Matters arising

Climate versus tectonics as controls on river profiles

https://doi.org/10.1038/s41586-022-05418-1

Received: 25 February 2022

Accepted: 5 October 2022

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ARISING FROM **S.-A. Chen et al. *Nature* https://doi.org/10.1038/s41586-019-1558-8 (2019)**

Identifying what drives the evolution of drainage basins is a major challenge in geomorphology[1,2] and the question of how strongly climate influences the longitudinal profiles of rivers has been debated for decades[3–5]. In a recent Article[5], Chen et al. used aridity and concavity data from 333,502 river longitudinal profiles to argue that climatic aridity is "a first-order control" on the evolution of drainage basins.

By contrast, here we show that four variables that Chen et al.[5] dismissed as having "no apparent relationship" with river profile concavity—gradient, relief, river length and drainage area—are, in fact, more strongly correlated than aridity with profile concavity. Therefore, we suggest that aridity is, at best, a second-order control on river profile concavity, after several other variables, including those linked to tectonic forcing.

Chen et al.[5] provide an important empirical verification of the relationship between climate and concavity that has long been predicted by the standard stream power model for river profiles[3]. However, characterizing aridity as a first-order control on river profile concavity requires a quantitative comparison with other potential controls. On the basis of a qualitative visual assessment, Chen et al.[5] argued that river profile concavity (as quantified by their Normalized Concavity Index (NCI)) is "not correlated with key river metrics such as river length, gradient, relief or basin area"; however, the relationships between NCI and these four metrics are obscured by the colour scales and binning intervals of the underlying plots (as shown in Extended Data Fig. 4 of ref. [5]). For example, in Extended Data Fig. 4b of ref. [5], a single extreme pixel dominates the entire colour range, masking any relationship between NCI and the slope. Moreover, a comparable plot of NCI and aridity was not provided, making it impossible for readers to assess the relative importance of aridity as a control on NCI.

Using the dataset associated with the previously published paper[6], we calculated that river profile concavity (as quantified by NCI) is correlated two to three times more strongly with four morphological variables (river length, gradient, relief and drainage area) than with climatic aridity (Fig. 1). Specifically, the Spearman rank correlation between NCI and aridity is only $\rho = -0.05$, whereas the rank correlations are markedly stronger between NCI and each of the four variables that Chen et al.[5] considered to have no apparent relationship: $\rho = -0.17$ for relief–NCI (more than 3× that of AI–NCI), $\rho = -0.14$ for mean gradient–NCI (almost 3× that of AI–NCI), $\rho = -0.12$ for drainage area–NCI (more than 2× that of AI–NCI) and $\rho = -0.09$ for river length–NCI (almost 2× that of AI–NCI). The normalization embedded in the definition of NCI guarantees that if the river profile is stretched vertically (thus increasing its gradient and relief) or horizontally (thus increasing its length and decreasing its gradient), the NCI remains unchanged. Therefore, the observed correlations between NCI and gradient, relief and length are not artefacts of how NCI is calculated.

Chen et al. suggest that aridity "overprints other plausible controls on profile concavity on the global scale" on the basis of theoretical simulations (Extended Data Fig. 6 of ref. [5]). However, those theoretical results are not necessarily in agreement with some data suggesting

