

Impacts of irrigation expansion on moist-heat stress based on IRRMIP results

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This is an interesting article demonstrating that the cooling effect of additional evapotranspiration created by irrigated agriculture also resulted in increased humidity so that the overall effect on the health of the population living in the neighbourhood of the irrigated fields and exposed to the moist-heat stress is less pronounced than when considering the cooling effect alone. Based on an ensemble of earth system – and climate models the authors estimate the impact of the irrigation expansion within the last century on the severity and frequency of heat waves and moist-heat extremes. The innovation is certainly the combination of distinct model estimates and the use of a large number of heat stress indicators. This allows to derive information about the uncertainty of simulation results. Interestingly, while the models disagree on the specific impact of irrigation expansion, they agree in general trends so that it is possible to generalize findings. This is extremely relevant.

The manuscript is well written and the results are nicely described in a number of high-quality tables and figures. I appreciate in particular the description of the models and of their setup in contained in the Supplementary Information. In general, I highly recommend to publish the manuscript in Nature Communications but have a few comments that might be considered in a revised version of the manuscript:

General comments:

1) The authors use a variety of Earth System – and Climate Models and compute the impact of irrigation expansion on a number of heat stress indices and if I understood it right, they also used additional heat stress indices described in Supplementary Note 3. Results are shown for the three indices Air temperature in 2 m height, HUMIDEX and wet-bulb-temperature while often the median of the model results is shown. I would appreciate when also information for distinct models will be provided similar to irrigation water withdrawal shown in Fig. 1. Maybe at least the heat indicators computed with the models simulating the highest and the lowest irrigation water withdrawal would be very helpful. If the heat stress was also computed for the indicators described in Supplementary Note 3, then I would highly appreciate when the authors make these results available as well. This could be done in a simple qualitative way in a summary table by showing the model as columns and the heat indicators as rows and then reporting whether irrigation expansion resulted in strong increase, moderate increase, no clear trend, moderate decrease or strong decrease.

2) To avoid confusion of the readers I suggest that the authors make very clear that they analysed specifically heat stress felt by humans while not looking into heat effects on irrigated plants. There is no doubt that plants receiving irrigation are less affected by heat stress, simply because of the cooling effect of ET on the canopy and foliar temperature. These positive impacts also appear when humidity is increased. What the authors studied are the indirect effects of irrigation on people living and working in the surrounding of irrigated fields.

Specific comments:

1) Please number the equations in the manuscript and refer then in the text to these numbers where appropriate.
2) Lines 332-336: So far I know FAOSTAT is providing data in general only for the period since 1961 so that I'm surprised that HYDE3.2 obtained the irrigation information for the pre-1961 period directly from FAOSTAT. Please check.

(Remarks on code availability)

Reviewer #2

(Remarks to the Author)

General Comments:

This study investigated the influence of irrigated cropland expansion on moist heat stress. With the latest results of six ESMs from a model comparison project, the authors examined the impacts of irrigation on human-perceived heat stress calculated with multiple different heat metrics. The relevant topic has been popular in recent years under the escalating heat stress worldwide, and the results of this study provide more solid evidence for such issues. The manuscript is generally well-written, most of the results are clearly presented, and it is suitable to be considered for publication in Nature Communications. Nonetheless, major revision is still needed to show more results for humidity changes and discuss why the results are potentially different from some existing studies. I list my specific comments as follows:

Major comments:

1. The impact of irrigation on moist heat stress has been a popular topic in recent years, and many studies have been done by using either global scale simulations or regional scale simulations. Most of these studies suggest that the irrigation in the heavily irrigated regions (e.g., northern India, North China Plain) tends to increase (either large or small) the extreme value of T_w in these regions, which is found for both regional and global simulations. However, in the results of this study, such enhanced T_w extremes are not observed for these regions (Figures 3 and 4). How can we understand this discrepancy, and what could be the potential reasons? Such a discussion and comparison are necessary to avoid confusing the community. I listed some existing studies as follows for the authors to check:

Regional simulations:

- Kang and Eltahir, North China Plain threatened by deadly heatwaves due to climate change and irrigation, Nature Communications, 2018.
- Mishra et al., Moist heat stress extremes in India enhanced by irrigation, Nature Geoscience, 2020.
- Jha et al., Limited influence of irrigation on pre-monsoon heat stress in the Indo-Gangetic Plain, 2022.

Global simulations:

- Krakauer et al., Effect of irrigation on humid heat extremes, ERL, 2020.

2. Moist heat stress or humid heat receives more attention as it could be closer to the heat stress the human body feels. In this regard, where the population gathers (i.e., urban area) should be paid greater attention, as it has more exposure (population scale) and hazard (urban heat island). For example, Guo et al. (2022) investigated the effects of irrigated cropland expansion on urban moist heat in northern India. They found cities with more considerable irrigated cropland expansion in the surrounding area could have higher T_w increase in recent decades. Currently, most of the ESMs may be unable to adequately represent the urban climate and urban heat island reasonably due to the lack of urban modules and the coarse spatial resolution. I think this also holds true for the current study; thus, the lack of urban representation in the simulation settings should be admitted as a limitation in the discussion part.

- Guo et al., Irrigated cropland expansion exacerbates the urban moist heat stress in northern India, ERL, 2022

3. The current manuscript shows the results based on air temperature and several heat metrics (e.g., T_w). To present the results more straightforwardly and facilitate the comparison with previous studies, I suggest the authors also provide the maps for the mean and extreme values of relative humidity and specific humidity (could be in the appendix), which is more straightforward for the readers to understand the changes of several heat metrics.

4. Compared to the previous studies, one of the strengths of the current study is the calculation of multiple heat metrics with different algorithms, and it reveals the uncertainty when choosing different heat metrics to quantify the impacts of irrigation. The uncertainty among different heat metrics and the selection of heat metrics in specific locations for application (e.g., heat health alert and climate change impact assessment) is also a big concern for environmental health scientists and physiologists. To highlight this issue, increase the readership of current studies and facilitate communications between researchers in different fields. The authors could add more discussion on this point by referring to some environmental health studies. Some references are provided as follows:

- Lo et al., Optimal heat stress metric for modelling heat-related mortality varies from country to country, International Journal of Climatology, 2023.
- Guo et al., Regional variation in the role of humidity on city-level heat-related mortality, PNAS Nexus, 2024.

Minor comments:

1. In line 70, the sentence "Evaporative cooling is the main way humans lose heat" is too strong. Evaporative cooling only works when the human body starts to sweat, and there are also other mechanisms for the human body to lose heat, such as convection heat exchange and radiation heat exchange.
2. Line 168, for "Consistent with a previous study using the Goddard Institute for Space Studies (GISS) climate model", please give the reference.
3. Figure A8 is referred to in the main text before A6 and A7. Maybe their sequence number should be adjusted.
4. Line 249, a strange "A5" here.
5. Lines 337-342, is the calculation based on daily maximum temperature and minimum RH only applied for CNRM-CM6-1, or is it applied for all six ESMs? It should be made more clear here. Additionally, what wind speed value (daily mean or maximum?) is used when calculating APT using daily maximum temperature and minimum RH?

6. There is no e in Figure A1, as the figure caption states.

7. In the caption of Figure 1, I assume the c-h represents the IWW for the tranirr simulations. It should be specified.

In addition, in panel b of Figure 1, the median of the 1901irr simulations (red color) is so close to the minimum value (the lower boundary). What is the reason? Moreover, according to the caption “for the 1901irr experiment of IPSL-CM6, irrigation is switched off”, if the irrigation is switched off for IPSL-CM6, then why the lower boundary of the red color in panel b is not 0?

