Unraveling the cascading mechanisms of rock-ice avalanche triggering hyper-mobility glacial debris flow in southeast Tibet

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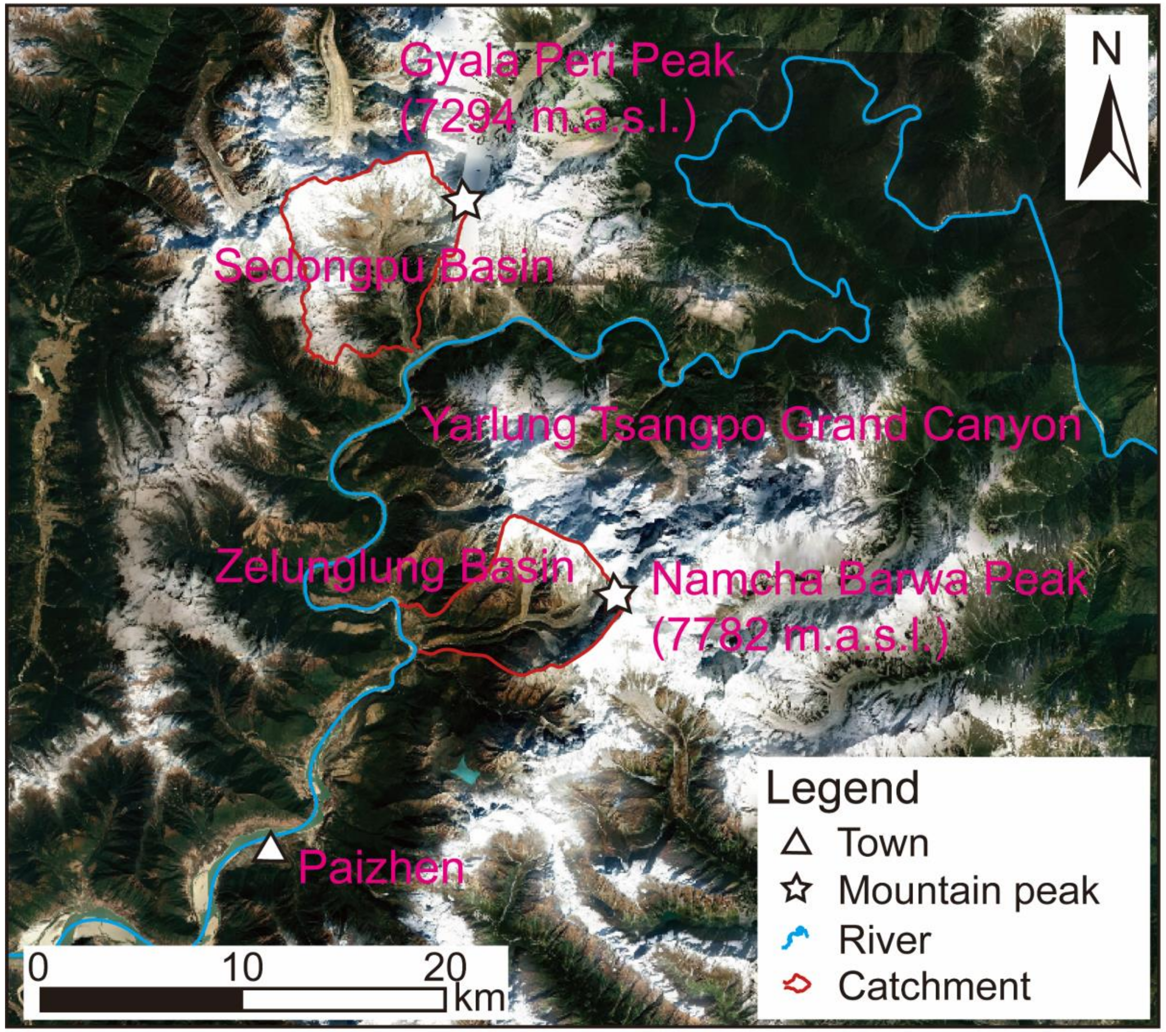
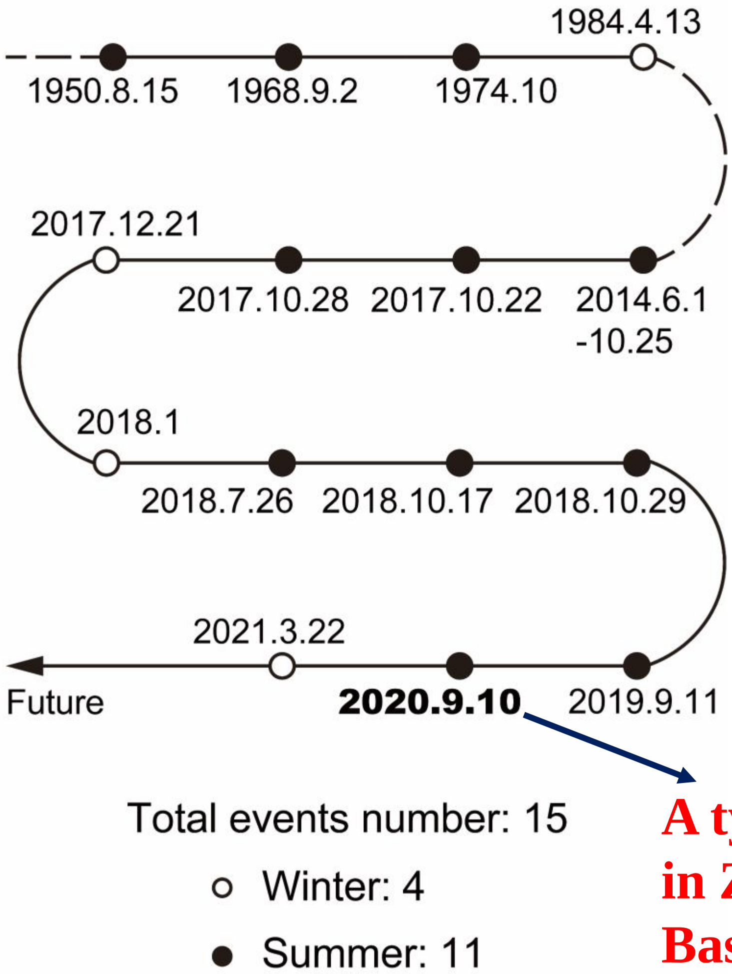
Events in two typical catchments in Yarlung Tsangpo Grand Canyon

