

Global South shows higher urban flood exposures than the Global North under current and future scenarios

Corresponding Author: Professor Chunlin 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 Professor Li,

Your manuscript titled "Global South shows higher urban flood exposures than the Global North under current and future scenarios" has now been seen by 2 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised quite substantial concerns that must be addressed. In light of these comments, we cannot accept the manuscript for publication, but would be interested in considering a revised version that fully addresses these serious concerns.

We hope you will find the reviewers' comments useful as you decide how to proceed. For further consideration in Communications Earth & Environment, the following editorial thresholds should be addressed in the revised manuscript:

******* Incorporate future hazard projections and clearly explain the role of flood defenses to accurately assess the changing risk landscapes.

******* Fully explain discrepancies in population exposure figures and provide thorough analysis of regional trends and anomalies to ensure data integrity and contextual relevance.

******* Clearly define the study's novel contribution and justify the relevance by identifying gaps in prior work to establish its significance within the existing literature.

Should additional work allow you to address these criticisms, we would be happy to look at a substantially revised manuscript. If you choose to take up this option, please either highlight all changes in the manuscript text file, or provide a list of the changes to the manuscript with your responses to the reviewers.

When resubmitting, please provide a point-by-point response to the reviewers' comments. Please submit your responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

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

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

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

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

Best regards,

Rahim Barzegar, PhD
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Consulting Editor
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This paper looks at trends and future projections of population exposure to floods globally. Although this is an important topic I have a few concerns with the analyses and presentation of the results. My major concern is that changes in the flood hazard have not been considered for the future. The authors justify this by citing other studies where flood hazard has been assumed static but it appears to me that these studies were only undertaking historical analyses. Given the focus of this work is urban flood exposure and it is in urban areas where increases in flood hazards are most likely given that increases in rainfall intensity and high impervious areas, I cannot see how changes in flood hazard can be ignored when looking at changes in flood exposure in the future.

The authors cite previous research that suggests that 1.8 billion people are exposed to 1 in 100 year flood risk. They then say that approximately 57% of people live in urban areas. As a simple calculation (obviously not allowing for heterogeneity in population distribution vs flood hazard distribution), this would suggest that more than 1 billion people could be exposed to urban floods. But the total number here based on Figure 1b appears to be less than 500 million. Why the discrepancy? this isn't discussed in the manuscript at all.

There are no details of whether flood defenses have been incorporated into the modelling and as acknowledged in the introduction, previous research has shown that the lack of flood defenses contributes to uneven flood exposure for low-income and Black communities.

Most of the discussion of the manuscript (from lines 194 to 228) could have been written even without doing the analyses

presented here and I think it needs to be substantially improved to reflect the findings from this work.

Minor comments

- five year periods of analysis seem quite short given that for much of the world ENSO is a major driver of hydrological variability and has cycles of 2-5 years. How much of the difference between periods is due to the short sample lengths?
- Line 104 - if flood prone land is being converted to urban land, i can't see how the proportion of population exposed to flooding can stay constant
- how are informal urban settlements accounted for in your results?
- Figure 4 - swapping around the colours for the periods here compared to the other figures is very confusing. Also are the period dates here correct? why is it 2000-2015 and then 2005-2010, 2010-2015 and 2015-2020?
- line 156 - what does rational population distribution mean?
- Table 1 - should be in supplementary material. this is not an effective way to communicate results.
- line 309 - how is significance of the getis-ord statistic defined?

Reviewer #2 (Remarks to the Author):

This manuscript analyses the global urban flood exposure during the historical and future periods in terms of urban area, population, and economic aspects, using existing global datasets, with a focus on inequalities and disparities. While the topic is still interesting, the novelties added by this study are not clear. There are existing studies on historical and future global flood exposure, and inequality aspects of urban flood impacts (see below for specific examples). What is new here exactly? The introduction articulates well the importance of the topic, but fails to clarify what are lacking from existing studies and hence correctly motivate this manuscript.

Example 1. On historical global flood exposure in urban areas

Cao, W., Zhou, Y., Güneralp, B., Li, X., Zhao, K., & Zhang, H. (2022). Increasing global urban exposure to flooding: An analysis of long-term annual dynamics. *Science of The Total Environment*, 817, 153012.

Example 2. On future global flood exposure under SSP

Rogers, J. S., Maneta, M. M., Sain, S. R., Madaus, L. E., & Hacker, J. P. (2025). The role of climate and population change in global flood exposure and vulnerability. *Nature Communications*, 16(1), 1287.

Example 3. On inequalities and disparities in urban flood impacts

McDermott, T. K. (2022). Global exposure to flood risk and poverty. *Nature Communications*, 13(1), 3529.

In Fig. 1, there is an interesting pattern: From 2015 to 2020, there were much higher increase in UEF and PEF across the globe than 2000-2015 period. When you look at EEF, however, there was a much lower increase in Central America, or even decrease in North America. Why did this happen?

That said, the analyses appear appropriate and reproducible.

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Version 1:

Decision Letter:

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Dear Professor Li,

Your revised manuscript titled "Global South shows higher urban flood exposures than the Global North under current and future scenarios" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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

Best regards,

Rahim Barzegar, PhD
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Communications Earth & Environment
Consulting Editor
Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

The authors have made substantial changes to the discussion and limitations section of the manuscript to address my

comments. Whilst I think it would be far better to have incorporated future changes in flood hazards due to climate change rather than static flood extents, I think the contributions of the manuscript are now clearer and I recommend publication.

Reviewer #2 (Remarks to the Author):

I appreciate the authors' efforts in addressing my and other reviewer's comments satisfactorily. Recommend acceptance as is.

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Manuscript ID: COMMSENV-25-1406

Article Title: Global South shows higher urban flood exposures than the Global North under current and future scenarios

To: *Communications Earth & Environment*

Re: Response to the Reviewers

Dear Anonymous Reviewers,

We sincerely appreciate your valuable comments and suggestions on our manuscript titled “*Global South shows higher urban flood exposures than the Global North under current and future scenarios*”. Your insightful feedback has been instrumental in improving the quality of our work, and has provided us with important guidance for our future research endeavors.

We have carefully addressed each of the reviewers’ comments and revised the manuscript accordingly. All changes made in the manuscript are highlighted in yellow for your convenience. In our point-by-point response letter, the corresponding excerpts from the revised manuscript are presented in *italics*, with the most relevant parts shown in blue.

We hope that the revised manuscript now meets the requirements for publication in *Communications Earth & Environment*. Below, we present a detailed, point-by-point response to the reviewers’ comments, along with a summary of the corresponding revisions.

Reviewer #1, COMMENTS #1: This paper looks at trends and future projections of population exposure to floods globally. Although this is an important topic I have a few concerns with the analyses and presentation of the results. My major concern is that changes in the flood hazard have not been considered for the future. The authors justify this by citing other studies where flood hazard has been assumed static but it appears to me that these studies were only undertaking historical analyses. Given the focus of this work is urban flood exposure and it is in urban areas where increases in flood hazards are most likely given that increases in rainfall intensity and high impervious areas, I cannot see how changes in flood hazard can be ignored when looking at changes in flood exposure in the future.

Author response: Thank you very much for your valuable comment. We completely agree that urban flood hazard is likely to change in the future due to climate change (e.g., more intense rainfall) and urbanization (e.g., increasing impervious surfaces), and that this may substantially affect exposure estimates. We appreciate the opportunity to clarify the reasons behind our approach and acknowledge its limitations.

