Quantifying variability in streamflow distributions to understand the relationships between climate, topography and erosion

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Motivation

- Rivers and the water they carry are important drivers of the erosional processes that shape landscape evolution.
- Understanding the characteristics of river discharge is of particular interest as fluvial incision occurs during flood events that overcome a threshold for erosion and the frequency of exceeding this threshold is influenced by both discharge magnitude and variability.
- Here, we employ a coupled climate-landscape evolution model to generate high resolution river discharge data. This discharged is used to drive a simple river incision model that we use to explore trends in mean discharge and discharge variability, channel concavity, fluvial relief, and fractional erosivity.

Methods

- Coupled Climate-Landscape Evolution Model

The landscape evolution model, Landlab, is coupled to the high-resolution atmospheric model, WRF (Weather Research and Forecasting) (**Fig. 1**). An initial landscape is generated in Landlab and projected in the location of the present day South American Andes (**Fig. 2**). This topography is used in the WRF simulations, precipitation from WRF is converted to discharge using WRF-Hydro and this discharge is used to drive erosion in the river incision model.

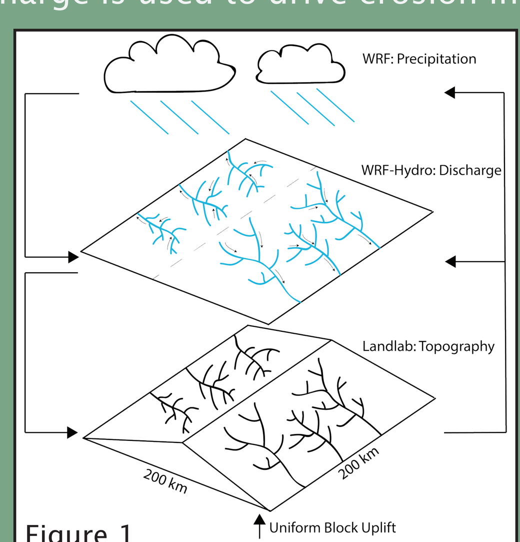


Figure 1

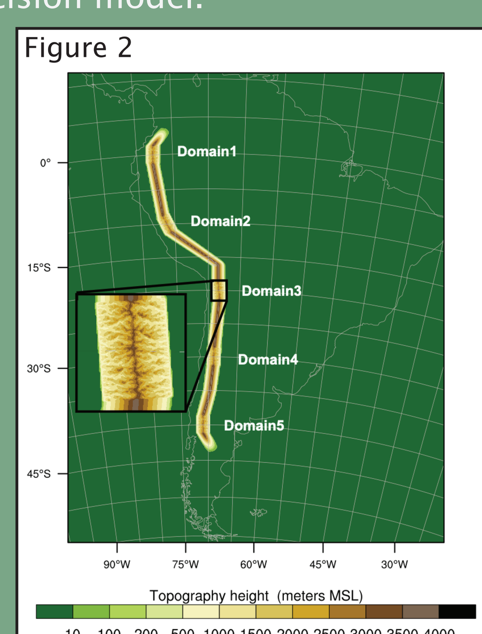


Figure 2

- River Incision Model (**Fig. 3**)

Detachment-limited river incision (I) occurs when the product of bed shear stress (τ_b) and a bedrock erodibility constant (k) overcomes a threshold shear stress (τ_c). τ_b is a function of discharge (Q) derived from WRF-Hydro, channel width (W), which scales with drainage area from the Landlab domain and channel slope (S), calculated within the incision model.

$$I = k(\tau_b - \tau_c), \tau_b > \tau_c \qquad \tau_b = \rho g \left(\frac{Q}{W \cdot n}\right)^{3/5} (-S)^{7/10}$$