Occurrence: more frequent since 2014, <u>**more in warm season (Apr-Oct)**</u>



Two basins prone to debris flow in southeast Tibet

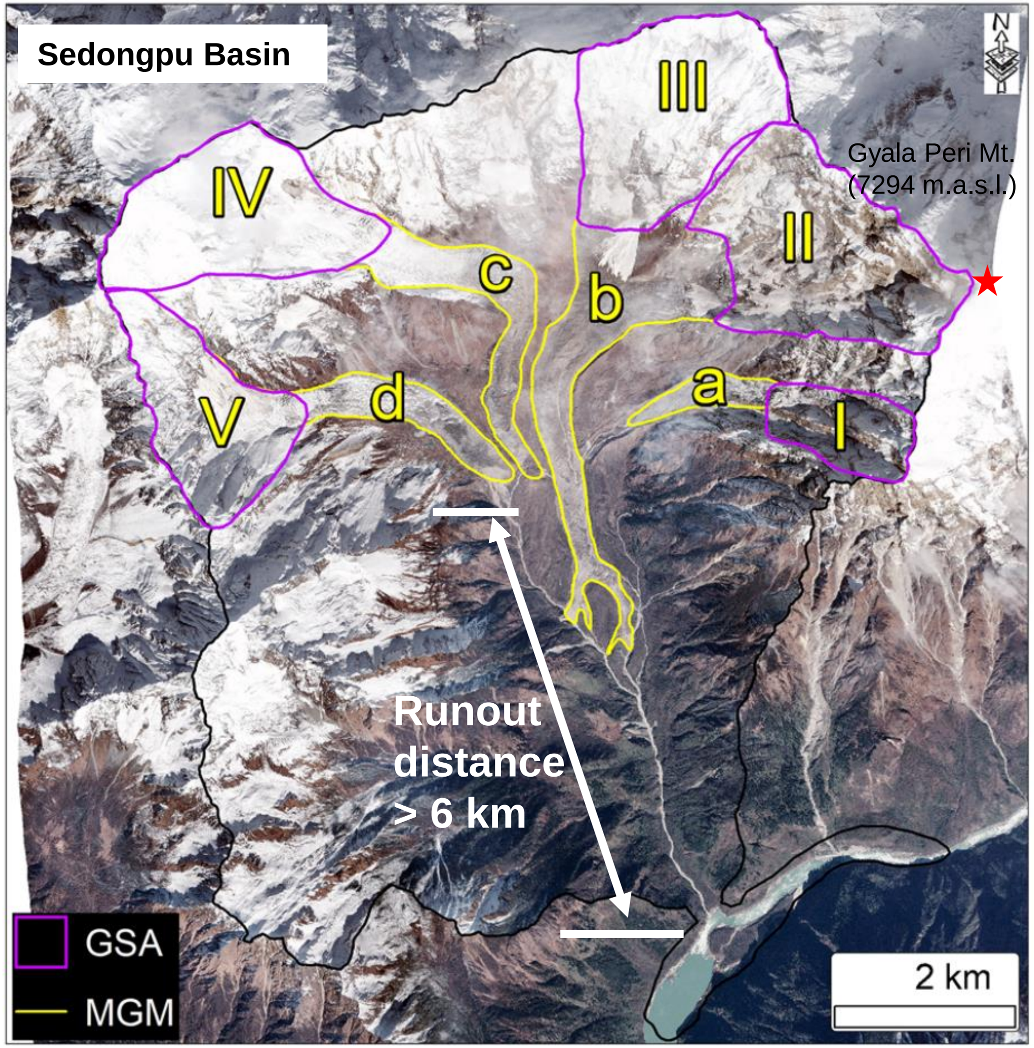


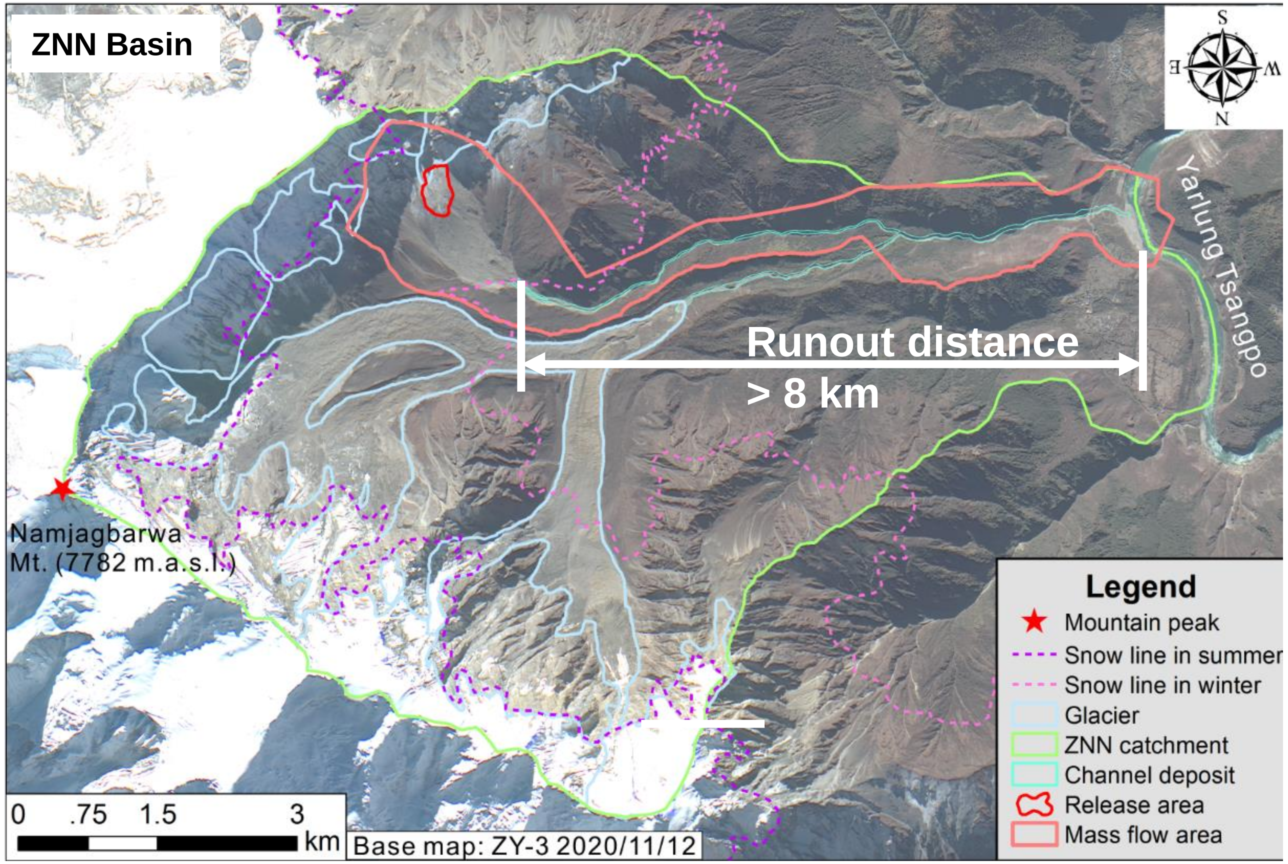
Events timeline

A typical event in ZNN(ZLL) Basin

Events in two typical catchments in Yarlung Tsangpo Grand Canyon

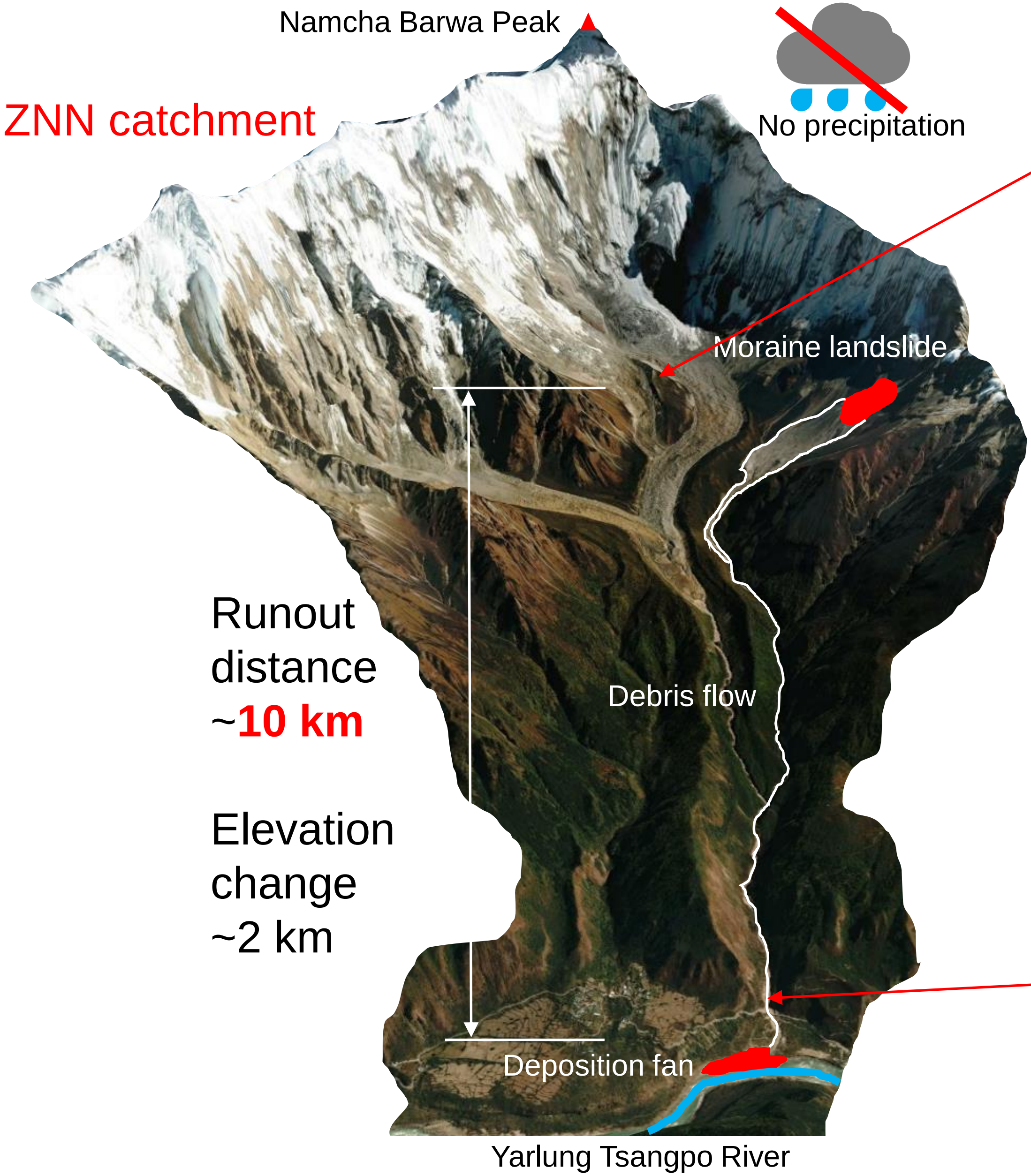
Consequence: **high mobility** to more frequently block the Yarlung Zangbo River