In this study, the global flood hazard data we used are based on the maximum extent of the 100-year return period flood events, developed by the European Commission, Joint Research Centre⁴³. This dataset assumes a static flood extent and does not simulate dynamic changes in flood hazard under future climate or land use conditions. The choice of this dataset was primarily due to the lack of globally consistent, high-resolution, and openly available flood hazard projections that integrate both climate change and urban development processes.

Currently, most global-scale flood modeling efforts are limited by the availability of detailed input data and computational feasibility. These data are particularly valuable for enabling standardized global comparisons of flood exposure, though we fully recognize that they may underestimate future flood risks, especially in rapidly urbanizing or climate-sensitive regions. Even under a conservative assumption of no change in hazard, our results highlight alarming trends in population and economic exposure and spatial inequality. This suggests that if hazard intensifies in the future, which is likely, the urban flood risk could be even more severe than our current estimates suggest.

We also note that some regional studies have incorporated future changes in flood hazard. For example, Gori⁴⁴ showed that floodplain expansion in Houston could reach 12.5% due to projected urbanization. Similarly, Sun⁴⁵ simulated the impact of future land-use change and climate scenarios

on flood risk in Shanghai. While such integrated simulations have provided valuable insights at local and regional levels, they remain relatively limited, and applying them consistently at the global scale remains challenging due to data, methodological, and computational constraints. We fully agree with the reviewer that incorporating dynamic flood hazard projections would enable more realistic exposure assessments, particularly in fast-growing urban areas, and we view this as a key direction for future research.

We have revised the Discussion section accordingly (see lines 273-278, 320-325 and 338) to clarify this limitation and highlight the importance of future improvements.

In the Discussion section: “Several factors play a crucial role in the formation and evolution of urban flood exposures, primarily involving flood formation, the increase in urban flood exposure, and human management strategies to mitigate exposure. Although climate change and urbanization drive changes in flood hazard and floodplain extents, our study relied on static 100-year floodplain data due to the current lack of globally consistent, high-resolution flood hazard projections that integrate both climate and land-use changes. This limitation, imposed by data availability and computational feasibility, may lead to underestimating future urban flood exposure, especially in rapidly developing or highly impervious regions. Addressing dynamic floodplain changes is an important direction for future research.

.....

This study also has several limitations. Firstly, the floodplain data used in this study were based on fixed extents of 100-year flood events and did not account for potential future changes in flood-prone areas driven by climate change, increased rainfall intensity, or urban expansion. Although some studies suggest that floodplains tend to remain relatively stable over time, particularly at large scales¹⁰, other research has indicated that urbanization can significantly alter inundation extents. As a result, using static floodplain boundaries may underestimate future urban flood exposure, especially in rapidly developing or highly impervious regions^{44,45}. Secondly, Future research should further incorporate dynamic floodplain changes, explore the interactive effects of socio-economic development, climate change, and urban flood exposures, consider the role of flood protection measures, and improve the representation of informal urban areas by integrating socioeconomic and urban morphology datasets. Additionally,”

References

10. Cao, W. et al. Increasing global urban exposure to flooding: An analysis of long-term annual dynamics. *Sci. Total Environ.* 817, 153012 (2022).
43. Joint Research Centre Data Catalogue. River Flood Hazard Maps at European and Global Scale. <https://data.jrc.ec.europa.eu/collection/id-0054> (2024).
44. Gori, A., Blessing, R., Juan, A., Brody, S. & Bedient, P. Characterizing urbanization impacts on floodplain through integrated land use, hydrologic, and hydraulic modeling. *J. Hydrol.* 568, 82–95 (2019).
45. Sun, Q. et al. Multi-scenario urban flood risk assessment by integrating future land use change models and hydrodynamic models. *Nat. Hazards Earth Syst. Sci.* 22, 3815–3829 (2022).

Reviewer #1, COMMENTS #2: The authors cite previous research that suggests that 1.8 billion people are exposed to 1 in 100 year flood risk. They then say that approximately 57% of people live in urban areas. As a simple calculation (obviously not allowing for heterogeneity in population distribution vs flood hazard distribution), this would suggest that more than 1 billion people could be exposed to urban floods. But the total number here based on Figure 1b appears to be less than 500 million. Why the discrepancy? this isn't discussed in the manuscript at all.

Author response: Thank you very much for your insightful comment and careful reading of our manuscript. We appreciate the opportunity to clarify this important point.

Our study specifically focuses on river flooding, as described in the Data section, where flood-prone zones are defined based on river flood hazard maps with a 1-in-100 years return periods. This focus on river flood hazards distinguishes our work from broader flood exposure estimates.

The figure we cited in the Introduction section— “Currently, approximately 1.81 billion people globally are facing a 1-in-100 years flood risk, with 89% residing in low- and middle-income countries”— comes from previous research that considers multiple flood types, including pluvial, riverine, and coastal flooding. As a result, their exposure estimate is larger, reflecting the combined impacts of these flood types globally. In contrast, our analysis is limited to urban exposure to river floods only, focusing on urban built-up areas within river flood-prone zones. This more specific scope naturally leads to a lower total number of exposed people (around 500 million), which explains the discrepancy noted.

We acknowledge that this distinction was not explicitly stated in the original Introduction section, which may have caused confusion. We have therefore revised the Introduction section to clearly emphasize that our study centers on river flooding, excluding coastal and pluvial floods, to avoid misinterpretation, specifically in lines 75-77, where we added the following text:

“To fill these gaps, we analyze urban flood exposure across historical (2000–2020) and future periods (2030–2100) under various Shared Socioeconomic Pathways (SSPs), covering multiple spatial scales including global, national, subnational, and the Global South–North divide. Specifically, our objectives are: Focusing specifically on river flooding, one of the most frequent and destructive flood types globally, our findings contribute to a better understanding of the interactions among urbanization, socioeconomic development, and flood risk. The results provide valuable insights for climate adaptation, disaster risk reduction, and equitable urban planning strategies.”

We hope this explanation addresses your concerns. Thank you again for helping us improve the clarity of our manuscript.

Reviewer #1, COMMENTS #3: There are no details of whether flood defenses have been incorporated into the modelling and as acknowledged in the introduction, previous research has shown that the lack of flood defenses contributions to uneven flood exposure for low-income and Black communities.

Author response: Thank you for your insightful comment. We acknowledge that our analysis did not incorporate flood defenses, which is an important limitation. This was primarily due to constraints in the original global flood hazard dataset we used (developed by European Commission, Joint Research Centre⁴³), which does not account for flood protection infrastructure.

There are three main reasons for this omission: 1) The lack of global-scale flood defense data: When creating the dataset, there is no globally consistent and publicly available dataset that provides detailed information on flood protection structures such as levees, floodwalls, or their design specifications. This lack of data makes it infeasible to model the protective effect of such infrastructure at a global scale. 2) Limitations of global terrain datasets: The flood hazard maps are based on widely used digital elevation models such as SRTM and HydroSHEDS. These datasets primarily represent natural terrain and do not capture small-scale or artificial features like levees or underground barriers. As a result, many critical defense structures are not reflected in the elevation data used for flood modeling. 3) Model simplification: The original flood hazard maps were generated using a 2D hydrodynamic model that simulates flood propagation based on natural topography and hydrological processes, without explicitly including the physical effects of flood defenses. For example, during floodplain inundation, the model assumes water spreads freely into surrounding areas, whereas in reality, flood protection systems may significantly delay or completely prevent such flow. While this simplification enables globally consistent modeling, it may overestimate flood risks in well-protected regions.

