Understanding glacier fluctuations in the Himalaya through simple models

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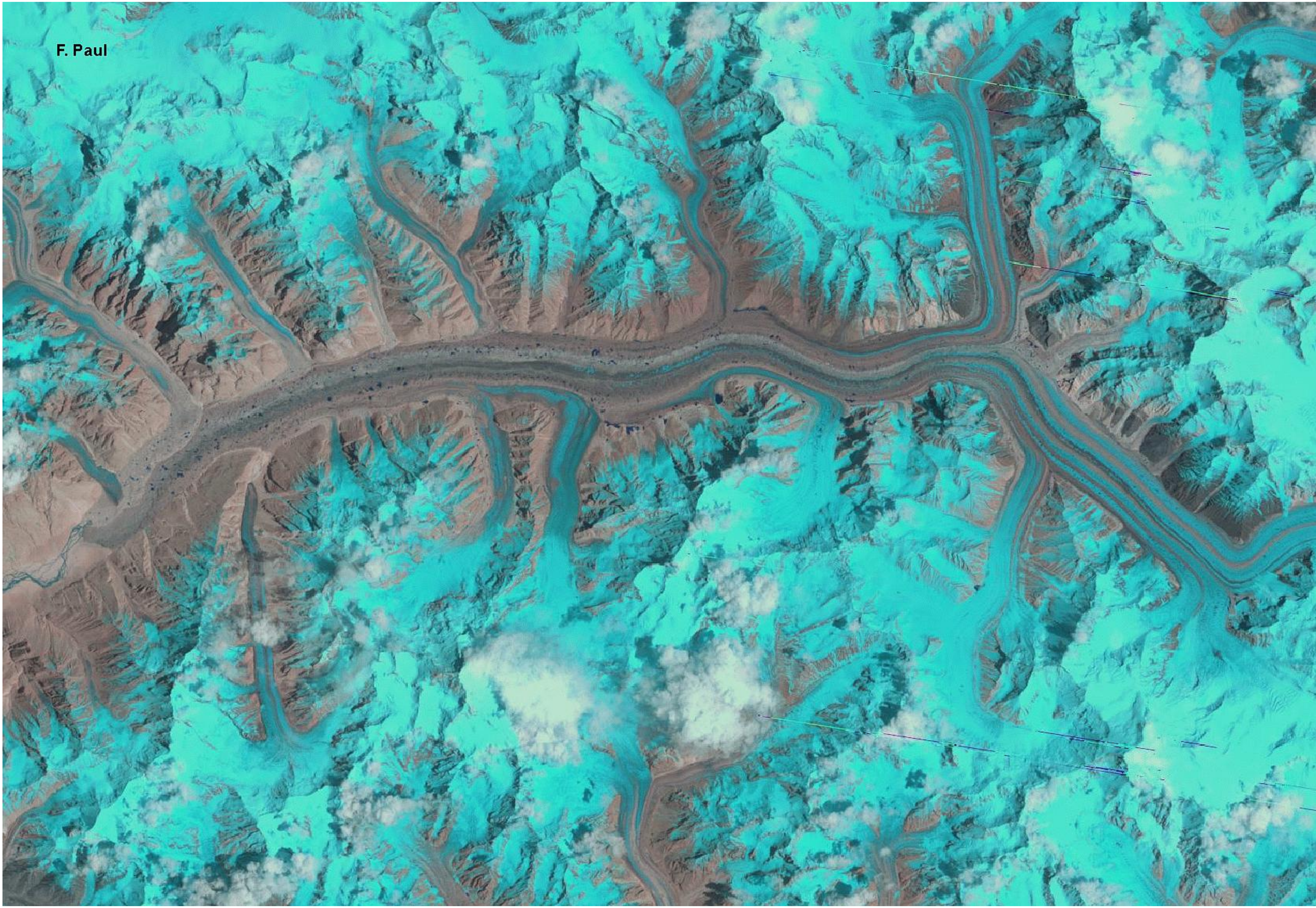
https://en.wikipedia.org/wiki/File:Glacial_lakes,_Bhutan.jp

Outline:

* Glaciers (basic processes; importance)
* Himalayan glaciers (characteristics; data and some puzzles)
* Results from a simple model glacier
* ...



Paul, F. (2015)

* Net **accumulation** above end-of-summer **snowline (ELA)**
(snowfall, avalanches, wind-blown snow, ...**)**

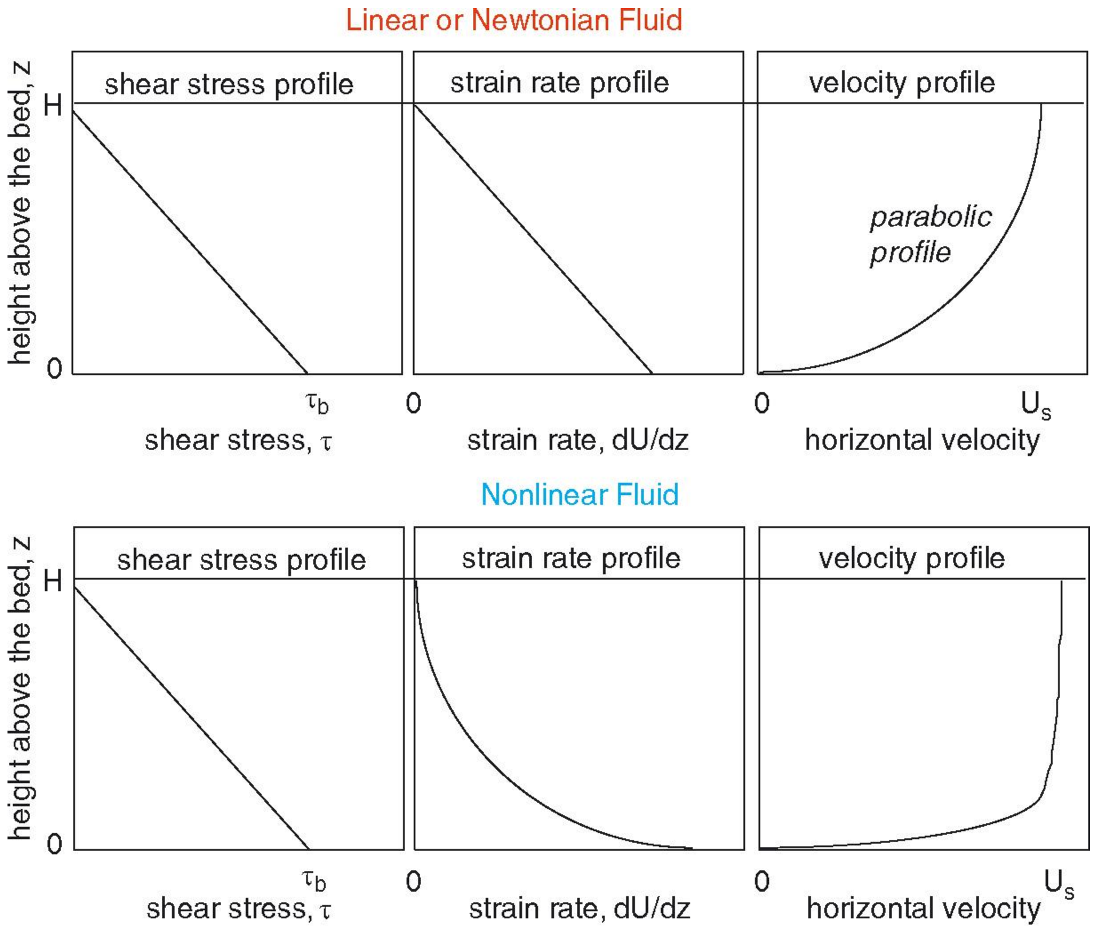
* Conversion of snow into ice
(compaction; reduction in albedo)

* 'slow' **Flow** of ice down-hill
* Ice is a ***hot*** solid => flows as a viscous liquid due to **creep**

$$v \pi R^2 = \frac{\pi R^4}{8\eta}\left(\frac{-\Delta P}{\Delta x}\right)$$

$R \sim 10^3$ m
$v \sim 100\text{m}/(10^7$ sec),
$dP/dx \sim \rho\, g \sin\alpha = 1000 \times 10 \times 0.1$ Pa/m
=> **$\eta \sim 10^{13}$ Pa-s !!!**

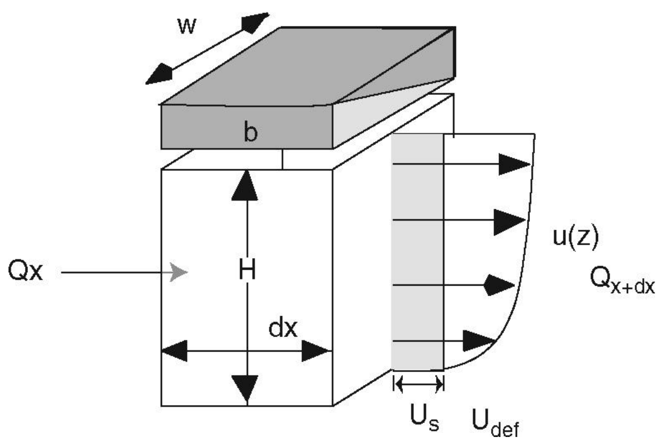
(Honey ~ 10 Pa-s, Water ~ 10^{-3} Pa-s, Air ~ 10^{-5} Pa-s)



[Anderson & Anderson, 2010]

* Viscosity of ice depends on shear stress;
  larger shear => lower viscosity
  (a **Shear-thinning** liquid)

* there is some **sliding** in addition to the **deformation**



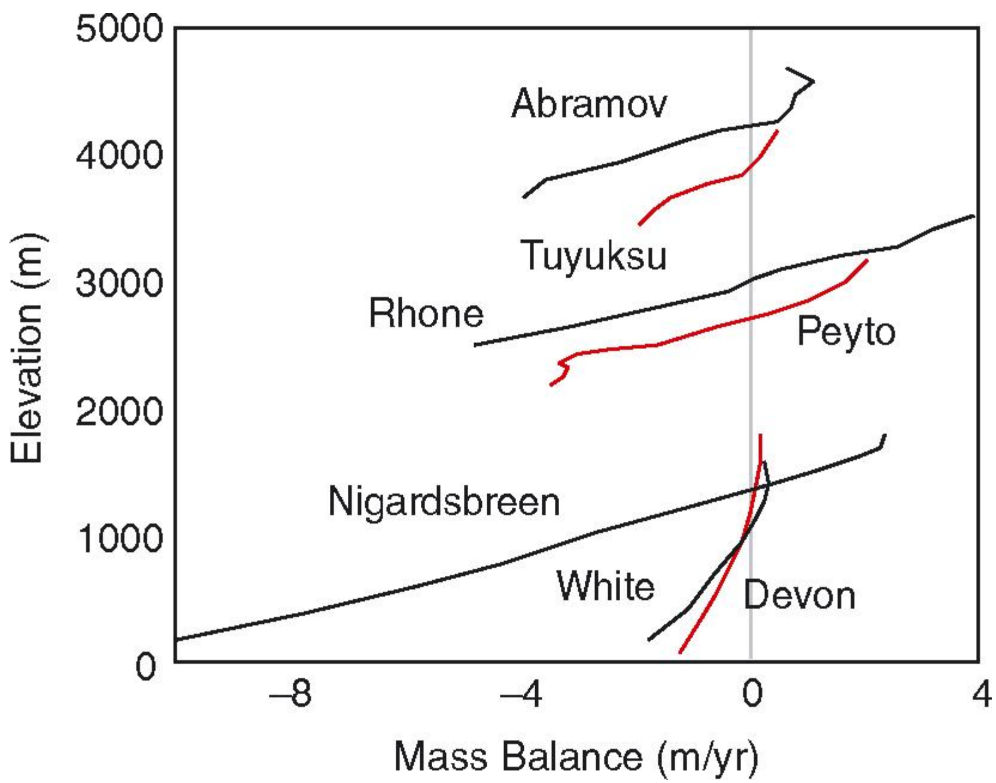
* Once below ELA, glacial ice **melts**.