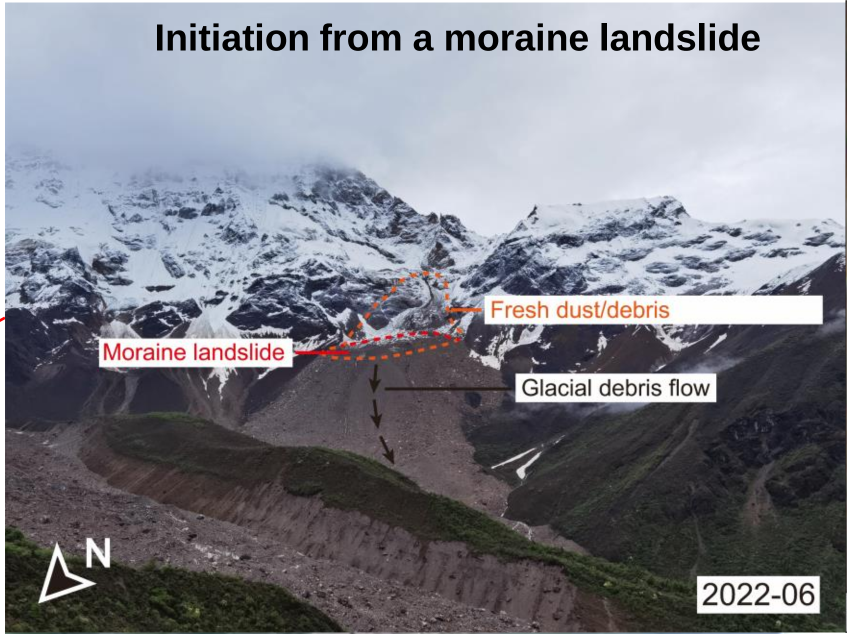


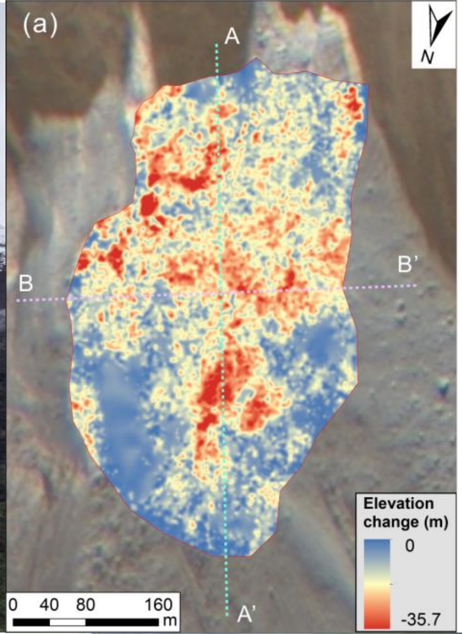


Li et al., 2021. More frequent glacier-rock avalanches in Sedongpu gully are blocking the Yarlung Zangbo River in eastern Tibet. Landslides.
Peng et al., 2022. Initiation mechanisms and dynamics of a debris flow originated from debris-ice mixture slope failure in southeast Tibet, China. Engineering Geology

