Glacial hazards

Risk assessment and mitigation

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fidelsteiner.github.io/#teaching

Topics

Terminology: Hazards. Risks. Mitigation.

Global ice and exposure to hazards

Types of glacial hazards

Hazard Assessment: Mapping and Modelling

Monitoring and risk mitigation

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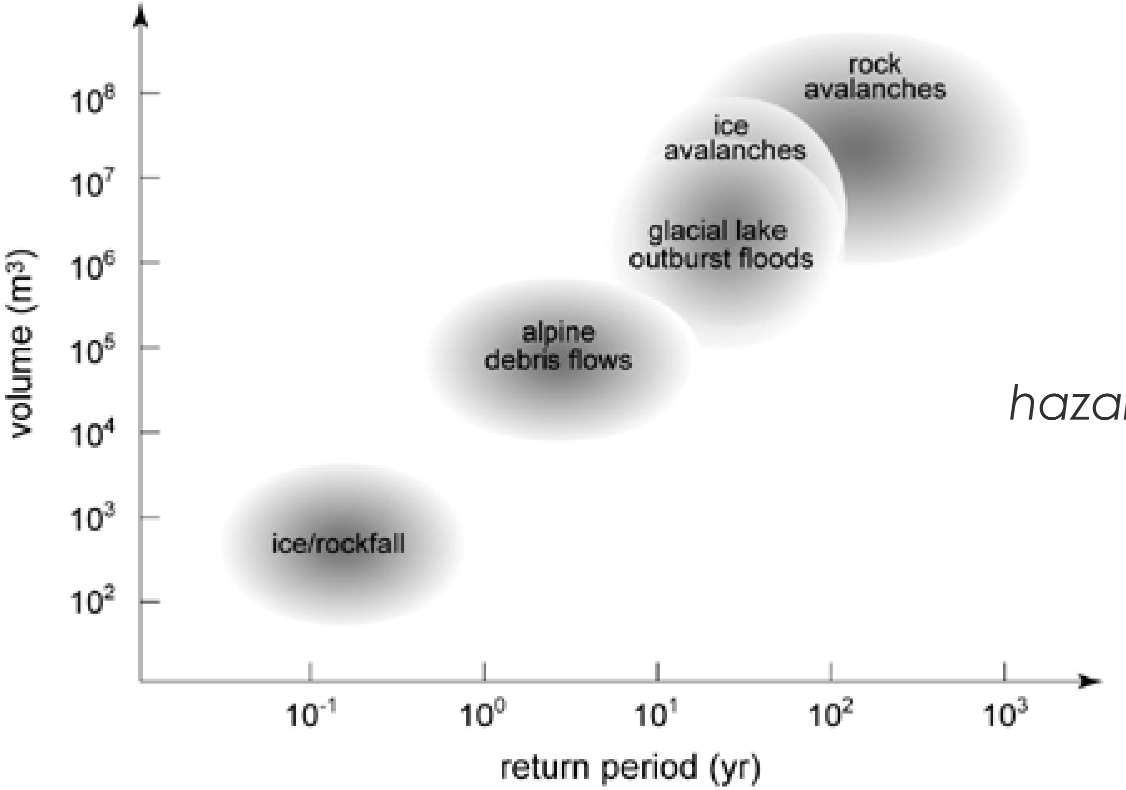
Glacial hazards vs cryosphere hazards

Cryosphere = glaciers – snow – permafrost – sea/lake ice

Other cryosphere hazards are…

- snow avalanches
- snow droughts
- permafrost change induced slope instabilities
- change of sea ice breakup

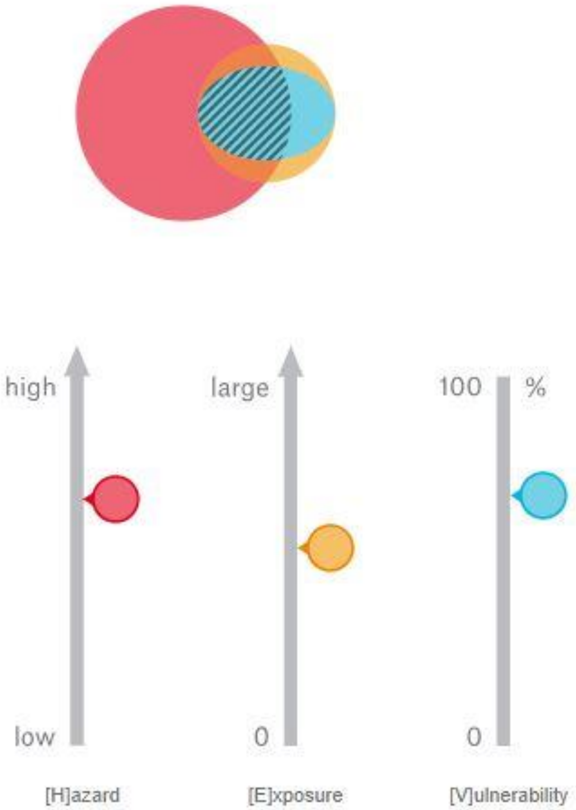
Return periods vs. volumes

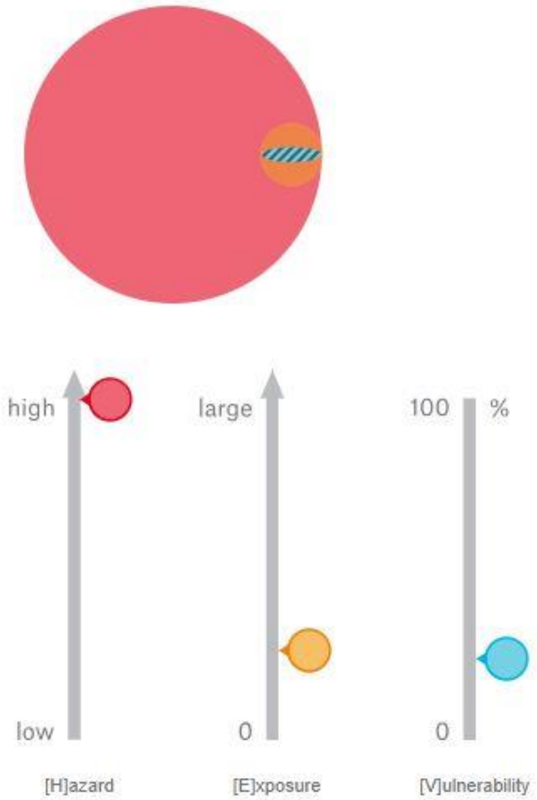


hazard = f(probability, intensity)

Geology Today, Volume: 28, Issue: 3, Pages: 98-104, First published: 25 May 2012, DOI: (10.1111/j.1365-2451.2012.00836.x)

*risk = hazard * exposure * vulnerability [*adaptive capacity *insurance penetration]*





MunichRe

Mitigation and adaptation

Mitigation – reducing risk from the occurrence of any undesirable event *or* minimize the degree of damage

Adaptation – prepare for damages that are to be expected (and possibly can't be avoided or mitigated)

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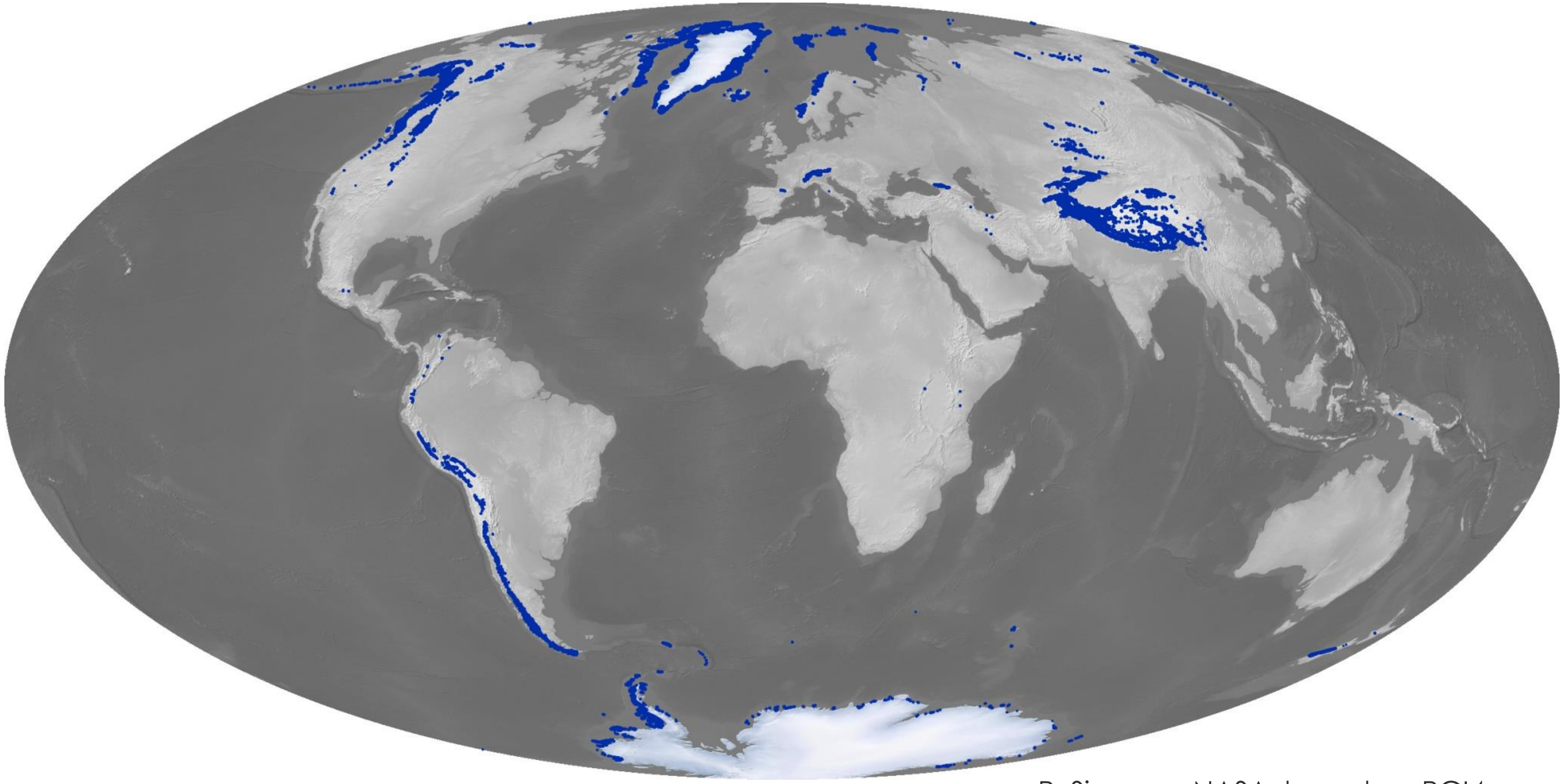
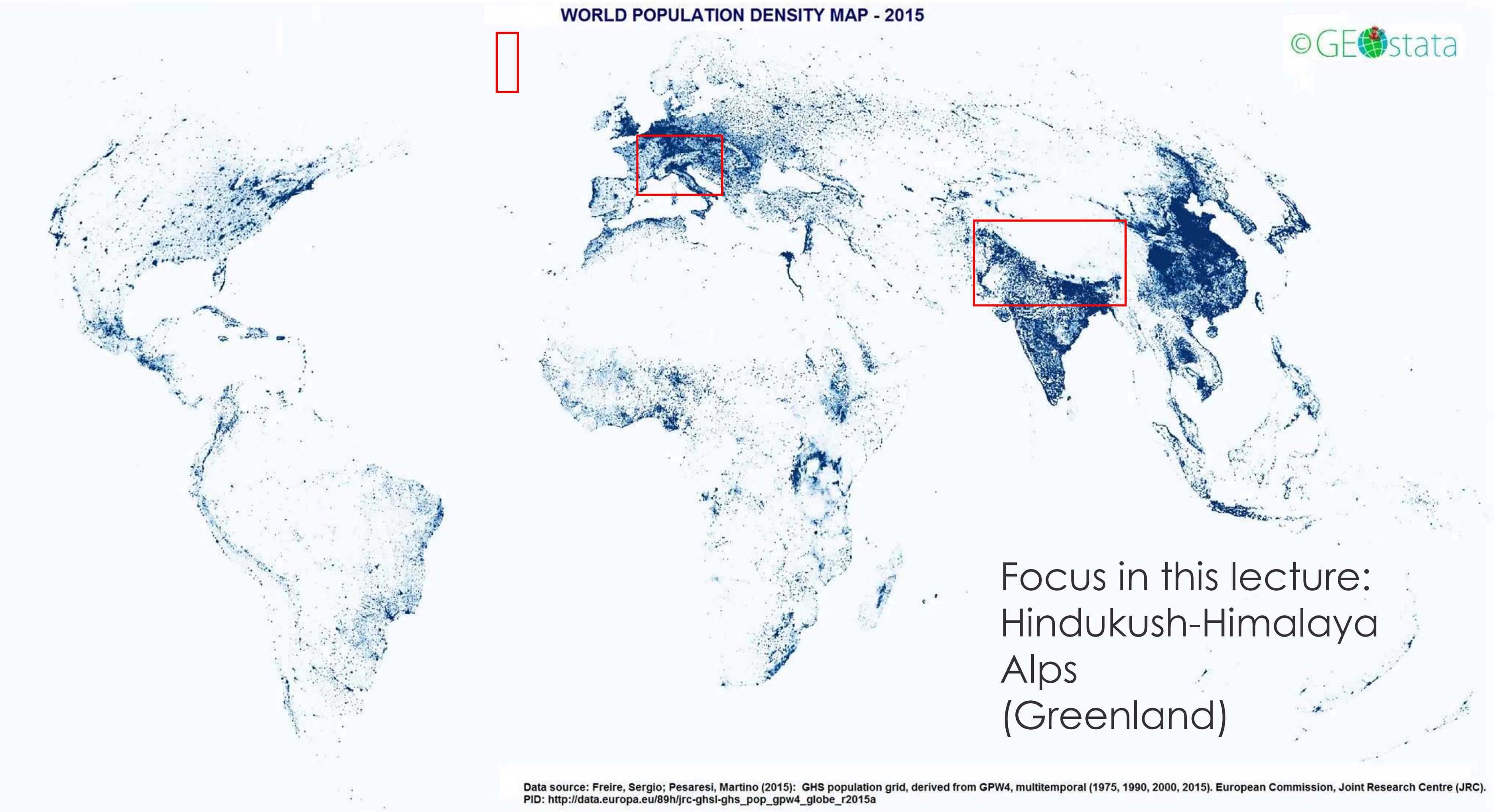
Glaciers globally

Total Area:
RGI: 734 933 km^2
WGI: 747 688 km^2



R. Simmon, NASA; based on RGI4 (2013)



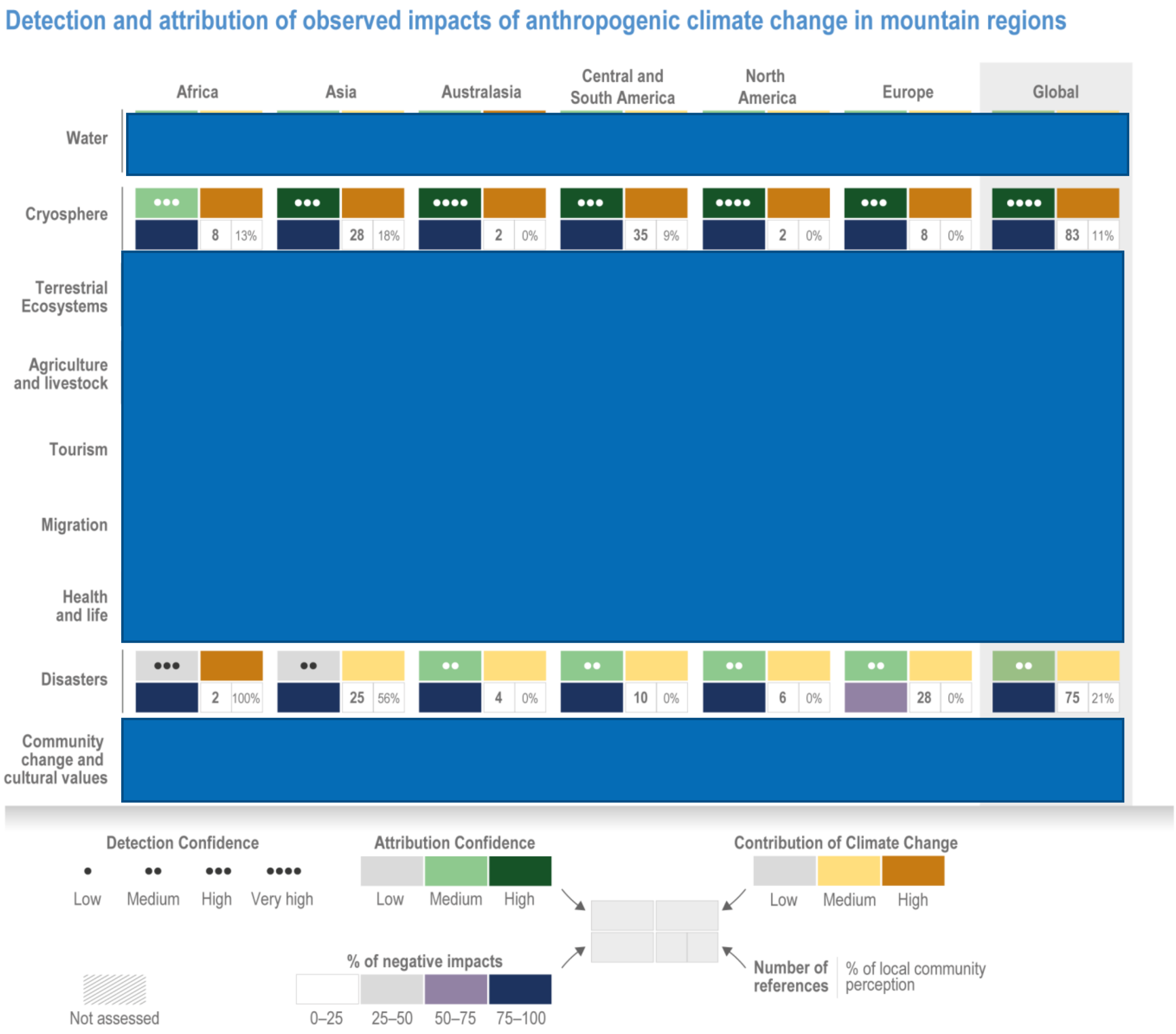
Focus in this lecture:
Hindukush-Himalaya
Alps
(Greenland)