Local surface **energy balance** determines melt rate

Net radiation budget dominates (~100W/m^2); albedo is important

Latent heat flux, sensible heat flux, ... (~10W/m^2)

* Specific **mass balance** is **linear** in elevation



* ELA is controlled by climate

* Given a steady climate,
glaciers reach a **steady-state**,

net accumulation = net ablation,

$$\int b(z;E)a(z)dz = 0 \, .$$

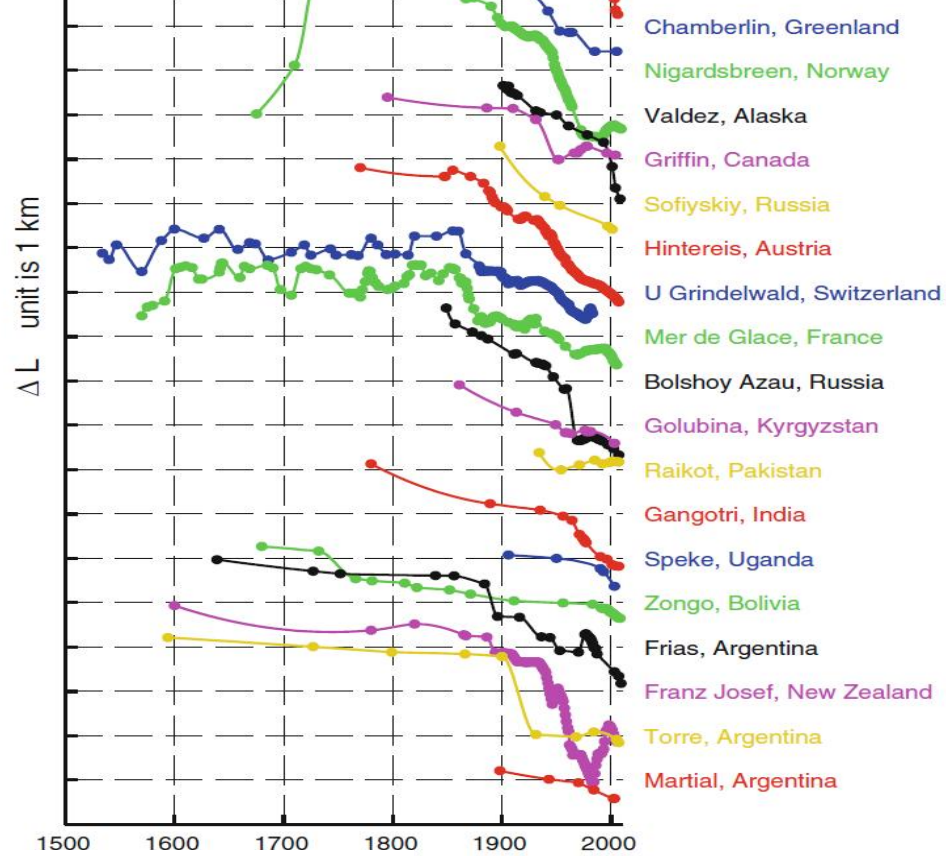
* Response time is large (~ decades)

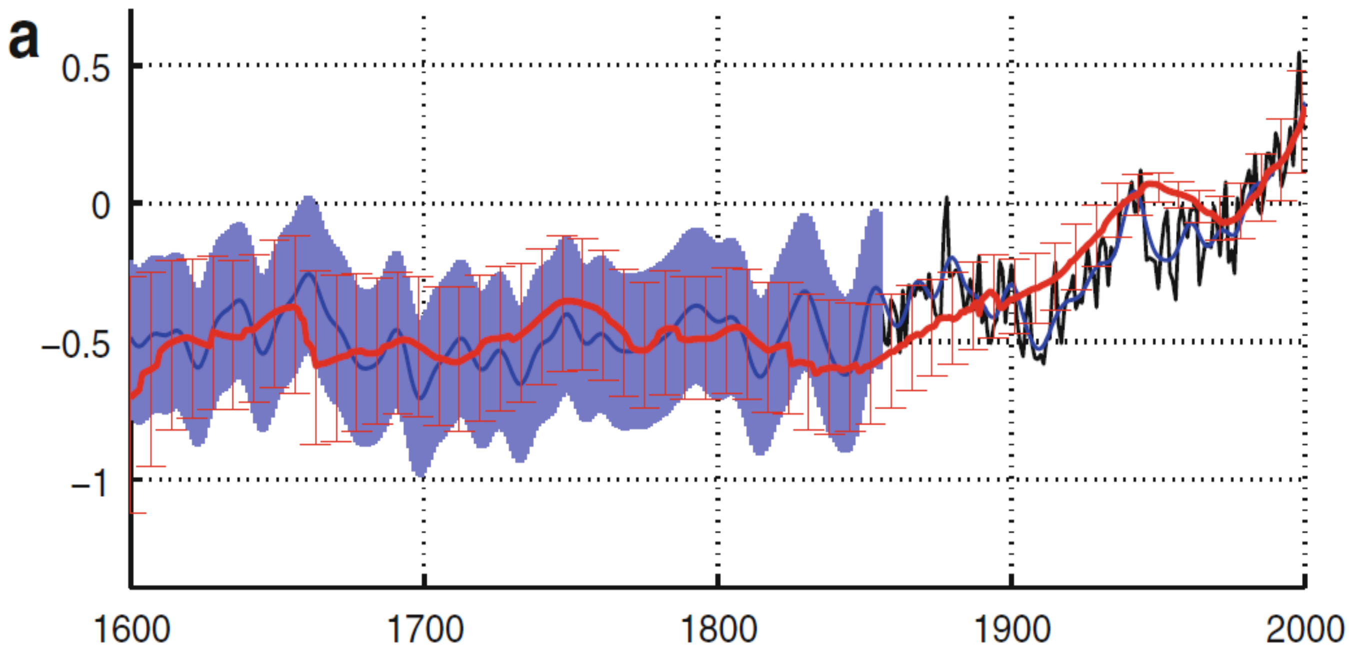
Why study glaciers?

** Temperature **reconstruction**

$$\frac{dL'(t)}{dt} = -\frac{1}{\tau}(cT'(t) + L'(t))$$

[Oerlemans, 05]





** In a warming climate glaciers shrink => mean **sea level rises**

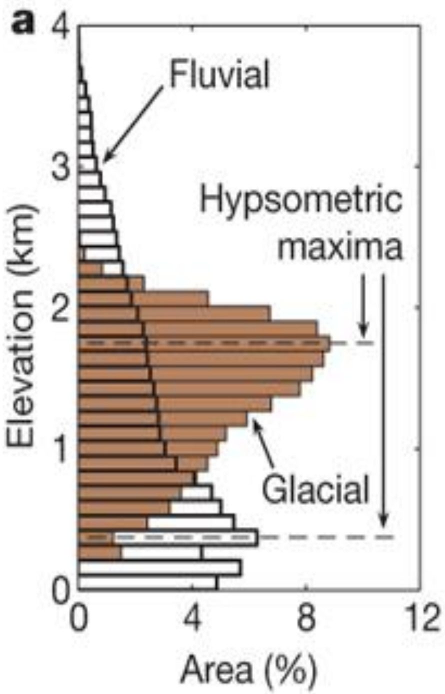
Antarctic Ice Sheet ~ 70m

Greenland ice sheet ~ 10m

mountain glaciers and ice caps ~ 1m

The present rate of sea level rise ~ 3mm/yr

** Glaciers shape mountain **landscapes** (erosion/transport/deposition)



* Glacial buzzsaw (eg Egholm et al, 2009)

** Glacier **melt-water** feeds rivers:

Glacier/snow melt contribution to present runoff in the Ganga:

* down-stream regions get a **relatively small** contribution from glaciers
* more important for the **upstream areas**
* snow-melt contribution becomes significant during MAM

* Maurya et al, 2010 ~**10%** in **winter, ~30%** in **summer** (at Rishikesh)
* Bookhagen et al, 2010 ~**18%** (at Rishikesh/upstream areas)
* Immerzeel et al, 2010 ~**10%** for the whole basin
* Siderius et al, 2013 ~**1-4%** of annual runoff at Farakka (**12-38%** during MAM)

A **large spread** in these different estimates.

(Better hydro-meteorological data-set; a detailed model with (dynamic) glaciers/snow; better descriptions of **debris covered area** and **avalanches** are needed.)

Himalayan glaciers

* relief/topography
  avalanches
  debris cover

  ISM, WD, ...