ZNN debris flow in 2020







V

1.14

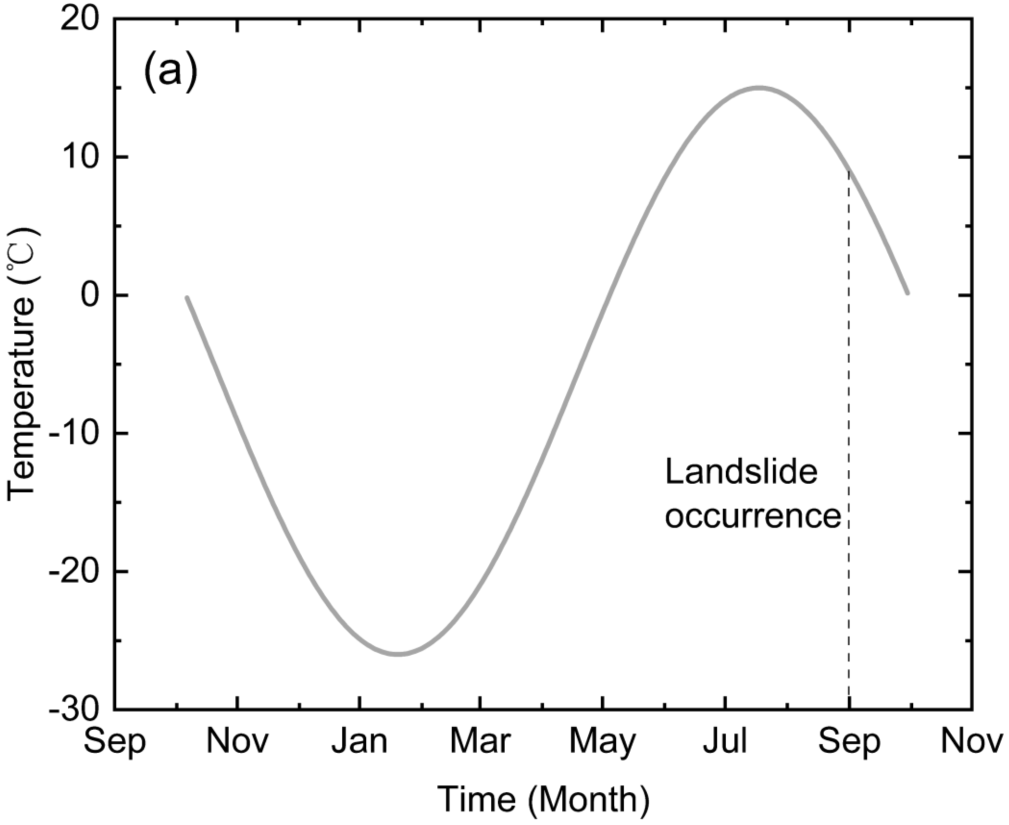
Mm^3

Dep

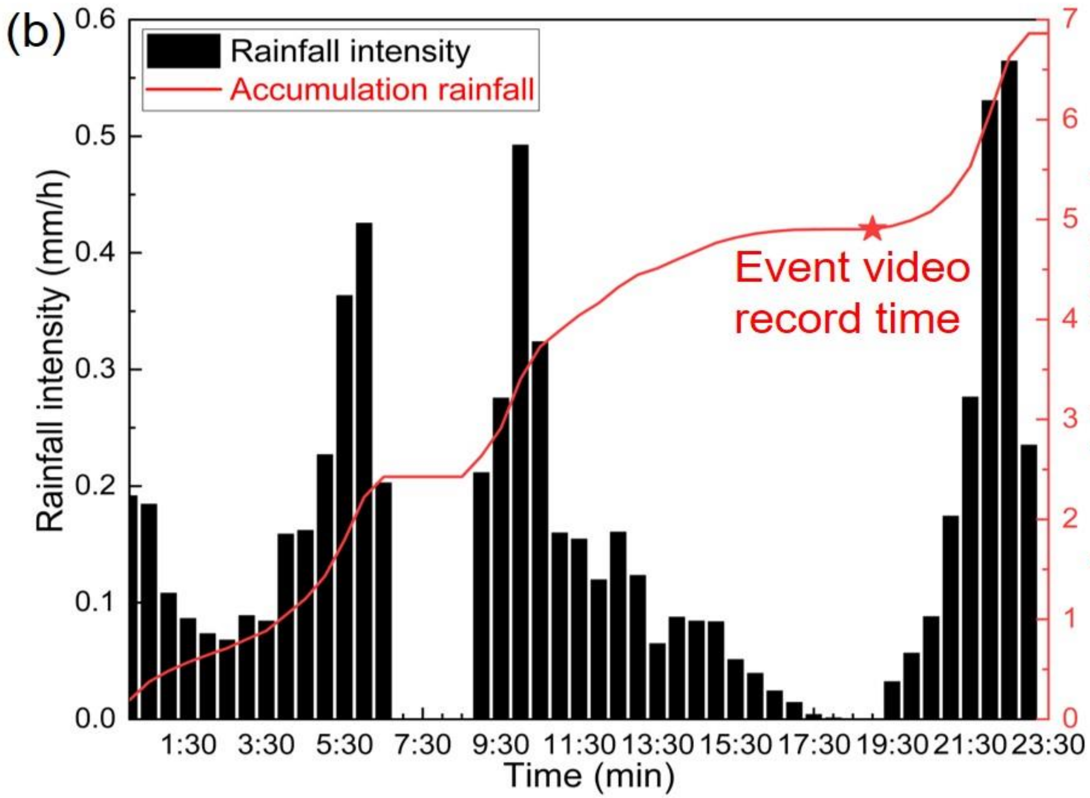
36 m

~9 m

Meteorological conditions



Air temperature
Sources: ERA5

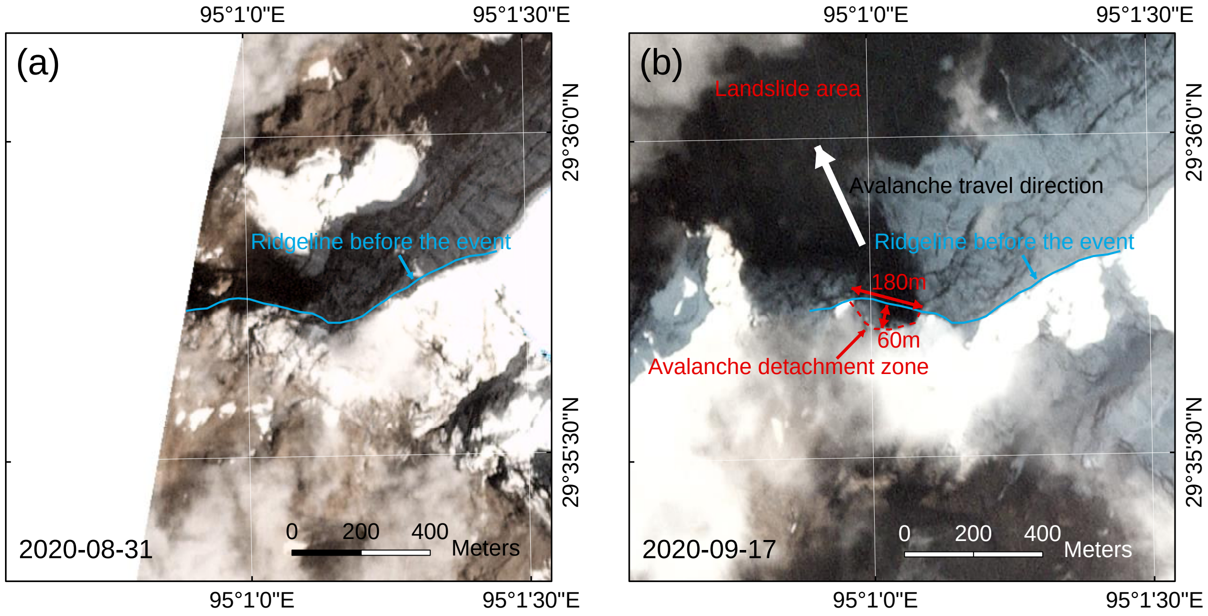


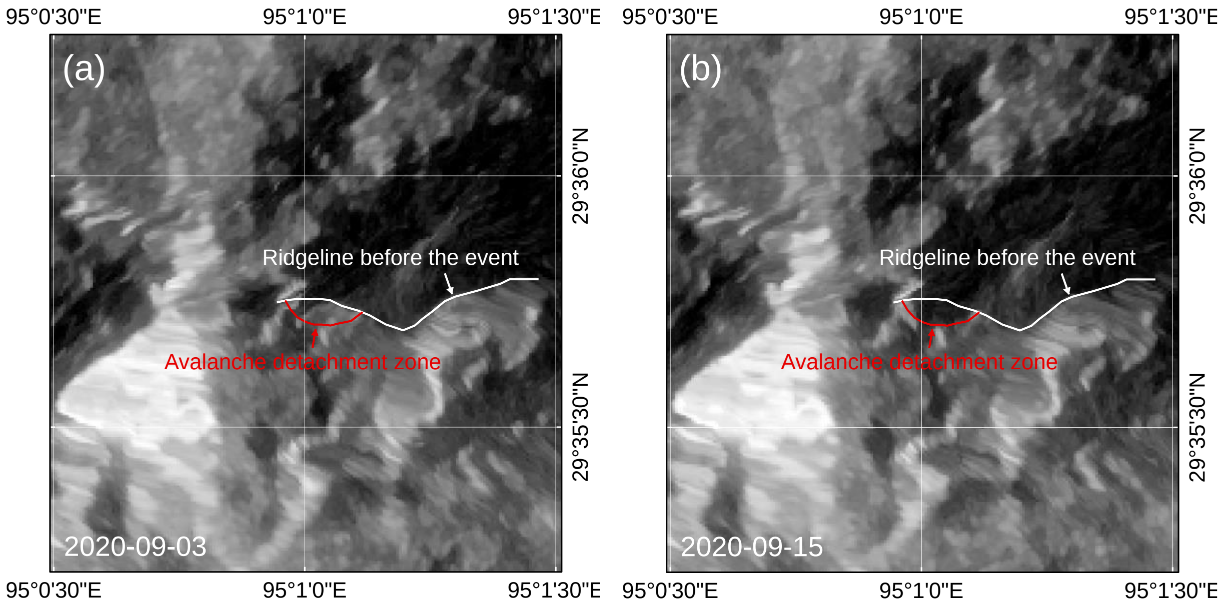
Precipitation
Sources: Rain gauge near Zhibai village and ERA5

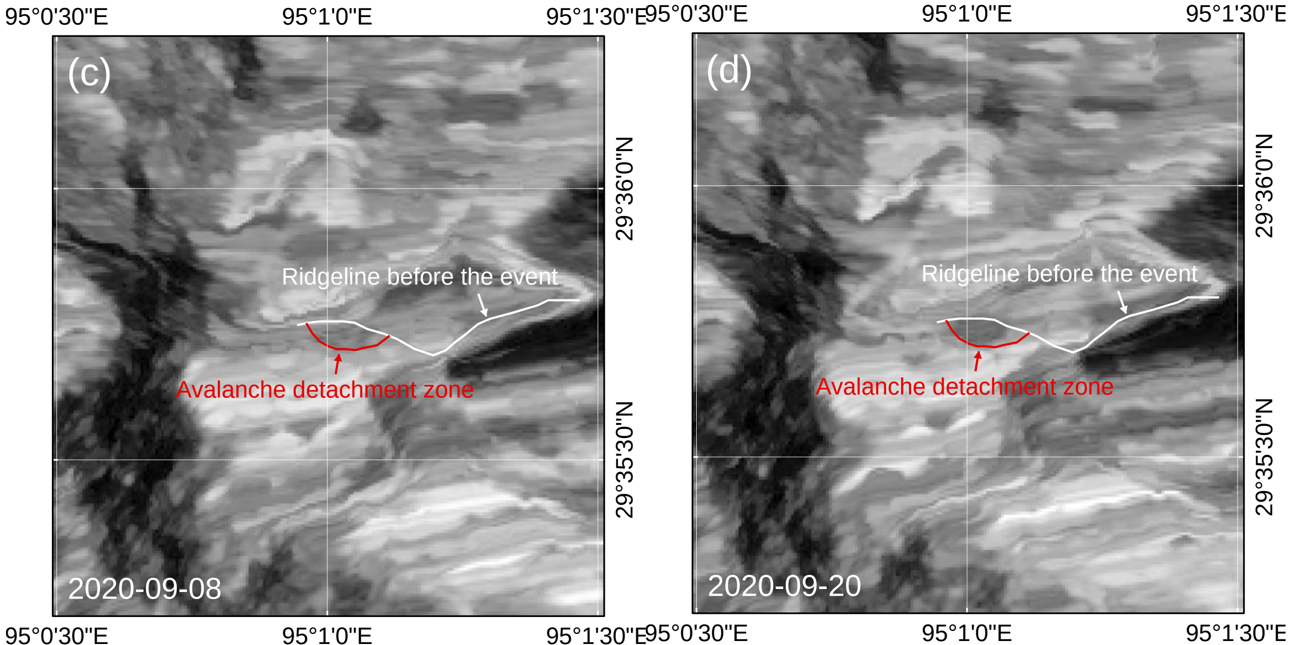
Cascading event under a **warm** and **little precipitation** condition

Q: Initiation and cascading mechanism?

