. We have revised the original statement in the manuscript as follows:

“Third, the LST data, although widely used, are sensitive to cloud cover, view angle, and surface emissivity variations, which may introduce overestimation or underestimation of the trends, particularly in humid regions where persistent cloudiness reduces observation frequency.”

L369 Check the reference numbers

Response: Thanks for pointing out this issue, which will lead to ambiguity. We have revised the unit from km³ to cubic kilometers, which is also shown as follows:

“Looking ahead, irrigated croplands are expected to expand by 70 million ha by 2050, with annual blue water consumption reaching 1,800 cubic kilometers^{47,48}.”

L434 I cannot find where the ground truth points are reported in the reference for this dataset. I presume these are a mixture of different land use types. How many have an irrigation classification? And over what time period were these made?

Response: Thanks for pointing out this issue. As reported in the reference paper of this dataset (Table 2 in Zhang et al., 2023), the pixel-wise quantitative assessment was implemented for six years, including 2001, 2004, 2009, 2010, 2012, and 2016, using more than 3000 ground truth samples for each year.

To reduce the unnecessary ambiguity, we have rephrased the sentence:

“This dataset was generated using machine learning applied to MODIS surface reflectance and spectral indices on the Google Earth Engine platform, achieving a mean accuracy of 81%⁵¹.”

L436 “exclude changes in irrigation extent” - How does this assumption affect results in time. Presumably irrigation area is increasing in time so this leads to an overestimate of irrigation intensity?

Response: Thank you for raising this point. As we noted in our response to Comment L353, our analysis is intentionally focused on persistently irrigated areas to minimize confounding effects from irrigation area expansion and to isolate the trend in cooling attributable to evolving irrigation practices (e.g., WSI adoption).

We acknowledge, however, that using a static irrigation extent introduces some uncertainty. In particular, because the national irrigated area has gradually expanded over the study period, our calculation of per-hectare IWU may slightly overestimate irrigation intensity in the earlier years—when fewer areas were under irrigation—and underestimate the effect of expanding WSI in newly irrigated zones.

To reflect this limitation, we have clarified the implications of using a static irrigation mask in the revised Discussion section as follows:

“Despite the robustness of our findings, several limitations warrant consideration. First, the irrigation maps used in this study, while independently validated, can not fully capture intra-seasonal variability or field-level irrigation practices such as rotation, deficit irrigation, or timing of water application. Moreover, the irrigation cooling trends assessed here are confined

to persistently irrigated areas over the past two decades. As a result, they may represent a conservative estimate of the actual trend magnitude, since newly irrigated regions adopting water-saving technologies were not included. Second, while we use per-hectare IWU as a proxy for WSI intensity, ...”.

L485 - “...during pairwise comparisons”. It is helpful to reference the relevant section. E.g (see section xx)

Response: Thanks for this good idea! We have revised this sentence as follows:

“DEM data were primarily used to filter valid pixels by constraining elevation differences between irrigated and non-irrigated reference areas during pairwise comparisons (shown in the next section).”

L782 summer – which months? L783 I’m not so familiar with the growing seasons in China - is it the summer growing season. Which months?

Response: Based on your comments, we have explained the specific months in the revised manuscript as follows:

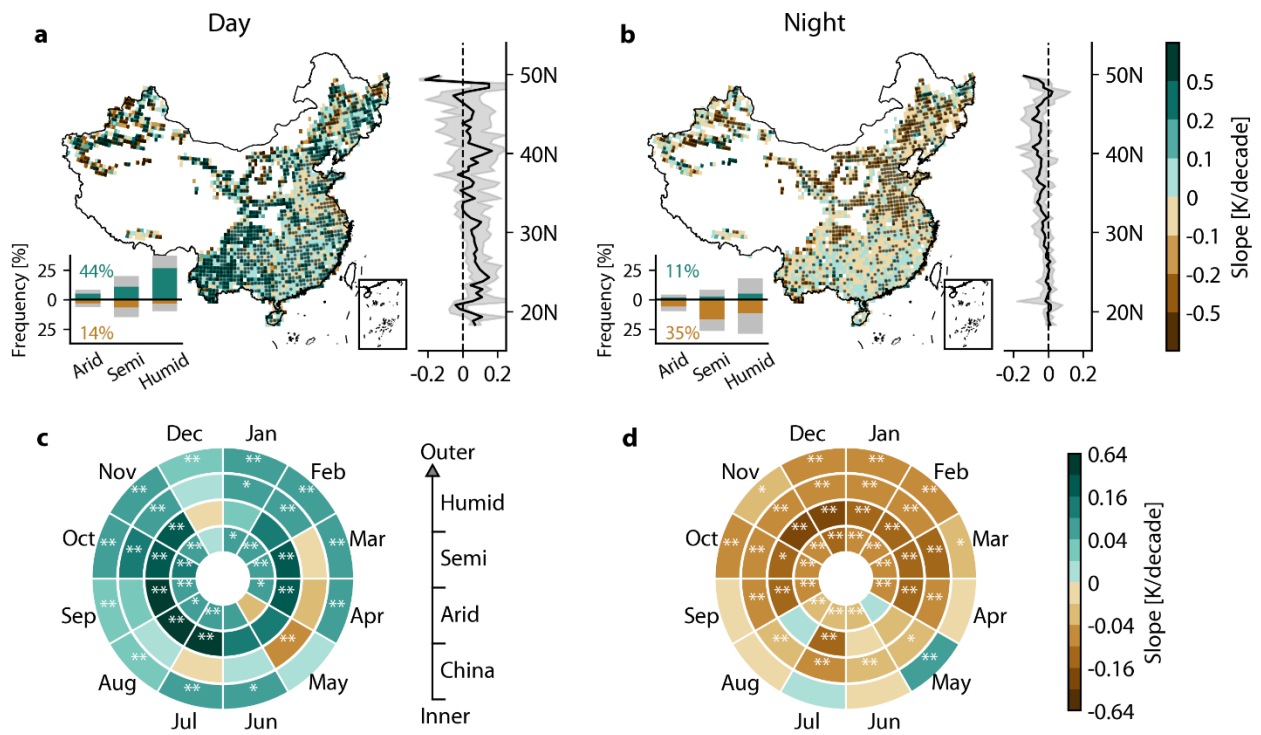
“Clear seasonal patterns were observed for Δ LST, especially in the daytime, characterized by evident cooling in summer (June, July, and August) and slight cooling (or warming) in winter (December, January, and February; Supplementary Fig. 2c), because irrigation practices are mainly implemented in the growing season (May to September).”

Figures 2 and 3. It is difficult to see the black dots particularly on the darkest shading. Fig3b Latitudinal mean upper bound looks truncated.

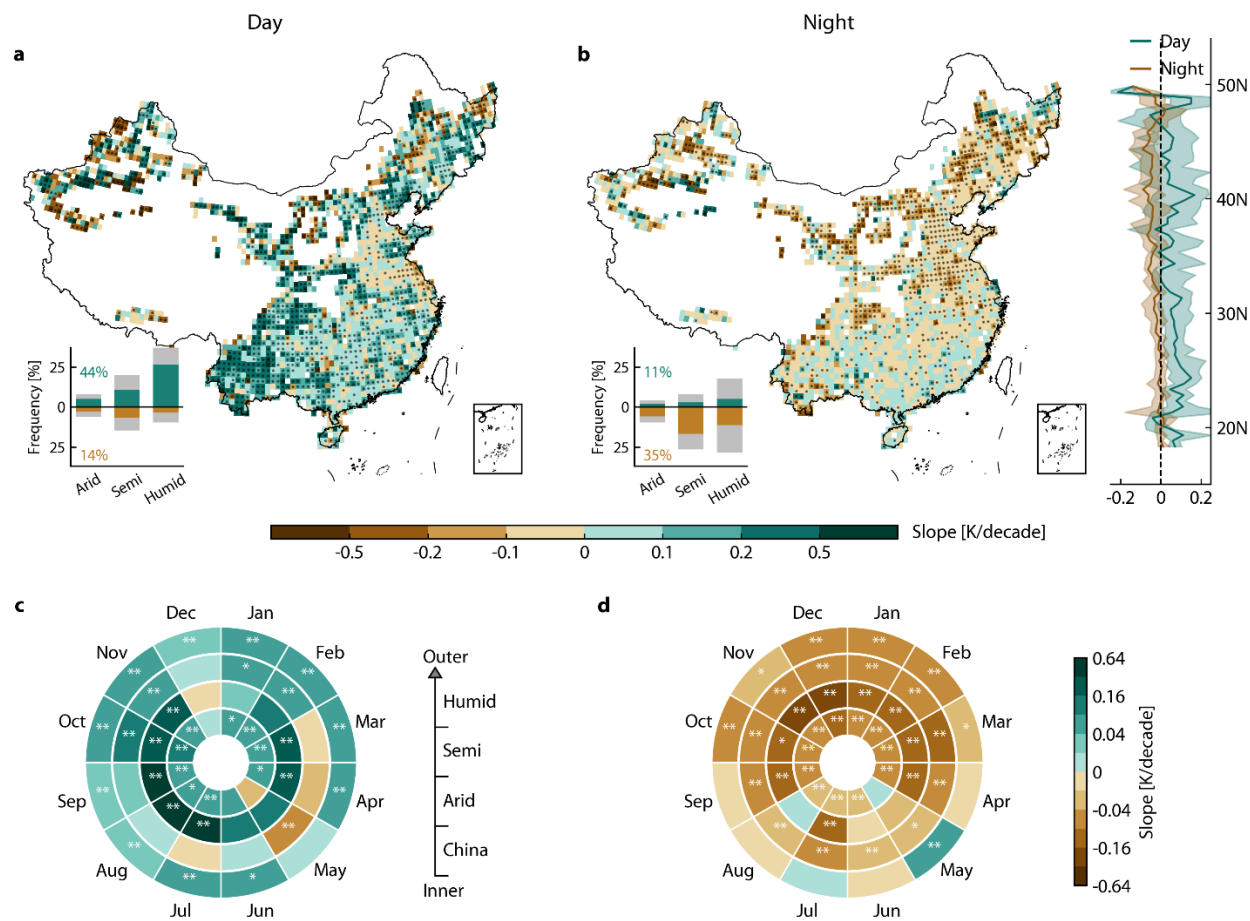
Response: Thanks for your comments to help us improve the figure illustration. We have reframed Figures 2 and 3 in the revised manuscript.

Specifically, we amplified the maps by moving the original color bar to the bottom of the maps and merging the two latitudinal panels, which is expected to mitigate the blurring effects of black dots and the darkest shading. We also addressed the issue of upper-bound truncation by extending the x-axis extent.

