Peer Review File

Manuscript Title: Increased heat risk in wet climate induced by urban humid heat

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

Review of “Increased Heat Risk in Wet Climate Induced by Urban Humid Heat”

The manuscript examines the role of urban heat island (UHI) and urban dry island (UDI) on wet bulb temperature over several urban areas considering the in-situ observations and CESM simulations using ERA5-Land hourly data as a boundary condition. The authors test the hypothesis that UDI can compensate for the adverse UHI health effect. In-situ observational data were obtained from 133 pairs of urban and rural weather stations. The authors report that the UHI effect is more substantial in a wetter climate. The higher Tw in the wet climate can lead to two-to-six extra dangerous heat stress days per summer. While I find the manuscript interesting, I have a few comments that the authors may like to address:

1. Coupling of air temperature and relative humidity plays a vital role in the variability of Tw during the day. I could not find any information if the in-situ observations of urban-rural pairs provide hourly data on temperature and humidity or not. This is important as daily average temperature, and humidity often do not give realistic estimates of Tw due to high temporal variability at a sub-daily time scale. Therefore, I would encourage authors to provide more information regarding the data.
2. Due to the strong coupling between temperature and humidity, the maximum Tw can occur at a different time in urban and rural areas. I am not sure if the authors examined the timing of the occurrence of maximum Tw using the in-situ observations/model simulations for urban and surrounding rural areas. There could be a significant difference in Tw because of the timing issue. Therefore, it would be better to resolve this.
3. Daytime UHI is complex, especially in irrigated regions (e.g., Kumar et al., 2017, Scientific Reports). UHI is more prominent during the night-time, as shown by the authors (Fig. 1 b,d). Therefore, UHI may play a more critical role in night-time heat stress than daytime, suggesting that the timing of maximum Tw during a day is essential to consider.
4. Authors have compared the differences in Tw and the contribution from UHI and UDI from in-situ data and model simulations. However, to fully ensure the reliability of model simulations, a comparison of diurnal temperature, humidity, and Tw for the urban-rural pairs of some representative locations for each climatic zones is required.
5. One could argue that the increment in modelled urban daytime Tw (0.17 deg C) could be compensated by the timing of maximum Tw in urban and rural areas. In this case, UHI during the day (when the highest heat stress occurs) may not significantly contribute to heat stress.

Referee #2 (Remarks to the Author):

The manuscript presents a very comprehensive analysis of the combined effect of urban heat and dry islands in modulating human heat stress. The study used both station data, after a very thorough quality control and a model to support the results. Overall, the results are of major importance for both understanding the impacts of the built environment on human heat stress, and planning mitigation interventions. The methods were clearly explained, and the results and discussion are very well written. My suggestion is for the paper to be published after the following minor clarifications have been provided.

Specific comments:

-The use of the we bulb temperature likely overestimates the "cooling" effect of urban dry islands. Wet bulb temperatures would be closely related to skin temperatures if there exists a not limiting supply of skin moisture for perspiration. Also, a difference in wind intensity inside and outside the city would further complicate the problem. I am not suggestion that the use of a wet bulb temperature is not a good proxy, but rather that this might be worth a discussion point.

-Lines 25-27. That would the case for thermal heat stress. The opposite would be true for cold stress. Worth clarifying the sentence.

-Lines 61-63. Regarding the tropics, where a distinct summer season does not exceed, can the authors confirm that the selected months always include the month with the highest wet bulb temperature for all cities?

-Line 178. This statement in not entirely true. Heat indices, such as the perceived environmental temperature and mean radiant temperature are based on thermodynamic principles.

-Regarding the use of the CESM model, I would like the following clarifications. What is the grid resolution of the model? To my understanding the difference for Tw derived from CESM was done using the sub grid values for the urban and rural tiles estimated by the land surface scheme (CLM) within CESM. I guess that within a grid point "lateral" heat and moisture transport between the rural and urban tiles are not included. If that is the case, could the authors include a discussion point on what the implications for that might be.

-In most city pairs, only a single pair of stations exist. However for a number of cities (e.g., Birmingham, Phoenix, Harrisburg etc.) multiple stations exist inside and outside the cities. Using those cities, it would be very useful if the authors could provide an estimate of the uncertainty of δT_w that might be related to the station location. E.g., using a bootstrap sampling of random pairs of stations for the cities where multiple stations exist and computing the expected uncertainty as e.g., the standard deviation of δT_w for those randomly chosen pairs.

-Finally, the authors compute the outdoor heat stress throughout this study. I expect that translation of this heat stress to health risks would be heavily dependent on access to air conditioning, which might be worth discussing, as heat risk would likely be most important for the most vulnerable cities with low access to A/C infrastructure.

Athanasios Paschalis

Referee #3 (Remarks to the Author):

Review for: "Increased Heat Risk in Wet Climate Induced by Urban Humid Heat"

The study examines how urban heat and urban dry islands (UHI, UDI) contribute to the urban wet-bulb island (ΔTw) as a measure of added moist heat stress in cities. Numerical simulations are performed for a large number of globally distributed cities to analyze the thermodynamic reasons for the formation of ΔTw. The topic is of high relevance; however, I have several concerns which should be addressed. Specifically, the study shows patterns of UHI opposite to existing literature without discussion of the mechanisms leading to these patterns. The study also shows stronger UDI in dry than wet climates, which is somewhat counterintuitive and I would also recommend further discussion of the mechanisms leading to this. I also have some doubts about the robustness of the model validation due to the small number of stations in dry and wet climates and the high variability of results within these groups.

Major comments:

L20 – 23: "The thermodynamic insights from our model calculation invite re-evaluation of the true benefit of vegetation as a strategy for urban climate adaptation." I do not see this demonstrated in detail in the manuscript, besides it being briefly mentioned in the discussion section and an unvalidated trial simulation with an urban ecohydrological model.

The introduction section needs significant improvement to highlight what are really the open questions which are answered in this study. Currently, the introduction focuses on technicalities (e.g. L42-L52) more suited for a limitations section but not as a general motivation of this study. Since, the main question is: can UDI offset UHI when it comes to heat stress in cities in different climates and the mechanistic explanation for the formation of ΔTw, the introduction should focus more on what are the common patterns of UHI and UDI globally and include literature focusing on the mechanisms leading to the formation of UHI/UDI, city effects on heat stress, vegetation effects on urban climate, etc.

L78-80, Fig. 1: I would recommend exploring the mechanisms which lead to a strong UDI in dry climates as this is somewhat counterintuitive. Converting pervious to impervious surfaces (e.g. urbanization) in wet climates could limit the moisture transport from surface to atmosphere if advection is limited and lead to the formation of UDI.

Figure 1 shows a larger UHI component in dry climates compared to wet climates, which is counter to what previous studies on surface UHI and air temperature UHI found (e.g. Zhao et al. 2014, Manoli et al. 2019, Chakraborty et al. 2022). I would recommend a more thorough explanation and comparison of this result to previous literature.

Figure 1: There are very few cities in the “wet” and “dry” category (17 and 15, respectively) compared to the intermediate category (101 cities). Due to the large variability and the limited number of cities in the “wet” and “dry” category, I currently doubt that these observations are sufficient as a robust validation of the model results. How sensitive are the results to the chosen precipitation groups? How sensitive are the average “wet” and “dry” results to random omission of cities from these classes? Would the results look different if the cities were grouped based on annual precipitation instead of summer precipitation?

L194-200: I do not see the additional value of these unvalidated simulations with the urban ecohydrological model, as they are currently presented in the manuscript. Generally, the discussion needs to be significantly improved considering the broader literature.

L268-270: What is the correlation of the amount of green space within the cities with its background climate (precipitation)? Does potentially higher green cover in wet cities explain the modelled urban moisture islands in these climates?

Minor comments:

L14-15: “…l, we show that the UDI effect is stronger than the UHI effect in dry climate (summer precipitation Ps < 180 mm) but the latter is stronger in wet climate (Ps > 570 mm).” I would recommend to be more specific: stronger in what?

L25 – L28: Provide references for these statements.