IPCC AR6 WGII

Summary of research on mountains as captured by the IPCC report (AR6)

Compilation of the essence of our current state of knowledge

Approved by governments (IPCC process)



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Glacier related hazards

glacier lake outburst floods (+ resulting events)

ice break offs (+ resulting events) / collapsing glaciers

glacier length variations

destabilization of frozen soils/slopes

Kaab et al., 2005

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Glacial Lake Outburst Floods (1)

British Columbia
Canada

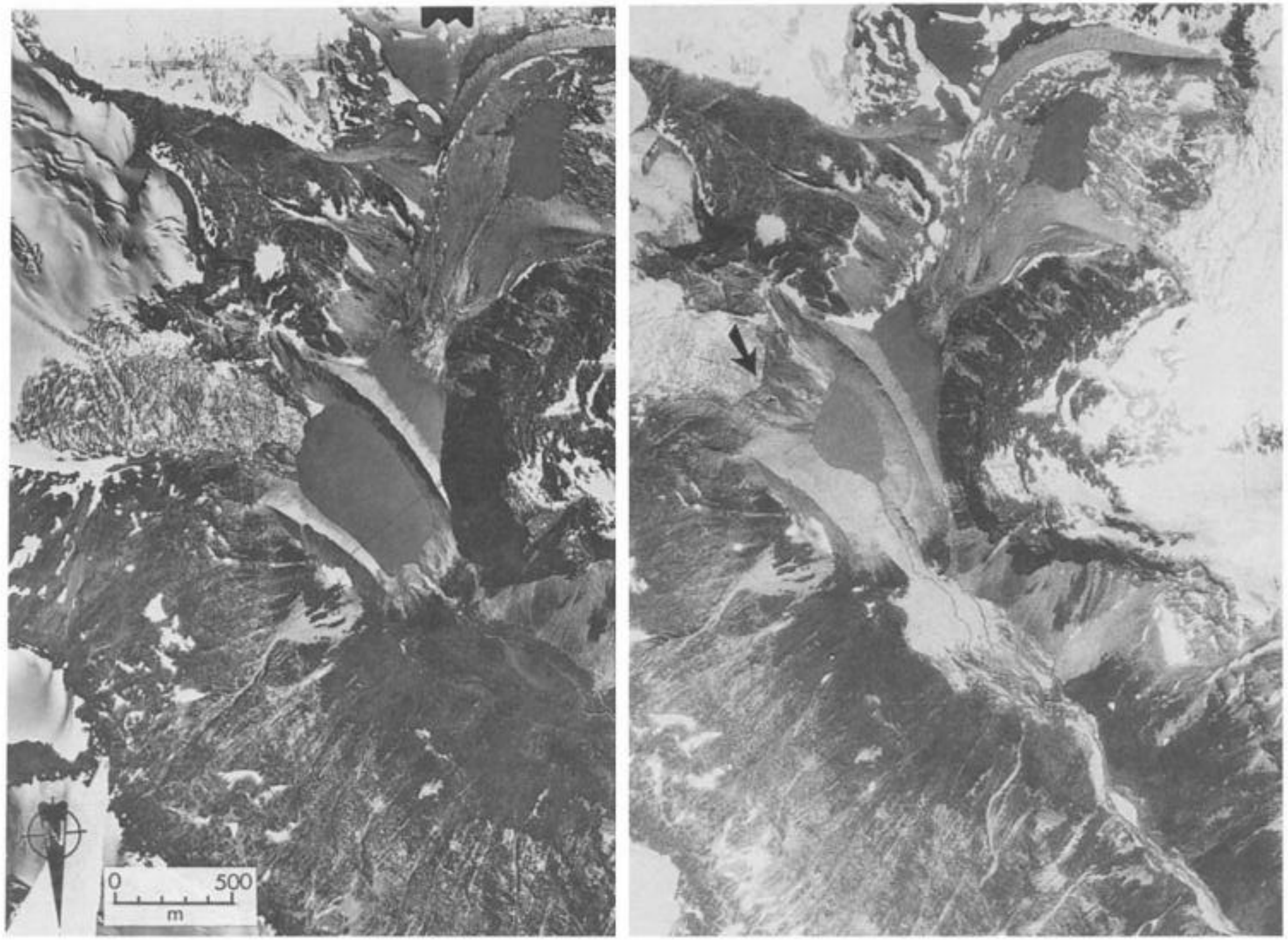
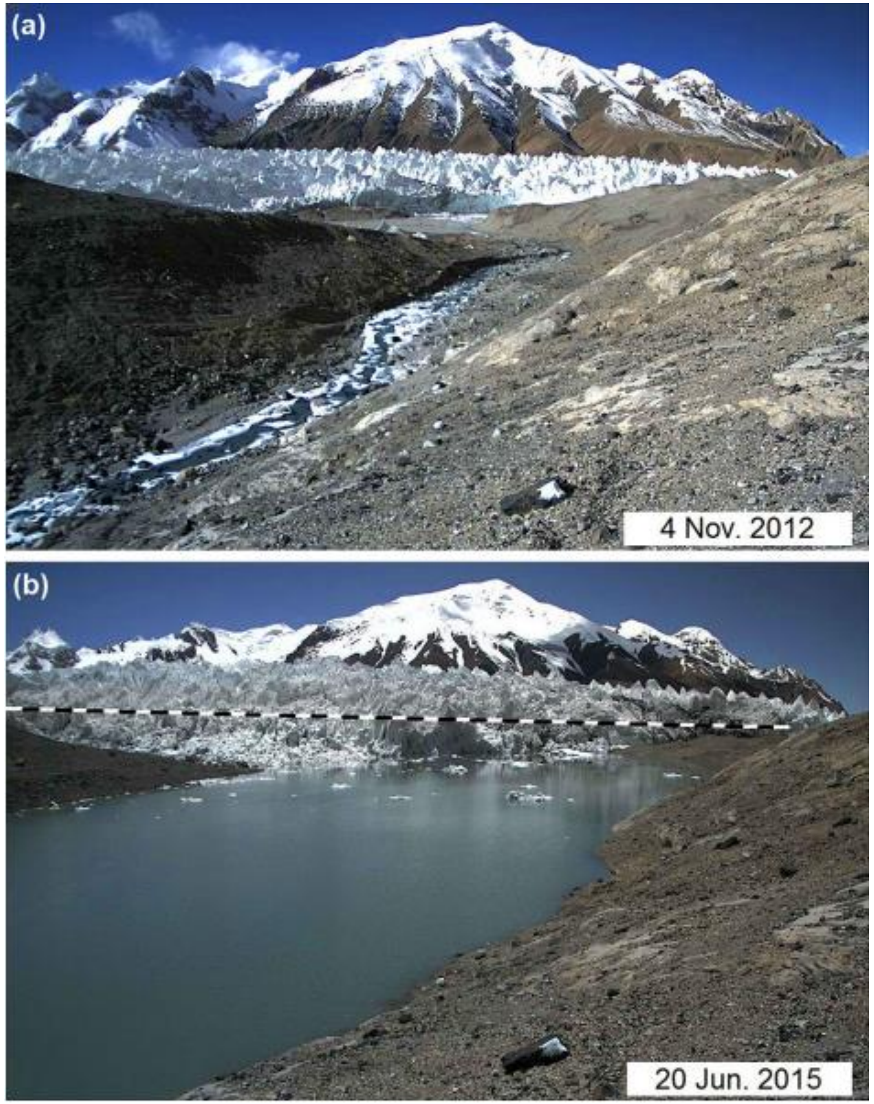


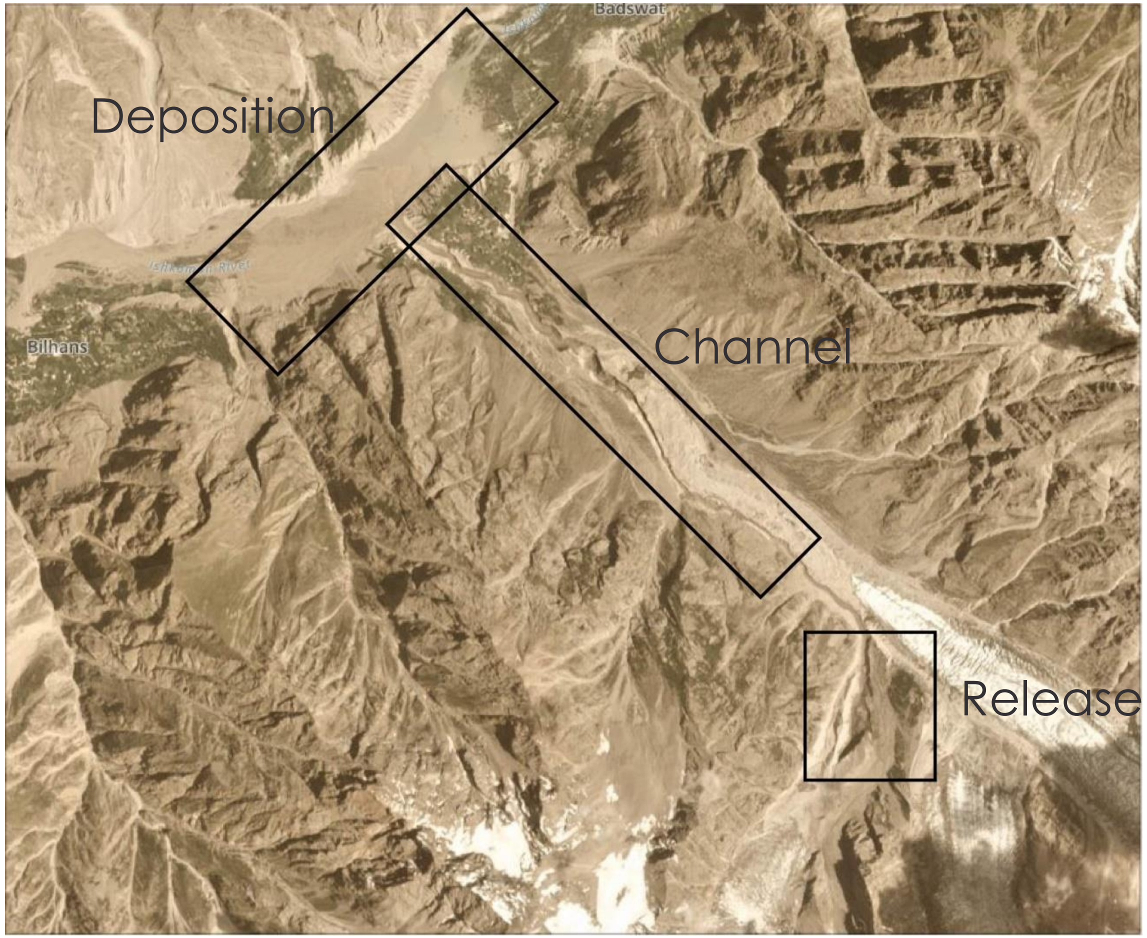
Fig. 12. Aerial photographs of Nostetuko Lake before (left, BC79069-190) and after (right, BC86048-147) the outburst flood of July 19, 1983. Failure occurred when toe of Cumberland Glacier (arrow) collapsed into the lake and generated waves that overtopped the moraine.

Glacial Lake Outburst Floods (2)



Kyagar Lake, Xinjiang, China, Geopraevent

Glacial Lake Outburst Floods (3)



Helicopter Image/Pakistan Army; Sat image Planet

Glacial Lake Outburst Floods - *Causes*

Mass movement into the terminal lake causing overtopping (destabilizing glacier/rock slopes)

Failure of a moraine dam (melting of ice cored moraine)

Surging glaciers damming a river (surges/melt season)

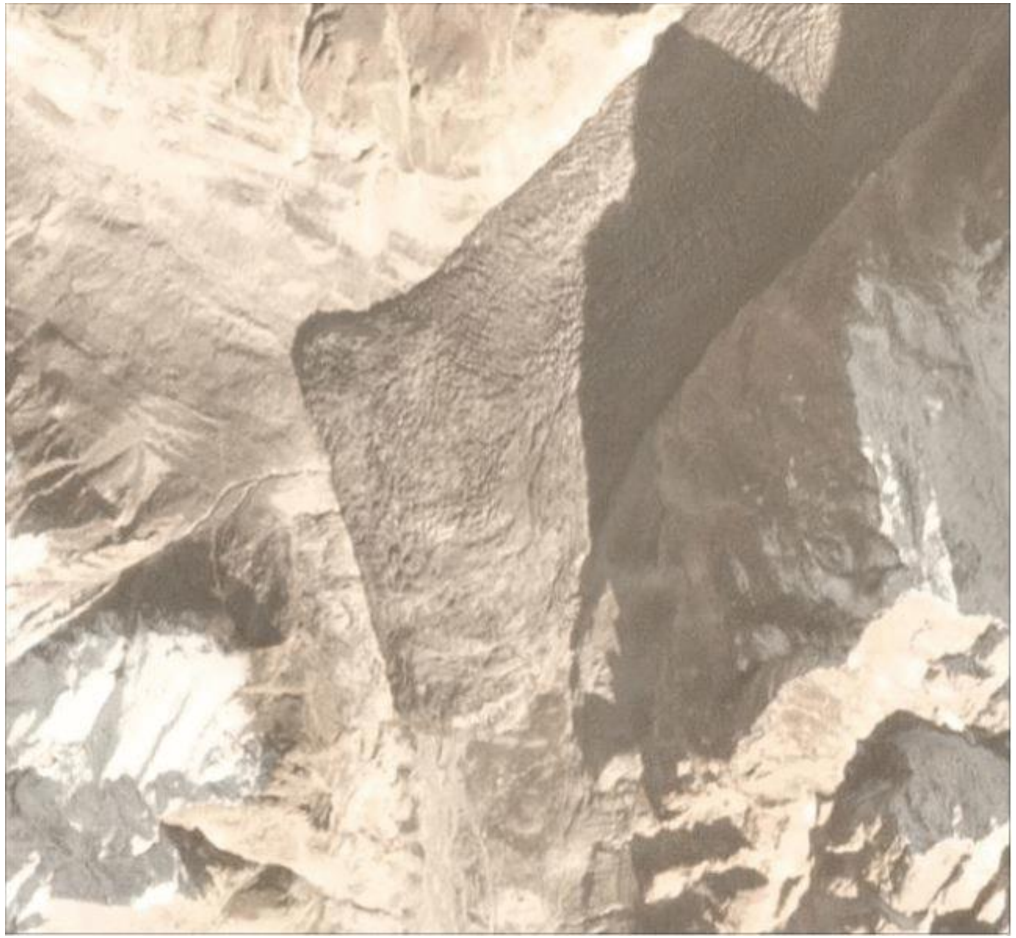
Failure of an englacial lake (internal melt)

Intense melt/rainfall

Growth of terminal lakes (2012)

Growth of terminal lakes (2017)