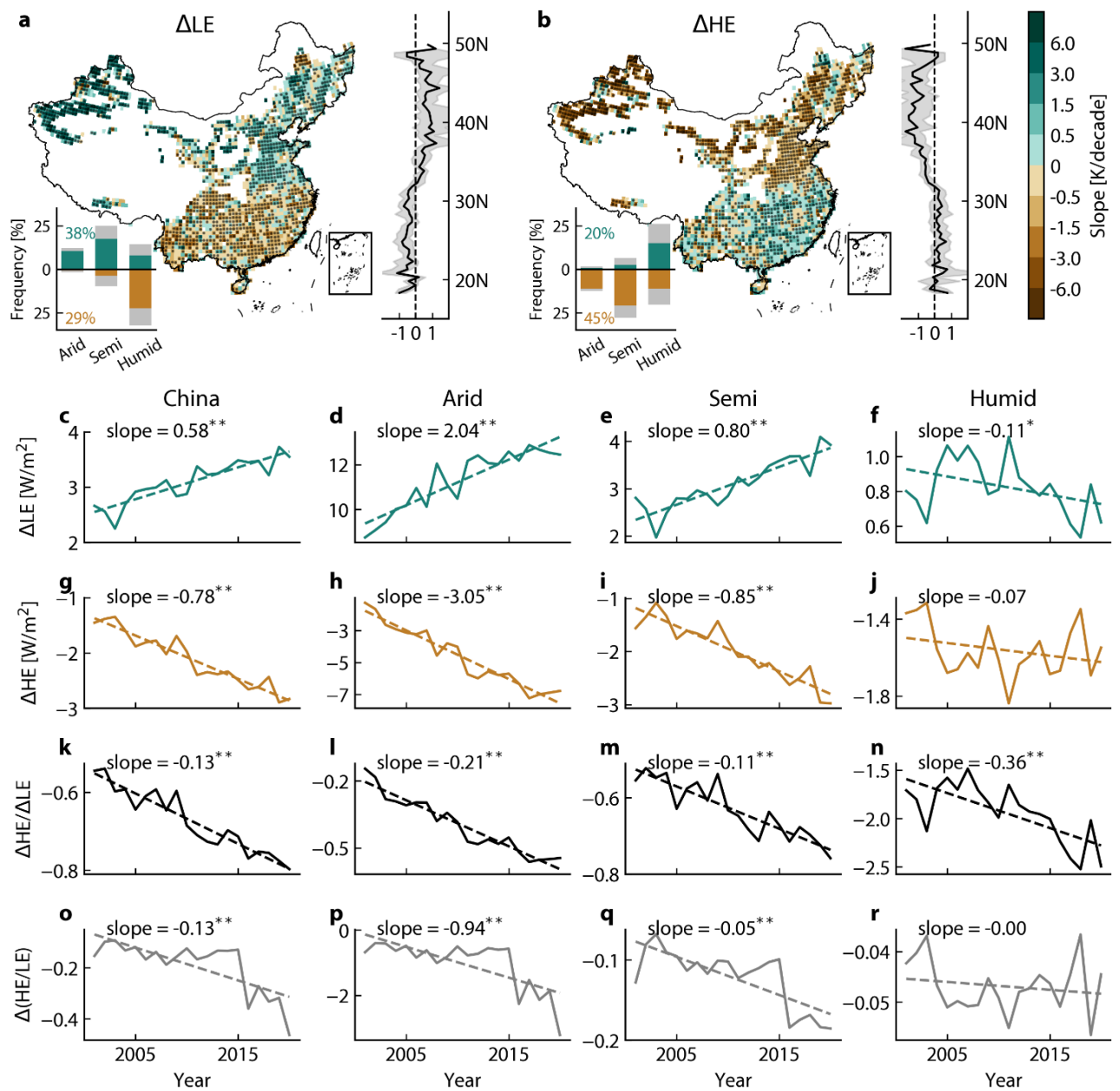
For your convenience, to see the improvements, below we show both the OLD and NEW Figures.



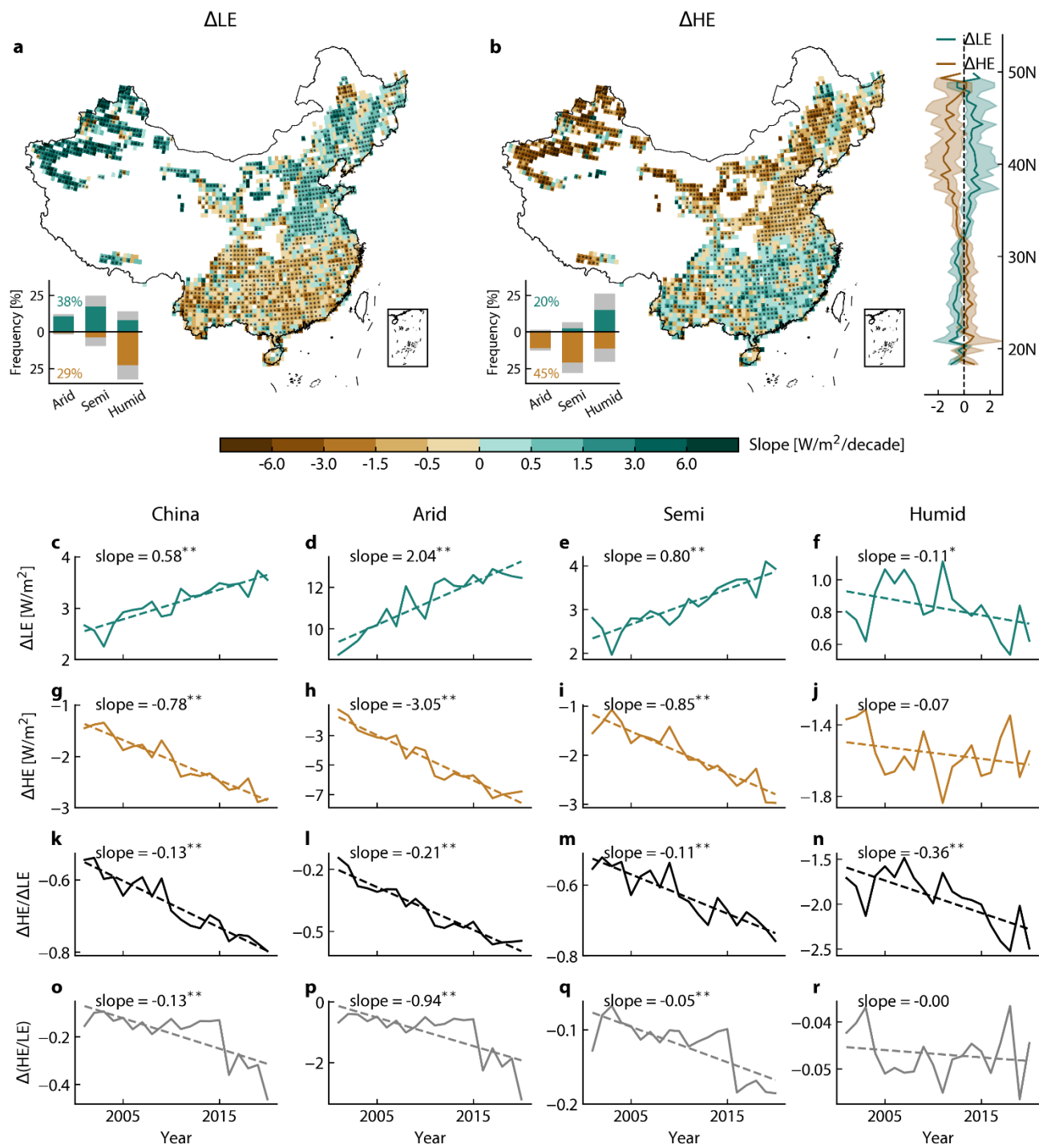
OLD Figure 2.



NEW Figure 2.



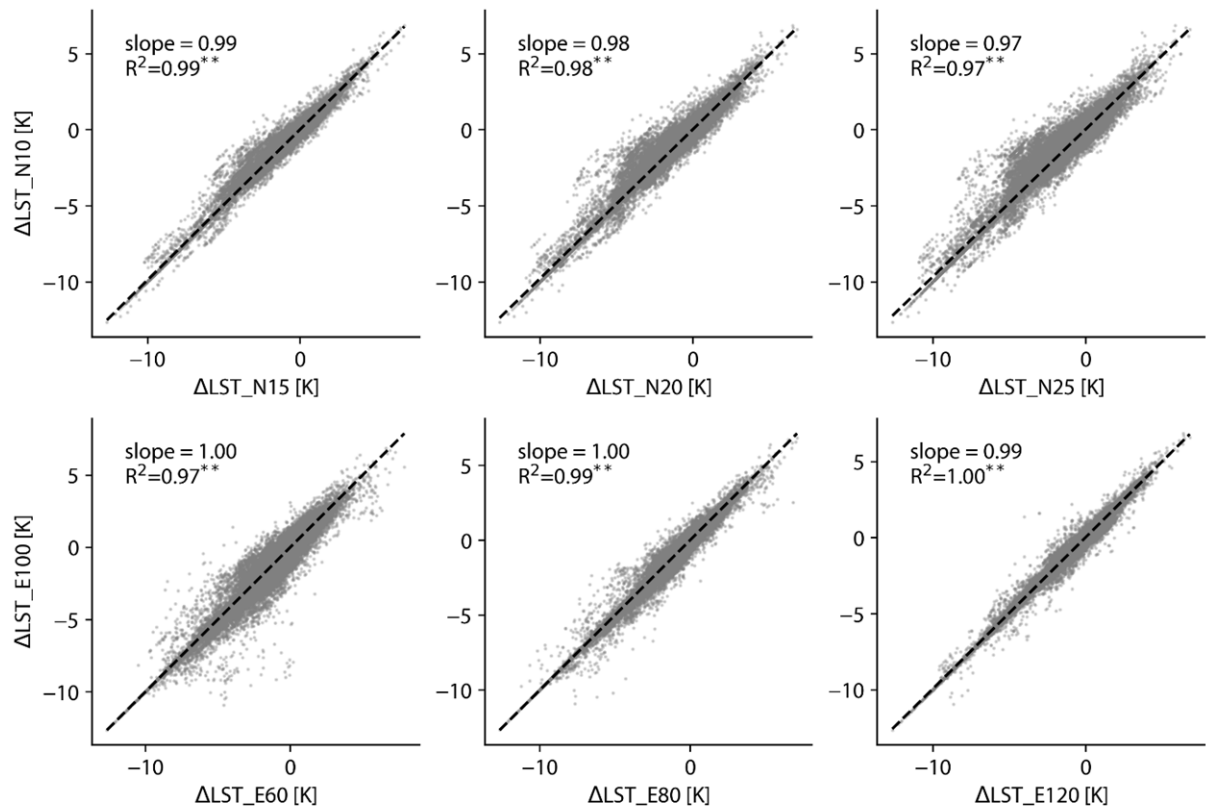
OLD Figure 3.