L75-76: negative Δe between “urban-rural” refers to an UDI, and positive Δe refers to an urban moisture island (UMI). This is clear in sentence L75-76, however, the terms “positive/negative contribution of UDIs” in later parts of the manuscript can be confusing. E.g. a positive contribution of UDI actually refers to a UMI.

L87 – 90: Due to the high number of simulation results, it is likely that you will get statistical significance even for small changes. However, in the observations you likely do not have a statistically significant result.

L98-108: This section is more suited for the methods section and not the results section.

L115: “During the daytime, dynamic mixing….” I would recommend: “During the daytime, changes in dynamic mixing between urban and rural sites…”

L128-130: The variation in the measurements is so large, that it is not clear if this pattern would stay, if one or two cities where omitted in the wet/dry group. Hence, I am not convinced that this is a robust pattern.

Fig. 3: Do not tilt Fig 3a and 1c. The result would be easier to read without the tilt.

L181-182: “We suggest that Tw may be more appropriate for cities in hot and humid climates than in dry or cold climates.” Provide additional reasoning for this.

L233-241: This paragraph can be simplified/shortened. If the authors wish to provide additional information regarding issues with meteorological stations in cities, this could be done in the supplementary material.

L274: How is the ERA5-Land hourly data upscaled to the blending-height for CESM?

L332-335: I am not sure the terms “offline” and “online” simulations are used in the correct way here. I understand a “offline simulation” as a simulation where the model is forced with a fixed meteorological forcing (i.e. without a mesoscale feedback of the land surface fluxes to the meteorological conditions at forcing height) and an “online simulation” as a simulation in which such feedback is included.

L336: I do not think this section is needed as a part of the main manuscript and could be moved into the supplementary material.

References:

Zhao, L., Lee, X., Smith, R. B. & Oleson, K. Strong contributions of local background climate to urban heat islands. Nature, 216–219 (2014).

Manoli, G. et al. Magnitude of urban heat islands largely explained by climate and population. Nature 573, 55–60 (2019).

Chakraborty, T., Venter, Z. S., Qian, Y., & Lee, X. (2022). Lower urban humidity moderates outdoor heat stress. AGU Advances, 3, e2022AV000729. https://doi.org/10.1029/2022AV000729

Author Rebuttals to Initial Comments:

Response to review 1

The manuscript examines the role of urban heat island (UHI) and urban dry island (UDI) on wet bulb temperature over several urban areas considering the in-situ observations and CESM simulations using ERA5-Land hourly data as a boundary condition. The authors test the hypothesis that UDI can compensate for the adverse UHI health effect. In-situ observational data were obtained from 133 pairs of urban and rural weather stations. The authors report that the UHI effect is more substantial in a wetter climate. The higher Tw in the wet climate can lead to two-to-six extra dangerous heat stress days per summer. While I find the manuscript interesting, I have a few comments that the authors may like to address:

1. Coupling of air temperature and relative humidity plays a vital role in the variability of Tw during the day. I could not find any information if the in-situ observations of urban-rural pairs provide hourly data on temperature and humidity or not. This is important as daily average temperature, and humidity often do not give realistic estimates of Tw due to high temporal variability at a sub-daily time scale. Therefore, I would encourage authors to provide more information regarding the data.

We fully agree with the reviewer on this point. That is the reason for why we used stations that provide hourly data instead those that only provide daily average values. We have described the data frequency in the Methods Section:

"First, the paired stations have simultaneous observations of both temperature and humidity at hourly or 3-hourly intervals for at least one summer during 2009 and 2019." [**L370**]

2. Due to the strong coupling between temperature and humidity, the maximum Tw can occur at a different time in urban and rural areas. I am not sure if the authors examined the timing of the occurrence of maximum Tw using the in-situ observations/model simulations for urban and surrounding rural areas. There could be a significant difference in Tw because of the timing issue. Therefore, it would be better to resolve this.

This is a good point. We have now examined the diurnal variations of urban and rural T_w from observational and model data. We find that the daily maximum T_w occurs at around the same time in both urban and rural areas. (Two examples of this comparison are given in **ED Fig. 6** below.)

3. Daytime UHI is complex, especially in irrigated regions (e.g., Kumar et al., 2017, Scientific Reports). UHI is more prominent during the night-time, as shown by the authors (Fig. 1 b,d). Therefore, UHI may play a more critical role in night-time heat stress than daytime, suggesting that the timing of maximum Tw during a day is essential to consider.

In response to this comment, we have added a new **ED Figure 8** and the following text to the Methods section:

"Cropland irrigation can influence urban-rural microclimatic gradients[45]. If moisture in the topsoil of the crop land unit falls below a pre-set threshold, irrigation water is added until soil moisture reaches field capacity. Timing of the daily peak Tw is not sensitive to irrigation. In grid cells in Northern India subject to irrigation, both urban and rural maximum Tw occur at around 13:00 to 14:00 local time" [**L423**]

The paper by Kumar et al. (2017) is now cited (ref 45).

In **Fig. R1**, we compare urban and rural T_w for grid cells in Northern India subject to irrigation. Irrigation does not change the timing of the maximum. Both urban and rural maximum T_w occur at around 1-2 pm local time.

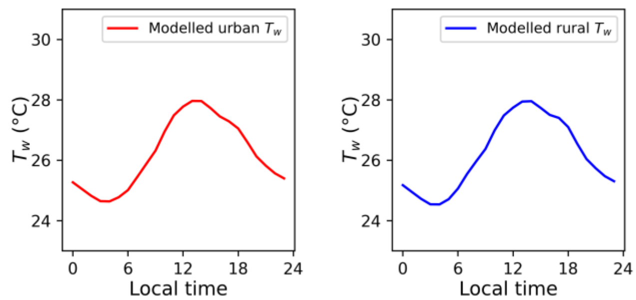


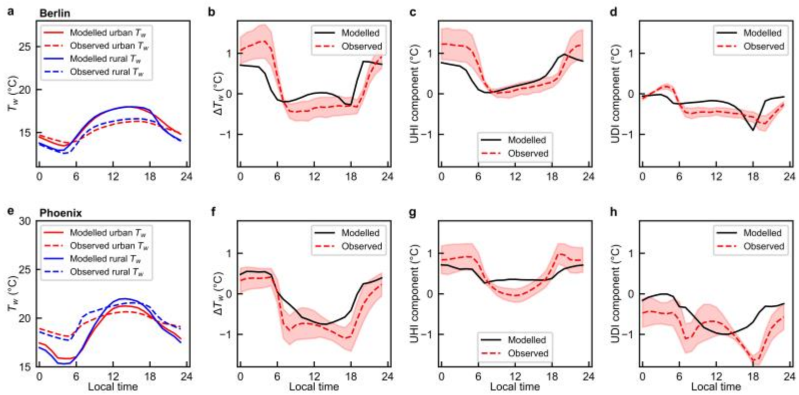
Fig. R1: Diurnal composites of urban and rural T_w for grid cells in Northern India subject to irrigation.

4. Authors have compared the differences in Tw and the contribution from UHI and UDI from in-situ data and model simulations. However, to fully ensure the reliability of model simulations, a comparison of diurnal temperature, humidity, and Tw for the urban-rural pairs of some representative locations for each climatic zone is required.

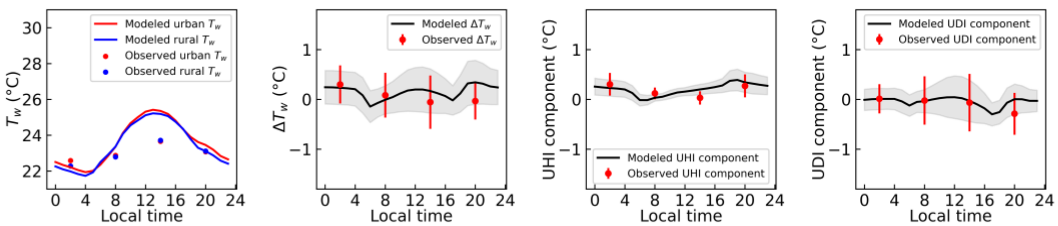
In response to this query, we have added two new ED Figures (ED Figs. 6 and 7) and the following text to the Methods Section:

"In Extended Data Fig. 6, we compare observed and modelled diurnal patterns of T_w, the urban wet-bulb island, and its UHI and UDI components for Berlin, Germany (in the intermediate climate zone) and Phoenix, USA (in the dry climate zone). We chose these two cities because there are multiple rural and urban stations. These station mesonets allow a total of 4 and 6 possible urban versus rural pairings for Berlin and Phoenix, respectively. The larger diurnal amplitude of the modelled T_w than that of the observed T_w is primarily caused by high amplitude biases of air temperature and humidity in the forcing data. Overall, the model has reproduced the observed diurnal patterns in urban-rural differences in T_w, air temperature and humidity.