Hazard chain: Rock-ice avalanche->Moraine landslide->glacier debris flow

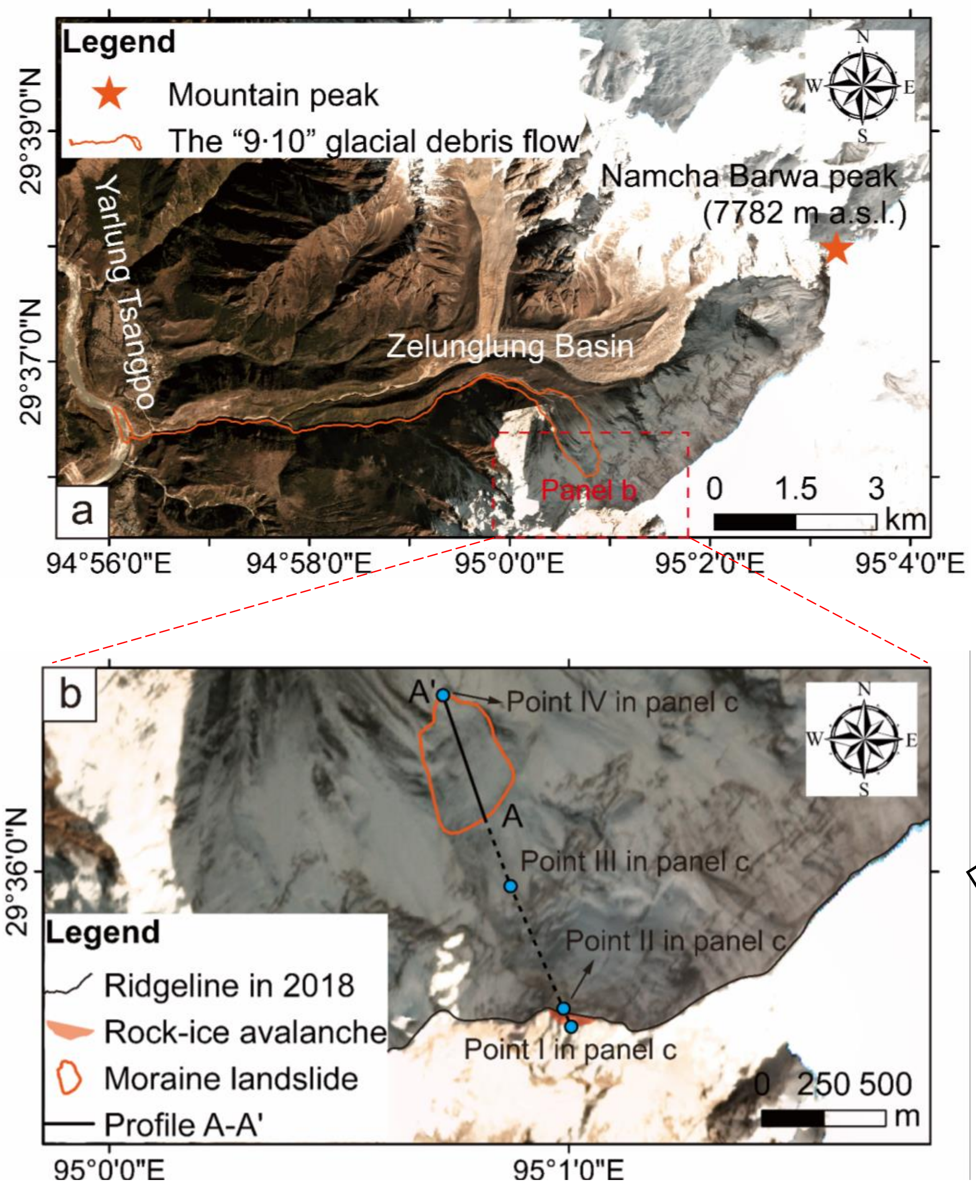


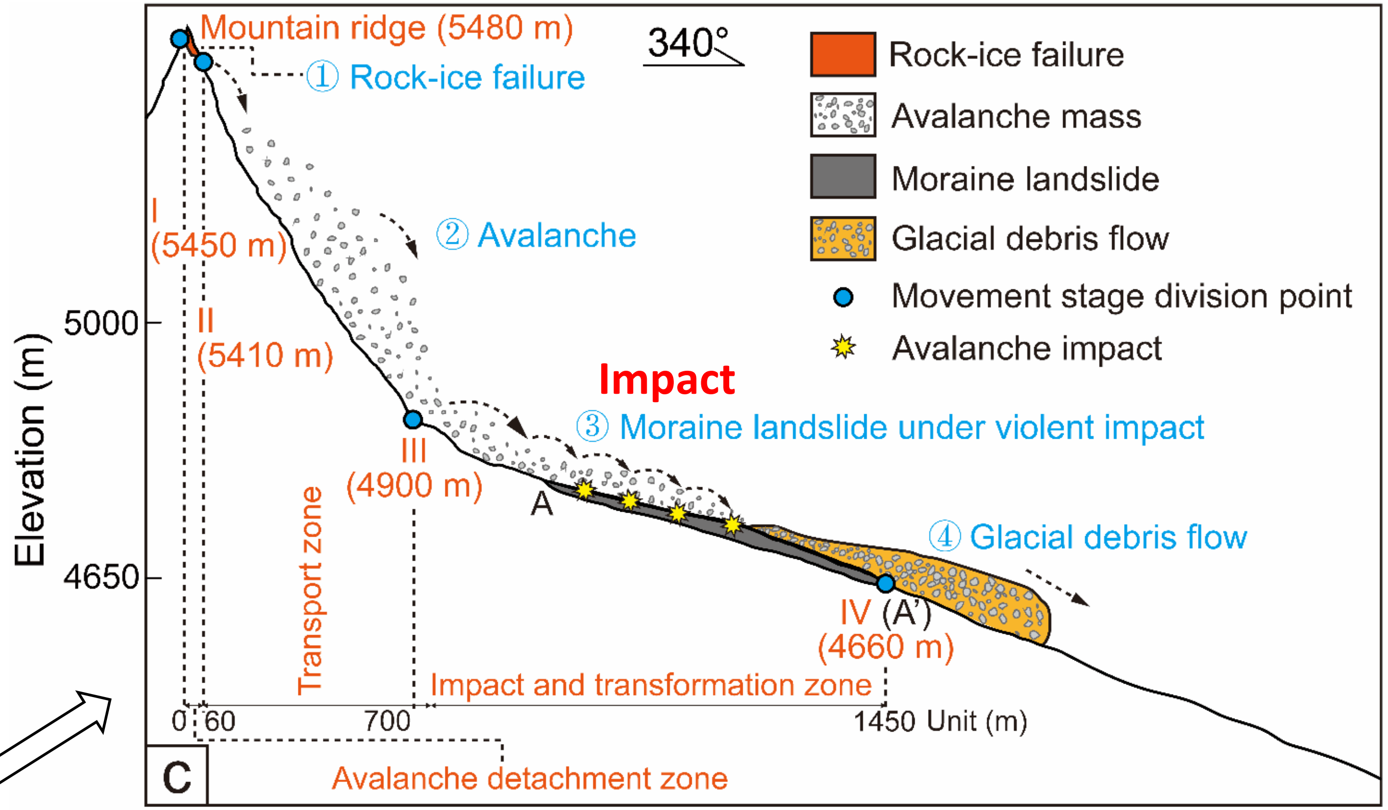




- ✓ Approximately 0.5-Mm^3 rock-ice avalanche on the ridge above the landslide area
- ✓ The avalanche was confined between 2020-09-08 and 2020-09-15, contemporary with the chain event
- ✓ Hypothesis: A **small** rock-ice avalanche triggered the hazard chain

Cascading chain: Rock-ice avalanche->Moraine landslide->glacier debris flow



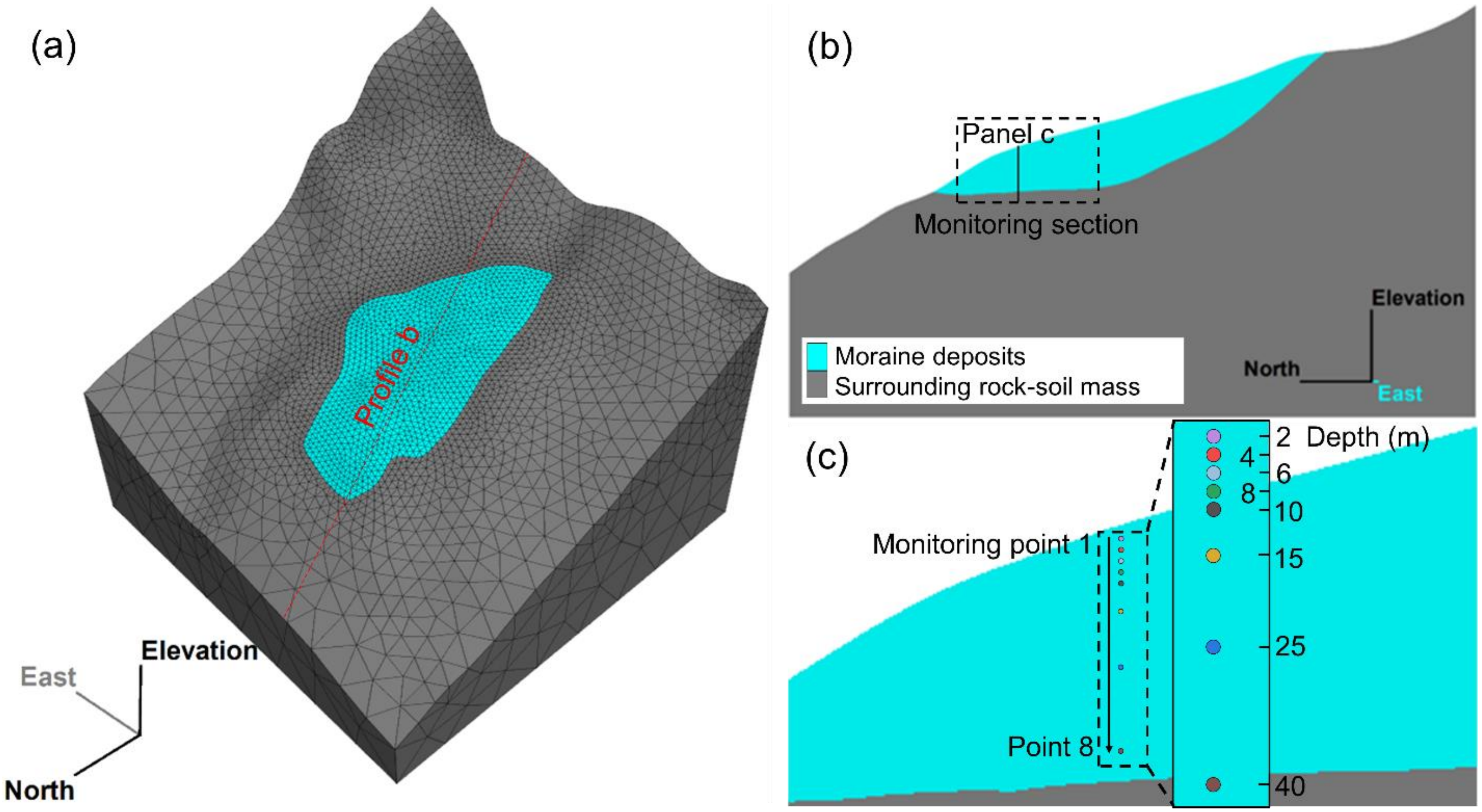


Hypothetical cascading process of the hazard chain

To be studied by multi-phase modelling

Multi-physics 3D modelling framework – FLAC3D

3D Thermal-Hydro-Mechanical (THM) coupling model



(1) Momentum balance equation

$$\nabla\cdot\boldsymbol{\sigma} + \rho\mathbf{g} = 0$$

$$\rho = nS_r[(1-u_i)\rho_w + u_i\rho_i] + (1-n)\rho_s$$

(2) Fluid mass balance equation

$$\frac{\partial P}{\partial t} = M\left(-\nabla\cdot\mathbf{q}_w - \alpha\frac{\partial \epsilon}{\partial t} + \beta\frac{\partial T}{\partial t}\right)$$

(3) Fluid transport equation

$$\mathbf{q}_w = -\mathbf{k}\nabla(P - \rho_w g)$$

$$\rho_w = \rho_0[1 - \beta_f(T - T_0)]$$

(4) Energy balance and heat transport equation

$$C^T = nS_r[(1-u_i)\rho_w C_w + u_i\rho_i C_i] + (1-n)\rho_s C_s$$

$$\mathbf{q}^T = -k^T\nabla T$$

$$k^T = (1-n)k_s^T + nS_r k_w^T$$

(5) THM coupling

$$\frac{\partial\sigma_{ij}}{\partial t} + \alpha\frac{\partial P}{\partial t}\delta_{ij} = 2G\left(\frac{\partial \epsilon_{ij}}{\partial t} - \alpha_t\frac{\partial T}{\partial t}\delta_{ij}\right) + \left(K - \frac{2}{3}G\right)\cdot\left(\frac{\partial \epsilon_{kk}}{\partial t} - 3\alpha_t\frac{\partial T}{\partial t}\right)\delta_{ij}$$

(6) Energy conservation equation with the water-ice phase transition

$$C^T\frac{\partial T}{\partial t} + \nabla\cdot\boldsymbol{q}^T + \rho_w C_w \mathbf{q}_w\cdot\nabla T + L\rho_i n S_r\frac{\partial u_i}{\partial t} + q_v^T = 0$$

Multi-physics 3D modelling framework

Table S2. Initial thermal-hydraulic parameters.

