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Climate’s watermark in the geometry of stream networks

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Abstract Branching stream networks are a ubiquitous feature of the Earth’s surface, but the processes that shape them, and their dependence on the climate in which they grow, remain poorly understood. Research has mainly focused on climatic controls of channel incision rates, while the climatic influence on planform geometry has often been overlooked. Here we analyze nearly one million digitally mapped river junctions throughout the contiguous United States and show that branching angles vary systematically with climatic aridity. In arid landscapes, which are thought to be dominated by surface runoff erosion, junction angles average roughly 45° in the driest places. Branching angles are systematically wider in humid regions, averaging roughly 72°, which is the theoretically predicted angle for network growth in a diffusive field such as groundwater seepage. The correlation of mean junction angle with aridity is stronger than with topographic gradient or downstream concavity. Thus, it may be possible to identify channelization processes from stream network geometry in relict landscapes, such as those on Mars.

1. Introduction

The branching river networks that cover most of Earth’s landscapes are a visually striking fingerprint of the processes that shape them [Rodriguez-Iiturbe and Rinaldo, 2001; Kirkby and Charley, 1967; Montgomery and Dietrich, 1992; Perron et al., 2012], and similar branching networks on Mars [Mars Channel Working Group, 2012] and Titan [Tomasko et al., 2005] may likewise hold clues to the evolution of these planetary bodies. However, the linkages between the structure of these networks and the processes that shape them remain poorly understood [Montgomery and Dietrich, 1992; Perron et al., 2012]. Understanding how climate regulates landscape evolution should yield insight into erosional mechanisms [Molnar, 2004; Riebe et al., 2004; Ferrier et al., 2013] and clues to paleoclimate, including on other planets [Pieri, 1980]. Although controls on vertical incision rates are relatively well characterized [Whipple, 2004; Riebe et al., 2004; Zaprowski et al., 2005; Ferrier et al., 2012, 2013], observational data for characterizing controls on the planform geometry of river networks have been relatively scarce [Zanardo et al., 2014].

Understanding how climate affects the spatial pattern (and not just the vertical rate) of landscape evolution requires both (1) understanding how different erosion mechanisms depend on climate and (2) defining the geometric fingerprints associated with each process. Headward growth of river networks has been attributed to two distinct erosional processes: channel incision by overland flow [Horton, 1932, 1945] and the extension of the valley head by diffusive processes such as groundwater seepage [Dunne, 1969]. Overland flow occurs when rainfall exceeds infiltration capacity (or falls on saturated ground) and then follows the path of steepest descent downslope. More than seventy years ago, Horton [1945] proposed that surface erosion results from shear stresses induced by “almost imperceptible” sheet flows that accumulate beyond a critical distance from drainage divides. Channel incision by flows that follow the topographic slope is the dominant mechanism of landscape dissection in modern landscape evolution models [Tucker and Bras, 1998; Whipple and Tucker, 1999; Dietrich et al., 2003]. It is also thought to be the dominant process of channelization in arid landscapes, where flash floods are relatively common, hillslopes are unvegetated, and infiltration capacity is relatively limited [Molnar, 2004; Molnar et al., 2006]. However, half century ago, Kirkby and Charley [1967] and Dunne [1969] questioned the applicability of the overland flow model in humid environments where soils are thicker [Pelletier and Rasmussen, 2009] and infiltration capacities are high. These landscapes are more likely to be shaped by groundwater seepage [Dunne, 1969] or other diffusive processes.
Figure 1. Illustrative examples of drainage networks in (a) arid and (b) humid climates. Planform view of a network on the arid Colorado Plateau in northwestern Arizona (precipitation = 239 mm/yr, potential evapotranspiration = 607 mm/yr), with mean branching angle $\alpha \approx 47^\circ \pm 2^\circ$ (Figure 1a). A network in humid central Vermont (precipitation = 1047 mm/yr, potential evapotranspiration = 513 mm/yr), with $\alpha \approx 74^\circ \pm 2^\circ$ (Figure 1b). (c) The measurement of the branching angle. Each channel segment (blue) between two junctions, or between a channel head and the next junction downstream, is represented by a series of points (light blue). For each junction we calculate the orientation of the orthogonal regression lines (black dashed lines) for the two upstream segments. The angle between the regression lines for the two tributaries defines their branching angle $\alpha$.

