Global dominance of tectonics over climate in shaping river longitudinal profiles

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River networks are striking features engraved into the surface of the Earth, shaped by uplift and erosion under the joint influence of climate and tectonics. How a river's gradient changes as it descends along its course—its longitudinal profile concavity—varies greatly from one basin to the next, reflecting the interplay between uplift and erosional processes. A recent global analysis has suggested that climatic aridity should be a first-order control on river profile concavity, but the importance of climate relative to other factors has not been tested at global scale. Here, we show, using recent global datasets of climate, river profiles and tectonic activity, that tectonics is much more strongly expressed than climate in global patterns of river profile concavity. River profiles tend to be more strongly concave in tectonically active regions along plate boundaries, reflecting tectonically induced spatial variations in uplift rates. Rank correlations between river profile concavity and four global tectonic proxies (basin-averaged channel gradients, distance to plate boundaries and two measures of seismic activity) are much stronger than those between river concavity and three climate metrics (precipitation, potential evapotranspiration and aridity). We explain the association between tectonic activity and increased river profile concavity through a simple conceptual model of long-term uplift and river incision. These results show that tectonics, and not climate, exerts dominant control on the shape of river longitudinal profiles globally.

Rivers dynamically shape Earth's landscapes1,2, ecosystems3 and human society4. River networks vary greatly across the globe, exhibiting diverse planform and elevation patterns5–7. A river can be characterized by its longitudinal profile, which quantifies how its elevation decreases—often steeply at first, then more gradually—as it flows from its source to its mouth8–11. Broadly, river longitudinal profiles are shaped by the interplay between tectonic forces, which drive spatial patterns of uplift and subsidence, and the processes of fluvial erosion and deposition, which modify the topographic relief created by tectonics12–16. River longitudinal profiles are typically concave (that is, steeper in the headwaters than further downstream), reflecting the joint influence of uplift patterns and river morphodynamics. Where tectonic uplift steepens the landscape, the steeper rivers that result tend to be more erosive, gradually counteracting the increased uplift. The erosivity of rivers also depends on the amount of streamflow available to move sediment and erode rock. Because headwaters have smaller streamflows, they must be steeper for incision to keep pace with uplift, but further downstream, larger streamflows can accomplish the same incision at a gentler river gradient. In steady state, this relationship between erosivity and streamflow results in the characteristic concave-up shape of river longitudinal profiles7,11. The same relationship could potentially lead to straighter or convex river profiles where streamflow declines downstream, as sometimes occurs in arid regions17.

Local and regional investigations have shown how tectonics can strongly influence river profile concavity18–21. By contrast, a recent global analysis12 argued that climatic aridity is a first-order control on river concavity, with arid regions having straighter river profiles. However, the underlying data22 reveal tremendous scatter in river concavity that is not explained by aridity, suggesting that other factors may be stronger controls. Thus we presently lack a quantitative understanding of the relative importance of different factors controlling river longitudinal profiles globally.

In this Article, we compare a recent global dataset of longitudinal profiles for 333,502 river segments (averaging ~30 km in length) with global data on river gradients, plate boundaries, seismic activity and climate7,20–24 to test the relative importance of tectonics versus climate as global controls on river profile concavity. These river segments span both erosional (bedrock channel) and depositional (alluvial channel) environments. We characterize each river segment’s longitudinal profile by its normalized concavity index (NCI), a dimensionless measure of its median deviation from a straight line (Methods and Fig. 1), thus indicating whether it is concave (–0.5 < NCI < 0; slope decreases downstream), straight (NCI = 0) or convex (0 < NCI < 0.5; slope increases downstream). NCI depends only on how slope varies downstream, not on the average slope of the river segment or its total relief.

Tectonic controls on river profiles

Globally, most river segments are concave-up, with channel slopes decreasing downstream (median NCI = −0.0755)21. NCI values vary regionally (Fig. 2), indicating a tendency toward more concave river segments in the Rocky Mountains, Andes, Himalaya and Tibetan Plateau, along the Pacific Ring of Fire and the East African Rift Valley, and in a mountain belt stretching from the Alps to the Zagros Mountains. These spatial patterns become more clearly visible when NCI values are aggregated (Methods) over the mesoscale river basins22 shown in Fig. 2, averaging out the local variability that would otherwise obscure many regional patterns.