(Remarks on code availability)

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

In my opinion, the questions raised by the reviewer have been satisfactorily addressed. I recommend it for publication.

(Remarks on code availability)

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1 Reviewer 1

1.1 Major comments

Reviewer 1 Comment 1

This is an interesting article demonstrating that the cooling effect of additional evapotranspiration created by irrigated agriculture also resulted in increased humidity so that the overall effect on the health of the population living in the neighbourhood of the irrigated fields and exposed to the moist-heat stress is less pronounced than when considering the cooling effect alone. Based on an ensemble of earth system – and climate models the authors estimate the impact of the irrigation expansion within the last century on the severity and frequency of heat waves and moist-heat extremes. The innovation is certainly the combination of distinct model estimates and the use of a large number of heat stress indicators. This allows to derive information about the uncertainty of simulation results. Interestingly, while the models disagree on the specific impact of irrigation expansion, they agree in general trends so that it is possible to generalize findings. This is extremely relevant. The manuscript is well written and the results are nicely described in a number of high-quality tables and figures. I appreciate in particular the description of the models and of their setup in contained in the Supplementary Information. In general, I highly recommend to publish the manuscript in Nature Communications but have a few comments that might be considered in a revised version of the manuscript.

Response We thank Reviewer 1 for these kind words and the valuable feedback that we used to improve our manuscript. Below, we address every comment carefully and explain the corresponding changes in the manuscript. There are several major changes we have done in the manuscript, which are listed as follows.

(1) Previously, we compared the outputs during the two periods (1901-1930 and 1985-2014) of *tranirr* to calculate the impacts of all forcings. This was based on an assumption that the difference in outputs during the period 1901-1930 between two experiments (*tranirr* and *1901irr*) is negligible. However, there was already irrigation expansion happening during the first 30 years, and we therefore changed the method of calculating the impacts of all forcings. Table 1 in the main text then has been modified as in TAB 1.

(2) We have rewritten section 'Irrigation expansion-induced impacts on energy fluxes' to improve the flow of the manuscripts and highlight the important changes more clearly.

(3) Before, in figures with agreement among models, only results with high agreement were shown. We now show all results and add hatches to indicate the agreement.

(4) Appendix figures have been moved to Supplementary Information.

TAB 1: Approach to separate the impacts of different forcings

Reference exp_period	New exp_period	Forcings
1901irr_1901-1930	tranirr_1985-2014	all forcings (greenhouse gas emissions, land use change, irrigation expansion, etc.)
1901irr_1901-1930	1901irr_1985-2014	all forcings except irrigation expansion
1901irr_1985-2014	tranirr_1985-2014	irrigation expansion

Reviewer 1 Comment 2

The authors use a variety of Earth System – and Climate Models and compute the impact of irrigation expansion on a number of heat stress indices and if I understood it right, they also used additional heat stress indices described in Supplementary Note 3. Results are shown for the three indices Air temperature in 2 m height, HUMIDEX and wet-bulb-temperature while often the median of the model results is shown. I would appreciate when also information for distinct models will be provided similar to irrigation water withdrawal shown in Fig. 1. Maybe at least the heat indicators computed with the models simulating the highest and the lowest irrigation water withdrawal would be very helpful. If the heat stress was also computed for the indicators described in Supplementary Note 3, then I would highly appreciate when the authors make these results available as well. This could be done in a simple qualitative way in a summary table by showing the model as columns and the heat indicators as rows and then reporting whether irrigation expansion resulted in strong increase, moderate increase, no clear trend, moderate decrease or strong decrease.

Response We agree with Reviewer 1 that showing results of other models and other heat metrics greatly adds value to this manuscript, so we added two sections in the Supplementary Materials (Supplementary Figures 1 and 2). Supplementary Figures 1 contain maps of irrigation water withdrawal (Figure S5), maps of impacts on absolute values of 2-meter air temperature, HUMIDEX, and wet-bulb temperature extreme events (Figure S6-S11), and maps of impacts on frequency of 2-meter air temperature, HUMIDEX, and wet-bulb temperature extreme events (Figure S12-S17) of six individual models. We now also refer to these sections in the main text wherever necessary. For example, in the caption of Figures 2 and 3:

Spatial pattern of irrigation expansion and simulated irrigation water withdrawal in different periods. [...]. [The figure showing results from all individual models can be found in Supplementary Figures 1. Multi-model mean simulated annual IWW with fixed irrigation extent \(1901irr\) during the two periods can be found in Figure A1e,f.](#)

Heat and moist-heat extremes and impacts of different forcings on them. [...] **d-l** Multi-model mean impacts of all forcings (ALL: greenhouse gas emissions, land use and land management change, irrigation expansion, etc.) (**d,e,f**), all forcings except irrigation expansion (ALL-IE: **g,h,i**), and irrigation expansion (IE: **j,k,l**) on the 99.9th percentile values of T_{2m} (**d, g, j**), HU (**e, h, k**), and T_w (**f,i,l**). Impacts are calculated by subtracting the values in the new exp_period

by those in the reference exp_period (see Table 1). Hatches indicate that signals (>0.1 or <-0.1) are agreed by ≥ 5 of 6 models (results for the individual models are presented in Supplementary Figures S7-11). Results for other extreme event percentiles (the 99th and 99.5th) are shown in Supplementary Figures S18-26.

To illustrate the differences across individual models, we show probability ratio calculated based on outputs from two models, CESM2 (FIG 1) and CNRM-CM6-1 (FIG 2). Results of other models can be found in Supplementary Figure 1.