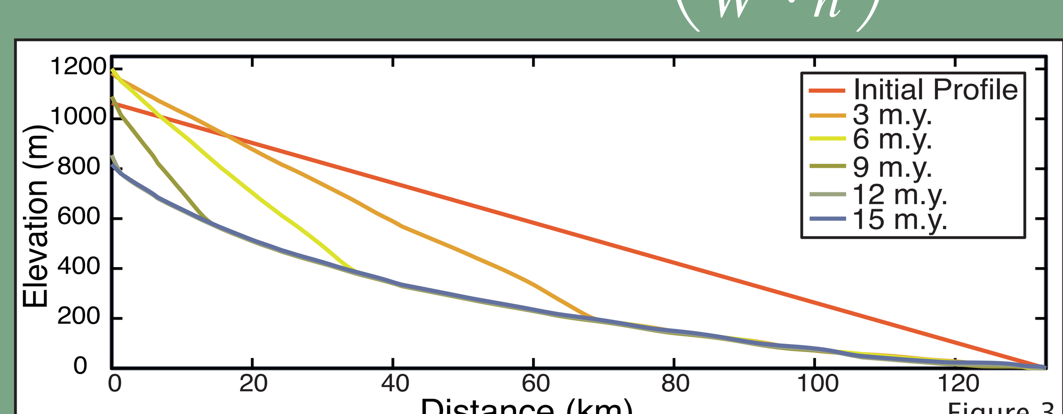


Figure 3

Experimental Design

- Five years of 6-hourly discharge data is generated from two WRF/WRF-Hydro simulations:

  1) low-topography mountain range (~100m)
  2) high-topography mountain range (~4km)

- Discharge is extracted along channels on east and west flank of the topography (**Fig. 4**) at 0°, 10°, 20°, 30° and 40° S.

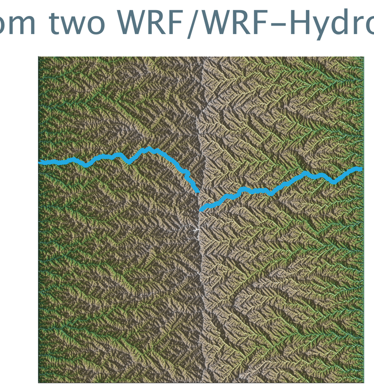


Figure 4

- Incision model is run to steady-state using 20 different discharge datasets, 10 from the low-topography simulation and 10 from the high-topography simulation.

