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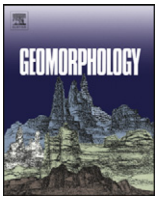

The influence of surface slope on the shape of river basins: Comparison between nature and numerical landscape simulations

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ABSTRACT

We investigate the influence of initial conditions of slope and surface roughness on the shape (length to width aspect ratio) of incipient drainage basins in numerical experiments of simple tilted surfaces using the CASCADE code of landscape evolution. Comparison with data on the shape of river basins in nature shows that simple rules of the steepest-descent routing of water are sufficient to account for a natural range of incipient drainage basin shape, independently of the erosion processes at work. To produce numerical basins that respect the main aspect ratio of natural drainage basins, one must use very low initial regional surface slopes of less than 1° at the scale of the entire drainage basins, and a local roughness slope of less than 3° at the scale of local surface irregularities. Numerical studies addressing real study cases may take advantage of the relation between local roughness and regional slope in order to produce catchment aspect ratios similar to the natural studied cases.

1. Introduction

In the last three decades, many questions have been addressed about the possible couplings between deep (mantle) and shallow (crustal) tectonics and superficial climate-controlled erosion (e.g., Molnar and England, 1990; Willett, 1999). These led to a considerable improvement in the mathematical modeling of surface processes, in particular with the advent of numerical models of landscape evolution, and with the quantitative analysis of increasingly available high-resolution datasets of the Earth's topography. While the approaches on these topics have followed different paths, the main studies have focused on numerical modeling of the development and evolution of fluvial landscapes, i.e. landscapes composed of channels and hillslopes, because their structure constitutes a fundamental control on relief in tectonically active areas.

While numerical models of erosion usually produce fluvial landscapes that look similar to nature, how to objectively assess this similarity remains an outstanding problem. As summarized in the review by Tucker and Hancock (2010), questions like what are the essential characteristics of a catchment or a landscape, and how can we quantitatively assess landscape differences (Hancock, 2003) are still challenging. Until now, models have been tested against data obtained with the slope–area relationship or with catchment hypsometry (Hancock et al., 2002; Willgoose et al., 2003) but these measures are often insufficient to discriminate between landscapes that seem visually different (Tucker and Hancock, 2010). Braun and Sambridge (1997) provided a quantitative assessment of the similarity between their model's results and natural landscapes by showing that the numerically produced dendritic river patterns respected the main laws of network composition and topographic surfaces that have similar scaling behavior as natural landscapes. They noted, however, that most possible networks, either natural or not, inevitably obey Horton's and Schumm's laws of network composition, as pointed out by Kirchner (1993), and thus these laws may not be used readily to validate models.

One consistent output from model–data comparison tests is the sensitivity of models to initial conditions. Testing the SIBERIA landscape evolution model (Willgoose et al., 1991a,b,c) against common geomorphological statistics (e.g., Horton's and Tokunaga's ratios, non-dimensional drainage density, magnitude, mean relief, and mean stream relief), Ijjasz-Vasquez et al (1992) concluded that the large variability observed in their numerical dendritic networks is not random and is instead directly related to differences in the initial conditions. A subsequent test of the SIBERIA model by Hancock (2003) also concluded that, for a good match between simulated and field descriptors such as the hypsometric curve, area–slope relationship, width function and cumulative area, all that is needed is a catchment with an aspect ratio matching that of the field data, thus similarly emphasizing the role of initial conditions.

Recently, Castelltort et al. (2009) presented new measures of the shape (length to width aspect ratio) of large-scale (10^1–10^3 km^2)

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incipient drainage basins formed on uniformly tilted surfaces. These data highlight the influence of regional surface slope versus surface roughness on the aspect ratio of incipient drainage basins. Steep and smooth slopes develop longer and narrower catchments than comparatively gently dipping and rougher surfaces.

In this brief report we use Castelltort et al.'s (2009) dataset to test the ability of the CASCADE landscape evolution model (Braun and Sambridge, 1997) to accurately reproduce drainage basin shape. The algorithm of routing water downstream used in the CASCADE is generic in essence (steepest slope) and is sufficient to reproduce the observations of natural basin shape. By tuning the ratio between regional slope and amplitude of the initial surface roughness, the initial drainage basin shape can be predicted. Numerical landscape evolution studies can thus choose the adequate initial conditions in order to generate drainage basins whose aspect ratios respect those commonly encountered in nature.