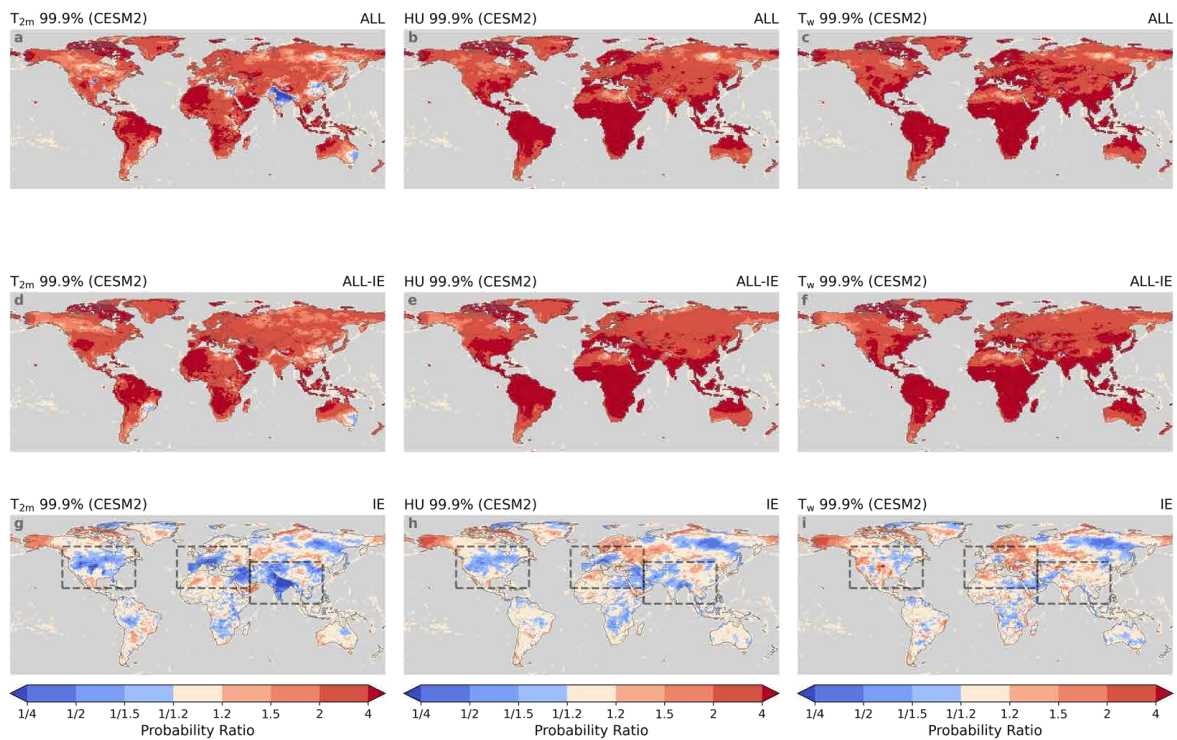


FIG 1: Impacts of different forcings on frequency of 2-meter air temperature, HUMIDEX, and wet-bulb temperature extreme event as simulated by CESM2. **a-i** Impacts of all forcings (ALL: **a**, **b**, **c**), all forcings except irrigation expansion (ALL-IE: **d**, **e**, **f**), and irrigation expansion (IE) on the frequency of the events in which 2-meter air temperature (T_{2m} : **a**, **d**, **g**), HUMIDEX (HU: **b**, **e**, **h**), and wet bulb temperature (T_w : **c**, **f**, **i**) exceed their 99.9th percentile values of the first 30 years (1901-1930) in the simulations without irrigation expansion (1901irr). Impacts are quantified by probability ratio (PR) which is calculated by dividing the events frequencies in the new exp_period by those in the reference exp_period (see Table 1 in main text), and the values are calculated based on CESM2 outputs. *This figure is adopted from Supplementary Figure S6.*

Additionally, to illustrate the difference across heat metrics, we show two metrics, the Discomfort Index (DI; FIG 3) and the temperature when 80% of the swamp coolers are approached (T_{s80} ; FIG 4). Results of other metrics can be found in Supplementary Figure 2.

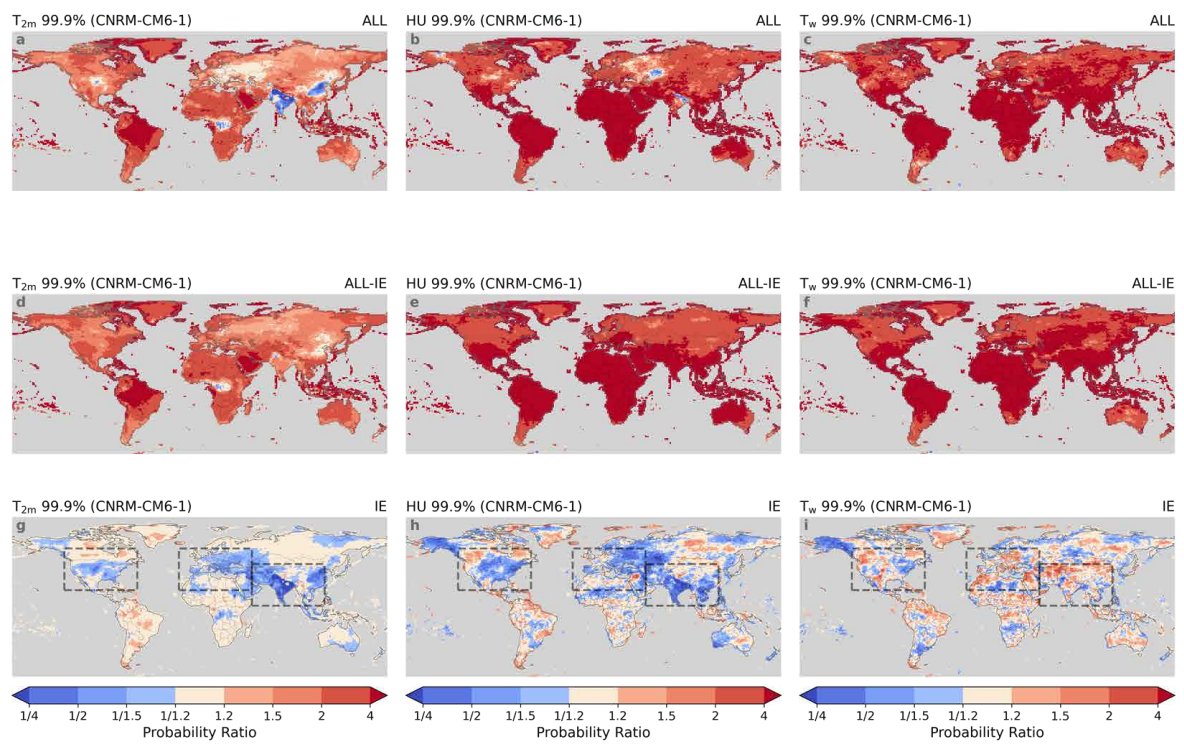


FIG 2: Same as FIG 1 but calculated based on CNRM-CM6-1 outputs. *This figure is adopted from Supplementary Figure S11.*