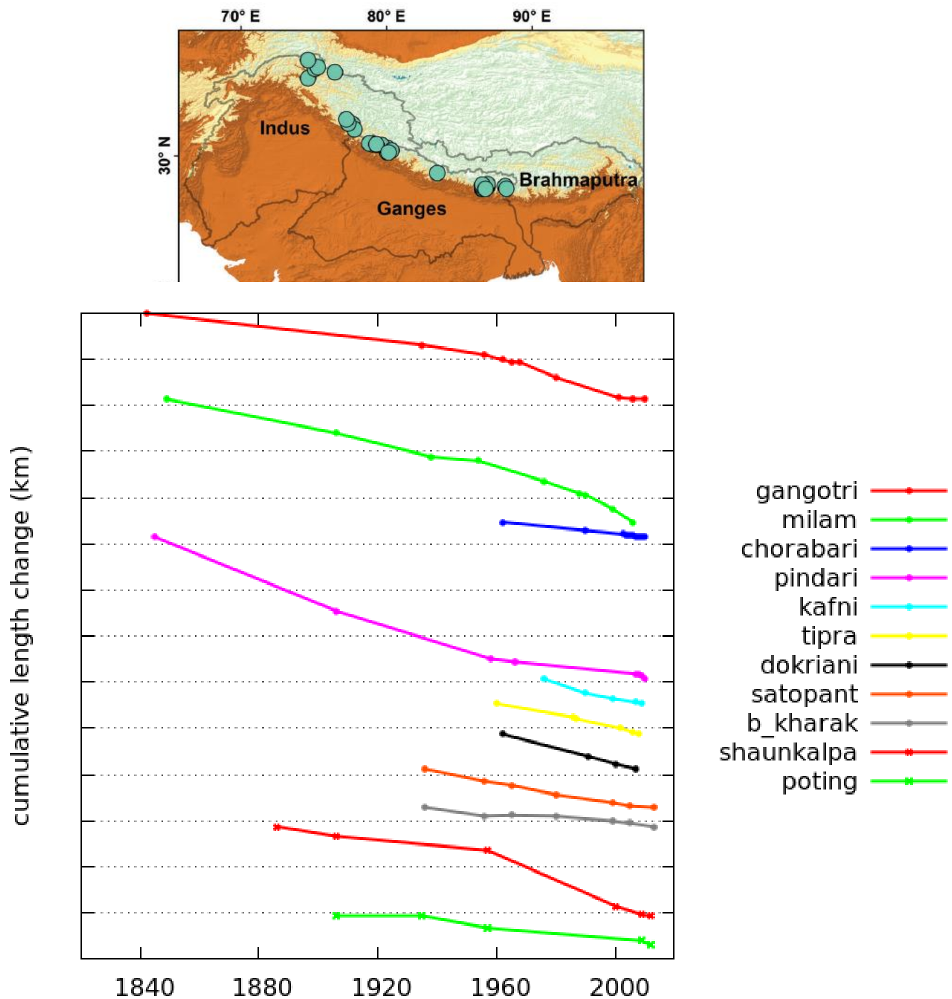
* data gaps
  (Long term data on Himalyan glaciers, Rivers, and climate is misssing)

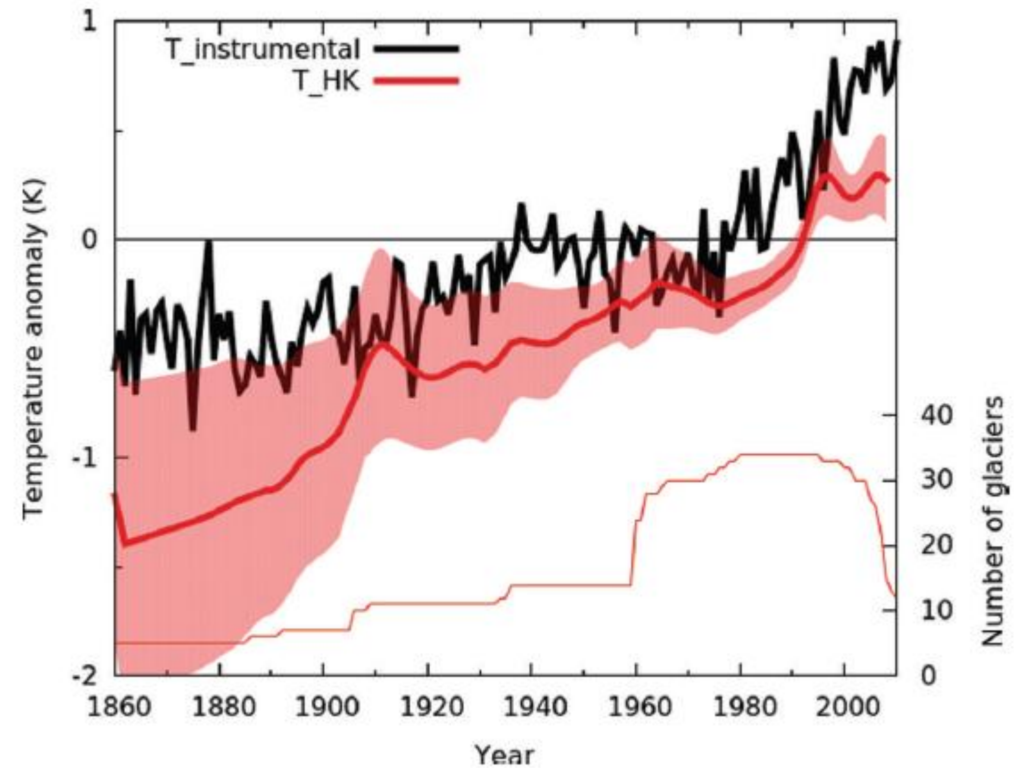
Questions:

* Recent changes (over decadal/century scale)
* Future changes under given climate scenarios
* Contribution of glacier melt-water in river run-off (and its future)
* Debris effects (on energy balance, flow, hydrology)
* Bedrock geometry and ice volume
* Role in landscape evolution, ...

*** Present status:**

Himalayan glaciers are **retreating/shrinking** more or less steadily over last **~150 yrs**





[Banerjee and Azam, 2015]

What is their future?

* Over the past five decades,
Net sp. Balance **~ -0.5 m** water equivalent (similar to global trends).

A crude estimate of their lifetime,
Typical mean thickness/ thinning rate ~ 100/0.5 yrs
~ **200 yrs**

(large glaciers are thicker)

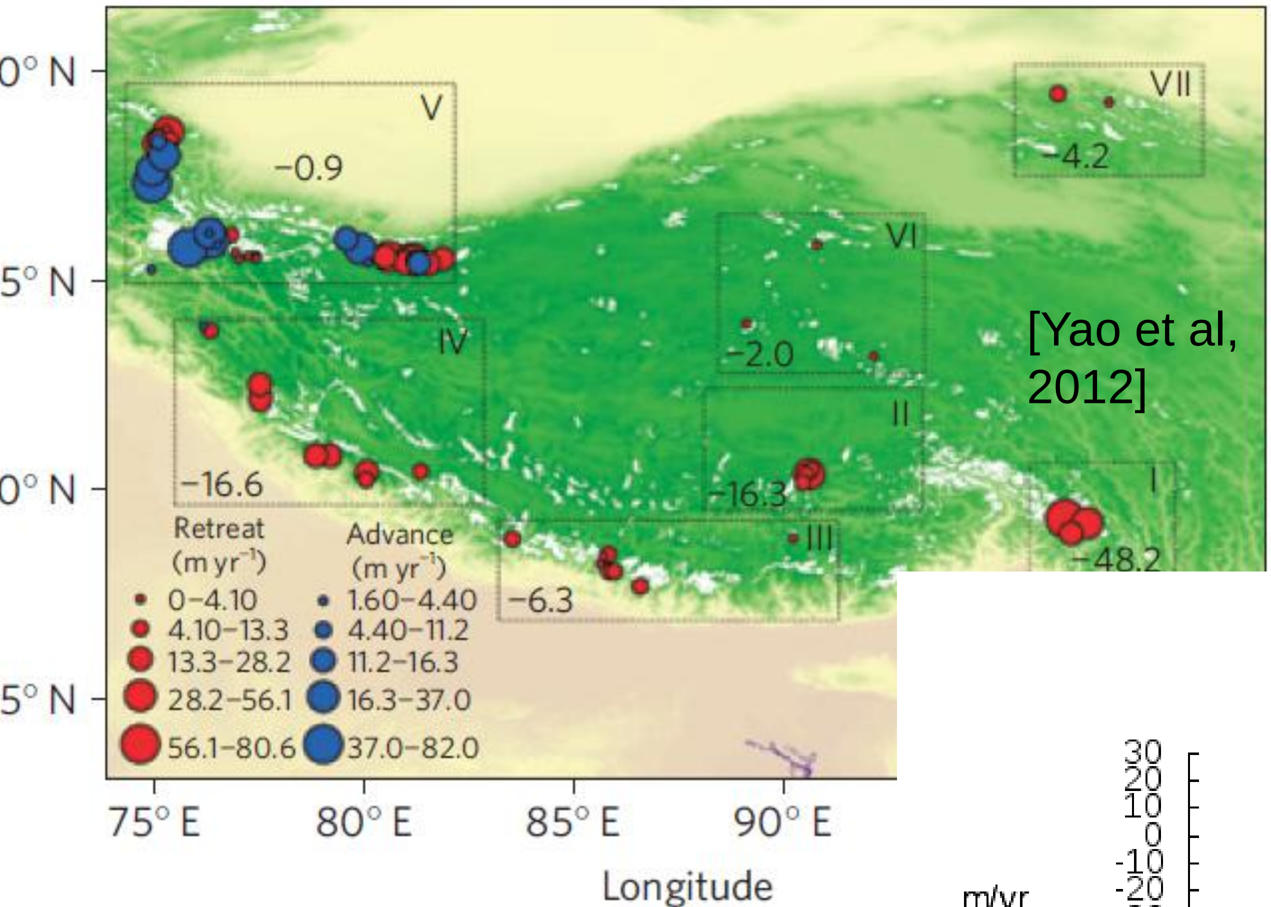
* Another estimate:

Present ELA in the Himalaya ~ **5000-5500m**
ELA is moving up (due to climatic change) with typical rates of **~10m/yr**