NEW Figure 3.

SI fig 13 The two lefthand plots on the top row have the same x axis label – is this correct?

Response: Thanks for pointing out this typo. We have updated the Figure as follows. Note that the figure number has been changed from Supplementary Fig. 13 to Supplementary Fig. 14.



Supplementary Fig. 14 | Sensitivity analysis of the pairwise comparison method using different window parameters in 2010. Sensitivity tests were conducted by varying two key parameters: the number of reference (non-irrigated) pixels (N) and the elevation difference threshold (E) used to match irrigated and control pixels. Results show how estimated ΔLST values respond to different parameter settings. $**p < 0.01$, $*p < 0.05$ based on Student's t-test.

Discussion- Impact on humid heat stress is not discussed but could also be mentioned.

Response: Thank you for this insightful suggestion. We agree that the interplay between irrigation, humidity, and human heat stress, particularly in humid regions, is an important and underexplored dimension. In response, we have incorporated this point into the fifth paragraph of the Discussion section in the revised manuscript, as follows:

“The weakening of irrigation-induced cooling under WSI may have tangible consequences for food security and human thermal exposure. Many staple crops such as maize, wheat, and rice

are highly sensitive to temperature extremes, particularly during reproductive stages, and even short-lived heatwaves can cause substantial yield losses³⁸. The attenuation of daytime cooling in irrigated regions could reduce the protective buffer that irrigation has historically provided against heat stress, especially during critical growth periods³⁹. In densely populated agricultural regions, this warming effect may also exacerbate human heat exposure, increase cooling energy demand, and undermine labor productivity during hot periods⁴⁰. Studies suggest that high-efficiency irrigation can lead to small but measurable increases in ambient temperature and vapor pressure deficit, potentially amplifying crop water demand even as total water use declines^{18,21}. Nevertheless, the reduced water use associated with WSI may help alleviate moist heat stress²¹. Large-scale irrigation has been shown to increase humidity, which in turn raises the maximum wet bulb temperature—exacerbating deadly heat conditions and threatening the ability of local farmers to work outdoors^{37,41}. These findings highlight the need to critically assess the resilience of agroecosystems and rural communities under climate-smart irrigation strategies, emphasizing the importance of integrative planning that balances water conservation with thermal regulation and crop productivity.”

Reviewer #3 (Remarks to the Author):

Summary

This manuscript by Zhang et al. investigates the biophysical climate impacts of water-saving irrigation (WSI) across China, drawing on two decades of satellite-based land surface temperature and energy flux observations. The authors show that widespread adoption of WSI has substantially weakened irrigation's daytime cooling effect while simultaneously intensifying nighttime cooling, with the balance of impacts varying by region and season. They attribute these changes primarily to shifts in irrigation water use (IWU) and altered surface energy partitioning. The study frames this as an emerging trade-off between improved water-use efficiency and reduced climate-mitigation capacity of irrigation, with implications for Earth system modelling and adaptation policy.

While the topic is timely and of potential relevance, in its current form the manuscript raises concerns regarding novelty, overlap with prior publications (notably Zhang et al. 2023), and the framing of WSI's climate implications. The key findings largely reiterate previously published results at a broader spatial scale, and some of the interpretive framing (particularly regarding the “negative” role of WSI) requires clarification and greater balance.

Response: We sincerely thank you for your time and effort in reviewing our manuscript with professional comments and suggestions. We appreciate your recognition of the relevance and timeliness of our study and understand your concerns regarding novelty, potential overlap with our earlier publication (Zhang et al. 2023, hereafter Z23), and the framing of water-saving irrigation (WSI) in the manuscript.

We would like to clarify that our previous work (Z23) was a regional case study focused solely on Xinjiang Province. In contrast, the current manuscript represents a substantial extension in both spatial scale and analytical depth. To be honest, we do not think Z23 compromised the novelty and contribution of this work, but instead, it highlighted the remarkable progress of this work.

Specifically:

(1) We analyze nationwide trends across diverse climate zones, revealing spatial heterogeneity

in the evolution of irrigation-induced cooling—most notably, that daytime cooling attenuation is strongest in arid and humid regions, but minimal in transitional zones.

- (2) We conduct a more comprehensive energy balance analysis, revealing that the increasing Bowen ratio plays a central role in the reduced cooling effect under WSI. This mechanistic understanding goes beyond the findings of Z23 and adds explanatory depth to the observed trends.
- (3) We also uncover the joint role of IWU and crop greening in modulating land-atmosphere exchanges. Interestingly, we find that, in some regions, latent heat fluxes did not decline despite reduced water inputs, likely due to enhanced transpiration from vegetation greening—an underexplored dynamic in the existing literature.

These contributions collectively offer novel insights into the evolving climate implications of WSI and underscore the importance of incorporating dynamic irrigation practices into Earth system models and adaptation policy.

To address your concerns, we have:

- (1) Clearly distinguished this study from Z23 throughout the manuscript;
- (2) Appropriately cited and contextualized prior work;
- (3) Reframed parts of the discussion to better balance the trade-offs of WSI, avoiding overly negative portrayals.

We hope these revisions clarify the novelty, contributions, and framing of the manuscript. Thank you again for your valuable input.

General Comments

1. The manuscript is well structured and written logically. It is easy for readers to follow the story. The figures are also legible, neatly layout, of great quality albeit densely packed.

Response: Thanks for your approval of this manuscript, which is important for us. We further optimized the layout of Figures 2 and 3 to make them more legible, as you can see from our response to Reviewer #2 or the manuscript revised.

2. The findings and conclusions in the manuscript are not so novel within the scope of Communications Earth & Environment. Since irrigation (application of water to support crop growth) induces cooling, it is axiomatic that increasing or decreasing IWU will alter this cooling effect (see also Liu et al., 2023; Braun and Schlenker 2023). Also, the manuscript's results are largely replicated findings by a group of the current authors in Zhang et al. (2023) [<https://doi.org/10.1016/j.agrformet.2023.109397>]. That study already reported that water-saving irrigation (WSI) (i) weakens biophysical cooling (especially late summer/early spring), (ii) intensifies nighttime cooling, and (iii) links cooling reduction to declining IWU. The only substantive difference is the geographic scope (Xinjiang vs. China), but the conclusions remain essentially the same.

Response: We appreciate that you raised the similarity between our pending work and the previous work (Z23). However, here we would like to argue that the Z23 and this work have different scopes, based on the following reasons:

(1) The whole country of China includes four climate zones (arid, semi-arid, semi-humid, and humid) with remarkably different agricultural irrigation systems and water-saving technology progresses, while Z23 only covered the arid zone of Xinjiang. Therefore, this study provides more information on the spatial pattern of the different local temperature responses to the water-saving irrigation transformation.

(2) In this study, the biophysical mechanism was thoroughly investigated by using the energy balance equation, while the Z23 did not involve any attribution analysis in terms of energy budget. Therefore, the comprehensive biophysical mechanism analyses in this study are conducive to understanding the impacts of water-saving irrigation and can help to guide climate model developments to project future climate changes.

Actually, Z23 is a regional experiment restricted to Xinjiang, a typical province in China that faces a severely arid climate and water scarcity, and has experienced a great expansion of water-saving irrigation in the last two decades. The conclusion that water-saving irrigation decreases daytime cooling but increases nighttime cooling in Z23 was an exciting finding and inspired us to expand the test region to the whole country. Therefore, we do not think Z23 compromised the novelty of this study; on the contrary, it is a good start and laid a solid foundation for the current study.

Compared to Z23, this manuscript makes a big advance in terms of both the more extensive pattern analyses of weakened irrigation cooling effects over China (including four climate zones) and the comprehensive investigation of the underlying mechanisms. Specifically, we found the temporal trends of irrigation cooling effects varied significantly across different climate backgrounds, characterized by the most prominent weakening trend in arid regions, followed by humid regions, but not significant in semi-arid and semi-humid regions. The discrepancies were attributed to the different stages of water-saving irrigation development and varied climate conditions, and diversified crop greening trends. More importantly, we disclosed the inherent mechanisms based on energy budget decomposition and found that the amplifying Bowen ratio (sensible heat / latent heat) controlled the weakened irrigation cooling trend. Interestingly, we found the energy fluxes were jointly modulated by the declining irrigation water use (soil moisture) and crop greening trend (increasing crop transpiration), which was rarely reported before and was expected to provide insights into the development of climate models to project future climate changes.

In our new manuscript, we did the following revisions thanks to your comments.

(1) In the Introduction, we acknowledged recent studies about water-saving irrigation's impact on local climate, including our previously published paper, and pointed out the limitations in the second paragraph, also shown as follows (Underlined contents are newly added).

“Nevertheless, most existing Earth system models and climate policy assessments still treat irrigation as a static and spatially homogeneous land surface process^{6,18}. This assumption may obscure the evolving climate impacts of irrigation, particularly as WSI adoption accelerates under increasing water scarcity. Recently, studies based on both in-situ climate stations and satellite observations revealed the declining irrigation cooling effect on surface temperature in Northwest China, due to the prosperous WSI promotion^{19,20}. However, on one hand, these studies were restricted to regional scale in arid regions and limits generalizations at broader scopes, especially across different climate backgrounds; one the other hand, the factors and mechanisms driving the changing cooling effects of irrigation over varied climate zones are still poorly investigated, impeding a deeper understanding of the shifting role of irrigation to mitigate climate warming.”

We also added one sentence at the end of the Introduction to emphasize the significance of this study: “Our findings about the divergent weakened irrigation cooling effects across different

climate zones and the underlying mechanisms due to increasing water-saving technologies highlight the importance of considering land management changes in models for projecting future climate changes.”

(2) In the Discussion, we highlighted the advancement of this study relative to the earlier progress (including Z23) in the last third paragraph, also shown as follows.

