

European coastal deformation drives unequal exposure to climate hazards

Corresponding Author: Professor Chisheng Wang

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 Wang,

Your manuscript titled "European coastal deformation drives unequal exposure to climate hazards" has now been seen by 3 reviewers, whose comments are appended below. You will see that they find your work of some potential interest. However, they have raised substantial concerns that must be addressed. In light of these comments, extensive revisions will be required before we can further consider the manuscript for publication. We would, however, be interested in considering a revised version that fully addresses these serious concerns. Specifically, a revised manuscript must:

1. Provide a detailed explanation of the population and asset exposure analysis methods to ensure transparency and reliability in evaluating climate-related risks.
2. Revise the analysis of socioeconomic vulnerability and assess current methods for evaluating social inequality to ensure alignment with EU policymaking priorities.

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

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.

If the revision process takes significantly longer than three months, we will be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

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:

Link Redacted

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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,

Olusegun Dada, PhD
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Alireza Bahadori, PhD
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Communications Earth & Environment
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

Title: European coastal deformation drives unequal exposure to climate hazards

This manuscript addresses an important topic; however, it requires major revisions to enhance its quality.

Abstract:

The abstract is well-written; however, the authors should clarify how these results will be beneficial to the European policymakers.

Keywords: The term "European Region" should be included as one of the keywords.

Introduction:

This section is good but could be improved by incorporating more recent literature.

In the second paragraph, the authors state, "Numerous coastal areas around the globe are already under continuing and intensifying pressure. By the 2050s." It would be beneficial for the authors to provide examples of at least five specific coastal areas.

Figure 2 is unclear. Which colour represents subsidence hotspots on the map?

The manuscript appears to be a lack of a regular format for this article, which should include the following sections:

1. Introduction
2. Results and Discussion
3. Methods (this is included in a separate file but not within the main article)
4. Limitations
5. Recommendations

Without these subheadings, it is challenging to review the article effectively. The authors need to revise the article accordingly and re-submit

Reviewer #2 (Remarks to the Author):

Dear authors,

The research presented in this manuscript is relevant and timely, particularly given the increasing threats posed by land subsidence and sea-level rise to coastal areas. The paper aims to deliver a pan-European assessment of coastal vulnerability by integrating vertical land motion data with land cover, SLR projections, and socioeconomic indicators. This is an important and ambitious effort that can make a valuable contribution to the field. However, I found that a few aspects of the manuscript remain unclear, so please see below my comments on that regard. I'm sorry for any potential harshness and I wish the authors the best.

Abstract:

I'm unsure if 100m can be considered high-resolution in the context of Interferometric Synthetic Aperture Radar data, please check.

-

Please add citations to where #4 is being cited since the claim at global scale and the only study being cited is about China. First paragraph – Please clarify that other impacts of climate change have also been observed and that subsidence and SLR are among them. The transition between global scale and general impacts of two specific hazards is too abrupt.

The acronym SLR is introduced in the first paragraph so I kindly suggest to use that every time sea level rise is mentioned. The study #10 is about port cities, not sure that claim on second paragraph can be supported by only that.

Citation #33 is misplaced.

Please clarify the extent, covered area, or resolution of a pixel. I'm unsure what 65mi pixels mean.

Fig 1. - Please include a legend, or something in the caption explaining what the blue and red dashed lines represent in the subplot figure.

Fig 1. - Please add the numbers of respective countries presented in the boxplots to the map to facilitate the communication.

Fig 1. - If you chose to keep the coordinate grid, please show the coordinates.

Fig 2. - Add labels to national boundaries; Add labels to seas/oceans.

Fig 2. – The gray boxes are stretched and not properly aligned to the maps.

Add citations to the sentence "...small islands, many of which are further challenged by resource scarcity."

Unless this is how the dataset is really called, I don't think the 100m land cover dataset should be referred to as "high-resolution"

Fig.3 – Please remove the figure title and use the caption for that.

Fig.3 – Is this land use or land cover? Caption is confusing and I also noticed that in the methodology both terms are used as synonyms (they are not).

The shift from Europe-wide statistics to regional case studies (Netherlands, UK, Italy) is too abrupt.

Fig. 5 - There is one label missing in panel C (above Lincoln).

Fig. 5 – An overview map is necessary to help readers locate where each subplot is in the bigger picture of each country.

Please avoid adding new topics or new information to the conclusion and focus on presenting the conclusion of this study.

For example, talking about significant risk from tsunamis is something that could have been mentioned earlier in the text and does not come from your lessons learned in the study.

Including a discussion (or at least acknowledging) uncertainties in the projections and the bathtub method would greatly strengthen the scientific rigor of this study. In the same context, authors assume that current demographic structures (e.g., % of elderly and children) remain static through 2050, which is unlikely given expected demographic shifts.

The 100 km inland buffer is reasonable, but somewhat arbitrary for the coastal zone definition. A brief justification would be great about this.

Transforming economic values to percentiles within each country may preserve national context, but it masks absolute disparities across countries. This limits cross-country interpretation of adaptive capacity and should be discussed.

The manuscript states that 24.767 million people and 8.371 million buildings will be affected. Maybe these figures suggest an unrealistic level of precision given the data that was used.

The mention of €3.4 trillion in asset value in the Netherlands lacks detail on how this figure was calculated.

Reviewer #3 (Remarks to the Author):

This paper claims to be the first to couple VLM with social vulnerability in a study of exposure to SLR across all of Europe.

1. VLM analysis:

The authors use an analysis of VLM that is mostly consistent with the analysis previously published by Thieblemont et al (2024) for the same region.

It is not clear to me how the VLM methods used for the current manuscript differ from Thieblemont et al, except that two overlapping time periods are used in the current manuscript. The authors cite Thieblemont et al 2024 in their Supplemental Material only in a very general way, referring to those authors' framing of the VLM source data, and does not clearly compare this new VLM to the Thieblemont et al results from 2024. However, the VLM assessment used here seems generally

consistent with the Thieblemont et al results. My point is that the VLM assessment itself is not novel, but the relationship to the work described in the current manuscript is not clear. In fact, a figure from the current manuscript (Figure 2) seems very similar to a figure in Thieblemont et al (Figure 7 in that paper), which was the first to identify the Schiavone region of Italy as vulnerable to SLR because of VLM. The authors should cite Thieblemont et al (2024) much more clearly in the VLM section of this new manuscript to identify their own original contributions vs. the contributions of that recent paper. It's also not clear why they used two strongly overlapping temporal periods to try to establish trends in VLM.

2. SLR scenario

The current manuscript notes that it is using an IPCC scenario for SLR in 2050, but the specific scenario is only mentioned in the supplemental material (SSP2 4.5). This should also be noted in the main manuscript since it is a key driver of their estimates of exposure.

3. Study areas

The authors state that they defined the coastal zone to be the zone 100 km from the shore, then go on to say that they used a "bathtub model" for SLR flooding exposure with a DEM. It's not clear whether they used the same Coastal Flood Plain extent as Thieblemont et al 2024, but their Figure 6 does appear to show those defined Coastal Flood Plains for their analysis of income levels. The authors should clarify which spatial extents were used for each analysis of population and asset exposure, and note whether the extents vary (is it sometimes the inundation-prone zone and at other times only the subsiding area within the inundation zone?) or whether they consistently used the Coastal Flood Plains defined in Thieblemont et al 2024.

Original contributions?

4. Land cover data and exposure analysis

The paper considers land cover using a highly simplified 5 category typology, and Fig 3 describes the distribution of "subsiding pixels" for each. The figure has some confusing labels ("land use cover", and the word "less") but is otherwise useful and interesting in spite of the simplicity of the land cover categories. Thieblemont et al 2024 also looked at land cover in relation to coastal subsidence, and came to similar conclusions about wetland subsidence rates being high. That older paper also used finer categories for the built environment (airports, rail lines, etc) which is more helpful than the current manuscript's use of "artificial areas" as a land cover category that lumps all aspects of the built environment into one category.

5. Exposure of buildings and other assets

Population and assets were characterized previously on a global scale that included the European region. Jongman et al 2012 reviewed global population exposure, including income levels, as well as asset exposure using GDP. Thieblemont et al 2024 used specific public assets (transportation infrastructure) for European coastal floodplains, which is arguably more useful than reporting the value of private assets since transportation systems are typically publicly-owned, intended to be permanent, and impact many aspects of a regional economy.

This manuscript used a global database of building footprints, and somehow integrated housing prices from cost of living data- but the method for the use of the data is unclear. As an economic analysis, this is unusual in my experience – other papers have used estimates of GDP, for example, which considers economic output in addition to private property values. Property values are usually used when a cost-benefit ratio is being calculated for adaptation, which is not the case here. While unsophisticated, the number of buildings and total value of housing could be used to represent asset values in the exposure zones. But the authors should provide more discussion of the details of their method in the supplemental materials in order for readers to determine the validity of their methods.

6. Population exposure and equity

Identifying the inequalities of exposure for populations is described by the authors as the primary contribution of the paper. They use a quartile approach to standardize income metrics as their measure of the relative level of private resources across regions and countries. While income is only an indirect measure of resources (it does not consider wealth in the form of property, or health status, or education level) it is not an unreasonable beginning for a discussion of vulnerability. The map they produce in Figure 6 is novel, to my knowledge.

They used census data to identify proportions of populations 65 years of age and over, or under 14 years of age, and then assumed that these proportions would hold true in 2050. However this is unlikely to be the case; demographic trends should have been considered instead of static proportions.

Finally, the authors used the presence of Roma settlements as an indicator of vulnerability, by focusing on the presence/absence of a group that has been described as especially vulnerable in regional analyses and policy.

7. Geographic scale used for comparisons

A series of country-scale assessments is used to characterize differences in exposure by area, population size, number of

buildings, and other assets. While normally country-scale comparisons can obscure important spatial patterns, the differences among these four are useful in pointing out the significance of SLR exposure for urban areas (with higher population, numbers of buildings, and other infrastructure assets).

Throughout, there is some lack of clarity about what the unit of analysis is for each variable. Were the demographic, economic and asset analyses all applied within the areas of the defined inundation zone that are subsiding? What is the threshold that defines "subsiding" land for this spatial analysis, is it -1 mm/year or simply <0?

Overall comments

This manuscript has a strong focus on the VLM analysis, and yet that is not novel. The authors want the reader to focus on their analysis of the exposure of people, buildings and land cover types, and especially on the exposure of people with lower incomes / different costs of living or property values / minority Roma settlements. While this socioeconomic exposure analysis may be new for subsiding areas of coastal flood risk, it's not clear that the methods used here are based on a knowledge of methods developed recently by experts in this type of socioeconomic analysis. The primary citation used for related work in the planning/socioeconomic literature seems to be from 2012 (Jongman et al). It's also not clear that the variables chosen to represent inequality are important to policy in the European Union. Since equity is a normative variable that has been defined in different ways over different historical periods, it would be helpful for the authors to identify metrics for inequality that are currently being used in EU policymaking. Adaptation planning will use some of the same socioeconomic characterizations as any other kind of planning.

I would suggest significant revisions to address (1) the relationship of the methods and results of this study to the methods and results of Thieblemont et al 2024; (2) a brief review of current methods for assessing social inequality, with an emphasis on methods relevant to EU policymaking and a revised analysis of socioeconomic vulnerability based on both; and (3) clarification of the spatial units used for each analysis.

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Version 1:

Decision Letter:

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Dear Professor Wang,

Your revised manuscript titled "European coastal deformation drives unequal exposure to climate hazards" 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,

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Alireza Bahadori, PhD
Senior Editor
Communications Earth & Environment
Consulting Editor
Communications Sustainability

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

Authors addressed all of my comments well.

Reviewer #2 (Remarks to the Author):

Dear authors, I'm satisfied with your revisions and appreciate the rigor and care taken in addressing each of my comments. From my end, the manuscript is ready for publication. Thank you.

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Response Letter to Reviewer Comments

We sincerely appreciate the efforts of the editors and reviewers. Your comments and suggestions have helped us to improve the quality of the manuscript.

In this response letter, the reviewers' comments are shown in black and our replies are shown in blue. The new text added to the manuscript is indicated in purple italics and new included references are listed all together at the end of this document. The corresponding pages and revised contents are indicated in the Article File document.

Reviewer #1:

Comments 1:

Title: European coastal deformation drives unequal exposure to climate hazards

This manuscript addresses an important topic; however, it requires major revisions to enhance its quality.

We are pleased to note that the reviewer recognized the importance of our study. We have addressed the comments by undertaking substantial revisions to enhance the manuscript. Key improvements include:

- (i) clarifying the policy relevance in the Abstract;
- (ii) integrating more recent literature into the Introduction;
- (iii) providing concrete examples of vulnerable coastal areas;
- (iv) improving the clarity of Figure 2;
- (v) restructuring the paper to incorporate Methods and Limitations sections.

We believe the reviewer's valuable feedback has significantly strengthened the work, and we extend our sincere appreciation for their input.

Comments 2:

Abstract:

The abstract is well-written; however, the authors should clarify how these results will be beneficial to the European policymakers.

We thank the reviewer for the positive feedback and valuable suggestion. We fully agree that emphasizing the policy relevance of our work is essential. As highlighted in EU guidelines, coastal protection planning at local and regional levels requires more detailed coastal flood risk assessments than are currently available at the pan-European scale^[1]. Building on this, we revised the abstract to underline the contribution of our study to policy applications. Specifically, we modified the sentence from:

Original: "This first pan-European assessment of coastal subsidence coupled with socioeconomic vulnerability highlights the urgent need for targeted adaptation strategies addressing both

physical hazards and social inequalities.”

(Page 1, lines 25–28)

Revised: “This first pan-European assessment of coastal subsidence and socioeconomic vulnerability provides scientific evidence for directing adaptation resources to vulnerable communities. It also highlights the urgent need for targeted adaptation strategies to address both physical hazards and social inequalities.”

This revision emphasizes the policy-relevant contribution of our findings by demonstrating how they provide a scientific basis for guiding adaptation resources and planning, thereby strengthening the connection between our results and their potential applications for European policymakers.

Comments 3:

Keywords: The term “European Region” should be included as one of the keywords.

We thank the reviewer for this helpful suggestion. We have revised the manuscript accordingly and added “European Region” to the list of keywords. See line 31 of the revised manuscript.

Comments 4:

Introduction:

This section is good but could be improved by incorporating more recent literature.

We are grateful to the reviewer for the constructive suggestion to include more recent literature. In response, we have substantially revised the Introduction to improve its timeliness and scholarly support. Key enhancements include:

- (i) elaborating on the multifaceted impacts of climate change to frame the discussion on RSLR;
- (ii) adding concrete examples of vulnerable coastal cities with citations from recent studies;
- (iii) citing a pivotal EU policy document to establish the importance of research on climate change inequality.

The specific revisions including citation of more recent literature are detailed below:

1. In the discussion of land subsidence and sea-level rise, we have expanded the narrative to explicitly include the observed impacts of climate change. The original sentence has been refined to better establish the context that RSLR is one of many interconnected climate-related threats.

Original: “The observed land subsidence and sea level rise (SLR) over the past century pose a significant threat to these coastal areas, and their vulnerability is constantly increasing with global climate change and ongoing human activities.”

(Page 2, lines 41–46)

Revised: “In particular, climate change exacerbates risks through multiple pathways, including the increasing frequency of extreme storm events, the degradation of coastal ecosystems, and sea-level rise (SLR)^[2–4]. Against this backdrop, land subsidence and SLR, observed over the past century, pose significant threats to coastal areas, whose vulnerability continues to intensify under ongoing climate change and human activities.”

Newly incorporated literature:

[2] He & Silliman (2019): This key review provides the theoretical framework that climate change exacerbates coastal risks through multiple pathways, including storms, ecosystem degradation, and SLR.

[3] Wu et al. (2024): Their modeling study quantifies the compound effects of SLR and extreme climate events, revealing the mechanism by which these factors, together with land subsidence, exacerbate flood risk.

