Reply to Comment by Seybold et al. Climate vs. tectonics as controls on river profiles

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The accompanying Comment[1] claims that our original study[2] disregarded correlations between our metric of river longitudinal profile concavity (NCI) and four morphometric variables (relief, channel gradient and length, and drainage area)[3]. Seybold et al.[1] show these four variables to be more highly correlated with NCI than Aridity Index (AI, a climatic classification metric), and they use these rank sum correlations to imply stronger controls of tectonics over climate. However, the correlations presented by Seybold et al.[1] are flawed for the following reasons: (1) It is well known that relief, river slope, length, and drainage basin area are interdependent with concavity[4-6] and, therefore, are not independent drivers of the concavity of long profiles. (2) These four morphometric variables co-evolve with NCI in response to external forcings including both tectonics and climate and, therefore, they cannot be considered independent metrics of tectonic activity. (3) The calculation of NCI uses relief, channel length and channel gradient in the equation (Eq. 1 in Chen et al.[2]), and therefore, there is a direct numerical dependency between those variables and NCI. For all these reasons, it is not defensible to correlate NCI with these internally dependent morphometric variables to make the point that tectonics exert a stronger control on long profile evolution than climate.

In Chen et al.[2] we normalised concavity by relief to enable comparison of channels across different scales through removal of scale-induced bias – the normalization does not remove dependency between NCI and its composite variables, nor does it remove the co-evolving relationship between these variables and NCI. The density scatterplots between these morphometrics and NCI were included in Chen et al.[2] (Extended Data Fig 4) as a bias check for NCI, and this is clearly stated in the figure caption and in the text (Chen et al.[2] Methods section on River long profile extraction). In the part of our Methods section focused on NCI, we mistakenly used the words "correlated with" instead of "biased by" in the following sentence of the original supplemental material (Chen et al.[2]): "*We confirmed that NCI values for extracted rivers in GLoPro are* <u>*not correlated with*</u> *key river metrics, such as river length, gradient, relief or basin area (Chen et al.[2] Extended Data Fig. 4).*" The wording has been corrected in the online Article to: "*We confirmed that NCI values for extracted rivers in GLoPro are not biased by key river metrics, such as river length, gradient, relief or basin area (Extended Data Fig. 4).*" This wording is now consistent with the caption of Extended Data Figure 4.

Our original study[2] concluded that climate (translated into streamflow generation) is a first-order control on river long profile concavity (NCI) based on four independent lines of evidence which included analysis of global NCI distributions by two climate classifications, modelling, and empirical analysis of streamflow. Our sensitivity analysis using a numerical model of long profile evolution revealed that downstream rate-of-change of discharge (α) is a first-order control on NCI compared to other drivers, including tectonic uplift rate (which we varied over two orders of magnitude up to 1 mm/y) and base level change (Chen et al.[2] Figs 3 and 6), and our analysis of empirical streamflow data demonstrated a direct link between α and AI climate classes.