“Compared to existing modeling studies in Indo-Gangetic Plain and North China Plain that heavily rely on accurately simulating IWU and soil moisture content^{22,23}, our satellite-based results directly capture the actual impact of irrigation on LST, avoiding uncertainties from model parameterizations and coarse spatial resolutions. The use of a finer-resolution, China-specific irrigation dataset⁴⁹ enabled a more comprehensive assessment of the irrigation cooling effect using more geographically sufficient samples, which was challenging for previous studies. The observed decline in cooling effects associated with the increasing WSI is consistent with recent findings. For example, a local study in Northwest China, based on meteorological station data, reported that large-scale adoption of WSI led to indirect warming and drying trends²⁰. Similarly, field experiments argued that drip irrigation increases sensible heat and raises soil temperature compared to traditional irrigation³⁸, further corroborating our findings. Unlike earlier studies using in situ observations or small-scale control experiments, our study reveals, for the first time, a country-scale pattern of the WSI’s impact on LST. Notably, our results also uncover contrasting diurnal trends in irrigation-induced, a dimension rarely addressed before. In contrast to our earlier study focused solely on Xinjiang, China²¹, this study covers a broader geographic extent, capturing spatial variations in the evolving cooling effects across four climate zones. Moreover, it provides the first comprehensive analysis of the underlying mechanisms, such as shifts in surface energy partitioning driven by the competing influences of crop greening and reduced IWU. These insights are essential for improving climate model representation and informing policies aimed at mitigating climate warming.”

(3) We rearranged the contents about the Xinjiang example in the fourth paragraph of the Discussion with a suitable citation of previously published papers (Zhang et al., 2023; Fu et al., 2022), also shown as follows.

“The climate impacts of WSI in China are spatially heterogeneous, with the most pronounced indirect warming occurring in arid zones. In arid regions, where agricultural production heavily relies on intensive irrigation, escalating water scarcity and cross-sectoral water competition

have facilitated rapid WSI expansion, leading to significant attenuation of the biophysical cooling¹⁶. Taking Xinjiang as an example, WSI techniques were imported in the late 1970s by the Xinjiang Production and Construction Corps and were gradually promoted to the whole of Xinjiang after 1998, leading to a 130% expansion of the WSI area and 26% reduction of IWU since the 21st century³⁸. As a result, significantly weakened irrigation cooling effects on surface air temperature (an average increase of 0.30 °C in growing-season temperature) and LST (daytime weakening trend: 0.21 °C/decade) were observed in Xinjiang in the last two decades^{20,21}. Specifically, the declining gaps of climatic factors (i.e. LST, ET, and VPD, etc.) between farms inside and outside Xinjiang Production and Construction Corps in our previous regional study²¹ stand as a good corroboration of the attenuated irrigation cooling effect in arid regions due to increasing WSI. However, semi-arid and semi-humid regions...

3. Irrigation is primarily an adaptation measure, yet the manuscript frames WSI in a negative light by emphasizing its reduced cooling effect. The cooling effect discussed arises largely from inefficient and wasteful irrigation practices. If WSI had been implemented from the outset, the cooling effect would have been negligible or absent, much like in a no-irrigation baseline. This weakens the premise that WSI should be viewed negatively. I suggest the authors clarify this distinction and carefully reassess how WSI is positioned.

Response: We appreciate your insightful comment. We would like to clarify that our intention was not to portray WSI in a negative light. On the contrary, we fully acknowledge that WSI plays a critical role in promoting long-term agricultural sustainability and addressing growing water scarcity.

Our study aims to highlight a previously underexplored biophysical side effect of WSI—namely, the attenuation of irrigation-induced cooling—which arises as a trade-off when shifting from traditional, water-intensive irrigation to more efficient systems. Rather than evaluating WSI as inherently detrimental, we seek to demonstrate that changes in irrigation practices can influence local climate regulation and, therefore, must be better represented in climate models and policy frameworks.

To avoid any unintended negative connotation, we have carefully revised the framing throughout the manuscript. In particular, we have updated the final paragraph of the Discussion to explicitly emphasize the benefits of WSI and propose integrated strategies that align water-use efficiency with climate adaptation and thermal regulation goals, which are shown below:

“Looking ahead, irrigated croplands are expected to expand by 70 million ha by 2050, with annual blue water consumption reaching 1,800 cubic kilometer^{50,51}. WSI is widely seen as a key strategy for sustainable agriculture, aiming to reduce water use without sacrificing crop yields. Beyond addressing the water scarcity problem, climate change mitigation is also a critical concern for future agricultural development. Our results show that widespread WSI adoption may attenuate irrigation-induced cooling and potentially intensify existing warming trends. While irrigated systems generally buffer against climate extremes better than rainfed ones³, the reduced cooling effect under WSI may undermine this advantage since the rising temperature has been reported to negatively affect grain yields⁵². Therefore, more strategic planning is needed to balance water conservation goals with the preservation of irrigation’s climate benefits. For instance, WSI could be prioritized in water-stressed regions where cooling effects are minimal, thereby maximizing water savings without significantly weakening local climate regulation. In addition, integrating real-time climate data, crop models, and remote sensing can enable adaptive irrigation scheduling that maintains adequate evaporative fluxes to sustain cooling during critical crop growth periods. Furthermore, policy frameworks and incentive programs should be carefully designed to avoid excessive reductions in irrigation that could undermine the protective cooling effect, particularly during heatwaves. This requires setting context-specific thresholds for water use reduction and ensuring smallholders have access to the tools, technologies, and knowledge needed to balance efficiency with climate resilience. Collectively, these strategies are essential for aligning water-saving interventions with the broader goal of maintaining thermal regulation in agricultural systems under a changing climate.”

4. The manuscript frequently refers to a “warming effect” of water-saving irrigation (WSI). I find this framing misleading. WSI itself does not actively cause warming; rather, it reduces the additional cooling effect that arises from inefficient, high-volume irrigation practices. In other words, the observed “warming” is more accurately described as a relative reduction in irrigation-induced cooling capacity compared to traditional, wasteful irrigation methods. If irrigation had been efficient from the outset, this artificial cooling effect would not exist, and no “warming” signal would be observed. I recommend that the authors carefully revise their terminology to reflect this nuance, for example, by stating that WSI attenuates irrigation-induced cooling or reduces the climate-buffering capacity of irrigation, rather than presenting it as a direct warming effect.

Response: Thanks for this thoughtful and important clarification. We agree that the term

“warming effect” may imply an active temperature increase, whereas our analysis more accurately reflects a relative reduction in the irrigation-induced cooling effect due to the adoption of WSI practices.

To reflect this nuance more precisely, we have revised our terminology throughout the manuscript. Specifically, (1) we now refer to this phenomenon as “reduce cooling” or “attenuated irrigation-induced cooling” rather than “warming”; (2) The original subsection title “Rising Bowen ratio explains net daytime warming” has been changed to “Rising Bowen ratio explains reduced daytime cooling”; (3) Phrases such as “daytime warming and nighttime cooling” have been replaced with “reduced daytime cooling and intensified nighttime cooling”, as now reflected in the Results section.

We have also updated the Title to improve accuracy and avoid misinterpretation. The revised title is: “Irrigation cooling effect reduced by water-saving practices”.

These revisions aim to clarify that WSI reduces the magnitude of the biophysical cooling benefit previously provided by traditional, high-volume irrigation, rather than actively warming the surface. We thank the reviewer again for encouraging this more accurate and balanced framing.

5. While avoiding WSI may indeed enhance the cooling effect of irrigation, this comes at the cost of wasting water, depleting a finite resource, and exacerbating long-term water scarcity. This paradox: short-term climatic cooling versus long-term hydrological depletion, is not sufficiently addressed in the manuscript. I recommend that the authors explicitly acknowledge and discuss this trade-off to provide a more balanced analysis.

Response: Thank you for highlighting this paradox between the short-term climatic cooling benefits of traditional irrigation and the long-term water resource challenges that WSI aims to address. We agree that this trade-off warrants explicit discussion to provide a more balanced and policy-relevant perspective.

We have now incorporated this dimension more clearly in the revised Discussion section, especially in the final paragraph, where we emphasize that:

- (1) WSI remains a crucial strategy for long-term water sustainability.
- (2) The reduction in cooling is an unintended consequence of this necessary transition.
- (3) Climate-smart irrigation policy must balance water-use efficiency with local climate

regulation objectives.

This addition complements our response to Comment #3 and helps position WSI not as a negative intervention, but as one that involves a trade-off between hydrological and biophysical outcomes. We believe this clarification improves the manuscript's framing and its relevance for both climate and water policy discourse.

6. The distinction between national-scale and regional results should be made clearer throughout the manuscript.

Response: Thank you for this suggestion. We agree that clarifying the distinction between national-scale and regional (climate zone) results improves the manuscript's readability and interpretability.

We have revised the text throughout the manuscript to clearly indicate the spatial scale of each analysis and result.

For instance, in the beginning paragraph of the Section *Spatial and seasonal patterns of LST cooling trends*: “Spatially, 58% of irrigated grid cells (at 0.5° resolution) across China exhibited statistically significant daytime LST trends over the 2001–2020 period (Fig. 2a).”

In the first paragraph of Section *Causal pathways from IWU to LST*:

“To elucidate the causal relationships among IWU, vegetation greenness (ΔEVI), surface energy fluxes, and LST, we applied a structural equation modeling approach both at the national and climate zone scales. We find that both IWU and ΔEVI significantly affect LST across China, albeit via different mechanisms and magnitudes (Fig. 5a).”

7. The authors often interpret correlations (e.g., between IWU and LST trends) as causal without fully accounting for potential confounders such as crop type, management practices, or regional policy changes. The regression and structural equation modelling still rely on observational data and assumptions thus possibly overstating causality. The authors should temper their claims and more explicitly acknowledge the limitations of correlation-based inference.

Response: Thanks for this important comment. We agree to be cautious with the terms delineating the relationship between IWU and LST trends. In the revised manuscript, we have

taken several steps to temper our causal interpretations and clarify the limitations of our approach.

For example, in the final paragraph of the *Declining water use and contrasting diurnal LST cooling trends* section, we used “tightly associated with” rather than “lead to”:

“Temporal trends in IWU strongly correlated with changes in LST cooling. Nationally, reductions in IWU were **tightly associated with** weakened daytime cooling and enhanced nighttime cooling ($R^2 = 0.76$ and 0.78 , respectively; Fig. 1m).”

In addition, we revised the second-to-last paragraph of the Discussion to more explicitly acknowledge the limitations of correlation-based inference and the need to control for potential confounding variables. The updated paragraph now reads:

“...Fourth, while our attribution framework and structural equation modeling help elucidate potential causal pathways, they are based on observational correlations and cannot fully substitute for controlled field experiments or process-based modeling³⁶. In addition, due to limited data availability—particularly at the national scale—we were unable to explicitly control for potential confounders such as crop type, field management practices, or regional policy interventions, all of which could influence surface energy dynamics and land surface temperature trends. Future research that integrates ground-based measurements, crop-specific biophysical modeling, and more detailed irrigation metadata will be essential for improving the attribution of irrigation-induced effects and strengthening the generalizability of our findings across diverse agroecological contexts.”