[4] Abdulla et al. (2025): This regional study on Qatar's coastline provides direct observational evidence of the significant trend of SLR and its associated threats under global warming, highlighting its universality and urgency.

2. In the statement regarding global coastal pressure, we have substantiated the claim by citing the latest research and providing specific examples of cities severely affected by land subsidence, thereby illustrating the immediate pressure from RSLR.

Original: “Numerous coastal areas around the globe are already under continuing and intensifying pressure.”

(Page 2, lines 48–51)

Revised: “Numerous coastal areas worldwide are already under intensifying pressure from relative sea-level rise. This risk is further exacerbated in cities undergoing severe land subsidence—such as Jakarta, Tianjin, Ho Chi Minh City, Venice, and New Orleans—where groundwater over-extraction and soft soil compaction significantly heighten their vulnerability to inundation^[5–10].”

Newly incorporated literature:

[5] Tay et al. (2022): Provides authoritative global data and a comparative benchmark on local land subsidence in major coastal cities, supporting our argument for cities like Jakarta, Tianjin, and Ho Chi Minh City.

[6] Anzidei et al. (2025): Offers a case-specific basis for Venice by quantifying the compound impact of land subsidence and climate-induced SLR through multi-temporal data analysis.

[7] Yu et al. (2023): Provides direct regional evidence for the Tianjin case, analyzing the superimposed effect of land subsidence and SLR and assessing the resulting inundation risk.

[8] Duffy et al. (2020): Supports the claim for Ho Chi Minh City by revealing the spatial pattern and rate of urban land subsidence using satellite data.

[9] Wu et al. (2022): Substantiates the significant inundation risk due to land subsidence in cities like Tianjin and Jakarta from a global perspective.

[10] Ohenhen et al. (2024): Strengthens the argument of urgent inundation pressure for coastal cities like New Orleans using precise quantitative assessments of land subsidence-induced territory loss.

3. In constructing the context for the relationship between European VLM patterns and social vulnerability, we cited fundamental EU policy documents to establish the policy relevance of research on climate inequality. The additional sentence is as follows:

(Page 4, lines 96–101)

More importantly, from an equity perspective, the risks associated with land subsidence are likely to be distributed highly unevenly across different social groups. At present, systematic understanding at the European scale of how the spatial patterns of ground subsidence interact with land cover and socio-economic factors to shape social vulnerability remains limited. This knowledge gap constrains progress toward the equitable adaptation goal of “no person and no place should be left behind”^[11, 12].

Newly incorporated literature:

[11] European Commission. The European Green Deal, 2021: This strategy introduces the imperative for a “just and inclusive” transition, thereby establishing the core conceptual framework for addressing inequalities arising from climate impacts and mitigation policies.

[12] Council of the European Union. Council Recommendation on ensuring a fair transition towards climate neutrality, 2022: This document explicitly outlines climate fairness as a current policy priority, providing actionable guidance to address disparities and protect the most vulnerable. Its content directly validates the societal and policy relevance of our research on differential climate impacts.

We believe that these substantive revisions, supported by a robust body of recent literature, have significantly enhanced the scholarly foundation, relevance, and clarity of our Introduction. We are grateful for the reviewer's insightful comment, which has greatly strengthened this section.

Comments 5:

In the second paragraph, the authors state, “Numerous coastal areas around the globe are already under continuing and intensifying pressure. By the 2050s.” It would be beneficial for the authors

to provide examples of at least five specific coastal areas.

We sincerely appreciate the reviewer's valuable suggestion regarding the inclusion of concrete examples of coastal regions. In response, we have revised the manuscript to incorporate five representative city cases that are currently experiencing considerable pressure from relative sea-level rise exacerbated by land subsidence. The selection of these cities was informed by the global study^[5], which systematically assessed the subsidence rates of 48 major coastal cities. Building on this study and drawing on additional relevant research findings, we ultimately selected Jakarta, Tianjin, and Ho Chi Minh City as Asian cities with high subsidence rates, together with Venice and New Orleans as well-documented cases in Europe and North America, to better illustrate the widespread and urgent nature of this issue.

Original: "Numerous coastal areas around the globe are already under continuing and intensifying pressure."

(Page 2, lines 48–51)

Revised: "Numerous coastal areas worldwide are already under intensifying pressure from relative sea-level rise. This risk is further exacerbated in cities undergoing severe land subsidence—such as Jakarta, Tianjin, Ho Chi Minh City, Venice, and New Orleans—where groundwater over-extraction and soft soil compaction significantly heighten their vulnerability to inundation^[5–10]."

The citation [5–10] refers to a set of recent studies that provide specific evidence for land subsidence and inundation risks in each of the named cities, as detailed in our response to Comment 4. We believe this addition has ultimately enhanced the clarity and persuasiveness of our work, and we are once again truly grateful to the reviewer for this valuable suggestion.

Comments 6:

Figure 2 is unclear. Which color represents subsidence hotspots on the map?

We sincerely thank the reviewer for raising this important point regarding the clarity of Figure 2. To address this concern and to better articulate the European VLM context, we have implemented substantial modifications to the figure. Specifically, we have revised the caption to explicitly state that the highlighted areas represent the identified subsidence hotspots. To further improve geographic orientation for the reader, we have also added labels for the ocean.

Additionally, we would like to explain that to more effectively present the overall VLM patterns across Europe, the original Figure 2 has been moved to the Supplementary Material as Figure S1. It has been replaced in the main text by a new, synthesized statistical figure that integrates continental-scale latitudinal gradients, coast-to-inland transitions, and regional variability. This new figure establishes a physical and statistical foundation for the exposure framework. The specific revisions are as follows:

The original Figure 2 has been relocated to Figure S1:

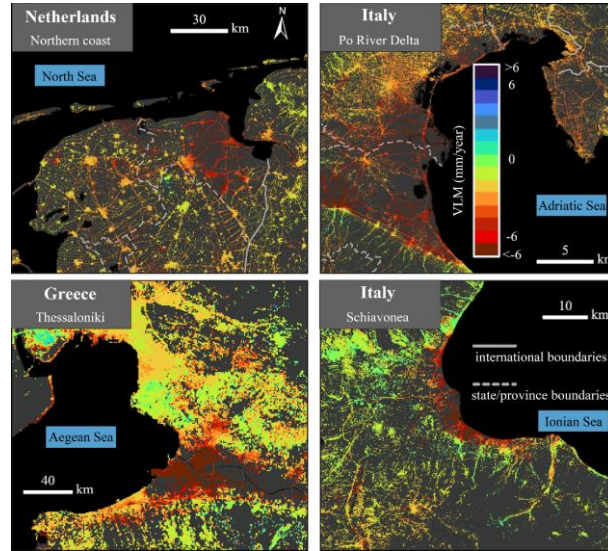


Fig. S1. | Major subsidence hotspots along the European coastal zone. The areas shown in the figure are respectively the northern coast of the Netherlands, Thessaloniki in Greece, the Po River Delta in Italy, and Schiavonea in Italy, representing subsidence-prone regions, with the red areas indicating zones of higher subsidence intensity. The first identification of Schiavonea is credited to Thiéblemont et al^[13].

The yellow-highlighted section corresponds to our modifications addressing the comment that the “subsidence hotspots were not clearly represented.”

(Page 8, lines 180–189)

The new Figure 2 (replacing the previous one):

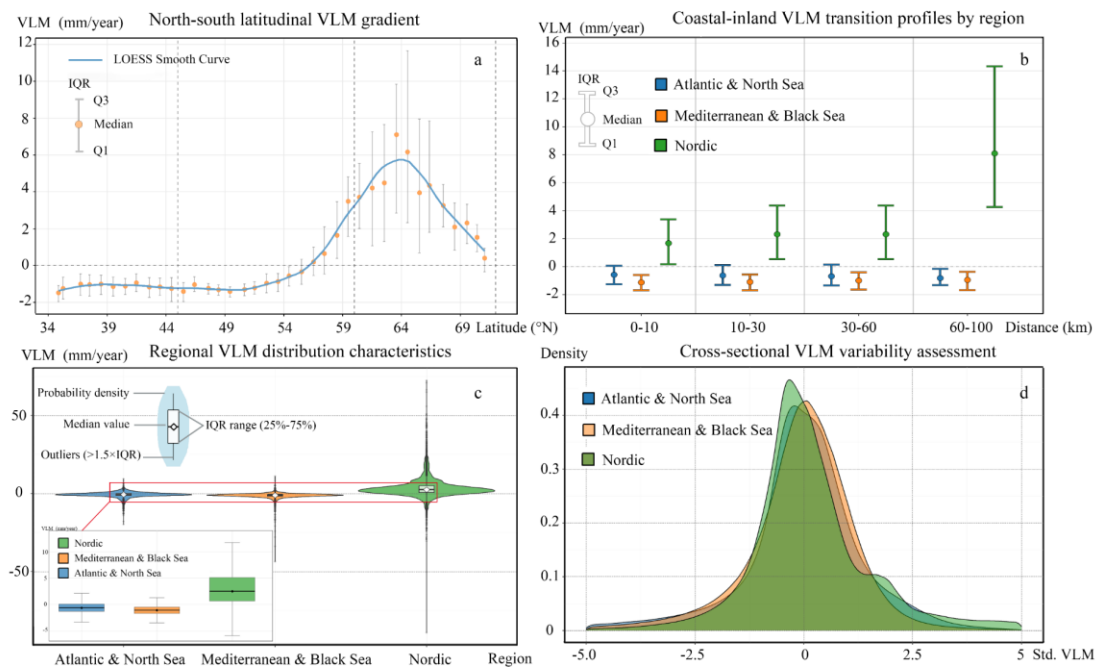


Fig.2 | Spatial gradients and transition patterns of VLM across European coastal zones. a, Latitudinal variations of VLM, showing the transition from Nordic uplift to Mediterranean subsidence. Orange dots are medians, and the blue line is a smooth curve. b, Coastal-to-inland

VLM transitions, grouped by distance. c, VLM distribution across regions, compared with violin and box plots. d, Standardized VLM density distributions for each region, normalized using the median-MAD method. By synthesizing the latitudinal gradient at the continental scale, the coast-to-inland transition, and regional variability, this visualization provides the physical and statistical basis for the exposure framework.

Comments 7:

The manuscript appears to be a lack of a regular format for this article, which should include the following sections:

1. Introduction
2. Results and Discussion
3. Methods (this is included in a separate file but not within the main article)
4. Limitations
5. Recommendations

Without these subheadings, it is challenging to review the article effectively. The authors need to revise the article accordingly and re-submit.

We sincerely thank the reviewer for emphasizing the importance of the manuscript's overall structure and agree on it. Consequently, in the revised version, we have integrated the Methods section from the supplementary material into the main text, forming a clear framework consisting of Introduction, Results, Conclusions (including limitations and recommendations), and Methods. The specific structure is outlined as follows:

1. Introduction

2. Results and Discussion

The Results section is organized under four subheadings, progressing logically from the overall distribution patterns of VLM to its association with land cover patterns, then to the projected impacts of RSLR under 2050 climate scenarios on population and assets, and finally to an exploration of climate change inequality in Europe. The four subheadings are as follows:

Patterns and Regional Characteristics of VLM across European Coastal Zones

Subsidence Exposure of National Land Cover in Coastal Zones

The Impact of Relative Sea Level Rise on Coastal Zones

Climate Change Inequality in Coastal Zones

3. Conclusions

Limitations and recommendations form an essential part of the Conclusions section. In the manuscript, we have openly addressed the study's limitations, and we believe this will provide a clear direction for future improvements and lay a foundation for enhancing the quality and effectiveness of subsequent research. The specific content of the limitations and recommendations is presented as follows.

(Page 20, lines 465–484)

“Nevertheless, several limitations should be acknowledged. First, the bathtub method itself has inherent constraints. Based on a static assumption of free water filling, it does not account for tidal dynamics, hydrodynamic processes, or drainage systems, which may affect the accuracy of the predictions. Second, in measuring asset exposure, we focus on building values to capture the potential direct losses to private wealth. This provides an important complement to existing GDP-based analyses; however, a comprehensive economic risk assessment should also incorporate public, commercial, and industrial assets. Third, in the treatment of economic indicators, converting values into within-country percentiles preserves the national context but obscures absolute cross-country differences, thereby limiting interpretations of adaptive capacity across nations. Finally, in terms of demographic structure, this study adopts future age-composition scenarios to better reflect projected population changes, yet the assumption that subnational trends follow national-level dynamics may not fully capture local heterogeneity.

Future research could build on this foundation by incorporating dynamic hydrological processes to more realistically simulate inundation patterns, while integrating multi-dimensional asset data, higher-resolution demographic information, and more detailed land-use classifications. Such refinements would enable a more nuanced identification of vulnerabilities across different built environments, contributing to a more comprehensive understanding of coastal subsidence risk and its inequalities. These efforts would also provide stronger scientific support for enhancing climate resilience and long-term spatial planning in European coastal regions.”

4. Methods

The complete methods have been moved from the supplementary material to the main text as an independent section. This ensures that readers can directly and fully access the technical details and implementation processes of the study, thereby enhancing its transparency and reproducibility (Page 21–26).

Please see revised manuscript (pages 2, 4, 19, and 21)

We believe that these adjustments have resulted in a more logical, coherent, and complete structure for the manuscript, which will help us better convey our focus on the unequal exposure of European coastal zones. We are truly grateful for the reviewer’s highly constructive guidance, which has significantly improved the quality of this study. We kindly invite the reviewer to examine the revised manuscript and look forward to any further feedback.

Reviewer #2:

Comments 1:

Abstract:

I'm unsure if 100m can be considered high-resolution in the context of Interferometric Synthetic Aperture Radar data, please check.

We thank the reviewer for raising this important point regarding the terminology for InSAR data resolution. We have revised the relevant descriptions throughout the manuscript to address this concern.

We would like to emphasize that within the specific context of the European Ground Motion Service (EGMS)—a continental-scale monitoring service—the 100-meter resolution product is among the highest resolution, freely available, and consistently processed datasets for Europe. Therefore, while we agree that 100m may not be considered “high-resolution” in an absolute sense for InSAR, we believe it represents a highly valuable and practical input for our regional-scale risk assessment.

To ensure precision and consistency, we have implemented the following changes:

1. In the Abstract:

Original: “Using high-resolution (100m) Interferometric Synthetic Aperture Radar data from the European Ground Motion Service (2019-2023), we developed a multi-source risk framework integrating vertical land motion patterns with land cover, population distribution, and socioeconomic indicators.”

(Page 1, lines 14–17)

Revised: “Using 100m resolution Interferometric Synthetic Aperture Radar data from the European Ground Motion Service (2019-2023), we developed a multi-source risk framework integrating vertical land motion patterns with land cover, population distribution, and socioeconomic indicators.”

2. In the Methods:

Original: “High-resolution (100 m) ground motion data for the European coastal zone, sourced from the European Ground Motion Service (EGMS).”

(Page 23, lines 561–562)

Revised: “Ground motion data for the European coastal zone at a standard resolution (100 m), sourced from the EGMS.”

We thank the reviewer again for this valuable feedback, which has helped us improve the accuracy

and clarity of our manuscript.

Comments 2:

Please add citations to where #4 is being cited since the claim at global scale and the only study being cited is about China.

We sincerely thank the reviewer for this insightful suggestion. The comment is well-noted. To better support our claim regarding the global-scale significance of coastal ecosystems, we have revised the manuscript by supplementing the citation with two authoritative references that provide this necessary global perspective.

(Page 2, lines 37–39)

Revised: “As an intermediate region connecting land and marine habitats, coastal areas are widely regarded as one of the most productive and respected ecosystems on Earth^[14-16]. ”

Newly incorporated literature:

[14] Costanza et al. (1998): This seminal paper provides a global valuation of ecosystem services, establishing coastal zones as among the most valuable biomes on Earth.

[15] Millennium Ecosystem Assessment (2005): This comprehensive synthesis represents a global scientific consensus on the critical importance and high productivity of coastal ecosystems for human well-being.