Many zones of strongly concave river segments (more yellow colours in Fig. 2) are associated with tectonic plate boundaries (black lines, Fig. 2). These include the subduction zones, transform faults, and rifts of the Pacific Ring of Fire and their associated

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NATURE GEOSCIENCE | VOL 14 | JULY 2021 | 503–507 | www.nature.com/naturegeoscience
mountain ranges; the convergent boundary between the Eurasian Plate and the African, Arabian and Indian plates, which is responsible for the uplift of the Alpine–Himalayan orogenic belt and the Tibetan Plateau; the East African Rift; the rifts and transform faults bounding the Yangtze, Amur and Okhotsk plates; the convergent boundaries between the South American plate and the Altiplano and North Andes plates; and the transform faults bounding the Caribbean Plate.

The spatial association of river segment concavity with plate boundaries shown in Fig. 2 suggests a strong tectonic control on river profiles. We quantitatively explore this possibility using four proxy measures of tectonic activity: mean river segment slope, distance to the nearest plate boundary and two metrics of seismic activity (Methods). The global patterns in these tectonic proxies (Fig. 3a–c) broadly correspond to the global pattern in river concavity (Fig. 2). Exceptions can be found—in Ireland, Uruguay, south-eastern China, south-eastern Brazil and southwest Australia, for example, areas of low tectonic activity are associated with strongly concave river segments. Nonetheless, river segment concavity correlates strongly (Fig. 4a–c) with all four of our proxies for tectonic activity: peak ground acceleration in the Global Earthquake Model (\(\rho = -0.36\)) and the Global Seismic Hazard...
Assessment Program model\textsuperscript{(12)} (Extended Data Fig. 1, $\rho = -0.31$), distance to the nearest plate boundary ($\rho = 0.23$) and mean river segment slope ($\rho = -0.37$).

**Climatic controls on river profiles**

We also tested the association of river profile concavity with three climatic indices: mean precipitation \textsuperscript{(22)} ($P$, $d$), mean potential evapotranspiration \textsuperscript{(23)} ($\text{PET}$, $e$) and climatic aridity (defined as $P/\text{PET}$, $f$). These are not clearly associated with either the tectonic plate boundaries or the global pattern in river profile concavity. World ocean basemap sources: Esri, Garmin, GEBCO, NOAA NGDC and other contributors.

These correlations are statistically significant because the sample size is large, but they are much weaker than the correlations between NCI and any of our indices of tectonic activity. All of our tectonic variables are much more strongly correlated with NCI than any of our climatic variables are, whether we treat the river segments separately or aggregate them into basins (Fig. 4 and Extended Data Figs. 1 and 2). Our results thus do not support the recent suggestion that climate, and specifically climatic aridity, is a first-order control on global patterns of river profile concavity\textsuperscript{(7)}. Partial correlation analyses that simultaneously consider both climatic and tectonic variables also indicate that tectonics is a much stronger control on river profile concavity than climate is (Supplementary section 1).
The association between tectonic activity and increased river profile concavity (more negative values of NCI) can be understood through a simple conceptual model of long-term uplift and river incision (Supplementary section 2). Tectonic activity, in whatever form (such as, continental collision, rifting, or subduction and arc formation), causes spatial variations in long-term uplift rates. To first order, higher uplift rates are expressed over geologic time as higher and steeper topography. Although relationships between uplift and elevation can vary for individual basins, we propose that the highest terrain, where the headwaters of river systems are found, will tend to correspond to higher long-term uplift rates than the adjacent lowlands. These contrasts in long-term uplift rates will usually be greater where tectonic activity is stronger. (Note that this model does not assert that the fastest rates of uplift coincidentally occur where the river headwaters are located. Instead, it asserts the opposite: that rivers’ headwaters will by definition be found high in their basins, where long-term uplift rates have tended to be faster.)

The large-scale topography will evolve according to the balance between uplift and river incision. Because steeper rivers tend to incise faster, all else being equal, landscapes whose uplift rates have been faster over the long term will usually have evolved to be both

**Fig. 4 | Correlations between river profile concavity and tectonic and climatic indices.** a–c, Basin-averaged and binned river profile concavity index (NCI) values are strongly correlated with three indices of tectonic activity: peak ground acceleration from the Global Earthquake Model (a), the distance to the nearest plate boundary (b) and mean river profile gradient (c). d–f, NCI values are only weakly correlated with three climatic indices: precipitation (d), potential evapotranspiration (PET, e) and aridity index (f). Spearman rank correlations (\(\rho\)) are shown for the unbinned, basin-averaged values. The rank correlations of the plotted (that is, binned) points are visibly stronger, but vary depending on the details of the binning. The error bars display the standard error of the mean for each bin; standard deviations are approximately nine times larger. A counterpart figure showing the same data, but without averaging over basins, is shown in Extended Data Fig. 2.
higher and steeper, compared to adjacent landscapes with slower long-term uplift rates. Regions with greater contrasts in uplift rates should also therefore exhibit greater contrasts in channel gradients, and thus should exhibit greater longitudinal profile concavity (Supplementary section 2).

