

Urbanization is projected to increase local surface temperature by 2100

Corresponding Author: Dr Xuecao Li

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

Version 0:

Decision Letter:

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Dear Dr Li,

Your manuscript titled "Urbanization Escalates Future Heat in 1km Global Land Surface Temperature Projections to 2100" has now been seen by 2 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. For the publication in Communications Earth & Environment, we request that you provide methodological and data details, associated uncertainty analysis, and an independent model validation.

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Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Mengze Li, PhD
Editorial Board Member

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This study aims to integrate background warming driven by climate change and localized warming induced by urbanization to project future urban land surface temperatures (LST). It presents a global 1 km resolution LST dataset spanning from 2020 to 2100, which could potentially support future studies on urban thermal environments. I see no fundamental methodological

issues, and the resulting dataset shows potential applicability. I recommend that the authors address the following points to improve clarity and completeness. Minor revision is suggested before acceptance.

Major comments:

1. The section “Estimating future LST considering urbanization-induced local warming effect” needs improvement to better clarify how climate change-induced global warming and urbanization-driven local warming were integrated in estimating future LST. Moreover, how were the interactions or potential non-linear effects between global warming and urbanization treated?
2. The authors suggest that the future slope of LST response to ISA approaches zero, indicating saturated urban expansion. Please clarify whether this convergence is derived from the model output or based on predefined assumptions. Are there empirical city-level cases supporting this trend?
3. Future warming may lead to an increased frequency of extreme heat events. Maybe consider adding a discussion on potential changes in future heatwaves to expand the applicability of this dataset for health and risk assessments.
4. In the ISA–LST relationship analysis, why were GADM level-2 administrative units chosen as the primary analysis unit instead of GUB-defined urban areas? Since some GADM level-2 administrative units can be very big in spatial coverage that they might cover different climate backgrounds, the response of LST to ISA in such a big area might vary a lot. And this may lead to a lot of noise and bad fitting performance.

Minor issues:

Line23: “its warming rates decreasing by 0.5–8% compared to the global rate across the four scenarios.” decrease

Line91: Fig.1 presents the distribution of 6,359 cities. What criteria were used for city selection?

Line125: “peak values” Not sure what you want to say here

Line146: “average”, maybe global average LST or average LST

Line147: “Earth’s surface”, please check whether it is “earth’s surface” or just “global territory”

Line161: “Fig.4 Urbanization-induced”, I suppose in Fig4 the dark purple points indicate an increase of 1°C instead of 0.1°C.

Line165: “Future slope of LST response to ISA change shows significant convergence, reflecting the plateaued global urban expansion.” Not sure, maybe rephrase a bit.

Line180: “cold regions, where LST stays below 10°C, the highest warming rates occur exceeding 170% under SSP3-7.0 and 240% under SSP5-8.5—owing to low initial temperatures, high climate sensitivity, ice-albedo feedback, Arctic amplification, and ecosystem vulnerability.” Just as mentioned by the authors, since these cold regions have rather low initial temperatures, comparing the increase rates might be confusing. For areas with an LST close to 0, you may get an extremely high growth rate with just a small magnitude of increase.

Line195: “Our study identifies several limitations that warrant attention in future research to enhance accuracy and scope.”

Maybe rephrase this.

Line198: “while our reliance on ISA as the indicator excludes factors such as building heights and green cover.” Please also note that, in addition to the size of ISA, the spatial configuration, i.e., the spatial pattern of impervious surface also has an impact on the LST.

Line255: “This GUB data represents upper limit of urban expansion.” Do you mean that the expansion of impervious surface does not extend beyond the GUB?

Line287: “then apply” then applied

Line306: “the standard deviations (SD) of most models align closely with observed values.” Not sure what this means. Comparing the magnitude of SD for what purpose?

Line369: “<http://data.ess.tsinghua.edu.cn>.” This link was changed a few years ago, please make changes accordingly.

Supplementary file Line73: “represents to” please remove “to”

Supplementary file Line86: The order of the panels in the caption is wrong.

Supplementary file Line65: Maybe add a color bar for the points of different colors on the map.

Reviewer #2 (Remarks to the Author):

This paper evaluates the effects from urbanization on the future warming, using CMIP6 projections and an empirical relationship between LST and ISA. The results are interesting, but I think the methodological framework needs to be improved and more uncertainty analysis are required before interpreting the results.

1. Although there present a separate methods section, I do think more details on how to project the urban LST should be mentioned in abstract and main text. Otherwise the readers can be confused when reading these parts.
2. The projection relies highly on the ISA and its relationship between LST, but no sensitivity or uncertainty analysis regarding this is provided. How do we know if the future ISA model is reliable? Whether an empirical linear function can describe the complex variability of LST in urban regions? What does a negative LST-ISA relationship mean and if this is even statistically/physically reasonable? Were the effects from other factors (e.g., climate change, socioeconomic conditions, population change, energy consumptions) teased out in our LST-ISA relationship analysis? Is a relationship established using data <20 years capably to be extended into the future?
3. Validation. The modeled LST is compared with MODIS LST, but note that the MODIS LST is in the equation to calculate the modeled LST, so this validation is not independent. Further, I don't understand Eq. 3 and Fig. S4. In Eq. 3, the input is MODIS 2020 LST, and ISA changes from 2003 to 2020, in this way, shouldn't the result be LST in 2003 rather than 2020? In Fig. S4, how to define pixels affected by urbanization-induced warming? 'Excluding those remained unchanged': unchanged in which period? It's impossible for temperature remain really unchanged, right? so I guess here you mean insignificant change (but how this is defined)? How could there be four MODIS LST observations, each for an SSP scenario? Is this comparison for some certain cities or across the globe? If it's across the globe, it's not a surprise that the correlation would be great as the temperature variability across climate regimes is so big.

4. Fig. 1a. Slope of LST and ISA: are those slope significant?
5. Line 96. 'Our estimated LST demonstrates strong spatial consistency with MODIS observations across historical and future periods'. How did you get future period observations?
6. Line 107-108. 'achieving an R2 greater than 0.9, confirming high consistency across both global and city scales'. See my comment 3. At global scales, the high R2 is expected. What does 'at city scales' mean? Is Fig. S4 plotted for some certain cities? If so, which cities?
7. 'but locally within cities, it amplifies warming by nearly 40 times'. '40 times' amplification is scary, did you calculate the ratio of slope? A minimal denominator (but is such small slope value significant?) will naturally give a huge ratio, but one should be cautious when interpreting such a ratio.
8. Line 166-168. 'Globally, these slopes trend toward zero as urbanization reach maturity in different cities at various stages, with ISA expansion eventually halting and the LST response gradually diminishing'. The change of slope trend depends highly on the ISA variability, but as I mentioned in Comment 2, is the modeled future ISA reliable? Further, from Fig. S7, in the start of your projection, the average slope is already near zero.
9. Line 286-287. 'Specifically, we categorized increment of ISA (Δ ISA) and corresponding LST (Δ LST) into 10% bins'. Not sure if I understand this, are those Δ ISA calculated for each year? If so, there should only be less than 20 points, how to categorize into each 10% bin?
10. More details on the data and methods (uncertainty analysis, significant test) are required. Additionally, the interpretation of the results need to be compared with previous studies.

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We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. In particular, for publication in Communications Earth & Environment, we request that you provide a thorough assessment and clarification on your methodology as requested by reviewer 2.

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Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Mengze Li, PhD
Editorial Board Member
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Martina Grecequet, PhD
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

I thank the authors for their effort in addressing my comments and for the discussion. I think the manuscript is suitable for publishing in its current form.

Reviewer #2 (Remarks to the Author):

The author addressed my comments carefully, which I appreciate a lot. However, I still have several concerns; the line number is in revised manuscript (marked).

1. Line 82-83: please show p-value here rather than R-values.
2. Line 204 'With then', do you mean 'Within'?
3. Line 206-207, please check grammar here
4. Line 209: so there are about a half of those cities where ISA and LST are not significantly correlated? Then in those cities, using the ISA-LST slope (which is insignificant) is not reasonable. I wonder how is your model performance at those cities?
5. Line 252-253, this sentence repeats previous sentence. Moreover, a higher relative warming rate does not mean a higher climate sensitivity or vulnerability. Climate sensitivity refers to how much the Earth's surface temperature will change in response to a change in radiative forcing. For vulnerability, in high-latitude cold region, 'warming' is not always a bad thing.
6. Methods. historical relationship between ISA and LST changes: I am still a little bit confused in this part. Like I previously commented, historical LST can be affected by so many factors, how did you tease out the impact from other factors? In your reply, you mentioned 'the socioeconomic and demographic conditions were considered in SSP scenarios' which I agree with, however, I think your LST-ISA slopes also include the effect from those socioeconomic and demographic conditions (if not, how did you tease out those effects)?
7. 'Using Δ ISA and Δ LST, rather than ISA and LST, allows us to more effectively isolate the impact of urbanization-induced warming, by minimizing the other influences such as background climate and topography.' I am confused here. Here your Δ LST is the difference of LST in year i compared with in starting year, right? How could this minimize other influences as the Δ LST (i.e., LST temporal change) should be an outcome of effects from urbanization and other factors like background climate?
8. 'While some cities exhibit a negative Δ ISA- Δ LST relationship, this is also reasonable as the per unit increase of ISA change (Δ ISA) results in the decline of per unit increase of LST change (Δ LST), suggesting the ISA driven warming effect becomes plateaued, not directly declines LST'. Maybe I misunderstood your method, shouldn't a negative slope denote a decline of LST (not a decline in LST increase) corresponding to an increase of ISA?
9. The English should be improved.