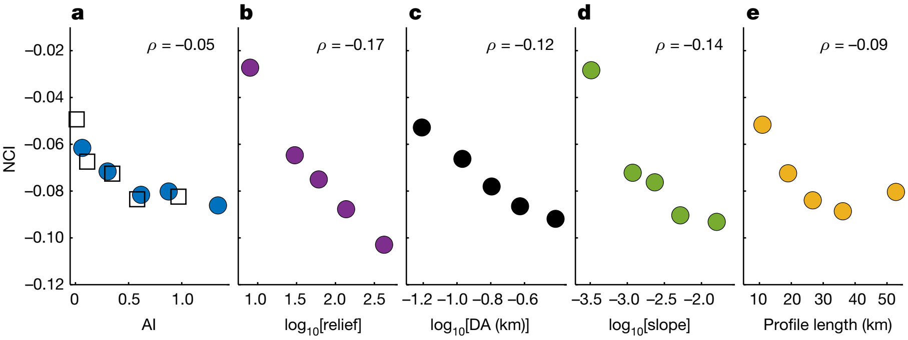

Fig. 1 | Empirical relationship of river profile concavity with climate aridity and four morphological variables. **a**–**e**, Circles show the relationhips between NCI and the Aridity Index (AI) (**a**), relief (**b**), drainage area (DA) (**c**), slope (**d**) and profile length (**e**), binned in five classes, each containing 20% of the data. Robust median statistics are used to calculate the medians of each class on both axes. **a**, Squares show the robust median relation between NCI and the five AI classes defined by Chen et al.[5]. NCI exhibits much stronger and more consistent trends with relief, drainage area and slope than with aridity. This is substantiated by rank correlation coefficients (ρ), calculated from the original data without binning.

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that river profile concavity might be linked to measures of tectonic forcing[7]. Climate is one of many influences on river profile concavity, but we suggest that it was not demonstrated to be a first-order control.

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Author contributions All authors contributed equally to this work.

Competing interests The authors declare no competing interests.

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Reply to: Climate versus tectonics as controls on river profiles

https://doi.org/10.1038/s41586-022-05419-0

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REPLYING TO H. Seybold et al. *Nature* https://doi.org/10.1038/s41586-022-05418-1 (2022)

In the accompanying Comment[1], Seybold et al. claim 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 that these four variables are more highly correlated with NCI than Aridity Index (a climatic classification metric), and they use these rank sum correlations to imply that tectonics have stronger control than climate over river profiles. 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 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; and (3) the calculation of NCI uses relief, channel length and channel gradient in the equation (equation (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 normalized 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 Extended Data Fig. 4 of Chen et al.[2] as a bias check for NCI, and this is clearly stated in the figure caption and in the text (Methods section 'River long profile extraction' in Chen et al.[2]). 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 Supplementary Information[2] "We confirmed that NCI values for extracted rivers in GLoPro are not correlated with key river metrics, such as river length, gradient, relief or basin area (Extended Data Fig. 4 of Chen et al.[2])." The wording has been corrected in an Author Correction[7] 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", which is consistent with the legend of Extended Data Fig. 4.

Our original study[2] concluded that climate (translated into streamflow generation) is a first-order control on river long profile concavity (NCI) on the basis of 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 yr^{-1}) and base level change (Fig. 3 and Extended Data Fig. 6 of Chen et al.[2]), and our analysis of empirical streamflow data demonstrated a direct link between α and Aridity Index 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[8–11] as a function of dryland runoff regimes[12–14], and is underpinned by stream power theory after relaxing the assumption of discharge–drainage area dependency. We highlighted the hitherto unacknowledged importance of zero to negative α values, which we found to be common in dryland ephemeral rivers (Extended Data Figs. 7 and 8 and Extended Data Table 2 of Chen et al.[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 discharge area is disconnected from drainage area, 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 in drainage basin morphometry in active margins—this effect is well understood on the basis of decades of literature (for example, refs. [4,15,16]), 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: in the Köppen–Geiger arid class, long profiles are distinctly straighter than in the humid climate classes; and within the non-humid Aridity Index-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'[17] as a dominant global control on channel long profiles. These results can be emphasized more clearly through a comparison of NCI within and outside zones of active uplift. Here we present an additional analysis of NCI with Aridity Index and Köppen–Geiger climate classes[3] for tectonic versus non-tectonic regions by masking GLoPro using an assumed threshold of >0.08g in peak ground acceleration[18], 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 peak ground acceleration is often used a proxy (albeit an imperfect one, as seismicity does