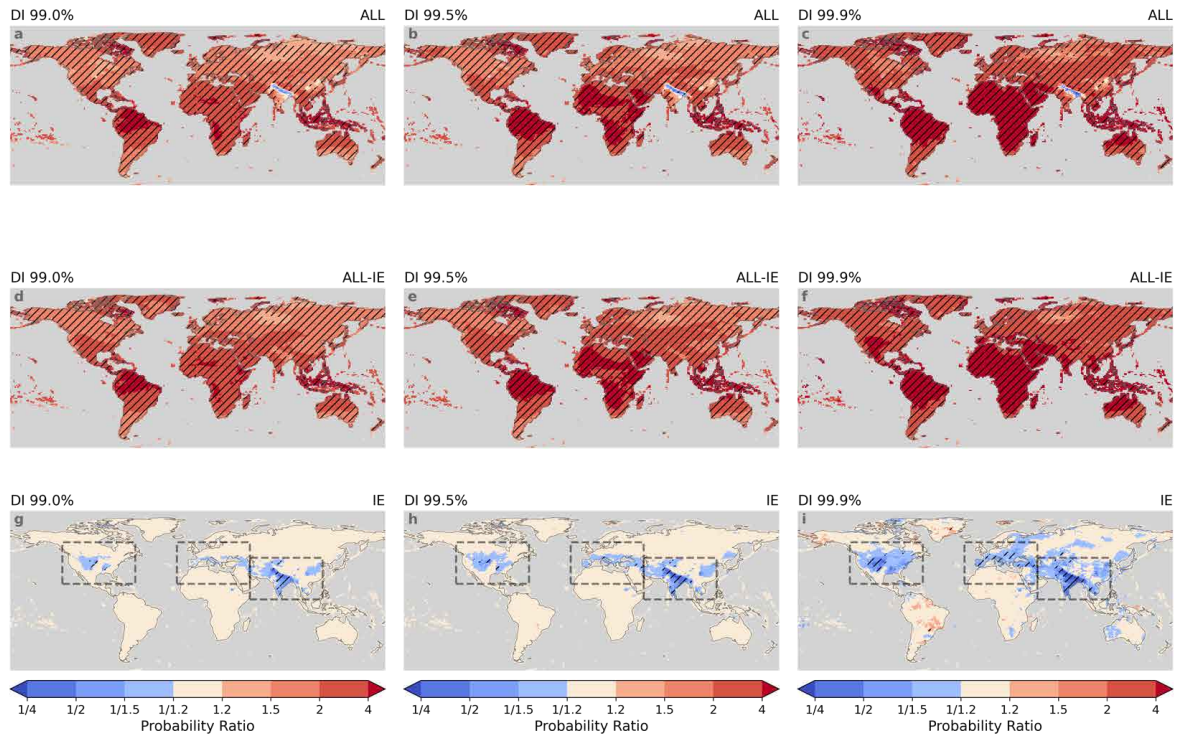


FIG 3: **a-i** Impacts of all forcings (ALL: **a, b, c**), all forcings except irrigation expansion (ALL-IE: **d, e, f**), and irrigation expansion (IE) on the frequency of the events in which Discomfort Index (DI) exceed its 99th (**a, d, g**), 99.5th (**b, e, h**), and 99.9th (**c, f, i**) percentile values of the first 30 years (1901-1930) in the simulations without irrigation expansion (*1901irr*) shown in Figure S22a-c. Impacts are quantified by probability ratio (PR) which is calculated by dividing the events frequencies in the new exp_period by those in the reference exp_period (see Table 1 in main text), and the values are the sixth root of the product of PR calculated from the outputs of six ESMs. Only signals (>1.2 or $<1/1.2$) agreed by ≥ 5 of 6 models are shown. *This figure is adopted from Supplementary Figure S22.*

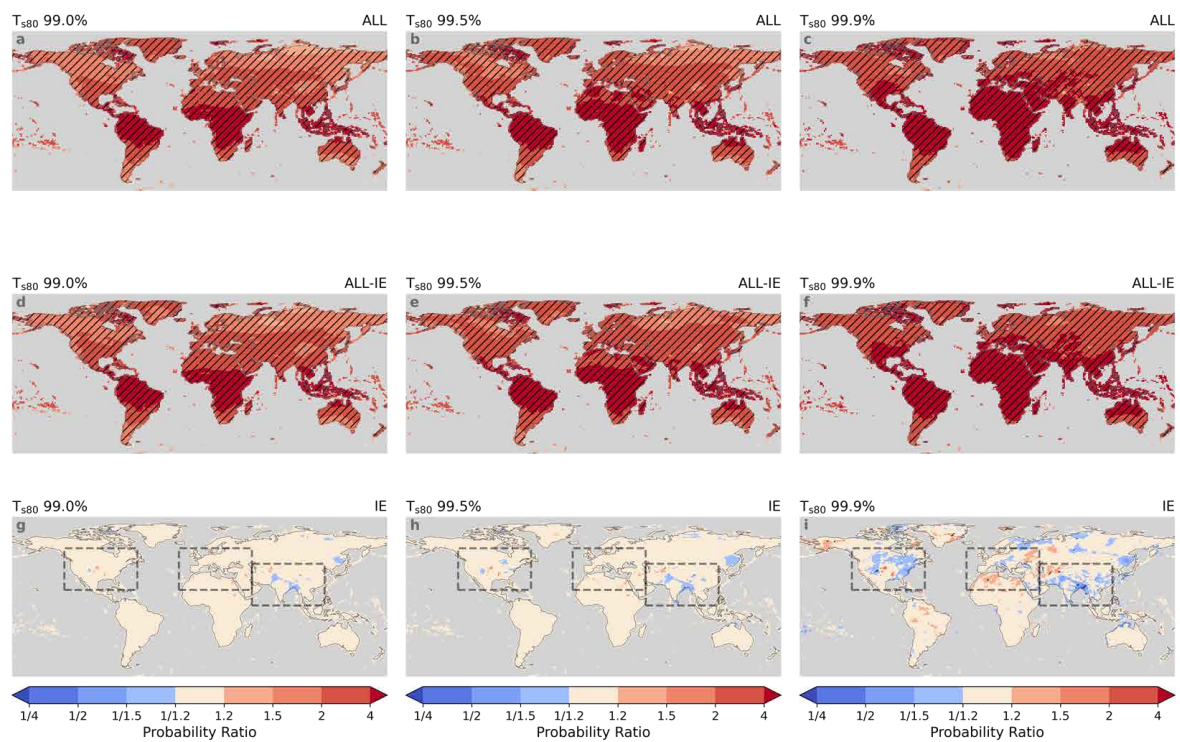


FIG 4: Same as FIG 3 bu for the temperature when 80% of the swamp coolers are approached (T_{s80}). This figure is adopted from Supplementary Figure S26.

Reviewer 1 Comment 3

To avoid confusion of the readers I suggest that the authors make very clear that they analysed specifically heat stress felt by humans while not looking into heat effects on irrigated plants. There is no doubt that plants receiving irrigation are less affected by heat stress, simply because of the cooling effect of ET on the canopy and foliar temperature. These positive impacts also appear when humidity is increased. What the authors studied are the indirect effects of irrigation on people living and working in the surrounding of irrigated fields.

Response

Thank Review 1 for this suggestion. We added some texts to clarify it.

L294-296

Note that both HU and T_w are designed for human beings, so the results here are not suitable for detecting irrigation-induced impacts on crops and natural plants, which requires better understanding of interactions between plant growth, temperature, and humidity.

1.2 Minor comments

Reviewer 1 Comment 4

Please number the equations in the manuscript and refer then in the text to these numbers where appropriate.

Response We thank the Reviewer for this suggestion. We have labeled all the equations and refer to them in the revised manuscript wherever necessary. For example,

L129-131:

Here we focus on T_{2m} , HUMIDEX (HU: Equation 2), and T_w (Equation 4) warm extremes, as many other metrics are weighted average values of T_{2m} and T_w .

Reviewer 1 Comment 5

Lines 332-336: So far I know FAOSTAT is providing data in general only for the period since 1961 so that I'm surprised that HYDE3.2 obtained the irrigation information for the pre-1961 period directly from FAOSTAT. Please check.

Response Thanks for finding this mistake. Actually the data during the pre-1961 period is from Siebert et al. (2015). We updated the manuscript:

L369-373

The irrigated land data from HYDE 3.2 during the period 1901-2014 has multiple sources: for the period pre-1960, the data is collected directly from the global

historical irrigation data set (HID) (1), and for the post-1960 period, the numbers are calculated by multiplying the term "area equipped for irrigation" in FAO statistics (2) by the fraction of actual irrigated area in area equipped for irrigation from HID.

2 Reviewer 2

2.1 Major comments

Reviewer 2 Comment 1

This study investigated the influence of irrigated cropland expansion on moist heat stress. With the latest results of six ESMs from a model comparison project, the authors examined the impacts of irrigation on human-perceived heat stress calculated with multiple different heat metrics. The relevant topic has been popular in recent years under the escalating heat stress worldwide, and the results of this study provide more solid evidence for such issues. The manuscript is generally well-written, most of the results are clearly presented, and it is suitable to be considered for publication in Nature Communications. Nonetheless, major revision is still needed to show more results for humidity changes and discuss why the results are potentially different from some existing studies.

Response We thank Reviewer 2 for these supportive words and the valuable suggestions which help us to improve this manuscript. Below, we address every comment carefully and explain the corresponding changes in the manuscript. There are several major changes we have done in the manuscript, which are listed as follows.

(1) Previously, we compared the outputs during the two periods (1901-1930 and 1985-2014) of *tranirr* to calculate the impacts of all forcings. This was based on an assumption that the difference in outputs during the period 1901-1930 between two experiments (*tranirr* and *1901irr*) is negligible. However, there was already irrigation expansion happening during the first 30 years, and we therefore changed the method of calculating the impacts of all forcings. Table 1 in the main text then has been modified as in TAB 1.

