The authors present a global dataset of landforms derived from a high-resolution DEM. They propose new ways to identify plain areas and their transition to hilly and mountainous terrain. The novel way to do this by identifying core areas and including transition areas through a cost distance analysis yields results that seem visually quite accurate when the map is overlayed onto a relief background. Plain and higher relief areas are neatly differentiated. This type of information can be quite useful for geographical and ecological macro studies. The precise workflow does miss details to be reproducible. It is a pity that proprietary software was used and the workflow described in general terms only, which makes replication more difficult. The choice for some cut off values or thresholds (slope, elevation, accumulated cost) is not always clearly explained or motivated.

Response:

Thank you for your valuable feedback. We appreciate your recognition of the dataset's potential for geographical and ecological macro studies.

We acknowledge the need for a more detailed workflow description to enhance reproducibility. In the revised version, we have provided additional details on the specific steps, including explanations of the principles guiding our selection of threshold values (slope, elevation, and accumulated cost).

To classify the hilly and mountainous areas the authors propose a new approach as an alternative to a moving windows analysis that has documented limitations. Landform relief is not calculated with reference to the nearest elevation data within a (small) window, but expressed with reference to a regional baseline calculated by creating a TIN on the basis of the elevation at the border of a mountain range (i.e. where it transitions to plain). In addition, the baseline elevation takes into account the elevation of points along water courses within the mountain to create a baseline surface to act as reference for the roughness calculations. Thresholds are applied to the elevation differences calculated by subtracting the baseline elevation from the actual surface elevation. The lowest elevation differences are labelled hills, followed by low relief mountain up to highest relief mountain. This leads to a conceptual problem. In my opinion, when one talks about a mountain or mountain range such as the Himalaya as a landform, one considers the mountain as a whole, from the foothills to the highest summits as the landform "highest relief mountain". Similarly when talking about the Jura or the Vosges mountains, one would talk about low relief mountains, but not consider only the mountain summits to be low, but the whole landform down to the foot slopes as being the low mountain.

Response:

Thank you for your valuable feedback. We carefully reviewed your concern and analyzed the potential reasons behind the differences in defining what constitutes a mountain. We think that the perception of a mountain is largely scale- and context-dependent. Below, we present two key considerations:

(1) Scale Perspective: In general geomorphometry, "landform" can refer to units at multiple scales. In our results, "mountain" in Level 1 (L1) aligns with the conventional, broader concept of a complete mountain entity. Levels 2 and 3 (L2 and L3) aim to capture local variations within that mountain by subdividing it according to specific altitude and relief thresholds. In other words, Levels 2 and 3 represent finer-scale morphological facets compared to the L1 "mountain." To avoid confusion about terms, we have renamed the L3 'mountain' classes to 'mountain slope', thereby clarifying that L3 focuses on local slope-based subdivisions rather than a single, unified mountain. This multi-scale approach allows users who only need a macroscopic view (i.e., one label for the entire mountain range) to rely on L 1. Meanwhile, researchers focusing on localized processes (e.g., slope erosion, microclimate differences, or altitudinal ecological zones) may benefit from the finer distinctions at Levels 2 and 3.

(2) Context Perspective: As you noted, viewing a mountain as a single entity is a common perspective, emphasizing its unified formation process and general independence. In our study, L1 was designed to capture this "common landform" notion of a mountain. In GBLU, we have improved the bounding precision of L1 with higher-resolution data and advanced methods. However, "mountain" can be a somewhat vague term—different definitions may be useful for different contexts [1]. Mountains often exhibit significant internal variability in altitude, relief, and slope, which in turn can influence climate, vegetation, biodiversity, and geomorphic processes. Because the GBLU dataset is intended for broad usage in geoscience, L2 and 3 highlight these internal subdivisions, which is particularly relevant for analyses of force accumulation, mountain ecosystems, and microclimatic gradients. Similar approaches are reported in the subfields of geoscience such as climate, ecology and biology [2-5]. From this perspective, subdividing what is commonly called "a single mountain" into multiple levels is necessary in many research scenarios.

In the revised manuscript, we have supplemented the text with more details on how each level's terminology is constrained to avoid ambiguity (Lines 99-106). Meanwhile, we have updated naming conventions within Level 3. Specially, Level 3 classes initially labeled as "mountain" have been renamed to

“mountain slope” to reflect their smaller-scale morphological nature. We hope these clarifications address your concerns.