In the wet climate zone, the observations are available only as one pair per city. Furthermore, observational hours vary among these sites. The most common observation hours are 2:00, 8:00, 14:00 and 20:00 local time. (Out of the 17 pairs, 11 have observations at these hours.) These are used for comparison with the model data (Extended Data Fig. 7). Both model and observational data indicate weak diurnal patterns in urban-rural differences in T_w, air temperature and humidity, which is consistent with the results shown in the main text (Fig. 1)" [**L439**]



ED Fig. 6: Comparison of observed and modelled diurnal patterns of wet-bulb temperature, the urban wet-bulb island, and its UHI and UDI components. a-d, Berlin; d-f, Phoenix. Red filled areas denote one standard deviation of all possible urban-rural combinations of site pairing.

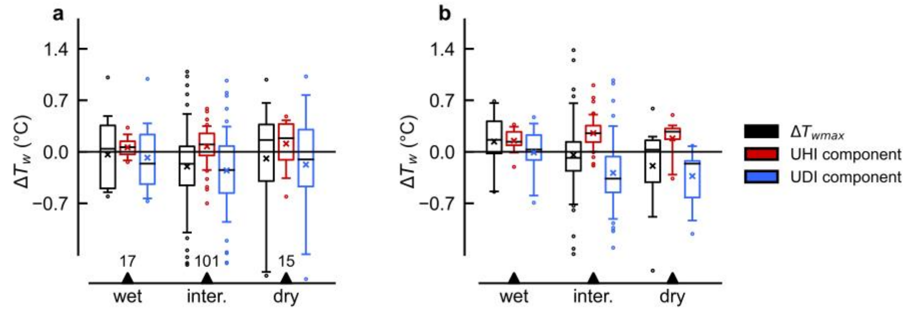


ED Fig. 7: Comparison of observed and modelled diurnal patterns of wet-bulb temperature, the urban wet-bulb island, and its UHI and UDI components in the wet climate zone. Gray areas denote one standard deviation of 11 model grids. Error bars denote one standard deviation of 11 site pairs.

5. One could argue that the increment in modelled urban daytime Tw (0.17 deg C) could be compensated by the timing of maximum Tw in urban and rural areas. In this case, UHI during the day (when the highest heat stress occurs) may not significantly contribute to heat stress.

In response, we have also calculated the wet-bulb island using the daily maximum T_w. The results (**new ED Fig. 8**) are nearly identical to those based on daytime mean values (Fig. 1 a & b).

"In some UHI studies, the UHI intensity is calculated as the difference in the daily maximum temperature between urban and rural land. To determine if the results in Fig. 1 are influenced by the timing of maximum T_w, we have calculated the urban wet-bulb island as the urban daily maximum T_w minus the rural daily maximum T_w. The results, given in Extended Data Fig. 8, are nearly identical to those based on daytime mean values (Fig. 1 a & b). For example, the mean modelled ΔT_w is 0.14 °C for the wet climate using this new procedure and that from Fig. 1b is 0.08 °C." **[L541]**



ED Fig. 8: Regional patterns of the urban wet-bulb island and its UHI and UDI components calculated from daily maximum T_w**.** a, observed; b, modelled. Box plots show the median (line), 25-75% range (box), 5-95% range (whiskers), and the mean value (cross).

Response to review 2

The manuscript presents a very comprehensive analysis of the combined effect of urban heat and dry islands in modulating human heat stress. The study used both station data, after a very thorough quality control and a model to support the results. Overall, the results are of major importance for both understanding the impacts of the built environment on human heat stress, and planning mitigation interventions. The methods were clearly explained, and the results and discussion are very well written. My suggestion is for the paper to be published after the following minor clarifications have been provided.

Thank you for your positive appraisal!

Specific comments:

-The use of the wet bulb temperature likely overestimates the “cooling” effect of urban dry islands. Wet bulb temperatures would be closely related to skin temperatures if there exists a not limiting supply of skin moisture for perspiration. Also, a difference in wind intensity inside and outside the city would further complicate the problem. I am not suggestion that the use of a wet bulb temperature is not a good proxy, but rather that this might be worth a discussion point.

We agree that assessment of thermal comfort is rather complex. The limitations of using wet-bulb temperature are now discussed.

“In the present study, T_w is used as the measure of humid heat stress which has equal weights on air temperature and humidity. Other heat stress indices weigh temperature more heavily than humidity (Extended Data Table 1). The urban heat stress will be stronger than our assessment if these indices are used. A condition implicit in the wet-bulb equation is that the human body is cloth-less, resting in the shade, and the skin is fully covered by sweat. We suggest that T_w may be more appropriate for cities in hot and humid climates, where the wet-bulb condition is more likely met, than in dry or cold climates. In the real world, heat stress is also influenced by other factors, such as wind speed, radiation and physical activities.” [**L517**]

-Lines 25-27. That would the case for thermal heat stress. The opposite would be true for cold stress. Worth clarifying the sentence.

This sentence has been changed to
“We argue that air temperature and air humidity are more likely to exceed dangerous heat stress thresholds in the daytime and during the summer than at night and during the winter.” [**L25**]

-Lines 61-63. Regarding the tropics, where a distinct summer season does not exceed, can the authors confirm that the selected months always include the month with the highest wet bulb temperature for all cities?

In response, we have added the following text to the Methods Section. The seasonality of low-latitude Tw, given in Fig. R2 below, indicates that on average, JJA and DJF are the hottest periods at low-latitudes (18 ^{o}S to 20 ^{o}N).

“The results presented here are for the summer season (JJA of the northern hemisphere and DJF of the southern hemisphere). For grids north of 20° N, the highest T_w always occurs in June, July, or August. For grids south of 18° S, the hottest month (month with the highest T_w) is always December, January, or February. The T_w seasonality is weaker in the tropics (between 18° S to 20° N) than at mid- to high latitudes. The hottest month can be March or April in some grid cells between 0° and 18° S and May or September in some grid cells between 0° and 20° N. On average, JJA in the Northern Hemisphere and DJF in the Southern Hemisphere are the hottest period of the year at these tropical latitudes.” **[L345]**

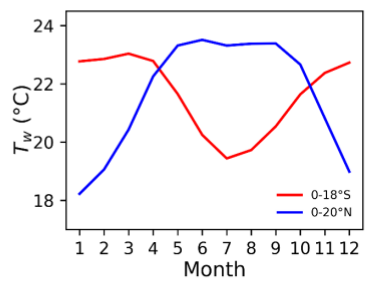


Fig. R2: Seasonal variations of T_w for grids within 0-18°S and 0-20°N.

-Line 178. This statement in not entirely true. Heat indices, such as the perceived environmental temperature and mean radiant temperature are based on thermodynamic principles.

We have removed this statement to avoid confusion. Thank you.

-Regarding the use of the CESM model, I would like the following clarifications. What is the grid resolution of the model? To my understanding the difference for Tw derived from CESM was done using the sub grid values for the urban and rural tiles estimated by the land surface scheme (CLM) within CESM. I guess that within a grid point “lateral” heat and moisture transport between the rural and urban tiles are not included. If that is the case, could the authors include a discussion point on what the implications for that might be.