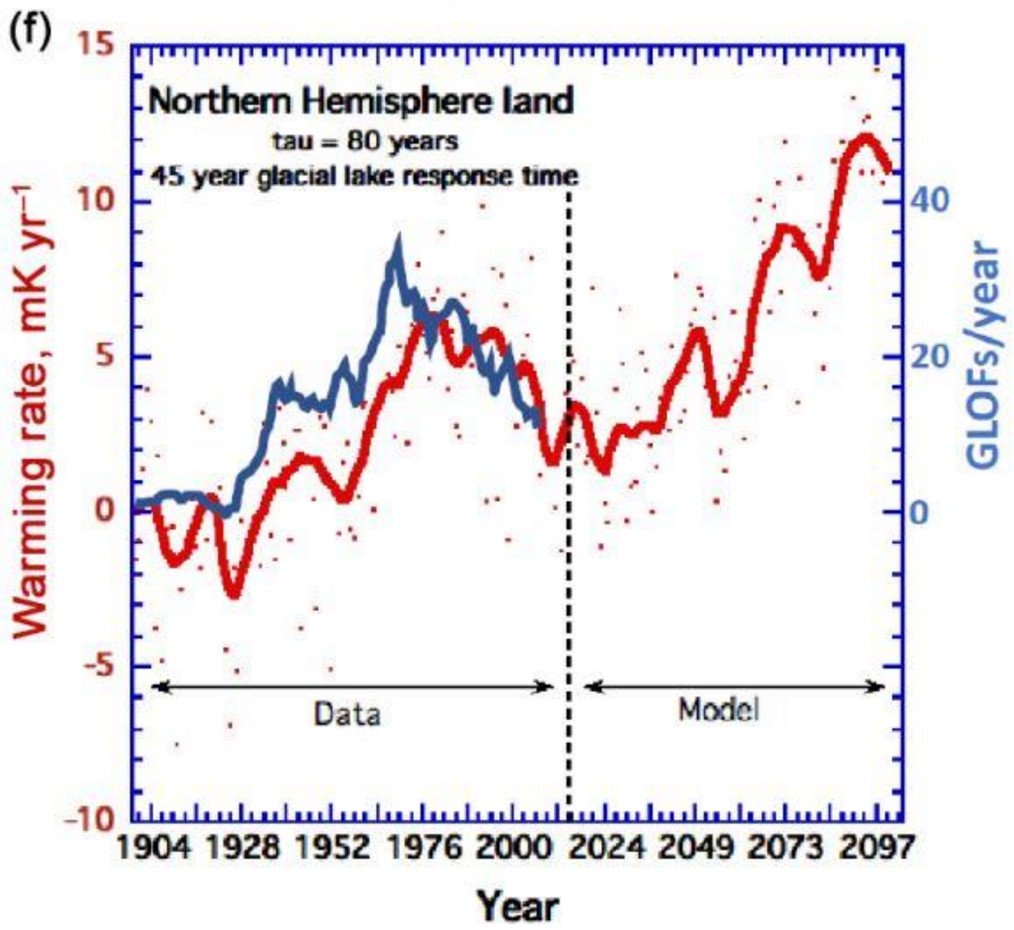
Surging glaciers



- Rapidly advancing glaciers block rivers
- Potentially hazardous lakes
- Interference with water supply
- Karakoram, Svalbard, Andes, Alaska

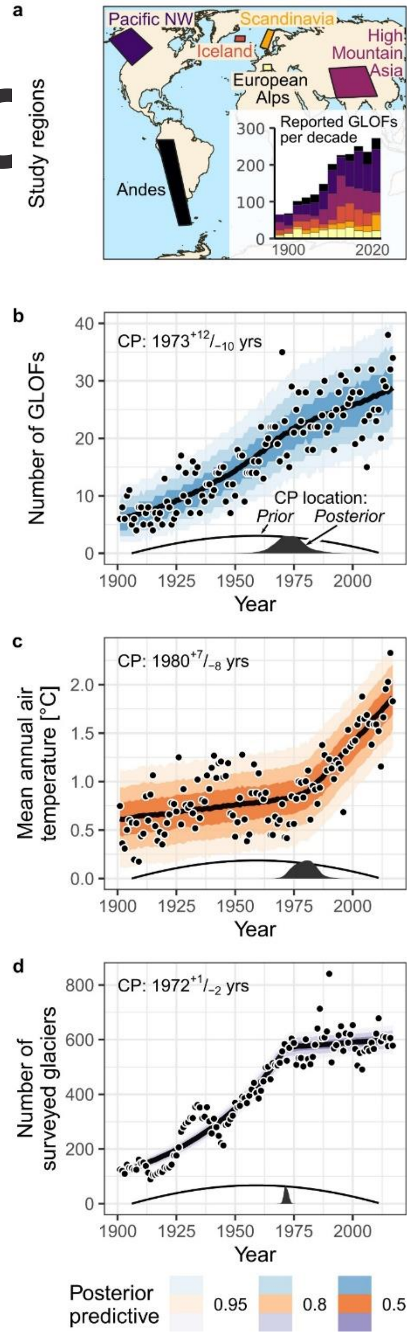
Glacier Lake Outburst Floods - *Causes*

- Link to climate change?
  - Seems very plausible and some indications
  - Difficult to proof with very little data
  - Data bias towards more observations in recent years



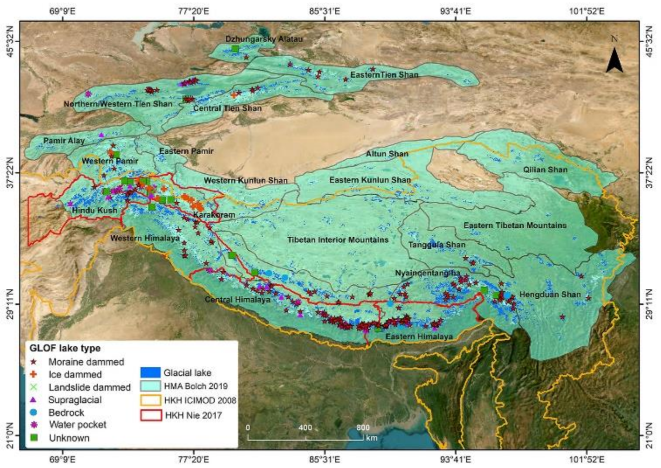
Harrison et al., 2018

Glacial Lake Outburst Floods - C



Veh et al., 2022

Glacial Lake Outburst Floods - *Causes*

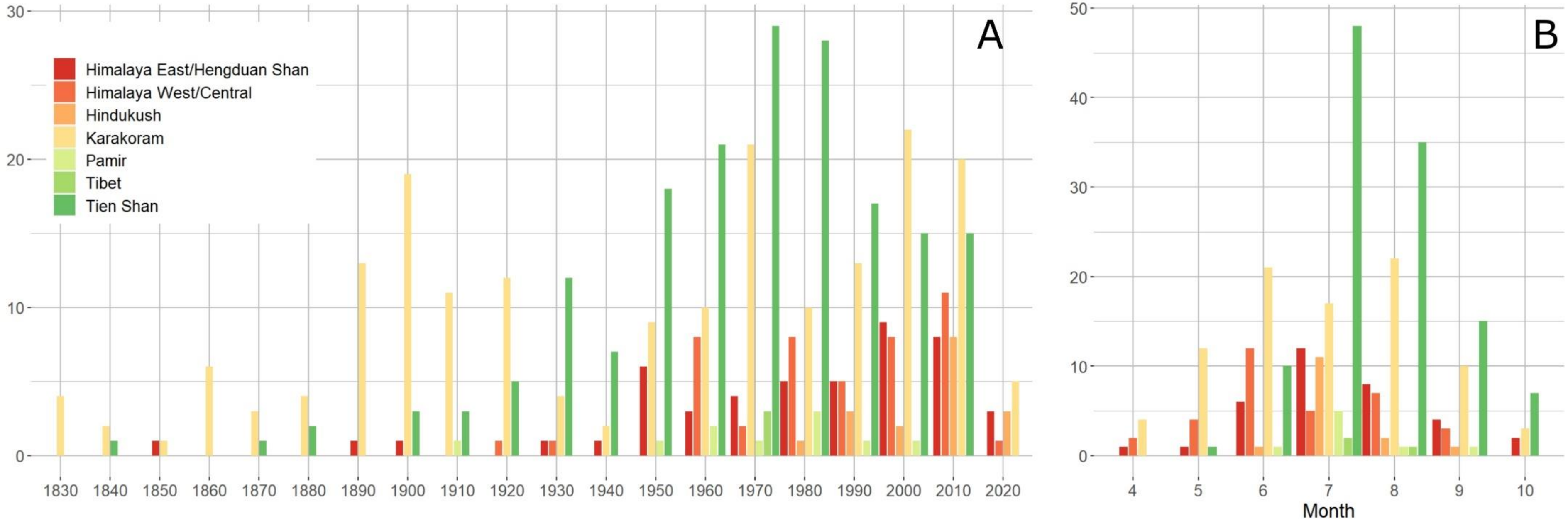


In High Mountain Asia ca 1000 people died in the last 100 years

Low frequency – high impact events

(Avalanches: 3000 people died, high frequency, medium impact;

Debris flows: preliminary 8000 people died, high frequency, varied impact)



Shrestha et al., 2023

Glacial Lake Outburst Floods - *Results*

Lake outbursts from moraine dammed lakes are stagnating, possibly increasing (Veh et al., 2022)

Lake outbursts from ice dammed lakes are decreasing (Veh et al., 2023)

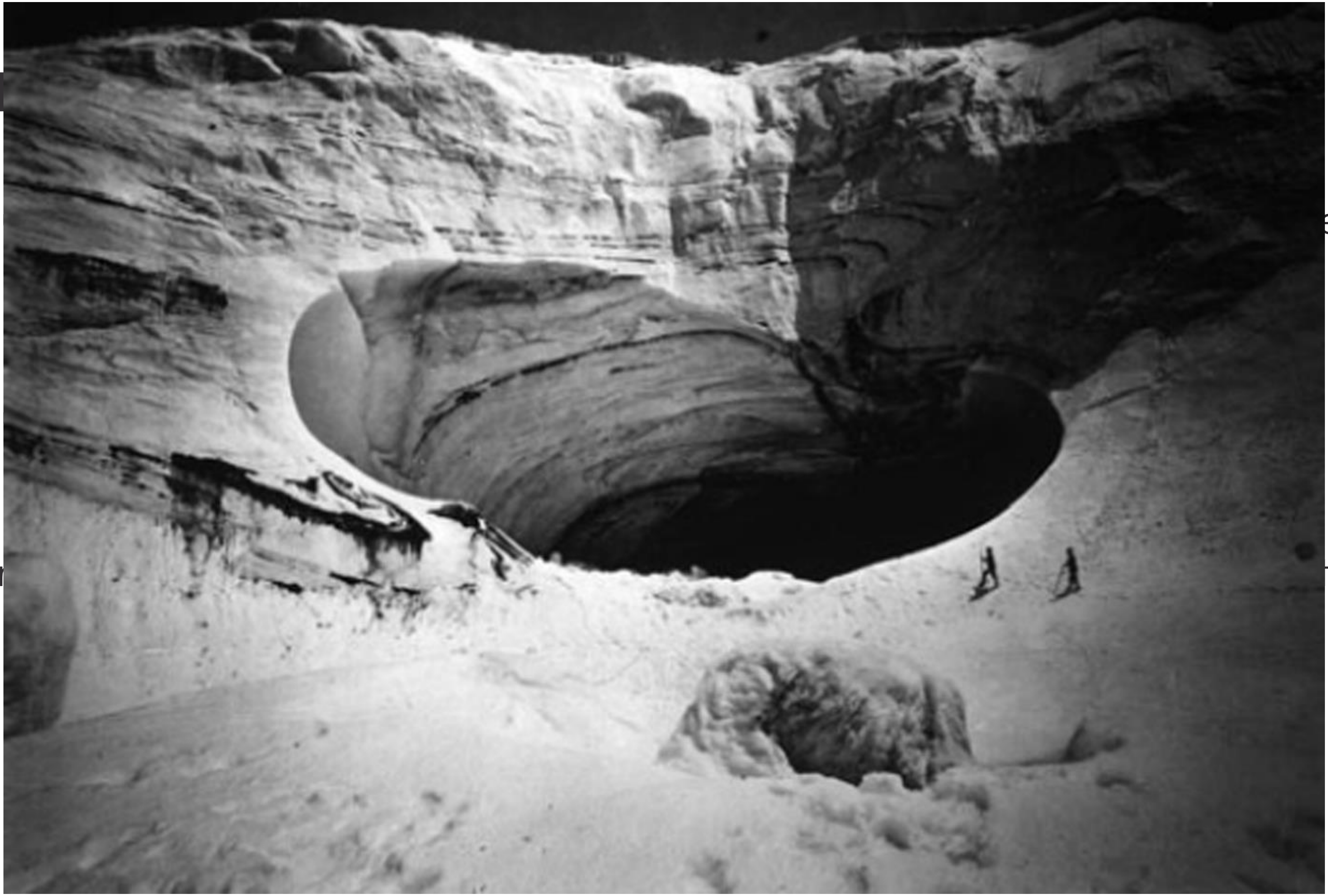
Outbursts from inside the ice (*waterpockets*) are an uncertain thing we need to investigate further

Gla

Lake o et al., 2022)

Lake o

Outbur tigate further



Tête Rousse (Mont Blanc Massif) in 1892; Vincent et al., 2017

Glacial Lake Outburst Floods - *Results*

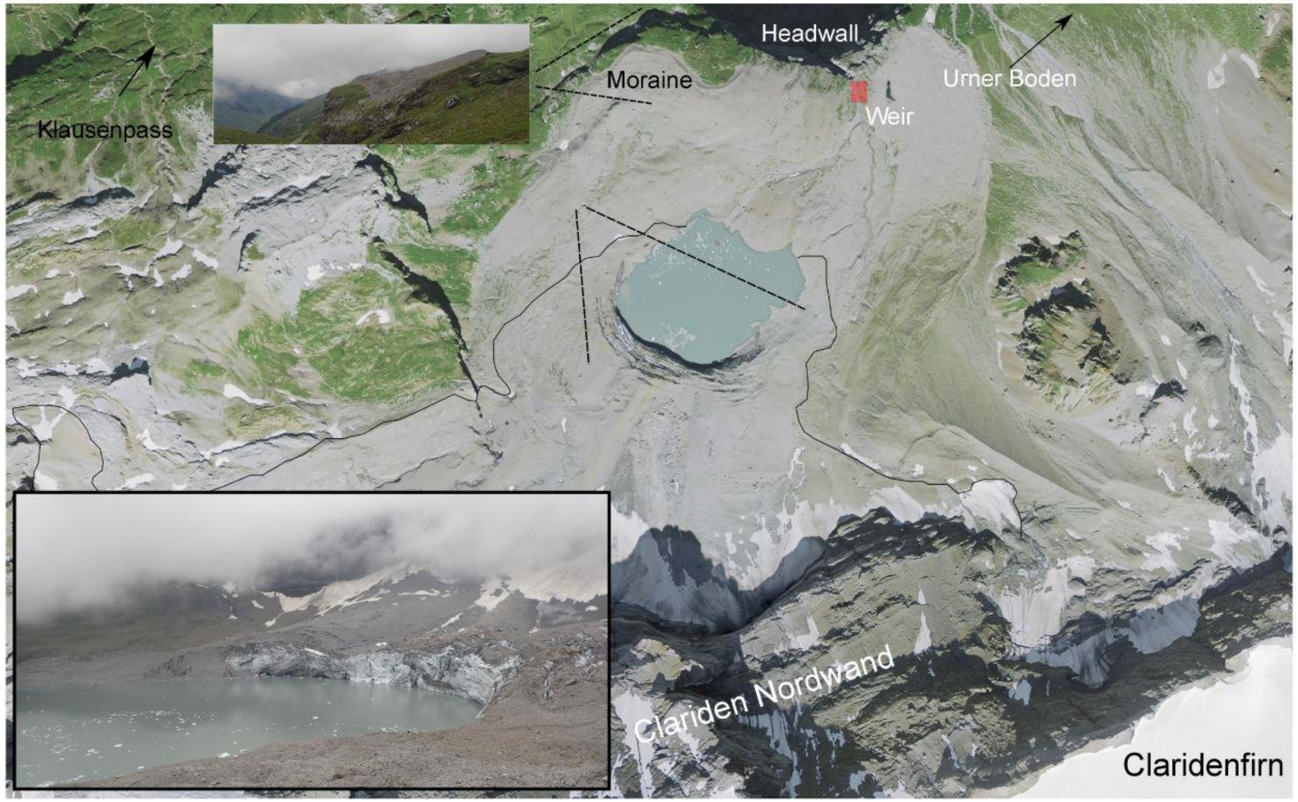
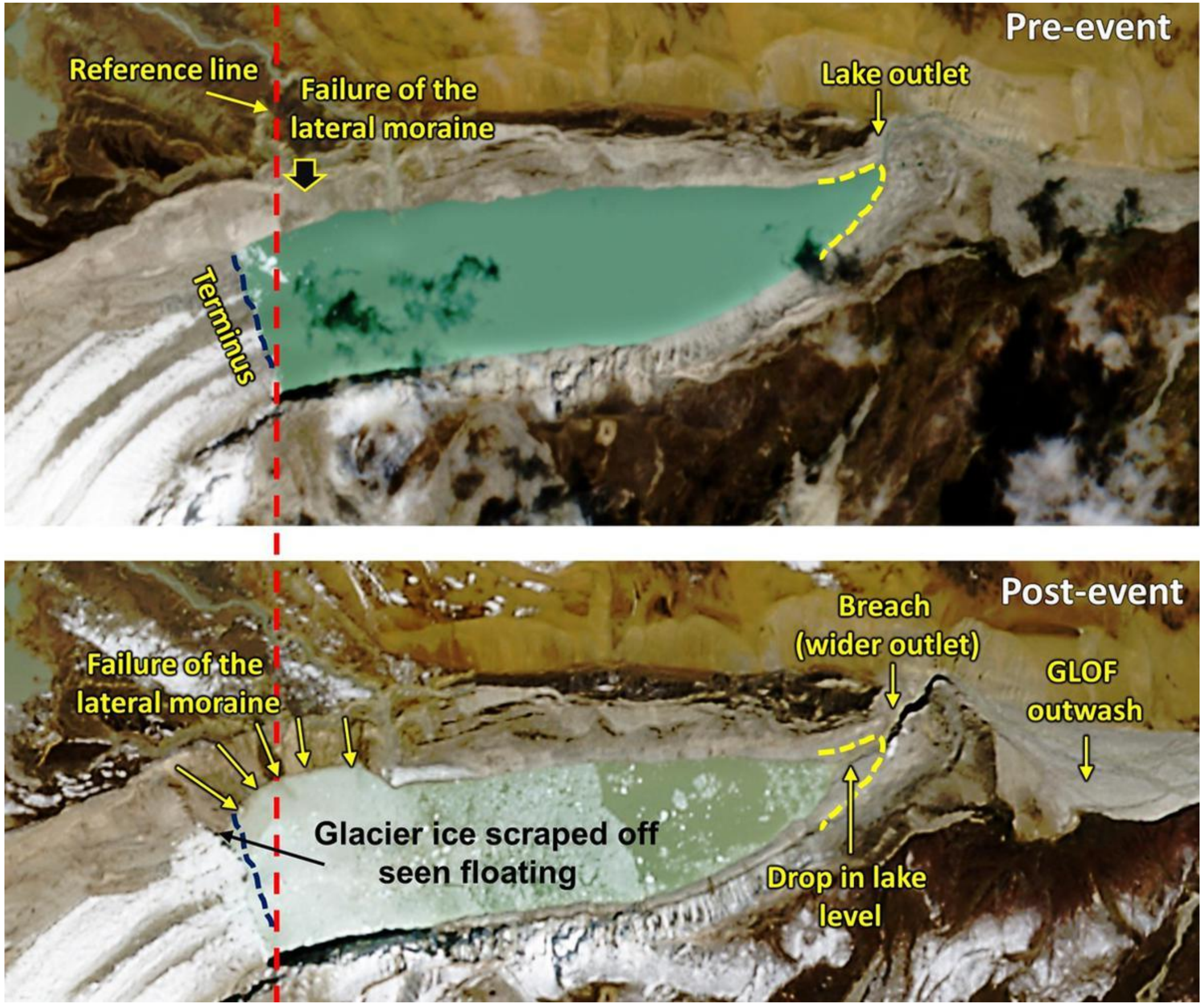


Figure 1: Griessseeli in an orthophoto from 2013 (main frame, swisstopo). The calving front as well as the frontal moraine of the glacier are shown in insets taken in August 2016 by the authors.