8. The “cooling effect” is measured against a non-irrigated baseline, but the manuscript doesn’t fully discuss how realistic or meaningful this comparison is for policy framing. Without irrigation, yields collapse in many arid areas, so comparing irrigated vs. non-irrigated land can exaggerate the climate “service” of irrigation. Recommend the authors justify or qualify their chosen baseline and clarify what counterfactual they intend (no irrigation vs. efficient irrigation).

Response: Thank you for raising this important point. We recognize that our initial framing may have caused some ambiguity, and we appreciate the opportunity to clarify.

In our study, the term “efficient irrigation” reflects a **temporal transition** rather than a fixed

experimental treatment. Specifically, we characterize water-saving irrigation (WSI) as an evolving process over time, during which per-hectare irrigation water use steadily declines due to the adoption of more efficient irrigation technologies and practices (as shown in Fig. 1). Unlike controlled experiments that impose abrupt changes in irrigation method, our approach captures a gradual, real-world shift observed across China over two decades.

To represent this process, we use the **declining irrigation water use per unit irrigated area** as a proxy for the expansion of WSI. This enables a time-series analysis in which we track how LST responses evolve with irrigation intensity over time.

Methodologically, we first derive the irrigation-induced LST difference (Δ LST) by comparing each irrigated pixel with its nearby non-irrigated counterpart (see Methods section). We then assess how this Δ LST signal changes over time and relate it to changes in irrigation water use, crop greenness, and surface energy fluxes. In this framework, the non-irrigated land serves as a relative reference point, not an idealized counterfactual, allowing us to detect shifts in irrigation's biophysical effect under real-world WSI transitions.

Following this helpful comment and aligned with Reviewer #2's suggestions, we have now revised the corresponding paragraph in the Introduction to more clearly introduce the key concept of Δ LST, explain how it is derived, and refer readers to the relevant section in the Methods for further details

“This study addresses key empirical and modeling gaps by providing the first large-scale observational assessment of how WSI alters irrigation-induced climatic effects. Focusing on China—a region experiencing rapid WSI expansion and high spatial heterogeneity—as a high-resolution natural laboratory, we test two hypotheses: (1) that widespread WSI implementation has attenuated irrigation's cooling effect, thereby contributing to regional warming; and (2) that the direction and magnitude of these effects vary across space and time, depending on WSI intensity and local climatic conditions. To investigate, here we use the declining irrigation water use per unit cropland area in China¹⁴ as a proxy for the expanding water-saving irrigation (WSI) technologies—the shift from traditional flood irrigation to more efficient irrigation practices. We first extract the changes in satellite-observed LST from MODIS (difference in LST between irrigated and nearby non-irrigated areas, denoted as Δ LST hereafter) and concurrent changes in energy fluxes caused by irrigation at the 1-km pixel scale. We then quantify their temporal trends at various temporal (annual, seasonal, and diurnal) and spatial (national, climate zone,

and provincial) scales. Last, we explore the underlying mechanisms by examining the relationship between temporal trends in Δ LST and irrigation water consumption, as well as the background climatic and environmental factors (see Methods). Our findings about the varying irrigation cooling trends across climate zones and the underlying mechanisms due to increasing water-saving practices highlight the importance of considering land management changes in models for projecting future climate changes.”

9. Although the authors suggest future works to integrate ground-based measurements, I believe this will be a very useful piece in distinguishing the manuscript from their previous work in Zhang et al. (2023).

Response: Thank you for this helpful suggestion. We agree that integrating ground-based measurements such as flux tower data and field-level irrigation observations would provide important empirical validation and could significantly strengthen future analyses. As noted in our earlier response, we have now emphasized the need for independent validation and clarified the limitations. Also, please refer to our response to Comment #2 for more details about the difference between this study and our previous one.

10. To reinforce their conclusions, I suggest that the authors incorporate an explicit temporal analysis comparing periods before and after widespread WSI adoption. While the current correlation between declining IWU and changes in LST trends is informative, a pre- vs. post-WSI comparison would more clearly demonstrate that the observed attenuation of cooling is attributable to the irrigation transition itself, rather than to concurrent climate variability or management changes. This would also help differentiate the present study from Zhang et al. (2023), by emphasizing the dynamic effects of WSI over time. Although the manuscript presents an interesting dataset and analysis, the findings largely reiterate conclusions already reported in prior work by the same group and others, with limited novel insight. Given these issues of originality and framing, I do not believe the manuscript meets the bar for publication in Communications Earth & Environment and recommend rejection in its current form.

The study may be better suited for a regional or applied journal more narrowly focused on irrigation management and hydrology, rather than Communications Earth & Environment, where novelty and broad significance are paramount.

Response: Thank you for this thoughtful and constructive comment. As noted in our response

to Comment #8, our study focuses on tracking the evolution of irrigation-induced cooling over time in response to the gradual implementation of WSI practices. Given the absence of detailed spatiotemporal metadata on the exact timing and locations of WSI adoption at the national scale, it is not feasible to conduct a clear-cut pre- vs. post-WSI comparison. Unlike controlled field experiments or model simulations, observational studies at large scales must rely on proxies that capture gradual transitions rather than discrete treatment phases.

In this study, we use the declining irrigation water use per unit irrigated area—documented consistently in government statistics and shown in Fig. 1—as a proxy for the expanding adoption of WSI technologies. This metric captures the shift from traditional flood irrigation toward more efficient methods such as drip and sprinkler systems. Through time series analysis of ΔLST (temperature difference between irrigated and nearby non-irrigated areas), we investigate how the biophysical cooling effect has changed as WSI has become more widespread.

While the analytical framework is consistent with our prior regional work (Zhang et al., 2023), the current study expands the geographic scope from a single arid province (Xinjiang) to the entirety of China’s irrigated croplands. This broader coverage enables novel insights into regional heterogeneity, seasonal divergence, and national-scale trade-offs between water-use efficiency and climate buffering—dimensions not previously explored. Furthermore, we extend the analysis by incorporating energy balance decomposition and structural equation modeling to better elucidate causal pathways and feedbacks.

We appreciate the suggestion to add an explicit temporal comparison and have now clarified in the revised Methods and Discussion sections why this is not feasible given data limitations. Nonetheless, our proxy-based time series approach offers a robust and scalable alternative for capturing long-term dynamics associated with WSI adoption.

In summary, this study provides the first national-scale observational assessment of how expanding WSI affects land surface energy balance and temperature regulation—an emerging issue with clear implications for adaptation policy, irrigation governance, and land-climate modeling. We hope our revisions, added clarifications, and strengthened framing will address your concerns.

Specific comments and/or recommendations

Abstract:

Instead of “Agricultural irrigation” consider “Irrigation” since irrigation, agricultural or otherwise modifies land-atmosphere interaction.

Response: Thanks for this good suggestion. We have deleted “Agricultural” in the revised Abstract.

INTRODUCTION

Line 47: “buffer crops against” might be substituted for “buffer crop growth” or “buffer food production”. Line 48: Also mention the threats or connect directly with the first sentence.

Response: We have updated the sentence accordingly:

“As the backbone of global agriculture, irrigation has long served as a primary adaptation strategy to buffer crop growth against these growing drought and heat threats.”

Line 49: modifies instead of “reshapes”

Response: Thanks, according to your comment, we have substituted “reshapes” with “modifies” as follows:

“Beyond its agronomic benefits, irrigation modifies land-atmosphere interactions by increasing latent heat flux and modulating surface energy budgets.”

Line 57: “unsustainable water withdrawals” Also see Huang et al. (2020) as possible citation.

Response: We are glad to see that Huang et al. (2020) is a good demonstration of water-saving irrigation leading to plausible reductions of irrigation water consumption without compromising crop production in maize. We have cited this literature in our revised manuscript.

Line 59: “... WSI technologies” Systems or technologies, use one for consistency.

Response: Thanks, we have unified the term to be WSI technologies throughout the manuscript.

Line 61: “...capacity of irrigation is being preserved...” But biophysical cooling results from

years of inefficient irrigation practices.

Response: Thanks for this comment. We have updated this sentence as follows:

“While this transition supports more sustainable water management, it is interesting to know whether the biophysical cooling results from years of inefficient irrigation practices is being preserved—or inadvertently weakened—as irrigation becomes more efficient.”

Line 68: “LST to irrigation changes...” Does this mean changes to irrigation systems? If so, then consider rephrasing.

Response: We have rephrased this sentence as follows:

“In particular, the diurnal asymmetry of these effects—the differential responses of daytime and nighttime LST to irrigation water use changes—remains poorly understood and is largely absent from global climate simulations.”

Line 71: “less constrained...” Do you mean less studied?

Response: Yes, it means “less studied” but we deleted this sentence because we think it is largely redundant to the front sentence.

Line 86: “...critical yet unrecognized trade-off...” Hard to say given the literature on this topic including earlier work by the authors.

Response: Thanks, we have rephrased the claim based on your comment as follows:

“These findings reinforce the critical trade-off between improved water-use efficiency and the land surface’s capacity to buffer climate warming.”

In addition, we removed this paragraph from the original manuscript and merged it into the first paragraph of the Discussion, as suggested by Reviewer #2. Please refer to the revised manuscript for more details.

RESULTS

Line 111: Refers to Fig. 1j instead of Fig. 1i

Response: Thanks for pointing out this typo. We have updated it in the revised manuscript.

Line 173: “reshaping surface energy balance” within or outside the regions?

Response: We have modified this sentence as follows:

“At the provincial level, spatial patterns of energy flux trends mirrored those at grid scale (Supplementary Fig. 7), reinforcing the dominant role of northern irrigated croplands in reshaping surface energy balance under WSI expansion across the national scale.”

Line 188: Incorporating analysis on time scales before and after WSI adoption could reinforce such conclusions.

Response: Thank you for this insightful suggestion. We agree that incorporating an explicit comparison of time periods before and after WSI adoption would ideally strengthen causal attribution. However, such an approach is difficult to implement at large scales using observational data, since we lack consistent, spatially resolved records of the exact timing and extent of WSI adoption across China.

In the absence of this information, we use the declining irrigation water use per unit irrigated cropland area—as reported in official statistics (see Fig. 1)—as a proxy for the gradual expansion of WSI technologies over the past two decades. This proxy captures the transition from traditional flood irrigation toward more efficient methods and allows for a time series analysis of how irrigation-induced cooling has evolved alongside these changes.