We have described the grid resolution in the Method Section:

“The model simulation was forced by the ERA5-Land hourly data[46] at the finest spatial resolution (25 km) configured for CESM.” [**L429**]

The following text has been added:

“In this modelling framework, the urban wet-bulb island (ΔT_w) is the T_w difference between the urban and the rural (vegetated and crop) land units in the same grid cell. Because CLM5 does not consider the lateral heat and moisture transport between the rural and urban land units, the modelled urban-rural microclimate gradients may be biased high in magnitude for small cities.” [**L411**]

-In most city pairs, only a single pair of stations exist. However for a number of cities (e.g., Birmingham, Phoenix, Harrisburg etc.) multiple stations exist inside and outside the cities. Using those cities, it would be very useful if the authors could provide an estimate of the uncertainty of δT_w that might be related to the station location. E.g., using a bootstrap sampling of random pairs of stations for the cities where multiple stations exist and computing the expected uncertainty as e.g., the standard deviation of δT_w for those randomly chosen pairs.

This is an excellent suggestion. We have conducted a bootstrap analysis. The results are presented as (new) **Table 1**. The findings are summarized in the main text and in the Methods section:

"The urban wet-bulb island is a city-scale property. Because most of the observations were made with a single pair of stations, some of the variability in Fig. 1a & c is caused by the inability of a single urban station to capture intra-city variations of microclimate. By applying a bootstrap method to the few cities with multiple station pairs, we estimate that the measurement uncertainty of ΔT_w is 0.12 to 0.52 ^{o}C (95% confidence interval; Table 1.)" **[L93]**

"The UHI, the UDI and the wet-bulb island are city-wide properties. Because the observation in most cities was made with only one pair of sites, the observed ΔT_w is subject to uncertainty arising from intra-city variations in microclimate. In several cities, observations are available from multiple pairs of sites. These are used to estimate the measurement uncertainty. The standard deviation of ΔT_w is 0.27 ^{o}C for Berlin, Germany (4 possible urban-rural combinations of site pairing) and 0.30 ^{o}C for Phoenix, USA (6 combinations; Extended Data Fig. 6). By applying a bootstrap sampling to the cities with more than three site pairs and with the data reported for Guangzhou, China[20] (a city in the wet climate zone), we estimate that the measurement uncertainty of ΔT_w is 0.12 to 0.52 ^{o}C (95% confidence interval; Table 1). We added Guangzhou in this analysis because the wet cities in our own dataset are equipped with only one site pair per city. The reader should be aware that the Guangzhou data were collected in the autumn season (September to November), so the intra-city variability is only an approximation of summer conditions." **[L527]**

Table 1 | Uncertainties in the observed urban wet-bulb island (^{o}C) caused by intra-city microclimate variability. CI: 95% confidence interval; S.E.: standard error of bootstrap sampling.

City	Phoenix	Harrisburg	Birmingham	Guangzhou[20]
Climate zone	Dry	Inter.	Inter.	Wet
	Daytime			
CI	(-1.20, -0.68)	(-0.49, -0.12)	(-0.05, 0.07)	(0.39, 0.65)
S.E.	0.20	0.09	0.03	0.07
	Nighttime			
CI	(-0.19, 0.38)	(0.68, 1.00)	(0.50, 0.63)	(0.97, 1.22)
S.E.	0.19	0.09	0.03	0.07

Please also refer to **Reviewer 1 point 4** and our response regarding uncertainties associated with site paring.

-Finally, the authors compute the outdoor heat stress throughout this study. I expect that translation of this heat stress to health risks would be heavily dependent on access to air conditioning, which might be worth discussing, as heat risk would likely be most important for the most vulnerable cities with low access to A/C infrastructure.

This is actually an important motivation for this study. We have now highlighted this point in the Introduction.

"How the UDI interacts with the UHI has important health implications, especially in cities in the Global South. Some of these cities are home to informal settlements with low access to air conditioning infrastructure and highly vulnerable to temperature extremes…" [**L28**]

Because we are already at the length limit allowed by the journal, we are unable to add an extended discussion here.

Response to review 3

The study examines how urban heat and urban dry islands (UHI, UDI) contribute to the urban wet-bulb island (ΔTw) as a measure of added moist heat stress in cities. Numerical simulations are performed for a large number of globally distributed cities to analyze the thermodynamic reasons for the formation of ΔTw. The topic is of high relevance; however, I have several concerns which should be addressed. Specifically, the study shows patterns of UHI opposite to existing literature without discussion of the mechanisms leading to these patterns. The study also shows stronger UDI in dry than wet climates, which is somewhat counterintuitive and I would also recommend further discussion of the mechanisms leading to this. I also have some doubts about the robustness of the model validation due to the small number of stations in dry and wet climates and the high variability of results within these groups.

Major comments:

1. L20 – 23: "The thermodynamic insights from our model calculation invite re-evaluation of the true benefit of vegetation as a strategy for urban climate adaptation." I do not see this demonstrated in detail in the manuscript, besides it being briefly mentioned in the discussion section and an unvalidated trial simulation with an urban ecohydrological model.

This is an inference we have made from our diagnostic results. One paragraph is devoted to this point in the Discussion section. We hope that the reviewer agrees that this is a useful contribution to the debate in the literature about how to best use green infrastructure for climate adaptation. In this revision, we have modified this paragraph to improve clarity, with the addition of two relevant citations (references 30 and 32).

Revised paragraph:
"Our diagnostic result invites rethinking of vegetation as a strategy to reduce urban heat stress. Urban vegetation can reduce air temperature by promoting evaporation, increasing albedo, and changing heat storage[30]. Evaporation on its own does not play a role in the formation of the urban wet-bulb island since it merely converts sensible heat to latent heat, bringing no change to the total MSE. The cooling relief of vegetation to humid heat is likely achieved via other biophysical changes. Urban vegetation may be beneficial at night because diabatic heating via heat storage is the main contributor to the nighttime urban wet-bulb island (Fig. 2). In Seoul, South Korea, street trees at a fractional cover of 30% reduce the nighttime heat storage by about 15 W m^{-2} (ref 31), which amounts to a reduction of about 0.30 °C in Tw according to our diagnostic analysis. A less studied effect of urban vegetation is change to dynamic mixing. According to the data from urban microclimate model simulations[25,32], planting of street trees reduces air temperature but raises air humidity, with the overall result being increases in wet-bulb temperature. One reason is that in the model domain, the urban landscape becomes aerodynamically smoother with increasing tree cover[33]. Heat dissipation is controlled by thermal roughness, not by momentum roughness. Rigid structures such as buildings have much lower thermal roughness than flexible and porous plant foliage[34,35]. It is not known if the thermal roughness of a complex urban landscape consisting of built structures and street vegetation will behave in the same way as its momentum roughness." **[L184]**

We have deleted the data figure from the urban ecohydrological model (original ED Figure 5). We cite this modelling study because it is one of the few papers that report the effect of urban vegetation on both air temperature and air humidity. Another modelling study (reference 32) also shows that planting of street trees increases the urban wet-bulb temperature (**Fig. R3**).

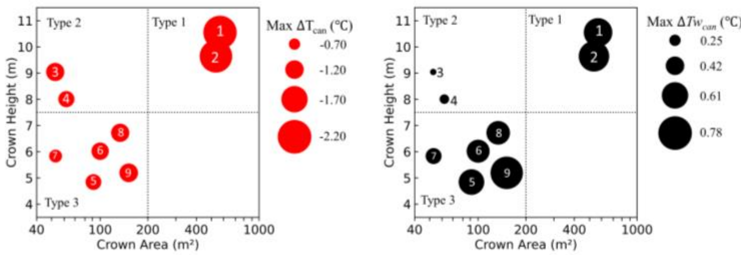


Fig. R3: Response of air temperature (left panel) and wet-bulb temperature (right panel) to planting of street trees in Hong Kong. Numbers stand for different tree species. Data source: ref 32.

2. The introduction section needs significant improvement to highlight what are really the open questions which are answered in this study. Currently, the introduction focuses on technicalities (e.g. L42-L52) more suited for a limitations section but not as a general motivation of this study. Since, the main question is: can UDI offset UHI when it comes to heat stress in cities in different climates and the mechanistic explanation for the formation of ΔTw, the introduction should focus more on what are the common patterns of UHI and UDI globally and include literature focusing on the mechanisms leading to the formation of UHI/UDI, city effects on heat stress, vegetation effects on urban climate, etc.

In response to this constructive comment, we have rewritten the Introduction Section. The paragraph on technicalities has been shortened and moved to the Methods Section [**L361**]. A new paragraph now provides a high-level assessment of the state of knowledge regarding UHI/UDI in humid climates at low latitudes. (Please note that we have been instructed by the Editor to limit this section to 500 words.)