(2) we have rewritten section 'Irrigation expansion-induced impacts on energy fluxes' to improve the flow of the manuscripts and highlight the important changes more clearly.

(3) Before, in figures with agreement among models, only results with high agreement were shown. We now show all results and add hatches to indicate the agreement.

(4) Appendix figures have been moved to Supplementary Information.

Reviewer 2 Comment 2

The impact of irrigation on moist heat stress has been a popular topic in recent years, and many studies have been done by using either global scale simulations or regional scale simulations. Most of these studies suggest that the irrigation in the heavily irrigated regions (e.g., northern India, North China Plain) tends to increase (either large or small) the extreme value of T_w in these regions, which is found for both regional and global simulations. However, in the results of this study, such enhanced T_w extremes are not observed for these regions (Figures 3 and 4). How can we understand this discrepancy, and what could be the potential reasons? Such a discussion and comparison are necessary to avoid confusing the community. I listed some existing studies as follows for the authors to check: Regional simulations: • Kang and Eltahir, North China Plain threatened by deadly heatwaves due to climate change and irrigation, Nature Communications, 2018. • Mishra et al., Moist heat stress extremes in India enhanced by irrigation, Nature Geoscience, 2020. • Jha et al., Limited influence of irrigation on pre-monsoon heat stress in the Indo-Gangetic Plain, 2022. Global simulations: • Krakauer et al., Effect of irrigation on humid heat extremes, ERL, 2020.

Response

We thank the reviewer for this suggestion. Indeed, we confirm that our results contain some discrepancies compared to previous studies on this topic, while other elements corroborate earlier findings. In the revised manuscript, we have now added text that discusses these differences, complementing the comparison with the Krakauer et al., 2020 ERL study which was already presented in the original submission:

L254-276

Different from the cooling impacts on temperature extremes, the impacts of irrigation on moist-heat extremes are less substantial. As mentioned above, over two intensely irrigated regions, India and East China, extreme events of T_w do not show pronounced changes in both magnitude and frequency (Figure 3 and 4) due to irrigation expansion. Two previous studies, a global one using the Goddard Institute for Space Studies (GISS) climate model (4) and a regional one based on Massachusetts Institute of Technology Regional Climate Model (5), found that irrigation increases the average values T_w more substantially than the extreme values over the same regions. It implies that the most extreme T_w events may not happen during the heavily irrigated season. Thus, we calculate multi-year mean monthly IWW during the period 1985-2014 of *tranirr* experiment (FIG 5), monthly maximum T_{2m} , HU, and T_w during the same period but of *1901irr* experiment (FIG 6, 7, and 8), which confirms this hypothesis. In India, high IWW appears in April to June, high T_{2m} extremes exist in May to June, while HU peaks from June to August, and T_w from July to August. This temporal mismatch has also been argued by some researchers (6; 7), both regarding heat and moist-heat extremes. Irrigation expansion-induced impacts on annual mean, maximum, minimum temperature (FIG 9) and specific humidity (FIG 10) also show that T_w is more substantially affected where both annual maximum temperature and spe-

cific humidity match temporally the irrigation season, like WCA and CNA. However, if limiting the study period to irrigation season, some studies still found evidence of irrigation-induced warming on T_w extremes in India (8; 3). Over East China, in contrast, the most intense irrigation season generally overlaps with the peak season for T_{2m} , HU , and T_w , and a previous study has attributed weak impacts of irrigation in this area to a lower intensity of AEI expansion than India and local climatic conditions (3).

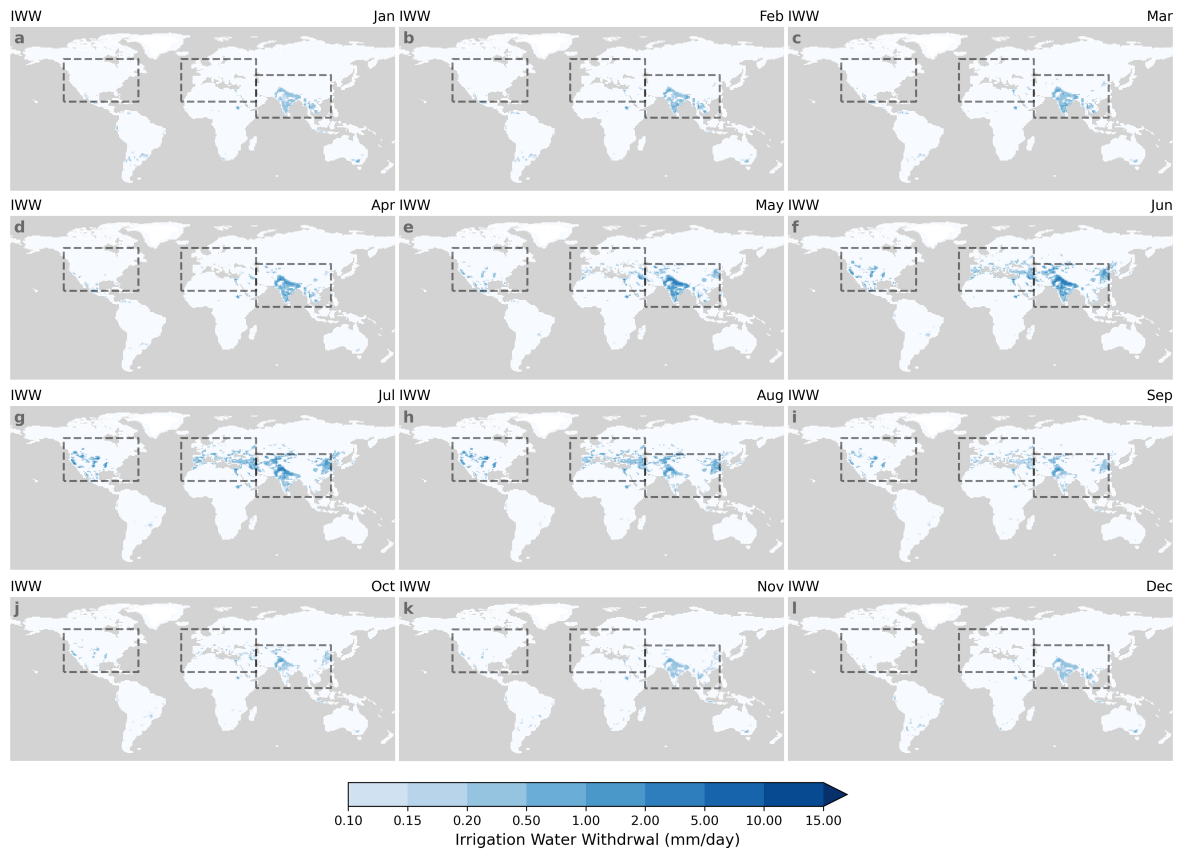


FIG 5: Multi-year mean monthly irrigation water withdrawal (IWW) during the period 1985-2014 of the experiment with irrigation expansion (*tranirr*). Results shown are average values of all six models. *This figure is adopted from Supplementary Figure A7.*