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Dear Dr Li,

Your manuscript titled "Urbanization Escalates Future Heat in 1km Global Land Surface Temperature Projections to 2100" has now been seen by our reviewer, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

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Best regards,

Mengze Li, PhD
Editorial Board Member
Communications Earth & Environment

Martina Grecequet, PhD
Senior Editor,

REVIEWERS' COMMENTS:

Reviewer #2 (Remarks to the Author):

The authors addressed my comments carefully, which I appreciate a lot. Please note that background climate also have temporal changes, so its impact on LST is not only the absolute values but also the trend/dynamics, as opposing to their reply to Comment 7.

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Reviewer1

Comment #1-0

This study aims to integrate background warming driven by climate change and localized warming induced by urbanization to project future urban land surface temperatures (LST). It presents a global 1 km resolution LST dataset spanning from 2020 to 2100, which could potentially support future studies on urban thermal environments. I see no fundamental methodological issues, and the resulting dataset shows potential applicability. I recommend that the authors address the following points to improve clarity and completeness. Minor revision is suggested before acceptance:

Response: thank you for your constructive comments, which are helpful to improve our manuscript. As recommended, we have carefully revised the relevant sections. A detailed point-by-point response is provided below.

Comment #1-1:

The section “Estimating future LST considering urbanization-induced local warming effect” needs improvement to better clarify how climate change-induced global warming and urbanization-driven local warming were integrated in estimating future LST. Moreover, how were the interactions or potential non-linear effects between global warming and urbanization treated?

Response: thank you for the valuable comment. In response to the first suggestion, we have thoroughly revised the section to more clearly articulate our approach to integrating global warming and urbanization-driven local warming in projecting future LST. Regarding the second suggestion, we did not explicitly account for potential interactions or nonlinear compounding effects between climate change–induced global warming and urbanization–driven local warming. Instead, we modeled their contributions additively, assuming that global warming and urbanization exert independent and cumulative influences on future LST. Capturing the complex interactions or nonlinear amplification effects between global and local warming processes would require sophisticated physical modeling (e.g., regional climate models or coupled urban climate simulations) and high-resolution input data on urban morphology, atmospheric feedbacks, and land–atmosphere energy exchanges, most of which are unavailable or inconsistent at a global scale. In future work, we plan to focus on specific urban regions and employ high-resolution regional climate models to better capture the nonlinear dynamics and potential interactions between urbanization and global warming, especially in rapidly developing or climate-sensitive regions. Accordingly, we revised our manuscript as below.

“Using dynamic regression models, we estimated future LST by incorporating urbanization’s local warming effect across four SSP-RCP scenarios. The dynamic regression model iteratively updated regression coefficients to estimate the local warming impacts. To establish a consistent starting point, we harmonized the difference between the observed LST from MODIS and the scenario-based modeled LST, mainly attributed to the discrepancy in observed and modeled ISAs (Eq. 3). This adjustment ensures that the baseline LST in 2020 aligns with the scenario-specific urban development trajectory. From this starting point, we projected LST forward at 5-year intervals (e.g., 2025, 2030), by adding the changed LST (i.e., urbanization induced-

warming effect (ΔLST) (Eq. 4). For example, the LST in 2025 is estimated by adding the urbanization induced-warming effect for 2025 (ΔLST_{2025}) (Eq. 5).” (Methods: Page 17, Line 384-394)

“In each iteration, the LST change in the next period (ΔLST_{t+1}) is determined by the current period's regressed slope ($Slope_t$) and the next period's ISA change (ΔISA_{t+1}) (Eq. 6). The regressed slope ($Slope_t$) itself is also dynamically updated using the ΔLST_t and ΔISA_t from the current period (Eq. 7). Similar as previous steps, we categorized ΔISA and corresponding ΔLST observations into 10% bins at each iteration to reduce variability. Fig. S16 illustrates the workflow of dynamic regression models.” (Methods: Page 18, Line 403-409)

“For improvement, future studies should incorporate additional urban environmental variables (e.g., building heights, vegetation), employ higher-resolution regional climate models, and focus on urbanization-induced localized extreme warming at finer scales^{5,25,26}. Addressing these gaps will refine urban thermal environment projections.” (Discussion: Page 13, Line 258-262)

Comment #1-2:

The authors suggest that the future slope of LST response to ISA approaches zero, indicating saturated urban expansion. Please clarify whether this convergence is derived from the model output or based on predefined assumptions. Are there empirical city-level cases supporting this trend?

Response: thank you. The observed convergence of the $\Delta LST - \Delta ISA$ slope toward zero is derived directly from our model outputs, rather than from any predefined assumptions. Specifically, in our modeling framework, the slope represents the relationship between ISA changes (ΔISA) and corresponding LST change (ΔLST). As future urban expansion slows down (i.e., ΔISA approaches zero), this naturally leads to a decreasing slope (Fig. S9). Furthermore, Fig. R1 presents the temporal trends of the ISA dataset used in our study, which clearly demonstrates that globally ISA growth slows down significantly and eventually plateaus. In addition, we illustrated the temporal convergence patterns of global cities in Supplementary Fig. S10, highlighting when ISA growth stabilizes across different regions.

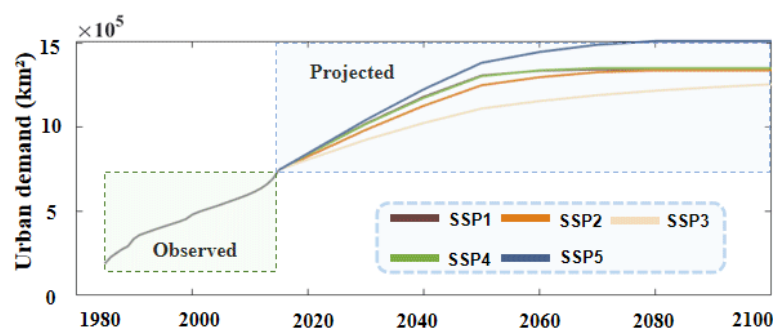


Fig. R1 Trend of global urban area dynamics (Source: He et al (2023)).

References:

1. He, W. et al. Global urban fractional changes at a 1 km resolution throughout 2100 under eight scenarios of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). *Earth System Science Data* **15**, 3623-3639 (2023).

Comment #1-3:

Future warming may lead to an increased frequency of extreme heat events. Maybe consider adding a discussion on potential changes in future heatwaves to expand the applicability of this dataset for health and risk assessments.

Response: thank you. We agree that projecting potential future heatwaves is an important extension of our dataset, particularly for public health and climate risk assessment. As suggested, we have now added a brief discussion on this point in the revised manuscript.

“This LST dataset with diverse scenarios not only supports targeted heat mitigation strategies and identification of vulnerable regions for climate-resilient urban planning, but also provide a valuable basis for estimating future air temperature and analyzing potential changes in heatwave events^{23,45}.” (Discussion: Page 13, Line 272-276)

Comment #1-4:

In the ISA–LST relationship analysis, why were GADM level-2 administrative units chosen as the primary analysis unit instead of GUB-defined urban areas? Since some GADM level-2 administrative units can be very big in spatial coverage that they might cover different climate backgrounds, the response of LST to ISA in such a big area might vary a lot. And this may lead to a lot of noise and bad fitting performance.

Response: thank you for your thoughtful comment. We chose GADM level-2 administrative units as the primary analysis unit for two main reasons. First, GADM level-2 units provide near-complete coverage of all global land surfaces, including both urban and non-urban areas (Fig.R2a). In contrast, GUB-defined urban areas only represent existing or projected urban extents (Fig.R2b). Since our analysis built upon the relationship between LST and ISA, and the urban extent (indicated as ISA) distributes within and beyond formal urban boundaries. Thus, relying on GUB only would result in incomplete ISA representation (Fig.R2b), particularly in peri-urban and their transitional zones. Second, GADM level-2 units are fine-scaled (e.g., counties in the United States or prefecture-level cities in China) (Fig.R2a), enabling to identify heterogenous climate zones within individual units.

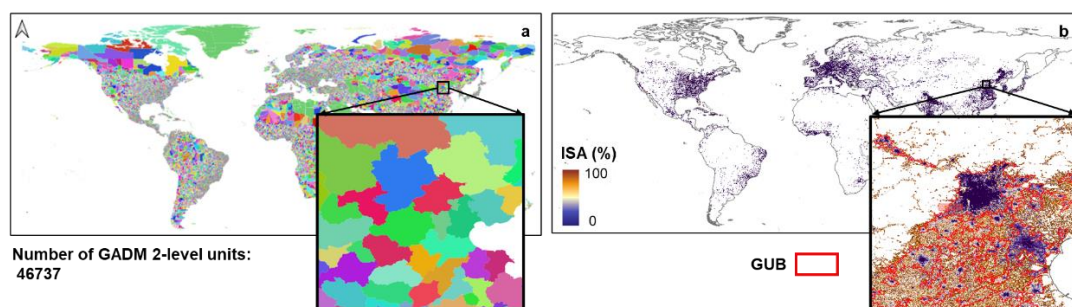


Fig. R2 Spatial patterns for GADM 2-level units (a) and the global ISA (b) distributions.

Comment #1-5:

Line23: “its warming rates decreasing by 0.5–8% compared to the global rate across the four scenarios.” decrease.

Response: done with revision.

Comment #1-6:

Line91: Fig.1 presents the distribution of 6,359 cities. What criteria were used for city selection?

Response: thank you. In our study, we modeled the Δ ISA– Δ LST relationship across over 46,090 GADM level-2 cities globally. However, it is difficult to visualize them simultaneously, therefore, we selected a representative subset of 6,359 cities with GUB areas larger than 100 km² in Fig. 1, to ensures sufficient spatial extent to present urban warming signals meanwhile maintaining the global representativeness. For clarity, we addressed this issue in our revised manuscript as follows.