To make it clear, we added the statement of this proxy in the last paragraph of the Introduction as follows:

“This study addresses key empirical and modeling gaps by providing the first large-scale observational assessment of how WSI alters irrigation-induced climatic effects. Focusing on China—a region experiencing rapid WSI expansion and high spatial heterogeneity—as a high-resolution natural laboratory, we test two hypotheses: (1) that widespread WSI implementation has attenuated irrigation’s cooling effect, thereby contributing to regional warming; and (2) that the direction and magnitude of these effects vary across space and time, depending on WSI intensity and local climatic conditions. To investigate, here we use the declining irrigation water use per unit of irrigated cropland in China¹⁵ as a proxy for the expansion of water-saving

irrigation (WSI) technologies—the shift from traditional flood irrigation to more efficient irrigation practices. We first extract the changes in satellite-observed LST from MODIS (difference in LST between irrigated and nearby non-irrigated croplands, denoted as Δ LST hereafter) and concurrent changes in energy fluxes caused by irrigation at the 1-km pixel scale. ...”

We also introduce the Δ LST concept and explain that our analysis tracks trends in the LST difference between irrigated and nearby non-irrigated croplands, along with concurrent changes in energy fluxes. We believe this proxy-based approach is a suitable and scalable alternative that captures the essence of a pre- vs. post-transition comparison, and we hope this clarification addresses your concern.

Line 199: As in the general comments, the section on attribution analysis is not entirely novel seeing that the biophysical cooling of irrigation results from the amount of applied irrigation water.

Response: Thank you for this comment. As noted in our earlier responses to the general comments, the central contribution of this study lies not merely in affirming that biophysical cooling scales with irrigation water use, but in extending the analysis to the national scale with high spatial resolution and climatic differentiation.

Specifically, our analysis goes beyond confirming this relationship by integrating detailed biophysical diagnostics—quantifying changes in energy partitioning between latent and sensible heat fluxes, examining shifts in Bowen ratio, and disentangling diurnal contrasts between daytime and nighttime effects. In doing so, we also identify the important, previously underappreciated role of vegetation greening (Δ EVI) in modulating irrigation-induced cooling. This adds nuance to the attribution analysis and offers new insights into the interplay between WSI, vegetation response, and surface energy fluxes across contrasting climate zones.

We hope these expanded analyses, together with the national-scale scope, support the novelty and added value of our work. Additional details can be found in our responses to General Comments #2 and #3.

Line 253: “longwave radiation” instead of “longwave emission”

Response: Thanks, we have made the update.

Line 284: Reading the manuscript to this point, it does not become entirely clear to the reader how the shift to WSI can warm land surface processes. The focus here remains the secondary benefits of irrigation as an adaptation measure, primarily to sustain crop growth and not for cooling land surfaces.

Response: Thank you for your thoughtful comment. We agree that the primary function of irrigation is to support crop growth, and that any associated cooling effect is a secondary benefit arising from changes in land-atmosphere interactions. We also acknowledge that our previous phrasing, particularly references to WSI “warming” the land surface, may unintentionally suggest that WSI directly causes warming, rather than attenuating an existing cooling effect.

To avoid potential misinterpretation, we have revised the language throughout the manuscript to more accurately reflect the nature of this trade-off. Specifically, we now describe the phenomenon as a “reduction in cooling” or “attenuation of the climate-buffering effect” of irrigation. In line with Reviewer #2’s suggestions, we have also revised the title of the manuscript to “Irrigation cooling effect reduced by water-saving practices” to better reflect the nuance.

Specifically, here we rephrased the sentence (Line 284) as follows.

OLD: “In many regions, this shift transforms irrigation from a biophysical buffer into a neutral or even warming land surface process.”

NEW: “In many regions, this shift from traditional to more efficient irrigation methods likely reduces the ability of irrigation to buffer climate warming.”

Line 293: “The climate impacts of WSI in China”

Response: Thanks, we have made the update.

End of Fig. 3 caption: “...in $\Delta(\text{HE}/\text{LE})$ ”

Response: Thanks for pointing out this typo. We have updated it in the revised manuscript.

References

Braun, T. and Schlenker, W., 2023. Cooling externality of large-scale irrigation (No. w30966).

National Bureau of Economic Research. <https://doi.org/10.3386/w30966>

Huang, G., Hoekstra, A.Y., Krol, M.S., Jägermeyr, J., Galindo, A., Yu, C. and Wang, R., 2020. Water-saving agriculture can deliver deep water cuts for China. *Resources, conservation and recycling*, 154, p.104578. <https://doi.org/10.1016/j.resconrec.2019.104578>

Liu, G., Wang, W., & Shao, Q. 2023. Recent decline of irrigation-induced cooling effect over the North China Plain in observations and model simulations. *Geophysical Research Letters*, 50, e2022GL101973. <https://doi.org/10.1029/2022GL101973>

Zhang, C., Dong, J., Leng, G., Doughty, R., Zhang, K., Han, S., Zhang, G., Zhang, X. and Ge, Q., 2023. Attenuated cooling effects with increasing water-saving irrigation: Satellite evidence from Xinjiang, China. *Agricultural and Forest Meteorology*, 333, p.109397. <https://doi.org/10.1016/j.agrformet.2023.109397>

Response: Thanks for providing these references, and we have included them in the revised manuscript.

Response to Reviewer's Comments

We sincerely thank the reviewers for their constructive and insightful feedback, which has substantially improved the clarity, quality, and robustness of our manuscript. We have carefully addressed each comment and revised the manuscript accordingly. Below, we provide a detailed point-by-point response to all general and specific reviewer comments, including corresponding changes made in the main text. For clarity, reviewer comments are presented in black, our responses in blue, and revised text is underlined within the responses.

Reviewer #1 (Remarks to the Author)

The manuscript was already in great shape, and with the incorporation of the improvements suggested by the other reviewers, it is now ready for acceptance.

Response: We sincerely thank you for your acknowledgement of our revisions and improvements.

Reviewer #2 (Remarks to the Author):

I have reviewed the revised manuscript, and find it has been significantly improved, addressing most of my previous comments and recommend for publication. In particular, thank you for adding the additional regional plots of Fig5.

Response: Thank you very much for your insightful and constructive comments, which have greatly contributed to improving the manuscript. We especially appreciate your suggestions regarding Fig. 1—your careful observations prompted us to revise and enhance the figure, resulting in a clearer and more informative presentation than the original version.

Some final minor comments.

Line 58: “In China alone, per-hectare irrigation water use has declined by more than 30% since 2000” – reference needed

Response: Thank you for pointing out this issue and we have added reference below.

Zhou, F., (2020). Deceleration of China's human water use and its key drivers. Proc. Natl Acad. Sci. USA, 117, 7702-7711

Lines 65: “For instance, drip irrigation is found to generate the least surface cooling” reference needed here too.

Response: We have added the reference below.

Yuan, T., (2023). Effects of different irrigation methods on regional climate in North China Plain: A modeling study. Agric. For. Meteorol., 342, 109728

L74-77: Consider shortening this sentence to clarify your point and L76 typo “one” should read “on”: “However, on one hand, these studies were restricted to a regional scale in arid regions and limits generalizations at broader scopes, especially across different climate backgrounds; one the other hand, the factors and mechanisms driving the changing cooling effects of irrigation over varied climate zones are still poorly investigated, impeding a deeper understanding of the shifting role of irrigation to mitigate climate warming.”

Response: Thank you for this helpful comment. We have revised the sentence to improve clarity and conciseness:

“However, previous studies have largely focused on arid regions, limiting their generalizability across diverse climate zones. Moreover, the mechanisms driving spatial variations in irrigation-induced cooling remain poorly understood, hindering a comprehensive understanding of irrigation’s evolving role in mitigating climate warming.”

Lines 346-349: “However, this impact is partially offset by a decrease in incoming solar radiation due to higher surface albedo from “brighter” soils (Supplementary Fig. 8l, Supplementary Fig. 10e)” . This is not correct – perhaps you mean the signal is offset by both a reduction in incoming solar radiation and higher surface albedos – as mentioned in the responses.

Response: Thank you for catching this and for your helpful clarification. We regret the inaccurate phrasing in the original sentence. Our intended meaning was that the reduced

absorbed solar radiation—due to higher surface albedo from “brighter” soils—partially offsets the warming impact. We have revised the sentence in the manuscript as follows:

“However, this impact is partially offset by a decrease in the absorbed solar radiation due to - higher surface albedo from “brighter” soils (Supplementary Fig. 8l, Supplementary Fig. 10e).”

Reviewer #3 (Remarks to the Author):

Summary

This manuscript by Zhang et al. investigates the biophysical climate impacts of water-saving irrigation (WSI) across China, drawing on two decades of satellite-based land surface temperature and energy flux observations. The authors show that widespread adoption of WSI has substantially weakened irrigation’s daytime cooling effect while simultaneously intensifying nighttime cooling, with the balance of impacts varying by region and season. They attribute these changes primarily to shifts in irrigation water use (IWU) and altered surface energy partitioning. The study frames this as an emerging trade-off between improved water-use efficiency and reduced climate-mitigation capacity of irrigation, with implications for Earth system modelling and adaptation policy.

General Comments

Zhang et al. have taken previous comments, positing WSI in the negative, into consideration to improve the manuscript. The added clarifications show the authors made a good effort in responding to my comments to improve the draft. I believe the current version of the manuscript has been significantly improved. Therefore, I recommend its publication, pending some minor revisions raised in the comments below when addressed to the satisfaction of the handling editor.

Response: We sincerely thank you for your positive assessment of the revised manuscript and for recognizing the efforts we made to address your earlier concerns. We greatly appreciate your constructive feedback, which has helped improve the clarity, balance, and framing of our study.

We are especially grateful for your support in supporting in recommending the manuscript for

publication, pending minor revision. We have carefully addressed the remaining points raised in the specific comments and have made corresponding edits to further strengthen the manuscript, as detailed below.

Specific comments and/or recommendations

Line : Comments and/or Suggestions

Line 74: Not entirely clear what is intended by “prosperous” WSI promotion

Response: We have replaced this word with “increasing”:

“Recently, studies based on both in-situ climate stations and satellite observations revealed the declining irrigation cooling effect on surface temperature in Northwest China, due to the increasing WSI promotion.”

Line 79: Here and through the manuscript, consider writing WSI technologies instead of WSI alone.

Response: Thank you for this helpful suggestion. We agree that explicitly stating “WSI technologies” improves clarity. To avoid redundancy throughout the manuscript, we have chosen to define the full term at its first appearance in the Introduction (Line 56), as follows:

“Water-saving irrigation technologies (denoted as WSI hereafter)—such as drip, sprinkler, and precision irrigation—are being promoted as cornerstones of climate-smart agriculture, to maximize crop water productivity while minimizing unsustainable withdrawals.”