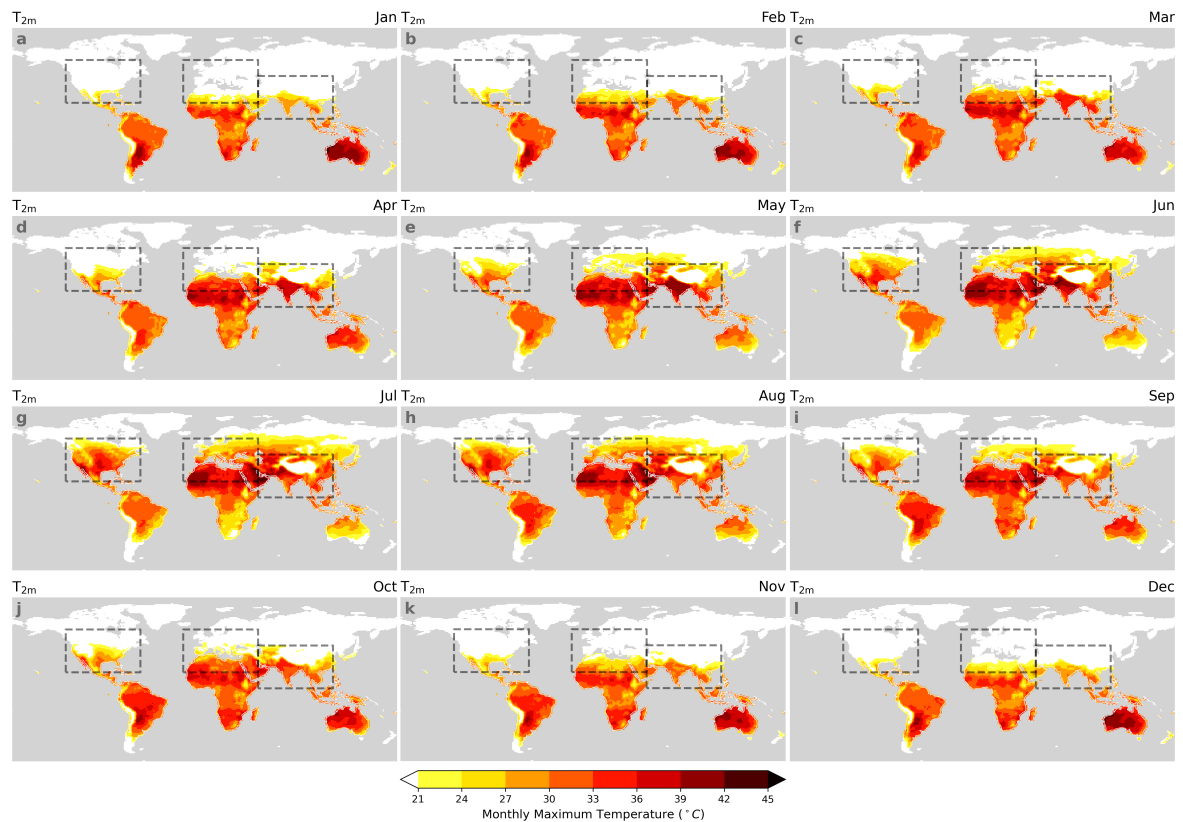


FIG 6: Multi-year mean monthly maximum 2-meter air temperature (T_{2m}) during the period 1985-2014 of the experiment without irrigation expansion (1901irr). Results shown are average values of all six models. *This figure is adopted from Supplementary Figure A8.*

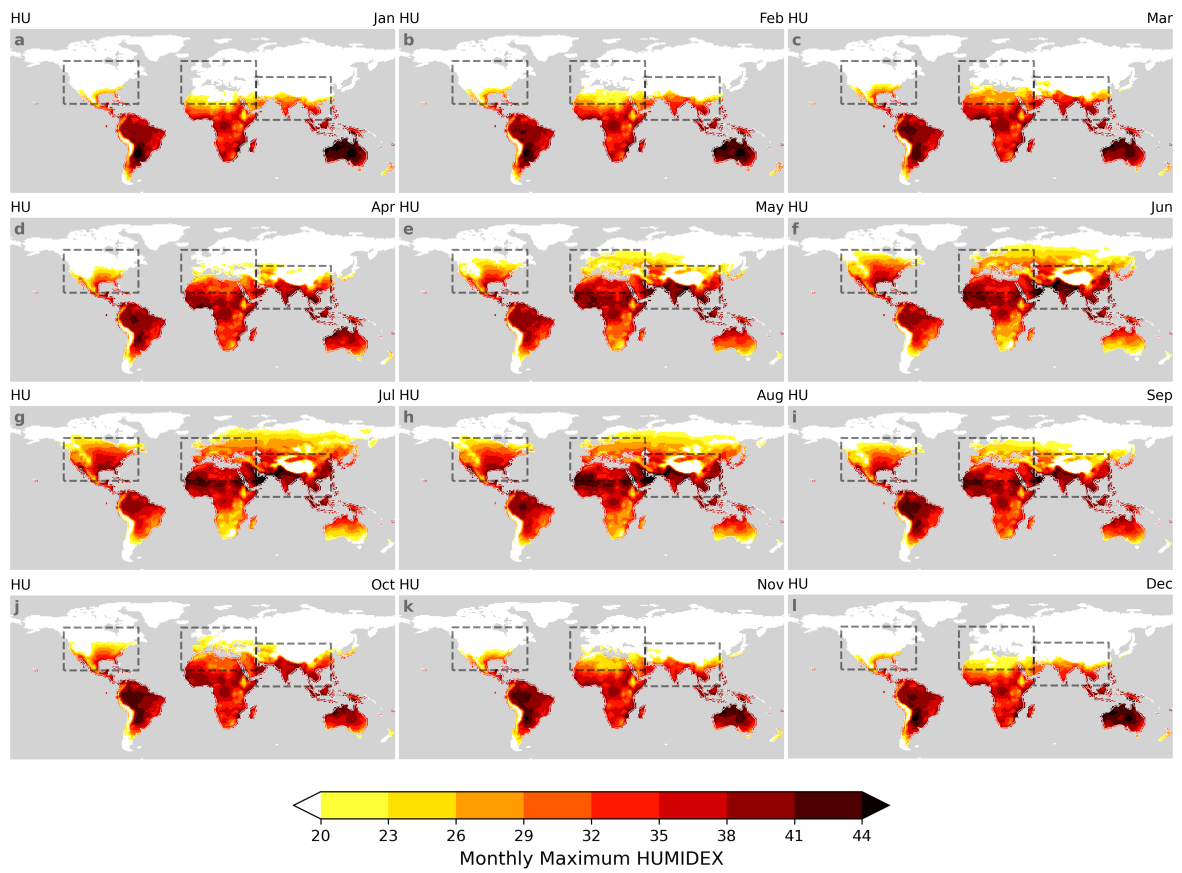


FIG 7: Similar to FIG 6 but for HUMIDEX (HU). *This figure is adopted from Supplementary Figure A9.*