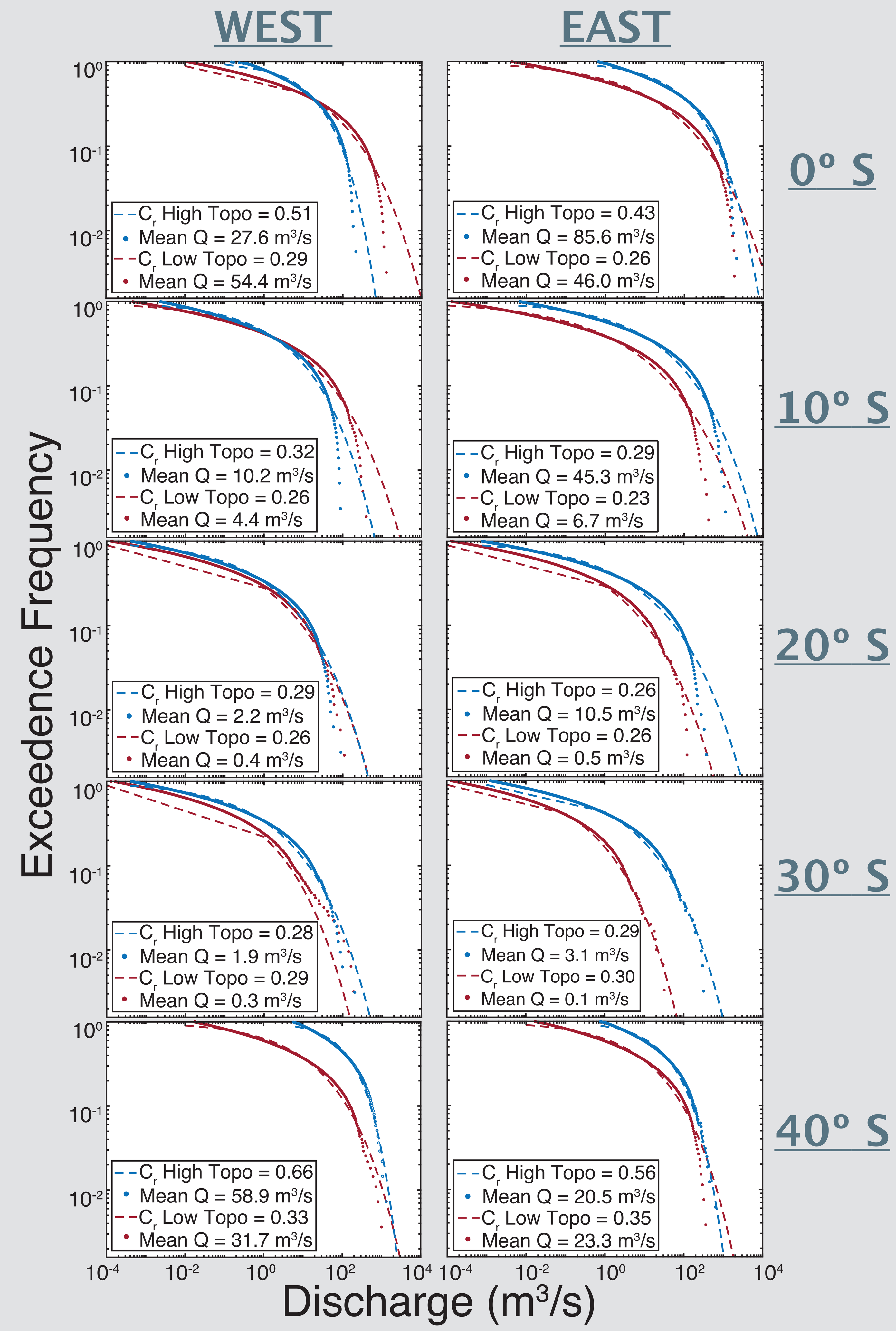
- **Model Parameters**

Run time	275 Myr
Time step	100 yr
Bedrock erodibility (k)	1.4×10^{-6} m s^2 kg^{-1}
Threshold shear stress (τ_c)	0.01 Pa^{-1}
Uplift Rate	0.1 mm yr^{-1}

Results

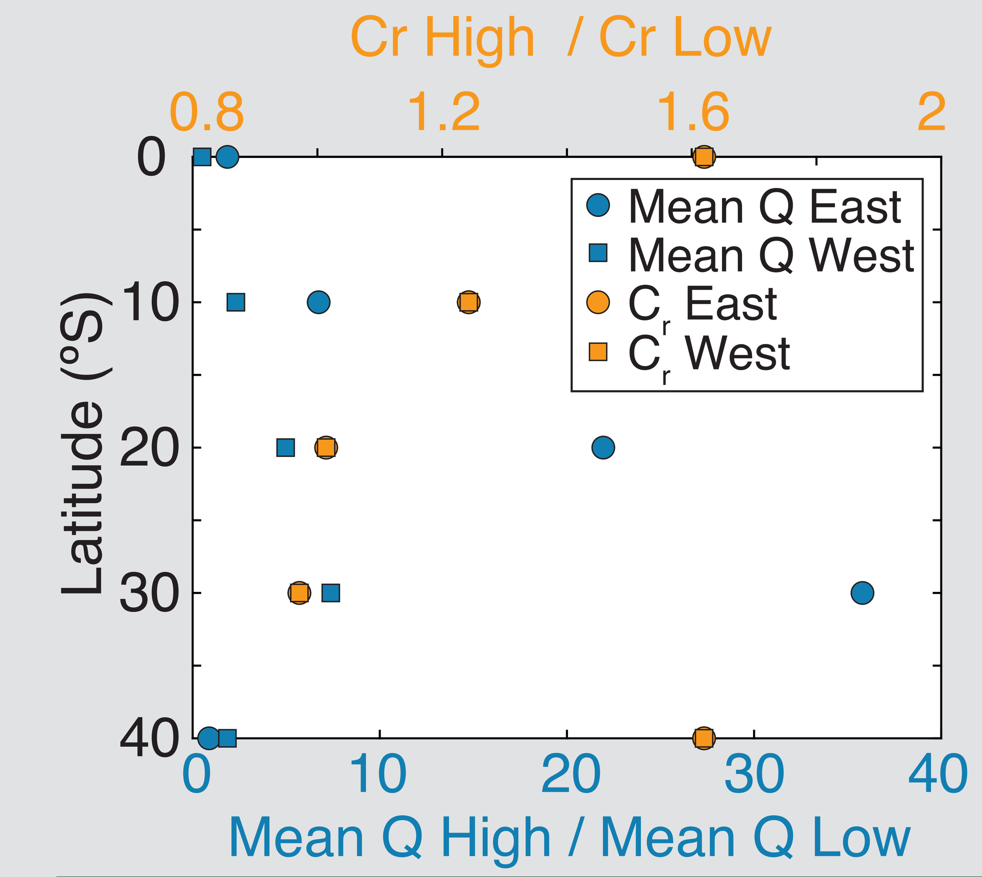
- Discharge
  - Discharge is recorded for 5 years at the outlet of each basin.
  - C_r represents the shape parameter in stretched exponential fit and describes discharge variability (Rossi et al., 2016).