Line 93: The acronym “WSI” has already been introduced in Line 56. No need for duplicates.

Response: We have removed “water-saving irrigation”:

“To investigate, here we use the declining irrigation water use per unit cropland area in China¹⁵ as a proxy for the expanding ~~water-saving irrigation (WSI) technologies~~—the shift from traditional flood irrigation to more efficient irrigation practices.”

Line 94: Add a sentence here about the irrigated area dataset used in the study and refer readers to the methods for further details.

Response: Thanks for this good suggestion. We have made below revision:

Based on an improved long-term irrigation area dataset we produced earlier²⁶ (Methods), we first extract the changes in satellite-observed LST from MODIS (difference in LST between irrigated and nearby non-irrigated areas, denoted as Δ LST hereafter) and concurrent changes in energy fluxes caused by irrigation at the 1-km pixel scale.

Line 106: It is not documented anywhere in the Methods section how the IWU was computed. Was it simply ET-effective precipitation? Or was this from well abstraction records? Since the study speaks of spatial dimension, one would assume ET was used as proxy for crop water consumption.

Response: Thanks for this comment. We described the details at the end of Methods subsection *Irrigation and land cover data* (Lines 493-496 in the first-round revised manuscript), which may not be clear enough. We rephrased the paragraph as follows.

“The statistical mean IWU per hectare was from China Water Resources Bulletin for 2003-2020, comprising the water use data for each province except Hong Kong, Macao, and Taiwan. To obtain the water use data in four climate zones, we first assigned the provincial IWU data to all 1-km irrigated cropland pixels within the province and then aggregated them to each climate zone according to their geographical locations (refer to Fig. 1 for the geographical boundaries of four climate zones).”

Line 109: “Shift” could be increase or decrease. Maybe a different phrase?

Response: We replaced “shift” with “declining trend”:

“This declining trend in irrigation intensity coincided with marked diurnal changes in LST associated with irrigation.”

Line 114: Consider using “a reduced cooling” instead of “an indirect warming”.

Response: We have replaced “an indirect warming” with “a reduced cooling”.

Line 150: Here and other subheadings, consider writing in full instead of abbreviations.

Response: We have tried to avoid use of abbreviations in all subheadings.

Line 162: Here and through the manuscript, for consistency, either use “per decade”, “/decade” or “decade⁻¹”. In this case, per decade might be most appropriate. See 173, 179, 199, and elsewhere.

Response: We have revised them as “per decade” in the main text.

Lines 164 – 166: Since this is not proven in this study, consider adding appropriate references.

Response: We have added references below:

32 Zhang, G. et al. Spatiotemporal patterns of paddy rice croplands in China and India from 2000 to 2015. *Sci. Total Environ.* 579, 82-92, doi:10.1016/j.scitotenv.2016.10.223 (2017).

33 Qiu, B. et al. National-scale 10-m maps of cropland use intensity in China during 2018 – 2023. *Sci. Data* 11, 691, doi:10.1038/s41597-024-03456-0 (2024).

Line 177: Which “north-south differences” is referred here? This assumes the preceding paragraph already discussed this which isn’t the case.

Response: We have rephrased this sentence and cited the corresponding Figure to make it clear: “Trends in $\Delta H E$ also shows north-south differences (Fig. 3b)”.

Line 189: Consider another phrase other than “amplification”.

Response: We have replaced “amplification” with “intensification”.

Line 201: Not entirely clear what “thermal efficiency” would mean in this context.

Response: Thank you for pointing this out. We agree that the term “thermal efficiency” may cause confusion in this context. Our intent was to convey that although total evapotranspiration (ET) is maintained, primarily through increased transpiration from vegetation, the shift in energy partitioning under WSI leads to less effective dissipation of surface heat via latent fluxes compared to traditional irrigation, particularly in terms of surface temperature reduction.

To clarify, we have revised the sentence in the manuscript as follows:

“This shift underscores a critical biophysical trade-off: even when total evapotranspiration is sustained through vegetation adaptation, the ability of irrigation to dissipate surface heat and cool the land is diminished under water-saving practices.”

Line 207: Spell IWU in full.

Response: We have spelled out the acronyms in all subsection titles.

Line 209: The abbreviation “IWU” has been previously defined.

Response: We have removed the spell-out words accordingly.

Line 212: “declining IWU—representing the widespread adoption of WSI”. Declining IWU does not necessarily mean adoption of WSI. Add a few sentences to the second point (Line 388) in the limitations of the study to highlight this as a limitation.

Response: Thanks for bringing this point to us. We have highlighted this limitation in the Discussion as follows.

“Moreover, using declining IWU per unit area as a proxy of the increasing WSI adoption may not always be appropriate at the pixel level, as a reduced mean IWU could also result from a constant total IWU spread over an expanding irrigation area within the same region.”

Line 215: In this context consider “land-atmosphere interaction” instead of “land-atmosphere coupling”

Response: We appreciate this good comment and have replaced “land-atmosphere coupling” with “land-atmosphere interaction”.

Line 235: Consider “reduced cooling” instead of “surface warming”.

Response: We have replaced “surface warming” with “reduced cooling”.

Line 275: Irrigation efficiency (IE) is a convoluted term and subject to multiple interpretations. This is appearing for the first time in the manuscript. For context, WSI has been presented and should be used consistently. The sentence in reference might need to be rephrased. Note that not all IE measures lead to water conservation or water saving.

Response: We have replaced “irrigation efficiency” with “WSI”.

Line 311: Consider using “introduced” instead of “imported”.

Response: We have replaced “imported” with “introduced”.

Line 337: replace “this warming” with “this reduced cooling”.

Response: We have replaced “this warming” with “this reduced cooling”.

Line 339: Again, as earlier in **Line 275**, “high-efficiency irrigation” is herein introduced as well as climate-smart irrigation strategies. These are terms that could have slight deviation from WSI. Since the study is around WSI, adopt a single defined terminology and use this through the manuscript.

Response: We have replaced “high-efficiency irrigation” with “WSI”.

Line 374: “irrigation-induced ...” Induced what? This appears to be an incomplete sentence.

Response: Thanks for pointing it out. We have revised the sentence as: “Notably, our results also uncover contrasting diurnal trends in irrigation-induced cooling effect, a dimension rarely addressed before.”

Line 411: “WSI could be prioritized in water-stressed...” As in previous round of comments, does this mean WSI prioritised in water-stressed regions while wasteful irrigation practices should be encouraged in other non-water stressed regions? This could be misleading with long-term implications for regional hydrology.

Response: Thanks for this observation. We did not intend to imply that inefficient or wasteful irrigation should be encouraged in any region. Rather, our intention was to emphasize that the prioritization and implementation of WSI strategies should be tailored to regional water availability and climatic context, balancing water conservation goals with potential impacts on local land-atmosphere interactions.

To avoid misunderstanding, we have revised the sentence in the manuscript as follows:

“For instance, the development of WSI should be guided by regional water availability and climatic context—prioritizing water-scarce areas to maximize water savings, while complementing it with management practices in humid regions that sustain both water efficiency and local climate regulation.”

Line 416: “... programs should be carefully designed to avoid excessive reductions in irrigation that could...” This could be misinterpreted as saying one has to irrigate at all costs even when there is no need to irrigate or in conditions where it becomes expensive or leads to long-term effects on water availability just to retain the cooling benefits of irrigation.

Response: We fully agree that irrigation should not be applied indiscriminately or at the expense of long-term water sustainability. Our intension was not to suggest irrigating purely for cooling purposes, but rather to emphasize the need for well-calibrated policies that avoid unintended climatic side effects, such as heightened heat stress, when reducing irrigation inputs for efficiency gains.

To clarify this point and prevent misinterpretation, we have revised the sentence as follows:

“Furthermore, policy frameworks and incentive programs should be designed to balance water-use efficiency with the co-benefits of irrigation-induced cooling, ensuring that efficiency gains do not inadvertently increase vulnerability to heat stress during critical periods like heatwaves.”

For Figures 1-5, would it be possible to increase the font size of the figure labels (i.e., a, b, c, d...) next to the figures? Or add them in parentheses to differentiate them from the axis label. For consistency and differentiation from running text, consider boldening these labels (i.e., a, b, c, d...) wherever they appear in the figure caption.

Response: Thanks for this suggestion. We have enlarged the label size in Figures 1–5.

Manuscript_13180: “Unintended warming from water-saving irrigation.”

Summary

This manuscript by Zhang et al. investigates the biophysical climate impacts of water-saving irrigation (WSI) across China, drawing on two decades of satellite-based land surface temperature and energy flux observations. The authors show that widespread adoption of WSI has substantially weakened irrigation's daytime cooling effect while simultaneously intensifying nighttime cooling, with the balance of impacts varying by region and season. They attribute these changes primarily to shifts in irrigation water use (IWU) and altered surface energy partitioning. The study frames this as an emerging trade-off between improved water-use efficiency and reduced climate-mitigation capacity of irrigation, with implications for Earth system modelling and adaptation policy.

While the topic is timely and of potential relevance, in its current form the manuscript raises concerns regarding novelty, overlap with prior publications (notably [Zhang et al. 2023](#)), and the framing of WSI's climate implications. The key findings largely reiterate previously published results at a broader spatial scale, and some of the interpretive framing (particularly regarding the “negative” role of WSI) requires clarification and greater balance.

General Comments

1. The manuscript is well structured and written logically. It is easy for readers to follow the story. The figures are also legible, neatly layout, of great quality albeit densely packed.
2. The findings and conclusions in the manuscript are not so novel within the scope of *Communications Earth & Environment*. Since irrigation (application of water to support crop growth) induces cooling, it is axiomatic that increasing or decreasing IWU will alter this cooling effect (see also [Liu et al., 2023](#); [Braun and Schlenker 2023](#)). Also, the manuscript's results largely replicate findings by a group of the current authors in Zhang et al. (2023) [<https://doi.org/10.1016/j.agrformet.2023.109397>]. That study already reported that water-saving irrigation (WSI) (i) weakens biophysical cooling (especially late summer/early spring), (ii) intensifies nighttime cooling, and (iii) links cooling reduction to declining IWU. The only substantive difference is the geographic scope (Xinjiang vs. China), but the conclusions remain essentially the same.
3. Irrigation is primarily an adaptation measure, yet the manuscript frames WSI in a negative light by emphasising its reduced cooling effect. The cooling effect discussed arises largely from inefficient and wasteful irrigation practices. If WSI had been implemented from the outset, the cooling effect would have been negligible or absent, much like in a no-irrigation baseline. This weakens the premise that WSI should be viewed negatively. I suggest the authors clarify this distinction and carefully reassess how WSI is positioned.
4. The manuscript frequently refers to a “warming effect” of water-saving irrigation (WSI). I find this framing misleading. WSI itself does not actively cause warming; rather, it reduces the additional cooling effect that arises from inefficient, high-volume irrigation practices. In other words, the observed “warming” is more accurately described as a *relative reduction in irrigation-induced cooling capacity* compared to traditional, wasteful irrigation methods. If irrigation had been efficient from the outset, this artificial cooling effect would not exist, and

no “warming” signal would be observed. I recommend that the authors carefully revise their terminology to reflect this nuance, for example, by stating that WSI *attenuates irrigation-induced cooling* or *reduces the climate-buffering capacity of irrigation*, rather than presenting it as a direct warming effect.