We believe these additions significantly strengthen the global context of our statement. We thank the reviewer again for the valuable feedback that has helped improve the robustness of our manuscript.

Comments 3:

First paragraph – Please clarify that other impacts of climate change have also been observed and that subsidence and SLR are among them. The transition between global scale and general impacts of two specific hazards is too abrupt.

We appreciate this reviewer’s constructive suggestion. We fully agree that providing a broader context of climate change impacts before introducing land subsidence and sea-level rise can enhance the logical coherence of the paragraph. The revised version now includes references to other observed impacts of climate change, such as the increasing frequency of extreme storm events and the degradation of coastal ecosystems, clarifying that sea-level rise is one among multiple climate-related threats.

Original: “The observed land subsidence and sea level rise (SLR) over the past century pose a significant threat to these coastal areas, and their vulnerability is constantly increasing with global climate change and ongoing human activities.”

(Page 2, lines 41–46)

Revised: “In particular, climate change exacerbates risks through multiple pathways, including the increasing frequency of extreme storm events, the degradation of coastal ecosystems, and sea-level rise (SLR)^[2-4]. Against this backdrop, land subsidence and SLR, observed over the past century, pose significant threats to coastal areas, whose vulnerability continues to intensify under ongoing climate change and human activities^[17, 18]. ”

We sincerely thank the reviewer once again for this helpful reminder. By reviewing and citing relevant literature, we have incorporated descriptions of other observed climate change impacts, which make the discussion of land subsidence and sea-level rise more contextually grounded and ensure a smoother transition between topics.

Comments 4:

The acronym SLR is introduced in the first paragraph so I kindly suggest to use that every time sea level rise is mentioned.

We sincerely thank the reviewer for this valuable suggestion regarding the consistent use of abbreviations. In response, we have thoroughly checked and revised the entire manuscript. Specifically, “SLR” is now clearly defined upon its first appearance in the introduction and used consistently throughout the text. Additionally, we have carefully reviewed and unified other acronyms such as “RSLR” and “VLM”. These revisions have significantly improved the standardization of the manuscript. We appreciate the reviewer's careful attention to this matter.

Comments 5:

The study #10 is about port cities, not sure that claim on second paragraph can be supported by only that.

We sincerely thank the reviewer for emphasizing the need to provide stronger references for the statement that the coastal population exposed to flood risks will rise significantly by 2070. In the original version, we directly cited the projections of Hanson et al. for global port cities to support a broader claim regarding coastal regions in general. We agree that this extrapolation lacked sufficient rigor and could not comprehensively substantiate the statement about wider coastal areas. To address this issue, we have added two key references to strengthen the rigor and comprehensiveness of the argument.

Original: “By the 2070s, total population exposed could grow more than threefold due to the combined effects of sea-level rise, subsidence, population growth and urbanisation with asset exposure increasing to more than ten times current levels or approximately 9% of projected global GDP in this period^[19]. ”

(Page 2, lines 52–54)

Revised: “By 2070, the population at risk of coastal flooding is expected to rise significantly due

to the combined effects of land subsidence, SLR, and urbanization^[19-21]. ”

Newly incorporated literature:

[20] Nicholls et al. (2007): This study projects that by the 2070s, the population exposed to coastal flooding in global port cities could increase more than threefold, emphasizing land subsidence and climate change as significant drivers of this trend.

[21] Shirzaei et al. (2021): This study mentions that the population affected by flooding is expected to approximately double by 2070.

These revisions make the statement on the projected increase in coastal population exposure by 2070 more robust and evidence-based. We sincerely appreciate the reviewer’s insightful Comments, which helped us improve the logical consistency and academic soundness of the manuscript.

Comments 6:

Citation #33 is misplaced.

We sincerely thank the reviewer for identifying this issue. Citation #33 refers to the European Ground Motion Service (EGMS) dataset used in our analysis. We agree that this reference is more appropriately placed in the Methods section, where data sources and processing steps are introduced. We have therefore moved citation #33 accordingly. Now, with the new cited references, it is citation #51 in the revised manuscript.

Comments 7:

Please clarify the extent, covered area, or resolution of a pixel. I’m unsure what 65mi pixels mean.

We thank the reviewer for this helpful comment. Since the VLM data used in this study are raster-based, the number “65 million” refers to approximately 65 million VLM pixels. To make the meaning of “65 million pixels” clearer to readers, we have added an explicit note on the pixel resolution and spatial coverage in the corresponding sentence.

Original: “By comparing two periods of VLM data in the European coastal zone, the analysis of approximately 65 million pixels of VLM change reveals that, around 19% of coastal zone pixels exhibit a deceleration in vertical motion, 22% show an acceleration, and the remaining 59% remain stable (Table 1). ”

(Page 4, lines 115–120)

Revised: “A comparison of VLM data for two consecutive periods (2018–2022 and 2019–2023) across the European coastal zone, covering approximately 65 million pixels (corresponding to the 100 m resolution grid covering the European coastal zone), indicates that the vast majority of coastal areas exhibit highly consistent VLM rates (Table 1): about 59% of the pixels show

variations within ± 0.5 mm/year, highlighting the overall stability of the dataset."

Comments 8:

Fig 1. - Please include a legend, or something in the caption explaining what the blue and red dashed lines represent in the subplot figure.

Fig 1. - Please add the numbers of respective countries presented in the boxplots to the map to facilitate the communication.

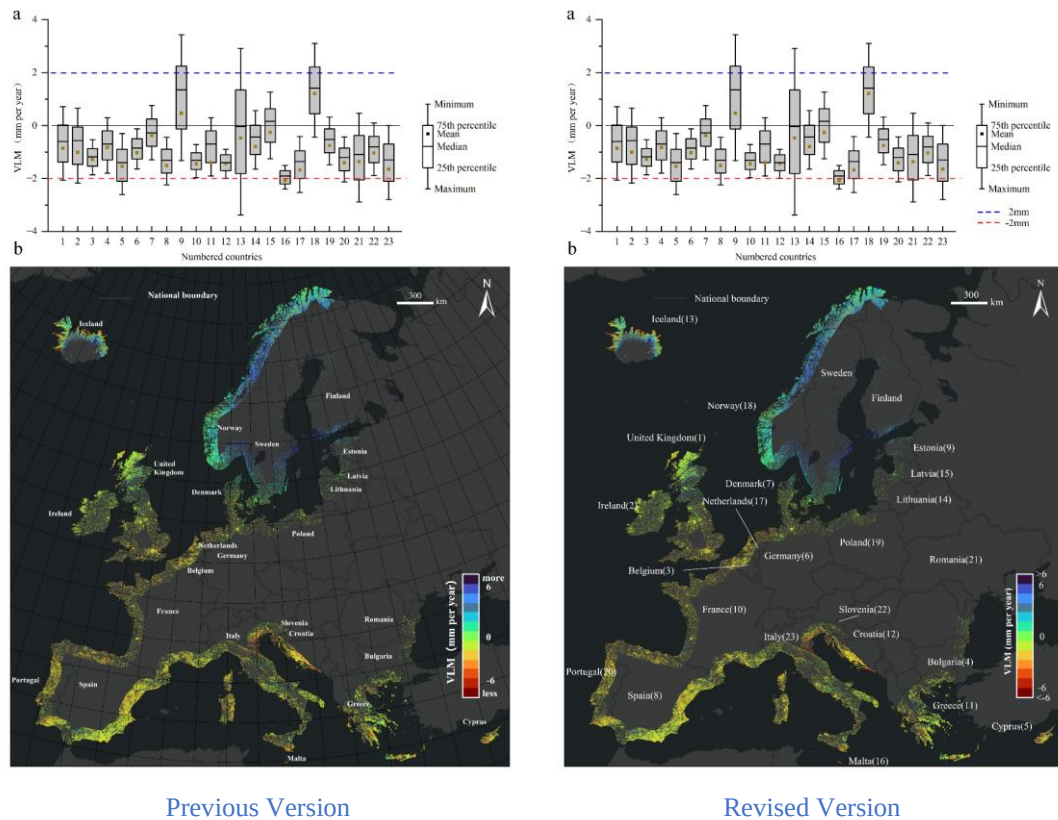
Fig 1. - If you chose to keep the coordinate grid, please show the coordinates.

We thank the reviewer for their valuable comments and constructive suggestions. All the recommendations regarding Fig 1 are highly pertinent, and we have thoroughly revised the figure accordingly. The specific modifications are detailed below:

1. Regarding the dashed line legend: We have added a clear legend to the figure indicating that the red dashed line represents the -2 mm/yr reference and the blue dashed line represents the $+2$ mm/yr reference. This enables readers to easily compare the national VLM values with these two thresholds.
2. Regarding the country numbering: We have clearly annotated the map with the corresponding numbers (as used in the boxplot) for each country region. This modification significantly facilitates the reader's ability to cross-reference between the geographical distribution and the statistical data.
3. Regarding the coordinate grid: We carefully considered the suggestion to display coordinates. To maintain a clean layout and emphasize the core information (such as country outlines and the newly added numbers), we ultimately decided to remove the coordinate grid for clearer visual presentation.

These revisions have substantially improved the informational completeness and readability of Figure 1. The revised figure has been updated in the manuscript.

To further illustrate the changes made, we provide a visual comparison below for your convenience:



We thank the reviewer again for your detailed and useful work.

Comments 9:

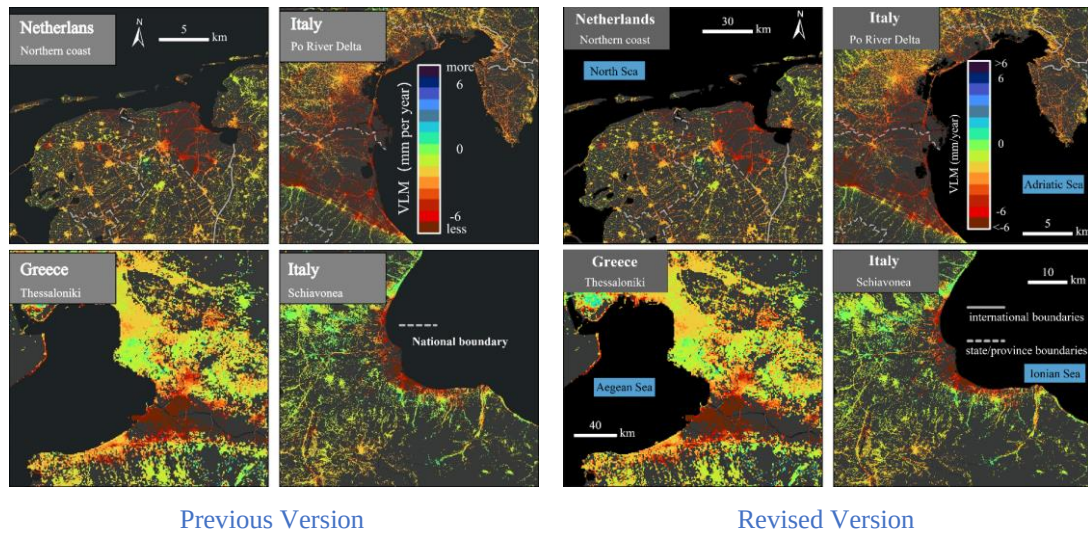
Fig 2. - Add labels to national boundaries; Add labels to seas/oceans.

Fig 2. – The gray boxes are stretched and not properly aligned to the maps.

We sincerely thank the reviewer for their insightful comments regarding the presentation of Fig 2. We have thoroughly addressed the specific issues raised:

1. Country boundaries and sea labels: We have added clear labels for the country/provincial boundaries as well as for the seas/oceans on the figure.
2. Gray text boxes: The stretched and misaligned gray text boxes have been carefully re-adjusted to ensure proper alignment with the corresponding map features.

The figure below demonstrates the direct revisions made to address your comments:



Following these essential corrections, to enhance the manuscript's narrative flow and statistical rigor, we have repositioned this figure. It has been moved to the Supplementary Material (designated as Fig. S1) and replaced in the main text by a new, more comprehensive figure (the new Figure 2) that effectively illustrates the continental-scale patterns, including the latitudinal gradient, coast-to-inland transitions, and regional variability of VLM across Europe. This change establishes a stronger physical and statistical foundation for the exposure framework.

(Page 8, lines 180–189)

The new Figure 2 (replacing the previous one):

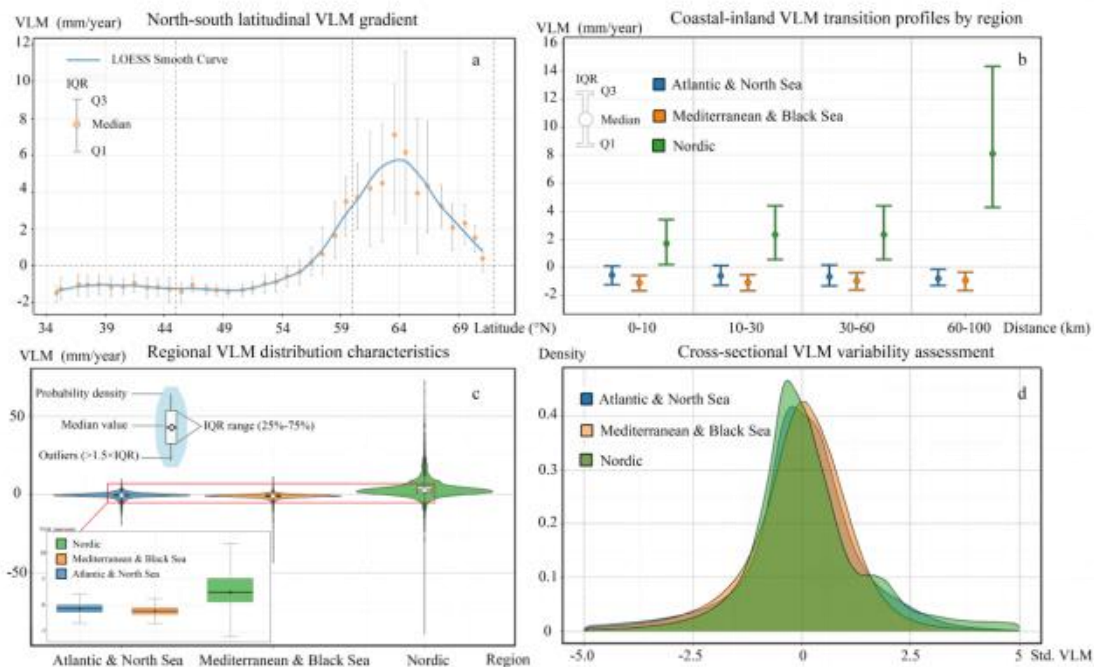


Fig.2 | Spatial gradients and transition patterns of VLM across European coastal zones. a, Latitudinal variations of VLM, showing the transition from Nordic uplift to Mediterranean subsidence. Orange dots are medians, and the blue line is a smooth curve. b, Coastal-to-inland VLM transitions, grouped by distance. c, VLM distribution across regions, compared with violin

and box plots. d, Standardized VLM density distributions for each region, normalized using the median-MAD method. By synthesizing the latitudinal gradient at the continental scale, the coast-to-inland transition, and regional variability, this visualization provides the physical and statistical basis for the exposure framework.

We consider these revisions have significantly help us to improve the clarity and professionalism of our visual presentation.

Comments 10:

Add citations to the sentence "...small islands, many of which are further challenged by resource scarcity."

Thank you sincerely for your valuable comment. You clearly pointed out that literature support should be provided for the statement on "resource scarcity of small islands", and we attach great importance to this suggestion. We have made targeted revisions to the relevant content in the original text. To ensure the rigor of the argument, we focused on reviewing relevant studies that focus on "the vicious cycle between multiple threats faced by small islands and resource scarcity". Based on the relevance and authority of the research conclusions, we finally selected and added two relevant literatures to systematically support the discussion on "resource scarcity of small islands" and the resulting climate vulnerability issues.