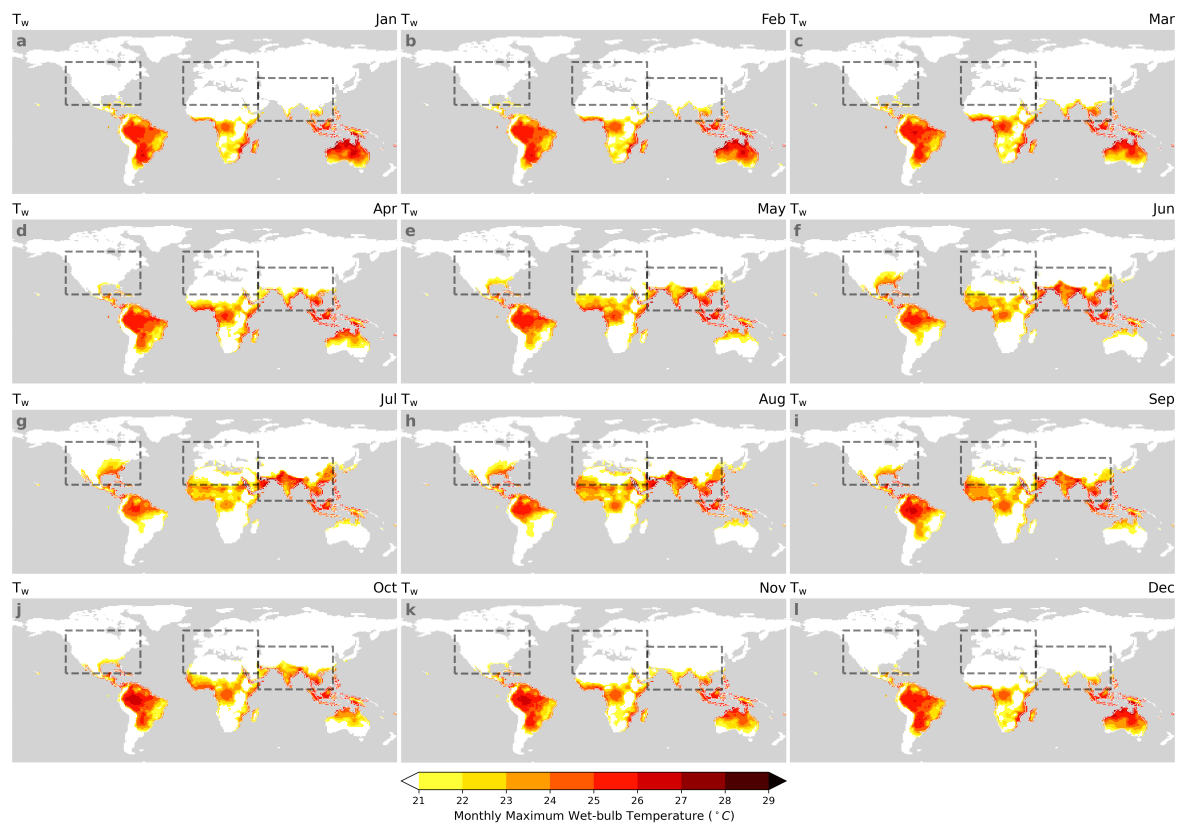


FIG 8: Similar to FIG 6 but for wet-bulb temperature (T_w). This figure is adopted from Supplementary Figure A10.

Reviewer 2 Comment 3

Moist heat stress or humid heat receives more attention as it could be closer to the heat stress the human body feels. In this regard, where the population gathers (i.e., urban area) should be paid greater attention, as it has more exposure (population scale) and hazard (urban heat island). For example, Guo et al. (2022) investigated the effects of irrigated cropland expansion on urban moist heat in northern India. They found cities with more considerable irrigated cropland expansion in the surrounding area could have higher T_w increase in recent decades. Currently, most of the ESMs may be unable to adequately represent the urban climate and urban heat island reasonably due to the lack of urban modules and the coarse spatial resolution. I think this also holds true for the current study; thus, the lack of urban representation in the simulation settings should be admitted as a limitation in the discussion part.

- Guo et al., Irrigated cropland expansion exacerbates the urban moist heat stress in northern India, ERL, 2022

Response Thank you for this suggestion. We have added the following text:

L284-288

In addition, the impacts of agricultural irrigation on neighbouring non-irrigated areas, especially urban areas with high population density, should be investigated more comprehensively. A previous study highlighted the higher exposure of cities surrounded by irrigated cropland in India to moist-heat stress, as a combined consequence of irrigation and urban heat island effect (3). Unfortunately, urban regions are still poorly resolved in current coarse-resolution ESMs.

Reviewer 2 Comment 4

The current manuscript shows the results based on air temperature and several heat metrics (e.g., T_w). To present the results more straightforwardly and facilitate the comparison with previous studies, I suggest the authors also provide the maps for the mean and extreme values of relative humidity and specific humidity (could be in the appendix), which is more straightforward for the readers to understand the changes of several heat metrics.

Response We agree that this additional information can be helpful for understanding the limited impacts of irrigation expansion on wet bulb temperature extremes. We therefore display the impacts of irrigation expansion on annual mean, minimum, and maximum values of daily mean, minimum, and maximum 2-meter air temperature (FIG 9), respectively, and did the same for specific humidity (FIG 10). We additionally calculated the multi-year mean monthly mean irrigation water withdrawal, maximum 2-meter air temperature, HUMIDEX, and wet-bulb temperature, to verify the temporal overlap between them (see updated text in Reviewer 2 Comment 2).

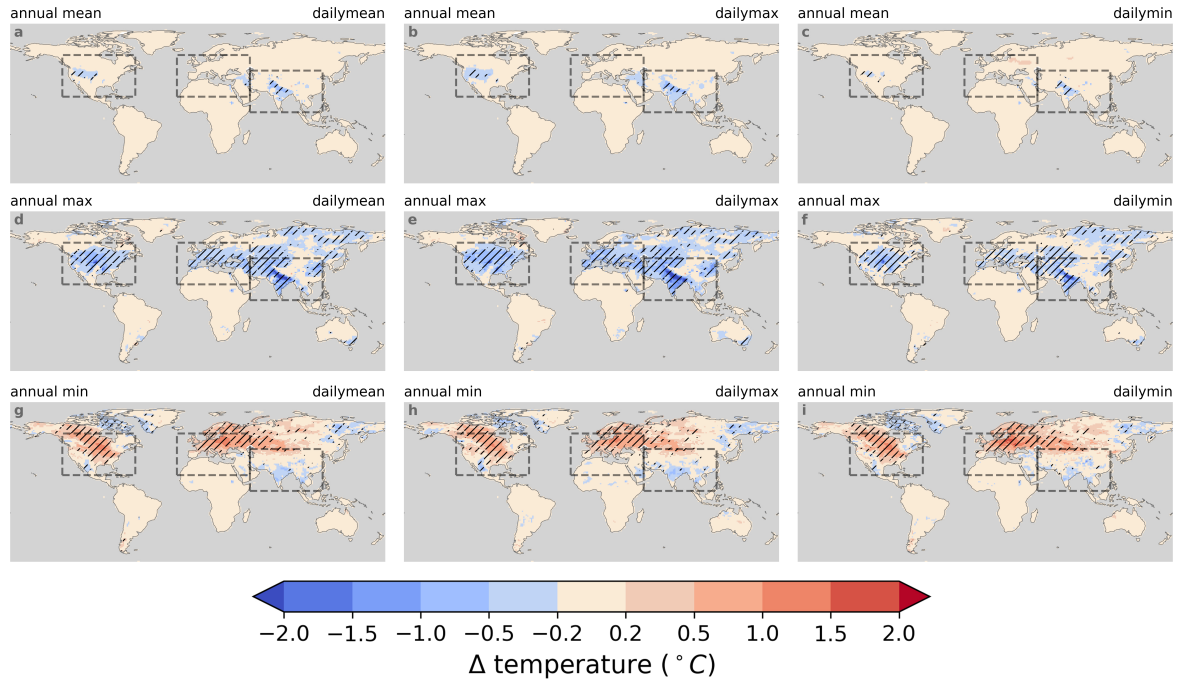


FIG 9: Impacts of irrigation expansion (IE) on the annual mean (**a**, **b**, **c**), annual maximum (**d**, **e**, **f**) and annual minimum (**a**, **d**, **g**) values of the daily mean (**a**, **d**, **g**), daily maximum (**b**, **e**, **h**), and daily minimum (**b**, **e**, **h**) 2-meter air temperature (T_{2m}). *This figure is adopted from Supplementary Figure A11.*