“Fig.1. Strong linear relationship between Δ LST and Δ ISA. (a) Slope derived from historical observations. (b) The R-value of linearly fitted model. Note: For clarity and analytical robustness, 6,359 GADM level-2 units with urban areas larger than 100 km² are included here.” (Results: Page 5, Line 99-102)

Comment #1-7:

Line125: “peak values” Not sure what you want to say here.

Response: thank you. We have revised the sentence and present the estimated LST by 2100 under each scenario.

“For future projections, overall, the global average LST rises from 19.0°C in 2020 to 20.1°C (5%), 21.7°C (13%), 23.6°C (23%), 24.9°C (30%) by 2100 under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 scenarios, respectively.” (Results: Page 8, Line 134-137)

Comment #1-8:

Line146: “average”, maybe global average LST or average LST.

Response: thank you for pointing it out. For clarify, we rephrased it as below.

*“Globally, urbanization’s contribution to **average LST** appears weak due to urban areas covering only 1-2% of the Earth’s land surface (Fig. 2) ³².” (Results: Page 9, Line 156-158)*

Comment #1-9:

Line147: “Earth’s surface”, please check whether it is “earth’s surface” or just “global territory”.

Response: done as suggested.

*“Globally, urbanization’s contribution to average LST appears weak due to urban areas covering only 1-2% of the **Earth’s land surface** (Fig. 2) ³²” (Results: Page 9, Line 156-158)*

Comment #1-10:

Line161: “Fig.4 Urbanization-induced”, I suppose in Fig4 the dark purple points indicate an increase of 1°C instead of 0.1°C.

Response: thank you. We have corrected Fig. 4 and thoroughly checked all figures and tables.

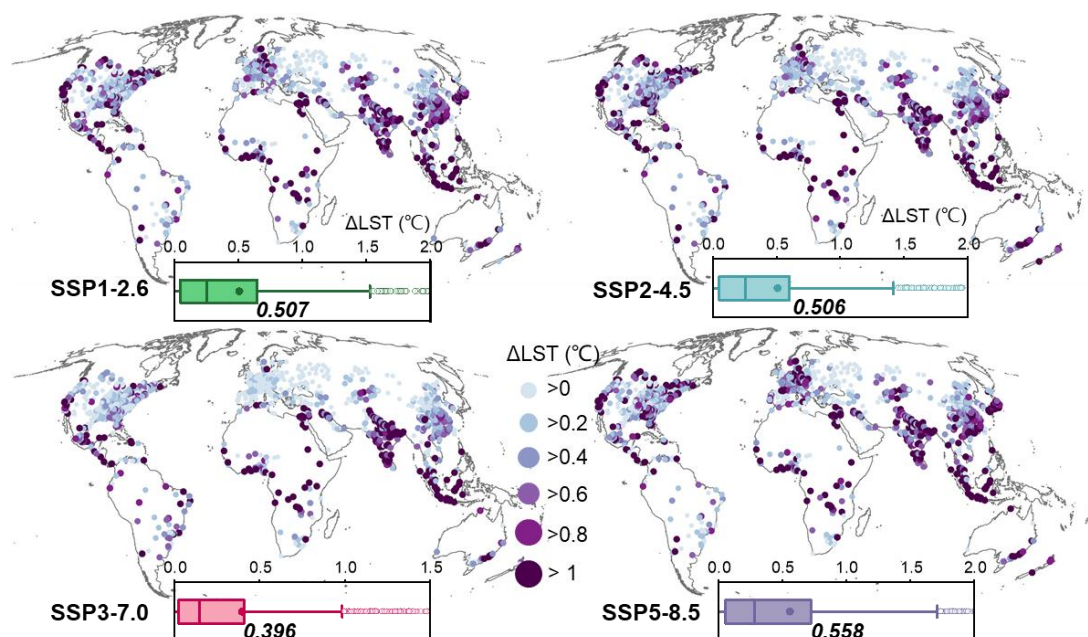


Fig. 4 Urbanization-induced extremely warming within urban areas in 2100 relative to 2020. In the box plot, the dots represent the mean values, while the horizontal line within each box indicates the median.

Comment #1-11:

Line165: “Future slope of LST response to ISA change shows significant convergence, reflecting the plateaued global urban expansion.” Not sure, maybe rephrase a bit.

Response: we are sorry about it. The slope of LST response to ISA change is projected to approach zero in many cities, which is in line with the slowing growth of ISA. For clarity, we have revised this sentence accordingly.

“Future slopes of LST response to ISA change would be convergence, reflecting reduced sensitivity of LST to urban expansion as ISA growth becomes plateaued.” (Discussion: Page 11, Line 210-211)

Comment #1-12:

Line180: “cold regions, where LST stays below 10°C, the highest warming rates occur exceeding 170% under SSP3-7.0 and 240% under SSP5-8.5—owing to low initial temperatures, high climate sensitivity, ice-albedo feedback, Arctic amplification, and ecosystem vulnerability.” Just as mentioned by the authors, since these cold regions have rather low initial temperatures, comparing the increase rates might be confusing. For areas with an LST close to 0, you may get an extremely high growth rate with just a small magnitude of increase.

Response: thank you for this comment. We agree that the term of “warming” can be misleading in cold regions with relatively low LST. For clarity, we revised this sentence as below.

“Notably, cold regions experience the greatest absolute warming, with average LST increases reaching 1–5 °C by 2100, slightly higher than those in other climate zones. However, due to the low baseline temperatures, the relative warming rates appear disproportionately large, exceeding 170% and 240% under SSP3-7.0 and SSP5-8.5, respectively, highlighting the noticeable climate sensitivity

and vulnerability in high-latitude ecosystems.” (Discussion: Page 12, Line 228-233)

Comment #1-13:

Line195: “Our study identifies several limitations that warrant attention in future research to enhance accuracy and scope.” Maybe rephrase this.

Response: done as suggested.

“Several limitations in this study deserve deepen consideration (i.e., data resolution, indicator selection, and model validation) in future work to enhance the robustness and applicability of urban temperature projections under future climate and urbanization scenarios.” (Discussion: Page 12, Line 249-252)

Comment #1-14:

Line198: “while our reliance on ISA as the indicator excludes factors such as building heights and green cover.” Please also note that, in addition to the size of ISA, the spatial configuration, i.e., the spatial pattern of impervious surface also has an impact on the LST.

Response: thank you. As suggested, we have modified the Discussion accordingly.

“Moreover, our reliance on ISA as the primary indicator indeed excludes other potential factors such as building heights, green cover and the spatial configuration of impervious surfaces.” (Discussion: Page 12, Line 254-256)

Comment #1-15:

Line255: “This GUB data represents upper limit of urban expansion.” Do you mean that the expansion of impervious surface does not extend beyond the GUB?

Response: sorry about it. The GUB data under the SSP5-8.5 scenario in 2100 represents an upper bound of future urban extent, allowing us to assess the maximum potential impactful regions of urban expansion on localized thermal environments and SUHI patterns. Although GUB defines the spatial extent of urban areas, it encompasses both high ISA (i.e., urban center) and low ISA (i.e., peri-urban within/beyond the GUB) simultaneously. For clarify, we have rephrased the sentence as below.

“Similarly, we incorporated GUB data across SSP5-8.5 scenario in 2100, representing a maximum impactful region of future urban growth, to delineate future urban areas and analyze localized LST and SUHI effects³².” (Data: Page 15, Line 316-318)

Comment #1-16:

Line287: “then apply” then applied.

Response: done as suggested.

Comment #1-17:

Line306: “the standard deviations (SD) of most models align closely with observed values.” Not sure what this means. Comparing the magnitude of SD for what purpose?

Response: thank you. The similarity in SD between model outputs and observations indicates the models can reasonably capture its spatial variability. For clarify, we revised this sentence as below.

“Moreover, the standard deviations (SD) of the MME and most models are close to observations,

206 *indicating that the spatial variability of LST is reasonably well captured.” (Methods: Page 17,*
207 *Line 376-378)*

208 **Comment #1-18:**

209 Line369: “[http://data.ess.tsinghua.edu.cn.](http://data.ess.tsinghua.edu.cn/)” This link was changed a few years ago,
210 please make changes accordingly.

211 **Response:** done with updated data sources as below.

212 *“The Gap-filled MODIS global daily land surface temperature dataset are available in*
213 *<https://doi.org/10.25380/iastate.c.5078492>. The GAIA and GUB dataset are collected at*
214 *<https://data-starcloud.pcl.ac.cn>. The future ISA dataset are derived from*
215 *<https://doi.org/10.6084/m9.figshare.20391117.v4>. The CMIP6 data are collected from [https://esgf-](https://esgf-node.llnl.gov/search/cmip6)*
216 *[node.llnl.gov/search/cmip6](https://esgf-node.llnl.gov/search/cmip6).” (Data availability: Page 19, Line 441-445)*

217 **Comment #1-19:**

218 Supplementary file Line73: “represents to” please remove “to”

219 **Response:** done as suggested.

220 **Comment #1-20:**

221 Supplementary file Line86: The order of the panels in the caption is wrong.

222 **Response:** done as suggested.

223 **Comment #1-21:**

224 Supplementary file Line65: Maybe add a color bar for the points of different colors on the map.

225 **Response:** done as suggested.

Reviewer 2

Comment #2-0

This paper evaluates the effects from urbanization on the future warming, using CMIP6 projections and an empirical relationship between LST and ISA. The results are interesting, but I think the methodological framework needs to be improved and more uncertainty analysis are required before interpreting the results.

Response: thank you for your constructive suggestions. In this revision, we have carefully addressed your concerns regarding the methodological framework and uncertainty analysis. Details can be referred to our point-by-point responses below.