We thank the reviewer for highlighting this important issue. As correctly noted, our model does not incorporate flood defense infrastructure such as levees, floodwalls, or drainage systems, which could significantly influence the actual level of exposure. We have now made this explicit in the Data section (see lines 354-359) by stating that flood defenses were not included in the flood modeling. We also revised the Discussion section (see lines 302-307, 328-329 and 339-340) to acknowledge that this omission could limit the accuracy of exposure estimates in areas with strong protection and potentially underrepresent disparities in underprotected regions, such as low-income and minority communities. This is an important direction for future research, particularly as more detailed and globally consistent flood defense datasets become available.

Please refer to the revised manuscript (e.g., lines 302-307, 328-329, 339-340, and 354-359) for more details.

In the Discussion section: *“Although urban flood exposures continue to rise in some areas, effective human management actions, such as appropriate flood control measures, can significantly mitigate these exposures. The construction of dams, reservoirs, and other hydraulic infrastructure is a key strategy for mitigating urban flood exposures². Many developed countries and regions possess advanced flood control infrastructure, which can reduce the impact of flooding on urban areas¹² However, due to the absence of globally consistent and publicly available data on flood protection systems, our analysis did not account for existing flood defenses. The global flood hazard dataset we adopted (from the European Commission, Joint Research Centre⁴³) assumes no protective infrastructure, as it is based on topography and natural hydrological processes alone.*

This limitation was necessary to ensure global comparability, but it may overestimate exposure in well-protected regions. We acknowledge this as a key limitation of our study and a priority for future research, especially as more detailed global datasets become available.

.....

This study also has several limitations. Firstly, Thirdly, the flood hazard data did not include flood defense infrastructure due to the lack of globally consistent information, which may lead to overestimation of exposure in well-protected areas. Future research should further incorporate dynamic floodplain changes, explore the interactive effects of socio-economic development, climate change, and urban flood exposures, consider the role of flood protection measures, and improve the representation of informal urban areas by integrating socioeconomic and urban morphology datasets. Additionally,

In the Data section: “The global 1 km resolution river flood hazard maps with a 1-in-100 year return period used in this research were developed by European Commission⁴³ and have been widely utilized in flood exposure analysis^{10,45,47}. It should be noted that this dataset does not account for flood defense infrastructure such as levees or floodwalls. This is primarily due to the current lack of globally consistent and detailed spatial data on such structures, including their location, elevation, and design standards. In the absence of such data, and to ensure comparability across regions, the underlying hydrodynamic model assumes natural terrain-based water flow without explicitly simulating the effects of flood defenses. While this approach supports uniform large-scale modeling, it may lead to conservative estimates of flood exposure in areas with strong protection systems.”

References

2. Dottori, F., Szewczyk, W., Ciscar, J.-C. & Zhao, F. Increased human and economic losses from river flooding with anthropogenic warming. *Nat. Clim. Change* 8, 781–786 (2022).
10. Cao, W. et al. Increasing global urban exposure to flooding: An analysis of long-term annual dynamics. *Sci. Total Environ.* 817, 153012 (2022).
12. Rentschler, J., Salhab, M. & Jafino, B. A. Flood exposure and poverty in 188 countries. *Nat. Commun.* 13, 3527 (2022).
43. Joint Research Centre Data Catalogue. River Flood Hazard Maps at European and Global Scale. <https://data.jrc.ec.europa.eu/collection/id-0054> (2024).
44. Gori, A., Blessing, R., Juan, A., Brody, S. & Bedient, P. Characterizing urbanization impacts on floodplain through integrated land use, hydrologic, and hydraulic modeling. *J. Hydrol.* 568, 82–95 (2019).
45. Sun, Q. et al. Multi-scenario urban flood risk assessment by integrating future land use change models and hydrodynamic models. *Nat. Hazards Earth Syst. Sci.* 22, 3815–3829 (2022).
47. Buttinger - Kreuzhuber, A. et al. Locally Relevant High - Resolution Hydrodynamic Modeling of River Floods at the Regional Scale. *Water Resour. Res.* 58, e2021WR030820 (2022).

Reviewer #1, COMMENTS #4: Most of the discussion of the manuscript (from lines 194 to 228) could have been written even without doing the analyses presented here and I think it needs to be substantially improved to reflect the findings from this work.

Author response: Thank you very much for this valuable comment. We carefully revised the Discussion section to better integrate and highlight the novel findings from our analyses. Specifically: 1) We replaced the original relatively general statements with concrete results drawn directly from our study, such as the quantified increase in urban flood exposure area (UEF), population (PEF), and economic exposure (EEF) in newly built-up urban areas worldwide during 2000–2020; 2) We emphasized the spatial heterogeneity revealed by our data, including significant regional disparities, such as the rapid growth of flood exposure in South Asia and sub-Saharan Africa compared to stagnation or slight decline in developed regions, supported by Gini coefficient analysis of exposure inequality; 3) We incorporated detailed interpretation of how our findings link to urbanization processes, for example, explaining the role of newly built-up areas overlapping with floodplains as a primary driver of increased exposure, rather than just general urban growth; 4) We added new discussion on the policy implications suggested by the data, such as the need for targeted flood risk management in rapidly urbanizing, high-exposure regions highlighted by our analysis.

Overall, the revised discussion now directly reflects and builds upon our original analytical results, providing a much more data-driven and insightful interpretation consistent with the reviewer's expectations.

The modified Discussion section is as follows:

“Variations in socioeconomic and environmental factors lead to diverse urban flood exposures patterns across regions. In East Asia, especially China, UEF levels are the highest globally (Fig. 1), primarily driven by rapid

expansion into flood-prone zones^{10,27}. Our results show that China's UEF is projected to increase by over 50% by 2020 compared to 2015 levels, in line with earlier national studies¹¹. This highlights how urban expansion in flood-prone regions directly intensifies exposure, a trend confirmed by our analysis of newly built-up urban areas (Fig. 5). In contrast, North America shows a relatively stable trend at the national level, as previously noted by Tellman²⁸, but our finer-scale analysis reveals that coastal cities in the US still face significant exposure. This indicates that subnational variation can be masked in broader-scale assessments, underscoring the value of high-resolution spatial analysis. South Asia, Southeast Asia, and Africa are experiencing a sharp rise in urban flood exposures (Fig. S2), driven by high population densities and rapid urban expansion in flood-prone zone²⁹. Future urban development in these regions must prioritize flood risk management to minimize potential losses.

Urban flood exposures are unevenly distributed between the Global South and the Global North, a pattern clearly revealed by our analysis using Gini coefficients and regional disaggregation (Fig. 6). Our results show that low- and middle-income countries, especially those in South Asia, Sub-Saharan Africa, and Southeast Asia, exhibit significantly higher levels of flood exposure relative to their urban population and built-up area. This disparity is projected to increase further under high-growth SSPs (e.g., SSP3), where rapid urban expansion continues in vulnerable flood-prone areas without corresponding improvements in flood protection infrastructure^{15,17}. The socioeconomic vulnerability in these areas further amplifies the impacts of flood exposure, putting livelihoods and well-being at risk¹². Moreover, the Gini coefficient values for urban flood exposure rise notably in future scenarios (Table S3), indicating a growing inequality in urban flood exposure distribution across countries and regions. These findings suggest that the Global South, where both adaptive capacity and infrastructure are often limited, is likely to bear a disproportionate share of future flood risk. Strengthening international collaboration to enhance flood defense and support climate adaptation in low-income countries is therefore critical to addressing this emerging aspect of climate injustice⁹. It is also important to note that our analysis may underestimate flood exposure in some of the most vulnerable areas, as both the Global Urban Boundary (GUB)⁴⁸ and projected urban expansion datasets⁵⁰ primarily capture formal urban areas. Informal settlements may be underrepresented in these datasets, particularly in low-income countries where such settlements are widespread. This data limitation underscores the need for future research to better incorporate informal urban areas into global flood exposure assessments.