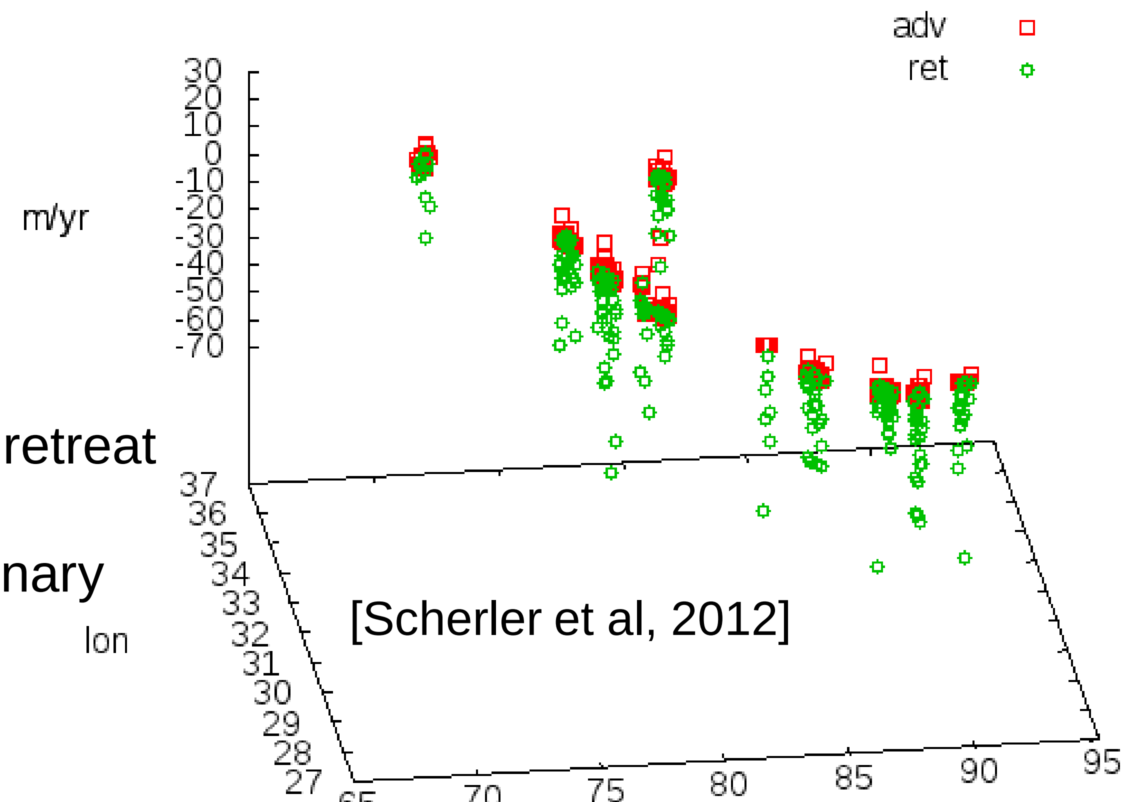
*Some accumulation area would be left for the next **few hundreds years** and the higher reaches would remain glacierised.
(available area at higher elevations decreases sharply)

(ice-thickness feedback, ice-albedo feedback, changing glacier area ...)

* Data on recent glacier fluctuations in the Himalaya



[Yao et al, 2012]



[Scherler et al, 2012]

Puzzle 1:

Wide ***variations*** in the retreat rates

(many advancing/stationary glaciers!)

Puzzle 2:

In the Himalayan data set,

- 128 debris covered (>10%) glaciers:

  52% retreating; **48%** advancing/stationary

- 61 relatively debris free (<10%) glaciers:

  82% retreating; **18%** stationary/advancing

[Scherler et al, 2012]

[Banerjee and Shankar, 2013]

But,

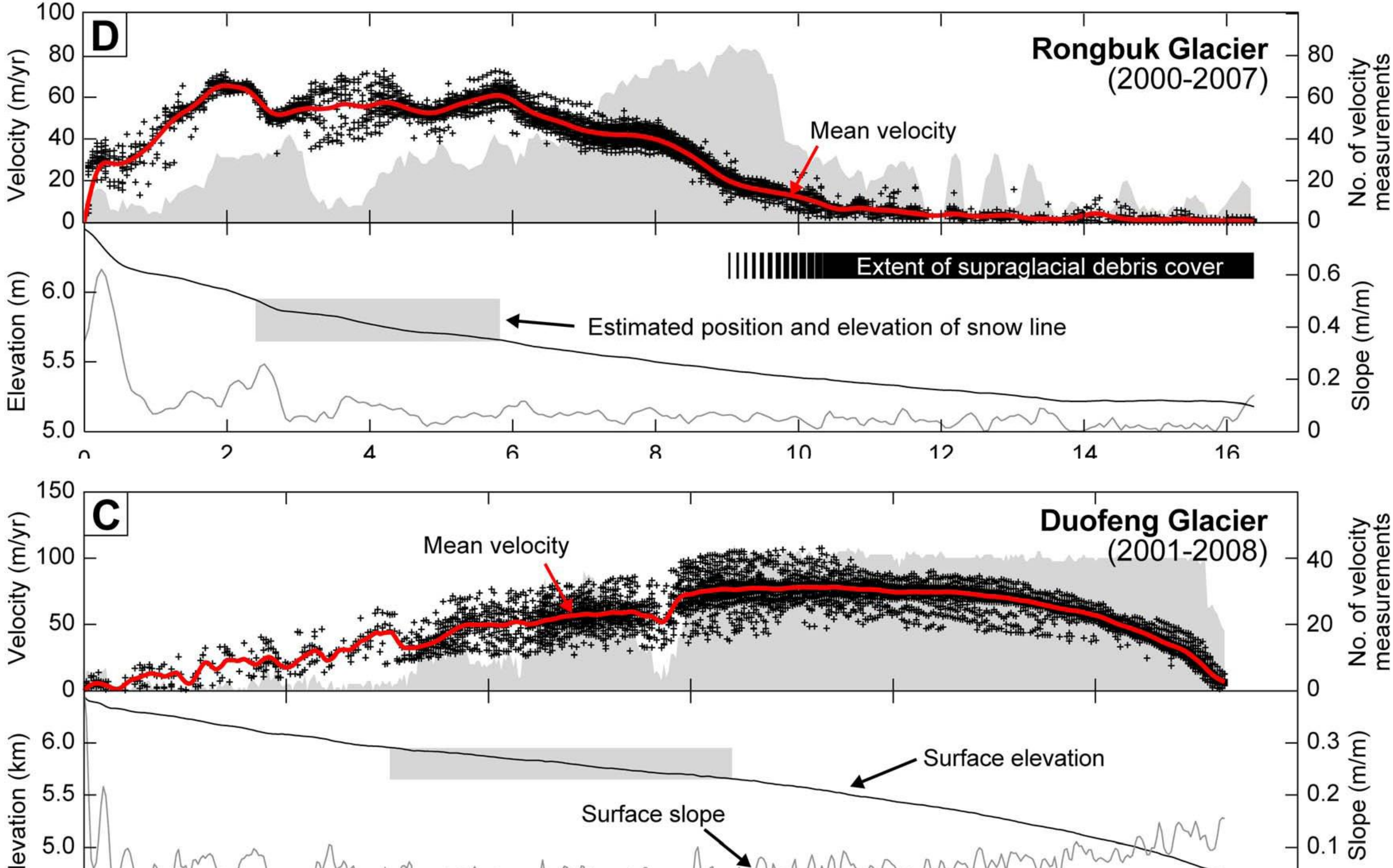
- Both must be seeing similar climate
- **Similar thinning** in clean and debris covered glaciers

[Gardelle et al 2012; Kaab et al 2012; Nuimura, 2012]

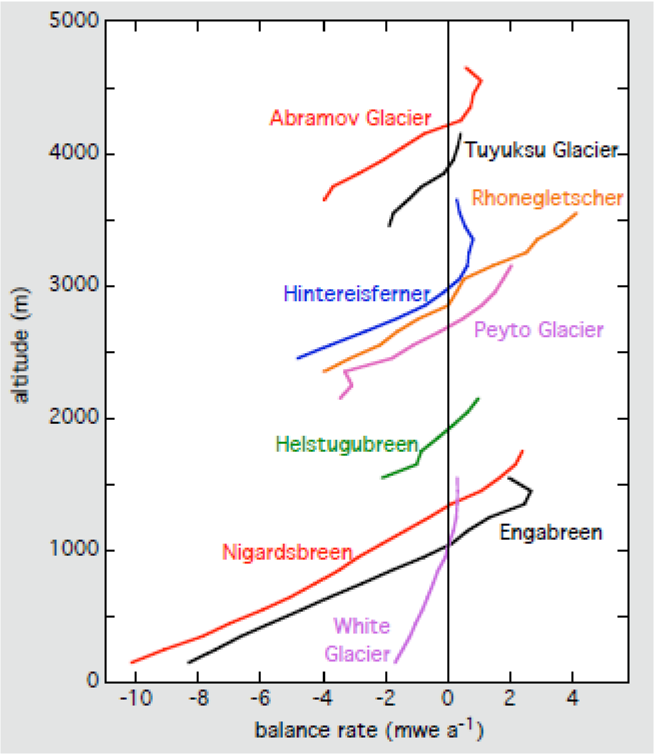
(*** Gardelle et el, 2013:: larger/similar/smaller thinning rates in debris covered glacier depending on region, in Pamir-Karamoram-Himalaya)

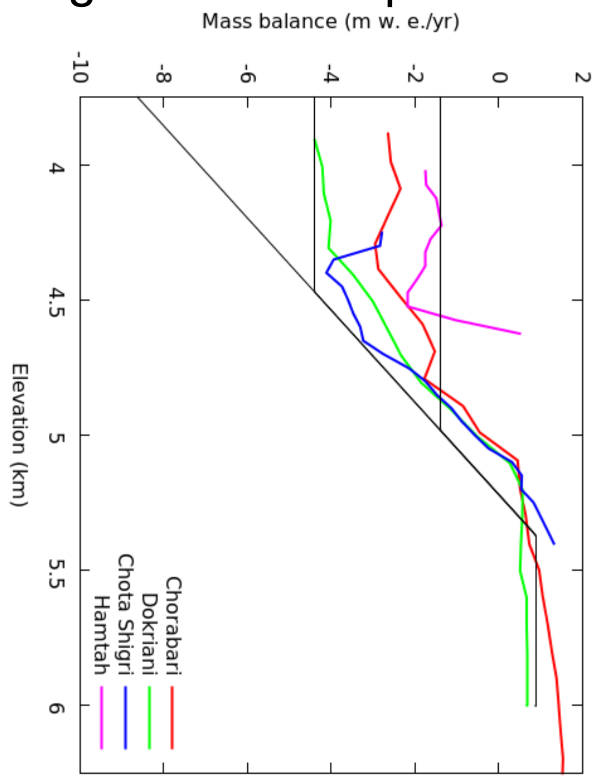
● **Puzzle 3:**

● Many extensively debris covered glaciers with a low veocity   (v<2.5m/yr) "***stagnant***" tongue and a ***steady*** front