  High C_r = low variability, Low C_r = high variability.



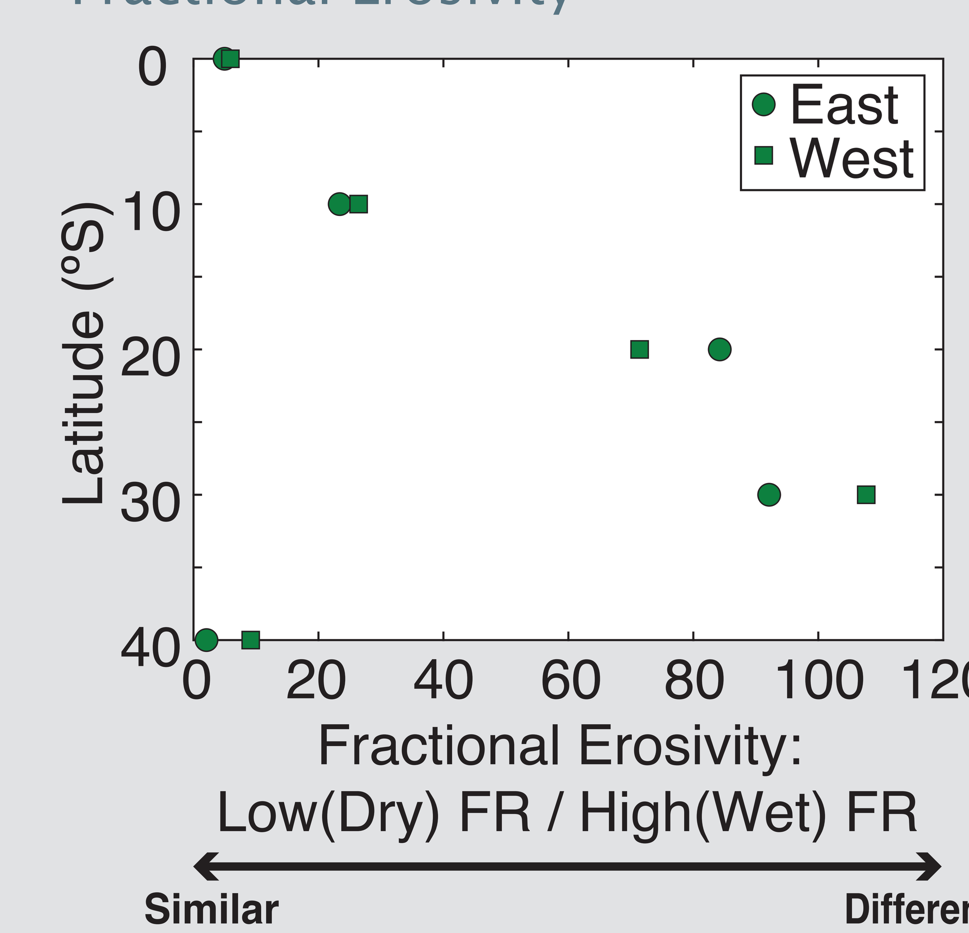
- **Topography influences mean discharge and discharge variability**
  - High topography produces higher mean discharge at all latitudes.
  - High topography produces less variable discharge at 0° and 40° S and has little influence on variability at 10°, 20° and 30° S.
  - High topography forces higher mean discharge on the eastern flank at 0°, 10°, 20° and 30° S, and on the western flank at 40° S.
- **Mean discharge and discharge variability are related**
  - Higher mean discharge values coincide with less variable discharge distributions (0° and 40° S).
- **Latitude influences discharge distribution**
  - The stretched exponential distribution fits discharge data well at 30° and 40° S, but discharge from lower latitudes may be better described with an exponential or inverse gamma distribution.