Original: "Europe, characterized by its highly indented coastline, hosts a large number of small islands, many of which are further challenged by resource scarcity. This limitation exacerbates their vulnerability to climate change by restricting their adaptive capacity, making subsidence a critical risk factor that directly threatens the long-term sustainability of these islands."

(Page 8-9, lines 197–200)

Revised: "Europe, characterized by its highly indented coastline, hosts a large number of small islands. Owing to their limited resources, these islands inherently face significant constraints, which exacerbate their vulnerability to climate change by restricting their adaptive capacity, making subsidence a critical risk factor that directly threatens their long-term sustainability^[22, 23]."

Newly incorporated literature:

[22] Lewis (2012): This study discusses the complex relationship between environmental degradation, resource scarcity, and human security in small island states. It highlights that despite their relatively small populations, small islands remain particularly vulnerable to climate change and variability due to their limited resources and adaptive capacity.

[23] van der Putte (2021): This chapter examines the major sustainability challenges faced by Small Island Developing States, including sea-level rise, storms, and resource limitations. It underscores how climate change exacerbates flooding, soil erosion, and water system disruption, thereby threatening the long-term resilience and development of small islands.

Comments 11:

Unless this is how the dataset is really called, I don't think the 100m land cover dataset should be referred to as "high-resolution"

Thank you very much for emphasizing the terminology rigor of the land cover dataset. We first verified the official full name and description of the "100m land cover dataset" (Urban Atlas 2018) used in the study, and confirmed that it does not mention any "High Resolution"-related terminology. Therefore, we conducted a systematic check and revision of the data descriptions in the text to enhance the rigor of our expressions.

1. "Subsidence Exposure of National Land Cover in Coastal Zones" Section

Original: "Leveraging the high-resolution Urban Atlas 2018 dataset (100m spatial resolution, 43 land use categories) from the Copernicus Earth Observation Programme, this study assesses the spatial exposure patterns of four land systems along European coastal zones."

(Page 9, lines 208–210)

Revised: "Leveraging the 100m resolution Urban Atlas 2018 dataset (43 land cover categories) from the Copernicus Earth Observation Programme, this study assesses the spatial exposure patterns of four land systems along European coastal zones."

2. Methods Section

Original: "The Urban Atlas 2018 encompasses 43 land use categories and was employed in this research as a high-resolution grid map with a spatial resolution of 100 meters."

(Page 22, lines 530–531)

Revised: "The Urban Atlas 2018 encompasses 43 land cover categories and was employed in this research as a grid map with a spatial resolution of 100 meters."

This revision is strictly based on the official information of the dataset to avoid misunderstandings caused by the use of non-official terminology, fully responding to your attention to the rigor of research details. Thank you again for your professional guidance, which helps us improve the accuracy of data descriptions.

Comments 12:

Fig.3 – Please remove the figure title and use the caption for that.

Fig.3 – Is this land use or land cover? Caption is confusing and I also noticed that in the methods both terms are used as synonyms (they are not).

We greatly appreciate your two valuable comments on Figure 3 and have implemented the

revisions one by one, with details as follows:

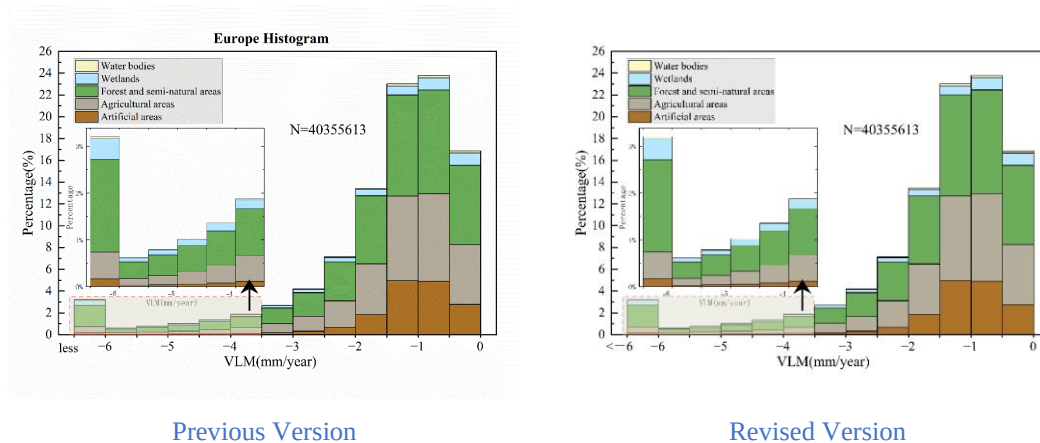
1. Adjustment of Figure 3's Caption and Label

In accordance with your suggestion to “delete the figure caption and optimize the label”, we have made two revisions: first, we deleted the original caption of Figure 3 to make the chart presentation more concise; second, we adjusted the ambiguous “less” label in the figure to “<-6”. By using a precise numerical range label, we avoid readers' confusion about data definition and improve the clarity of information transmission.

2. Clarification of “Land Use” and “Land Cover” Terminology.

We sincerely thank you for pointing out the terminology confusion issue—previously, we incorrectly used “land use” and “land cover” as synonyms in the text (including the Methods section), ignoring their essential differences. After re-verifying the official definition of the Urban Atlas 2018 dataset used and the research scenario, we confirmed that this study focuses on the “land cover” category. Based on this, we have thoroughly checked the entire text, uniformly revising all confusingly used “land use” to “land cover”, with a particular focus on verifying the consistency of terminology in the Methods section, thus completely avoiding confusion for readers caused by terminology misuse.

To intuitively show the revision effects, a comparison of the original and revised figures is attached below for you to clearly check the adjustments:



This revision strictly follows your guidance, not only optimizing the details of chart presentation but also standardizing the use of academic terminology, further enhancing the rigor of the research expression. Thank you again for your careful attention to details and professional correction.

Comments 13:

The shift from Europe-wide statistics to regional case studies (Netherlands, UK, Italy) is too abrupt.

Thank you very much for pointing out the issue of insufficient coherence when transitioning from

the overall European overview to specific cases. To address this shortcoming, we supplemented the transitional logic with “clarifying case representativeness” as the core: on one hand, we clearly explained the research purpose of shifting from the overall to the regional level—to further explore the “association between subsidence patterns and artificial areas”; on the other hand, we strengthened the rationality of selecting the Netherlands, the United Kingdom, and Italy by emphasizing the typicality of these cases. Ultimately, this connects the European-wide statistical analysis and regional case studies into a complete logical chain of “overall overview - targeted exploration - case verification”, effectively resolving the abrupt transition in the original version and avoiding logical discontinuity.

Original: “Regional case analyses demonstrate significant correlations between subsidence patterns and artificial areas distribution, as exemplified by three representative regions: the Netherlands, the United Kingdom, and Italy.”

(Page 13, lines 296–299)

Revised: “To further explore how exposure patterns are associated with artificial areas, we selected representative cases with typical population and infrastructure exposure across Europe. Analyses of the Netherlands, the United Kingdom, and Italy reveal significant correlations between subsidence patterns and the distribution of artificial areas.”

Thank you again for your careful attention to the textual logic of the research. This revision not only optimizes content coherence but also helps us further improve the hierarchy and rigor of the research expression.

Comments 14:

Fig. 5 - There is one label missing in panel C (above Lincoln).

Fig. 5 – An overview map is necessary to help readers locate where each subplot is in the bigger picture of each country.

Thank you very much for your detailed comments on Figure 5. We have completed two targeted revisions based on your suggestions, with details as follows:

1. Supplementary Label for Missing Part in Figure 5 Panel C

After verification, the missing label above “Lincoln” in Panel C of Figure 5 (which you pointed out) has the same content as the label below, i.e., “Lincoln”. We have added the “Lincoln” label at this position to avoid misunderstandings caused by incomplete labeling and ensure the integrity and accuracy of the panel information.

2. Addition of Overview Maps for Each Subplot’s Location in Corresponding Countries

To help readers clearly locate each subplot’s position within its corresponding country, we have specifically added a set of overview maps: for each subplot in Figure 5 (e.g., subplots related to the Netherlands, the UK, and Italy), we marked its specific regional scope within

the country it belongs to in the overview maps. This allows readers to intuitively connect the details of each subplot with the overall spatial pattern of the country, reducing the difficulty of spatial positioning during reading.

Attached below is the revised Figure 5 incorporating the above two revisions:

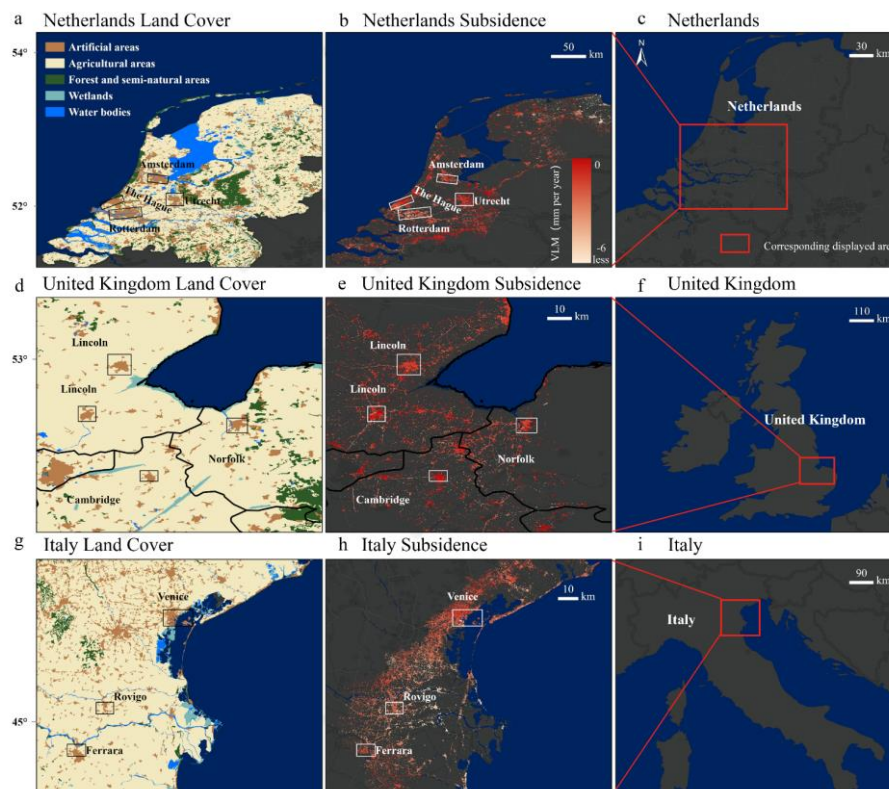


Fig.5 | Examples of regions with significant exposure to land subsidence. a, National land cover map for the Netherlands area. **b,** Land subsidence across the Netherlands. **c,** Overview map that helps locate the relevant area within the Netherlands. **d,** Land cover in parts of the United Kingdom. **e,** Distribution of land subsidence in parts of the United Kingdom. **f,** Overview map that helps locate the relevant area within the United Kingdom. **g,** Land cover in parts of Italy. **h,** Distribution of land subsidence in parts of Italy. **i,** Overview map that helps locate the relevant area within Italy.

This revision focuses on the “information integrity” and “clarity of spatial positioning” you concerned about, further improving the readability and clarity of Figure 5. Thank you again for your careful control of the figure details, which helps us optimize visualization of our results.

Comments 15:

Please avoid adding new topics or new information to the conclusion and focus on presenting the conclusion of this study. For example, talking about significant risk from tsunamis is something that could have been mentioned earlier in the text and does not come from your lessons learned in the study.

Thank you very much for pointing out the issue in the conclusion section of this study. Your

comments are highly targeted and crucial for improving the logical coherence and content focus of the paper. Initially, we included relevant content in the conclusion section to elaborate on the connection between “land subsidence” and “the vulnerability of coastal cities to compound hazards,” and further clarify that land subsidence is not an isolated engineering or environmental issue, but rather a “core variable that links the risk accumulation of various coastal natural hazards.” However, we later realized that this analysis of compound hazard correlations is not the direct research object of this study—our core focus is on the research conclusions regarding land subsidence itself. Placing the non-core content about compound hazard correlations in the conclusion section not only deviates from the core research results but may also confuse the paper’s logical context.

Therefore, we have made some adjustments in strict accordance with your suggestions: all content related to “the connection between land subsidence and compound hazards” in the original conclusion has been deleted, and instead, this content has been integrated into the introduction section for a brief introduction. This adjustment not only retains the supplementary role of this content in explaining the research background (clarifying the background attribute of land subsidence in the coastal risk system) but also better aligns with the paper’s narrative logic of “background contextualization-core research elaboration-conclusion distillation,” ensuring that the conclusion section fully focuses on the core findings of this study.

Original (Deleted): “Land subsidence and the high concentration of people and assets along the coasts have dramatically increased the vulnerability of cities to compounded hazards (e.g., tsunamis, earthquakes). This is because the largest and most destructive hazard events usually pose a greater risk to human life than smaller, more frequent events. Historical events have shown that the Mediterranean Sea and its adjacent regions continue to be at significant risk from tsunami hazards. During a tsunami event, areas of subsidence are more susceptible to deeper and wider inundation due to lower ground levels, which increases the risk of human exposure and infrastructure damage. Thus, land subsidence is not an isolated engineering or environmental issue, but is a central variable in the compounding of risks associated with a variety of coastal natural hazards, including tsunamis, storm surges and earthquakes.”

(Page 2, lines 56–57)

Revised: “Subsidence also amplifies the impacts of other coastal hazards, such as tsunamis and storm surges, by lowering ground levels and increasing the depth and extent of inundation^[24, 25].”

We believe these changes have significantly improved the logical flow of the paper and ensured the conclusion is concise and focused. Thank you again for your insightful feedback, which helped us to improve the quality of our work.

Comments 16:

Including a discussion (or at least acknowledging) uncertainties in the projections and the bathtub method would greatly strengthen the scientific rigor of this study. In the same context, authors assume that current demographic structures (e.g., % of elderly and children) remain static through 2050, which is unlikely given expected demographic shifts.

Thank you very much for your valuable comments. Your suggestions on “supplementing the discussion of uncertainties in projections and the bathtub method” and “optimizing the static assumption of demographic structure” are crucial for improving the scientific rigor and practical significance of this study. We fully agree with these suggestions and have made revisions accordingly.

1. Discussion of Uncertainties

We have added a new paragraph in the Conclusion to explicitly acknowledge the key uncertainties and limitations inherent in our projections. The added text reads:

(Page 20, lines 465–476)

“Nevertheless, several limitations should be acknowledged. First, the bathtub method itself has inherent constraints. Based on a static assumption of free water filling, it does not account for tidal dynamics, hydrodynamic processes, or drainage systems, which may affect the accuracy of the predictions. Second, in measuring asset exposure, we focus on building values to capture the potential direct losses to private wealth. This provides an important complement to existing GDP-based analyses; however, a comprehensive economic risk assessment should also incorporate public, commercial, and industrial assets. Third, in the treatment of economic indicators, converting values into within-country percentiles preserves the national context but obscures absolute cross-country differences, thereby limiting interpretations of adaptive capacity across nations. Finally, in terms of demographic structure, this study adopts future age-composition scenarios to better reflect projected population changes, yet the assumption that subnational trends follow national-level dynamics may not fully capture local heterogeneity.”

2. Update on Population Projection Data

To improve the accuracy and forward-looking nature of population exposure calculations, the population projection data has been updated in the revised manuscript:

We adopted the global 1 km grid population projection dataset published by Wang et al. (2022), and selected the 2050 population distribution data based on the SSP2 Shared Socioeconomic Pathway from this dataset^[26]. Compared with the previously used “existing population spatial distribution data,” this dataset can more reasonably and accurately reflect the characteristics of population risk distribution under the 2050 RSLR scenario, significantly enhancing the reliability and practical reference value of the exposure assessment in this study.