Figure 1 shows drainage networks in two contrasting erosional environments. The network shown in Figure 1a lies in the arid Colorado Plateau in northwestern New Mexico, whereas the network shown in Figure 1b comes from the more humid landscape of central Vermont. One visually obvious difference between the two networks is that the Vermont networks appear to have distinctly wider junction angles. This visual impression is borne out by measurements (as described below) that reveal that the Vermont network’s mean branching angle is $\sim 74^\circ \pm 2^\circ$ (mean $\pm 1\sigma$ standard error), in contrast to the Colorado Plateau network’s mean branching angle of $47^\circ \pm 2^\circ$. The networks in Figure 1 suggest that junction angles may be a useful diagnostic tool for characterizing the planform geometry of river networks and in particular that junction angles may vary systematically with climate, potentially reflecting the relative dominance of different erosional processes under different climatic conditions.

2. Analysis

2.1. Data Sources, Drainage Networks, and Junction Angles

To explore whether the geometry of drainage networks generally responds to climatic controls as suggested by Figure 1, we analyzed stream junctions throughout the contiguous United States, as mapped in the NHDPlus Version 2 data set [McKay et al., 2014]. This data set provides the centerline locations and connectivity of river segments spanning the continental U.S. at a resolution of approximately 30 m. Channel slope is also provided for most of the segments. The NHDPlus data set is an enhanced version of the medium-resolution National Hydrography Dataset (NHD), which does not depict channel networks' smallest tributaries [Benstead and Leigh, 2012; Fritz et al., 2013]. Thus, our analysis excludes many junctions between small streams but instead focuses on streams that can be reliably mapped and that have the strongest imprint on the landscape. Our analysis is also necessarily restricted, for reasons of data availability, to the contiguous United States. Digital maps of global stream networks are available but only at much coarser ($\sim 1$ km) resolution and thus could only resolve much larger rivers. NHDPlus is the best publicly available channel network data set that covers a large area and, importantly for our purposes, spans a wide range of climatic regimes. Of the nearly one million stream junctions in the data set, roughly 6% can be attributed to distributary junctions (e.g., in deltas), rejoining braided streams, artificial side channels, or canals. We excluded these, leaving 934,207 junctions for analysis.
To obtain the branching angles at each junction, we first mapped the NHDPlus stream networks on a conformal (i.e., angle-preserving) projection for the contiguous United States (Lambert conformal cone 102004). From the connectivity attributes in the NHDPlus data set, we identified the stream segments that meet at each junction in the network. Each tributary segment is defined by a series of \((x, y)\) pairs of coordinates connected in the downstream direction. Using these points, we calculated the average orientation of each tributary stream (between each junction, or channel head, and the next junction downstream) by fitting a straight line using orthogonal regression [Samuelson, 1942; Rayner, 1985]. The average orientation of each stream segment is given by the direction of its regression line, which is independent of the actual segment length. The angle between the fitted lines for each pair of upstream tributaries defines their branching angle, as shown in Figure 1c. This approach measures the angle between the mean directions of the two tributary valleys, rather than the local angle at which the two channels join (which is presumably a less durable feature of the landscape and more affected by fluctuations like meandering, which strongly depend on the local flow geometry). We also calculated the mean slope at each junction as the average of the NHDPlus slope attribute values of the two tributary stream segments. Finally, we averaged all the junction angles in each HUC6 (Hydrologic Unit Code-6) drainage basin. These basins average 17,000 km\(^2\) in size and usually contain several thousand junctions. Figure 2a shows a map of these basin-wide averages. Although the standard deviation of the branching angle distribution in each basin is around 25°, the standard error of the mean branching angle is usually smaller than 2°. A clear trend emerges: branching angles in the humid eastern U.S. tend to be wider than those in the arid western U.S., with notable exceptions in the humid Pacific Northwest. This spatial pattern suggests that mean junction angles may be correlated with the climatic aridity-humidity continuum.