* * A (simple) description of debris-covered glaciers is required

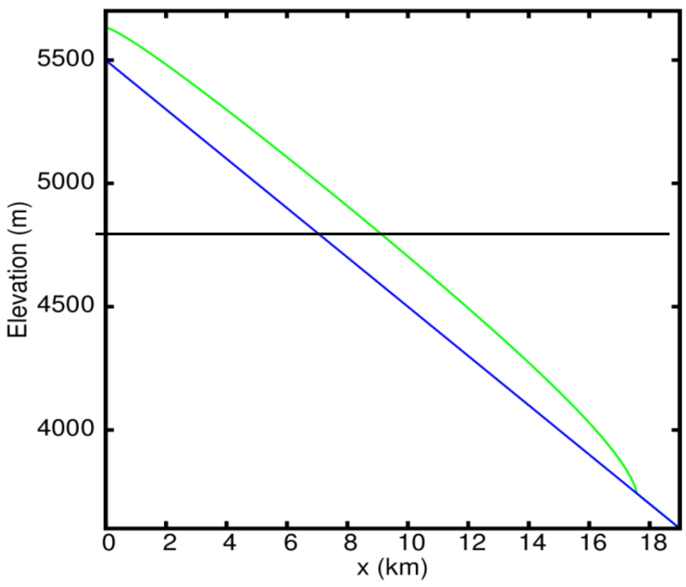




* 1d Flowline model of glaciers:

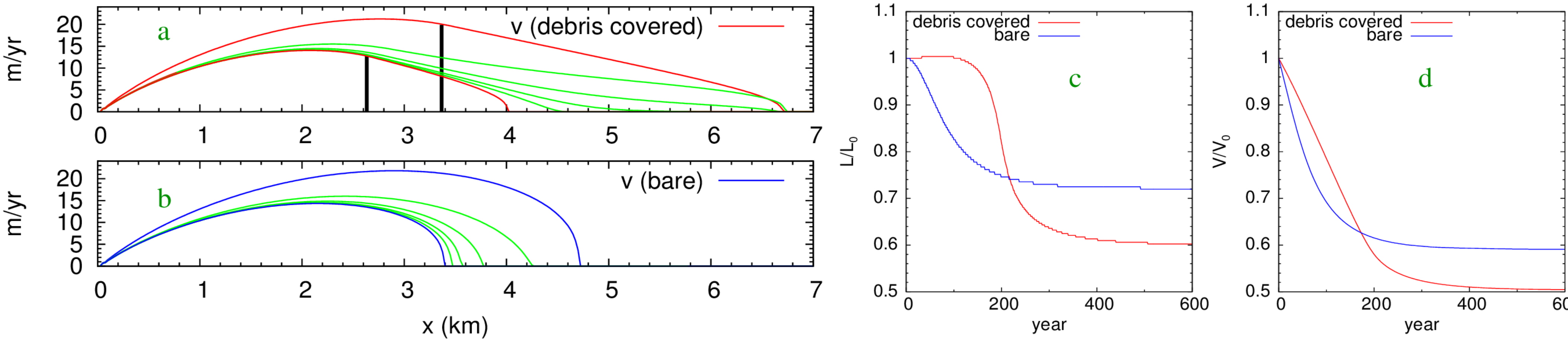
$$\partial_t H = -\partial_x(HU) + B$$
$$U = f_d(\rho g H \partial_x(H+z))^3 H + f_s(\rho g H \partial_x(H+z))^3 / H$$

H: ice thickness
U: flow velocity (function of H, slope)
B: mass balance function (two parameters: balance gradient, ELA)



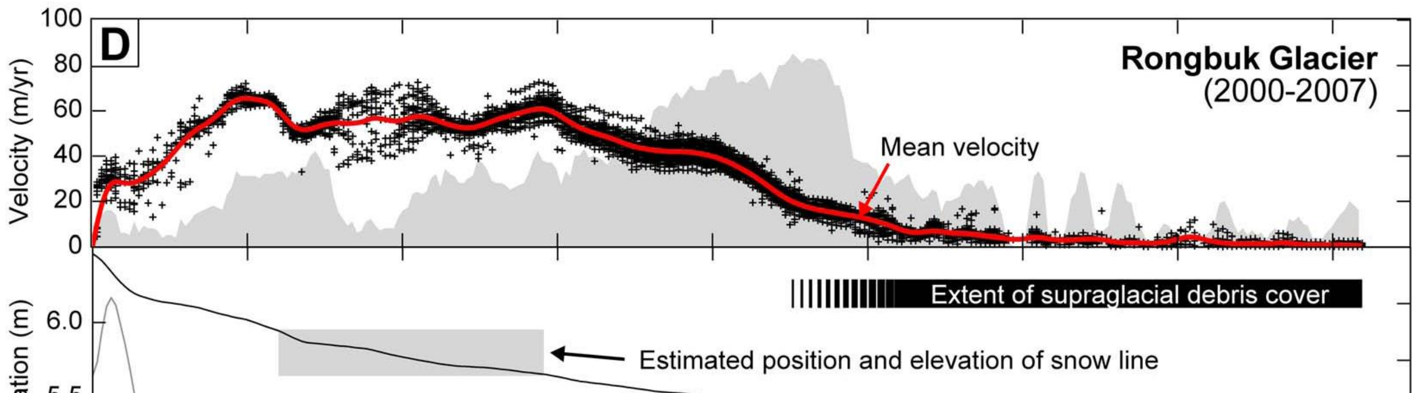
•Results:

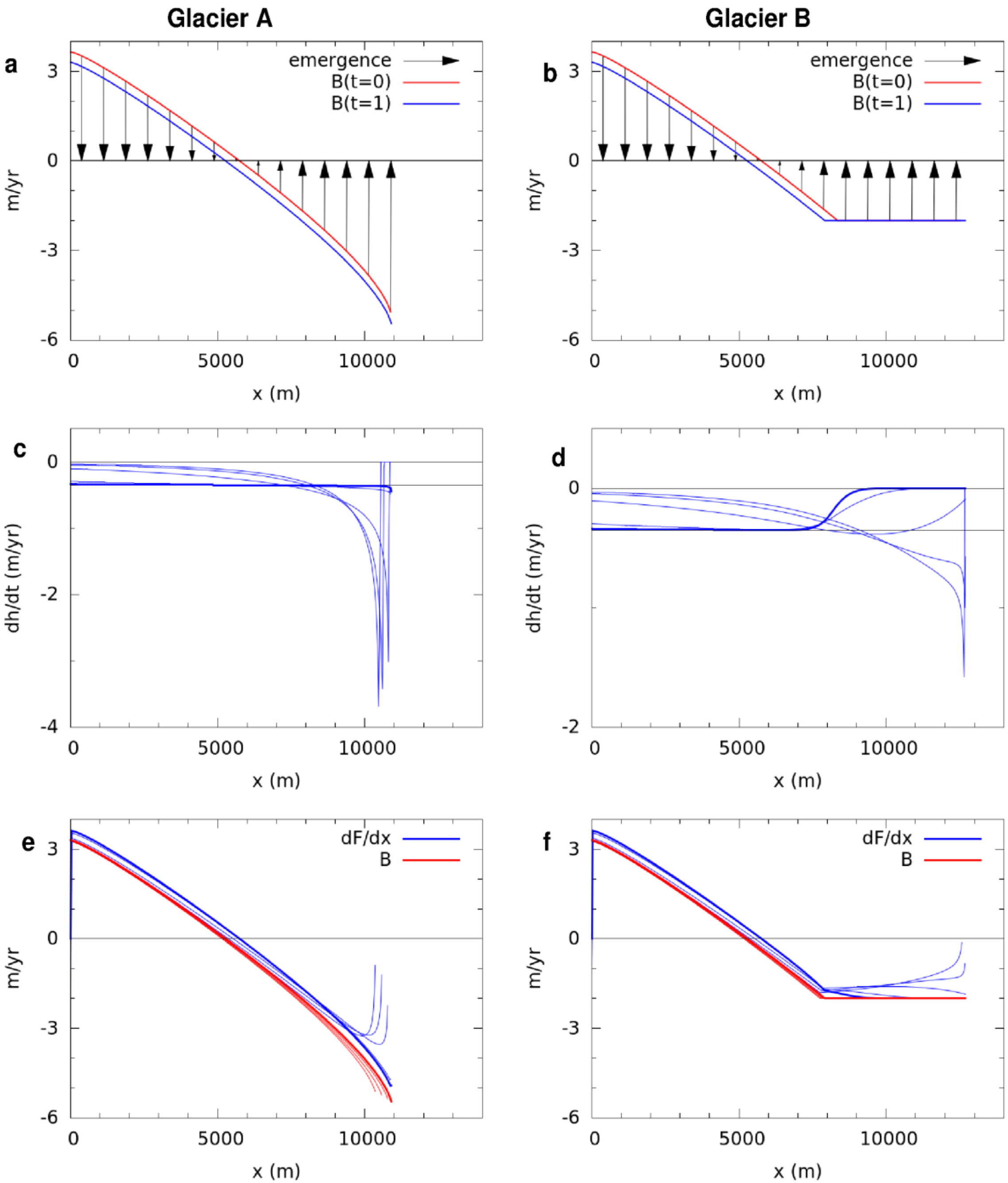
Banerjee and Shankar, 2013



- For debris covered glaciers, initial period of ***stagnation*** and ***thinning*** (*downwasting*), without any frontal retreat
- For clean glaciers, thinning and retreat are simultaneous
- Volume loss curves are similar

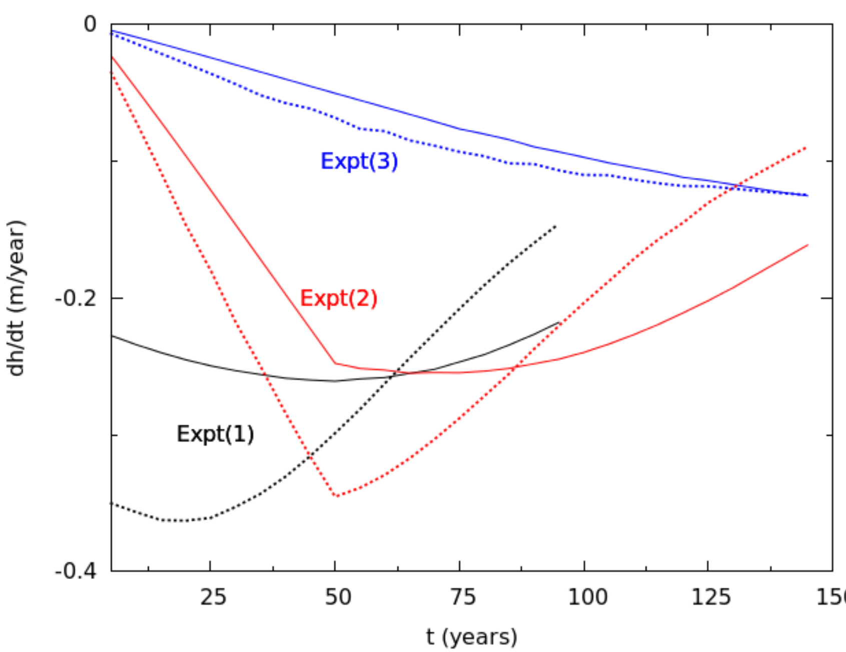
- **Puzzle 3** resolved!