[1] Evans, I.S., 2012. Geomorphometry and landform mapping: What is a landform?. Geomorphology, 137(1), pp.94-106.
[2] Antonelli, A., Kissling, W.D., Flantua, S.G., Bermúdez, M.A., Mulch, A., Muellner-Riehl, A.N., Kreft, H., Linder, H.P., Badgley, C., Fjeldså, J. and Fritz, S.A., 2018. Geological and climatic influences on mountain biodiversity. Nature geoscience, 11(10), pp.718-725.
[3] García-Ruiz, J.M., Arnáez, J., Lasanta, T., Nadal-Romero, E. and López-Moreno, J.I., 2024. The Main Features of Mountain Vegetation and Its Altitudinal Organization. The Timberline. In Mountain Environments: Changes and Impacts: Natural Landscapes and Human Adaptations to Diversity (pp. 167-202). Cham: Springer Nature Switzerland.
[4] Rahbek, C., Borregaard, M.K., Antonelli, A., Colwell, R.K., Holt, B.G., Nogues-Bravo, D., Rasmussen, C.M., Richardson, K., Rosing, M.T., Whittaker, R.J. and Fjeldså, J., 2019. Building mountain biodiversity: Geological and evolutionary processes. Science, 365(6458), pp.1114-1119.
[5] Rahbek, C., Borregaard, M.K., Colwell, R.K., Dalsgaard, B.O., Holt, B.G., Morueta-Holme, N., Nogues-Bravo, D., Whittaker, R.J. and Fjeldså, J., 2019. Humboldt’s enigma: What causes global patterns of mountain biodiversity?. Science, 365(6458), pp.1108-1113.

In some cases the transitions from different categories of mountain to hilly land is well captured in this approach, typically in ancient eroded landscapes with remnants of higher mountains. The dissected rolling hill landscape gets the label hills, while the remaining inselbergs are classified as mountain.
However, the story is very different in younger mountain areas such as the European Alps or Himalayas. If one looks at the GBLU map without legend overlaid onto a relief map, valley-like shapes appear very distinctly that follow the actual valleys of these mountains. When looking at the legend, one sees that these are actually classified as hills. The same holds for flat valley bottoms inside the mountains, these are classified plains, even if they are long, narrow and sinuous.
In my conceptualization of a mountain, the mid slopes of high mountains do not pertain to the landform class middle relief mountain. They are mid slopes of a high mountain. Similarly, mountain valleys are not hills, just because the local surface elevation is below a certain threshold.
Response:

Thank you for your detailed analysis of our results, particularly regarding ancient eroded landscapes. We appreciate your in-depth perspective, and in response to the issues you raised, our considerations are as follows:

First, to avoid semantic confusion, we have renamed all Level 3 “mountain” to “mountain slope”. This change clarifies that Level 3 targets finer-scale morphological units rather than large, unified mountain bodies.

Secondly, we fully acknowledge the importance of valleys in geomorphological research. One major challenge in classifying valleys lies in the absence of a unified definition, particularly regarding the valley extent or boundary on the mountainous slope. This ambiguity is often greater than that for mountains. Moreover, “valley” and “mountain” highlight fundamentally different concepts—one emphasizes downward incision, and the other highlights upward uplift. Thus, if we were to include both “valley” and “mountain” within a single classification system, we would need to define a conceptual interface to separate them. However, there is no broadly accepted standard for doing so. From a technical standpoint, it is also difficult to classify valleys because they typically lack a pronounced terrain break, which complicates classification in traditional approaches.

Although GBLU does not explicitly label “valleys,” it does provide a basis for valley extraction. As you noted, the polygons in GBLU—be they categorized as “hill” or “plain”—often capture the shapes of valleys. Our approach captures the cumulative characteristics of landform objects and uses slope accumulation to delineate subunits within a mountain. Thus, even though “valley” is not designated as a distinct category, the GBLU already produces polygons that effectively represent valley-like features. Once a user identifies a specific mountainous region of interest, they can extract those GBLU patches with valley-like shapes (classified as plain or hill, for instance) and reassign them as “valley,” thereby defining the valley object according to their own study’s requirements.