3. Optimization of the Demographic Structure Assumption

We recognize that the previous assumption that “the proportions of the elderly, children, and other age groups in the study area remain unchanged until 2050” is inconsistent with the

objective trend of dynamic changes in demographic structure, and may lead to deviations in the estimation of future exposure risks for vulnerable age groups. Therefore, we have introduced the authoritative population projection data published in the United Nations' *World Population Prospects 2024*^[27] to reflect changes in the future demographic structure, and adopted the “proportion adjustment method” to calculate the age-group proportions of the study area in 2050: specifically, we first take the baseline age-group proportions of the study area in 2024 as the foundation, calculate change factors by combining the national-level age-group proportion projection data from *World Population Prospects 2024*, then adjust the baseline age-group proportions of the study area using these change factors, and finally obtain the estimated age-group proportions of the study area in 2050. Details are as follows:

(Page 26, lines 639–648)

$$f_{c,age} = \frac{q_{c,age}^{2050}}{q_{c,age}^{2024}} \quad (1)$$

Where $q_{c,age}^{2024}$ and $q_{c,age}^{2050}$ are the national population shares of age group age in country c for 2024 (WPP estimate) and 2050 (WPP projection), respectively. This factor $f_{c,age}$ projects the relative change in the national age structure.

$$\bar{r}_{A,age}^{2050} = r_{A,age}^{2024} \times f_{c,age} \quad (2)$$

This estimates the future absolute share $\bar{r}_{A,age}^{2050}$ of age group age in study area A for 2050, by applying the national change factor ($f_{c,age}$) to its initial local share ($r_{A,age}^{2024}$).

$$r_{A,age}^{2050} = \frac{\bar{r}_{A,age}^{2050}}{\sum_{age} \bar{r}_{A,age}^{2050}} \quad (3)$$

This final step normalizes the projected shares from Equation (2) so that the proportions for all age groups within area A sum to 100%.”

This method can effectively break away from the limitations of static assumptions, making the future demographic structure of exposed areas more in line with the expected population change trends at the global and regional levels, thereby improving the rationality of estimating exposure risks for vulnerable age groups. Meanwhile, we also objectively acknowledge the shortcomings of this method: its core assumption that “the trend of demographic structure change at the subnational level (study area) is consistent with that at the national level” may fail to fully capture local demographic differences in age structure changes across different regions; regarding this limitation, we have added relevant explanations in the conclusion section of the revised manuscript to ensure the rigor of the study.

(Page 20, lines 473–476)

“Finally, in terms of demographic structure, this study adopts future age-composition scenarios to better reflect projected population changes, yet the assumption that subnational trends follow national-level dynamics may not fully capture local heterogeneity.”

We believe that these revisions have substantially strengthened the study by incorporating a critical discussion of limitations and by implementing a more robust and forward-looking

demographic projection. We thank the reviewer again for these valuable suggestions.

Comments 17:

The 100 km inland buffer is reasonable, but somewhat arbitrary for the coastal zone definition. A brief justification would be great about this.

We sincerely thank the reviewer for this valuable comment. The 100 km inland buffer indeed involves a degree of convention and operational consideration, and your suggestion helped us clarify its rationale to make the paper more rigorous.

In response, we have added a brief justification and supporting references in the manuscript. The selection of this buffer distance was based on the following considerations:

1. Alignment with research conventions: 100 km is a widely used area definition in large-scale coastal studies. This study refers to the scale settings of multiple similar studies to ensure the comparability of results with existing research;
2. Coverage of core processes: This range can fully include typical coastal socio-economic and environmental processes affected by relative sea-level rise, effectively covering the interactive area of human activities, ecosystems, and coastal natural processes, and avoiding omitting key affected scopes;
3. Scale and feasibility: The 100 km extent offers a balance between computational efficiency and spatial representativeness, avoiding both the omission of critical coastal areas and the inclusion of excessive inland regions.

Original: “In this study, the European coastal zone is defined as the area extending up to 100 kilometers inland from the coastline of European seas.”

(Page 21, lines 511–514)

Revised: “In this study, the European coastal zone is defined as the area extending up to 100 kilometers inland from the coastline of European seas. This distance is consistent with previous large-scale coastal studies, as it captures the socio-economic and environmental characteristics of coastal regions while ensuring analytical feasibility at the continental scale^[10, 28, 29].”

We believe this addition clarifies the rationale behind our operational definition and thank the reviewer for the suggestion, which has improved the clarity of our methods.

Comments 18:

Transforming economic values to percentiles within each country may preserve national context, but it masks absolute disparities across countries. This limits cross-country interpretation of adaptive capacity and should be discussed.

Thank you very much for your perceptive point regarding the issue that “the transformation of economic values into within-country percentiles masks absolute disparities between nations and thus limits the cross-country interpretation of adaptive capacity”—your observation directly addresses the core limitation at the methodological level and provides a crucial direction for us to more comprehensively refine the research design.

We initially chose this transformation method primarily to serve the research objective of “assessing inequality in economic vulnerability of coastal zones within nations”: by eliminating interference from differences in currency exchange rates and price levels across countries, we aimed to more clearly present the relative economic status of exposed areas within their respective countries, thereby focusing on the distribution differences of economic capacity across different coastal zones in the same nation. However, your comment made us deeply realize that the method’s insufficiency in the cross-country comparison dimension needs to be prioritized for supplementation. Therefore, we have carried out two aspects of improvement work targeting this limitation, with the specific revisions as follows:

1. Explicitly stating method limitations: A new explanation has been added to the conclusion section of the revised manuscript, clearly stating:

(Page 20, lines 471–473)

“Third, in the treatment of economic indicators, converting values into within-country percentiles preserves the national context but obscures absolute cross-country differences, thereby limiting interpretations of adaptive capacity across nations.”

2. Supplementing background information on absolute economic values: To help readers understand the context of absolute economic disparities between countries, we have incorporated gridded GDP projection data provided by Murakami et al^[30]. We selected GDP data for 2050 under the SSP2 scenario and created the “Statistical Chart of Absolute GDP Values of European Countries (2050).” This chart intuitively presents the absolute economic levels of exposed areas across different countries, providing a reference for readers to understand the cross-country economic context.

The supplementary figure for GDP is as follows:

(Page 16-17, lines 363–370)

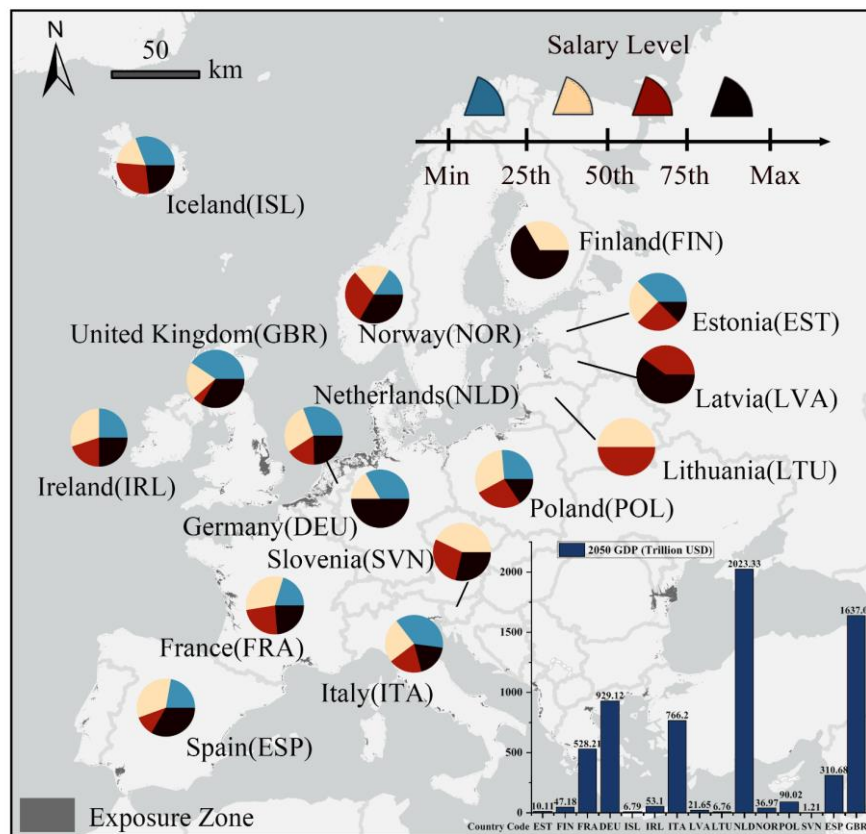


Fig.6 | Distribution of Salary Levels by Exposure Zone in Europe. The pie chart shows the wage distribution of the exposed regions in the country, divided into four categories from low to high. The black shaded area is the submerged exposed area. Some data samples that are too few or cannot be collected are not listed in the figure. Detailed data can be seen in Table S4. The lower-right panel presents a bar chart of projected gross domestic product (GDP, in trillions of U.S. dollars) for selected European countries in 2050, based on Murakami et al.^[30], providing a standardized reference for comparing the absolute economic capacity of the exposed countries.

The sections highlighted in yellow correspond to our explanations of the newly added content concerning the GDP of European countries in 2050.

These revisions not only retain the suitability of the original method for the research objective of “assessing within-nation inequality” but also effectively make up for its insufficiency in cross-country interpretation through targeted supplements, further enhancing the completeness and rigor of the research conclusions. Thank you again for raising this critical issue—your comments not only helped us accurately improve the discussion on methodological limitations but also made the presentation of research results more practically valuable.

Comments 19:

The manuscript states that 24.767 million people and 8.371 million buildings will be affected. Maybe these figures suggest an unrealistic level of precision given the data that was used.

Thank you very much for your careful observation! You pointed out that presenting the affected population and building data as “24.767 million people” and “8.371 million buildings” with three decimal places might imply an unrealistic level of precision—and this reminder has allowed us to more rigorously examine the rationality of our data representation. Indeed, the precision of the original numerical presentation did not match the inherent uncertainties of the data itself, which could easily mislead readers into perceiving the data as “absolutely accurate.”

To address this, we have revised the relevant results, adjusting the number of affected residents and buildings to a numerical representation that better aligns with the actual data precision: in the revised manuscript, we have optimized the original data to “nearly 25 million residents” and “more than 8 million buildings,” avoiding overemphasis on unnecessary decimal precision and more objectively reflecting the reliability of the data.

Original: “Within these exposed areas, an estimated 24.767 million residents and 8.371 million structures are expected to be directly affected, accounting for 8.6% of the total coastal population and 6.8% of the total building stock in Europe, respectively.”

(Page 12, lines 272–274)

Revised: “Within these exposed areas, nearly 25 million residents and more than 8 million buildings are expected to be directly affected, accounting for 8.6% of the total coastal population and 6.8% of the total building stock in Europe, respectively.”

Additionally, we have thoroughly checked all numerical precision representations throughout the manuscript, corrected other potential inconsistencies in precision, and ensured the uniformity and academic rigor of data presentation across the text. Thank you again for your careful reminder—this adjustment makes the presentation of research results more consistent with the actual data situation and further enhances the professionalism of the manuscript.

Comments 20:

The mention of €3.4 trillion in asset value in the Netherlands lacks detail on how this figure was calculated.

Thank you very much for carefully pointing out that the calculation of the €3.4 trillion asset value in the Netherlands lacks details! Your reminder helped us realize that we previously only briefly mentioned the calculation basis (building footprints and housing price data) in the “Methods and Materials Document” and did not elaborate on the calculation logic in the main text—making the data sources and calculation process insufficiently clear, which indeed requires supplementary details.

To address this issue, we have optimized the manuscript structure and content in two aspects:

1. **Supplementary calculation details:** We reorganized the format to integrate the core calculation logic from the original “Methods and Materials Document” into the “Research Methods” chapter of the main text, and added a detailed description for the asset value calculation—

clarifying its core logic as “estimating the value of each asset unit through the spatial correlation of per-unit-area housing cost data and building footprint data, and then aggregating to obtain the total exposed asset value in the Netherlands.” The specific revised expression is as follows (with the yellow-highlighted part being the newly added content):

(Page 24-25, lines 600–605)

“Building exposure assessment utilized Microsoft's Building Footprints dataset to count the number of structures located in exposed areas^[31]. For economic impact analysis, country-level housing price data were integrated from Statista and Numbeo databases (Table S2)^[32, 33]. Assuming the affected properties are a total loss, the potential economic loss caused by RSLR was estimated by calculating the product of the total exposed built-up area and the property price per unit area.”

2. Supplementary explanation of method limitations: We also clearly recognize the limitation of the current asset exposure measurement—due to data availability and research focus, we currently focus only on building values to capture potential direct losses to private wealth (which provides an important complement to existing GDP-based analyses), but have not included public assets, commercial assets, and industrial assets, which are key components of a comprehensive economic risk assessment. Therefore, we have added a relevant limitation explanation in the “Conclusion” chapter of the revised manuscript, with the specific expression:

(Page 20, lines 468–471)

“Second, in measuring asset exposure, we focus on building values to capture the potential direct losses to private wealth. This provides an important complement to existing GDP-based analyses; however, a comprehensive economic risk assessment should also incorporate public, commercial, and industrial assets.”

This series of adjustments not only clearly presents the data sources and core logic of asset value calculation, but also reflects the rigor of the research by proactively explaining limitations. As this is our response to the final review comment, we would also like to express our sincere gratitude for your careful guidance throughout the process—every comment of yours has helped us to improve the details and depth of the manuscript.

Reviewer #3:

Comments 1:

VLM analysis:

The authors use an analysis of VLM that is mostly consistent with the analysis previously published by Thieblemont et al (2024) for the same region.

It is not clear to me how the VLM methods used for the current manuscript differ from Thieblemont et al, except that two overlapping time periods are used in the current manuscript. The authors cite Thieblemont et al 2024 in their Supplemental Material only in a very general way, referring to those authors' framing of the VLM source data, and does not clearly compare this new VLM to the Thieblemont et al results from 2024. However, the VLM assessment used here seems generally consistent with the Thieblemont et al results. My point is that the VLM assessment itself is not novel, but the relationship to the work described in the current manuscript is not clear. In fact, a figure from the current manuscript (Figure 2) seems very similar to a figure in Thieblemont et al (Figure 7 in that paper), which was the first to identify the Schiavone region of Italy as vulnerable to SLR because of VLM. The authors should cite Thieblemont et al (2024) much more clearly in the VLM section of this new manuscript to identify their own original contributions vs. the contributions of that recent paper. It's also not clear why they used two strongly overlapping temporal periods to try to establish trends in VLM.

We thank the reviewer for highlighting the relation to Thiéblemont et al. (2024) and our temporal setup. In the revision, we have provided several concise clarifications to enhance transparency:

- (i) while both studies utilize the EGMS dataset and the continental-scale analysis by Thiéblemont et al. (2024) offers valuable background context, our research was conceived and executed independently. Their work is cited in our manuscript specifically to acknowledge their prior identification of key subsidence hotspots, which provides a useful reference frame for parts of our analysis;
- (ii) we specify that the 2019–2023 EGMS Ortho vertical velocity field serves as the baseline for all main-text analyses, whereas the 2018–2022 dataset is used only for inter-epoch quality and consistency checks; and
- (iii) we have replaced Figure 2 with a spatial summary of latitudinal gradients, coast-to-inland transitions, and regional variability, and in the original figure we explicitly acknowledged Thiéblemont et al's prior identification of the Schiavonea hotspot.

These revisions improve methodological clarity while preserving the study's core focus on inequality and exposure.

To address the reviewer's concerns thoroughly, the detailed revisions are as follows:

1. Clarify the link to Thiéblemont et al. (2024) and the study's original contribution

To make clear the independent methodological basis and original value of our research, we added

the following paragraph to the Introduction:

(Page 4, lines 101-105)

“To address these challenges, a multi-source data fusion analysis framework was developed. Building on the continental VLM mapping provided by EGMS, the framework integrates land cover, socio-economic, and population data to enable a critical transition: transforming physical subsidence patterns in coastal zones into spatially explicit assessments of socio-economic vulnerability^[13].”