Steiner et al, 2016

- Relatively small lake in Switzerland
- Rapid growth due to glacier retreat
- Potential threat from ice break offs into the lake
- Huge damage potential due to expensive hydropower plant below

South Lonak



Pre-event
Reference line
Failure of the lateral moraine
Lake outlet
Terminus
Post-event
Breach (wider outlet)
GLOF outwash
Failure of the lateral moraine
Glacier ice scraped off seen floating
Drop in lake level

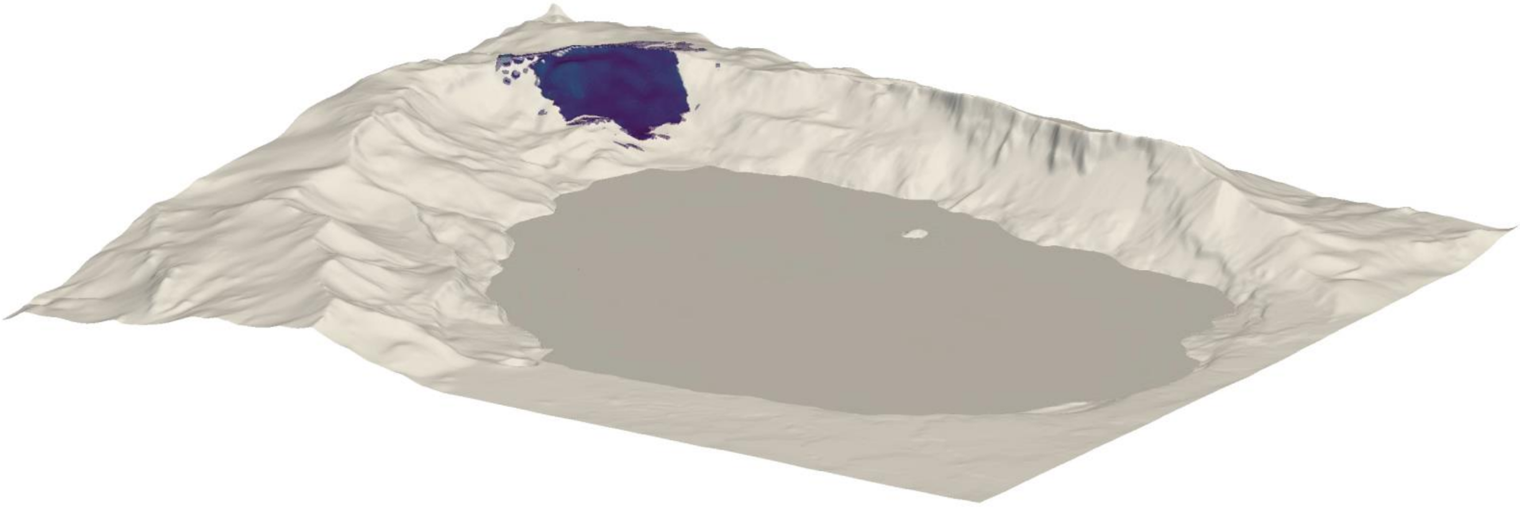
Impact waves

- Possible precursor of outburst flood
- Multi-hazard problem (landslide/avalanche + waves + dam failure + flood)
- Part of dam risk assessment in mountainous areas (wave run up height included in 'freeboard')

Figure 11: Schematic sketch showing a typical glacial lake outburst chain resulting from an initial mass movement (from, Worni et al., 2014). (1) A mass movement (ice, rock or debris) enters a lake, producing (2) a displacement wave that (3) overtops and (4) incises and erodes the dam area. (5) A flood then travels downstream where (6) populated areas and infrastructure are exposed. Note that displacement waves can be catastrophic with or without erosion of the dam area, and as such, can threaten also apparently stable bedrock dammed lakes.

Allen et al., 2017, GAPHAZ

Impact waves



Rauter et al., 2022

Glacial Lake Outburst Floods - *Results*

- Downstream flood hazard
- Large deposits of sediments (permanent damage to agriculture)

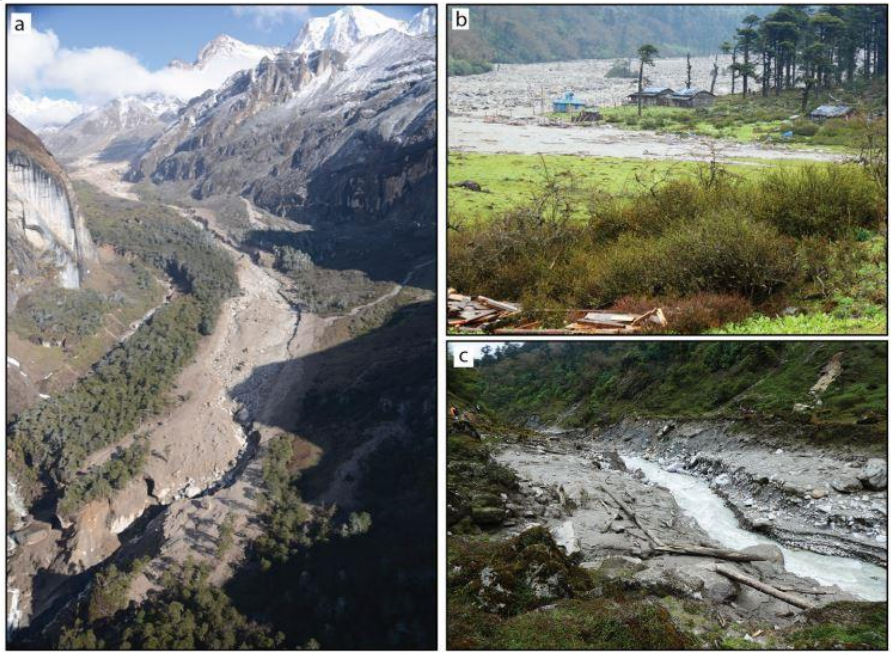
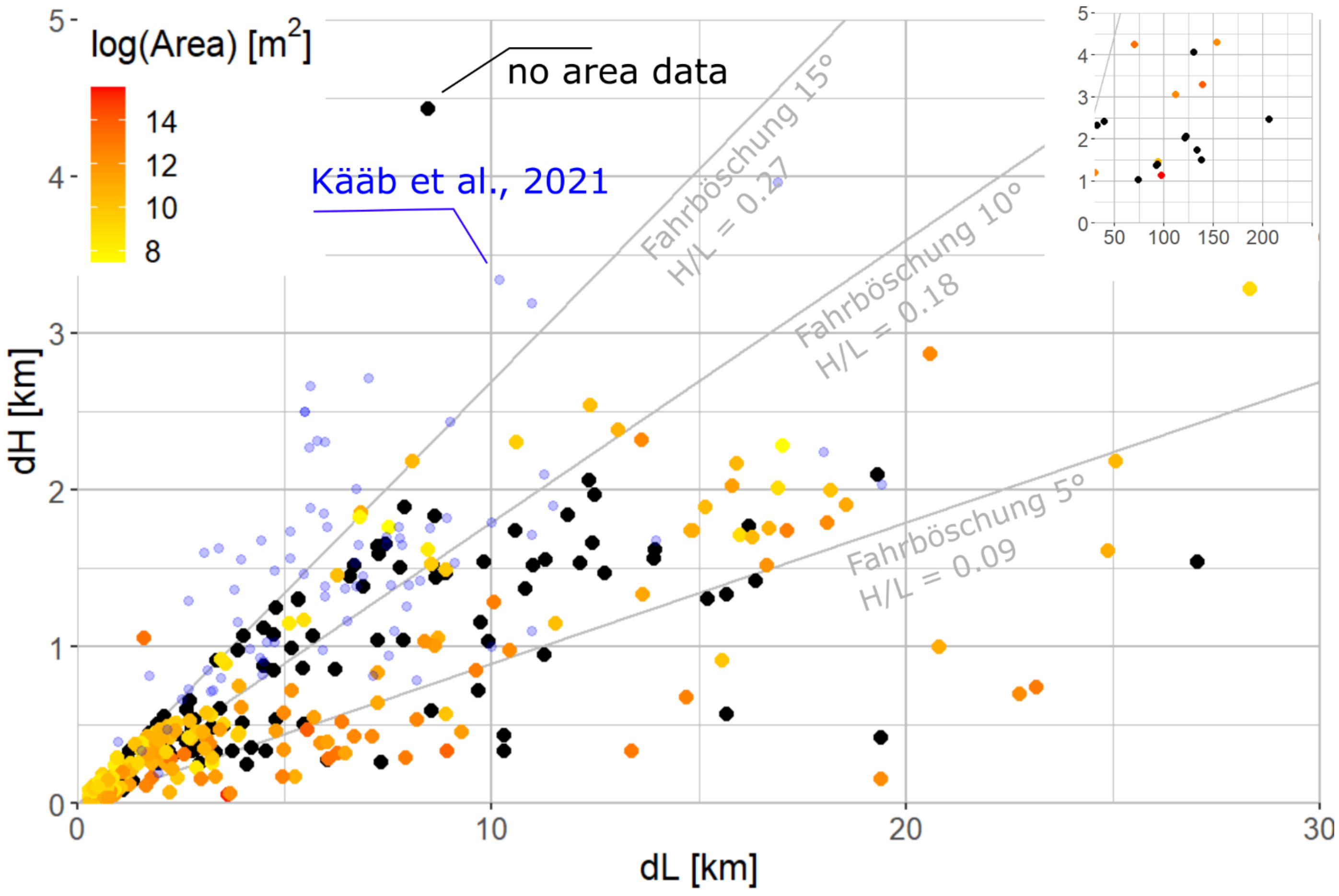


Fig. 13 **a** The flood path from the air. **b** The destruction at Yangle Kharka, where four buildings were destroyed. **c** The narrowed flood channel below Yangle Kharka

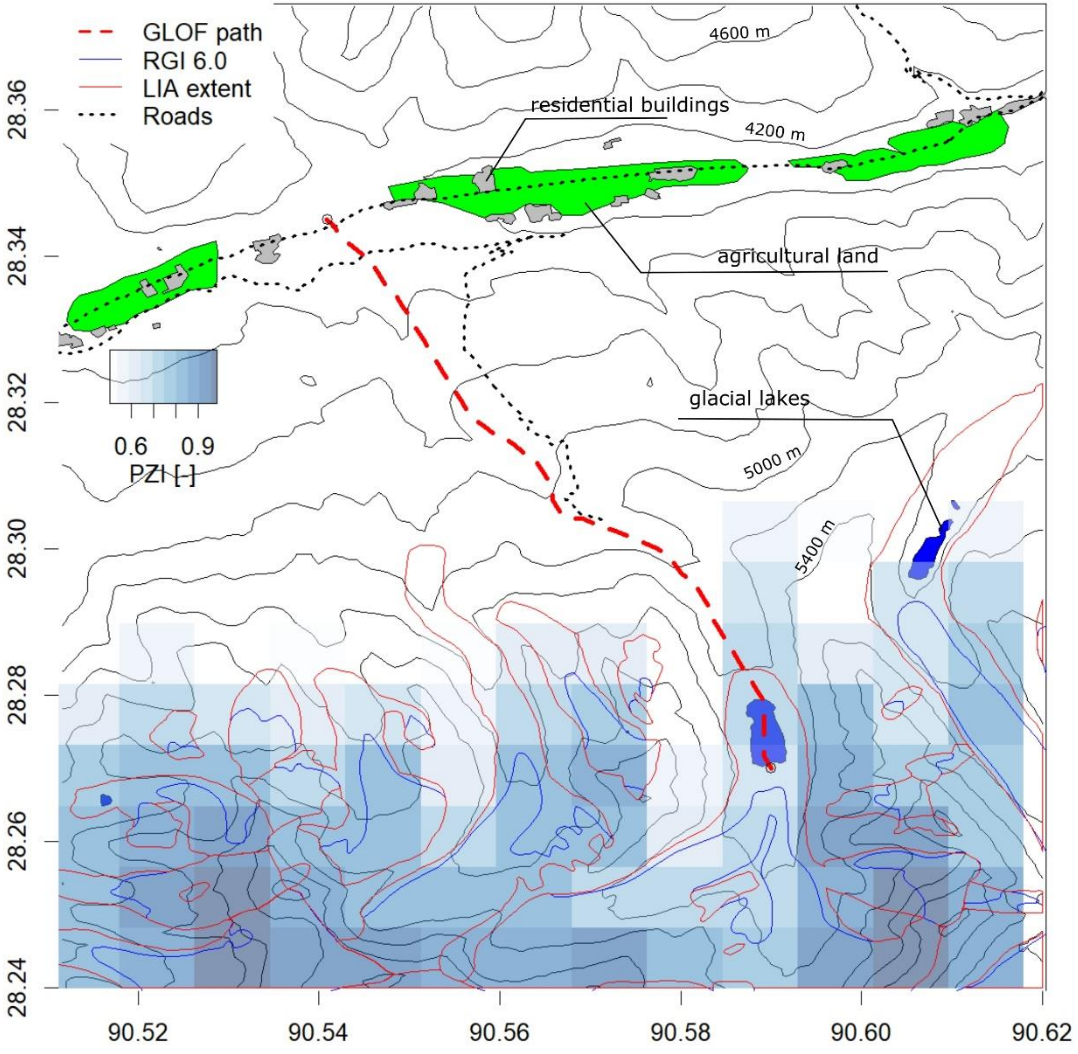
Byers et al., 2018

Glacial Lake Outburst Floods - *Results*



Shrestha et al, 2023

Glacial Lake Outburst Floods - *Results*



Shrestha et al, 2023

Glacier related hazards

glacier lake outburst floods (+ resulting events)

ice break offs (+ resulting events) / collapsing glaciers

glacier length variations

destabilization of frozen soils/slopes

Ice break offs + collapsing glaciers

- Increasingly dangerous with receding glacierettes/hanging glaciers
- Added danger in seismically active regions