Materials		Specific heat Cv/ (J·kg^{-1}·°C^{-1})	Thermal conductivity coefficient K/(W·m^{-1}·°C^{-1})	Fluid mobility coefficient k/(m^2·Pa^{-1}·s^{-1})	Thermal expansion coefficient β/(°C^{-1})
Moraine deposits	Above the ice point	1203	1.69	1.0e-12	4.3e-6
	Below the ice point	987	2.11	1.0e-14	−2.0e-5
Surrounding rock-soil mass	Above the ice point	816	2.7	1.0e-15	3.0e-6
	Below the ice point	816	2.7	1.0e-18	−1.5e-5
Water-ice	Above the ice point	4190	0.52	/	2.1e-4
	Below the ice point	1880	2.21	/	−1.5e-3

Table S3. Initial physical and mechanical parameters.

Materials	Density ρ/(Kg/m^3)	Internal friction angle Φ/ (°)	Internal cohesion C/(kPa)	Elastic modulus E/(MPa)	Poisson's ratio
Moraine deposits	2000	35	37	10	0.35
Surrounding rock-soil mass	2650	50	1500	20000	0.25

Table S4. Parameters for impact force calculation.

Density ρ/(Kg/m^3)	Impact velocity v/(m/s)	Normal recovery coefficient e_n	Slope inclination of buffer layer (°)	Thickness of the buffer layer (m)
2650	25	0.3	20	5

$$A = a \cdot \pi \frac{D^2}{4}$$

$$V = a \cdot \pi \frac{D^3}{6}$$

$$D = \frac{3V}{2A}$$

$$F_{\text{nmax}} = k\left[\frac{m v_{\text{bn}}(1+e_{\text{n}})}{\Delta t} + mg\cos\alpha\right]$$

$$\Delta t = \frac{1}{100}\left(0.097mg + 2.21h + \frac{0.09}{v_{\text{bn}}^2} + 1.2\right)$$

$$v_{\text{bn}} = \sqrt{2gH}$$

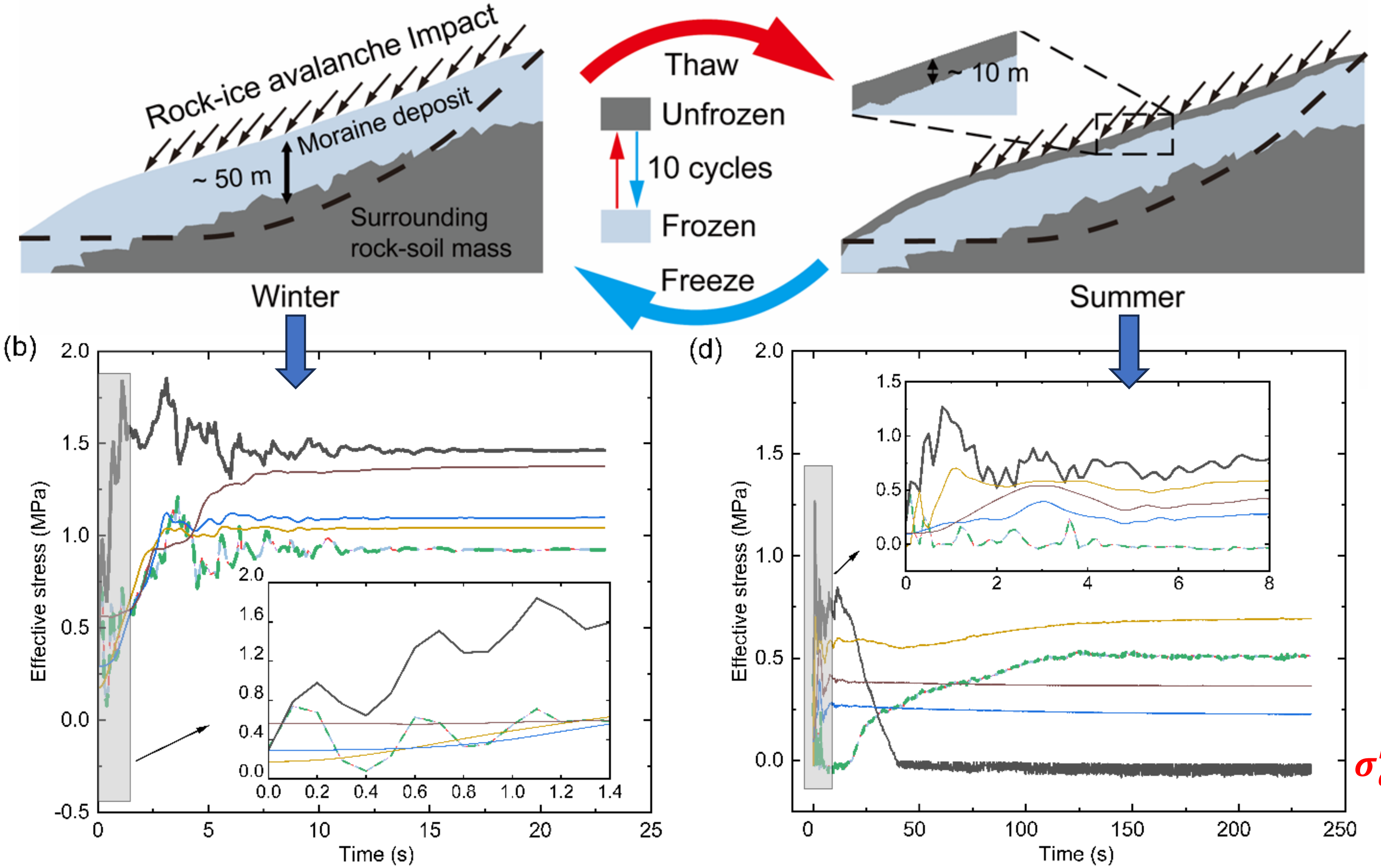
$$q = \frac{4F_{\text{nmax}}}{\pi D^2}$$

Impact boundary condition: 45 degree to the horizontal line

Parameters are all adopted as common values found in Literature, without elaborate calibration

Results and discussion

In warm seasons, water-ice phase results in superficial **high water content**, favoring the generation of excess pore pressure and "**liquefaction**" under avalanching impact.