**2.2. Branching Angles and Aridity**

To explore the relationship between junction angles and climate, we quantified the climatic conditions at each stream junction using the UN Environment Program’s aridity index \(\Lambda I = P/PET\) [Middleton and Thomas (Eds.), 1997], where \(P\) and \(PET\) are the precipitation rate and potential evapotranspiration rate, respectively. Larger values of \(\Lambda I\) are thus associated with more humid climates while smaller values characterize more arid landscapes. We computed \(\Lambda I\) at 4 km resolution using precipitation and temperature data from PRISM averaged over the period 1900–2012 [PRISM Climate Group, 2012]. Although this 112 year record is short compared to the time scales of river network evolution, we would expect the relative pattern of aridity to persist even as
the average climate changes, such that relatively arid sites remain relatively arid, barring large-scale reorganization of atmospheric circulation [Riebe et al., 2004]. Thus, we would expect that the overall relative pattern of aridity obtained from the 112 year instrumental record should be representative of longer periods of time, even if the absolute aridity values may differ.

Figure 2b shows values of \( AI \) averaged over the same hydrologic basins that were used to compute mean branching angles in Figure 2a. Comparing the two maps, one immediately sees that wider branching angles tend to occur in more humid regions and that the narrowest average branching angles are found in the driest parts of the southwest. We quantified the relationship between aridity and branching angle by delimiting 23 bins on a logarithmic scale of \( AI \) and computing the mean angle of all stream junctions in each \( AI \) bin. The resulting correlation function, which gives the mean angle as a function of the logarithm of the aridity index, is shown in Figure 2c, where the mean angle approaches roughly 72° under the most humid conditions (high values of \( AI \)). The most arid regions, by contrast, are characterized by mean junction angles of 45° - 50°. Between these two end-member extremes, junction angles increase systematically along the climatic continuum from \( AI = 0.2 \) to \( AI = 2.0 \) (i.e., \( \log_{10} AI \) between −0.7 and +0.3). For any given value of \( AI \), individual junction angles exhibit considerable variability. Figures 2d and 2e show the distributions of individual junction angles for the arid \((AI \leq 0.2)\) and humid \((AI \geq 2)\) end-members, where the mean values are 47° ± 1° and 72° ± 1°, respectively, and the standard deviation is approximately 35° in each case. Consequently, individual stream junctions’ branching angles only weakly reflect the aridity of the landscape. The unambiguous correlation shown in Figure 2c emerges through “big data” aggregation of many junction angle measurements, averaging over measurement and mapping errors, geological heterogeneity, and natural perturbations during network evolution. Aggregating junction angles over large landscape units allows the identification of relationships that would not be revealed from small-sample case studies. For the same reason, however, these relationships should not be interpreted as describing individual junctions or local groups of junctions.

### 2.3. Signatures of Climate and the Impact of Slope

Erosional signatures of climate are more likely to be expressed in junctions between low-order streams, whereas higher-order junctions are more likely to have been reshaped through time by in-stream flow processes [Howard, 1971; Pieri, 1984] or catchment reorganization [Willett et al., 2014; Shelef and Hilley, 2014]. As with any branching network, the lowest-order streams comprise most of the junctions in our data set and thus dominate the overall statistics.

To test how branching geometry varies with network hierarchy, we separately analyzed the angle-aridity relation for stream bifurcations of different Horton-Strahler orders in our network, as shown in Figure 3a. We define a junction of order \( n \) as one that is formed where two tributaries of order \( n \) join, thus creating a stream of order \( n + 1 \) in the downstream direction. For simplicity this definition neglects side branches where lower order tributaries join higher-order streams (because this creates many different combinations of orders), although such side branches comprise a substantial fraction of the complete data set shown in Figure 2c. As Figure 3a shows, all orders exhibit increases in branching angle with increasing aridity index (that is, with increasing climatic humidity) independent of side branches of lower order entering major streams. One might expect the relationship between branching angles and aridity to become weaker for higher-order junctions due to channel migration and catchment reorganization during the evolution of the network [Willett et al., 2014; Shelef and Hilley, 2014]. Furthermore, with increasing stream order and flow discharge, in-stream fluvial processes may become increasingly important in shaping the branching structure. Several theories for the branching angles of river junctions have been suggested, such as the geometric model [Howard, 1971; Pieri, 1984], the minimum work model [Howard, 1971, 1990; Serres and Roy, 1990], or the momentum balance model [Mosley, 1976]. These models are based on geometric factors such as longitudinal profile concavity or slope and water discharge and aim to predict the local angles at which two river segments should meet rather than the branching angle of the two upstream tributary valleys (supporting information).

The tendency of higher-order streams to branch at wider angles suggests not only a possible effect of drainage reorganization but also a dependence on topographic gradients. Lower order channels are typically located in the headwaters of the stream network and thus are typically steeper than higher-order, lower gradient channels, as shown in Figure 3b. Therefore, the narrowing of junction angles at lower orders may partly reflect a narrowing of junction angles with increasing channel gradients (Figures 3a and 3c).