Several factors play a crucial role in the formation and evolution of urban flood exposures, primarily involving flood formation, the increase in urban flood exposure, and human management strategies to mitigate exposure. Extreme climate change is a major driver of urban flooding. Global climate change has exacerbated the uneven distribution of precipitation over space and time, increasing the frequency of extreme rainfall events, including heavy storms and short-duration intense rainfall, in specific regions³⁰. In cities experiencing extreme precipitation, intense rainfall over a short period exceeds the drainage system's capacity, leading to increased surface runoff and resulting in severe urban flooding³¹. Meanwhile, urbanization has significantly altered natural hydrological processes, further increasing the exposure of urban flooding. The expansion of impervious surfaces, such as roads and buildings, reduces rainwater infiltration, increases surface runoff, and leads to higher flood peaks and prolonged water accumulation^{32,33}. Particularly in low-lying areas and former flood-prone zone, rapid urban expansion has replaced natural wetlands and flood detention zones, which once essential for regulating the water cycle, increasing urban flood susceptibility^{34,35}. Although climate change and urbanization drive changes in flood hazard and floodplain extents, our study relied on static 100-year floodplain data due to the current lack of globally consistent, high-resolution flood hazard projections that integrate both climate and land-use changes. This limitation, imposed by data availability and computational feasibility, may lead to underestimating future urban flood exposure, especially in rapidly developing or highly impervious regions. Addressing dynamic floodplain changes is an important direction for future research.

The high concentration of population and assets in urban areas has significantly heightened the exposures to urban flooding. Urbanization process has concentrated large numbers of residents and economic activities, further expanding the extent and impact of urban flood exposures. The high density of population and economic activities makes the potential damage and losses from urban flooding more severe^{13,36}. Moreover, rapid urbanization has not only increased the occupation of flood-prone zone but also outpaced the development of urban infrastructure, making it insufficient to cope with growing demands, which further exacerbates urban flood exposures³⁷. In particular, urban flood exposures have significantly increased in low-income and high-density urban areas, where limited emergency response capacity and a lack of disaster awareness exacerbate the severity of catastrophic consequences^{27,38,39}. Our study's results confirm these patterns at the global scale. We found that urban flood exposure in terms of area, population, and economic value has risen sharply in rapidly urbanizing regions, particularly in low-income and densely populated areas of South Asia, Southeast Asia, and Africa. These findings highlight the unequal burden of flood risks, with vulnerable urban populations facing disproportionate exposure increases. The insufficient development of flood protection infrastructure and emergency response capacity in these regions likely amplifies their vulnerability, underscoring the urgent need for targeted adaptation strategies.

Although urban flood exposures continue to rise in some areas, effective human management actions, such as appropriate flood control measures, can significantly mitigate these exposures. The construction of dams, reservoirs, and other hydraulic infrastructure is a key strategy for mitigating urban flood exposures². Many developed countries and regions possess advanced flood control infrastructure, which can reduce the

impact of flooding on urban areas¹². In recent years, flood management measures have gradually shifted towards integrated governance, which includes not only the construction of flood control facilities but also improvements to urban drainage systems⁴⁰, green infrastructure⁴¹, and land use planning⁴². Enhancing urban emergency management capacity and improving flood control infrastructure can effectively reduce urban flood exposures, particularly during extreme climate events, thereby mitigating catastrophic losses. Therefore, the enhancement of integrated management measures and green infrastructure is an essential part of future strategies for addressing urban flood exposures. However, due to the absence of globally consistent and publicly available data on flood protection systems, our analysis did not account for existing flood defenses. The global flood hazard dataset we adopted (from the European Commission, Joint Research Centre⁴³) assumes no protective infrastructure, as it is based on topography and natural hydrological processes alone. This limitation was necessary to ensure global comparability, but it may overestimate exposure in well-protected regions. We acknowledge this as a key limitation of our study and a priority for future research, especially as more detailed global datasets become available.

This study systematically analyzed the spatiotemporal evolution of global urban flood exposures by combining historical urban area, population and economy data for 2000–2020 with SSPs simulation data for 2030–2100, offering a comprehensive understanding of both past and future exposure dynamics. Unlike most previous studies that focused solely on one dimension, such as urban area, population, or economy, we simultaneously assessed urban flood exposures in all three dimensions (UEF, PEF, and EEF), providing multidimensional support for exposure analysis and expanding the theoretical framework for related research. In addition, by focusing on newly built-up areas, we revealed how urban expansion directly contributes to increased flood exposure, underscoring the close link between urban growth and flood risk. Furthermore, by applying inequality metrics such as the Gini coefficient across multiple spatial scales, including national and subnational levels as well as the divide between the Global South and Global North, we uncovered not only the overall magnitude of exposure but also its evolving inequality patterns. These findings provide scientific evidence for equitable flood risk governance, climate adaptation, and forward-looking urban planning, especially in the Global South, where the challenges are particularly acute.

This study also has several limitations. Firstly, the floodplain data used in this study were based on fixed extents of 100-year flood events and did not account for potential future changes in flood-prone areas driven by climate change, increased rainfall intensity, or urban expansion. Although some studies suggest that floodplains tend to remain relatively stable over time, particularly at large scales¹⁰, other research has indicated that urbanization can significantly alter inundation extents. As a result, using static floodplain boundaries may underestimate future urban flood exposure, especially in rapidly developing or highly impervious regions^{44,45}. Secondly, SSPs used in the study did not account for risk mitigation strategies, and their assumptions involve some uncertainty, such as land planning, infrastructure improvements, or relocation measures that managers may implement. This limits the applicability of the findings to realistic policy scenarios, which were not fully explored in the study. Thirdly, the flood hazard data did not include flood defense infrastructure due to the lack of globally consistent information, which may lead to overestimation of exposure in well-protected areas. Fourthly, both the historical and projected urban area datasets used in this study do not explicitly capture informal settlements, which may lead to underestimation of flood exposure in these particularly vulnerable areas. It should be noted that the use of 5-year periods in the historical analysis was primarily constrained by the temporal resolution of available datasets. While this approach enables the detection of general trends in urban flood exposure, it may be affected by short-term hydrological variability, particularly in regions sensitive to ENSO cycles. ENSO typically operates on 2–5 year intervals and can significantly influence flood risk through its impact on precipitation and river discharge. As such, exposure estimates for individual 5-year periods should be interpreted with caution. Our focus remains on longer-term patterns over the full study period, and future research could incorporate ENSO indices to explicitly assess the extent of its influence on temporal variability in flood exposure. Future research should further incorporate dynamic floodplain changes, explore the interactive effects of socio-economic development, climate change, and urban flood exposures, consider the role of flood protection measures, and improve the representation of informal urban areas by integrating socioeconomic and urban morphology datasets. Additionally, accounting for policy-related decision-making factors regarding risk mitigation and adaptation would offer a more in-depth and realistic analysis of future urban flood exposure management.”

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Reviewer #1, COMMENTS #5: Five year periods of analysis seem quite short given that for much of the world ENSO is a major driver of hydrological variability and has cycles of 2-5 years. How much of the difference between periods is due to the short sample lengths?