$$\partial_t H = -\partial_x(HU) + B$$

* the steady state is balance btn emergence (submergence) and melting (accumulation)
After a warming event,
* initial volume loss controlled by mass-balance change
* velocities relaxes slowly
* subsequently, the evolution of flux changes controls thinning



[Banerjee, 2016*]

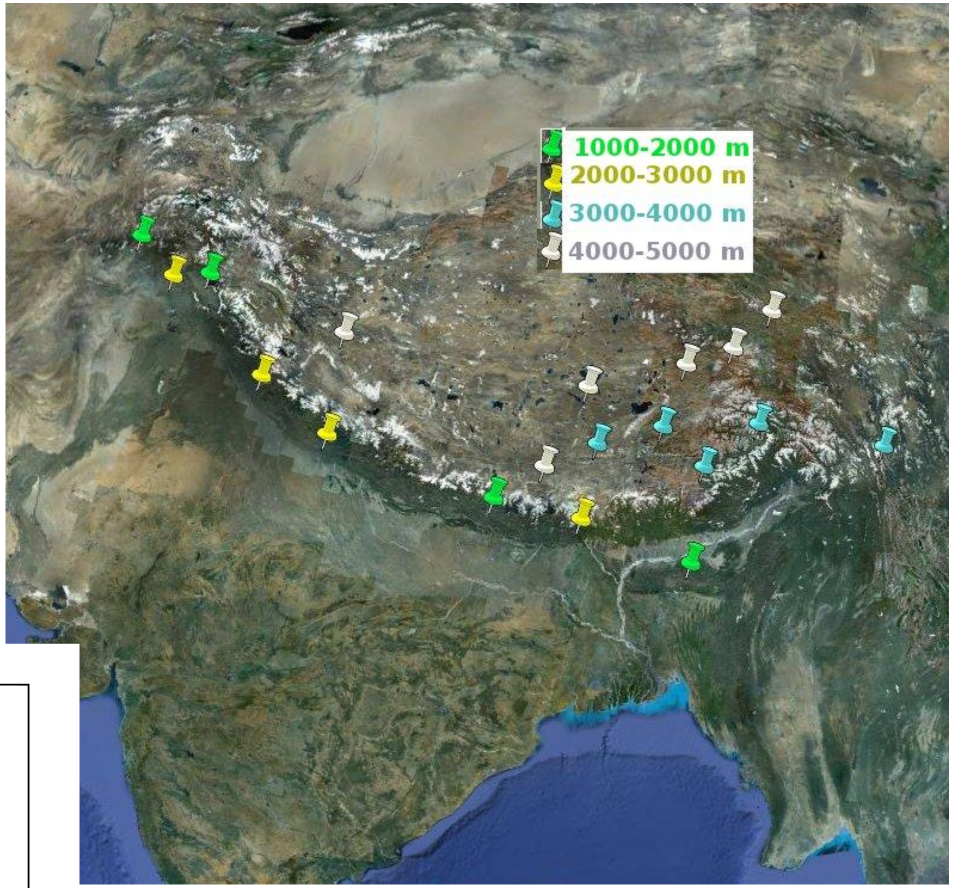
- Resolution of **Puzzle 2**:
  - Some of the debris covered glaciers showing small or no retreat, are losing ice by thinning (downwasting).
- Assume all debris covered glaciers with > 5% stagnant area (v<2.5m/yr) are shrinking,
  - The percentage of shrinking debris covered glaciers is up from ***52%*** to ***73%***.
    - ***(73 + 27 = 100; 82 +18 = 100)***

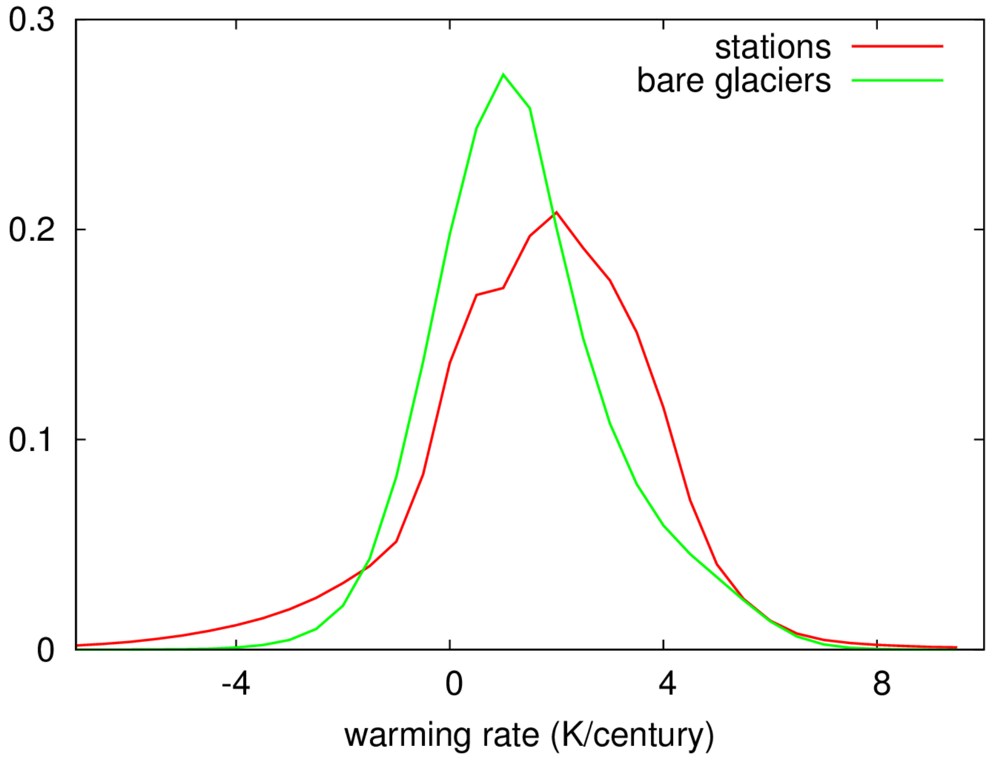
Retreat rate distribution for clean glaciers => warming rate distribution

1.4 (1.7) K/century

consistent with available weather station data
(GHCNM, 19 stations)

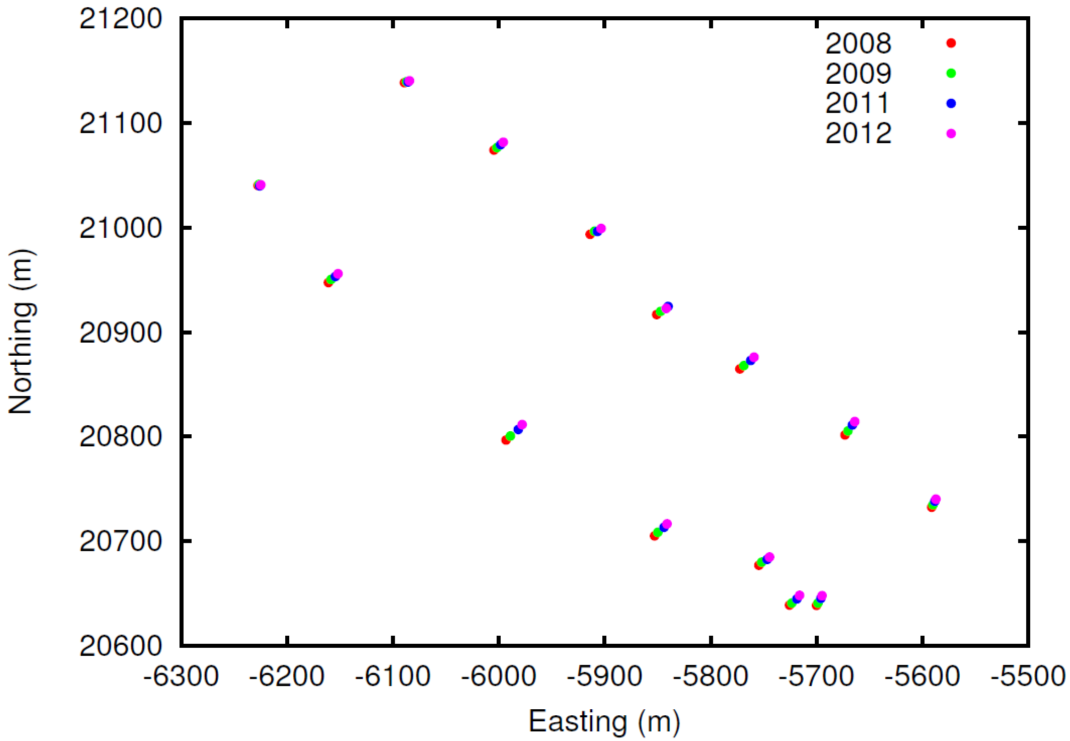
1.6 (2.2) K/century





□ (**Puzzle 1** solved)