- Mean Discharge vs. Discharge Variability



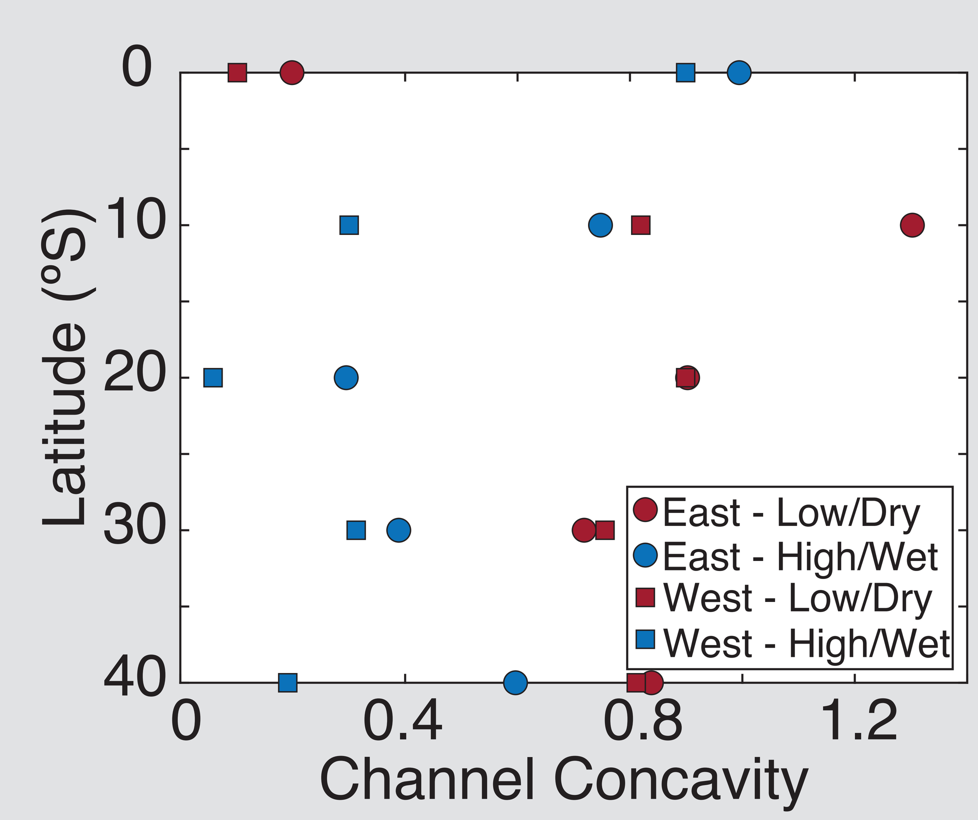
- Discharge variability between high- and low-topography experiments varies most at 0° and 40° S and least at 10°, 20° and 30° S.
- Mean discharge between high- and low-topography experiments varies most at 10°, 20° and 30° S and least at 0° and 40° S.

- Fractional Erosivity



- At all latitudes, high-topography climates are more erosive (FE>1).
- High-and low- topography climate erosivity are more similar at 0° and 40° S and less similar at 10°, 20° and 30° S.