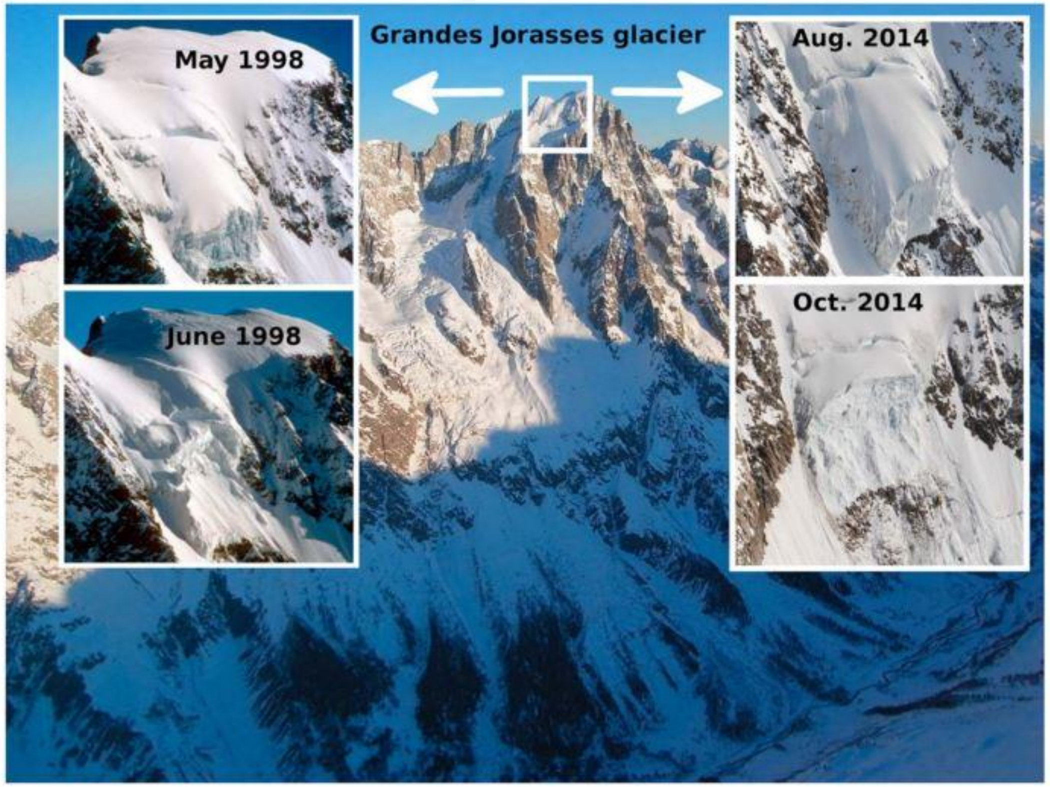


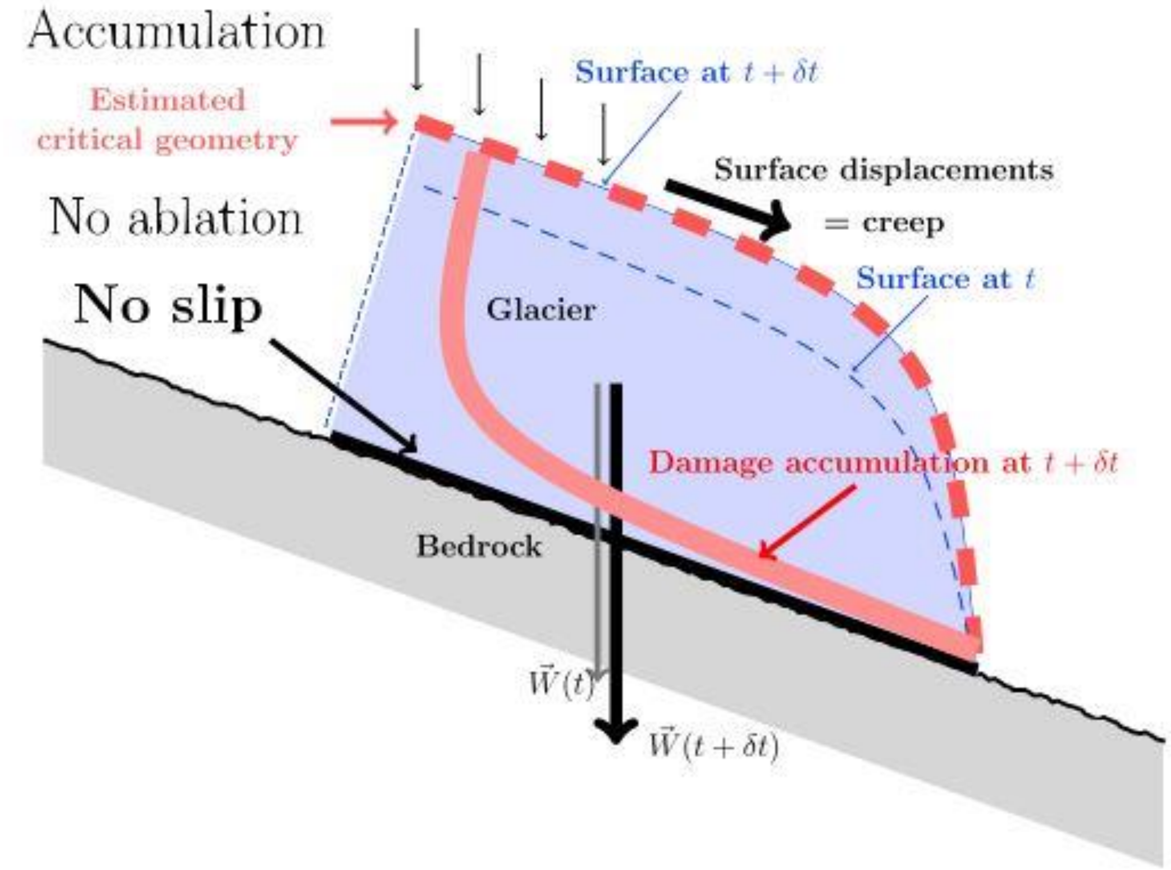
Figure 7. South side of the Grandes Jorasses and the Italian Val Ferret. (left inset) Evolution of the hanging glacier from May to June 1998. (right inset) Evolution of the hanging glacier from August to October 2014.

Faillettaz et al., 2015

Ice break offs + collapsing glaciers

Causes –
cold based: damage propagation

- 3 glacier types
  - cold based
  - warm based
  - polythermal



Faillettaz et al., 2015

Causes –
transition from cold to warm based

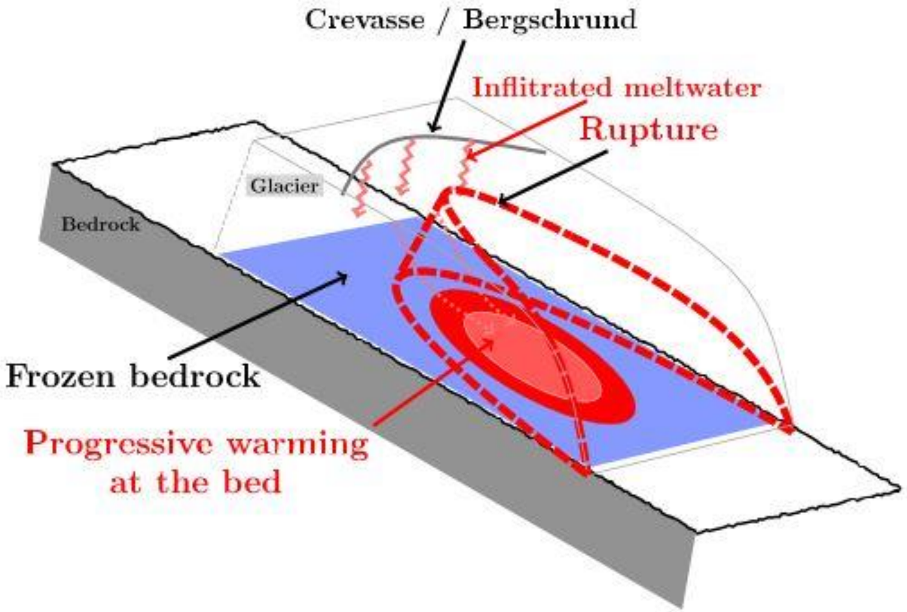


Figure 12. Schematic evolution of the instability initiated by a rapid localized warming at the ice-bedrock interface.

Faillettaz et al., 2015

Causes –
warm based; hydraulic slip

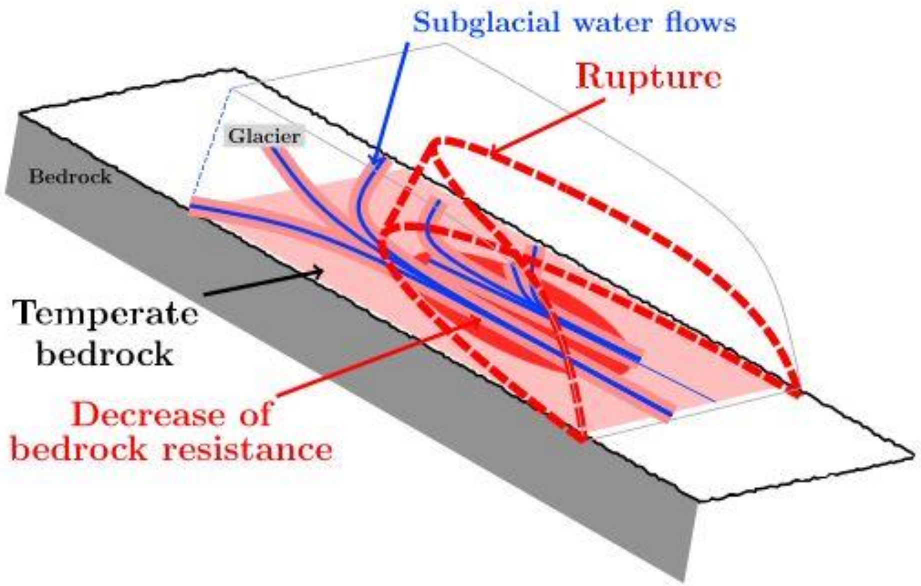


Figure 16. Schematic evolution of the instability for the case of a balanced glacier with a decreasing basal resistance due to increasing subglacial water pressure.

Faillettaz et al., 2015

Results – disasters in remote locations (Uttrakhand, India, 7 February 2021)

At 10:30 local time a major debris flow was witnessed and shared on social media, hitting a hydropower plant under construction

By 19:00 local time satellite imagery of the event had become available that allowed us to document the reason for the event

>200 people dead

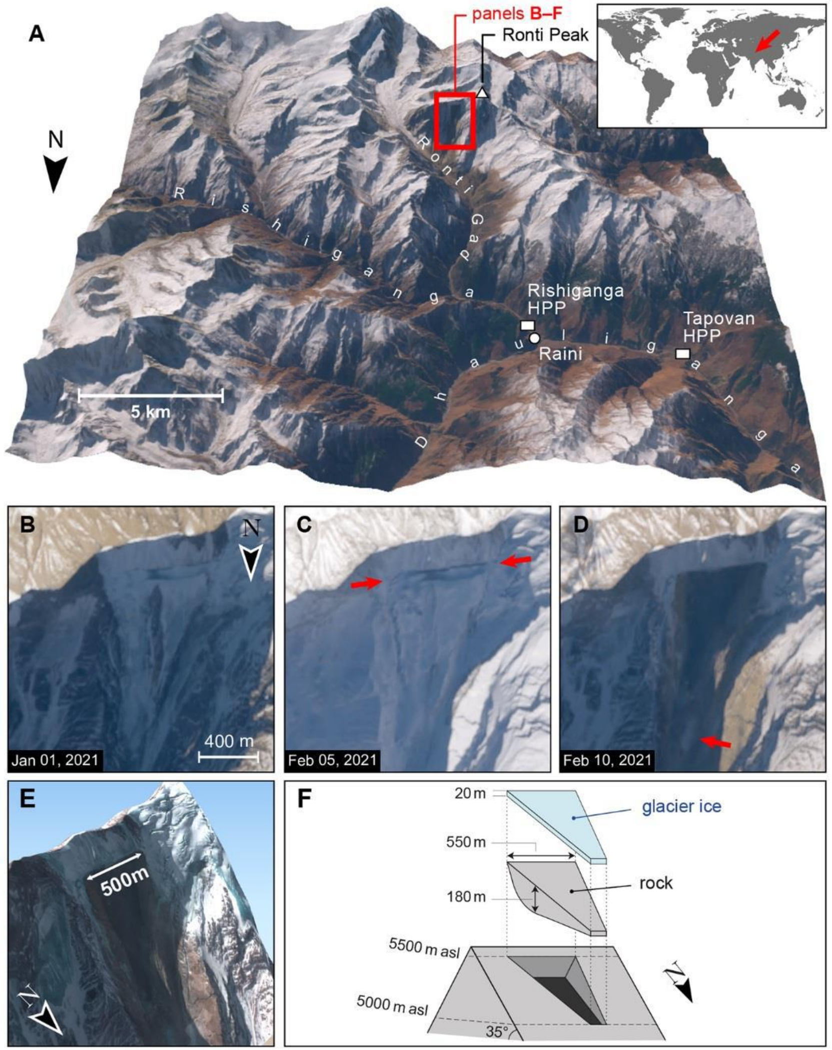
https://www.youtube.com/watch?v=6ucU0Rcx5n4

Results – Uttrakhand rock fall/debris flow

rockfall mixed with ice

mobilization of deposited debris

Transition into debris flow

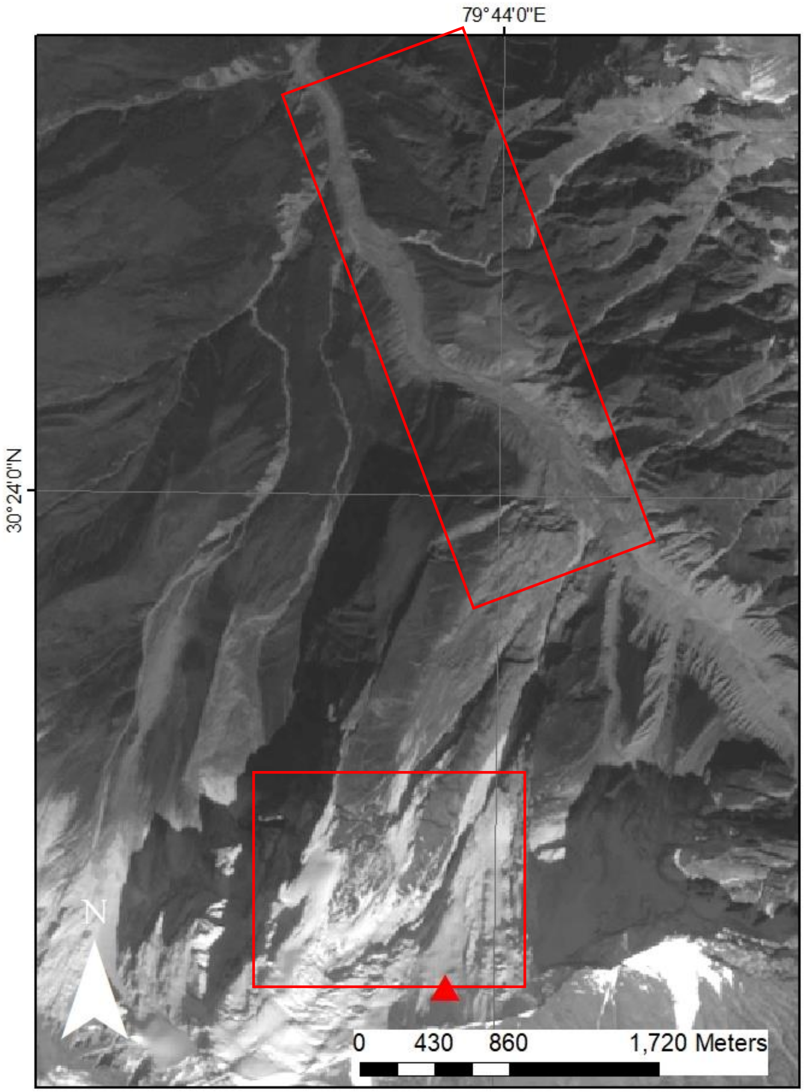


Shugar et al., 2021

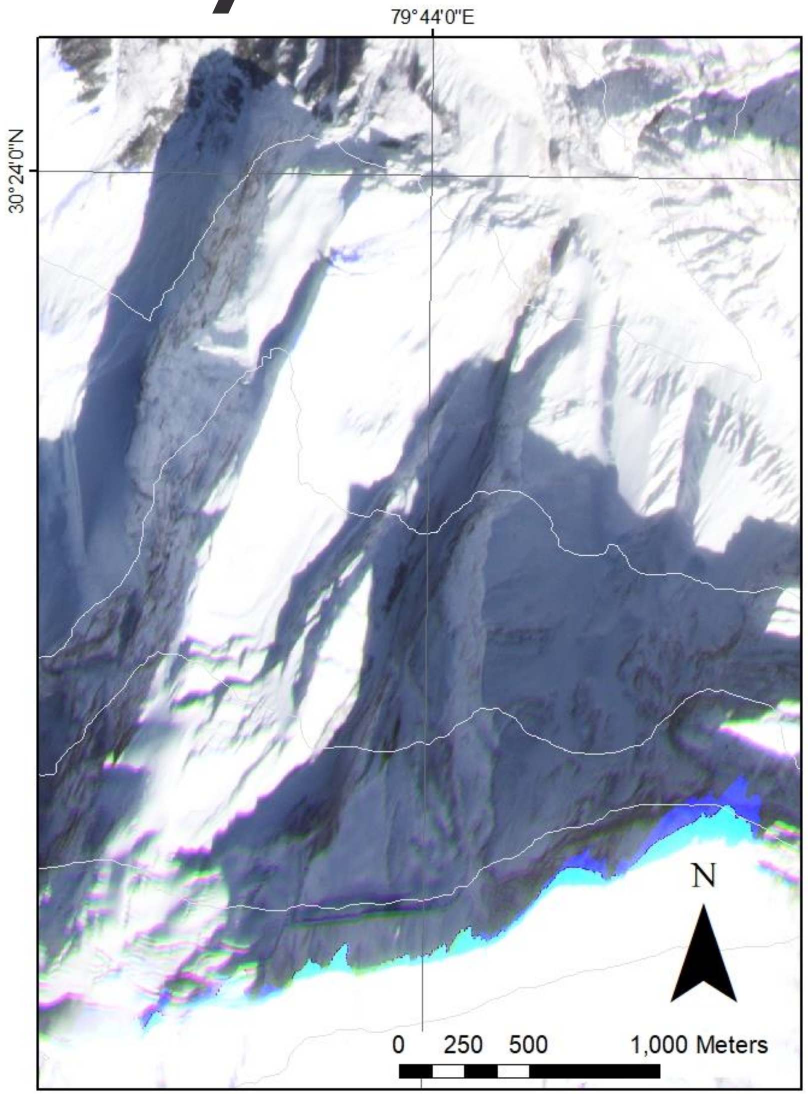
Climate change? Bad luck?