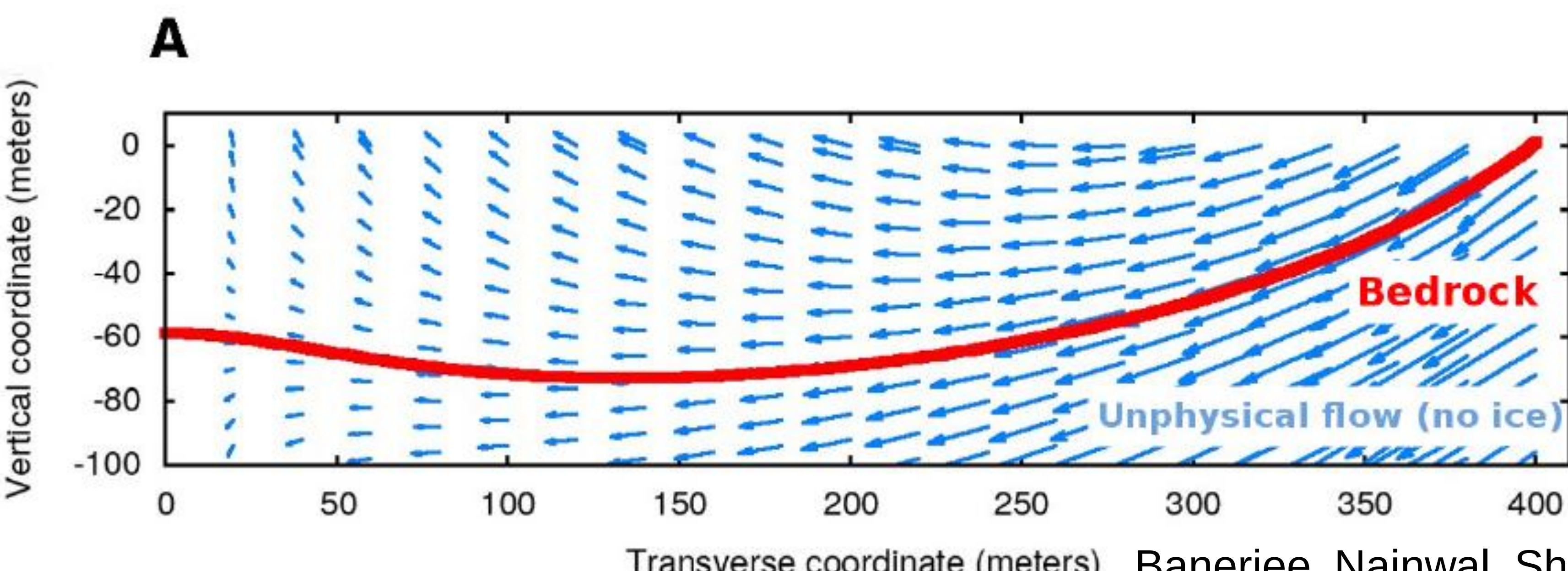
Thank You.



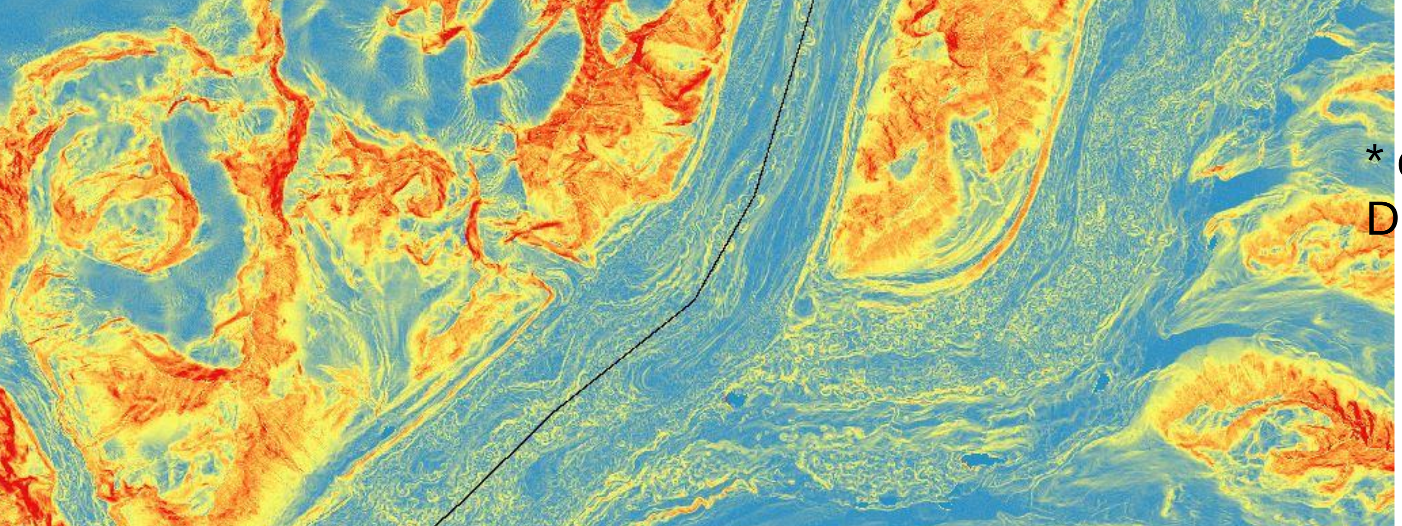
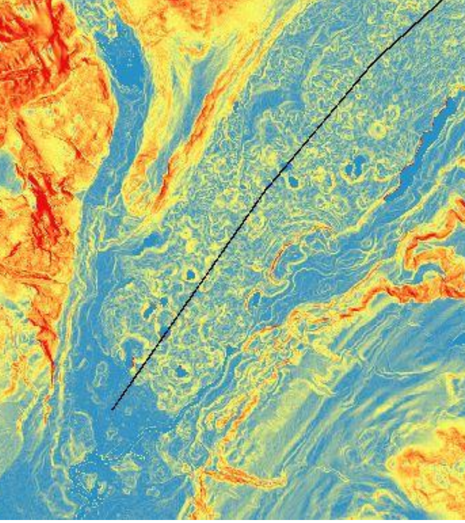
Inversion of surface velocities

$$\partial_j \sigma_{ij} + \rho\, g_i = 0$$

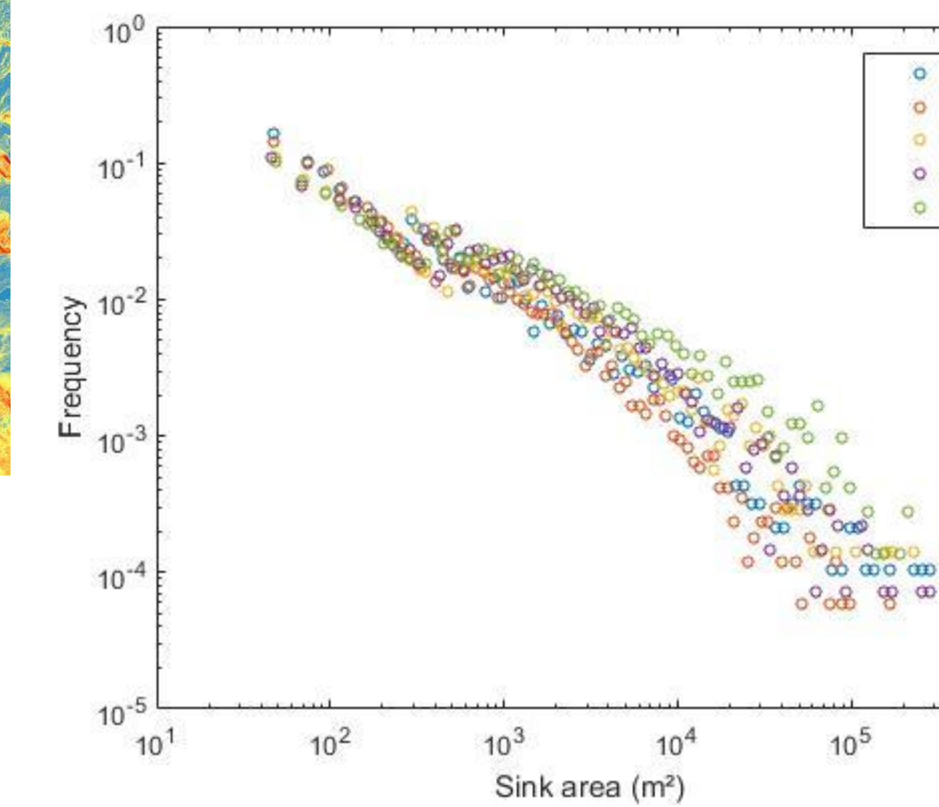
$$\frac{1}{2}\left(\partial_i v_j + \partial_j v_i\right) = A s^2 s_{ij}$$

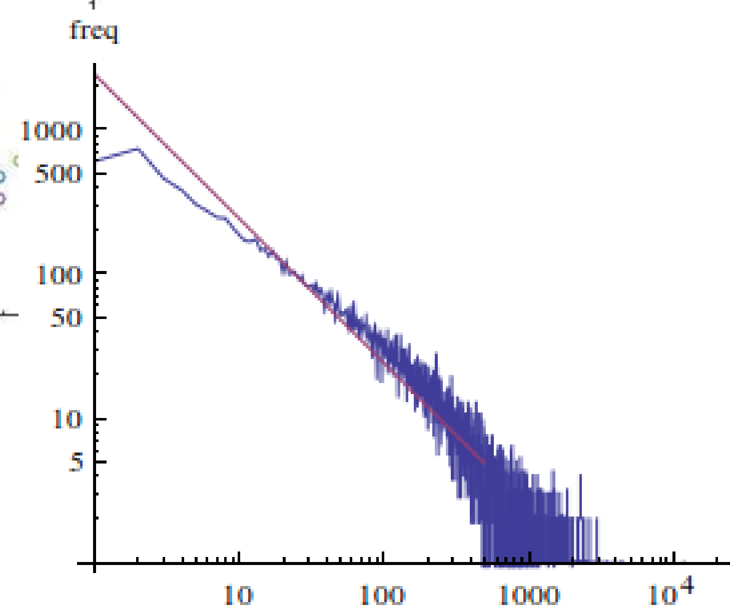


Banerjee, Nainwal, Shankar, ... (201*)