One would expect flows (including subsurface flows) in steeper landscapes to be oriented more strongly along the downslope gradient vector of the surrounding terrain. Thus, all else equal, we would expect steeper
Figure 3. (a) Relationships between mean branching angle and aridity for junctions of different Horton-Strahler orders. (b) For each order, the mean channel gradient decreases by typically a factor of 2. (c) Decreases in mean branching angles with increasing channel gradient (here calculated as the mean of the gradients of each junction’s two tributaries), for humid (\(A_I \geq 2\)), intermediate (\(0.2 < A_I < 2\)), and arid (\(A_I \leq 0.2\)) climates. (d) Increases in mean branching angles with increasing humidity, for shallow (\(s \leq 0.003\)), intermediate (\(0.003 < s < 0.03\)), and steep (\(s \geq 0.03\)) channel gradients. Error bars show standard errors, where they are larger than the plotting symbols.

Streams to have narrower branching angles, reflecting the greater slope-parallel component of the gravitational forces acting on the flow. As Figure 3c shows, branching angles are indeed systematically narrower in steeper stream networks, narrowing on average by 10° for each factor-of-10 increase in tributary gradients. However, regardless of gradient, mean junction angles still become systematically wider with increasing humidity (Figure 3d).

Figure 4. Mean branching angle for each HUC 6 basin in the contiguous United States is more strongly correlated (a) with mean climatic aridity than (b) with mean channel gradient or (c) with stream network concavity.
Figure 5. Relationships between mean junction angles and the water table ratio and its three main components. The water table ratio (WTR), calculated following Gleeson et al. [2011], describes the degree to which groundwater aquifers are connected to the surface (high WTR, blue) or disconnected from it (low WTR, red). (a) Maps of WTR and its three main components: annual recharge [Wolock and McCabe, 1999], aquifer hydraulic conductivity [Gleeson et al., 2014], and surface elevation [Survey, 2014], along with plots of mean junction angles as functions of these three components. (b) Systematic increase in mean junction angle with increasing WTR. Error bars show standard errors, where they are larger than the plotting symbols.

For similar slopes our analysis reveals a roughly 20° shift in mean junction angle between arid and humid end-member landscapes (Figures 3c and 3d). This shift, which persists over the entire range in slope, could potentially arise from the dominance of different channel-forming processes in the wet and dry end-member regimes [Horton, 1945; Montgomery and Dietrich, 1992; Kirkby and Charley, 1967; Dunne, 1969, 1978, 1990; Molnar, 2004; Molnar et al., 2006]. The histograms in Figures 3c and 3d show that the tails of the aridity and slope distributions represent only a small fraction of stream junctions in the data set. Nonetheless, their absolute numbers are considerable, given the nearly one million junctions in the data set, and they are important for defining the end-member extremes.

Several simulation models for drainage basin evolution suggest that branching angles are largely controlled by channel slope or by stream network concavity, which is defined by the exponent θ in the slope-area relation $S = kA^\theta$ [Howard, 1994; Sun et al., 1994; Sólyom and Tucker, 2007]. To test these hypotheses we calculated the mean slopes and concavity exponent θ for all HUC-6 basins in the contiguous United States and compared their correlations with branching angles to that of aridity. Figure 4 shows that the correlation of aridity with mean branching angles is much stronger than that of mean channel slope or concavity, which have been proposed as major controls on stream network geometry.
2.4. Water Table Ratio and Branching Angles

A further clue suggesting a mechanistic linkage between climate, channelization processes, and junction angles arises from the analysis of the water table ratio [Haitjema and Mitchell-Bruker, 2005; Gleeson et al., 2011]. The water table ratio (WTR) is a dimensionless number describing how closely a groundwater aquifer is coupled to surface processes [Haitjema and Mitchell-Bruker, 2005]. The water table ratio is a combination of groundwater recharge $R$, hydraulic conductivity $\kappa$, and surface elevation $d$ [Gleeson et al., 2011], as shown in Figure 5 for the continental United States.