New paragraph:
"Current knowledge of these urban microclimate effects is limited for high heat-stress regions in humid climates, such as South Asia, the Tropical Africa, and the Amazon Basin. Satellite data show that the daytime surface UHI (urban-rural difference in land surface temperature) is stronger in more humid climate[13,14]. One underlying mechanism is that cities in humid climates are less efficient in dissipating heat from the surface to the lower atmosphere than the surrounding rural land[13,15]. A working hypothesis is that the low convection efficiency of urban land should also enhance the daytime air UHI intensity (urban-rural difference in air temperature) in humid climates. Reduction in urban evaporation due to vegetation removal is a key mechanism of the UDI formation[3]. The UDI phenomenon has been observed in several mid-latitude cities[16–18] in background climates where evaporation is water-limited. But in low-latitude humid climate where evaporation is energy-limited, urban air may become more moist than the rural background[19,20]. It is not known if these local results can be extended to broader geographic regions." [**L38**]

3. L78-80, Fig. 1: I would recommend exploring the mechanisms which lead to a strong UDI in dry climates as this is somewhat counterintuitive. Converting pervious to impervious surfaces (e.g. urbanization) in wet climates could limit the moisture transport from surface to atmosphere if advection is limited and lead to the formation of UDI.

Thank you for this recommendation. In response, we have added a figure (new **Fig. 4**) and a subsection to the main text.

"**The urban dry island in wet and dry climates**

Both the observational and the modelling data show that the daytime UDI is stronger in the dry climate (that is, a more negative UDI component) than in the wet climate (Fig. 1a & b; Fig. 4). Although the above diagnostic analysis does not differentiate the UDI and the UHI components, a similar reasoning can be deployed to explain this UDI climate gradient. First, if a stronger dynamic mixing occurs over urban areas than over rural areas, water vapour released from the urban surface will dissipate faster to the upper boundary layer, leading to the UDI formation. In the modelling domain, mixing is indeed stronger for urban (mean daytime r_a = 14 s m^{-1}) than for rural areas (r_a = 18 s m^{-1}) in the dry climate. Second, reduction in the urban water vapour source due to removal of vegetation, which is akin to reduction in diabatic heating for T_w, is a known contributor to the UDI[3]. In addition, many cities in the dry climate are surrounded by irrigated cropland. Cropland irrigation humidifies the rural air via surface evaporation, further strengthening the UDI. We hypothesize that these changes in the surface vapour sources create a stronger UDI in the dry climate because surface evaporation is water-limited than in the wet climate where surface evaporation is energy-limited.

The occurrence of strong UDIs in the dry climate is somewhat counterintuitive because some greenspaces in arid cities are irrigated (e. g, urban lawns and parks in Salt Lake City, USA[37]). In our model domain, the irrigation option is activated for cropland but not for urban land. The urban weather stations we used are located in built-up neighborhoods (impervious surface fraction greater than 0.45, Methods), so the humidifying effect of urban greenspaces is minimal." [**L138**]

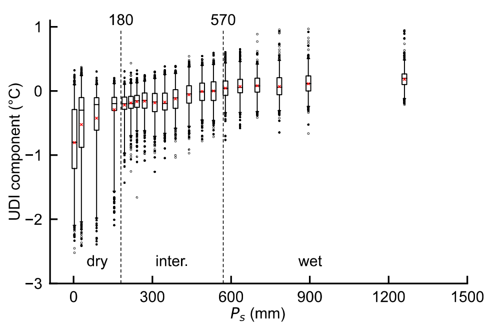


Fig. 4 | The modelled daytime UDI component is more negative (stronger UDI) with decreasing summer precipitation. Each data bin consists of 1819 grids. Box plots show the median (line), 25-75% range (box), 5-95% range (whiskers), and the mean value (cross).

We wish to point out that we are not the first to report UDIs for arid cities. For example, this phenomenon has been observed in Cairo, Egypt (Robaa 2013), Phoenix, USA (Saffell and Ellis 2002), Aksaray and Konya, Turkey (Çiçek and Türkoğlu 2009; Çiçek and Türkoğlu 2007) and Nicosia, Cyprus (Pyrgou et al., 2020). We also want to draw the reviewer's attention to **ED Fig 6h**, which shows a strong UDI observed in Phoenix, USA (**response to review 1, point 4**).

4. Figure 1 shows a larger UHI component in dry climates compared to wet climates, which is counter to what previous studies on surface UHI and air temperature UHI found (e.g. Zhao et al. 2014, Manoli et al. 2019, Chakraborty et al. 2022). I would recommend a more thorough explanation and comparison of this result to previous literature.

Once again, we are not the first to report the negative correlation between the air UHI and climate wetness. In response, we have added a paragraph in the Discussion Section.

"The results presented above offer partial support for the convection efficiency hypothesis. The daytime convection efficiency of urban land becomes lower than rural land in a wetter climate, so more MSE is trapped in the urban surface air, leading to a more positive ΔT_w (Fig. 1a & b, Extended Data Fig. 4a). But this hypothesis alone cannot fully explain the air UHI spatial pattern, which shows higher values in a drier climate in an opposite trend to ΔT_w. A negative correlation of the air UHI with climate wetness has been reported in ref 28 and is suggested by the air UHI dependence on latitude[29]." [**L176**]

Please also refer to point 2 above.

Zhao *et al.*, (2014) and Manoli *et al.*, (2019) are cited (refs 13 and 14). We omit the paper by Chakraborty et al. (2022) because their study has a limited geographic scope (western Europe).

5. Figure 1: There are very few cities in the "wet" and "dry" category (17 and 15, respectively) compared to the intermediate category (101 cities). Due to the large variability and the limited number of cities in the "wet" and "dry" category, I currently doubt that these observations are sufficient as a robust validation of the model results. How sensitive are the results to the chosen precipitation groups? How sensitive are the average "wet" and "dry" results to random omission of cities from these classes? Would the results look different if the cities were grouped based on annual precipitation instead of summer precipitation?

We agree that the small number of station pairs for the wet and dry climate is a limitation of this study. We hope that our work will spur more urban observations in these regions.

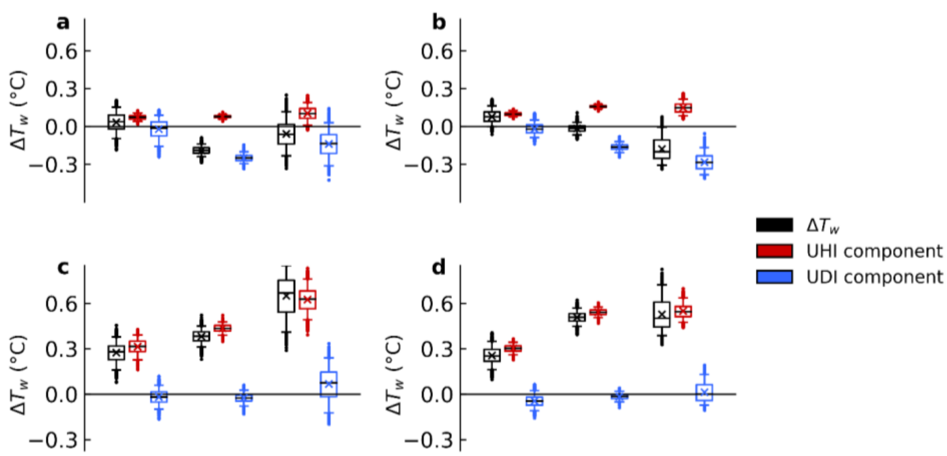
The precipitation thresholds were chosen so the three categories coincide with the Köppen climate classification:
"…these three regions roughly coincide with the tropical, dry, and temperate & boreal climate in the Köppen climate classification." [**L355**]

The focus of this study is summer heat stress. For this reason, we feel that summer precipitation is a more appropriate choice than annual precipitation for probing the mechanisms underlying the formation of the urban wet-bulb island.