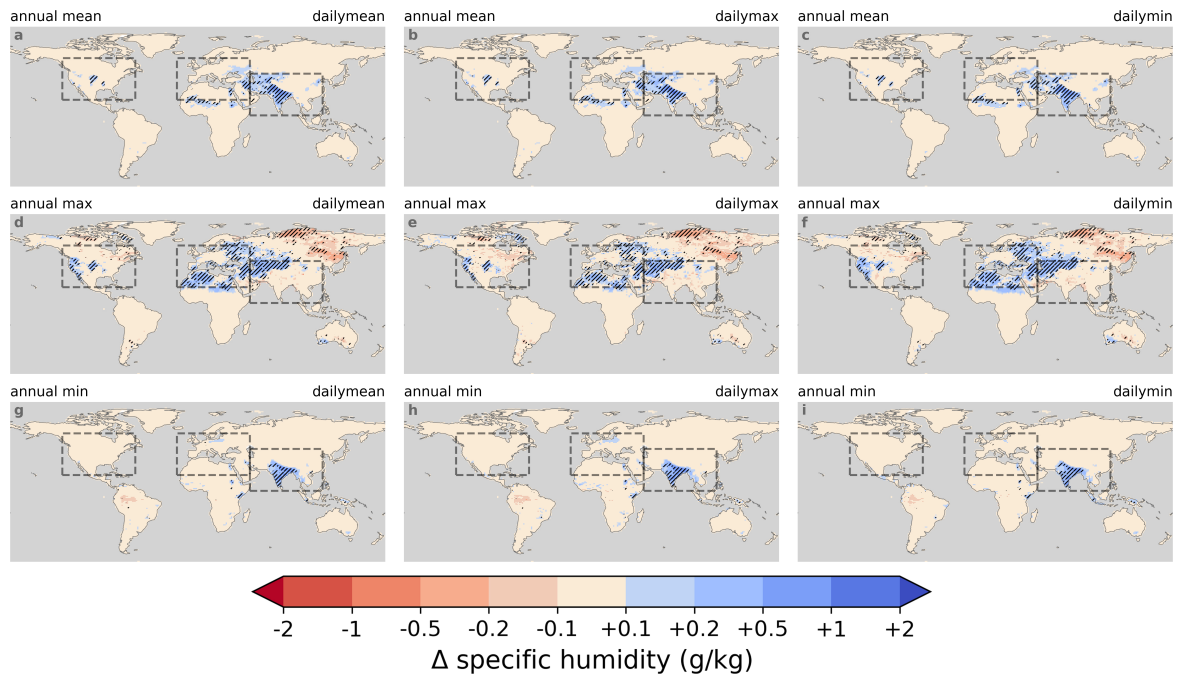


FIG 10: Same as FIG 9 but for specific humidity. *This figure is adopted from Supplementary Figure A12.*

Reviewer 2 Comment 5

Compared to the previous studies, one of the strengths of the current study is the calculation of multiple heat metrics with different algorithms, and it reveals the uncertainty when choosing different heat metrics to quantify the impacts of irrigation. The uncertainty among different heat metrics and the selection of heat metrics in specific locations for application (e.g., heat health alert and climate change impact assessment) is also a big concern for environmental health scientists and physiologists. To highlight this issue, increase the readership of current studies and facilitate communications between researchers in different fields. The authors could add more discussion on this point by referring to some environmental health studies. Some references are provided as follows: • Lo et al., Optimal heat stress metric for modelling heat-related mortality varies from country to country, International Journal of Climatology, 2023. • Guo et al., Regional variation in the role of humidity on city-level heat-related mortality, PNAS Nexus, 2024.

Response Thank you for the suggestion, we now added the following discussion:

L290-294

Furthermore, previous studies have assessed the suitability of various moist-heat metrics based on their correlation with local mortality datasets, and discovered that the optimal metric varies among countries and cities (9; 10). The range of moist-heat metrics presented here enables finely tailored investigation of irrigation's impacts on environmental health at local scales.

2.2 Minor comments

Reviewer 2 Comment 6

In line 70, the sentence "Evaporative cooling is the main way humans lose heat" is too strong. Evaporative cooling only works when the human body starts to sweat, and there are also other mechanisms for the human body to lose heat, such as convection heat exchange and radiation heat exchange.

Response

We changed our wording to:

L70

Evaporative cooling is one of the main ways humans lose heat.

Reviewer 2 Comment 7

Line 168, for "Consistent with a previous study using the Goddard Institute for Space Studies (GISS) climate model", please give the reference.

Response We have added the reference to Krakauer et al. (2020 ERL) (4).

Reviewer 2 Comment 8

Figure A8 is referred to in the main text before A6 and A7. Maybe their sequence number should be adjusted.

Response Thank you for the suggestion. We have updated the order of these figures in the Appendix.

Reviewer 2 Comment 9

Line 249, a strange “A5” here.

Response This is a typo, we wanted to refer to the Figure A5. This is now corrected:

L183-185

We also calculate irrigation expansion’s impacts on other moist-heat metrics ([Figure A5](#), description of metrics can be found in Supplementary Note 3).

Reviewer 2 Comment 10

Lines 337-342, is the calculation based on daily maximum temperature and minimum RH only applied for CNRM-CM6-1, or is it applied for all six ESMs? It should be made more clear here. Additionally, what wind speed value (daily mean or maximum?) is used when calculating APT using daily maximum temperature and minimum RH?

Response Thank you for pointing this out. We added the following clarification in the Method section:

L398-400

Other metrics described in Supplementary Note 3 are also calculated based on simulations by all six models, except that we do not calculate the apparent temperature from CNRM-CM6-1 outputs, given the lack of the appropriate wind speed variable.

Reviewer 2 Comment 11

There is no e in Figure A1, as the figure caption states.

Response Thanks for finding this mistake. We have corrected it.

Reviewer 2 Comment 12

In the caption of Figure 1, I assume the c-h represents the IWW for the tranirr simulations. It should be specified. In addition, in panel b of Figure 1, the median of the 1901irr simulations (red color) is so close to the minimum value (the lower boundary). What is the reason? Moreover, according to the caption “for the 1901irr experiment of IPSL-CM6, irrigation is switched off”, if the irrigation is switched off for IPSL-CM6, then why the lower boundary of the red color in panel b is not 0?

Response Thanks for pointing out the lack of clarification here. We have updated the caption of this figure.

a Global and regional time series of area equipped for irrigation (AEI) in 1901-2014. The area equipped for irrigation data is from the Land-Use Harmonization phase 2 (LUH2) project (11), and the grid cells corresponding to IPCC reference regions are indicated in Figure 2a. **b** Simulated mean global irrigation water withdrawal (IWW) with (blue: *tranirr*) by all six models and without (red: *1901irr*) irrigation expansion by five models (except IPSL-CM6). The line indicates the median value of six (or five) models and the range indicates the maximum and minimum values. Note that IWW of CNRM-CM6-1 is applied as an external input, which is the irrigation fluxes from a global reconstructed hydrological dataset based on simulations (12)., and for the *1901irr* experiment of IPSL-CM6, irrigation is switched off. **c-h** Global and regional IWW (with irrigation expansion) simulated by CESM2 (c), CESM2_gw (d), NorESM (e), E3SM (f), CNRM-CM6-1 (g) and IPSL-CM6 (h).

The reason for the median of the 1901irr simulations (red color) is so close to the minimum value (the lower boundary) and why the lower boundary of the red color in panel b is not 0 is that we only show the simulated IWW of five models here (IPSL-CM6 excluded).

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