This addition serves to clarify that, although both studies make use of the EGMS dataset, our analysis was designed and implemented entirely independently. The citation of Thiéblemont et al. (2024) is included solely to acknowledge their prior identification of established subsidence hotspots, which provides contextual reference for our work. The principal contribution of our study lies in integrating validated VLM patterns with land use, socioeconomic, and population information to assess vulnerability and exposure inequality, thereby shifting the analytical focus from the description of physical processes toward the evaluation of societal impacts.

2. Elaborate the Purpose of Using Two Overlapping Time Periods (Focus on EGMS Data Stability Assessment)

Regarding your question about the “unclear logic of using overlapping time periods (2018–2022, 2019–2023),” we supplemented explanations from two aspects: “baseline setting” and “data validation”:

1) Define the baseline:

We explicitly confirm that the “2019–2023 EGMS Ortho vertical velocity field” is the baseline for all main-text analyses, stating:

(Page 24, lines 581-582)

“We carry forward the empirically observed 2019–2023 VLM rate to 2050 as a constant-rate baseline.”

Meanwhile, we added a note in the European-wide VLM distribution map (Figure 1):

(Page 7, lines 157-158)

“The 2019–2023 VLM patterns are reproducible across epochs, supporting the use of the 2019–2023 baseline for downstream land-cover and socioeconomic analyses.”

2) Add EGMS data stability assessment in the main text:

We reoriented the analysis of the two overlapping time periods (2018–2022 and 2019–2023) to verify the temporal stability of the EGMS-derived VLM data.

Original: “Natural factors such as crustal structure and glacial isostatic adjustment (GIA), as well as anthropogenic activities including groundwater extraction and mining, influence the velocity of VLM. Accelerated VLM can exacerbate environmental risks, such as more frequent flooding and infrastructure damage, whereas decelerated VLM may help mitigate disaster threats and provide ecosystems—such as mangrove forests—with additional time to adapt to sea-level changes. A conservative threshold of ± 0.5 mm/year is adopted to distinguish between minor fluctuations and considerable acceleration or deceleration^[29]. By comparing two periods of VLM data in the European coastal zone, the analysis of approximately 65 million pixels of VLM change reveals that, around 19% of coastal zone pixels exhibit a deceleration in vertical motion, 22% show an acceleration, and the remaining 59% remain stable (Table 1). In the inland regions of Europe along the Atlantic coast, about half of the areas show stable VLM velocity changes, while the rest experience significant fluctuations. Notably, over 25% of these areas have VLM rate changes greater than 1 mm/year. In contrast, the coastal regions of the Mediterranean and Black Seas largely display minimal changes in VLM rate. Compared to the Atlantic coast and the broader European coastal zone, a smaller number of regions exhibit significant variations in the rate of vertical land motion, with only 14% of the areas showing changes exceeding 1 mm/year (Table S1). This may result from the weaker vertical component of tectonic activity in the Mediterranean and Black Sea coastal regions, negligible effects of GIA, effective anthropogenic regulation, and favorable hydroclimatic conditions^[34, 35]. Collectively, these factors reduce the variability of vertical land motion to a significantly lower level compared to the Atlantic coastal region, which is influenced by post-glacial rebound, substantial sediment compaction, and intensive human development^[36, 37]. ”

(Page 4-5, lines 112–134)

Revised: “Natural factors such as crustal structure and glacial isostatic adjustment (GIA), as well as human activities including groundwater extraction, can influence the observed VLM signals. To evaluate the stability of EGMS data in representing VLM rates, a conservative threshold of ± 0.5 mm/year was adopted as a reference for identifying fluctuations^[29]. A comparison of VLM data for two consecutive periods (2018–2022 and 2019–2023) across the European coastal zone, covering approximately 65 million pixels (corresponding to the 100 m resolution grid covering the European coastal zone), indicates that the vast majority of coastal areas exhibit highly consistent VLM rates (Table 1): about 59% of the pixels show variations within ± 0.5 mm/year, highlighting the overall stability of the dataset. Specifically, around 53% of the Atlantic coastline shows no significant change in VLM rates, while the proportion is as high as 71% along the Mediterranean and Black Sea coasts, further underscoring the reliability of the data in these regions. Although roughly 25% of the Atlantic coastline displays VLM rate changes exceeding 1 mm/year, revealing genuine land motion differences, the EGMS data overall remain consistent across different coastal regions. In particular, in areas such as the Mediterranean and Black Sea coasts—where tectonic activity is relatively weak, GIA effects are limited, and human activities are more effectively regulated—VLM observations appear more stable, demonstrating the robustness and regional applicability of the dataset^[34, 35]. In summary, the high stability of EGMS data across different temporal windows provides a reliable basis for its application in monitoring

coastal ground motion.

Table 1 | Fluctuation characteristics of coastal VLM rates in Europe between consecutive observation periods
(Unit: mm per year)

Region	>0.5	-0.5 ≤ Change ≤ 0.5	<-0.5
Atlantic	22%	53%	25%
Med & Black Sea	14%	71%	15%
Europe	19%	59%	22%

Notes: Med & Black Sea refers to the Mediterranean and Black Sea region. ”

3. Adjust Figure 2 and Acknowledge Thiéblemont et al’s Contribution

To address the issue that “the original Figure 2 is similar to Figure 7 in Thiéblemont et al. (2024),” we made two key adjustments:

- 1) Move the original Figure 2 to supplementary material and label the source:

The original “European coastal subsidence hotspot map” was adjusted to Supplementary Figure S1, with a clear note acknowledging Thiéblemont et al.’s contribution:

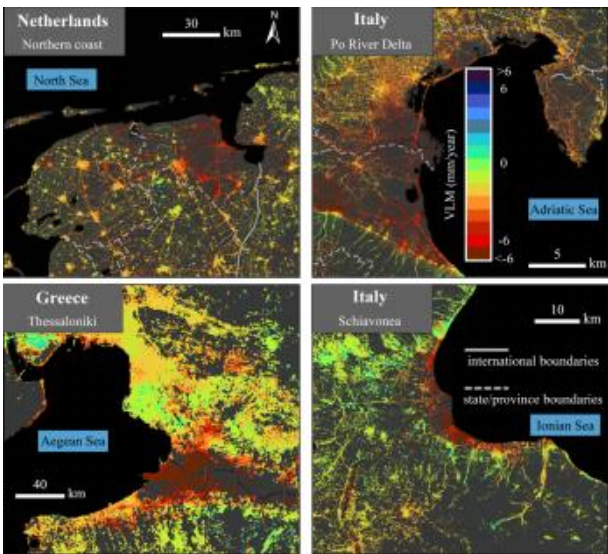


Fig. S1. | Major subsidence hotspots along the European coastal zone. The areas shown in the figure are respectively the northern coast of the Netherlands, Thessaloniki in Greece, the Po River Delta in Italy, and Schiavonea in Italy, representing subsidence-prone regions, with the red areas indicating zones of higher subsidence intensity. The first identification of Schiavonea is credited to Thiéblemont et al^[13].

- 2) Add a new Figure 2 to illustrate the overall VLM pattern of Europe:

We added a “Spatial Gradients and Transition Patterns of VLM Across European Coastal

Zones” (Figure 2) and supplemented text to explain its scientific significance:

(Page 7, lines 160–178)

“Moving southward from Northern Europe, the continent-wide pattern of VLM reveals a pronounced north–south gradient, with coastal uplift prevailing across Northern Europe, while subsidence dominates along the Mediterranean and Black Sea coasts (Fig. 2).

According to high-precision monitoring data from the EGMS, four major coastal subsidence hotspots have been identified (Fig. S1): the northern coast of the Netherlands, Thessaloniki in Greece, the Po River Delta in Italy, and Schiavonea in Italy. Notably, Schiavonea represents a newly identified subsidence hotspot based on EGMS data, whose discovery not only enhances the understanding of subsidence patterns along European coastlines but also provides new scientific insights into regional crustal movements^[38]. Along the Atlantic coast of Western Europe, the average VLM rates are generally below 2 mm/year; low-lying countries such as the Netherlands and Belgium face particularly pronounced coastal subsidence, with annual VLM rates exceeding 1 mm/year. In comparison, coastal regions in the United Kingdom, Ireland, and western France exhibit relatively moderate subsidence, with annual rates typically below 1 mm/year. In most areas of the Mediterranean coast of southern Europe, where the VLM is below 1 mm/year, the coastal zone is sinking more severely than in the countries north of the Mediterranean. When viewed from a finer spatial scale, coastal-to-inland VLM patterns show distinct regional contrasts (Fig. 2). Subsidence-dominated coasts, such as the Atlantic–North Sea and Mediterranean–Black Sea regions, display relatively uniform rates inland, whereas uplift-dominated northern areas exhibit a clear inland-increasing trend, highlighting Europe’s complex VLM dynamics.”

The yellow highlighted parts indicate the revised content.

The new Figure 2 includes four subplots to comprehensively present the spatial characteristics of VLM:

(Page 8, lines 180–189)

The new Figure 2 (replacing the previous version):

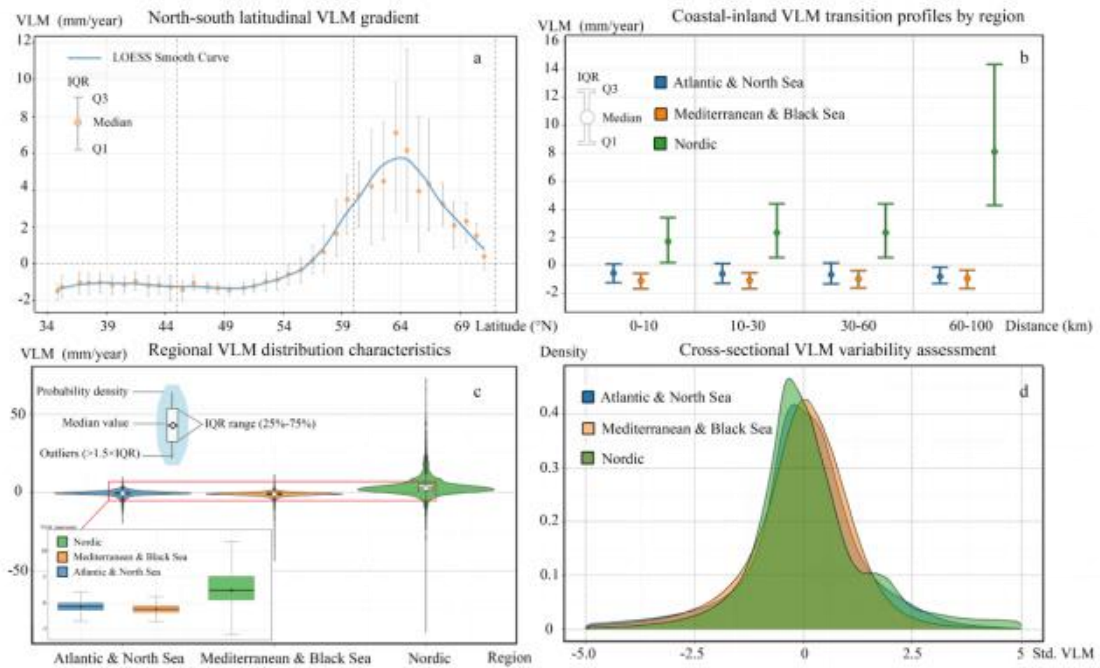


Fig.2 | Spatial gradients and transition patterns of VLM across European coastal zones. a, Latitudinal variations of VLM, showing the transition from Nordic uplift to Mediterranean subsidence. Orange dots are medians, and the blue line is a smooth curve. b, Coastal-to-inland VLM transitions, grouped by distance. c, VLM distribution across regions, compared with violin and box plots. d, Standardized VLM density distributions for each region, normalized using the median-MAD method. By synthesizing the latitudinal gradient at the continental scale, the coast-to-inland transition, and regional variability, this visualization provides the physical and statistical basis for the exposure framework.

In conclusion, the above revisions not only clarify the methodological inheritance and original boundaries between this study and Thiéblemont et al. (2024) but also clearly explain the scientific purpose of the temporal setup. Meanwhile, the adjustment of figures improves the originality and relevance of the result presentation. Throughout the revision process, we maintained methodological transparency without deviating from the core research goal of “socioeconomic vulnerability and exposure assessment.” We sincerely appreciate your constructive comments and hope that our responses address your concerns.

Comments 2:

SLR scenario

The current manuscript notes that it is using an IPCC scenario for SLR in 2050, but the specific scenario is only mentioned in the supplemental material (SSP2 4.5). This should also be noted in the main manuscript since it is a key driver of their estimates of exposure.

We sincerely appreciate the reviewer's key comment on the annotation of the SLR scenario. The SSP2-4.5 scenario from the IPCC (Intergovernmental Panel on Climate Change) is the core driver of this exposure assessment. Previously, this scenario was only mentioned in the supplementary

material, leading to insufficient information presentation. We have completed systematic revisions in accordance with the reviewer's comment, and the specific modifications are as follows:

1. Supplementary Information of SLR Scenario in the Main Text

We have integrated a clear reference to the SSP2-4.5 scenario directly into the narrative of the main text (Section: “The Impact of Relative Sea Level Rise on Coastal Zones”).

Original: “The study focuses on the European coastal zone, integrating high-resolution VLM and DEM datasets, combined with SLR projections, to construct inundation risk maps under relative SLR scenarios.”

(Page 11, lines 262–264)

Revised: “The study focuses on the European coastal zone, integrating VLM and DEM datasets, combined with SSP2 4.5 SLR projections, to construct inundation risk maps under relative SLR scenarios.”

2. Migration of Method Section and Integration of SLR Content

Recognizing the importance of methodological transparency, we have transferred the detailed methods from the supplementary material to a formal section within the main manuscript. Specifically, the “Exposure Assessment” subsection now provides a clear overview of the SLR data, stating:

(Page 23, lines 567–568)

SLR (Sea Level Rise): Projected geocentric SLR estimates under the SSP2-4.5 scenario, derived from IPCC assessment report^[39].

We are confident that these modifications successfully highlight the key driver of our analysis and significantly improve the overall readability and robustness of the manuscript. Thank you for prompting this improvement.

Comments 3:

Study areas

The authors state that they defined the coastal zone to be the zone 100 km from the shore, then go on to say that they used a “bathtub model” for SLR flooding exposure with a DEM. It’s not clear whether they used the same Coastal Flood Plain extent as Thieblemont et al 2024, but their Figure 6 does appear to show those defined Coastal Flood Plains for their analysis of income levels. The authors should clarify which spatial extents were used for each analysis of population and asset exposure, and note whether the extents vary (is it sometimes the inundation-prone zone and at other times only the subsiding area within the inundation zone?) or whether they consistently used the Coastal Flood Plains defined in Thieblemont et al 2024.

Original contributions?

We sincerely appreciate the reviewer’s critical questions regarding the definition of the coastal zone and the spatial extents used for population and asset exposure analyses. These insights have been invaluable in enhancing the transparency of our methods, and we provide a detailed clarification below:

1. Explicit Delineation of Coastal Flood-Prone Zones: Differences Between Bathtub Model Results and Thiéblemont et al.

First, we explicitly clarify that the coastal spatial extent used in our study is not the same as the “Coastal Flood Plains” defined by Thiéblemont et al.

The initial geographic scope of our study is defined as the 100 km coastal zone—we refer to this area as the “European coastal zone” and use it as the foundation for all subsequent analyses integrated with VLM data. To derive the core flood-prone areas within this 100 km zone, we calculated Europe’s coastal exposure risk zones using a bathtub model—this model is tailored to project inundation risk under Relative Sea-Level Rise for Europe’s coastal zones by 2050.