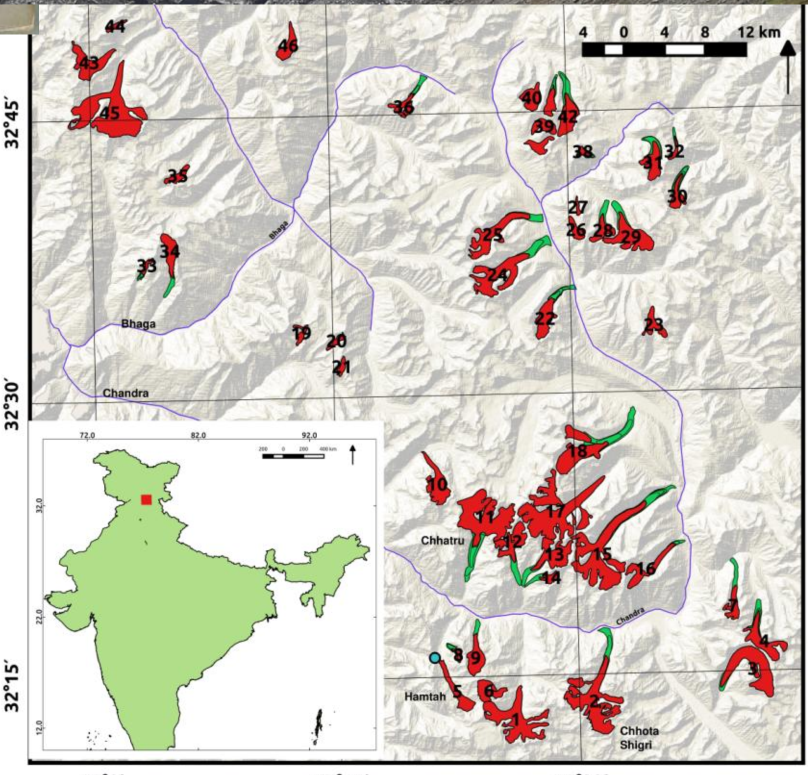



* evolution of surface topography in
Debris covered glaciers





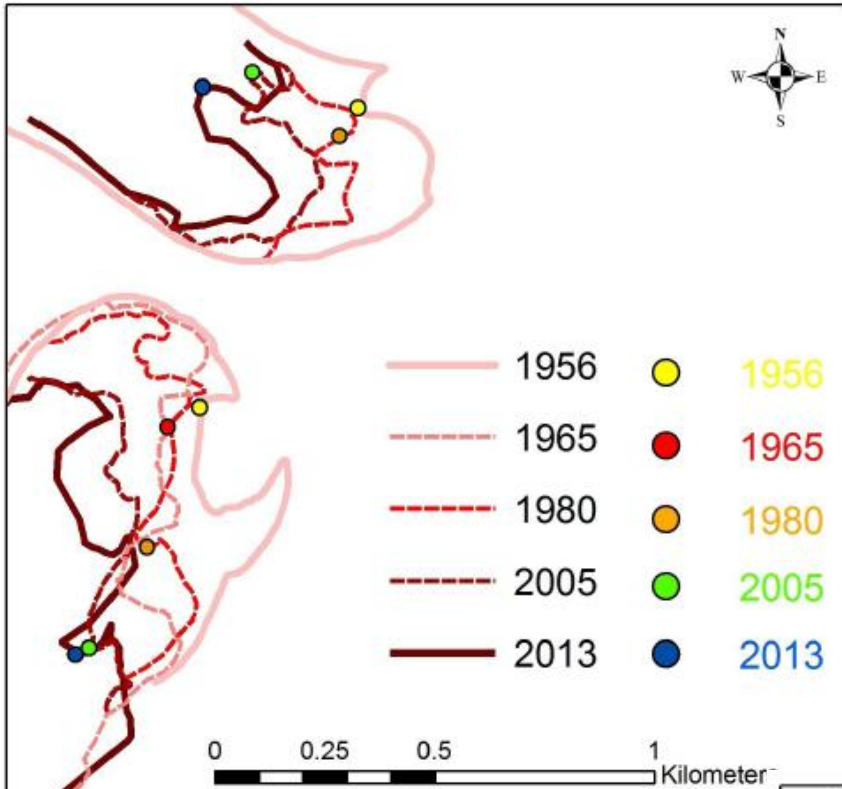
Anderson, Scherler, Banerjee

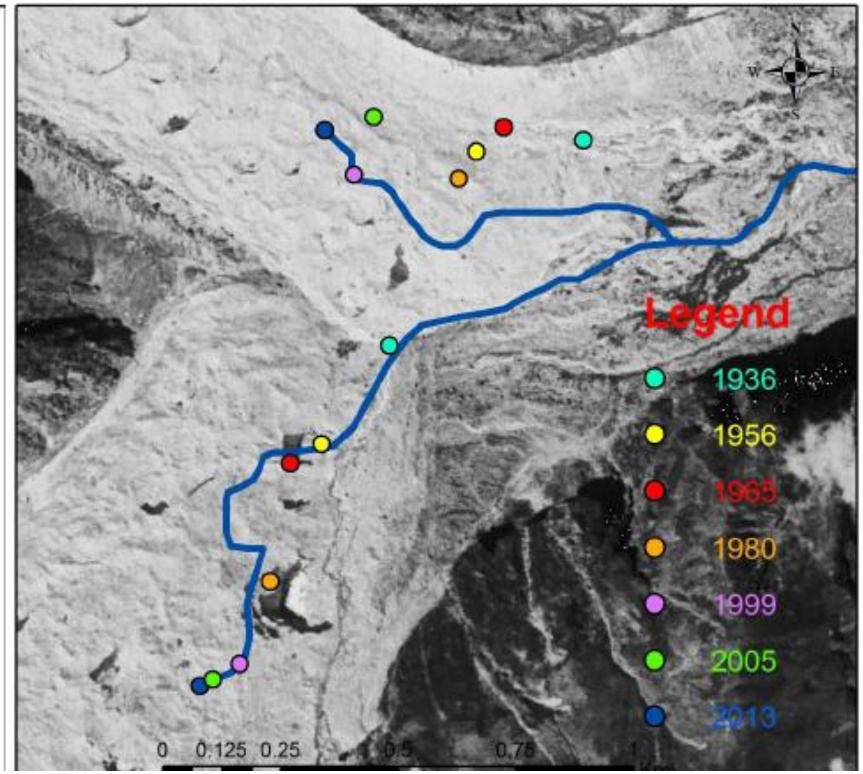


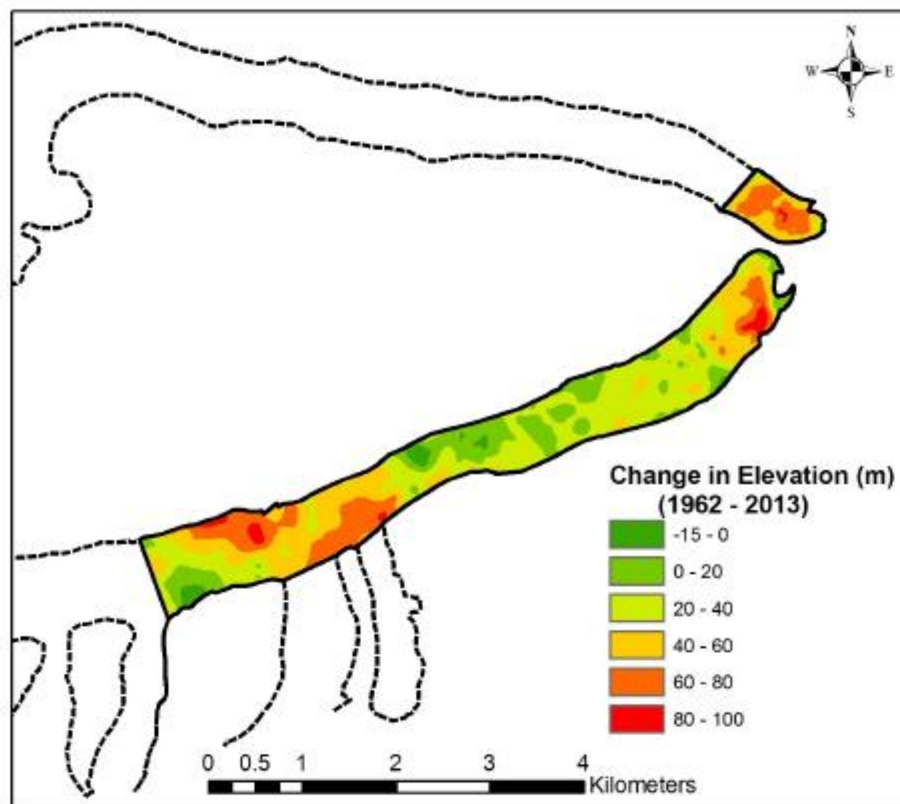
*Century-scale glacier fluctuaion in Lahaul
[Reshma]

* Debris-ice coupled flowline model
[Nikhil]

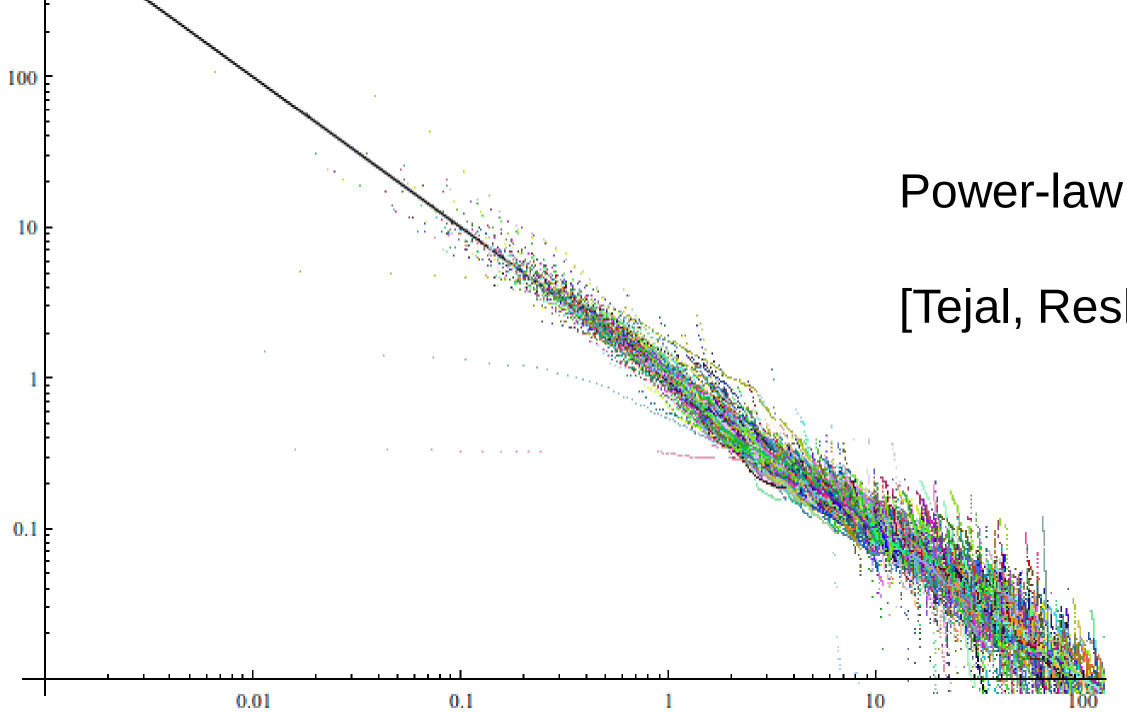
* Avalanche contribution in Hamtah
[Banerjee, Shankar, 2014]







[Nainwal, Banerjee and others, 2015]



Power-law profiles in great escarpment foothills

[Tejal, Reshma, Nishant, Sourav]