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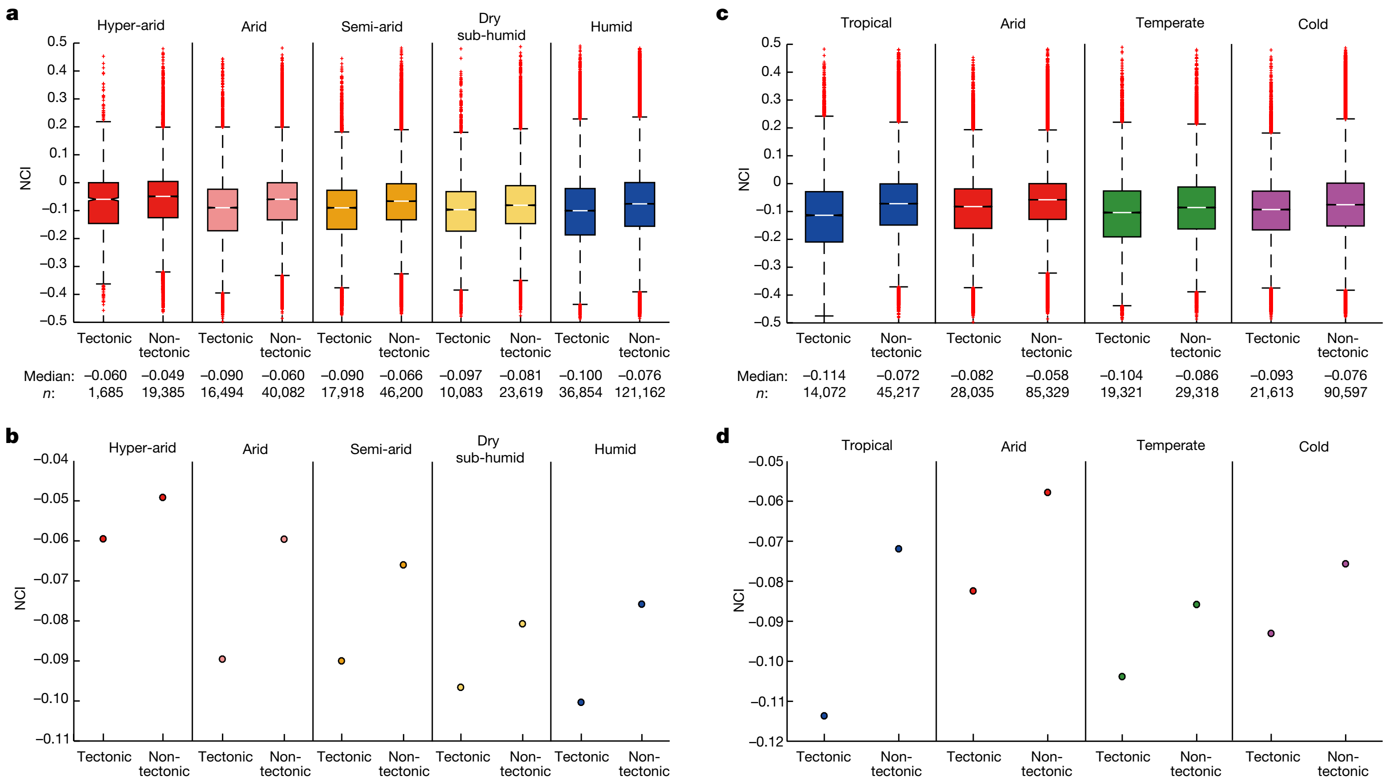

Fig. 1 | NCI classified by aridity in tectonic v. non-tectonic regions. a, Distributions of NCI based on Aridity Index. **b**, Median values from the Aridity Index distributions in **a**. **c**, Distributions of NCI based on Köppen–Geiger index values. **d**, Median values from the Köppen–Geiger distributions in **c**.

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 discharge from drainage area. 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[19]. However, the influence of tectonics on channels outside 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 influence relief only in zones where uplift rate is high[20].

In summary, Seybold et al.[1] present correlations between the morphometric variables of channel relief, slope, length, drainage area and NCI that are flawed on three counts: (1) these morphometric variables cannot be considered as independent metrics of tectonic activity, as they are 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 zones of high uplift, nor how or 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 as 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[17,19–22]. Further evidence to assess the role of climate in drainage basin evolution will require that regional biases in geomorphic analyses focused only in tectonically active zones are overcome.

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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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