When I look at the methods and results of this paper, I think of the product as something like "Map of relief classes and relative (or regional) elevation zones", and I am convinced that this classification is useful for different scientific applications. Ontologically I don't think that the presented map units should be thought of as representations of landforms.

In summary, I commend the authors for what seems to be a very detailed and precise work and the product and the work that has gone into its production. Also, the results seem to be useful for certain research applications. I do not

however agree with the authors that what is represented here are landforms, ontologically speaking.
The distinction I make here is further illustrated in the figure.

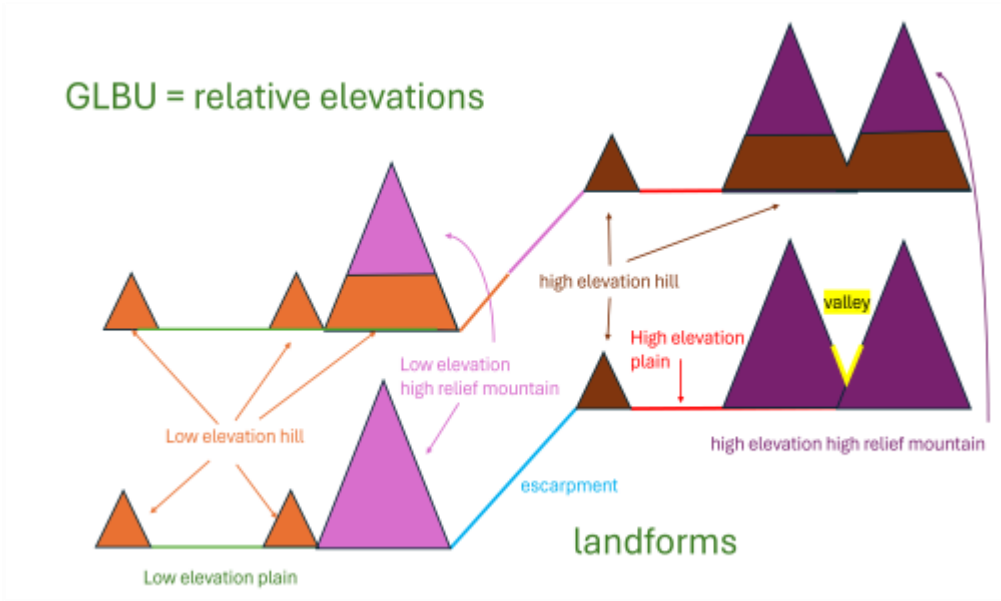

Figure: Upper transect: how I understand the current version of the GLBU. Lower transect: how I think landforms should be conceptualized in this context.

Response:

Thank you for acknowledging the potential applications of our dataset. As noted in our earlier reply, the term “landform” carries multiple meanings, and its specific interpretation depends closely on the chosen scale and disciplinary context. In terms of scale, Levels 2 and 3 in our classification indeed differ from the broader notion of a mountain (i.e., Level 1), yet they all reflect the underlying morphology of the Earth’s surface. To avoid semantic confusion, we have renamed all Level 3 “mountain” categories to “mountain slope”, thus distinguishing them from the more general, higher-level concept of a mountain. From an application standpoint, given that geomorphology intersects with subfields of geoscience such as climate and ecology, we provide a conventional categorization (i.e., the plain and mountain) at Level 1 while also offering finer distinctions at Levels 2 and 3 to meet more specialized research needs. For further details, please refer to above response.

Regarding the data availability, the authors have presented the resources they developed on Zenodo. The files are easily accessible and useable in open source software. Files are presented in folders by 10 degree latitudinal bands, and it is quite easy to find a region of interest. All terrestrial areas of the world seem to be included in the data. There is a possible issue for global level use

of the data in that it consists of many different tiles that need to be mosaiced, but this can be coded.

Response:

Thank you for your suggestion. In this revised version, we have improved the file organization by mosaicking the tiles into 10° × 10° regions. These mosaicked files are now grouped into folders based on their latitude for easier access and use.

The validation is done against a number of similar products where one of the main differences is the resolution of the source layers (DEM), this product being based on very high resolution sources (~30 m at the equator.) The identification of plains seems to be more accurate than in any of the products with which it is compared.

Response:

Thank you for your comment. As you mentioned, more accurate plain boundaries are an important improvement of our dataset, thanks to the innovative approach employed in our methodology.