This simple model excludes many other potentially important factors, including climate, sedimentation, and cover materials, and spatial variations in precipitation rates and bedrock erodibility. Some of these factors may contribute to the apparent relationship between tectonics and concavity. For example, in addition to having faster uplift rates, high topography tends to be underlain by stronger and denser rock, and tends to produce coarser sediments, both of which can locally steepen headwater channels and increase concavity. However, all of these factors also vary independently of tectonics, and probably account for some of the scatter in the relationship between tectonics and concavity.

Although geomorphic theory and regional empirical studies both suggest that climatic influences should be reflected in longitudinal profile concavity, the data presented here demonstrate that, across the globe as a whole, the river segment concavity index NCI correlates only weakly with climate, and much more strongly with tectonic activity. The connections between tectonics and river profiles have been examined in numerous local and regional studies, but our analysis merges recent global datasets to reveal how, at a global scale, tectonic activity is generally associated with greater river profile concavity. This relationship is not only supported by our global data synthesis, but also by a simple model of long-term uplift and river incision (Supplementary section 2).

Together, our results indicate the dominance of tectonics over climate in shaping river longitudinal profiles globally, suggesting that many rivers’ profile concavities may have remained largely unaffected by changes in climate over geological time, instead reflecting spatial patterns in the slow dance of Earth’s crust. We close by noting that a substantial fraction of the variance in river profile concavity remains unexplained by either the tectonic or climatic variables considered here. Some of this unexplained variance is measurement noise, but probably not all. It is thus likely that global patterns in river profile concavity contain clues to other explanatory factors that are yet to be discovered.

Online content
Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41561-021-00720-5.

Received: 24 March 2020; Accepted: 26 February 2021; 
Published online: 12 April 2021

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Methods

River longitudinal profiles. We used a recent global compilation of longitudinal profiles for 333,502 river segments extracted from NASA’s 30-m-resolution Shuttle Radar Topography Mission Digital Elevation Model (SRTM-DEM), and those segments’ associated NCI values. The NCI is defined as the median value of a river profile’s vertical deviation from a straight line connecting its endpoints, normalized by its total topographic relief:

\[ \text{NCI} = \text{median} \left( \frac{z_L - z_0}{z_{\text{max}} - z_{\text{min}}} \right) \]

where \( z_0 \) and \( z_L \) are the elevations of the river and the straight line at each point \( L \) along the profile segment, and \( z_{\text{max}} \) and \( z_{\text{min}} \) are its most upstream and downstream elevations (Fig. 1). In the usual case that channel gradients decrease downstream (concave profiles), NCI will be positive; conversely, where channel gradients become steeper downstream (convex profiles), NCI will be negative. NCI depends only on how slope varies downstream, not on the river profile’s average slope or total relief. NCI values are not shown for latitudes above 60°N and 56°S, where SRTM topography is unavailable.

The individual profile segments’ average 30.2 km in length, with 10th and 90th percentiles of 10.9 and 52.8 km. Because these segments are much shorter than the lengths of major rivers, NCI values tend to reflect local profile concavity rather than the transitions from mountain headwaters to lowland rivers. These river profile segments were obtained from digital terrain data using a flow accumulation algorithm, which may not always be accurate, particularly in hyper-arid settings.

Tectonic proxies. We used four proxies for tectonic activity. First, the Global Earthquake Model’s Global Seismic Hazard Map (GEM, version 2018.1; ref. 20) depicts, at 4-km resolution, the PGA that has a 10% probability of being exceeded in 50 years. The map collates national and regional probabilistic seismic hazard information into a consistent global framework. Technical details are available at https://hazard.openquake.org/gem. Second, in the Supplementary Information, we also analyse the Global Seismic Hazard Assessment Program’s global seismic activity map (GSHAP; ref. 21), which quantifies the PGA predicted to occur with a 475-year return period. These PGA predictions are based on catalogues of observed earthquakes and active faults, as well as models of seismic wave propagation. Third, we use the distance of the segment midpoint to the nearest plate boundary24. The fourth proxy is the mean gradient, calculated for each length of major rivers, NCI values tend to reflect local profile concavity rather than the transitions from mountain headwaters to lowland rivers. These river profile segments were obtained from digital terrain data using a flow accumulation algorithm, which may not always be accurate, particularly in hyper-arid settings.