As Figure 5a shows, mean junction angles increase more or less systematically with recharge but do not show a clear relationship with either conductivity or elevation. However, when these three measures are combined to form the WTR, they exhibit a strong and systematic relationship with mean junction angles (Figure 5b). Wider junction angles are found where the WTR predicts a strong coupling between surface and subsurface flows, and in locations with the largest WTRs, mean junction angles approach 72°, the theoretically expected value for networks formed by groundwater-driven erosion [Devauchelle et al., 2012]. Conversely, landscapes with decoupled aquifers (i.e., small WTRs) show much smaller mean branching angles.

3. Discussion

The continental U.S., like any land mass, does not present a perfect natural experiment; all combinations of aridity and landscape characteristics are not equally probable. Thus, for example, much of the landscape characterized by $0.1 < \log_{10} A/I < 0$ lies in the Great Plains, between the Mississippi and the Rocky Mountains, where a broad regional gradient from west to east creates many parallel drainages and thus contributes to the narrowing of the junction angles. This may account for the anomalously low mean branching angle in the corresponding $\log_{10} A/I$ bin in Figure 2. More generally, the intermountain West is both steep and arid, and thus one might question whether the narrow mean junction angles that characterize this landscape are due to its climate or its topography. The answer is that both factors matter, but as Figures 3c and 3d show, there is a clear trend toward wider junction angles with increasing humidity, even when controlled for differences in topographic gradient.

The general trend toward wider junction angles in more humid landscapes can be hypothesized to reflect a shift in relative dominance among channel-forming geomorphic processes along climate gradients. Infiltration of precipitation into the ground, and thus the potential for diffusive geomorphic transport processes, such as groundwater flows, is more prevalent in humid landscapes than in arid ones [Kirkby and Chorley, 1967; Dunne, 1969]. Conversely, arid and semiarid landscapes are more likely to be shaped by erosion due to surface runoff, because greater aridity is associated with decoupled groundwater aquifers, more episodic precipitation [Molnar, 2004; Molnar et al., 2006], and sparser vegetation, which is less effective in inhibiting surface erosion. As surface erosion is more likely to be oriented along the topographic gradient, we would expect junction angles to generally be narrower where surface runoff is more common. This expectation is borne out by Figures 2a–2e, which show a general trend toward narrower junction angles in more arid climates and wider junction angles in more humid climates. The same trend is observed not only across all junctions as a whole (Figure 2) but also for individual orders and specific ranges of topographic gradients (Figures 3c and 3d).

The hypothesis that branching angles generally reflect the relative dominance of the underlying channelization processes is supported by recent theoretical studies which show that network growth in groundwater fields should favor a particular angle — $2\pi/5$ or 72° — at which valley heads branch [Devauchelle et al., 2012; Petroff et al., 2013]. This result requires only that valley heads advance in the direction that captures a diffusive flux, such as groundwater flow. However, it is unclear how strictly this theoretical result should be applied to the long time scales of river basin evolution and to the large spatial scales examined in our study.

For branching angles shaped by surface and near-surface flows, one would expect these flows to be more focused in a slope-parallel direction; thus, the prevailing topographic gradient would tend to give nearby flows more similar orientations and thus narrower junction angles. Consistent with this hypothesis, the mean branching angles in our data set are considerably smaller in arid landscapes which are expected to be shaped by overland flow and increase toward the theoretically expected value of 72° in the most humid landscapes (and at low gradients and low stream orders), as shown in Figures 2 and 3.
These observations suggest that the trend toward wider mean branching angles in more humid landscapes may result from an increased relative importance of diffusive processes close to the channel heads. The analysis of the water table ratio (Figure 5) additionally supports this interpretation. With increasing order the mean junction angle shifts to larger values, suggesting an increased influence of drainage reorganization shaped by in-stream flow processes [Howard, 1971, 1990].

The systematic variation of branching angle with climate and erosional mechanisms may provide a basis for reconstructing ancient climates and identifying erosional mechanisms from relict landscapes, including those on Mars. Globally, about two thirds of the water flowing into rivers is thought to be derived from subsurface flows [Dirmeyer et al., 2006; Oki and Kanae, 2006]. Our analysis suggests that the relative dominance of subsurface flows, or any other mechanism of diffusive network growth, may leave a characteristic geometric imprint in the branching geometry of stream networks. Thus, our results suggest that climate has a significant impact on stream junction angles, leaving a characteristic watermark on much of the Earth's surface environment.

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A table with branching angle, x,y coordinates of each junction, and the aridity value attributed to this junction is provided as supporting information.

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