Author response: Thank you very much for your insightful comment. We agree that interannual hydrological variability, particularly influenced by ENSO events, which typically follow 2–5 year cycles, may influence short-term flood exposure estimates in many regions. In our study, the 5-year time intervals were adopted primarily due to limitations in the temporal resolution of available input data. This allowed us to utilize consistent, harmonized datasets across the historical period while still providing sufficient temporal granularity.

We acknowledge that shorter periods may be influenced by climate anomalies such as ENSO. However, our primary aim is to reveal broader spatial and temporal patterns of urban flood exposure over the 2000–2100 period, rather than interpreting short-term fluctuations. To address this concern,

we have added a note in the Discussion section (lines 331-338) emphasizing that results for individual 5-year periods should be interpreted with caution in regions affected by ENSO-related variability. We also highlight the importance of considering long-term trends as more robust indicators. In future work, we aim to further explore the potential influence of large-scale climate drivers such as ENSO on urban flood exposure dynamics.

Please refer to the revised manuscript (see lines 331-338) for more details.

"This study also has several limitations. Firstly..... It should be noted that the use of 5-year periods in the historical analysis was primarily constrained by the temporal resolution of available datasets. While this approach enables the detection of general trends in urban flood exposure, it may be affected by short-term hydrological variability, particularly in regions sensitive to ENSO cycles. ENSO typically operates on 2–5 year intervals and can significantly influence flood risk through its impact on precipitation and river discharge. As such, exposure estimates for individual 5-year periods should be interpreted with caution. Our focus remains on longer-term patterns over the full study period, and future research could incorporate ENSO indices to explicitly assess the extent of its influence on temporal variability in flood exposure. Future research should"

Reviewer #1, COMMENTS #6: Line 104 - if flood prone land is being converted to urban land, I can't see how the proportion of population exposed to flooding can stay constant.

Author response: Thank you for your valuable comment. We understand your concern regarding the apparent contradiction between the increasing conversion of flood-prone land and the stable or declining proportion of exposed population. We would like to clarify that our analysis specifically focuses on newly built-up urban areas, not the entire urban system. The indicators PUEF, PPEF, and PEEF refer to the proportion of new urban land, population, and economic activity that is exposed to flooding within the newly developed areas in each period. Therefore, these proportions reflect the composition of exposure in new urban development, rather than changes in exposure relative to the total existing urban population or assets.

In many cases, although newly built-up areas include more flood-prone zones (increasing absolute UEF), these areas are often designated for non-residential purposes and thus contribute less to population and economic exposure. Moreover, urban expansion into non-flood-prone zones often accounts for a larger share of population and economic growth, resulting in a stable or even declining proportion of flood-exposed development within the newly added urban areas.

We have revised the corresponding paragraph in the manuscript to better clarify this definition (see lines 134–141). Thank you again for your helpful suggestion.

"From 2000 to 2020, UEF, PEF, and EEF in newly built-up areas globally showed significant increases, with UEF rising by 7.41×10^{10} km², PEF increasing by 2.17×10^8 , and EEF growing by 2.15×10^{12} USD (Fig. 4). However, it is worth noting that the proportions of population and economic activity exposed to flooding within newly built-up areas (i.e., PPEF and PEEF) have decreased or remained stable in many regions from 2000 to 2020. This is because our analysis specifically focuses on newly built-up urban areas, where PPEF and PEEF represent the shares of newly added urban population and economic activity located in flood-prone zones. While the total urban land exposed to flooding (that is, UEF) has increased, the shares of population and economic activity exposed within newly developed urban areas have not shown a corresponding increase. This indicates that, in many cases, the proportion of new development occurring in flood-prone zones has remained relatively stable over time."

Reviewer #1, COMMENTS #7: How are informal urban settlements accounted for in your results?

Author response: Thank you for your insightful comment regarding the treatment of informal urban settlements in our analysis.

Our study uses both historical and projected urban extent data, with a consistent focus on capturing the core built-up areas where population and economic activities are most concentrated. Specifically, historical urban areas are derived from the Global Urban Boundary (GUB) dataset⁴⁸, which is based on 30 m resolution impervious surface data⁴⁹ and identifies urban land through high-density built-up features. Future urban expansion is projected using a dataset developed by Chen⁵⁰, which simulates global urban growth under the Shared Socioeconomic Pathways (SSPs). While these projections are not directly based on impervious surface data, they reflect expected urban

expansion in areas of high population and economic intensity, and are thus conceptually aligned with the GUB in representing densely inhabited urban spaces.

Informal settlements, which are often characterized by irregular structures, limited infrastructure, and variable or low impervious surface coverage, may only be partially captured in these datasets. This is particularly true where such settlements fall below the detection threshold of imperviousness or where their morphology differs from formal built-up areas. Consequently, our analysis may underestimate urban flood exposure in these areas.

We acknowledge this as a limitation of our study, primarily due to the lack of globally consistent, high-resolution data on informal settlements. Addressing this gap is an important direction for future research. Incorporating urban morphology, socioeconomic indicators, and fine-scale population data may improve the representation of informal settlements in global flood exposure assessments.

We have added corresponding clarifications to the Discussion section (see lines 258-262, 329-331 and 340) and the Data section (see lines 363-367) to acknowledge this limitation and its potential implications.

In the Discussion section: “Urban flood exposures are unevenly distributed between the Global South and the Global North, a pattern clearly revealed by our analysis using Gini coefficients and regional disaggregation (Fig. 6). It is also important to note that our analysis may underestimate flood exposure in some of the most vulnerable areas, as both the Global Urban Boundary (GUB)⁴⁸ and projected urban expansion datasets⁵⁰ primarily capture formal urban areas. Informal settlements may be underrepresented in these datasets, particularly in low-income countries where such settlements are widespread. This data limitation underscores the need for future research to better incorporate informal urban areas into global flood exposure assessments.

.....
This study also has several limitations. Firstly, Fourthly, both the historical and projected urban area datasets used in this study do not explicitly capture informal settlements, which may lead to underestimation of flood exposure in these particularly vulnerable areas. Future research should further incorporate dynamic floodplain changes, explore the interactive effects of socio-economic development, climate change, and urban flood exposures, consider the role of flood protection measures, and improve the representation of informal urban areas by integrating socioeconomic and urban morphology datasets. Additionally,

In the Data section: “The historical urban area data are from the Global Urban Boundary (GUB) dataset⁴⁸, which was developed based on the 30 m resolution Global Annual Impervious Area dataset⁴⁹, covering the period from 2000 to 2020 in 5-year intervals. Future urban expansion data are derived from global urban land expansion projections under the Shared Socioeconomic Pathways (SSPs) by Chen⁵⁰, with a spatial resolution of 1 km and covering 2030 to 2100 in 10-year intervals. Both datasets focus on mapping built-up urban areas with high population and economic density, and are widely used for global urban analyses. However, it is important to note that informal settlements, which are typically characterized by irregular structures and low or variable impervious surface coverage, may be underrepresented, particularly in the GUB dataset. This limitation could result in an underestimation of flood exposure in such areas, especially in low-income or rapidly urbanizing regions.”

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Reviewer #1, COMMENTS #8: Figure 4 - swapping around the colours for the periods here compared to the other figures is very confusing. Also are the period dates here correct? why is 2000-2015 and then 2005-2010, 2010-2015 and 2015-2020?

Author response: Thank you very much for pointing this out. We sincerely apologize for the confusion caused by the inconsistent color usage and the incorrect time period labeling.