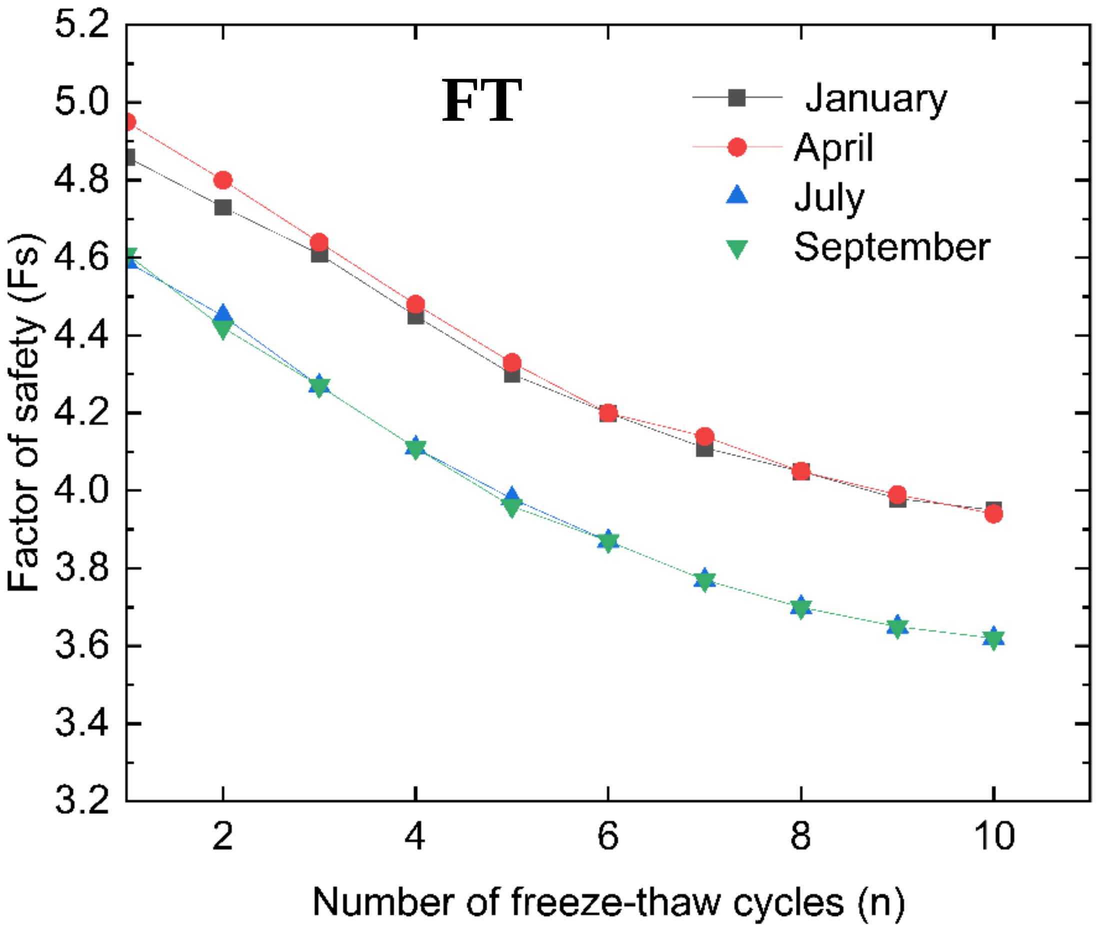


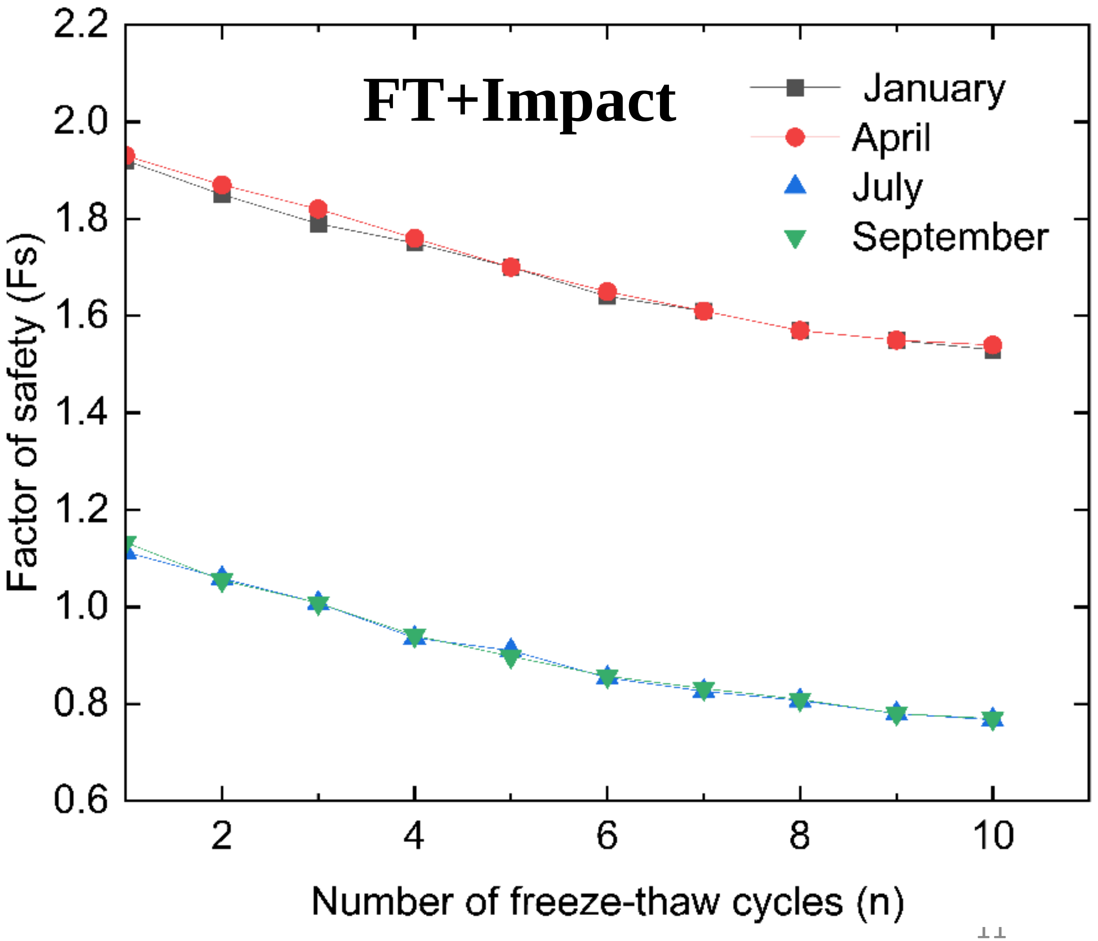
$\sigma'_{depth\sim 10m} \rightarrow 0$

Results and discussion

FT: The moraine deposit tends to remain globally stable solely under the effect of freeze-thaw cycles, despite FS decreases

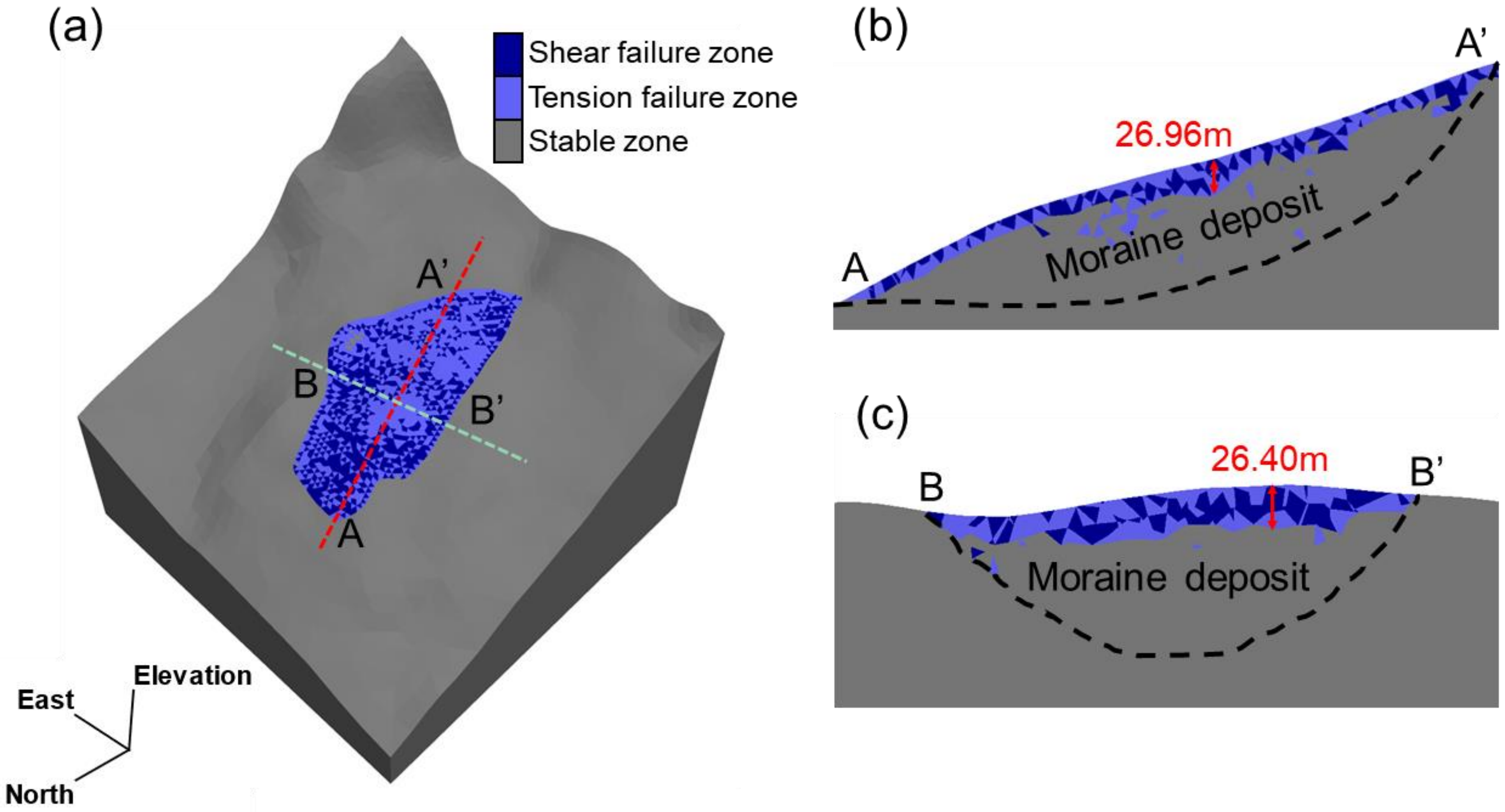
FT+Impact: Rock-ice avalanches are the direct trigger of this type of hazard chain