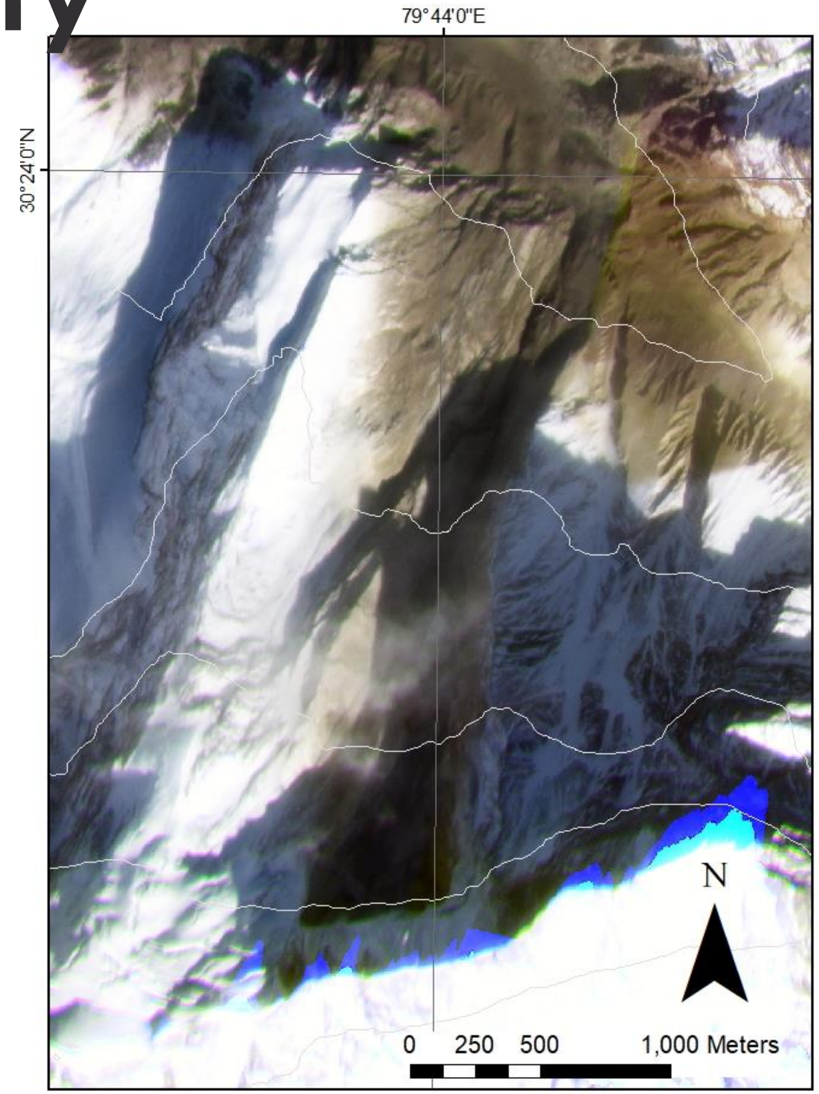
Previous ice avalanche in 2016

Ice/debris deposited in valley below



6 February vs 9 February

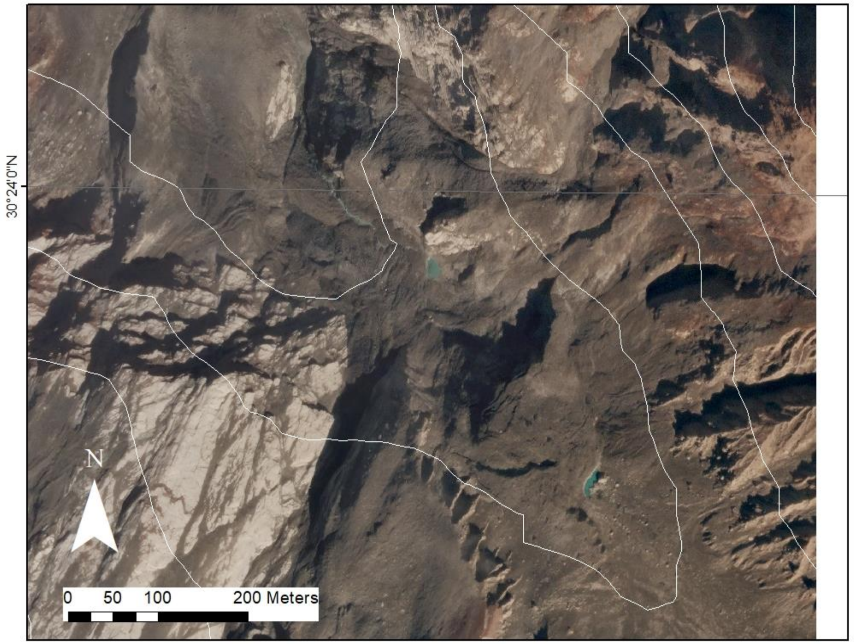




Impact hypothesis

1. Energy used for instantaneous melt (335 kJ needed for each kg of ice at 0°C)

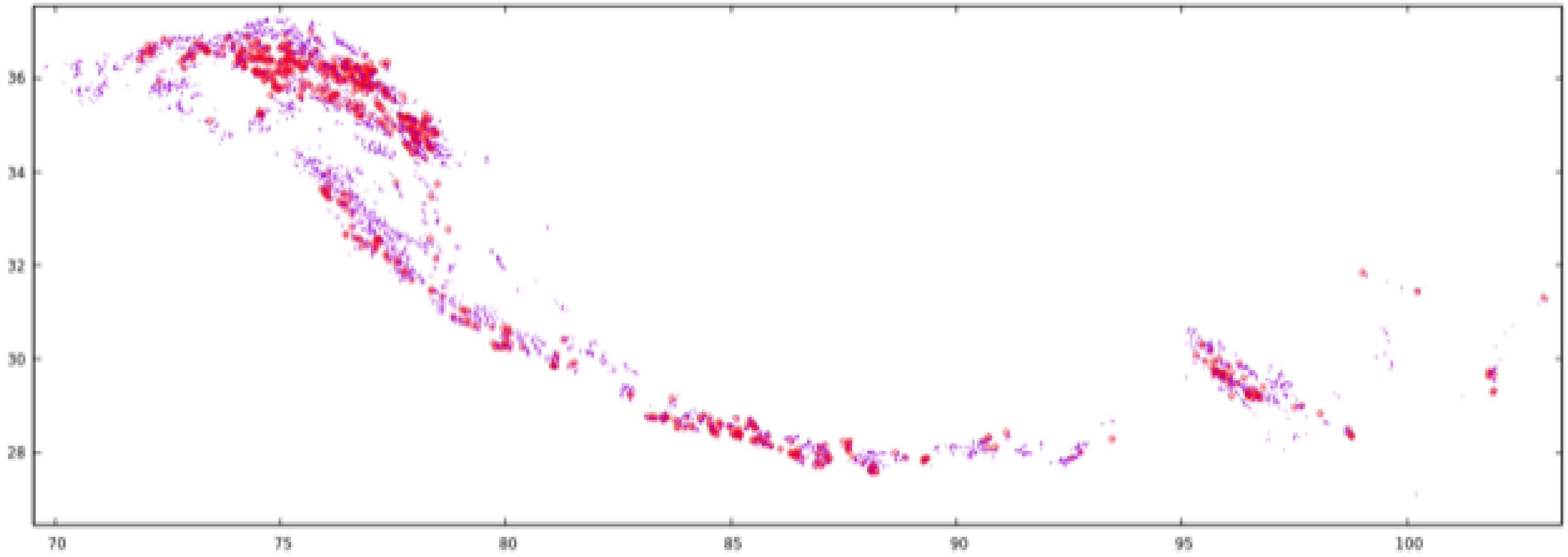
2. Energy used to blast a crater (equivalent to meteorites, studies on planets)



Is scaling this up possible?

Hanging glaciers in the Hindukush – Himalaya

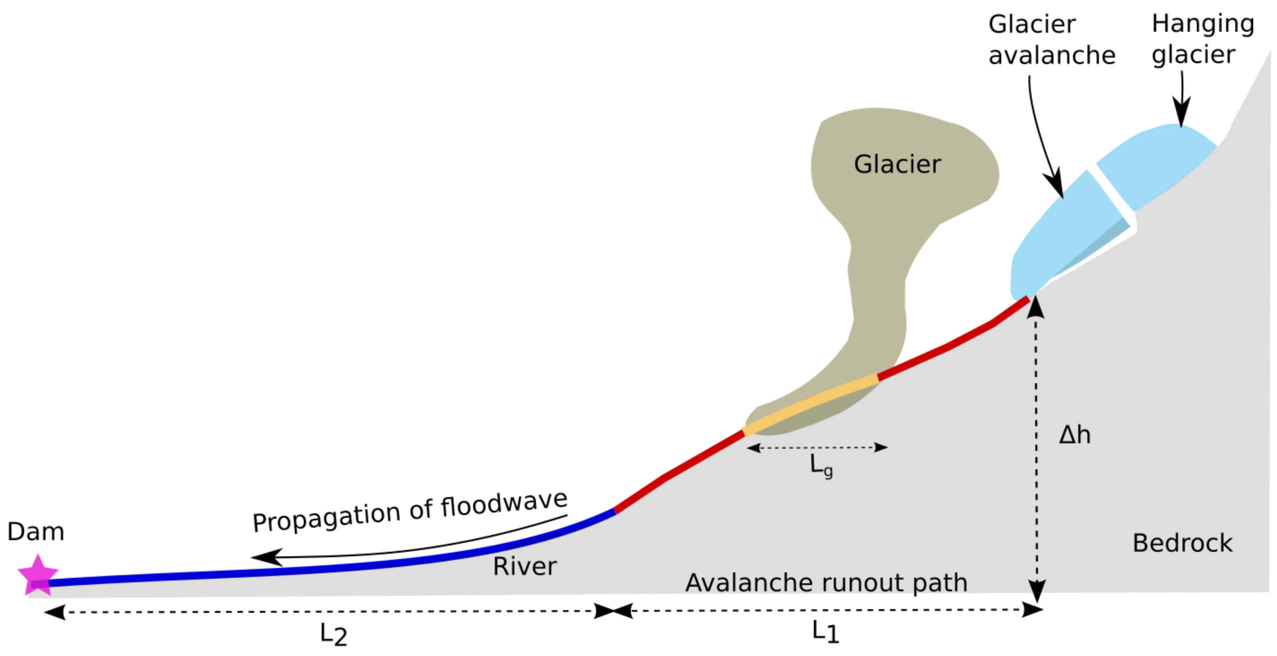
- steep slope and small size



Laha et al., 2024

Is scaling this up possible?

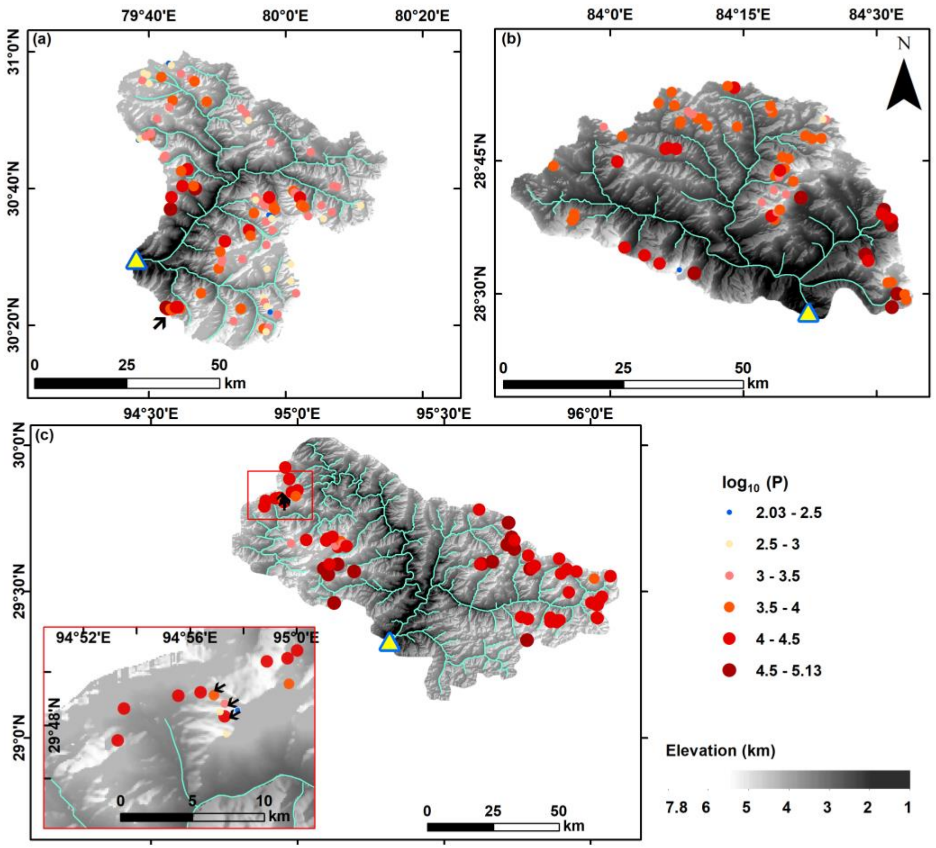
Simple model as a function of volume, slope and surface friction



Laha et al., 2024

Is scaling this up possible?