First, regarding the color scheme: Fig. 1 and Fig. 4 represent different types of temporal data. Fig. 1 shows five specific years (2000, 2005, 2010, 2015, and 2020), while Fig. 4 reflects changes over four time intervals (2000–2005, 2005–2010, 2010–2015, and 2015–2020). In Fig. 1, we used the following color scheme: 2000: white; 2005: grey; 2010: green; 2015: blue; 2020: red. To improve consistency and help readers intuitively associate the intervals with their starting years, we have

revised Fig. 4 using a matching logic: 2000–2005: white, 2005–2010: grey, 2010–2015: green, 2015–2020: blue. This harmonized scheme preserves the chronological order while avoiding potential confusion. We have also revised the figure legend and caption accordingly.

Second, regarding the period labeling error: You are absolutely right, the label “2000–2015” in the original version of Fig. 4 was incorrect. It should have been “2000–2005.” This was an oversight on our part, and we have corrected the label in both the figure and the caption in the revised manuscript. We are grateful for your careful review and thoughtful suggestions, which have helped us improve the clarity and accuracy of our presentation.

The modified Fig. 4 is as follows:

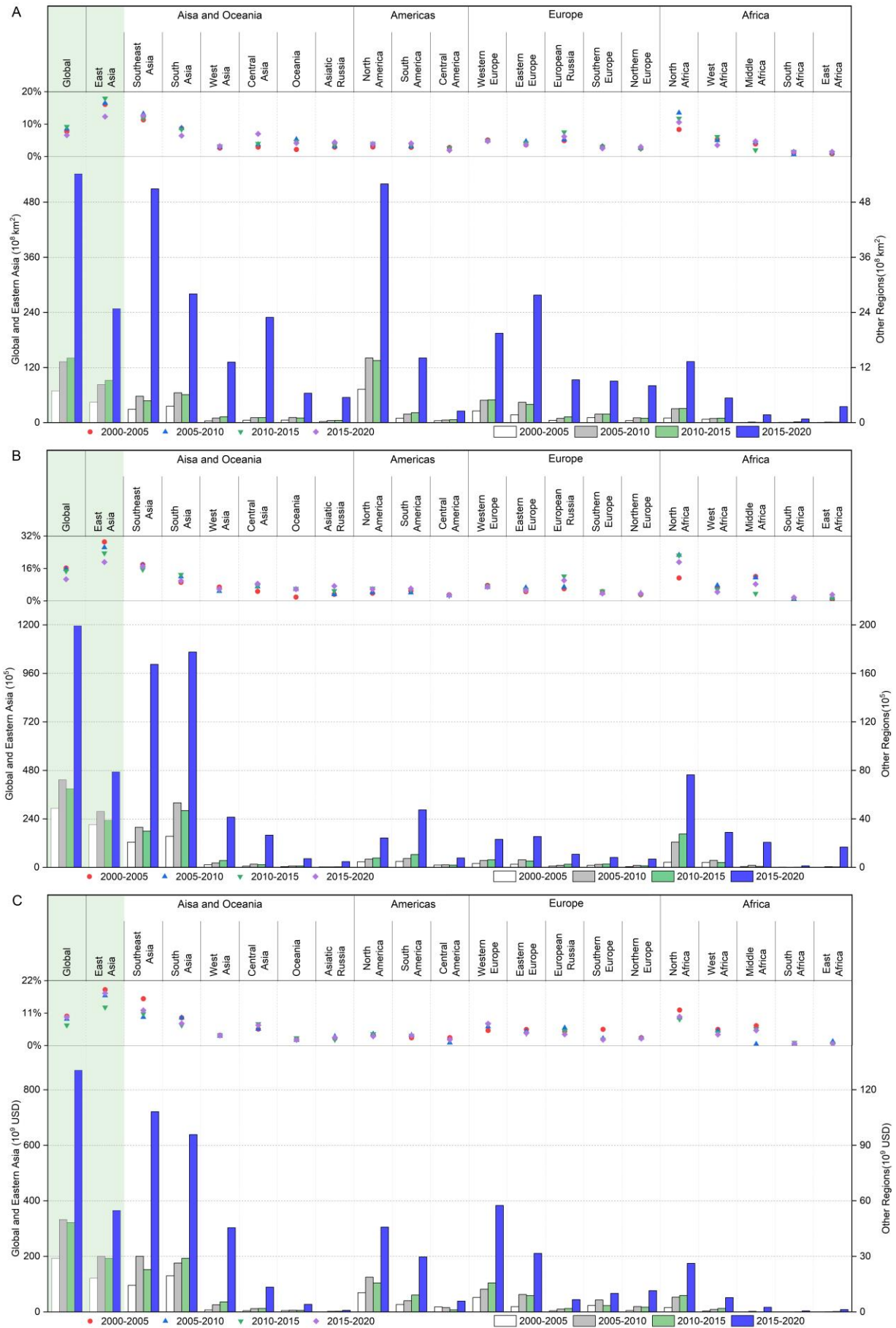


Fig. 4. Flood exposures in newly built-up urban areas from 2000 to 2020. The scatter plots show the proportion of newly added urban land, population, and economic activity located in flood-prone areas. The bar charts show the absolute amount of newly developed urban land, population, and economy exposed to flooding. **(A)** UEF and PUEF. **(B)** PEF and PPEF. **(C)** EEF and PEEF.

Reviewer #1, COMMENTS #9: line 156 - what does rational population distribution mean?

Author response: Thank you for your question regarding the term “rational population distribution” in our manuscript. By “rational population distribution”, we refer to the strategic and planned allocation of population growth and urban development to minimize exposure to flood risk. This includes directing population and infrastructure away from flood-prone areas, improving land-use planning, and encouraging urban expansion in safer zones through effective policy interventions.

We will clarify this term in the revised manuscript to avoid ambiguity and to better highlight the role of planned urban development and flood risk management in mitigating exposure (see lines 196–199).

“Specifically, at the global scale, PUEF increased most significantly under SSP3 (5.84%) and decreased slightly under SSP1 (-1.34%), indicating that regional competition and unsustainable urbanization may lead to further development of flood-prone zone as built-up areas—a trend effectively mitigated by the sustainable development pathway of SSP1.This implies that population exposures in these regions can be reduced through rational population distribution, which involves concentrating populations and infrastructure away from flood-prone areas, strengthening land-use planning, and promoting urban development in safer locations through effective policy measures, along with effective flood management.”

Reviewer #1, COMMENTS #10: Table 1 - should be in supplementary material. This is not an effective way to communicate results.

Author response: Thank you for your thoughtful suggestion. We acknowledge that Table 1 was not have been the most effective way to communicate the results. In response, we have converted the table into a more intuitive visual format and relocated it to the Supplementary as Fig. S2. We hope this revised figure offers a clearer and more accessible summary of the key patterns, thereby improving the overall presentation of our findings.

Accordingly, we revised the relevant sentence in the main text (lines 177-178) to:

“The global UEF, PEF, and EEF were projected to continue rising, but the spatial distribution will largely remain consistent with historical patterns (Fig. S1), with high values concentrated in East Asia, South Asia, and the western and southern regions of the United States. PUEF, PPEF, and PEEF exhibited more varied patterns, and the magnitude of their changes from 2030 to 2100 is detailed in Supplementary Fig. S2.”