Comment #2-1:

Although there present a separate methods section, I do think more details on how to project the urban LST should be mentioned in abstract and main text. Otherwise the readers can be confused when reading these parts.

Response: thank you. As suggested, we included descriptions about urban LST estimation in the abstract and the main text parts in our revised version.

“Here, we developed a 1km resolution global LST dataset (2020-2100, 5-year intervals), combining climate change-induced global warming and urbanization-driven local warming, which were estimated using CMIP 6 multi-model ensembled LST, and the dynamic regression model calibrated iteratively between the impervious surface area (ISA) and LST, respectively.” (Abstract: Page 2, Line 17-22)

“Next, we estimated urbanization-induced warming by establishing dynamic regression models between LST (from MODIS) and the impervious surface area (ISA). These models were iteratively updated and applied with inputs of estimated ISA in future to characterize the urbanization-induced warming effect.” (Main: Page 4, Line 61-65)

Comment #2-2:

The projection relies highly on the ISA and its relationship between LST, but no sensitivity or uncertainty analysis regarding this is provided. How do we know if the future ISA model is reliable? Whether an empirical linear function can describe the complex variability of LST in urban regions? What does a negative LST-ISA relationship mean and if this is even statistically/physically reasonable? Were the effects from other factors (e.g., climate change, socioeconomic conditions, population change, energy consumptions) teased out in our LST-ISA relationship analysis? Is a relationship established using data?

Response: we appreciate these insightful and critical comments. As suggested, we added a new section titled “*Uncertainty Analysis*” in our revised manuscript, addressing two key concerns regarding the input datasets and the employed model.

For the input datasets, the estimation of future ISA under diverse SSP-RCP scenarios serves as the main input for LST prediction. Specifically, the future ISA were estimated at the grid scale (1km) with a full consideration of historical parthways of satellite-derived urban extent time series (i.e., 1985-2015) and harmonzed future SSP-RCP scenarios (2020-2100) from Land

Use Harmonization (Version2) (Hurtt et al., 2011). Hence, the estimated future ISA is relatively reliable regarding its long-term evolution trajectory (with an overall R^2 of 0.9), meanwhile the RMSE of modeled ISA using the advanced cellular automata model is 0.08 averaged at the grid scale (He et al., 2023). It is worthy to note that here we cannot physically explicit quantify the effects from other factors (e.g., climate change and socioeconomic conditions) into the spatially explicit LST-ISA relationship due to data availability, particularly at a fine scale. Instead, they were considered in the estimated ISA under diverse SSP-RCP scenarios. For example, the socioeconomic and demographic conditions were considered in SSP scenarios, while the RCP scenarios account for future radiative forcing and greenhouse gas emissions. These factors were included in the employed LUH2 dataset, which were mainly derived from multiple Integrated Assessment Models.

Another concern is the uncertainty associated in the **LST estimation model**. Yes, we do admit that the proposed empirical linear relationship cannot completely characterize the variability of LST in urban regions. Even though, it is worthy to note that the calibrated LST-ISA model performs well across worldwide cities (i.e., around 60% of the cities exhibited distinct $\Delta ISA - \Delta LST$ correlations with R -values > 0.5 , and about half of them showed statistically significant relationships). As suggested, in this revision, we measured the uncertainty by calculating the 95% confidence interval of the regressed slope (Fig. S8a) and assessed statistical significance of models (Fig. S8b). Majority of cities (~61%) exhibit relatively low uncertainty, with slope ranges typically within 0–0.04 °C/%, more certain in China cities ranging from 0–0.01 °C/%. While for some cities that present a negative $\Delta ISA - \Delta LST$ relationship, it is also reasonable as the per unit increase of ISA change (ΔISA) results in the decline of per unit increase of LST change (ΔLST), suggesting the ISA driven warming effect becomes plateaued, not directly declines LST. Also, for some cities located in semi-arid regions, urban growth may coincide with cooling trends at a certain degree due to land cover transitions (e.g., from bare soil to green spaces), climate adaptation policies, or concurrent climate variability, which can contribute to such a negative relationship. Here, the proposed dynamic regression model can adaptively adjust the relationship between ISA and LST, depending on localized climate and background contexts, with considering of temporal contexts. We also analyzed the regressed slopes across different climate zones (Fig. SI). We acknowledged this uncertainty and discussed future perspectives on this issue in our revised manuscript.

“We evaluated the uncertainties in our estimated LST under future SSP-RCP scenarios from two main aspects. One is the uncertainties associated with the inputted ISA data in the future, while another is the employed LST estimation model. The ISA projections used in this study are relatively reliable as it shows good harmonization with long-term historical pathways (1985–2015) of city growth and future diverse SSP-RCP scenarios from the Land Use Harmonization (LUH2) dataset³³. Differ from other binary (i.e., urban and non-urban) urban extent scenarios data^{34,35}, here we used the 1km ISA fraction data that can well characterize the urbanization level at the grid scale, i.e., the modeled ISA data show a good agreement with historical urban extent time series data ($R^2 > 0.9$, $RMSE = 0.08$)³¹. Although other relevant factors such as climate policy, socioeconomic development, population growth, and energy consumption were not distinctly considered in our estimated LST, they were included with specific scenarios in the SSP-RCP scenarios. For instance, the socioeconomic and demographic conditions were

considered in SSP scenarios, while the RCP scenarios account for future radiative forcing and greenhouse gas emissions³⁶.

We further evaluated the uncertainties associated with the $\Delta ISA-\Delta LST$ relationship. With then 95% confidence intervals of derived slope (Fig. S8), we measured the uncertainty of the resulting LST with the increase of ISA. For most worldwide cities, the range of derived slope typically within 0–0.04 °C/% ISA increase, while China showing the smallest uncertainty (mostly 0–0.01 °C/%), suggesting the ISA induced warming is distinct (Fig.S8a). Results of statistical significance also indicate that approximately half of the cities showed statistically significant correlations ($p < 0.1$) (Fig.S8b), while around 60% demonstrated correlations with R -values > 0.5 (Fig. 1). It is worthy to note that although the linear assumption is simple, it can capture robust linkage between urban form and temperature across many cities. Despite that, we have to acknowledge that the $\Delta ISA-\Delta LST$ relationship may not be linear in certain regions, it is feasible and robust for implementation such a linear model at the global scale, across 46,090 GADM level-2 units with diverse urban environment^{13,30}. While this simplification may introduce uncertainty at a certain degree, it provides a scalable and explicable framework for global application. In the future, with incorporating of spatially explicit factors such as vegetation, albedo, and urban morphology, the interactions between urban form and LST can be further explored through a data mining approaches.” (Section: Uncertainty Analysis, Page 10-11, line 175-208).

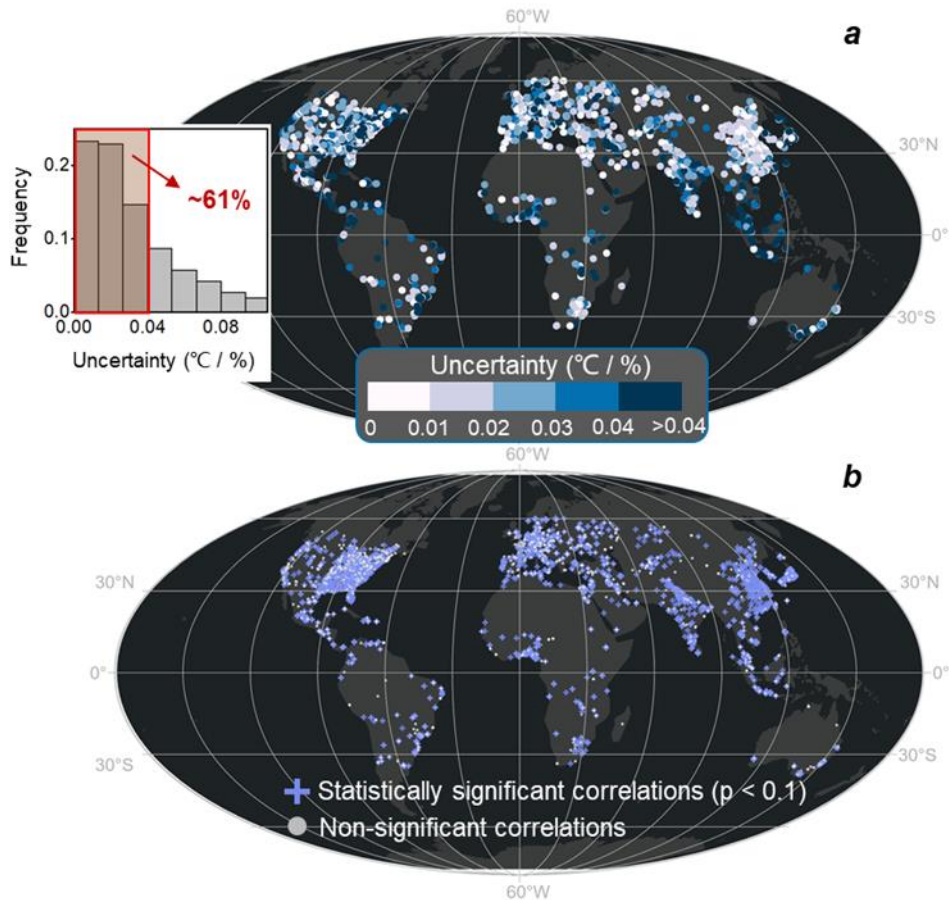


Fig. S8 Spatial uncertainty (a) and statistical significance (b) of the $\Delta ISA-\Delta LST$ relationship.

We also discussed the slope sensitivity across different climate zones, and explained the negative Δ ISA– Δ LST relationship in our revised manuscript.