Lacking knowledge on hydropower/infrastructure locations



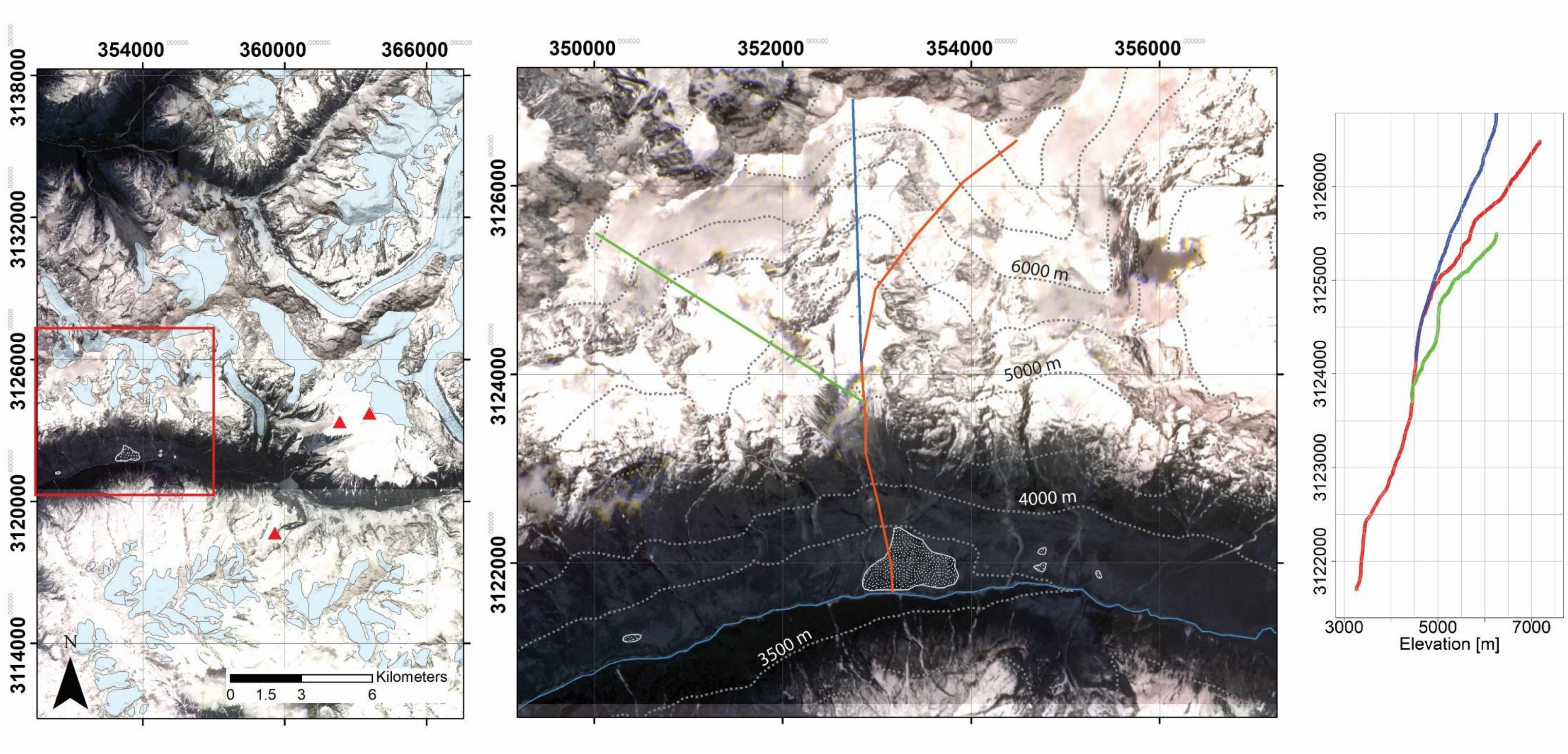
Laha et al., 2024

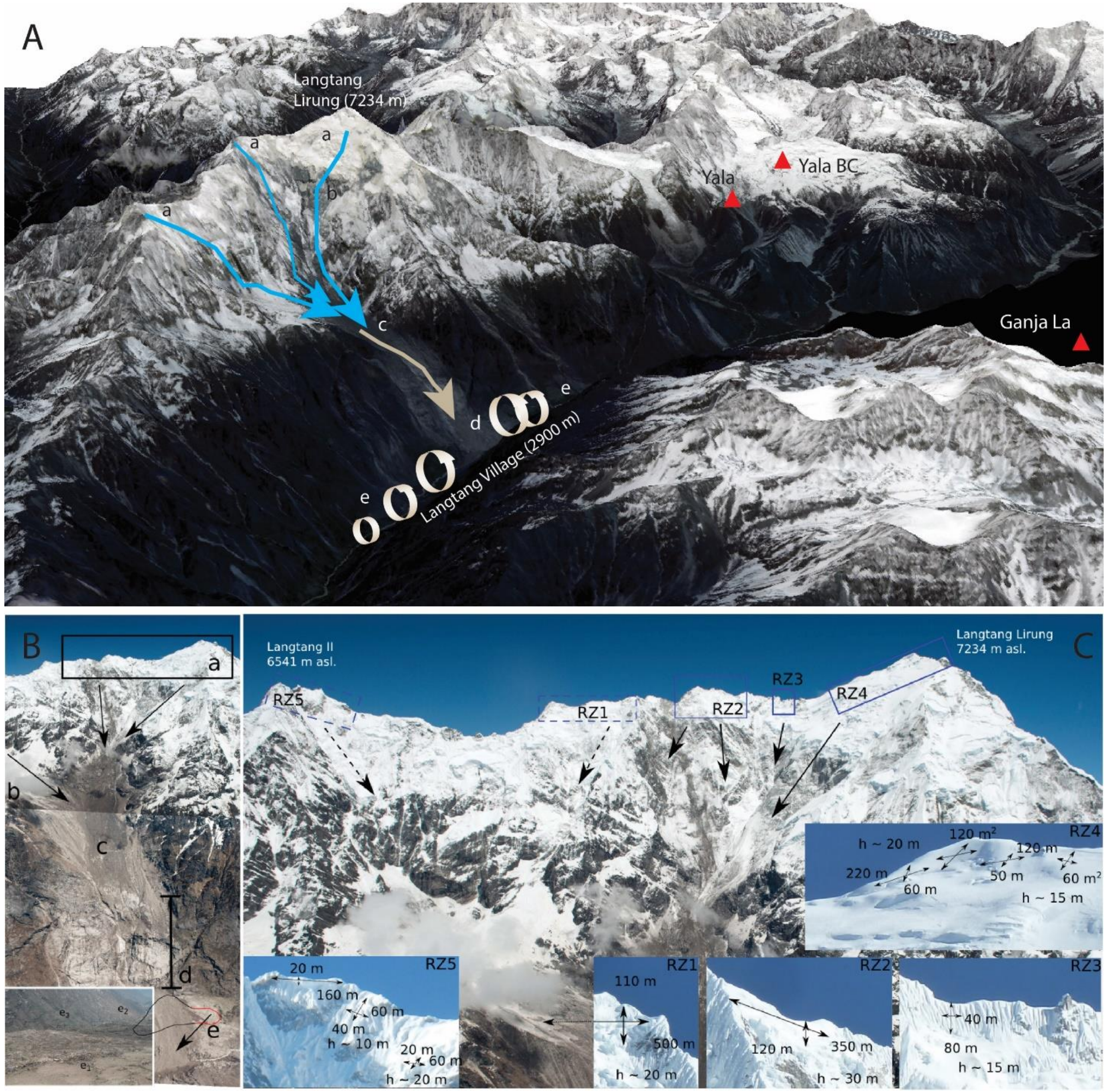
Results – co-seismic events

- Gorkha earthquake 2015 in Nepal
- >4000 co-seismic landslides
- Ice-break offs that caused deposits of up to 100 m depth
- Multi-hazard (ice break off + avalanche + debris flow)

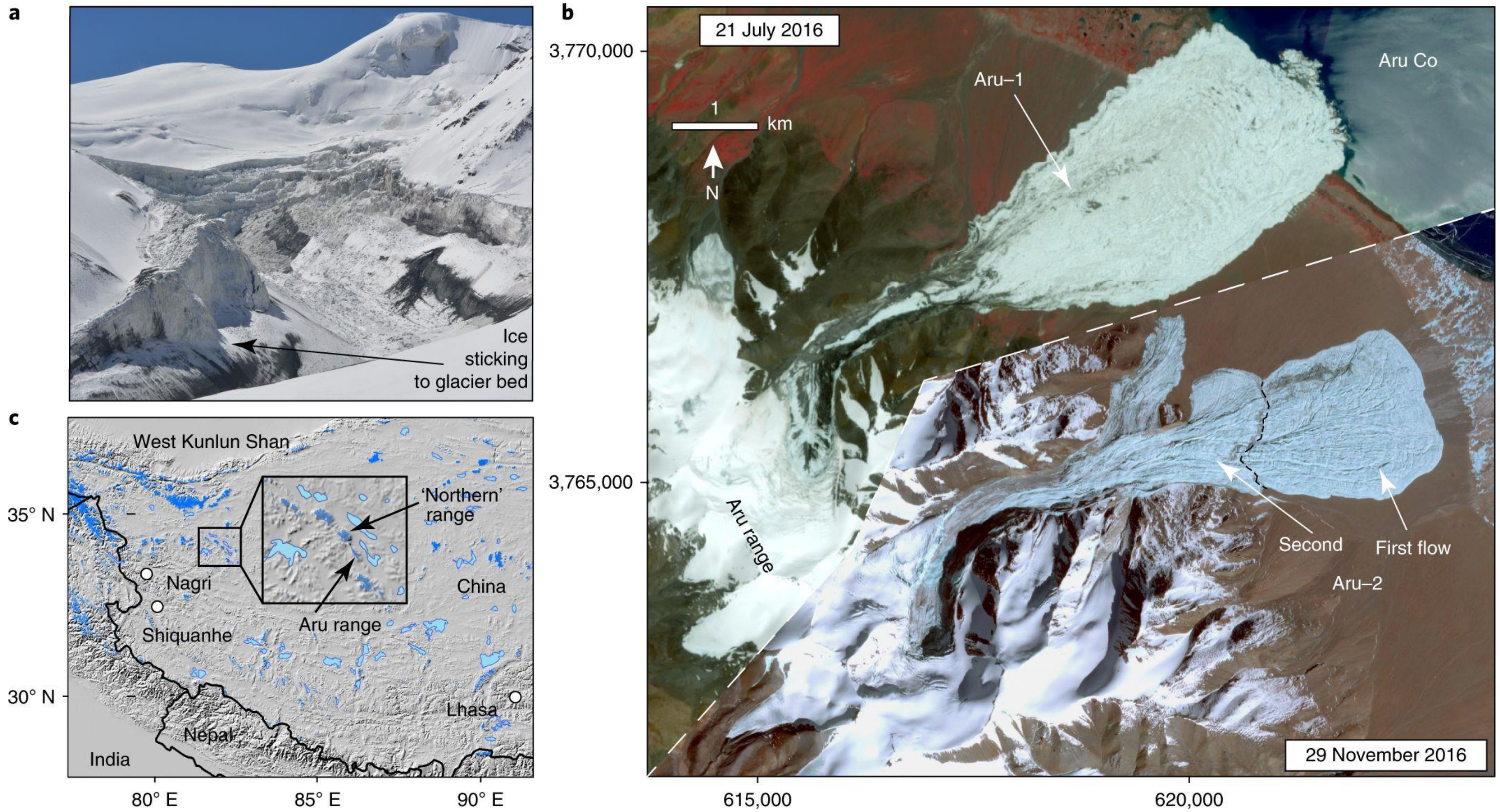
Kargel et al., 2016

Results – co-seismic events




A
Langtang
Lirung (7234 m)
a
a
a
b
c
d
e
e
Langtang Village (2900 m)
Yala
Yala BC
Ganja La
B
a
b
c
d
e
e_1
e_2
e_3
C
Langtang II
6541 m asl.
Langtang Lirung
7234 m asl.
RZ5
RZ1
RZ2
RZ3
RZ4
h ~ 20 m
120 m²
120 m
220 m
60 m
50 m
60 m²
h ~ 15 m
20 m
160 m
60 m
40 m
h ~ 10 m
20 m
60 m
h ~ 20 m
110 m
500 m
h ~ 20 m
120 m
350 m
h ~ 30 m
40 m
80 m
h ~ 15 m

Results – Internal glacier collapse

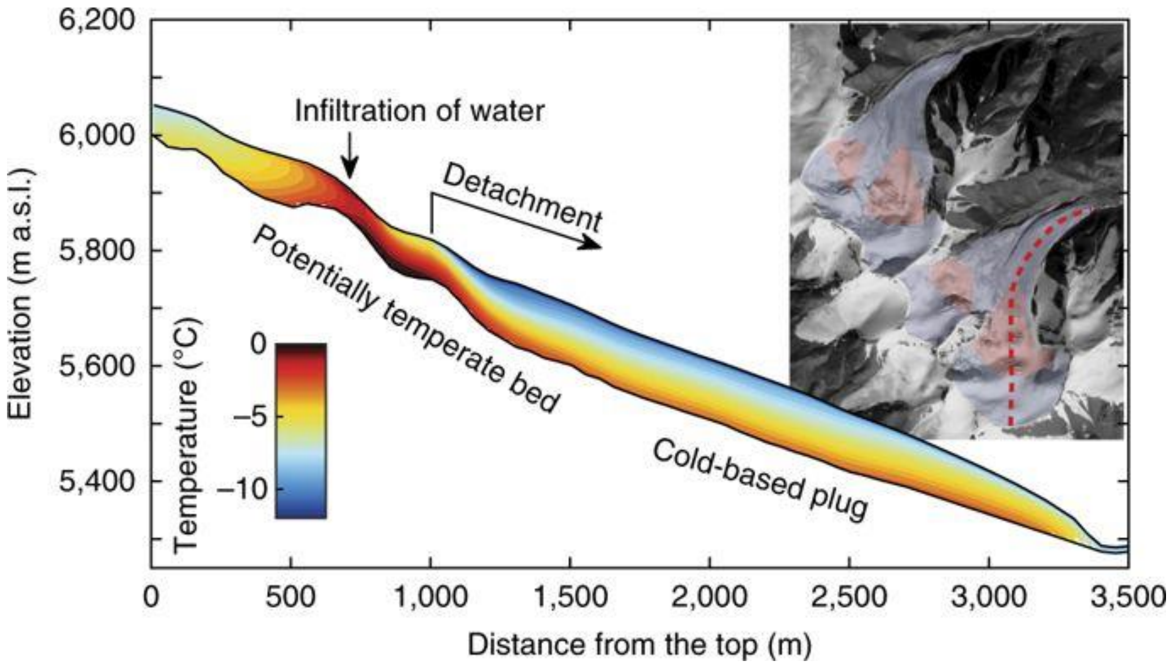


Kaab et al., 2018

- Regional temperature increase leads to internal 'melt lakes'
- Once pressure becomes too high and ice instable, the glacier 'fails'
- So far singular events (2) but with catastrophic consequences (>125 deaths in Russia during the Kolka slide in 2002)

Kaab et al., 2018

Gilbert et al., 2018



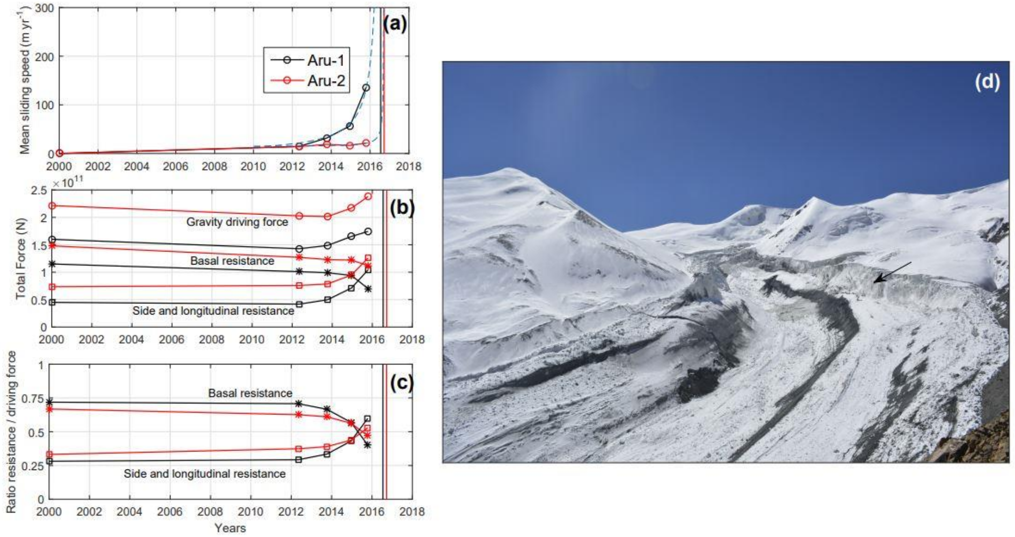


Figure 9. **(a)** Mean sliding speed of the detachment zone for Aru-1 (black) and Aru-2 (red) glaciers. The dashed blue lines show predicted speed following an empirical law of slope failure (Voight, 1990). **(b)** Force balance acting on the detachment of Aru-1 (black) and Aru-2 (red). **(c)** Ratio of resisting force over driving force for Aru-1 (black) and Aru-2 (red). Vertical lines show collapse dates in the three panels. **(d)** The Aru-2 glacier detachment zone on 4 October 2016 (Picture from T. Yao). The side resistance computed in the force balance analysis arises from lateral shearing on the right side of the detachment (black arrow).

Glacier related hazards

glacier lake outburst floods (+ resulting events)