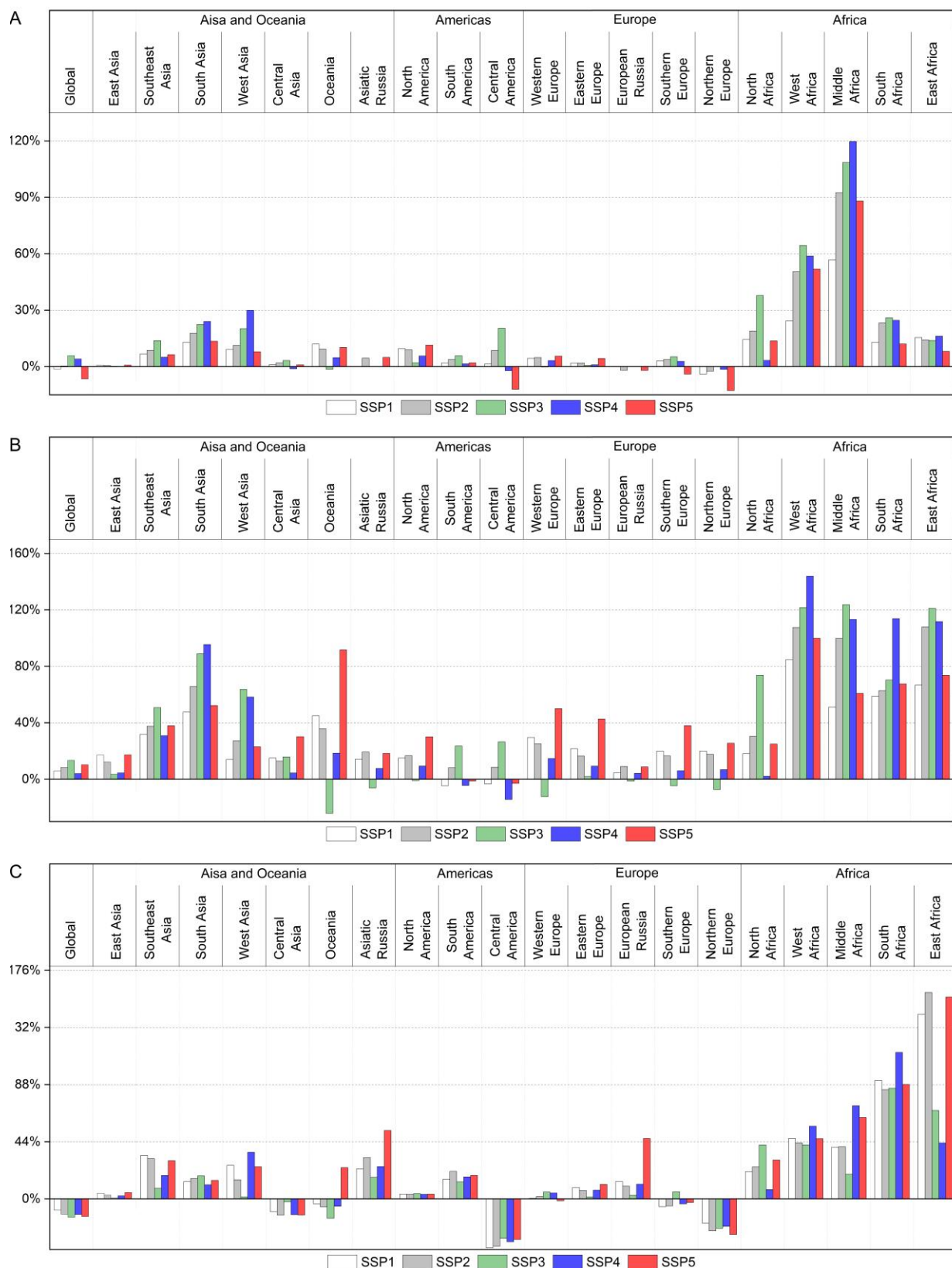


Fig. S2 Future changes in PUEF, PPEF, and PEEF under different SSPs. (A) PUEF. (B) PPEF. (C) PEEF.

Reviewer #1, COMMENTS #11: line 309 - how is significance of the Getis-ord statistic defined?

Author response: Thank you for pointing this out. The significance of the Getis-Ord G_i^* statistic is determined by calculating the corresponding z-score and p-value for each spatial unit. A location is identified as a hotspot (i.e., a statistically significant high-value cluster) if its z-score is significantly greater than zero and the p-value falls below a given threshold (commonly 0.05), indicating spatial clustering of high values. Conversely, a coldspot (low-value cluster) is identified when the z-score is

significantly less than zero with a p-value below 0.05. Locations with non-significant z-scores (p-value ≥ 0.05) are considered to have no statistically significant clustering.

In this study, we adopted a significance level of 0.05 to define hotspots and coldspots. To improve clarity and reproducibility, we have revised and expanded the Data section to more clearly describe the spatial units used in the Getis-Ord G_i^* analysis and the criteria applied for determining statistical significance (see lines 403–408). We appreciate this comment, which helped us improve the clarity of our methodology and ensure greater transparency in our analytical framework.

“To determine whether a location is a statistically significant hotspot or coldspot, we calculated the z-score and corresponding p-value for each unit. A location is considered a statistically significant hotspot if it has a positive z-score and p-value < 0.05, indicating a cluster of high values. Conversely, a negative z-score and p-value < 0.05 identify coldspots, or clusters of low values. Values with p-value ≥ 0.05 are regarded as not statistically significant and are excluded from hotspot or coldspot interpretation. This statistical framework allows for robust identification of significant spatial clusters in urban flood exposure.”

Reviewer #2, COMMENTS #1: This manuscript analyses the global urban flood exposure during the historical and future periods in terms of urban area, population, and economic aspects, using existing global datasets, with a focus on inequalities and disparities. While the topic is still interesting, the novelties added by this study are not clear. There are existing studies on historical and future global flood exposure, and inequality aspects of urban flood impacts (see below for specific examples). What is new here exactly? The introduction articulates well the importance of the topic, but fails to clarify what are lacking from existing studies and hence correctly motivate this manuscript.

Example 1. On historical global flood exposure in urban areas

Cao, W., Zhou, Y., Güneralp, B., Li, X., Zhao, K., & Zhang, H. (2022). Increasing global urban exposure to flooding: An analysis of long-term annual dynamics. *Science of The Total Environment*, 817, 153012.

Example 2. On future global flood exposure under SSP

Rogers, J. S., Maneta, M. M., Sain, S. R., Madaus, L. E., & Hacker, J. P. (2025). The role of climate and population change in global flood exposure and vulnerability. *Nature Communications*, 16(1), 1287.

Example 3. On inequalities and disparities in urban flood impacts

McDermott, T. K. (2022). Global exposure to flood risk and poverty. *Nature Communications*, 13(1), 3529.

Author response: Thank you very much for this valuable and constructive comment. We fully agree that clearly articulating the novel contributions of our study is essential. In response, we have revised the Introduction (see lines 63–71) and the Discussion section (see lines 308–319) to more clearly highlight how our study complements and extends existing research.

Specifically, our work builds upon previous studies in several important ways:

1) Multi-dimensional assessment: While Cao et al. (2022) focused on historical changes in flood-exposed urban areas, our study extends the analysis by evaluating flood exposure in terms of urban land (UEF), population (PEF), and economic activity (EEF), with the aim of providing a more comprehensive understanding of urban flood risk.

2) Focus on newly built-up areas: Rogers et al. (2025) examined future global flood exposure under SSPs, primarily considering the roles of climate and population change. Our study adds a new perspective by explicitly analyzing flood exposure within newly urbanized areas. This approach allows us to directly link urban expansion patterns to emerging flood risks, which are often overlooked in other projections.