“This climatic variation highlights the crucial role of environmental context in shaping urbanization’s thermal impact, reflecting the sensitivity of the Δ ISA– Δ LST relationship to different climatic zones” (Results: Page 5, Line 95-97)

“While some cities exhibit a negative Δ ISA– Δ LST relationship, this is also reasonable as the per unit increase of ISA change (Δ ISA) results in the decline of per unit increase of LST change (Δ LST), suggesting the ISA driven warming effect becomes plateaued, not directly declines LST (Fig. 1a).” (Results: Page 4, Line 73-77)

Reference:

1. Hurtt, G. C. et al. Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Climatic change* **109**, 117-161 (2011).
2. He, W. et al. Global urban fractional changes at a 1 km resolution throughout 2100 under eight scenarios of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). *Earth System Science Data* **15**, 3623-3639 (2023).

Comment #2-3:

Validation. The modeled LST is compared with MODIS LST, but note that the MODIS LST is in the equation to calculate the modeled LST, so this validation is not independent. Further, I don't understand Eq. 3 and Fig. S4. In Eq. 3, the input is MODIS 2020 LST, and ISA changes from 2003 to 2020, in this way, shouldn't the result be LST in 2003 rather than 2020? In Fig. S4, how to define pixels affected by urbanization-induced warming? 'Excluding those remained unchanged': unchanged in which period? It's impossible for temperature remain really unchanged, right? so I guess here you mean insignificant change (but how this is defined)? How could there be four MODIS LST observations, each for an SSP scenario? Is this comparison for some certain cities or across the globe? If it's across the globe, it's not a surprise that the correlation would be great as the temperature variability across climate regimes is so big.

Response: thank you for raising these questions. We have to admit that our previous statement may cause some confusions, and we have rephrase our descriptions with added details in this revision. First, we acknowledged that our validation is not independent, as the estimated LST in future was built upon remotely sensed MODIS LST results, with updates of ISA-induced LST changes. As such, our validation was done from two aspects: one is the historical Δ ISA– Δ LST relationship (Fig. 1b) and another is the 2020 modeled LST in 2020 accounting for ISA-induced changes under different scenarios (Fig. S4–S5), ensuring that our estimated future LSTs are harmonized with historical observations. For clarify, we have revised texts accordingly.

“Statistically, around 60% of these cities with R-values exceeding 0.5 (Fig. 1b), affirming the robustness of our historical linear regression models.” (Results: Page 4, Line 79-81)

“At global scale, the estimated LST under diverse SSP-RCP scenarios align well with observed LST from MODIS in 2020, achieving an R^2 greater than 0.9 (Fig. S4). While at the city scale, around 70% cities show R^2 values above 0.7, with typical cities highlighted such as Chicago (0.89), New Delhi (0.90), and Beijing (0.82) under the scenario of SSP1-2.6 (Fig. S5).” (Results:

Page 6, Line 115-119)

Second, while regarding the Eq. (3), we have rephased the associated explanation to improve clarity. We agree with your concern that the LST in 2003 plus the Δ LST estimated from Δ ISA equals the LST in 2020. Indeed, we implemented this validation and present our results in Fig. 1. Essentially, the Eq. (3) aims at harmonizing the difference between the observed LST from MODIS and the scenario-based modeled LST, mainly attributed to the discrepancy in observed and modeled ISAs. Given that Δ ISAs from the observations and scenarios share with the same starting point (i.e., ISA in 2003), thus the offset can be further simplified as the difference between modeled and observed ISA in 2020. The assumption behind Eq. (3) is that urbanization (i.e., indicated by ISA) contributes to the LST change, which was quantified using Eq. (1) at the city scale. To verify this assumption, we also did a comparison (Fig. S4-5) between observed and modeled LST (with scenarios). Accordingly, we rephrased Eq. (3) with updated symbols and explanations in our revised manuscript.

“To establish a consistent starting point, we harmonized the difference between the observed LST from MODIS and the scenario-based modeled LST, mainly attributed to the discrepancy in observed and modeled ISAs (Eq. 3). This adjustment ensures that the baseline LST in 2020 aligns with the scenario-specific urban development trajectory.” (Methods: Page 17, Line 387-391)

$$LST_{2020, \text{harmonized}} = LST_{2020} + Slope_{his} \times (ISA_{2020}^s - ISA_{2020}^o) \quad (3)$$
“ ISA_{2020}^s and ISA_{2020}^o represent the modeled ISA in 2020 under different SSP-RCP scenarios and observations from satellite, respectively.” (Methods: Page 18, Line 400-401)

Third, we apologized for the confusion raised in Fig. S4, in which the y-axis and x-axis indicate the scenario-based and observed LST in 2020, respectively. Each point in Fig. S4 represents the average LST within the urban domain ($GUB > 100 \text{ km}^2$), with a total of 1,979 records. Despite that, it is worthy to note that although the ISA in 2020 has become an observation now, the modelling of ISA with scenarios (i.e., at an interval of 5-years) actually started from 2015, because the employed GAIA data spans from 1985-2018 (He et al., 2023). Here we defined pixels affected by urbanization-induced warming as those associated with ISA change during 2003-2020, which directly related to the LST change. We further measured the agreement between the modeled and observed LST for those changed pixels in Fig. S4. The updated data description and figure captions are as below.

“Future ISA projections (2015–2100, per five-year) were generated using an S-shaped urban growth model combined with the Logistic-Trend-CA model, calibrated with historical trends (1985–2015) derived from GAIA data (1985–2018). Although the ISA for 2020 is observational now, our modeling starts in 2015 to align with the temporal interval of future scenarios and the temporal span of GAIA^{31,49}” (Data: Page 14, Line 297-302)

“Fig. S4 Comparison between modeled LST (with scenarios) and observed LST (from MODIS) in 2020 at the global scale. Note: each point represents the average LST value with a city ($GUB > 100 \text{ km}^2$), with a total of 1,979 units. When aggregating pixels to the city level, we excluded those without ISA changes.” (Supplementary Information: Page 5, Line 40-43)

Finally, as suggested, we implemented a city-scale validation across the globe, with typical

cities highlighted (i.e., Chicago, New Delhi, and Beijing) (Fig. S5). Overall, around 70% of cities reach good agreement with R^2 above 0.7, suggesting robust performance at the city scale. We also included this additional analyses in our revised manuscript.

“At global scale, the estimated LSTs under diverse SSP-RCP scenarios align well with observed LST from MODIS in 2020, achieving an R^2 greater than 0.9 (Fig. S4). At the city scale, around 70% cities show R^2 values above 0.7, with typical cities highlighted such as Chicago (0.89), New Delhi (0.90), and Beijing (0.82) under the scenario of SSP1-2.6 (Fig. S5).” (Results: Page 6, Line 115-119)

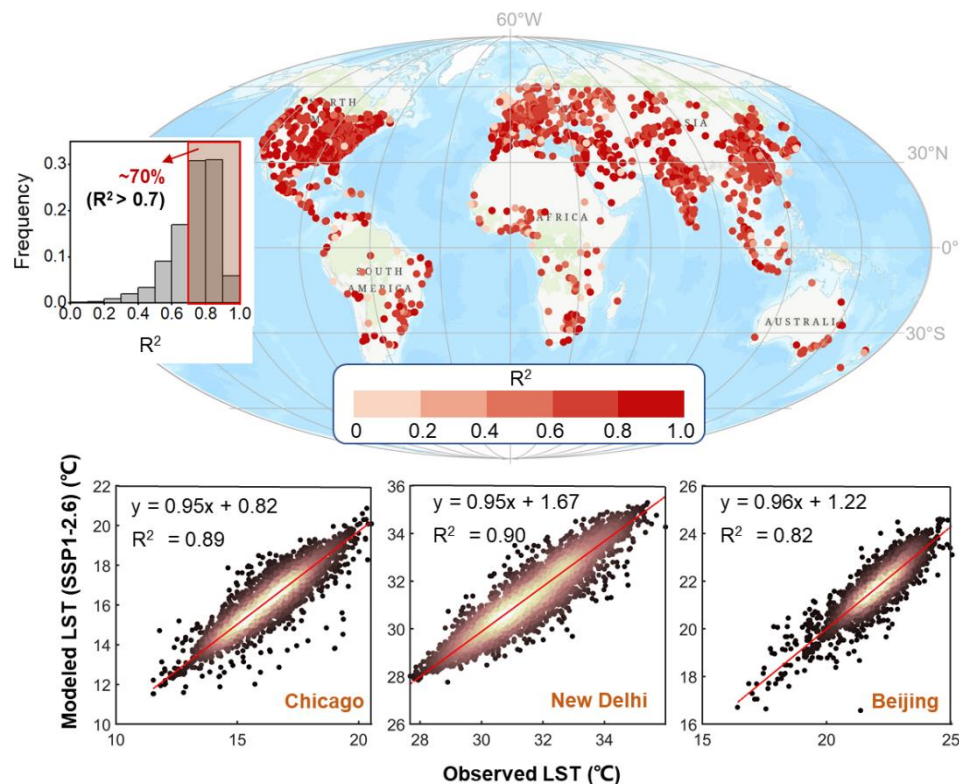


Fig. S5 Comparison between modeled LST (SSP1-2.6) and observed LST (from MODIS) in 2020 at the city scale. The filtering criteria of changed pixels are the same as Fig. S4.

Comment #2-4:

Fig. 1a. Slope of LST and ISA: are those slope significant?

Response: thank you. As suggested, we added the significance level (i.e., $\Delta LST - \Delta ISA$ relationship) in our revised manuscript (see Fig. S8b and our response to Comment #2-2). Also, we measured the uncertainty of the slope in added section of “*Uncertainties Analysis*”.