To eliminate ambiguity about how these flood-prone zones were generated, we have migrated relevant methodological content from the “Material and Methods” section to the dedicated “Methods” subsection in the main text. This migration ensures readers can directly link the spatial extent of our flood-prone zones to their underlying calculation logic, thereby avoiding confusion with the “Coastal Flood Plains” defined by Thiéblemont et al. The detailed calculation process is provided below:

(Page 23-24, lines 558–592)

“We used a bathtub model to predict flood risk in European coastal countries (Fig. S2)^[10, 40-42]. The evaluation mainly used the following datasets:

VLM (Vertical Land Motion): Ground motion data for the European coastal zone at a standard resolution (100 m), sourced from the EGMS^[43].

DEM (Digital Elevation Model): A 30 m resolution DEM from the Copernicus Programme, serving as the baseline topographic dataset^[44].

SLR (Sea Level Rise): Projected geocentric sea level rise estimates under the SSP2-4.5 scenario, derived from IPCC assessment reports^[39].

MSL (Mean Sea Level): Standardized MSL referenced to a global datum, provided by the Permanent Service for Mean Sea Level (PSMSL)^[45, 46].

The VLM rates are resampled to match the 30 m resolution of the DEM using bilinear

interpolation. Assuming the 2019–2023 VLM rate persists from 2022 to 2050 (constant-rate baseline), the elevation is projected from the DEM reference year (2022) to the target year (2050)^[10].

$$DEM_{mod} = DEM_{2022} + VLM \times \Delta t \quad (1)$$

In which DEM_{mod} represents the projected future elevations (2050) after adjusting for VLM; DEM_{2022} provides the initial elevation data for 2022; VLM is used to quantify the annual uplift or subsidence of the land surface; Δt is a time-dependent adjustment factor (in years), converting the VLM rate to cumulative elevation change over the period from 2022 to the target year (2050, $\Delta t=28$). We carry forward the empirically observed 2019–2023 VLM rate to 2050 as a constant-rate baseline.

Meanwhile, based on the SSP2-4.5 scenario predicted by IPCC, the median SLR rate was selected to estimate the sea level by 2050. To avoid duplicate calculations of ground subsidence, the “novlm” (no vertical land motion) version is used for prediction^[39]. During the prediction process, the SLR rate is assigned to the nearest tidal station, and the adjusted tidal station data is used to predict the 2050 sea level. Finally, the inundation risk is evaluated by subtracting the adjusted DEM elevation from the estimated average sea level (Eq.2)^[10].

$$Inun = DEM_{mod} - (SLR_{50} + MSL)(2)$$

In which $Inun$ represents the estimated exposure value; DEM_{mod} is the corrected elevation model updated using the VLM projections; SLR_{50} represents the 50th percentile of IPCC's prediction of global SLR by 2050; and MSL denotes the mean sea level.”

2. Consistency of Spatial Extents for Population and Asset Exposure Analyses

We confirm that the spatial extent used for all population and asset exposure analyses is fully consistent—there is no switching between “inundation-prone zones” and “subsiding areas within inundation zones.” All exposure indicators, including counts of exposed population, values of building stock, and economic output in at-risk areas, are calculated exclusively within the “coastal flood-prone zones derived from the bathtub model” described above.

To reinforce this consistency and prevent reader confusion, we have included detailed calculations for indicators such as exposed population in the methods section. The specific calculation process is provided below:

(Page 24-25, lines 594–605)

“To delineate spatially continuous submerged units, a connectivity analysis is conducted on the computed results. Under the assumption that no flood control measures are implemented, regions exhibiting negative exposure values in the analysis are identified as high-risk coastal flood zones by 2050. Following the identification of these exposure zones, subsequent analyses quantify the vulnerability of three key coastal elements: (1) land area, (2) population, and (3) buildings. Population exposure was quantified by extracting and

aggregating projected population data for the year 2050 under the SSP2 scenario within the delineated inundation zones (Table S1)^[26]. Building exposure assessment utilized Microsoft's Building Footprints dataset to count the number of structures located in exposed areas^[31]. For economic impact analysis, country-level housing price data were integrated from Statista and Numbeo databases (Table S2)^[32, 33]. Assuming the affected properties are a total loss, the potential economic loss caused by RSLR was estimated by calculating the product of the total exposed built-up area and the property price per unit area.”

In conclusion, all population and asset exposure analyses in this study consistently rely on the “2050 European coastal flood-prone zones” derived from the bathtub model, which are distinct from the “Coastal Flood Plains” defined by Thiéblemont et al. By incorporating detailed methodological descriptions—including a step-by-step workflow for the bathtub model and explicit explanations of the indicator calculations—we have enhanced the transparency of our spatial framework, ensured the reproducibility of our analyses, and clarified the spatial scope for readers. We sincerely thank the reviewer for highlighting this important point, which has considerably improved the clarity and rigor of our methods.

Comments 4:

Land cover data and exposure analysis

The paper considers land cover using a highly simplified 5 category typology, and Fig 3 describes the distribution of “subsiding pixels” for each. The figure has some confusing labels (“land use cover”, and the word “less”) but is otherwise useful and interesting in spite of the simplicity of the land cover categories. Thiéblemont et al 2024 also looked at land cover in relation to coastal subsidence, and came to similar conclusions about wetland subsidence rates being high. That older paper also used finer categories for the built environment which is more helpful than the current manuscript’s use of “artificial areas” as a land cover category that lumps all aspects of the built environment into one category.

We sincerely appreciate the reviewer’s constructive feedback on land cover data and exposure analysis, which has helped us refine the clarity and rigor of our study. Below is our detailed response to each point raised:

1. Revision of Figure 3 Labels and Ambiguous Terminology

The reviewer correctly noted the confusing labels (“land use covers”) and ambiguous term (“less”) in Figure 3. We have addressed these issues as follows:

- (i) The incorrect label “land use covers” has been revised to the scientifically accurate term “land cover” to align with standard terminology in land surface research.
- (ii) The vague term “less” (originally intended to describe pixels with high subsidence rates) has been replaced with the precise scientific threshold “< -6 mm/year”. This explicitly indicates pixels where the annual subsidence rate exceeds 6 mm, eliminating ambiguity for readers.

The revised version of Fig. 3 reflecting these improvements is shown below.

(Page 10, lines 232–234)

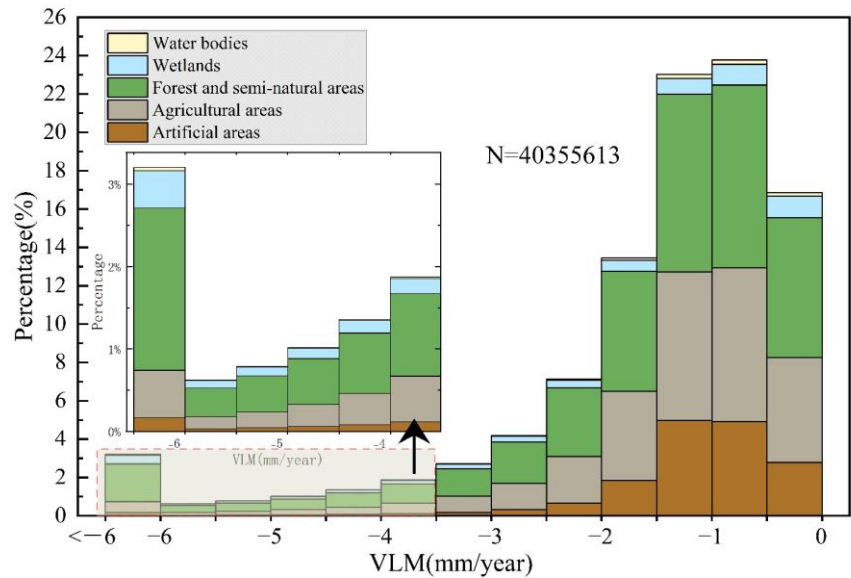


Fig.3 | Subsidence frequency distribution by land cover. *N* is the number of pixels and *VLM* is vertical land motion.

2. Consistency of Wetland Subsidence Conclusions with Thieblemont et al. (2024)

We agree with the reviewer that our conclusion regarding “higher subsidence rates in wetlands” aligns with the findings of Thieblemont et al. Importantly, our conclusion is independently derived from systematic analysis of EGMS data and land cover classification data—a consistency that reinforces the robustness of this observation across different research frameworks.

As evidenced in Table 2 of our manuscript, the average subsidence rate of wetlands is 2.3 ± 3.1 mm/year, which is the highest (most negative) among all land cover categories. This quantitative data directly supports our conclusion and further validates the alignment with Thieblemont et al.

3. Land Cover Classification and the Use of “Artificial areas”

We fully acknowledge the value of the more detailed land cover classification of built environments (e.g., airports, railway lines, industrial zones) used in Thiéblemont et al, which indeed provides important insights for localized and infrastructure-specific analyses. However, our study has a different analytical objective — to conduct a continental-scale assessment of exposure risk across European coastal regions.

To achieve this, we deliberately aggregated all built environment features into a single “Artificial areas” category. This methodological design enables us to

- (i) present a clear and coherent visualization of exposure patterns across large spatial extents, avoiding excessive fragmentation that would obscure continental-scale trends;
- (ii) facilitate straightforward comparisons among major land cover types (e.g., wetlands, artificial areas, agricultural areas) in terms of exposure to sea-level rise and land subsidence;
- (iii) maintain methodological consistency with our study’s emphasis on broad, cross-regional risk characterization rather than site-specific infrastructure analysis.

In the revised manuscript, we have also added the following clarification to the Methods section to clearly define this category:

(Page 22, lines 531–534)

“For the purposes of this study, four primary land cover types were selected: artificial areas (land cover types where the original natural environment has been fundamentally altered by human activity), agricultural areas, forests and semi-natural areas, and wetlands.”

We also recognize that this macro-level approach cannot fully capture the heterogeneity of subsidence processes among different types of built environments. Accordingly, we have added a clarification in the Discussion section, suggesting that future research could integrate finer-grained land-use classifications and dynamic hydrological processes to more accurately capture localized inundation dynamics and the vulnerability of critical infrastructures.

(Page 20, lines 478–484)

“Future research could build on this foundation by incorporating dynamic hydrological processes to more realistically simulate inundation patterns, while integrating multi-dimensional asset data, higher-resolution demographic information, and more detailed land-use classifications. Such refinements would enable a more nuanced identification of vulnerabilities across different built environments, contributing to a more comprehensive understanding of coastal subsidence risk and its inequalities. These efforts would also provide stronger scientific support for enhancing climate resilience and long-term spatial planning in European coastal regions”

Once again, we sincerely thank the reviewer for these valuable comments, which have helped to enhance the accuracy, clarity, and overall contextualization of our land cover and exposure analysis.

Comments 5:

Exposure of buildings and other assets

Population and assets were characterized previously on a global scale that included the European region. Jongman et al 2012 reviewed global population exposure, including income levels, as well as asset exposure using GDP. Thieblemont et al 2024 used specific public assets (transportation

infrastructure) for European coastal floodplains, which is arguably more useful than reporting the value of private assets since transportation systems are typically publicly-owned, intended to be permanent, and impact many aspects of a regional economy.

This manuscript used a global database of building footprints, and somehow integrated housing prices from cost of living data- but the method for the use of the data is unclear. As an economic analysis, this is unusual in my experience – other papers have used estimates of GDP, for example, which considers economic output in addition to private property values. Property values are usually used when a cost-benefit ratio is being calculated for adaptation, which is not the case here. While unsophisticated, the number of buildings and total value of housing could be used to represent asset values in the exposure zones. But the authors should provide more discussion of the details of their method in the supplemental material in order for readers to determine the validity of their methods.

Thank you very much for your valuable comments on the asset exposure assessment method and the rationality of indicator selection in this study. You accurately pointed out the issues in our manuscript, including the unclear description of the asset value estimation method and the need for further clarification on the reasons for selecting residential property value as an indicator. This feedback is crucial for improving the transparency of the research method and the credibility of the conclusions. We have made targeted revisions based on your suggestions, and the specific responses and revision details are as follows:

1. Enhanced methodological transparency

We have relocated the methodological details previously included in the Supplementary Material to the main Methods section and added explicit explanations of the calculation procedures. The revised text now clearly states:

(Page 24-25, lines 600–605)

“Building exposure assessment utilized Microsoft’s Building Footprints dataset to count the number of structures located in exposed areas^[31]. For economic impact analysis, country-level housing price data were integrated from Statista and Numbeo databases (Table S2)^[32, 33]. Assuming the affected properties are a total loss, the potential economic loss caused by RSLR was estimated by calculating the product of the total exposed built-up area and the property price per unit area.”

2. Justification and discussion of the approach

We selected residential property value as the core indicator for assessing asset exposure. This choice does not negate the value of GDP or public asset indicators but rather provides a complementary, bottom-up perspective:

- (i) Compared with GDP, residential property value directly corresponds to the stock of physical assets at risk of permanent inundation, aligning more closely with the core

- definition of asset exposure—that is, the physical scale of assets facing hazard risks.
- (ii) Compared with public assets, residential property represents a major component of private wealth and an important part of national capital stock. Its inclusion therefore offers a valuable complementary perspective in coastal flood risk assessments.

At the same time, we acknowledge the limitation of this approach—that a comprehensive economic risk assessment should integrate multiple asset types and indicators. Accordingly, we have explicitly added a discussion of this limitation in the revised Discussion section to ensure the methodological rigor of our study.

(Page 20, lines 468–471)

“Second, in measuring asset exposure, we focus on building values to capture the potential direct losses to private wealth. This provides an important complement to existing GDP-based analyses; however, a comprehensive economic risk assessment should also incorporate public, commercial, and industrial assets.”

We believe these revisions have contributed to improving the transparency and conceptual robustness of our methodological framework. By focusing on residential property value, the approach enables a direct assessment of the potential physical losses associated with permanent inundation. This focus complements existing top-down economic assessments based on GDP or public assets, providing a more granular understanding of how climate risks may translate into private wealth impacts. We sincerely thank the reviewer again for the constructive comments, which have greatly enhanced the overall quality and rigor of our study.

Comments 6:

Population exposure and equity

Identifying the inequalities of exposure for populations is described by the authors as the primary contribution of the paper. They use a quartile approach to standardize income metrics as their measure of the relative level of private resources across regions and countries. While income is only an indirect measure of resources (it does not consider wealth in the form of property, or health status, or education level) it is not an unreasonable beginning for a discussion of vulnerability. The map they produce in Figure 6 is novel, to my knowledge.

They used census data to identify proportions of populations 65 years of age and over, or under 14 years of age, and then assumed that these proportions would hold true in 2050. However this is unlikely to be the case; demographic trends should have been considered instead of static proportions.

Finally, the authors used the presence of Roma settlements as an indicator of vulnerability, by focusing on the presence/absence of a group that has been described as especially vulnerable in regional analyses and policy.

We sincerely thank the reviewer for the insightful and constructive comments regarding our

analysis of population exposure and equity across economic, demographic, and ethnic dimensions. In response, we have made the following major revisions to strengthen the conceptual coherence, methodological rigor, and empirical accuracy of this section:

- (i) We explicitly linked the empirical indicators (economic, age, and ethnic) to the theory of social vulnerability and the European Union's (EU) Just Resilience policy framework, thereby establishing a coherent analytical logic and enhancing the explanatory strength of our inequity assessment.
- (ii) We supplemented the salary-level distribution map (Fig. 6) with projected 2050 GDP data for each country, allowing for a better understanding of both the relative economic status of exposed regions within countries and the standardized comparison of their absolute economic capacities across Europe.
- (iii) We incorporated future demographic changes using population projection data from the United Nations and recalculated the proportions of elderly and child populations through a proportional adjustment method.

1. Integration with social vulnerability theory and EU policy framework

We have systematically revised the analysis of socioeconomic vulnerability and the assessment of social inequality to ensure consistency between the research framework and the EU's policy priorities. Specifically, the revision was carried out along two main directions: (1) reviewing literature and empirical frameworks in the field of social vulnerability to extract academically recognized multidimensional indicator systems; and (2) aligning indicator selection with the EU's "Just Resilience" framework to ensure conformity with its policy orientation. This revision provides a solid theoretical foundation while ensuring that our analysis directly responds to the EU's growing concern over inequality in the context of climate change.