3) Temporal and spatial evolution of inequality: While McDermott (2022) emphasized global disparities in flood risk, our analysis quantifies inequalities across subnational, national, and global levels and traces how these disparities evolve over time under different Shared Socioeconomic Pathways. In particular, we highlight the widening exposure gap between the Global South and Global North, providing insights into future climate justice and risk governance challenges.

We hope these clarifications help to better position the unique contributions of our work. We believe our findings offer a valuable addition to the literature, particularly with respect to understanding the implications of urbanization for future flood exposure and inequality, and informing more targeted and equitable adaptation strategies.

Please refer to the revised manuscript (e.g., Lines 63-71, and 308-319) for more details.

In the Introduction section: *“While existing studies have explored global flood exposure from various perspectives, such as historical dynamics of flood-prone urban areas¹⁰, future population-driven exposure projections²⁶, and inequality in flood risks⁵, several critical gaps remain. First, most previous research has focused on a single exposure dimension (e.g., urban area or population), lacking a comprehensive, multi-dimensional assessment. Second, the role of urban expansion in shaping future flood exposure has not been sufficiently investigated. Third, while some studies have examined inequality in flood risk, few have analyzed how such disparities evolve over time under different future socioeconomic scenarios.*

To fill these gaps, we analyze urban flood exposure across historical (2000–2020) and future periods (2030–2100) under various Shared Socioeconomic Pathways (SSPs), covering multiple spatial scales including global, national, subnational, and the Global South–North divide. Specifically, our objectives are:”

In the Discussion section: *“This study systematically analyzed the spatiotemporal evolution of global urban flood exposures by combining historical urban area, population and economy data for 2000–2020 with SSPs simulation data for 2030–2100, offering a comprehensive understanding of both past and future exposure dynamics. Unlike most previous studies that focused solely on one dimension, such as urban area, population, or economy, we simultaneously assessed urban flood exposures in all three dimensions (UEF, PEF, and EEF), providing multidimensional support for exposure analysis and expanding the theoretical framework for related research. In addition, by focusing on newly built-up areas, we revealed how urban expansion directly contributes to increased flood exposure, underscoring the close link between urban growth and flood risk. Furthermore, by applying inequality metrics such as the Gini coefficient across multiple spatial scales, including national and subnational levels as well as the divide between the Global South and Global North, we uncovered not only the overall magnitude of exposure but also its evolving inequality patterns. These findings provide scientific evidence for equitable flood risk governance, climate adaptation, and forward-looking urban planning, especially in the Global South, where the challenges are particularly acute.”*

References

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26. Rogers, J. S., Maneta, M. P., Sain, S. R., Madaus, L. E. & Hacker, J. P. The role of climate and population change in global flood exposure and vulnerability. *Nat. Commun.* 16, 1287 (2025).

Reviewer #2, COMMENTS #2: In Fig. 1, there is an interesting pattern: From 2015 to 2020, there were much higher increase in UEF and PEF across the globe than 2000-2015 period. When you look at EEF, however, there was a much lower increase in Central America, or even decrease in North America. Why did this happen?

Author response: Thank you very much for this insightful and valuable comment. In response, we revisited the original dataset and confirmed that several subnational regions in North and Central America experienced declines in economic exposure to urban flooding (EEF) between 2015 and 2020. We further extended our analysis to Southern and Northern Europe, where we observed similar patterns. For instance, regions such as New York, New Jersey, Lazio, Emilia-Romagna, and England exhibited substantial reductions in both the absolute value of EEF and its share of regional GDP (PEEF). To better understand this trend, we also examined UEF, PEF, and their corresponding proportions (PUEF and PPEF). We found that although UEF and PEF generally increased across most regions, in certain areas such as New Jersey, the proportion of urban land and population exposed to flooding declined, despite an increase in absolute exposure. This suggests that flood-sensitive urban planning may have helped redirect new development away from high-risk zones, thereby reducing the concentration of economic assets in flood-prone areas. We believe these regional declines in EEF are linked to improved land-use planning, economic decentralization, and risk-informed decision-making in more economically developed contexts. To clarify this point, we have added a new paragraph in the Results section (see lines 95-109) and included a detailed summary of key regions in Supplementary Table S2.

“While most regions experienced increasing trends in UEF and PEF from 2015 to 2020, several economically developed areas showed a decline in EEF. This pattern is particularly evident in North America, Central America, Southern Europe, and Northern Europe. A summary of key regions with significant decreases in EEF

and PEEF is provided in Supplementary Table S2. For instance, New York (-9.13 billion USD), Lazio (-17.43 billion USD), and England (-18.65 billion USD) all experienced significant reductions in EEF, both in absolute terms and relative to their regional GDP (PEEF). Interestingly, in some of these regions such as New Jersey, although the exposed urban area and population increased, their proportional exposure (PUEF and PPEF) declined, suggesting that new development may have shifted to lower-risk zones. These trends likely reflect the influence of land-use regulation, economic restructuring, and strategic investment in protective infrastructure. However, it is important to note that despite these localized declines, most regions in North America, Central America, Southern Europe, and Northern Europe still experienced increases in UEF and PEF, indicating that the overall trend across these subcontinents remains one of rising flood exposure, albeit with important regional differences. These findings highlight a nuanced picture: although most regions within North America, Central America, Southern Europe, and Northern Europe experienced rising trends in UEF and PEF, there are exceptions where economic exposure decreased due to effective spatial planning and resilience investments. Such cases illustrate how policy and planning can offset some of the risks associated with urban expansion, even if the overall exposure continues to rise.”

Table S2. Regions with declines in EEF and PEEF from 2015 to 2020 and related urban and population exposure to urban flooding.

Subcontinental region	Subnational region	The change of UEF (10 ⁷ km ²)	The change of PUEF	The change of PEF	The change of PPEF	The change of EEF (billion USD)	The change of PEEF
North America	New York	2.66	0.18%	91212	0.16%	-9.13	-1.11%
	New Jersey	1.37	-0.02%	33185	-0.16%	-7.50	-2.43%
	Wisconsin	-1.71	0.74%	16838	-0.13%	-6.01	-3.60%
	Illinois	-0.34	0.69%	31300	-0.01%	-5.51	-0.24%
	Massachusetts	1.29	-0.05%	28690	0.42%	-4.25	-1.74%
Central America	Oregon	2.74	-1.63%	54478	0.11%	-3.92	-4.82%
	Ciudad de México	0.43	-1.29%	-94388	-0.86%	-3.08	-0.70%
	Estado de México	-0.17	-0.38%	147338	-0.11%	-1.91	-1.37%
	Panamá	0.17	-2.46%	13212	0.05%	-0.92	-2.76%
	Querétaro	0.00	0.40%	3855	0.21%	-0.12	-0.42%
Southern Europe	San José	0.09	-0.04%	289	0.01%	-0.01	-0.03%
	Lazio	0.94	-7.14%	71557	-3.47%	-17.43	-6.93%
	Emilia-Romagna	0.69	0.57%	74665	0.95%	-0.58	-1.04%
	Grad Zagreb	0.26	2.95%	7673	-0.21%	-0.40	-2.39%
	Lisboa	0.17	-1.37%	1687	-0.15%	-0.11	-0.12%
Northern Europe	England	1.97	-0.10%	300808	-0.04%	-18.65	-1.34%
	Viken	-0.09	-19.45%	1562	-15.07%	-4.17	-22.89%
	Telemark	0.17	-14.46%	7060	-6.85%	-1.47	-14.81%
	Dublin	0.17	0.70%	4510	0.36%	-0.35	-0.43%