In response this comment, we have added a section (Uncertainty Analysis) to Methods where we discuss measurement uncertainties associated with site representation and with intra-city microclimate variability (**response to review 2**). We have added a figure (**Extended Data Fig. 9**) and the following text regarding the ΔT_w sensitivity to precipitation thresholds and to random omission of cities.

"The small number of station pairs for the wet and the dry climate is a limitation of this study. To test the sensitivity to precipitation thresholds, we first changed the dry threshold by 40 mm from 180 mm to 140 mm and 220 mm. The observed dry-climate mean ΔT_w is -0.12 °C (daytime) and 0.48 °C (nighttime) with the 140 mm threshold and -0.04 °C (daytime) and 0.64 °C (nighttime) with the 220 mm threshold. The original dry-climate mean ΔT_w is -0.05 °C (daytime) and 0.65 °C (nighttime; Fig. 1a & c). Next, we adjusted the wet threshold by 40 mm from the original 570 mm to 530 mm and 610 mm. The observed wet-climate mean ΔT_w is -0.10 °C (daytime) and 0.19 °C (nighttime) with the 530 mm threshold and 0.02 °C (daytime) and 0.30 °C (nighttime) with the 610 mm threshold. The original wet-climate mean ΔT_w is 0.03 °C (daytime) and 0.28 °C (nighttime; Fig. 1a &c). These responses are small. The day-versus-night contrast and the climate wetness gradient are unaffected by these threshold changes.

To quantify the uncertainties of ΔT_w due to random omission of cities, we randomly sampled 75% of the site pairs in each of the three categories. This process was repeated 1000 times. The resulting statistics are given in Extended Data Fig. 9. In about 4/5 of the cases, the daytime mean ΔTw is positive in the wet region and negative in the dry region. At night, the mean ΔT_w is always positive. This sensitivity analysis suggests that we are likely to get statistically significant daytime results if more site pairs are available in the wet region." **[L549]**



ED Fig. 9: Statistics from random omission of site pairs. a, observed daytime; c, observed nighttime; b, modelled daytime; d, modelled nighttime ΔT_w and its components. Box plots show the median (line), 25-75% range (box), 5-95% range (whiskers), and the mean value (cross).

Additional details regarding the sensitivity to precipitation thresholds are given in Figs. R4 and R5 below.

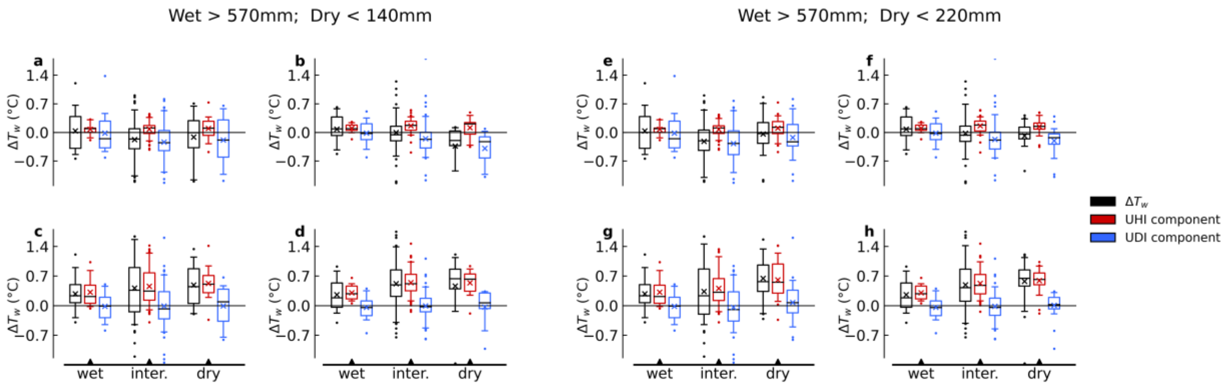


Fig. R4: Sensitivity of the urban wet-bulb island and its UHI and UDI component to dry-region precipitation threshold. a, e, observed daytime; c, g, observed nighttime; b, f modelled daytime; d, h, modelled nighttime ΔT_w.

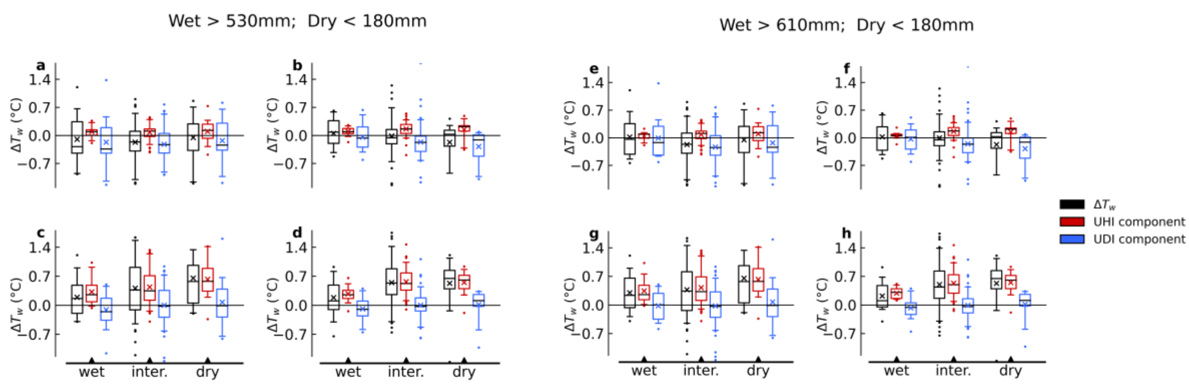


Fig. R5: Sensitivity of the urban wet-bulb island and its UHI and UDI component to wet-region precipitation threshold. a, e, observed daytime; c, g, observed nighttime; b, f modelled daytime; d, h, modelled nighttime ΔT_w and its components.

6. L194-200: I do not see the additional value of these unvalidated simulations with the urban ecohydrological model, as they are currently presented in the manuscript. Generally, the discussion needs to be significantly improved considering the broader literature.

Original ED Figure 5 is removed. Thank you. We have improved the discussion (e. g., **points 1, 3 & 4**).

7. L268-270: What is the correlation of the amount of green space within the cities with its background climate (precipitation)? Does potentially higher green cover in wet cities explain the modelled urban moisture islands in these climates?

The climate model assigns a fraction of the urban land to pervious soil cover (with the ability to evaporate water), but it does not treat urban greenspace explicitly. The modelled UDI component is not correlated with pervious land fraction in the city ($R^2 < 0.01$), but it is correlated with summer precipitation (new **Fig. 4**).

The correlation with precipitation leads to the following hypothesis:
"We hypothesize that these changes in the surface vapour sources create a stronger UDI in the dry climate because surface evaporation is water-limited than in the wet climate where surface evaporation is energy-limited." [**L150**]

Minor comments:

L14-15: "…l, we show that the UDI effect is stronger than the UHI effect in dry climate (summer precipitation Ps < 180 mm) but the latter is stronger in wet climate (Ps > 570 mm)." I would recommend to be more specific: stronger in what?

This sentence is changed to
"…we show that the UDI effect is more than enough to offset the UHI effect on heat stress in dry climate (summer precipitation $P_s < 180$ mm) but the UHI effect is stronger than the UDI effect in wet climate ($P_s > 570$ mm)" **[L13]**

L25 – L28: Provide references for these statements.
"Air temperature and air humidity are more likely to exceed dangerous health thresholds in the daytime and during the summer than at night and during the winter. The UDI can bring more cooling relief if it occurs during summer daylight hours."

This sentence expresses our own opinion. It is changed to:
"We argue that air temperature and air humidity are more likely to exceed dangerous heat stress thresholds in the daytime and during the summer than at night and during the winter..." [**L25**]

L75-76: negative Δe between "urban-rural" refers to an UDI, and positive Δe refers to an urban moisture island (UMI). This is clear in sentence L75-76, however, the terms "positive/negative contribution of UDIs" in later parts of the manuscript can be confusing. E.g. a positive contribution of UDI actually refers to a UMI.

We have changed the wording to improve clarity. Thank you.

L87 – 90: Due to the high number of simulation results, it is likely that you will get statistical significance even for small changes. However, in the observations you likely do not have a statistically significant result.