5. While avoiding WSI may indeed enhance the cooling effect of irrigation, this comes at the cost of wasting water, depleting a finite resource, and exacerbating long-term water scarcity. This paradox: short-term climatic cooling versus long-term hydrological depletion, is not sufficiently addressed in the manuscript. I recommend that the authors explicitly acknowledge and discuss this trade-off to provide a more balanced analysis.
6. The distinction between national-scale and regional results should be made clearer throughout the manuscript.
7. The authors often interpret correlations (e.g., between IWU and LST trends) as causal without fully accounting for potential confounders such as crop type, management practices, or regional policy changes. The regression and structural equation modelling still rely on observational data and assumptions thus possibly overstating causality. The authors should temper their claims and more explicitly acknowledge the limitations of correlation-based inference.
8. The “cooling effect” is measured against a non-irrigated baseline, but the manuscript doesn’t fully discuss how realistic or meaningful this comparison is for policy framing. Without irrigation, yields collapse in many arid areas, so comparing irrigated vs. non-irrigated land can exaggerate the climate “service” of irrigation. Recommend the authors justify or qualify their chosen baseline and clarify what counterfactual they intend (no irrigation vs. efficient irrigation).
9. Although the authors suggest future works to integrate ground-based measurements, I believe this will be a very useful piece in distinguishing the manuscript from their previous work in Zhang et al. (2023).
10. To reinforce their conclusions, I suggest that the authors incorporate an explicit temporal analysis comparing periods before and after widespread WSI adoption. While the current correlation between declining IWU and changes in LST trends is informative, a pre- vs. post-WSI comparison would more clearly demonstrate that the observed attenuation of cooling is attributable to the irrigation transition itself, rather than to concurrent climate variability or management changes. This would also help differentiate the present study from Zhang et al. (2023), by emphasising the dynamic effects of WSI over time.

Although the manuscript presents an interesting dataset and analysis, the findings largely reiterate conclusions already reported in prior work by the same group and others, with limited novel insight. Given these issues of originality and framing, I do not believe the manuscript meets the bar for publication in *Communications Earth & Environment* and recommend **rejection in its current form**. The study may be better suited for a regional or applied journal more narrowly focused on irrigation management and hydrology, rather than *Communications Earth & Environment*, where novelty and broad significance are paramount.

Specific comments and/or recommendations

Line : Comments and/or Suggestions

Abstract:

Instead of “Agricultural irrigation” consider “Irrigation” since irrigation, agricultural or otherwise modifies land-atmosphere interaction.

INTRODUCTION

Line 47: “... buffer crops against ...” might be substituted for “buffer crop growth” or “buffer food production”.

Line 48: Also mention the threats or connect directly with the first sentence.

Line 49: modifies instead of “reshapes”

Line 57: “... unsustainable *water* withdrawals ...” Also see [Huang et al. \(2020\)](#) as possible citation.

Line 59: “... WSI *technologies*” Systems or technologies, use one for consistency

Line 61: “... capacity of irrigation is being preserved ...” But biophysical cooling results from years of inefficient irrigation practices.

Line 68: “LST to irrigation changes ...” Does this mean changes to irrigation systems? If so, then consider rephrasing.

Line 71: “less constrained ...” Do you mean less studied?

Line 86: “... critical yet unrecognized trade-off ...” Hard to say given the literature on this topic including earlier work by the authors.

RESULTS

Line 111: Refers to Fig. 1j instead of Fig. 1i

Line 173: “reshaping surface energy balance” within or outside the regions?

Line 188: Incorporating analysis on time scales before and after WSI adoption could reinforce such conclusions.

Line 199: As in the general comments, the section on attribution analysis is not entirely novel seeing that the biophysical cooling of irrigation results from the amount of applied irrigation water.

Line 253: “... longwave *radiation* ...” instead of longwave emission”

Line 284: Reading the manuscript to this point, it does not become entirely clear to the reader how the shift to WSI can warm land surface processes. The focus here remains the secondary benefits of irrigation as an adaptation measure, primarily to sustain crop growth and not for cooling land surfaces.

Line 293: “The climate impacts of WSI *in China* ...”

End of Fig. 3 caption: “... in $\Delta(\text{HE/LE})$ ”

References

Braun, T. and Schlenker, W., 2023. *Cooling externality of large-scale irrigation* (No. w30966). National Bureau of Economic Research. <https://doi.org/10.3386/w30966>

Huang, G., Hoekstra, A.Y., Krol, M.S., Jägermeyr, J., Galindo, A., Yu, C. and Wang, R., 2020. Water-saving agriculture can deliver deep water cuts for China. *Resources, conservation and recycling*, 154, p.104578. <https://doi.org/10.1016/j.resconrec.2019.104578>

Liu, G., Wang, W., & Shao, Q. 2023. Recent decline of irrigation-induced cooling effect over the North China Plain in observations and model simulations. *Geophysical Research Letters*, 50, e2022GL101973. <https://doi.org/10.1029/2022GL101973>

Zhang, C., Dong, J., Leng, G., Doughty, R., Zhang, K., Han, S., Zhang, G., Zhang, X. and Ge, Q., 2023. Attenuated cooling effects with increasing water-saving irrigation: Satellite evidence from Xinjiang, China. *Agricultural and Forest Meteorology*, 333, p.109397. <https://doi.org/10.1016/j.agrformet.2023.109397>

Manuscript_13180_1: "Irrigation cooling effect reduced by water-saving practices."

Summary

The manuscript by Zhang et al. investigates the biophysical climate impacts of water-saving irrigation (WSI) across China, drawing on two decades of satellite-based land surface temperature and energy flux observations. The authors show that widespread adoption of WSI has substantially weakened irrigation's daytime cooling effect while simultaneously intensifying nighttime cooling, with the balance of impacts varying by region and season. They attribute these changes primarily to shifts in irrigation water use (IWU) and altered surface energy partitioning. The study frames this as an emerging trade-off between improved water-use efficiency and reduced climate-mitigation capacity of irrigation, with implications for Earth system modelling and adaptation policy.

General Comments

Zhang et al. have taken previous comments, positing WSI in the negative, into consideration to improve the manuscript. The added clarifications show the authors made a good effort in responding to my comments to improve the draft. I believe the current version of the manuscript has been significantly improved. Therefore, I recommend its publication, pending some minor revisions raised in the comments below when addressed to the satisfaction of the handling editor.

Specific comments and/or recommendations

Line :	Comments and/or Suggestions
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Line 74:	Not entirely clear what is intended by "prosperous" WSI promotion
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Line 79:	Here and through the manuscript, consider writing WSI technologies instead of WSI alone.
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Line 93:	The acronym "WSI" has already been introduced in Line 56. No need for duplicates.
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Line 94:	Add a sentence here about the irrigated area dataset used in the study and refer readers to the methods for further details.
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Line 106:	It is not documented anywhere in the Methods section how the IWU was computed. Was it simply ET-effective precipitation? Or was this from well abstraction records? Since the study speaks of spatial dimension, one would assume ET was used as proxy for crop water consumption.
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Line 109:	"Shift" could be increase or decrease. Maybe a different phrase?
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Line 114:	Consider using "a reduced cooling" instead of "an indirect warming".
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Line 150:	Here and other subheadings, consider writing in full instead of abbreviations.
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Line 162: Here and through the manuscript, for consistency, either use “per decade”, “/decade” or “decade⁻¹”. In this case, per decade might be most appropriate. See 173, 179, 199, and elsewhere.
Lines 164 – 166: Since this is not proven in this study, consider adding appropriate references.

Line 177: Which “north-south differences” is referred here? This assumes the preceding paragraph already discussed this which isn’t the case.

Line 189: Consider another phrase other than “amplification”.

Line 201: Not entirely clear what “thermal efficiency” would mean in this context.

Line 207: Spell IWU in full.

Line 209: The abbreviation “IWU” has been previously defined.

Line 212: “declining IWU—representing the widespread adoption of WSI”. Declining IWU does not necessarily mean adoption of WSI. Add a few sentences to the second point (Line 388) in the limitations of the study to highlight this as a limitation.

Line 215: In this context consider “land-atmosphere interaction” instead of “land-atmosphere coupling”

Line 235: Consider “reduced cooling” instead of “surface warming”.

Line 275: Irrigation efficiency (IE) is a convoluted term and subject to multiple interpretations. This is appearing for the first time in the manuscript. For context, WSI has been presented and should be used consistently. The sentence in reference might need to be rephrased. Note that not all IE measures lead to water conservation or water saving.

Line 311: Consider using “introduced” instead of “imported”.

Line 337: replace “this warming” with “this reduced cooling”.

Line 339: Again, as earlier in **Line 275**, “high-efficiency irrigation” is herein introduced as well as climate-smart irrigation strategies. These are terms that could have slight deviation from WSI. Since the study is around WSI, adopt a single defined terminology and use this through the manuscript.

Line 374: “irrigation-induced ...” Induced what? This appears to be an incomplete sentence.

Line 411: “WSI could be prioritized in water-stressed...” As in previous round of comments, does this mean WSI prioritised in water-stressed regions while wasteful irrigation practices should be encouraged in other non-water stressed regions? This could be misleading with long-term implications for regional hydrology.

Line 416: “... programs should be carefully designed to avoid excessive reductions in irrigation that could...” This could be misinterpreted as saying one has to irrigate at all costs even when there is no need to irrigate or in conditions where it becomes expensive or leads to long-term effects on water availability just to retain the cooling benefits of irrigation.

For Figures 1-5, would it be possible to increase the font size of the figure labels (i.e., a, b, c, d...) next to the figures? Or add them in parentheses to differentiate them from the axis label. For consistency and differentiation from running text, consider boldening these labels (i.e., a, b, c, d...) wherever they appear in the figure caption.