Results and discussion

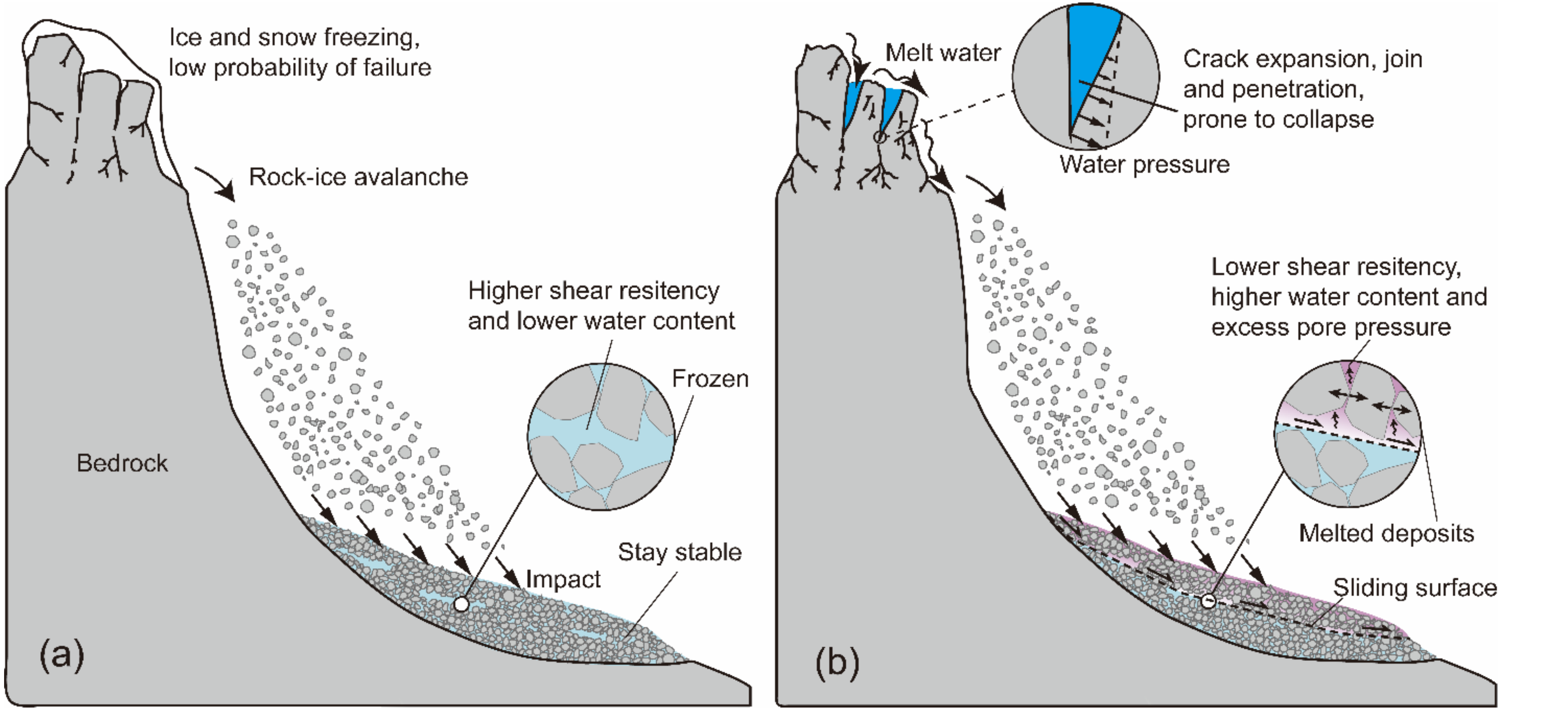
The simulated landslide event on 2020 Sep 10



	Simulation	Observation
Landslide area	0.102 km^2	0.134 km^2
Maximum elevation changes	A-A': 26.96 m B-B': 26.40 m	A-A': 26.8 m B-B': 24.1 m
Total landslide volume	1.44×10^6 m^3	1.14×10^6 m^3

Key Cascading point

Avalanches and freeze-thaw cycles together govern the occurrence of these cascading chain events



- ✓ In warm seasons, high water content in moraine deposits **favors** the failure and even liquefaction of moraine mass under **small avalanche impact**
- ✓ In addition, rock-ice avalanches are more often in warm seasons, making this type of hazard chain more frequent

Debris flow simulation

Averaging the two empirical parameters along the flow path

Entrainment rate in r.avaflow

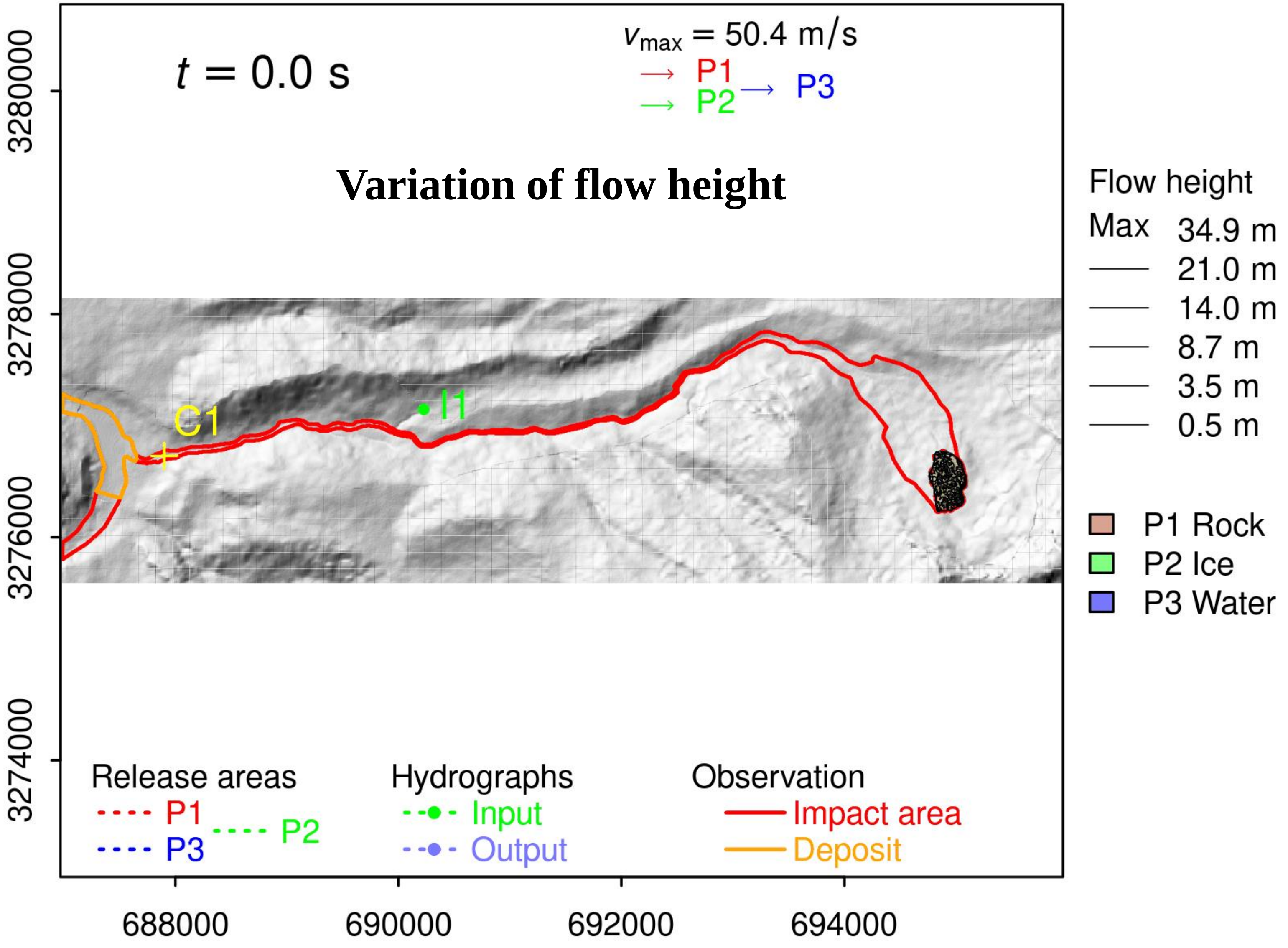
$$q_{E,1} = C_E|M_1 + M_2 + M_3|\alpha_{1,E}$$

$$q_{E,2} = C_E|M_1 + M_2 + M_3|\alpha_{2,E}$$

$$q_{E,3} = C_E|M_1 + M_2 + M_3|\alpha_{3,E}$$

Phase transition rate in r.avaflow

$$q_{tran} = C_{PT}e_{kin}$$



Conclusion

- A **small** avalanche can trigger a hyper-mobility cascading event in warm season
- Freeze-thaw cycles as ***controller*** and rock-ice avalanching as ***trigger*** together governs this type of hazard chain
- **Initial water content** of moraine deposit is imperative for cascading transition and mobility gain – by liquefaction
- **Entrainment** facilitates later-stage mobility

Part 1: Huang et al., 2023. Interplay of freeze-thaw cycles and avalanche impact on glacial landslidedebris flow geohazard chain in the southeastern Tibetan Plateau. JGR Earth Surface to be resubmitted after revision.
Part 2: Wang et al., 2023. The mechanisms of high mobility of a glacial debris flow using the Pudasaini-Mergili multi-phase modeling, Engineering Geology, Volume 322, 2023, 107186, ISSN 00137952,https://doi.org/10.1016/j.enggeo.2023.107186.

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Welcome to any discussion and collaboration!