The reviewer is correct. The observational result for the wet climate is not significant from zero due to the large variability and the small number of site pairs, a point we have noted **[L87].**

Please refer to our reply to Comment 5. The random omission analysis suggests that we are likely to get statistically significant results if more site pairs are available in the wet region.

L98-108: This section is more suited for the methods section and not the results section.

This paragraph has been shortened. We include this brief method description here to help the readers navigate the contents. They can comprehend the results that follow, without the need to read the Methods Section first (which is not available in the print version of the journal).

L115: "During the daytime, dynamic mixing…." I would recommend: "During the daytime, changes in dynamic mixing between urban and rural sites…"

Revised.

L128-130: The variation in the measurements is so large, that it is not clear if this pattern would stay, if one or two cities where omitted in the wet/dry group. Hence, I am not convinced that this is a robust pattern.

We have softened the language here:
"The paired observations suggest that the urban web-bulb island may be dependent on climate wetness, …" [**L127**]

Fig. 3: Do not tilt Fig 3a and 1c. The result would be easier to read without the tilt.

Modified.

L181-182: "We suggest that Tw may be more appropriate for cities in hot and humid climates than in dry or cold climates." Provide additional reasoning for this.

We have expanded this part:
"…A condition implicit in the wet-bulb equation is that the human body is cloth-less, resting in the shade, and the skin is fully covered by sweat. We suggest that T_w may be more appropriate for cities in hot and humid climates, where the wet-bulb condition is more likely met, than in dry or cold climates…" [**L520**]

L233-241: This paragraph can be simplified/shortened. If the authors wish to provide additional information regarding issues with meteorological stations in cities, this could be done in the supplementary material.

We decide to keep this paragraph here so other groups can reproduce this methodology. The meta information on the chosen stations (original Extended Data Table 2) is now moved to supplementary data. Thank you.

L274: How is the ERA5-Land hourly data upscaled to the blending-height for CESM?

Bilinear interpolation was used to upscale the ERA5-Land hourly data to the blending height.

L332-335: I am not sure the terms “offline” and “online” simulations are used in the correct way here. I understand a “offline simulation” as a simulation where the model is forced with a fixed meteorological forcing (i.e. without a mesoscale feedback of the land surface fluxes to the meteorological conditions at forcing height) and an “online simulation” as a simulation in which such feedback is included.

We have replaced “online” and “offline” with “modelled” and “calculated”.

L336: I do not think this section is needed as a part of the main manuscript and could be moved into the supplementary material.

We feel that it is helpful to have this in the Methods Section, in part to respond to reviewer 2’s comments and also to make the point that other heat indices weigh temperature more heavily than humidity. Some readers may be interested in our quantification of the weighting factors.

We now cite this part in the main text:
“Other heat indices can also be expressed as a linear combination of the UHI and the UDI components (Methods)” [**L76**]

References:

Zhao, L., Lee, X., Smith, R. B. & Oleson, K. Strong contributions of local background climate to urban heat islands. Nature, 216–219 (2014).

Manoli, G. et al. Magnitude of urban heat islands largely explained by climate and population. Nature 573, 55–60 (2019).

Chakraborty, T., Venter, Z. S., Qian, Y., & Lee, X. (2022). Lower urban humidity moderates outdoor heat stress. AGU Advances, 3, e2022AV000729. https://doi.org/10.1029/2022AV000729

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Çiçek, Ihsan, and Necla Türkoğlu. 2007. "The Effects of urbanization on relative humidity and water vapor pressure in Konya." *Turkish Journal of Geographical Sciences* 5: 13–25.

Çiçek, Ihsan, and Necla Türkoğlu. 2009. "The effects of urbanization on water vapour pressure in a semi-arid climate." *Theoretical and Applied Climatology* 95: 125–34.

Gómez-Navarro, Carolina, Diane E. Pataki, Eric R. Pardyjak, and David R. Bowling. 2021. "Effects of vegetation on the spatial and temporal variation of microclimate in the urbanized Salt Lake Valley." *Agricultural and Forest Meteorology* 296: 108211.

Pyrgou, Andri, Panos Hadjinicolaou, and Mat Santamouris. 2020. "Urban-rural moisture contrast: regulator of the urban heat island and heatwaves' synergy over a Mediterranean city." *Environmental Research* 182: 109102.

Robaa, S M. 2013. "Urban-suburban/rural differences over Greater Cairo, Egypt." *Atmósfera*. 157-171

Saffell, Erinanne M, and Andrew W Ellis. 2002. "Urban-rural humidity variations in Phoenix, Arizona." *Journal of the Arizona-Nevada Academy of Science* 34: 53-62.

Reviewer Reports on the First Revision:

Referees' comments:

Referee #1 (Remarks to the Author):

Authors have done a wonderful job in addressing my comments. I have only one minor comment about the previous comment #1. The comment #1 was about the station-based observations not about the model simulations as mentioned by the authors in response. I think this has been addressed in the ED Fig. 6 and 7.

Vimal Mishra

Referee #2 (Remarks to the Author):

The authors have now fully addressed my comments.

I also believe that the authors have managed to address all the comments from all reviewers adequately, clarifying all aspects of the work

I think this is a great science contribution and looking forward to seeing it published.

Referee #4 (Remarks to the Author):

Review of "Increased Heat Risk in Wet Climate Induced by Urban Humid Heat" (manuscript number 2022-08-13336B).

The article is well written, and the results are novel and original. In particular, the focus on wet-bulb temperature, the partitioning of temperature and humidity effects, and the quantification of extra dangerous heat-stress days is a significant contribution with important implications for cities around the world. In my opinion, the manuscript still needs some improvements (see detailed comments below) but, overall, it is suitable for publication.

General Comments
1. I agree with referee 3 that the sentences on the benefit of urban vegetation (Lines 21-22 and 184) can be a bit misleading. The authors have added a nice discussion on the topic but, given the relevance of greening strategies in the climate adaptation debate, further clarifications are needed (or some rephrasing). Urban vegetation is not explicitly considered here (e.g. shading effects at pedestrian level are disregarded, there is no impact of urban vegetation on observed or simulated UHI/UDI as the focus is on highly impervious stations and the model has no urban vegetation component). Also, there are geographic differences in the effect/benefit of vegetation (as discussed

also by the authors). All these aspects deserve more careful consideration.
2. I think the abstract/introduction would benefit from some clarifications on wet-bulb temperature - how it is related to UHI/UDI and why it is considered a good indicator for heat stress. Also, some of the information provided in the Methods (e.g. Lines 522-524) would be useful in the main text to help the reader understand (upfront) the implications (and limitations) of this analysis.
3. Replying to a comment on the discrepancy between surface and air UHI trends with precipitation, the authors have included a few references and mentioned a “negative correlation of air UHI to climate wetness”. This, however, is in contrast with other results presented in the literature (e.g. Zhang et al. 2022). A more thorough explanation and comparison would be useful here.
4. Even if the impact of humidity on heat risk is widely acknowledged (e.g. Mora et al. 2017, Raymond et al. 2020), epidemiological studies do not show a significant effect of humidity on temperature-related mortality (e.g. Armstrong et al. 2019). Given that this is a central point here (e.g. lines 203-204), a discussion along this line might be beneficial.

Specific comments
Lines 25-26: this statement needs references or clarifications – canopy UHI is known to be highest at night (and often negligible during daytime).
Line 33: “threshold …”, it would be useful, for readers with different backgrounds, to clarify upfront how Tw is related to temperature and humidity.
Line 39: some references are needed here
Lines 43-45: any evidence to support this? In general, canopy UHI should decrease during daytime, even in humid climates (e.g. Mughal et al. 2020, Wang et al. 2016).
Lines 45-46: start a new paragraph here – or better connect the discussion on UHI with UDI.
Line 108: “Using … flux”, clarify where this is explained/shown (e.g. Methods?)
Line 113: “model data” or model results/simulations?
Lines 131-132 and 133: I guess this should be DeltaTw vs precipitation. Also, extended Fig. 4 is not showing a spatial covariance, right?
Lines 141-142: what do you mean by “the above diagnostic analysis does not differentiate the UHI and UDI components”? Isn’t this the aim of this analysis?
Fig. 5: DeltaN should be defined also in the text.