Comment #2-5:

Line 96. 'Our estimated LST demonstrates strong spatial consistency with MODIS observations across historical and future periods'. How did you get future period observations?

Response: we are sorry for this confusion. Essentially, we compared the observed LST (from MODIS) with estimated LST (SSP-RCP scenarios) in 2020. Although the ISA in 2020 has become an observation now, the modelling of ISA with scenarios (i.e., at an interval of 5-years)

actually started from 2015, because the employed GAIA data spans from 1985-2018 (He et al., 2023). As suggested, we rephrased this sentence as below.

“Future ISA projections (2015–2100, per five-year) were generated using an S-shaped urban growth model combined with the Logistic-Trend-CA model, calibrated with historical trends (1985–2015) derived from GAIA data (1985–2018). Although the ISA for 2020 is observational now, our modeling starts in 2015 to align with the temporal interval of future scenarios and the temporal span of GAIA^{31,49}.” (Data: Page 14, Line 298-303)

“Our estimated LST under diverse SSP-RCP scenarios show good spatial consistency with observed LST from MODIS during the historical period and retains this spatial pattern in future projections.” (Results: Page 6, Line 104-106)

Comment #2-6:

Line 107-108. 'achieving an R^2 greater than 0.9, confirming high consistency across both global and city scales'. See my comment 3. At global scales, the high R^2 is expected. What does 'at city scales' mean? Is Fig. S4 plotted for some certain cities? If so, which cities?

Response: thank you. As we explained in Comment #2-3, Fig. S4 was plotted for the globe, of which each point represents a city with urban area above 100 km² (in total 1,979). As suggested, we also included city-scale validation in our revised manuscript (Fig. S5). Below are changes in updated version.

“At global scale, the estimated LST under diverse SSP-RCP scenarios align well with observed LST from MODIS in 2020, achieving an R^2 greater than 0.9 (Fig. S4). While at the city scale, around 70% cities show R^2 values above 0.7, with typical cities highlighted such as Chicago (0.89), New Delhi (0.90), and Beijing (0.82) under the scenario of SSP1-2.6 (Fig. S5).” (Results: Page 6, Line 115-119)

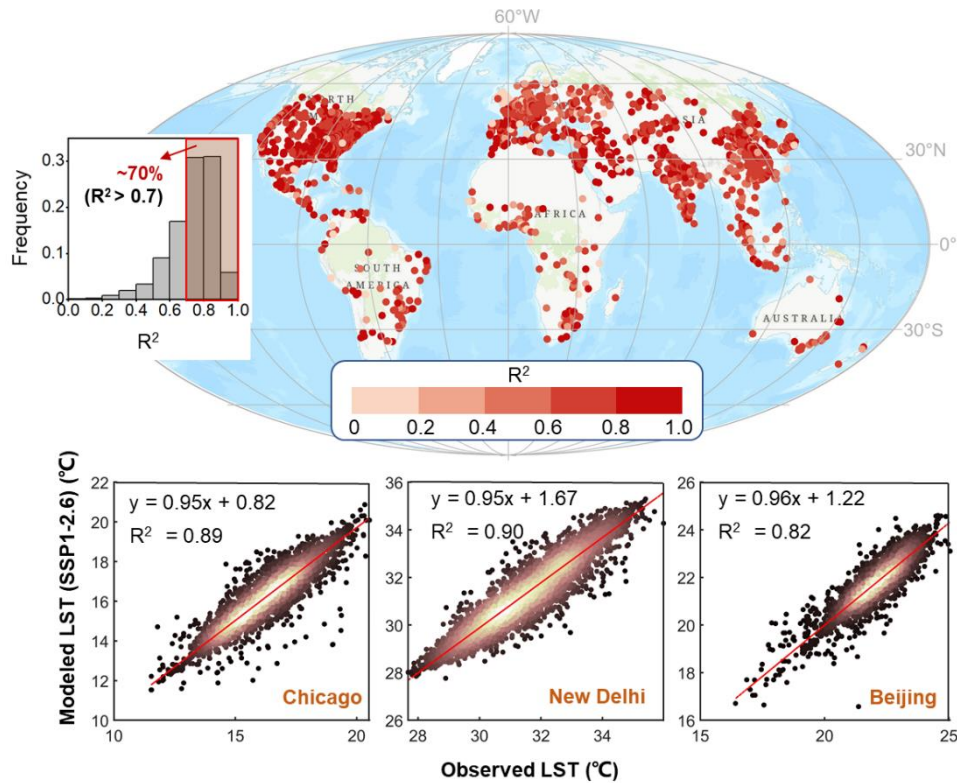


Fig. S5 Comparison between modeled LST (SSP1-2.6) and observed LST (from MODIS) in 2020 at the city scale. The filtering criteria of changed pixels are the same as Fig. S4.

Comment #2-7:

'but locally within cities, it amplifies warming by nearly 40 times'. '40 times' amplification is scary, did you calculate the ratio of slope? A minimal denominator (but is such small slope value significant?) will naturally give a huge ratio, but one should be cautious when interpreting such a ratio.

Response: thank you for pointing this out. We are sorry for this confusion. In fact, we initially intended to state that “the warming rate driven by urbanization within urban area (0.121-0.444°C/year) is, on average, about 40 times higher than the global mean (0.003-0.01°C/year)”. This is not a direct amplification based on slope ratios. For clarify, we have rephrased it in our revised manuscript.

“Regarding urbanization’s contribution, its impact on global LST remains minor (0.003-0.01°C/year) (Fig. S6a), but locally within cities, urbanization can substantially intensify warming (0.121-0.444°C/year) (Fig. S6b), with growth plateauing after 2060 in aligns with the ISA expansion ³¹.” (Results: Page 8, Line 143-146)

Comment #2-8:

Line 166-168. 'Globally, these slopes trend toward zero as urbanization reach maturity in different cities at various stages, with ISA expansion eventually halting and the LST response gradually diminishing'. The change of slope trend depends highly on the ISA variability, but as I mentioned in Comment 2, is the modeled future ISA reliable? Further, from Fig. S7, in the start of your projection, the average slope is already near zero.

Response: thank you for valuable suggestions. Regarding the reliability of modeled ISA, we provided detailed explanations in our response to Comment #2-2, with added results in revised manuscript. The estimated future ISA is relatively reliable regarding its long-term evolution trajectory (with an overall R^2 of 0.9), meanwhile the RMSE of modeled ISA is 0.08 averaged at the grid scale (He et al., 2023). We also have added a brief evaluation of ISA projection in the Data section in this revision.

“The modeled ISA data show a good agreement with historical urban extent time series data ($R^2 > 0.9$, $RMSE = 0.08$)³¹.” (Uncertainty Analysis: Page 10, Line 184-185)

While regarding the Fig. S7, it is worthy to note that here we used ΔISA and ΔLST for model development rather than ISA and LST values. The reason behind this selection is to quantify the magnitude of urbanization-induced warming (i.e., temperature change per unit increases in impervious surface), not the absolute temperature. With the urbanization processing going on, the slope tends to be smaller (e.g., even to zero), reflecting the ISA-induced warming efficiency becomes plateaued during the maturity stage of urbanization (Li et al., 2017), which was characterized in our dynamic regression model (Fig. S9). Despite the mean slope in 2025 is close to zero, it is worthy to note that more than 40,000 GADM units were plotted together, of which many of them either have very limited urban extents or not distinct growth over past decades. As suggested, we explained this issue with included methodological details in our revised manuscript.

“Using ΔISA and ΔLST , rather than ISA and LST, allows us to more effectively isolate the impact of urbanization-induced warming, by minimizing the other influences such as background climate and topography.” (Methods: Page 16, Line 353-355)

Reference:

1. He, W. et al. Global urban fractional changes at a 1 km resolution throughout 2100 under eight scenarios of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). *Earth System Science Data* **15**, 3623-3639 (2023).
2. Li, X., Zhou, Y., Asrar, G. R., Imhoff, M. & Li, X. The surface urban heat island response to urban expansion: A panel analysis for the conterminous United States. *Science of the Total Environment* **605**, 426-435 (2017).

Comment #2-9:

Line 286-287. 'Specifically, we categorized increment of ISA (ΔISA) and corresponding LST (ΔLST) into 10% bins'. Not sure if I understand this, are those ΔISA calculated for each year? If so, there should only be less than 20 points, how to categorize into each 10% bin?

Response: sorry for this confusion. The ΔISA and ΔLST are not calculated annually, instead, they represent the change between 2003 and 2020. To reduce noise, we grouped all pixels within each unit into 10% quantile bins based on their ΔISA values (Li et al., 2018; Shi et al., 2023). Within each bin, we computed the mean ΔISA and corresponding mean ΔLST for model development. For clarity, we revised the text accordingly in our manuscript as below.

“To quantify urbanization-induced warming, we first established a historical relationship between changes in ISA and LST over the period 2003–2020. For each GADM level-2 unit, we analyzed LST responses to ISA changes at the pixel level. This analysis covered 46,090 of 46,737 global administrative units, ensuring nearly complete global representation.

Specifically, we grouped both the ISA change (ΔISA) and the corresponding LST change (ΔLST) into 10% quantile bins at the pixel-level in each unit^{30,52}. Using these binned data, we applied the ordinary least squares regression to determine the linear relationship between ΔISA and ΔLST (i.e., the slope) as defined in Eq. (1)³⁰.” (Methods: Page 16, Line 345-353)

Reference:

1. Li, H. et al. A new method to quantify surface urban heat island intensity. *Science of the total environment* **624**, 262-272 (2018).
2. Shi, Z. et al. Modeling the intensity of surface urban heat island based on the impervious surface area. *Urban Climate* **49**, 101529 (2023)..