2. Incipient river basins on tilted surfaces

To measure the aspect ratio of a drainage basin, several methods can be used that depend on the choice of a dominant basin length (e.g. the longest channel length and length along the main valley axis to the drainage divide), basin area and basin orientation, and produce non-unique results. The method of computing the convergence angle of river basins as defined in Castelltort et al. (2009) leads to a unique measure of drainage basin shape independent of such choices. Considering a simplified rectangular basin of length L_b and width W_b, with $L_b > W_b$, the convergence angle is defined as the angle α that determines the aspect ratio of a basin:

$$\tan\alpha = \frac{1}{2}\cdot\frac{W_b}{L_b}. \quad (1)$$

Instead of enclosing a natural basin within a synthetic rectangle of dimensions L_b and W_b, the convergence angle method is based on calculating source–outlet vectors (Fig. 1). A source–outlet vector is defined as the vector between the current pixel and the basin outlet. After extracting the river network in order to define the catchment boundary, every pixel in the basin is linked with the outlet pixel in order to define the population of source–outlet vectors. The convergence angle is such that half of the source–outlet vectors possesses an azimuth comprised between $+\alpha$ and $-\alpha$ of the main median basin azimuth, and is thus found by taking half of the angular difference between the first and third quartiles of the azimuths of all source–outlet vectors (Castelltort

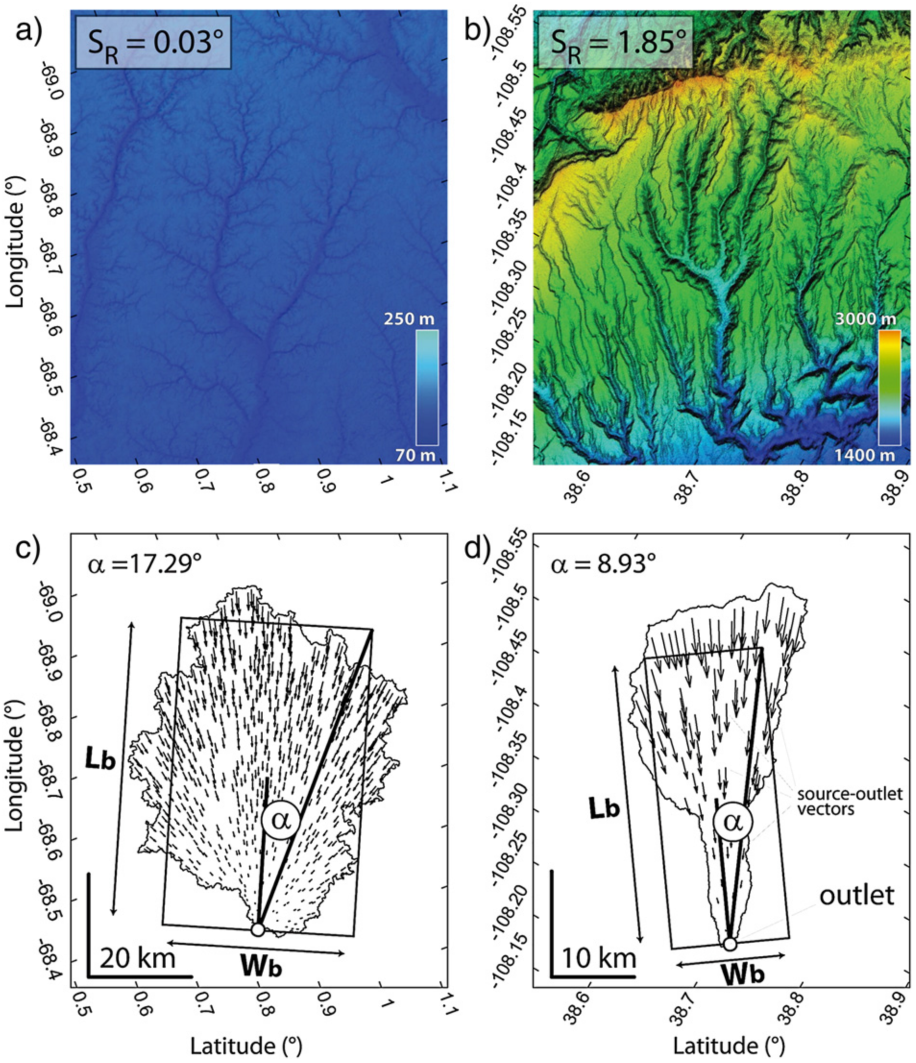

Fig. 1. Definition of the convergence angle α of river basins and influence of surface slope (S_R) in nature. a) and b) Digital elevation models (DEMs) of two examples of river basins in (a) South America and (b) North America (basin codes respectively SA5_4 and S6_3 in Castelltort et al., 2009). c) and d) Obtained convergence angles for the two basins. The steeper surface of basin S6_3 (d) displays a narrower basin and a smaller convergence angle than the gently dipping surface of basin SA5_4 (c). The synthetic rectangular basins of length L_b and width W_b are unique and obtained from the computed convergence angle (which sets the ratio between length and width) and a given drainage area of the considered basin.