Climate data. We used three climate indices with global coverage at 4-km resolution: precipitation (WorldClim v. 1.4; ref. 22), potential evapotranspiration23 and climatic aridity. The aridity index is defined as the ratio of mean precipitation to mean potential evapotranspiration. Accordingly, higher aridity index values reflect more humid climates and lower values reflect drier climates. Although these climate indices are measured over timescales much shorter than the timescales of river profile evolution, their spatial pattern is broadly consistent with longer-term proxies such as channel gradient and proximity to plate boundaries.

Profile and basin statistics. We extracted climatic and tectonic variables for each pixel in each river segment. These values were then averaged to yield mean values for each segment. Based on the coordinates of each segment’s midpoint, we assigned it to one of the level-5 HydroSHED basins (\( m = 28,405 \text{ km}^2 \)) shown in Figs. 2 and 3. On average, each HydroSHED basin contains 84 river profile segments.

Next, we averaged the NCI and the climatic and tectonic indices over all profile segments within each HydroSHED basin (Figs. 2 and 3). The basin-averaged values for all variables are provided in Supplementary Table 1. For the plots in Fig. 4, the basin-averaged values were binned into 50 bins, each containing 2% of the data. The reported error bars display the standard error of the mean for each bin.

Data availability

All data used in this study are available in the Supplementary Information or via the cited sources. The model outputs that support the findings of this study are available in Supplementary Table 1. NCI, aridity and slope data are available at https://doi.org/10.17636/010581ed2. Precipitation data2 are available at https://www.worldclim.org/data/v1.4/worldclim14.html. Potential evapotranspiration data are available at https://cgrarcsi.community/data/global-aridity-and-pet-database/. Plate boundary data24 are available at https://github.com/fraxen/tectonicplates. HydroSHEDS data25 are available at https://www.hydrosheds.org. GEM data20 are available at https://www.globalquakemodel.org. GSHAP data are available at https://www.gfz-potsdam.de/en/GSHAP. Source data are provided with this paper.

Code availability

The numerical code we used to analyse the data is available upon request.

Acknowledgements

We thank the Global Earthquake Model Foundation for providing the Global Earthquake Model’s Global Seismic Hazard Map.

Author contributions

H.S., J.P.P., J.W.K. and W.R.B. conceived the idea and designed the study. H.S. analysed the data. J.W.K. led the analysis in Supplementary section 2, with contributions from W.R.B. and H.S. All authors contributed to interpreting the results. W.R.B. and J.W.K. led the writing, with contributions from all authors.

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at https://doi.org/10.1038/s41561-021-00720-5.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41561-021-00720-5.

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Peer review information Nature Geoscience thanks Kelin Whipple and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: James Super; Tamara Goldin.

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Extended Data Fig. 1 | Correlations between river profile concavity and peak ground acceleration in the Global Seismic Hazard Assessment Program model (GSHAP²¹). Panel (a) and panel (b) display these correlations with and without averaging over basins, respectively. The rank correlations are similar to those reported in the main paper for peak ground acceleration from the Global Earthquake Model²⁰ (Fig. 4a) and Extended Data Fig. 2a.
Extended Data Fig. 2 | See next page for caption.
Extended Data Fig. 2 | Correlations between river profile concavity and tectonic and climatic indices without averaging over basins. Binned river segment concavity index (NCI) values are strongly correlated with three indices of tectonic activity: peak ground acceleration from the Global Earthquake Model (a), the distance to the nearest plate boundary (b), and mean river profile gradient (slope, c). NCI values are only weakly correlated with three climatic indices: precipitation (P, d), potential evapotranspiration (PET, e), and aridity index (P/PET, f). Spearman rank correlations (ρ) are shown for the un-binned values. The rank correlations of the plotted (that is, binned) points are visibly stronger, but vary depending on the details of the binning. The data are averaged within 50 bins each containing 2 percent of the data.