Comment #2-10:

More details on the data and methods (uncertainty analysis, significant test) are required. Additionally, the interpretation of the results need to be compared with previous studies.

Response: thank you. As suggested, we enhanced details regarding uncertainty analysis and significant test in Materials and Methods. Bellows are selected examples.

“This process allows us to use data from 2020-2100 for future LST estimation under diverse scenarios while reserving satellite observations from 2015-2020 for evaluation of model performance and uncertainty.” (Data: Page 14, Line 307-310)

“Additionally, we quantified the uncertainty of the slope estimates using 95% confidence intervals and assessed statistical significance based on p-values.” (Methods: Page 16, Line 358-360)

Additionally, we also expanded the Discussion section to include detailed comparisons of our results with previous studies as follows (Li et al., 2017; Zhou et al., 2022).

“Globally, these slopes trend toward zero as urbanization reach maturity in different cities at various stages, with ISA expansion eventually plateaued and thus the LST response gradually diminishing (Fig. S9) ...This finding aligns well with the study by Li et al, which suggests that UHI does not increase indefinitely along with urban growth³⁷.” (Discussion: Page 11, Line 212-219)

“Locally, urbanization drives SUHI increases through changes in impervious surfaces^{13,30,44}, elevating it by approximately 0.013 °C per decade, from 1.56 °C in 2020 to about 1.66 °C in 2100 (Fig. S12). Although urbanization contributes significantly to local warming, its effect on the global scale remains relatively modest⁴³, underscoring the critical influence of land use changes on SUHI, particularly under the contexts of global warming.” (Discussion: Page 12, Line 241-246)

Reference:

1. Li, X., Zhou, Y., Asrar, G. R., Imhoff, M. & Li, X. The surface urban heat island response to urban expansion: A panel analysis for the conterminous United States. *Science of the Total Environment* **605**, 426-435 (2017).
2. Zhou, D., Xiao, J., Frohking, S., Zhang, L. & Zhou, G. Urbanization contributes little to global warming but substantially intensifies local and regional land surface warming. *Earth's Future* **10**, 1029 (2022).

Reviewer 1

I thank the authors for their effort in addressing my comments and for the discussion. I think the manuscript is suitable for publishing in its current form.

Response: we sincerely thank the reviewer for their positive feedback and for affirming that the manuscript is now suitable for publication. We are grateful for their valuable comments, which have significantly strengthened the quality of our paper.

Reviewer 2

Comment #2-0

The author addressed my comments carefully, which I appreciate a lot. However, I still have several concerns; the line number is in revised manuscript (marked).

Response: we appreciate your continued engagement and constructive suggestions. We have meticulously addressed each of the remaining points raised (as detailed below) and are confident that the manuscript is now significantly improved.

Comment #2-1:

1. Line 82-83: please show p-value here rather than R-values.

Response: thank you. As suggested, we have updated Fig. 1 to include the p-values. The corresponding sentence in the main texts have been updated accordingly.

“Statistically, more than half of the cities showed significant correlations ($p < 0.1$) (Fig. 1b).”
(Results: Page 4, Line 78-79)

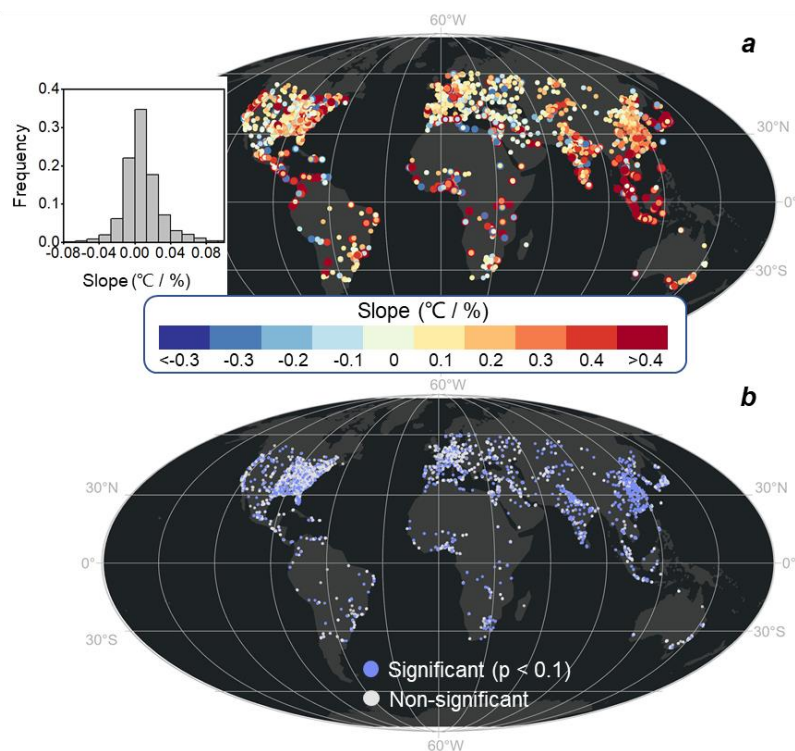


Fig. 1. Linear relationships between ΔLST and ΔISA . (a) Slope derived from historical observations. (b) Statistical significance of linearly fitted model. Note: here we included 6,359 GADM level-2 units with urban areas larger than 100 km² in our study.

Comment #2-2:

Line 204 'With then', do you mean 'Within'?

Response: we are sorry for this confusion and have revised it accordingly as below.

“Within the 95% confidence intervals of derived slope (Fig.S8), we assessed the range of uncertainty in LST responses to ISA increase.” (Uncertainty Analysis: Page 11, Line 192-193)

Comment #2-3:

Line 206-207, please check grammar here.

Response: done as suggested.

“For most worldwide cities, the derived slopes typically range from 0 to 0.04 °C/% ISA increase. While for China, it exhibits the smallest uncertainty, with slopes mostly ranging from 0 to 0.01 °C per %. Overall, these findings indicate that the ISA-induced warming is distinct.” (Uncertainty Analysis: Page 11, Line 193-196)

Comment #2-4:

Line 209: so there are about a half of those cities where ISA and LST are not significantly correlated? Then in those cities, using the ISA-LST slope (which is insignificant) is not reasonable. I wonder how is your model performance at those cities?

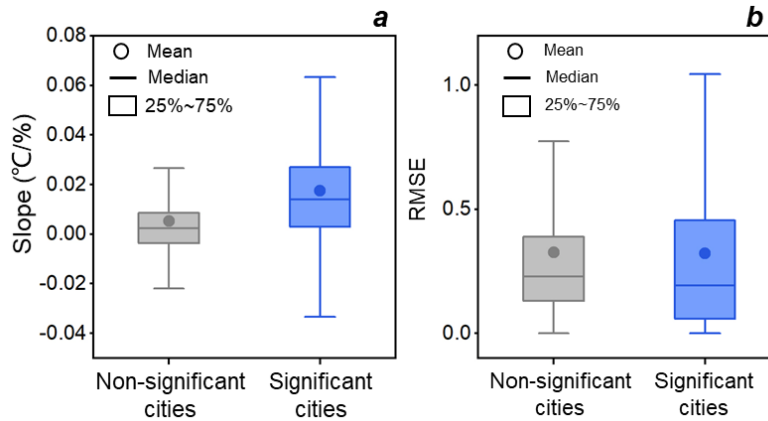
Response: we thank the reviewer for this important question regarding the model performance in cities where the $\Delta ISA-\Delta LST$ relationship is not significant. We agree that this is a crucial point and are pleased to clarify our approach. Indeed, the relationship is not statistically significant in approximately half of the studied cities. We argue that the impact of this on our overall results and future projections is limited for two primary reasons.

On one hand, our future LST projections do not rely solely on the city-specific $\Delta ISA-\Delta LST$ slope. Instead, they integrate two key components: (1) the large-scale climate background signal derived from CMIP6 models, and (2) the local, ISA-driven warming component (Fig. S14). This means that even in cities with a statistically weak local relationship, the projection is strongly informed by the robust regional climate forcing, thereby mitigating potential bias from the local term.

On another hand, an insignificant statistical relationship often occurred in cities where the historical change in ISA (ΔISA) was not so distinct. If past urban expansion was limited, it is reasonable to assume future ISA changes will also be minor, thus minimizing the potential contribution of this factor to error. Besides, the weak correlation itself suggests that other factors (e.g., vegetation, albedo, humidity) are the dominant drivers of LST variation in these specific cities. Consequently, the contribution of the uncertain ISA component to the total future warming is inherently small.

To directly address the question of model performance, we specifically evaluated the slope and Root Mean Square Error (RMSE) for cities with significant versus non-significant relationships. We found that the impact of insignificant $\Delta ISA-\Delta LST$ slopes to future warming is limited (Fig. R1a) because (1) ΔISA during the historical period are small, implying that their future ISA changes are also minor, and (2) the average RMSE was nearly identical between the two groups (Fig. R1b). This demonstrates that the model's accuracy is not compromised in cities with an

insignificant $\Delta\text{ISA}-\Delta\text{LST}$ relationship, and our future estimates for these cities remain robust. This approach is consistent with established literature (Peng et al., 2012; Li et al., 2017; Rao et al., 2021; Li et al., 2023), where the overall association between urban factors like ISA and LST is emphasized over strict statistical significance at the individual city level. For clarify, we enhanced the Discussion section with a thorough explanation for the statistically insignificant regression results.



70

71 **Fig. R1** Comparison of slope (a) and RMSE (b) between cities with significant and non-
72 significant $\Delta\text{ISA}-\Delta\text{LST}$ relationships.