Overall the manuscript is sufficiently concise, the language clear, although it could benefit from some minor edits here and there (see below). On several points the methods section should be developed a bit further to allow full replication of the work flow.

Overall the language is clear and very understandable, but some suggestions for minor improvements are given.

Response:

We appreciate your feedback and have carefully revised the manuscript. We have expanded the methods section to provide more details for the replication (Lines 159-186 and Lines 214-235), and build a code repository to publish our workflow. More details can be found in https://github.com/nnu-dta/GBLU-code.

As said, in my opinion the layers presented in this work do not represent landforms. However I think that the classification of relief in plains and mountains with different values of elevation and relief intensity (roughness) can be quite useful for a series of environmental applications. My recommendation would therefore to revise the title and some sections of the text where the product is labelled as a map of landforms and replace this with formulations that more accurately reflect what is shown, that is, not to speak of landforms but about a map of relief (roughness) and elevation classes (or something

similar) instead. This would require rather limited changes to the text and figures.

Response:

Thank you for your suggestion. As noted in our previous responses, landforms have inherent scale and context dependencies. To avoid misunderstanding, we have clearly defined the concepts and scale limitations of the landform types discussed in this study within the manuscript. We have substituted the term “landform” with “relief” or “elevation”. Additionally, we have revised some category names in our classification system; specifically, we changed “mountain” at L3 to “mountain slope” to better reflect its terrain-related implications. To ensure comprehensibility in both general geomorphometry and related specific fields, we have retained the term “landform” in the title and in certain sections of the text.

Specific comments

35-36: I would add evolution or genesis to this list of research subfields of geomorphology

Response: Thank you for your suggestion. We have added "genesis" to this list (Line 35).

43: I would add that field work is an essential component of landform mapping (geomorphology)

Response: Thank you for your suggestion. We have added “the survey based on the field work” in this sentence. (Line 43)

46-47: there is a more recent product produced by Amatulli et al. that might be useful to refer to here: Amatulli, G., McInerney, D., Sethi, T., Strobl, P., & Domisch, S. (2020). Geomorpho90m, empirical evaluation and accuracy assessment of global high-resolution geomorphometric layers. Scientific Data, 7(1), 162. https://doi.org/10.1038/s41597-020-0479-6

Response: We have added this reference as your suggestion. (Line 47)

56-58: However, as the authors stated, unsupervised classification based methods to perform higher-resolution global landform classification require an international team with knowledge of geomorphological development in a variety of climatic and physiographic settings. > do you address this?

Response: Thank you for your question. In fact, we cannot fully resolve this issue. We included this statement because, as Iwahashi (Iwahashi and Yamazaki, 2022) described, unsupervised methods (such as clustering) require

considerable effort to determine the geomorphological meaning of each category. This is challenging since these derived classes may differ significantly from conventional landform perception. In our study, we hope to optimize this process by pre-defining the landform classification system before applying our technical methods, and we based this system on a comprehensive review of existing work.

69-70: not clear if this paper only object is to classify the shape or also something about the material (lithology) and / or genesis, / evolution. Methods and final product seem to be focusing on shape irrespective of material / genesis.

Response: This study focuses primarily on the fundamental morphology of landforms. We have changed them to “maintaining the morphological integrity of the identified landforms” and “diverse and complex environmental factors have shaped different types of increase the complexity landform morphology”. (Lines 70-71)

80: objective: "to construct a global classification system for landforms that integrates geomorphological knowledge," : not clear where the geomorphological knowledge comes in in the method

Response: After careful consideration, we think that the term "knowledge" could potentially cause misunderstandings. Therefore, in the revised manuscript, we replaced it with "a global classification system for landforms that integrates domain consideration of landform-related studies". (Line 82)

82: typo: "high-resolutiojn" > high-resolution

Response: Thank you for your comment. Based on your suggestions and those of the other reviewers, to avoid misunderstanding regarding “high-resolution,” we have revised the sentence to:“(4) to make available a comprehensive global dataset of landform units.” (Line 84)

99-100 "The first-level (L1) types are defined as ‘plain’ and ‘mountain’, reflecting the most fundamental morphological characteristics of landforms." If I understand it well, the first level distinguishes between plain and non-plain (i.e. hills and mountains), as all that is not plain is later subdivided into several classes of hills and mountains, not mountains alone.