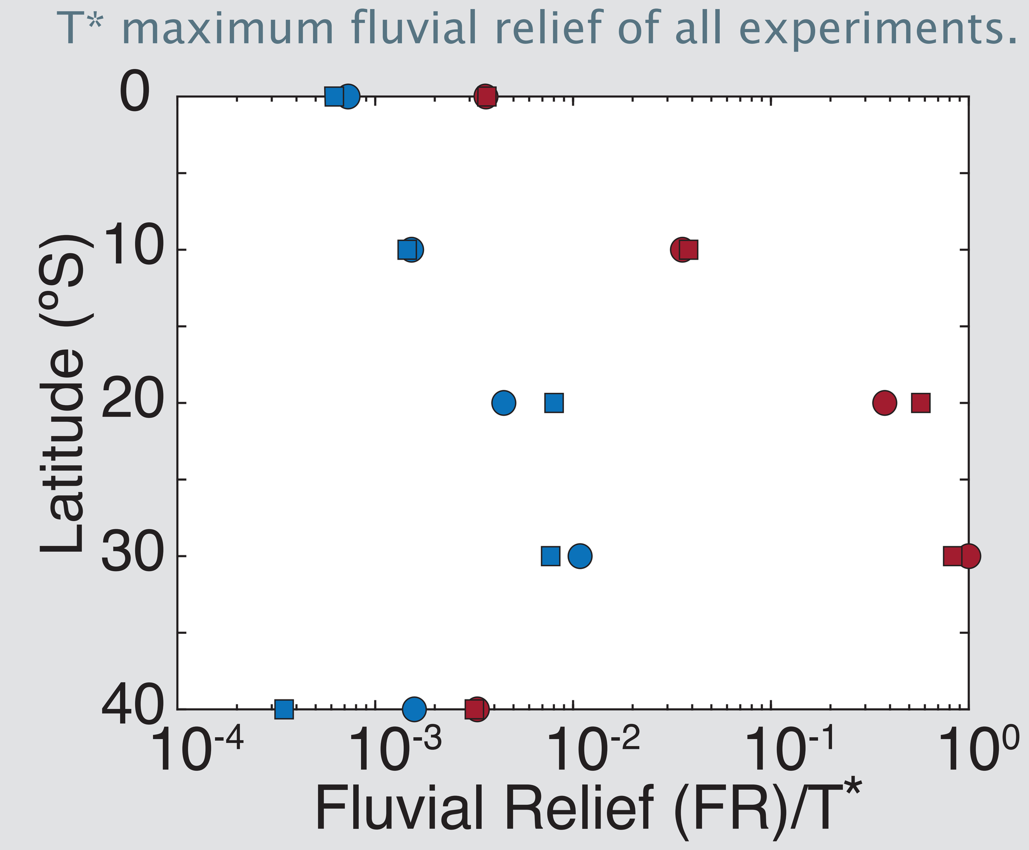
- Channel Concavity



- Concavity is high in simulations with lower mean discharge.
- Discharge variability has little influence on concavity.
  - Similar C_r values produce a large range of concavity values.

- Fluvial Relief

T* maximum fluvial relief of all experiments.



- Fluvial relief is higher in simulations with lower mean discharge (10°, 20° and 30° S).
- Fluvial relief is also higher in simulations with more discharge variability.

Summary

- Fractional erosivity is highest (high- and low-topography experiments have different erosive efficiency) at 10°, 20° and 30° S, where mean discharge varies by 1-2 orders of magnitude. Fractional erosivity is lowest (high- and low-topography experiments have similar erosive efficiency) at 0° and 40° S, where discharge variability varies most. This suggests **mean discharge may be more important than discharge variability in driving erosion,** but this will depend on the chosen threshold value.
- The presence of **high-topography** has a major influence on **discharge variability in wet climates** (0°, 10° and 40° S), and on **mean discharge in dry climates** (20° and 30° S).
- High-topography climates are more erosive, as a result, channel concavity and fluvial relief are both lower in these experiments.