73 “Although about half of the cities exhibit insignificant $\Delta\text{ISA}-\Delta\text{LST}$ correlations, this does not
74 substantially undermine the reliability of our future projections. First, our projection
75 framework does not solely rely on city-specific slopes but integrates both the large-scale
76 climate background (from CMIP6) and the ISA-driven component. Second, the weak
77 correlations in some cities are mainly attributed to their limited ISA expansion in historical
78 period, implying that their future ISA changes will be limited. In such cases, other
79 environmental factors beyond impervious surfaces are likely to dominate the thermal
80 environment.” (Discussion: Page 12-13, Line 241-248).

81 **Reference:**

- 82 1. Peng, S. et al. Surface urban heat island across 419 global big cities. *Environmental science & technology* **46**,
83 696-703 (2012).
- 84 2.Li, X., Zhou, Y., Asrar, G. R., Imhoff, M. & Li, X. The surface urban heat island response to urban expansion: A
85 panel analysis for the conterminous United States. *Science of the Total Environment* **605**, 426-435 (2017).
- 86 3.Rao, Y., Dai, J., Dai, D. & He, Q. Effect of urban growth pattern on land surface temperature in China: A multi-
87 scale landscape analysis of 338 cities. *Land Use Policy* **103**, 105314 (2021).
- 88 4.Li, L. et al. Divergent urbanization-induced impacts on global surface urban heat island trends since 1980s.
89 *Remote Sensing of Environment* **295**, 113650 (2023).

90 **Comment #2-5:**

91 Line 252-253, this sentence repeats previous sentence. Moreover, a higher relative warming
92 rate does not mean a higher climate sensitivity or vulnerability. Climate sensitivity refers to
93 how much the Earth's surface temperature will change in response to a change in radiative
94 forcing. For vulnerability, in high-latitude cold region, 'warming' is not always a bad thing.

Response: we thank the reviewer for this critical insight. We agree that our use of the terms “climate sensitivity” and “vulnerability” was inaccurate and have therefore removed that sentence from our manuscript (*Discussion: Page 12, Line 226-228*).

Comment #2-6:

Methods. historical relationship between ISA and LST changes: I am still a little bit confused in this part. Like I previously commented, historical LST can be affected by so many factors, how did you tease out the impact from other factors? In your reply, you mentioned 'the socioeconomic and demographic conditions were considered in SSP scenarios' which I agree with, however, I think your LST-ISA slopes also include the effect from those socioeconomic and demographic conditions (if not, how did you tease out those effects)?

Response: we thank you for raising this crucial point regarding confounding factors. First of all, we fully acknowledge that historical LST changes are influenced by multiple factors. As we stated in our response to **Comment #2-4**, other factors in addition to the ISA, may also impact the LST, particularly for those cities with relatively weak ΔLST – ΔISA relationships. Despite that, ISA serves as a robust and integrative proxy for the overall effect of urbanization, which is intrinsically linked to socioeconomic and demographic conditions (*Wei et al., 2021; Chakraborty et al., 2024*).

Given that ISA is not just a physical metric, it is a well-established proxy for anthropogenic activities. Historical changes in ISA (ΔISA) reflect the culmination of socioeconomic and demographic forces (*Brelsford et al., 2020; Shi et al., 2023; Yang et al., 2021*). Therefore, the historical ΔISA – ΔLST relationship inherently captures the warming effect associated with these underlying human drivers. We do not need to "tease them out" separately because they are embodied in the proxy variable itself. Besides, by modeling the change in LST as a function of the change in ISA (ΔLST – ΔISA) over historical period, our approach inherently controls for static, time-invariant confounders such as topography, elevation, and baseline regional climate. This strengthens the inference that the correlated changes are linked to the process of urbanization.

In summary, socioeconomic and demographic conditions are not omitted; they are implicitly incorporated through the ISA proxy in both the historical model calibration and the future application under SSP scenarios. The historical slope thus represents the aggregate warming effect per unit of urban expansion, which includes all associated anthropogenic activities. As suggested, we have revised the manuscript to explicitly state this rationale as below.

“Moreover, while our approach does not explicitly incorporate other potential factors (e.g., building heights, green spaces and anthropogenic heat emissions), the ISA indicator provides a physical measurement of urbanization that serves as a proxy for its associated socioeconomic and demographic conditions, which are thus implicitly reflected in both the historical ΔISA – ΔLST relationship and the future projections under SSP scenarios” (*Discussion: Page 13, Line 253-258*)

Reference:

1. Wei, S. et al. Estimating Chinese residential populations from analysis of impervious surfaces derived from satellite images. *International Journal of Remote Sensing* **42**, 2303-2326 (2021).

2. Chakraborty, T. et al. Large disagreements in estimates of urban land across scales and their implications. *Nature communications* **15**, 9165 (2024).
3. Brelsford, C., Coon, E. T., Moran, E. & Allen-Dumas, M. Urban scaling as validation for predictions of imperviousness from population. *Geophysical Research Letters* **47**, e2020GL089742 (2020).
4. Shi, Z. et al. Modeling the intensity of surface urban heat island based on the impervious surface area. *Urban Climate* **49**, 101529 (2023).
5. Yang, Q., Huang, X., Yang, J. & Liu, Y. The relationship between land surface temperature and artificial impervious surface fraction in 682 global cities: spatiotemporal variations and drivers. *Environmental Research Letters* **16**, 024032 (2021).

Comment #2-7:

'Using ΔISA and ΔLST , rather than ISA and LST , allows us to more effectively isolate the impact of urbanization-induced warming, by minimizing the other influences such as background climate and topography.' I am confused here. Here your ΔLST is the difference of LST in year i compared with in starting year, right? How could this minimize other influences as the ΔLST (i.e., LST temporal change) should be an outcome of effects from urbanization and other factors like background climate?

Response: thank you for this insightful comment. We acknowledge that ΔLST is not solely driven by urbanization (ΔISA) but also by other factors, particularly background climate and its change. It is worthy to note that here we used ΔISA and ΔLST (temporal changes) instead of absolute values, to more effectively isolate the urbanization-induced impact, as the impact of time-invariant factors (e.g., topography and elevation) was minimized. In Eq. (1), the slope represents the urbanization-induced warming (Shi et al., 2023; Li et al., 2023; Shen et al., 2021, 2023), that is, the marginal increase in LST for each unit increase in ISA . While the intercept (α) accounts for the large-scale background climate change and other non-urbanization factors, this term characterizes the LST change when the ΔISA is zero, representing background thermal environmental change in urban and rural areas. By focusing on the slope of ΔLST – ΔISA , we quantified the localized urban warming effect while the intercept captures the impact of other factors such as background climatic change.

$$\Delta LST_{his} = Slope_{his} \times \Delta ISA_{his} + \alpha \quad (1)$$

where $Slope_{his}$ denotes LST change per unit ISA change during the historical period. ΔLST_{his} and ΔISA_{his} are the LST and ISA changes from 2003 to 2020, respectively, and α is the offset, accounting for large-scale background climate change and other non-urbanization factors.

“In Eq. (1), temporal changes (i.e., ΔISA and ΔLST), rather than absolute values, help mitigate the influence of time-invariant factors, such as topography and elevation. The coefficient α accounts for large-scale background climate and other non-urbanization factors. This approach isolates urbanization-induced warming, distinguishing it from the effects of other factors.” (Methods: Page 17, Line 354-358)

Reference:

1. Shi, Z. et al. Modeling the intensity of surface urban heat island based on the impervious surface area. *Urban Climate* **49**, 101529 (2023).
2. Li, L. et al. Divergent urbanization-induced impacts on global surface urban heat island trends since 1980s.

Remote Sensing of Environment **295**, 113650 (2023)

3. Shen, P., Zhao, S. & Ma, Y. Perturbation of urbanization to Earth's surface energy balance. *Journal of Geophysical Research: Atmospheres* **126**, e2020JD033521 (2021).

4. Shen, P., Zhao, S., Ma, Y. & Liu, S. Urbanization-induced Earth's surface energy alteration and warming: A global spatiotemporal analysis. *Remote Sensing of Environment* **284**, 113361 (2023).

Comment #2-8:

'While some cities exhibit a negative $\Delta ISA-\Delta LST$ relationship, this is also reasonable as the per unit increase of ISA change (ΔISA) results in the decline of per unit increase of LST change (ΔLST), suggesting the ISA driven warming effect becomes plateaued, not directly declines LST'. Maybe I misunderstood your method, shouldn't a negative slope denote a decline of LST (not a decline in LST increase) corresponding to an increase of ISA?

Response: thank you for this insightful question, which highlights a potential source of confusion in our original description. Yes, you are correct that a negative slope in the $\Delta ISA-\Delta LST$ relationship indicates that an increase in ΔISA (impervious surface area change, reflecting urbanization) is associated with a decrease in ΔLST (land surface temperature change), ultimately leading to a reduction in LST. For clarity, we have revised the relevant text as follows.

"While some cities exhibit a negative $\Delta ISA-\Delta LST$ relationship, as each unit increase in ΔISA can correspond to a decline in ΔLST , resulting in slightly decreased LST." (Results: Page 4, Line 73-75)

Comment #2-9:

The English should be improved.

Response: thank you. The language has been polished by native speakers. We believed the revised version should meet the requirement of *Communications Earth and Environment*.

1 **Reviewer 2**

2 **Comment #2-0**

3 The authors addressed my comments carefully, which I appreciate a lot. Please note that
4 background climate also have temporal changes, so its impact on LST is not only the absolute
5 values but also the trend/dynamics, as opposing to their reply to Comment 7.

6 **Response:** thank you. First of all, thank you for your positive comments to our revision. While
7 regarding Comment #7, it is worthy to note that the “*time-invariant*” factors specifically refer
8 to topography and elevation, rather than the background climate. We fully acknowledge that
9 the background climate does change over time and can influence LST trends and dynamics.