References
Armstrong, B., Sera, F., Vicedo-Cabrera, A. M., Abrutzky, R., Åström, D. O., Bell, M. L., ... & Gasparrini, A. (2019). The role of humidity in associations of high temperature with mortality: a multicountry, multicity study. Environmental health perspectives, 127(9), 097007.

Manoli, G., Fatichi, S., Schläpfer, M., Yu, K., Crowther, T. W., Meili, N., ... & Bou-Zeid, E. (2019). Magnitude of urban heat islands largely explained by climate and population. Nature, 573(7772), 55-60.

Mora, C., Dousset, B., Caldwell, I. R., Powell, F. E., Geronimo, R. C., Bielecki, C. R., ... & Trauernicht, C. (2017). Global risk of deadly heat. Nature climate change, 7(7), 501-506.

Mughal, M. O., Li, X. X., & Norford, L. K. (2020). Urban heat island mitigation in Singapore: Evaluation using WRF/multilayer urban canopy model and local climate zones. Urban Climate, 34, 100714.

Raymond, C., Matthews, T., & Horton, R. M. (2020). The emergence of heat and humidity too severe for human tolerance. Science Advances, 6(19), eaaw1838.

Wang, W., Zhou, W., Ng, E. Y. Y., & Xu, Y. (2016). Urban heat islands in Hong Kong: statistical modeling and trend detection. Natural Hazards, 83(2), 885-907.

Zhang, Z., Paschalis, A., Mijic, A., Meili, N., Manoli, G., van Reeuwijk, M., & Fatichi, S. (2022). A mechanistic assessment of urban heat island intensities and drivers across climates. Urban Climate, 44, 101215.

Author Rebuttals to First Revision:

Response to reviewer 4

The article is well written, and the results are novel and original. In particular, the focus on wet-bulb temperature, the partitioning of temperature and humidity effects, and the quantification of extra dangerous heat-stress days is a significant contribution with important implications for cities around the world. In my opinion, the manuscript still needs some improvements (see detailed comments below) but, overall, it is suitable for publication.

Thank you!

General Comments

1. I agree with referee 3 that the sentences on the benefit of urban vegetation (Lines 21-22 and 184) can be a bit misleading. The authors have added a nice discussion on the topic but, given the relevance of greening strategies in the climate adaptation debate, further clarifications are needed (or some rephrasing). Urban vegetation is not explicitly considered here (e.g. shading effects at pedestrian level are disregarded, there is no impact of urban vegetation on observed or simulated UHI/UDI as the focus is on highly impervious stations and the model has no urban vegetation component). Also, there are geographic differences in the effect/benefit of vegetation (as discussed also by the authors). All these aspects deserve more careful consideration.

In response to this concern, we have replaced the last sentence in Abstract (original L21-21) – "The thermodynamic insights from our model calculation invite re-evaluation of the true benefit of vegetation as a strategy for urban climate adaptation" – with the following (less controversial) statement:

"The risk of extreme humid heat is projected to increase in the future, and these urban effects may further amplify the risk." (**L18**)

The sentence in original L184 – "Our diagnostic result invites rethinking of vegetation as a strategy to reduce urban heat stress" – has been removed. We now state:

"Although our urban climate model does not explicitly consider urban vegetation, some inferences can be made from the above thermodynamic insights regarding the use of vegetation for adaptation to humid heat." (**L184**)

2. I think the abstract/introduction would benefit from some clarifications on wet-bulb temperature - how it is related to UHI/UDI and why it is considered a good indicator for heat stress. Also, some of the information provided in the Methods (e.g. Lines 522-524) would be useful in the main text to help the reader understand (upfront) the implications (and limitations) of this analysis.

We have added the following text near the end of the Introduction section:

"We use the wet-bulb temperature (T_w) to measure the combined effect of temperature and humidity on heat stress. Because it is the lowest temperature that can be achieved by evaporation of water in an air parcel, T_w is a good approximation of the skin temperature of a cloth-less and perspiring human body. This approximation may be more appropriate in hot and humid climates than in dry or cold climates.” (**L57**)

3. Replying to a comment on the discrepancy between surface and air UHI trends with precipitation, the authors have included a few references and mentioned a “negative correlation of air UHI to climate wetness”. This, however, is in contrast with other results presented in the literature (e.g. Zhang et al. 2022). A more thorough explanation and comparison would be useful here.

This is a good point. We now offer a more thorough discussion in relation to the published literature. Two references are added here (refs 13 and 32).

“…But this hypothesis alone cannot fully explain the air UHI spatial pattern, which shows higher values in a drier climate in an opposite trend to ΔTw (ED Fig. 2c). The relationship between the air UHI and precipitation is complex. A negative correlation of the air UHI with climate wetness has been reported in ref[30] and is suggested by the air UHI dependence on latitude[31]. Other authors have reported insignificant[13] or positive correlation[32]. The divergence among these studies is probably caused by large intracity variations in the observed air temperature or uncertainties related to model representation of rural irrigation.” (**L176**)

The paper by Zhang et al. (2022) is cited (ref 32).

4. Even if the impact of humidity on heat risk is widely acknowledged (e.g. Mora et al. 2017, Raymond et al. 2020), epidemiological studies do not show a significant effect of humidity on temperature-related mortality (e.g. Armstrong et al. 2019). Given that this is a central point here (e.g. lines 203-204), a discussion along this line might be beneficial.

Thank you for this suggestion. We now acknowledge this point:

“…The urban heat stress will be stronger than our assessment if these indices are used. Although a meta analysis of mortality data clearly demonstrates the importance of humidity[54], epidemiological studies generally do not show strong evidence for the humidity effect (e. g., ref[55]). In the real world, heat stress is also influenced by other factors, such as wind speed, radiation and physical activities. A condition implicit…” (**L529**)

The papers by Mora and Armstrong are now cited (refs 54 & 55).

Specific comments

Lines 25-26: this statement needs references or clarifications – canopy UHI is known to be highest at night (and often negligible during daytime).

Our data partially supports the reviewer’s statement (Fig. 1 and ED Fig. 2). However, because rural background temperature and humidity are lower at night than during the day, the nighttime UHI has little effect on the urban heat burden (Fig. 4).

We have changed this statement to:
“Air temperature and air humidity are more likely to exceed dangerous heat stress thresholds in the daytime and during the summer because of higher background temperature and humidity than at night and during the winter.” (**L23**)

Line 33: “threshold …”, it would be useful, for readers with different backgrounds, to clarify upfront how Tw is related to temperature and humidity.

We have added the information near the end of this section (**response to main point 2**).

Line 39: some references are needed here

We now cite two studies showing that these regions experience high heat stress (refs 11 and 12) and two other studies showing lack of UHI observations in these regions (refs 13,14) (**L36**).

Lines 43-45: any evidence to support this? In general, canopy UHI should decrease during daytime, even in humid climates (e.g. Mughal et al. 2020, Wang et al. 2016).

This is a working hypothesis we set out to test. In the Discussion section, we provide evidence both for and against it (**response to main point 3**).

Lines 45-46: start a new paragraph here – or better connect the discussion on UHI with UDI.

Done (new paragraph). Thank you.

Line 108: “Using … flux”, clarify where this is explained/shown (e.g. Methods?)

We now cite “equation 7, Methods” here (**L105**).

Line 113: “model data” or model results/simulations?

Changed.

Lines 131-132 and 133: I guess this should be DeltaTw vs precipitation. Also, extended Fig. 4 is not showing a spatial covariance, right?

We have switched to ΔTw versus precipitation as suggested. ED Figure 4 follows the method described in ref 15. We refer the result as spatial covariance, to be consistent with that study.

Lines 141-142: what do you mean by “the above diagnostic analysis does not differentiate the UHI and UDI components”? Isn’t this the aim of this analysis?

Our diagnostic framework works for MSE or Tw but it does not work for the components (either UHI or UDI). To improve clarity, we have changed this sentence to:

“Although the above diagnostic analysis cannot differentiate the UDI and the UHI components, a similar reasoning can be deployed to explain this UDI climate gradient.” (**L138**)

Fig. 5: DeltaN should be defined also in the text.

Done.