Response: Thank you for your comment. We have given considerable thought to this naming. In some cases, as you mentioned, hills formed by the erosion

of ancient mountains can be regarded as a subclass of mountains. Therefore, to better capture the general concept of landforms at Level 1, we have retained both category names in L1.

102: "This classification perspective aids researchers in conducting macro-scale studies" This is indeed a valuable distinction
Response: Thank you for your recognition.

113: "the area the missing from FABDEM" > the area missing from FABDEM
Response: Thank you for pointing that out. We have corrected it to "the area missing from FABDEM."

120: "The following sections provide details that should allow users to reproduce our results." : some more details would be needed to achieve this I think
Response: Thank you for your comment. We have supplemented the manuscript with detailed computational information: (1) we have added the rationale for constructing the accumulated cost (AS) and provided a detailed computational process (Lines 159-186); (2) we have included the detailed calculation process for the new relief metric (Line 214-235).

123: Fig 1: "accumulate slope " > accumulated slope?
"Interecting with flat landforms" > Intersecting with flat landforms
"Eliminating fragement blocks" > Eliminating fragment blocks
Response: We have changed this figure as your suggestion.

125: data preprocessing or data pre-processing (see figure, perhaps harmonize?)
Response: We have removed the hyphen (”-”) in the section title to ensure consistency throughout the manuscript.

130: "data from latitudes below 70° are transposed onto the Behrmann projection, and the remaining data are transported onto the Lambert azimuth equal-area projection. " : suggested edit: Tiles between 70° N/S are reprojected to the equal area Behrmann projection, and the tiles polewards of 70° N/S to Lambert azimuthal equal-area.
Response: Thank you for your suggestion. We have replaced the original text with the revised version as you suggested. (Lines 136-141)

132-133: this first sentence is more of a statement that would perhaps be better in the introduction. Starting this section with the second sentence works quite well.

Response: We have removed the first sentence and now begin the section with the second sentence for improved flow and clarity.

140: Fig 2b typo: "varient" > variant

Response: We have changed this figure as your suggestion.

147: how large must the continuous area of plain be to be considered a core area? I.e. how many contiguous pixels constitute a plain core area? Do you also apply a shape criterion, or can a very long area of contiguous plain pixels also constitute a core plain area?

Response: Thank you for your question. An area must be greater than 0.1 km^2, and we do not apply any shape criterion. In practice, due to slope limitations—especially in mountainous regions—it is rare to include plain core areas with an extremely elongated shape. We have added explanation in the revised manuscript. (Lines 159-161)

148-150: it is not clear to me what the cost layer is in this calculation: elevation, slope, or something else? Same holds for 'cost' in Fig 2a.

Response: In our calculation, the cost layer represents the slope layer. We have clarified this in the manuscript Line 181. Additionally, we have updated the description in Figure 2a to explicitly state that "cost" refers to slope, improving clarity for readers.

149: "The AS is calculated as the minimum cumulative cost of each position to the nearest landform core along a specific path" Would it not be more precise to say: The AS is calculated as the minimum cumulative cost of each position to the nearest plain core along a specific path.

Response: We have modified the sentence as your suggestion. (Line 182)

155-156: not clear to me how such an algorithm achieves the most direct integration of geomorphological knowledge and expertise

Response: Thank you for your suggestion. We have modified the sentence to: “Segmenting landforms through the determination of the thresholds for landform derivatives is one of the most common methods used in

geomorphological studies and transforms geomorphological qualitative perception towards quantitative computation." (Lines 187-188)

160: does T2 have a dimension and a unit? 1500-2000, is that length in meters, or slope in degrees or something else?

Response: Thank you for your question. T2 is measured in degree·meters (°·m), representing the accumulated cost-distance where slope (degrees) serves as the cost factor and distance (meters) accumulates along the path.

161-162: "but needs to be determined by integration with expert knowledge within different geomorphic regions". Not clear if you state that this should be done or that it has been done, and if so how?