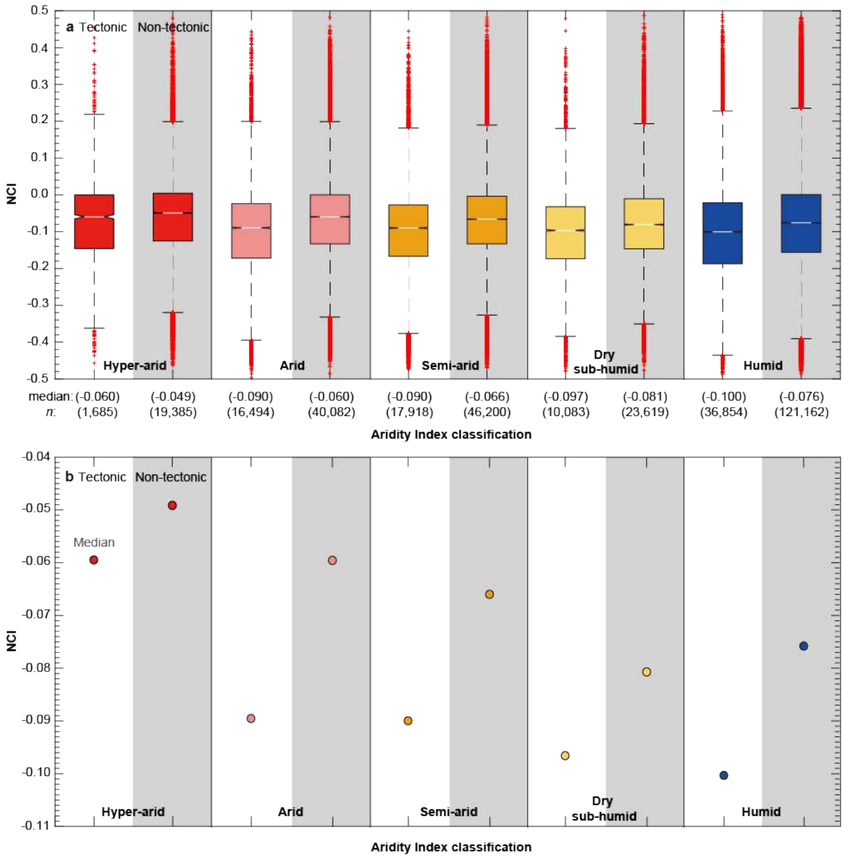
Leveraging this empirical and modelling evidence, we provided a new theoretical explanation[2] that links climate to NCI through the cascade from: aridity, to runoff-generation, to the downstream rate-of-change in discharge (α), to long profile concavity. This theoretical framework is supported by our previous work explaining straight long profiles in arid regions[7-10] as a function of dryland runoff regimes[11-13] and is underpinned by stream power theory after relaxing the assumption of discharge-area (Q-A) dependency. We highlighted the hitherto unacknowledged importance of zero to negative α values which we found to be common in dryland ephemeral rivers (Chen et al.[2] Extended Data Figs 7, 8 and Extended Data Table 2). Therefore, this analysis is not simply an "empirical verification of the stream power model" as suggested by Seybold et al.[1], but rather an extension of stream power theory into the domain where Q is disconnected from A leading to straighter long profiles.

Seybold et al.[1] suggest that tectonic uplift is the key control on long profile concavity globally. We do not dispute the importance of tectonic uplift on drainage basin morphometry in active margins - this effect has been well understood based on decades of literature, e.g.[4,14-15], as we acknowledged in Chen et al.[2]. The real question we addressed in Chen et al.[2] was whether a climatic signal can be detected across the globe, despite strong tectonic and other controls that are geographically restricted. We found that the signal of aridity was expressed within two independent climate classifications: a) in the Köppen-Geiger (K-G) Arid class, long profiles are distinctly straighter compared to the humid climate classes, and b) within the non-humid AI climate classes[2], distributions of profiles are monotonically straighter with higher aridity from Dry Sub-humid to Hyper-arid.

Our complete analysis revealed 'climate-sensitive flow accumulation'[16] as a dominant global control on channel long profiles. These results can be emphasised more clearly through a comparison of NCI within and outside of zones of active uplift. Here we present an additional analysis of NCI with AI and K-G climate classes for tectonic v. non-tectonic regions by masking GLoPro using an assumed threshold of >0.08g in peak ground acceleration[17] (PGA), which measures seismic activity. This threshold conservatively defines areas of high uplift coinciding with current active margins. It should be noted that there is no global dataset of tectonic uplift, so PGA is often used a proxy, however an imperfect one, since seismicity does not always correspond with uplift. Our analysis revealed that: 1) only 25% of channels in GLoPro (n=83,041) fall in tectonically active regions; 2) the aridity signal leading to straighter profiles in drier basins is systematically stronger in the 75% of channels in GLoPro (n=250,461) that lie outside of tectonically active zones (as expected); and 3) NCI distributions become less negative (straighter) with increasing aridity classes for both tectonic and non-tectonic areas (Fig 1).

We conclude that the signal of aridity in NCI is, therefore, expressed in both tectonic and non-tectonic regions across the globe, and most strongly in increasingly arid regions outside zones of high tectonic uplift, where rainfall-runoff regimes tend to disconnect Q from A. These results also suggest a spatially restricted influence of tectonics and the more global influence of climate on landscape morphometrics such as long profiles. Specifically, long profiles in zones of high uplift rates are likely to be affected by both climate and tectonic uplift, creating a mixed signal[18]. However, the influence of tectonics on channels outside of potentially high uplift zones (75% of the channels studied) apparently declines in favour of a stronger climate signature across most of the global land area (Fig.1). This conclusion is corroborated by other studies showing that long profile concavity is most sensitive to spatial patterns in runoff, and that rock uplift rates only influence relief in zones where uplift rate is high[19].