In particular, the revision centers on the premise that unequal vulnerability to climate change primarily stems from social inequality^[47]. The selected indicators—age structure, income level, and Roma communities—were carefully considered within this conceptual framework. Contemporary studies on social vulnerability commonly encompass both demographic characteristics and socioeconomic status^[48]. Reduced access to resources is often associated with the marginalization of minority groups, while demographic characteristics determine how different population groups are differentially affected by environmental hazards. Accordingly, we identified the population below and above working age as key demographic indicators to capture age-related sensitivity to climate impacts, and included the Roma population to highlight their high exposure and more limited adaptive capacity under the combined pressures of social and climatic stressors^[49, 50].

Furthermore, income level was used as an essential economic indicator of adaptive capacity. In general, increases in wages and salaries imply greater access to resources and higher resilience to disasters. Based on this rationale, we analyzed income levels in flood-prone coastal zones across European countries to examine the socioeconomic conditions and potential inequality risks these areas face under RSLR conditions.

The selection of these indicators is fully consistent with the EU's Just Resilience principle, which emphasizes inclusiveness and fairness in climate adaptation processes, with a particular focus on the elderly, economically disadvantaged populations, and vulnerable regional or ethnic groups^[51]. Our indicator framework reflects this policy orientation and embodies a justice-oriented approach to understanding climate risk within European coastal regions.

To further strengthen the rationale of our climate inequality assessment, we added the following paragraph in the section "Climate Change Inequality in Coastal Zones":

(Page 15, lines 335–350)

"Climate change imposes unequal and uneven burdens across regions, necessitating a more nuanced understanding of this global crisis^[52]. Climate risks are deeply coupled with social vulnerability, which is commonly assessed through indicators such as economic deprivation, dependent age structures, and systemic marginalization based on ethnic or group identity^[48]. These dimensions collectively characterize differences in sensitivity and adaptive capacity among social groups when facing environmental hazards. Within this context, the present study situates its assessment under the European Union's "Just Resilience" objective, emphasizing that climate adaptation planning should ensure the inclusion and protection of the most vulnerable populations, including those differentiated by age, health status, economic conditions, and place of residence^[51]. Integrating this policy framework with the social structure of Europe, the situation of Roma communities provides a critical analytical focus: they are not only economically disadvantaged but also experience persistent social exclusion based on ethnic identity, rendering them particularly susceptible to compounded inequalities under climate impacts^[49, 50]. Accordingly, this study integrates economic, age, and ethnic dimensions to systematically assess the spatial distribution of climate risk along European coasts, thereby revealing patterns of social inequity that may persist despite the EU's Just Resilience objectives."

2. Incorporation of future economic capacity (GDP projections)

To complement the existing wage-level map (Fig. 6), we added projected 2050 GDP data for European countries using the SSP2 scenario from Murakami et al.^[30]. This provides a standardized reference for comparing both relative income inequality and absolute economic capacity among exposed countries.

(Page 16-17, lines 363–370)

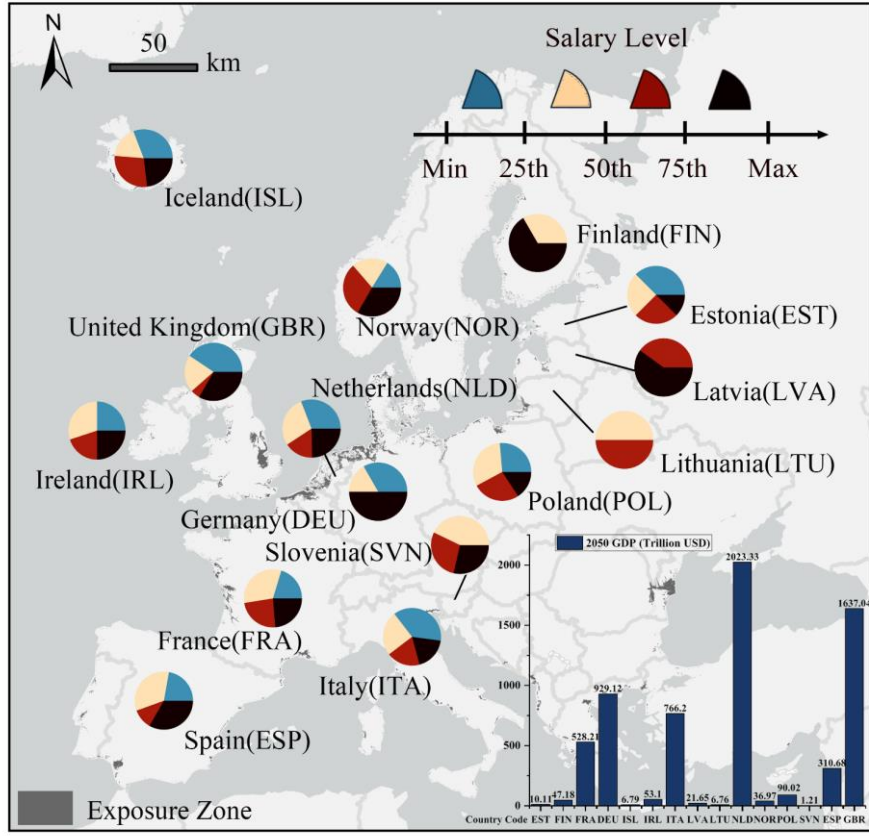


Fig. 6 | Distribution of Salary Levels by Exposure Zone in Europe. The pie chart shows the wage distribution of the exposed regions in each country, divided into four categories from low to high. The black shaded area represents the submerged exposed area. The lower-right panel presents a bar chart of projected gross domestic product (GDP, in trillions of U.S. dollars) for selected European countries in 2050, based on Murakami et al.^[30], providing a standardized reference for comparing the absolute economic capacity of the exposed countries.

3. Revised population projection approach

We agree that assuming constant age proportions to 2050 does not reflect demographic trends. Therefore, we improved the estimation by incorporating national-level population projections from the United Nations World Population Prospects (2024). We adjusted the local age composition of the exposed population using proportional change factors derived from each country's projected demographic shift between 2024 and 2050. Details are as follows:

(Page 26, lines 639–648)

$$f_{c,age} = \frac{q_{c,age}^{2050}}{q_{c,age}^{2024}} \quad (1)$$

Where $q_{c,age}^{2024}$ and $q_{c,age}^{2050}$ are the national population shares of age group age in country c for 2024 (WPP estimate) and 2050 (WPP projection), respectively. This factor $f_{c,age}$ projects

the relative change in the national age structure.

$$\bar{r}_{A,age}^{2050} = r_{A,age}^{2024} \times f_{c,age} \quad (2)$$

This estimates the future absolute share $\bar{r}_{A,age}^{2050}$ of age group age in study area A for 2050, by applying the national change factor ($f_{c,age}$) to its initial local share ($r_{A,age}^{2024}$).

$$r_{A,age}^{2050} = \frac{\bar{r}_{A,age}^{2050}}{\sum_{age'} \bar{r}_{A,age'}^{2050}} \quad (3)$$

This final step normalizes the projected shares from Equation (2) so that the proportions for all age groups within area A sum to 100%. ”

This method can effectively overcome the limitations of static assumptions, making the future demographic structure of exposed areas more in line with the expected population change trends at the global and regional levels, thereby improving the rationality of estimating exposure risks for vulnerable age groups. Meanwhile, we also acknowledge the limitations of this method: its core assumption that “the trend of demographic structure change at the subnational level (study area) is consistent with that at the national level” may fail to fully capture local demographic differences in age structure changes across different regions; regarding this limitation, we have added relevant explanations in the conclusion section of the revised manuscript to ensure the rigor of the study.

(Page 20, lines 473–476)

“Finally, in terms of demographic structure, this study adopts future age-composition scenarios to better reflect projected population changes, yet the assumption that subnational trends follow national-level dynamics may not fully capture local heterogeneity. ”

We are confident that these revisions have significantly enhanced the conceptual soundness and methodological robustness of our equity analysis. We deeply appreciate the reviewer's constructive feedback, which has greatly help us to improve our manuscript.

Comments 7:

Geographic scale used for comparisons

A series of country-scale assessments is used to characterize differences in exposure by area, population size, number of buildings, and other assets. While normally country-scale comparisons can obscure important spatial patterns, the differences among these four are useful in pointing out the significance of SLR exposure for urban areas (with higher population, numbers of buildings, and other infrastructure assets).

Throughout, there is some lack of clarity about what the unit of analysis is for each variable. Were the demographic, economic and asset analyses all applied within the areas of the defined inundation zone that are subsiding? What is the threshold that defines “subsiding” land for this spatial analysis, is it -1 mm/year or simply <0?

We would like to thank the reviewer for these insightful comments, which have helped us identify areas that require clarification in our methods. Below is our point-by-point response:

1. Regarding the Unit of Analysis

The reviewer correctly pointed out the need to clarify the unit of analysis. In our study, the primary unit for reporting and comparison is indeed the national scale. However, as the reviewer astutely inferred, the calculations for each country are not based on overall national-level data. To ensure accuracy, all analyses (of population, economy, and assets) were first conducted at the most granular spatial level available within the subsiding and inundated areas. Specifically, for each country:

- (i) We identified all coastal areas projected to be inundated under the 2050 sea-level rise scenario.
- (ii) We extracted population, economic, and asset data exclusively for these affected areas. For population and building data, results related to projected inundation were obtained directly through spatial calculations. For economic data and data on elderly and child populations, to ensure the most accurate results, we retrieved data for the inundated areas based on the characteristics of publicly available data in each country—this process involved using specific administrative units of each country to obtain economic data for the projected inundated regions.
- (iii) These values were aggregated to generate the final national-level exposure assessment results for cross-country comparison.

We agree that this critical detail was not sufficiently explained in the original manuscript. We have now revised the Methods section to clearly state that the analysis was conducted within the delineated projected inundated areas, and the results were then aggregated to the national level for ease of comparison.

(Page 25, lines 608-616)

“To comprehensively investigate the different responses of European coastal countries to the pressing challenge of RSLR, we systematically collected statistical data for the exposed areas, including economic and demographic indicators from the official statistical offices of various European countries. The dataset consists of the most recently published annual or monthly data from each country's national statistical office, with the geographic granularity determined by the smallest administrative unit level for which data is made publicly available in each respective country. The exposed population and assets were then aggregated to the national level to produce the final results for international comparison. This approach ensures that the country-scale estimates are grounded in detailed spatial calculations.”

2. Regarding the Threshold for “Subsiding” Land

We apologize for failing to precisely define “subsiding” land. In this spatial analysis, we defined “subsiding” areas as any land with a VLM rate of less than 0 mm/year—we considered all regions showing a negative trend ($VLM < 0$).

We recognize that this is a critical parameter that must be clearly defined. We have now added an explicit statement of this definition in the section of the Methods section where VLM data analysis is introduced. The revised text now clearly states:

(Page 21, lines 499-500)

“For this study, “subsiding land” was defined as all areas exhibiting a VLM rate of less than 0 mm/year.”

Additionally, regions with negative exposure values in the bathtub model analysis were identified as high-risk coastal flood zones under the context of relative sea-level rise. This is clearly specified in the “Exposure Assessment” subsection of the Methods section:

(Page 24, lines 595-597)

“Under the assumption that no flood control measures are implemented, regions exhibiting negative exposure values in the analysis are identified as high-risk coastal flood zones by 2050.”

Once again, we appreciate these valuable comments, which have significantly improved the clarity and rigor of our manuscript.

Overall comments:

This manuscript has a strong focus on the VLM analysis, and yet that is not novel. The authors want the reader to focus on their analysis of the exposure of people, buildings and land cover types, and especially on the exposure of people with lower incomes / different costs of living or property values / minority Roma settlements. While this socioeconomic exposure analysis may be new for subsiding areas of coastal flood risk, it's not clear that the methods used here are based on a knowledge of methods developed recently by experts in this type of socioeconomic analysis. The primary citation used for related work in the planning/socioeconomic literature seems to be from 2012 (Jongman et al). It's also not clear that the variables chosen to represent inequality are important to policy in the European Union. Since equity is a normative variable that has been defined in different ways over different historical periods, it would be helpful for the authors to identify metrics for inequality that are currently being used in EU policymaking. Adaptation planning will use some of the same socioeconomic characterizations as any other kind of planning.

I would suggest significant revisions to address (1) the relationship of the methods and results of this study to the methods and results of Thieblemont et al 2024; (2) a brief review of current methods for assessing social inequality, with an emphasis on methods relevant to EU policymaking and a revised analysis of socioeconomic vulnerability based on both; and (3) clarification of the spatial units used for each analysis.

We sincerely thank the reviewer for their insightful, systematic, and constructive feedback on the

overall manuscript. These comments have astutely pinpointed three core dimensions critical to elevating the quality of our research: the clarity of our study's core focus (distinguishing VLM analysis from socioeconomic exposure assessment), the relevance of our methodological design to cutting-edge scholarship and policy needs, and the alignment between our inequality indicators and European Union (EU) policy frameworks. Your guidance has provided a clear roadmap for refining our work, ensuring it is more rigorous in logic, transparent in positioning, and actionable in policy implications. Below we provide a detailed response to the key concerns raised:

1. VLM analysis and relation to Thieblemont et al.

We agree that VLM analysis is not the core innovation of this study. The main contribution lies in using VLM as a physical basis to integrate socioeconomic data for assessing inequalities in coastal flood exposure. While both studies utilize EGMS VLM data, our analysis focuses on the transition from physical subsidence patterns to socioeconomic exposure, with Thieblemont et al cited solely as a reference for subsidence hotspots.

The original hotspot map similar to that in Thieblemont et al has been moved to the Supplementary Material (Fig. S1) with clear attribution. The new Fig. 2 presents Europe-wide VLM spatial gradients, highlighting unique analytical dimensions essential for the socioeconomic exposure analysis.

2. Socioeconomic inequality indicators, theoretical basis, and EU policy relevance

We have systematically revised the analysis of socioeconomic vulnerability and social inequality to ensure that the research framework aligns with the European Union's policy priorities. This revision enhances the theoretical coherence of the study and strengthens its connection to the EU's emphasis on fairness and inclusiveness in climate adaptation.

The selected indicators—income level, age structure, and Roma settlements—are theoretically well-founded and closely aligned with the EU's "Just Resilience" principle. By integrating economic, demographic, and ethnic dimensions, the analysis reveals how disparities in income, age composition, and social marginalization jointly shape differences in sensitivity and adaptive capacity among population groups. The inclusion of Roma communities further highlights the multiple disadvantages faced by socially marginalized populations under combined pressures, thereby uncovering spatial patterns of social inequality across Europe's coastal regions. Overall, the revised framework demonstrates enhanced analytical consistency, empirical rigor, and policy relevance.

3. Spatial units clarification

All population, building, and economic exposure analyses are based on the 2050 European coastal flood-prone zones derived from the bathtub model. In the revision, we have paid particular attention to the description and terminology of the spatial units, ensuring clarity and consistency, and have provided detailed explanations of the calculation procedures in the

Methods section. This enables readers to accurately understand the spatial scale corresponding to each step of the analysis.

Summary of key revisions:

- (i) Clarified study boundaries and methodological independence from Thieblemont et al.
- (ii) Integrated socioeconomic indicators with social vulnerability theory and the EU “Just Resilience” policy, reinforcing both methodological rigor and policy relevance.
- (iii) Specified spatial units and ensured transparent explanation of calculation procedures.

We would like to express our sincere gratitude once again to the reviewer for your thoughtful, comprehensive, and constructive feedback on the overall manuscript. Your insights have not only resolved ambiguities in the original study but also driven the systematic refinement of our research framework—substantially improving the clarity of our core contribution, the rigor of our analysis, and the policy value of our findings. We hope that the revisions we have made have addressed the key points in your overall comments as thoroughly as possible.

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