Response: Thank you for your comment. We have revised the statement as follows: "This threshold range is provided as a reference but gentle adjustments to the thresholds may be required in some special areas, such as small islands, through human-computer interaction." (Lines 193-194)

162: "In some cases, it may exceed the recommended threshold range." – not clear where and when

Response: Thank you for your question. The statement refers to specific cases where terrain complexity makes it challenging to apply standard threshold values. By referencing hillshade data and satellite imagery, we identified special terrain structures, including small islands, where traditional watershed and TIN-based methods struggle to perform effectively within predefined threshold ranges. We have added explanation in the revised manuscript. (Line 195)

165-167: "This novel method avoids the negative effect of local window analysis and is beneficial for maintaining the landform semantics for each block." Visual inspection of a number of tiles indeed shows a neat identification of the borders of plains and their transition to hilly or mountainous terrain.

Response: We appreciate your recognition of how our method effectively delineates the boundaries between plains and transition zones.

176-177: "a method that fails to account for geomorphological semantics, and which therefore disregards the integrity of a mountain. " I would argue that the classification of L2 landforms proposed in this paper does just that. I do not see any landform concept reflected in the classes, and even less so in the map units corresponding to these classes. See general comments above

Response: Thank you for your comment. We have provided detailed responses in the general comment section; please refer to that for further information.

192: "on basis of the plain boundary" > on the basis of the plain boundary
Response: We have corrected "on basis of the plain boundary" to "on the basis of the plain boundary."

192-193: "To refine the representation of surface relief, we also take into account linear features representing the rivers. " I suppose you do not consider all rivers and streams to construct your TIN of mountain base. Rivers and streams go up to great altitudes. Which sections of mountain rivers did you consider to construct the TIN?
Response: In this step, we employed the hydrologic analysis workflow from digital terrain analysis to extract the drainage network. We did not include all rivers or streams; instead, we retained only those of relatively higher order, such as primary or secondary channels. Specifically, we established a segmentation threshold based on flow accumulation—only river networks with values above this threshold were preserved. For reference, in an 11°×11° area, we set a threshold of 200,000, and we adjust this value in accordance with local geomorphic features. For example, in areas with more valleys, the threshold is increased. Regardless of these adjustments, as you mentioned, the final extracted river network does not extend to higher elevation areas.

206: was there any reasoning behind the selection of these elevation bands? 0-1000, 1000-3500, 3500-5000 and >5000?
Response: The selection of these elevation bands (0–1000 m, 1000–3500 m, 3500–5000 m, and >5000 m) was based on previous studies, particularly those by Zhou et al. and research on European landscapes. These elevation thresholds reflect major geomorphic and climatic transitions and were chosen to ensure a meaningful classification of landforms based on both process-based and regional geomorphic considerations. Detail information are as follows:
0–1000 m: Represents regions primarily influenced by fluvial erosion, where river dynamics play a dominant role in shaping the landscape.
1000–3500 m: Corresponds to the corrosion function line, a threshold that marks significant shifts in geomorphic processes.
3500–5000 m: Represents areas where periglacial and high-altitude processes become more dominant.

>5000 m: Aligns with the average elevation of modern glaciers, where glacial processes are the primary drivers of landform development.

207-208: idem

Response: We carefully reviewed this sentence, but we were unable to fully follow your comment.

277: Figure 7. Comparison between the GBLU and the Global Mountain Biodiversity Assessment (GMBA) projects. > Figure 7. Comparison between the GBLU and three mountain definitions presented on the Global Mountain Explorer (https://rmgsc.cr.usgs.gov/gme/)

Response: Thank you for the reminding. We have corrected the figure caption as you suggested.

278-279: this does not seem to be entirely accurate: "We conducted a more detailed comparison for mountain regions using the Global Mountain Biodiversity Assessment (GMBA) (Snethlage et al., 2022) as reference data." The three definitions are from three different institutions (WCMC, GMBA and USGS) but have conveniently been presented together on the Global Mountain Explorer (https://rmgsc.cr.usgs.gov/gme/). The latest mountain definition is the one by Snethlage et al (2002) which can be obtained from https://www.earthenv.org/mountains (scroll down to: Download the GMBA Mountain Definition v.2 here.)

Response: Thank you. We have corrected it in the revised manuscript.

337: "fundamental role in supporting the identification of landforms that incorporates complex semantics." > not clear what semantics means in this context

Response: In this section, our aim is to emphasize some background knowledge from various specific studies. We changed “complex semantics” to “domain background” in the revised manuscript. (Line 371)

344 "influencinge community structure and function," > influencing community structure and function,

Response: We have corrected it.