In summary, Seybold et al.[1] present correlations between the morphometric variables of channel relief, slope, length, drainage basin area and NCI that are flawed on three counts: 1) these morphometric variables cannot be considered as independent metrics of tectonic activity, since they also influenced by climate; 2) these morphometric variables are interdependent with concavity and, therefore, are not independent drivers of concavity change and; 3) these morphometric variables are used in the calculation of our normalized concavity index (NCI). Beyond presenting rank sum correlations, Seybold et al. have not provided a mechanistic explanation of how tectonics influences NCI within or outside of zones of high uplift, nor how/why tectonic drivers of long profile evolution should be stronger than climatic drivers in parts of the world where tectonic uplift is low. We argue that since potentially high uplift zones are spatially restricted to 25% of the rivers in our global database, tectonics cannot be a first-order control on NCI at the global scale. Climate on the other hand, and its influence on streamflow regimes, is ubiquitous in shaping river basins around the globe with and without high uplift. Our findings are corroborated by steadily mounting evidence pointing to the nuanced relationship between climate and streamflow patterns and its dominant control on the topographic development of drainage basins[16,18-21]. Further evidence to assess the role of climate in drainage basin evolution will require overcoming regional biases in geomorphic analyses focused only in tectonically active zones.



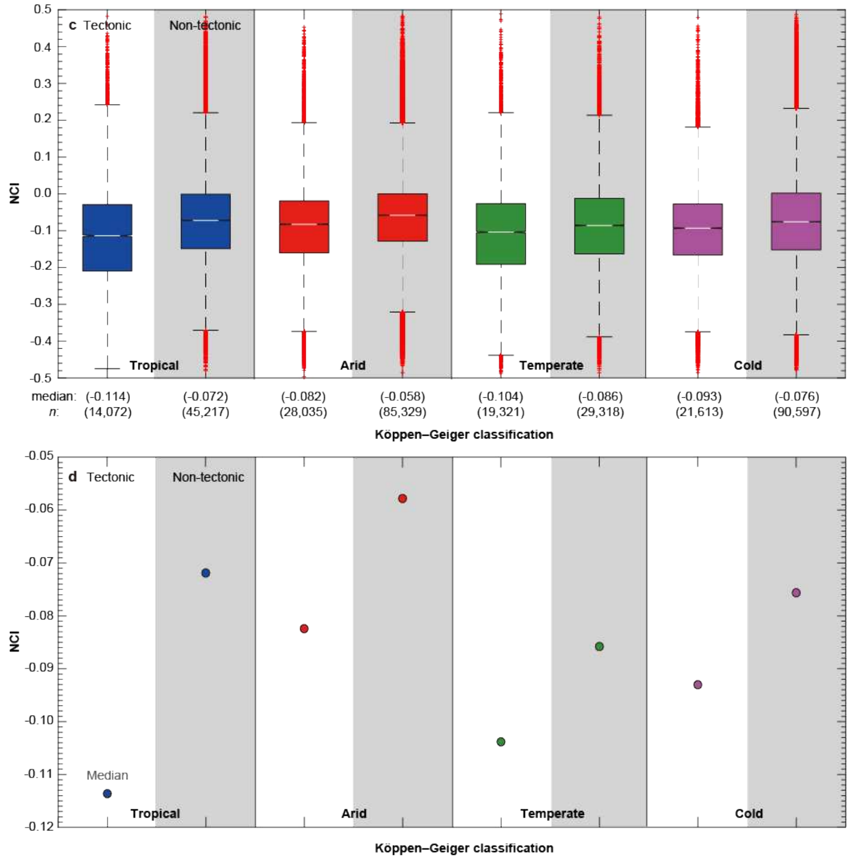


Figure 1. NCI classified by aridity in tectonic v. non-tectonic regions: a) distributions of NCI based on AI; b) median values from the AI distributions in a; c) distributions of NCI based on K-G; and d) median values from the K-G distributions in c.

Author contributions

K.M. wrote the reply and all other authors provided edits. S-A.C. produced Fig. 1.

Competing interests

The authors declare no competing interests.

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