ice break offs (+ resulting events) / collapsing glaciers

glacier length variations

destabilization of frozen soils/slopes

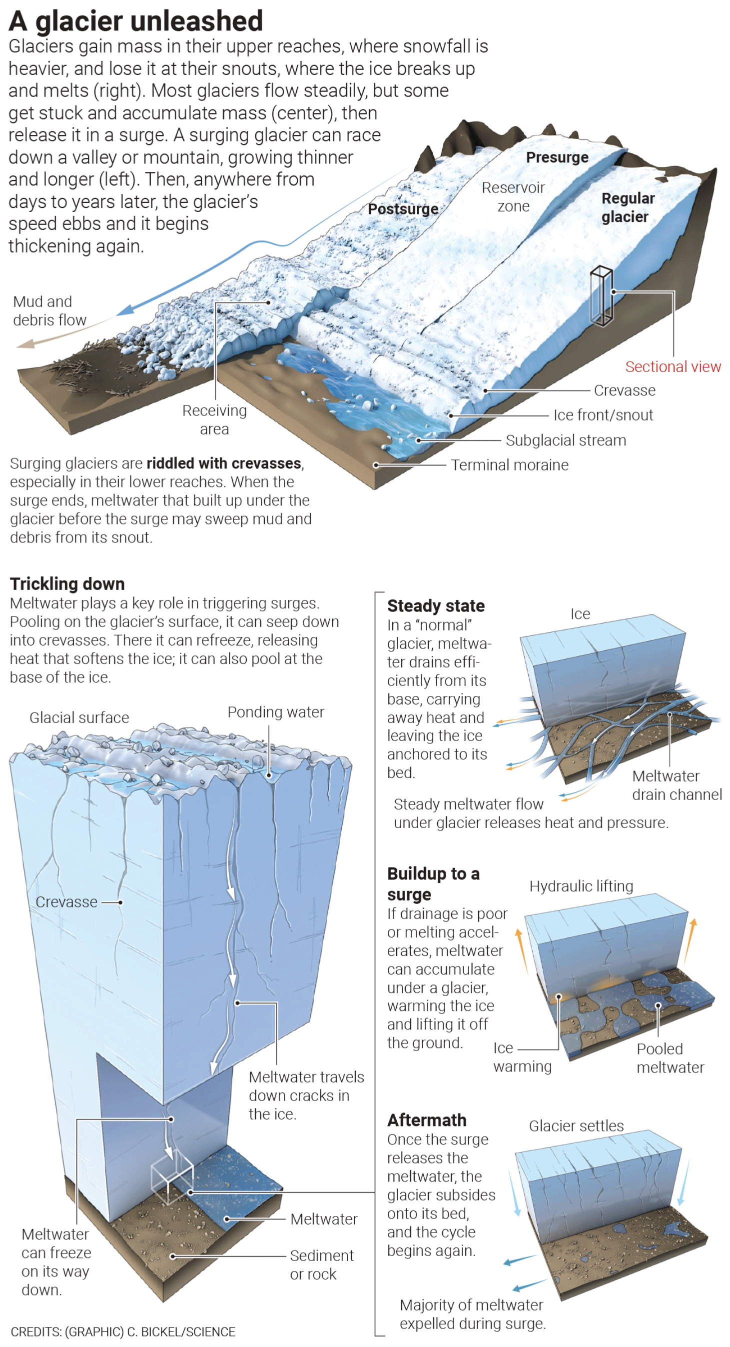
Glacier length variations surges

Glacier tongues extend within days to weeks by 100s of meters

Decadal return period

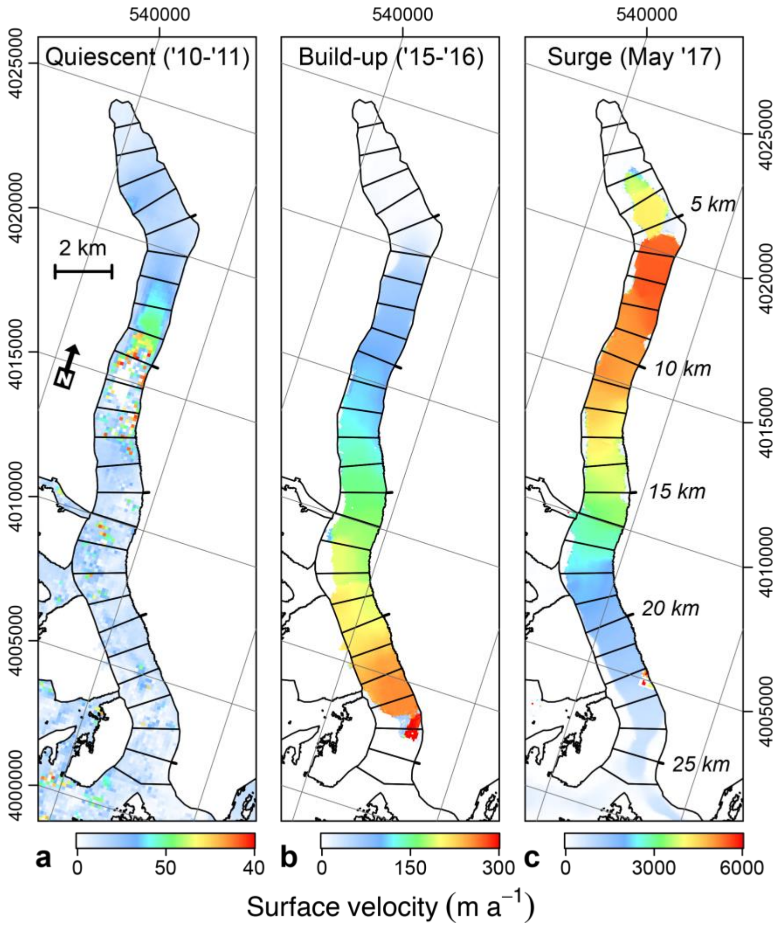
No net mass gain or loss

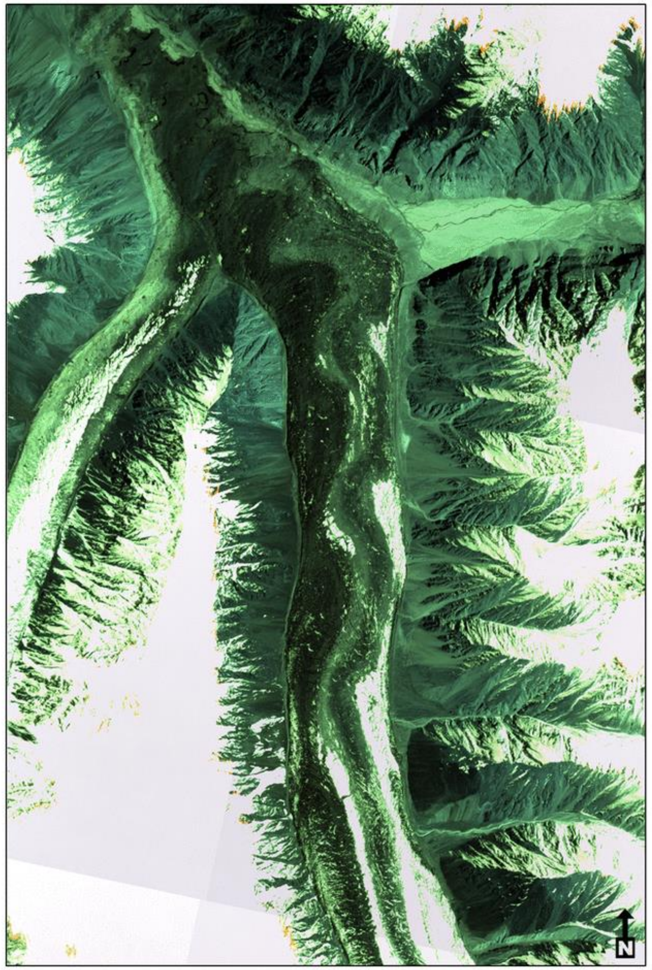
Unclear why these events happen – no apparent link to changing climate



Surge in Karakoram 2017

Glacier velocities from remote sensing





Steiner et al., 2018, Cryosphere

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destabilization of frozen soils/slopes

Kaab et al., 2005

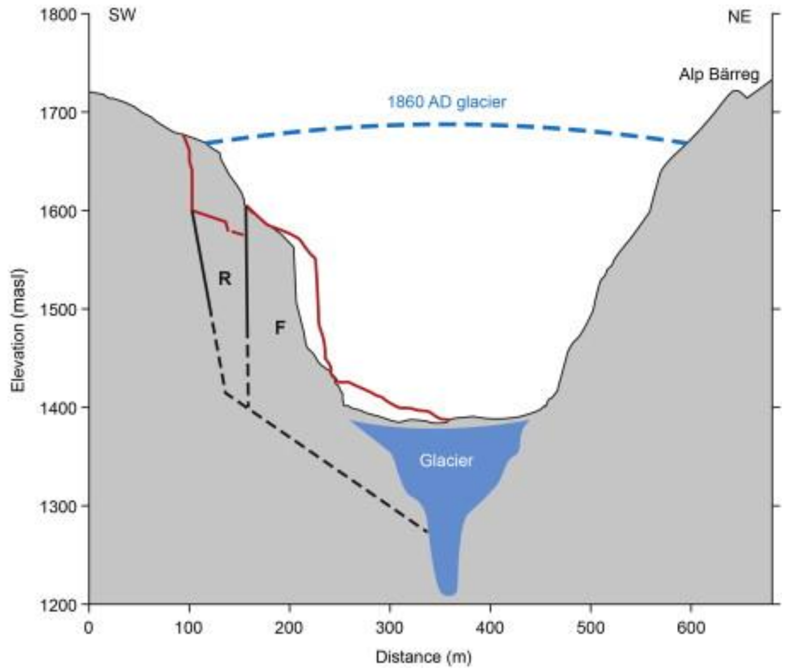
Destabilization of frozen soil

Increased rock slope failure in post-glaciated environments

Dependent on geology

Freeze-thaw within rock cracks

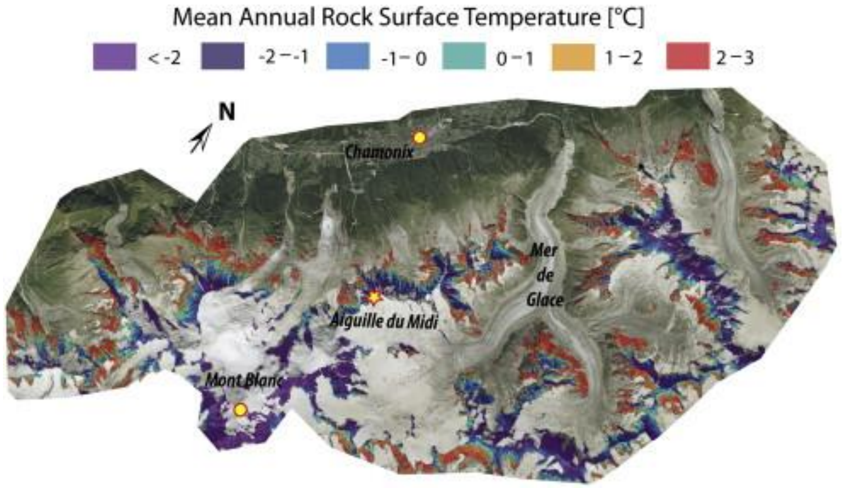
Isostatic rebound after deglaciation



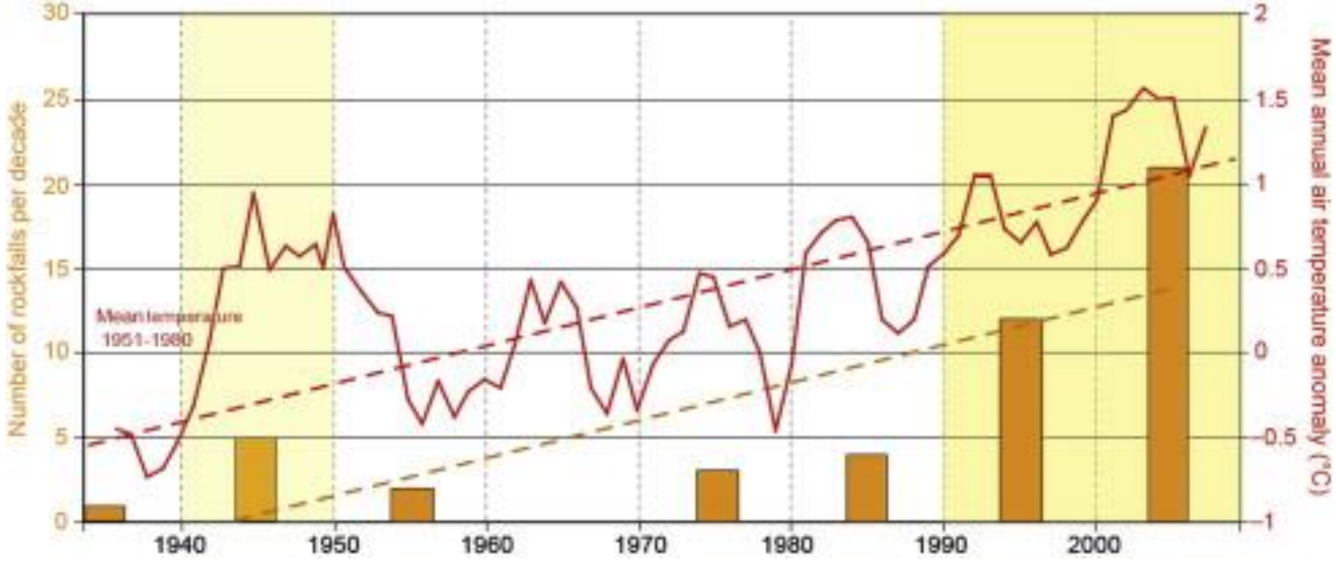
Deline et al., 2015

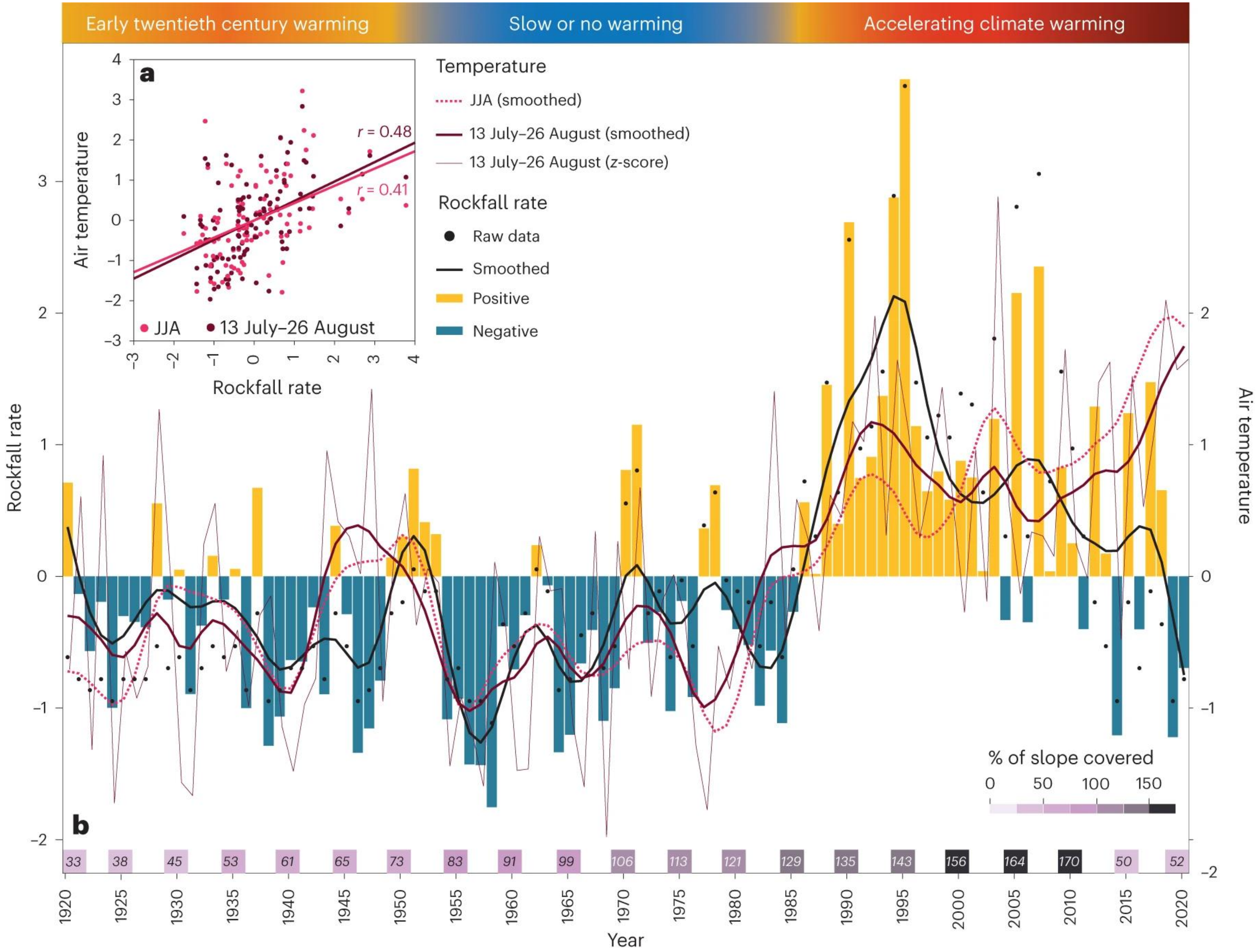
Destabilization of frozen soil

- Likely direct link with increasing temperatures

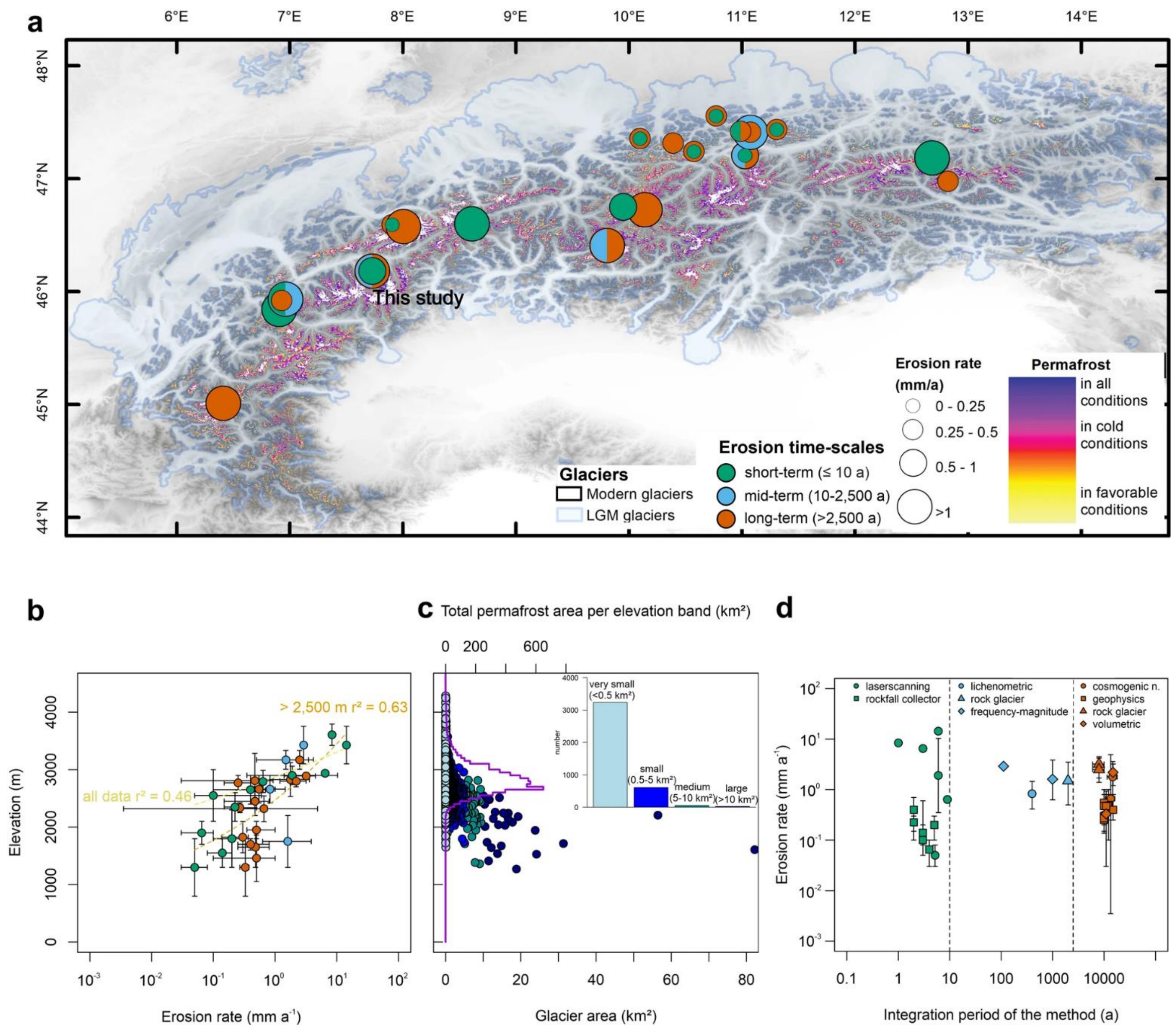


Deline et al., 2015





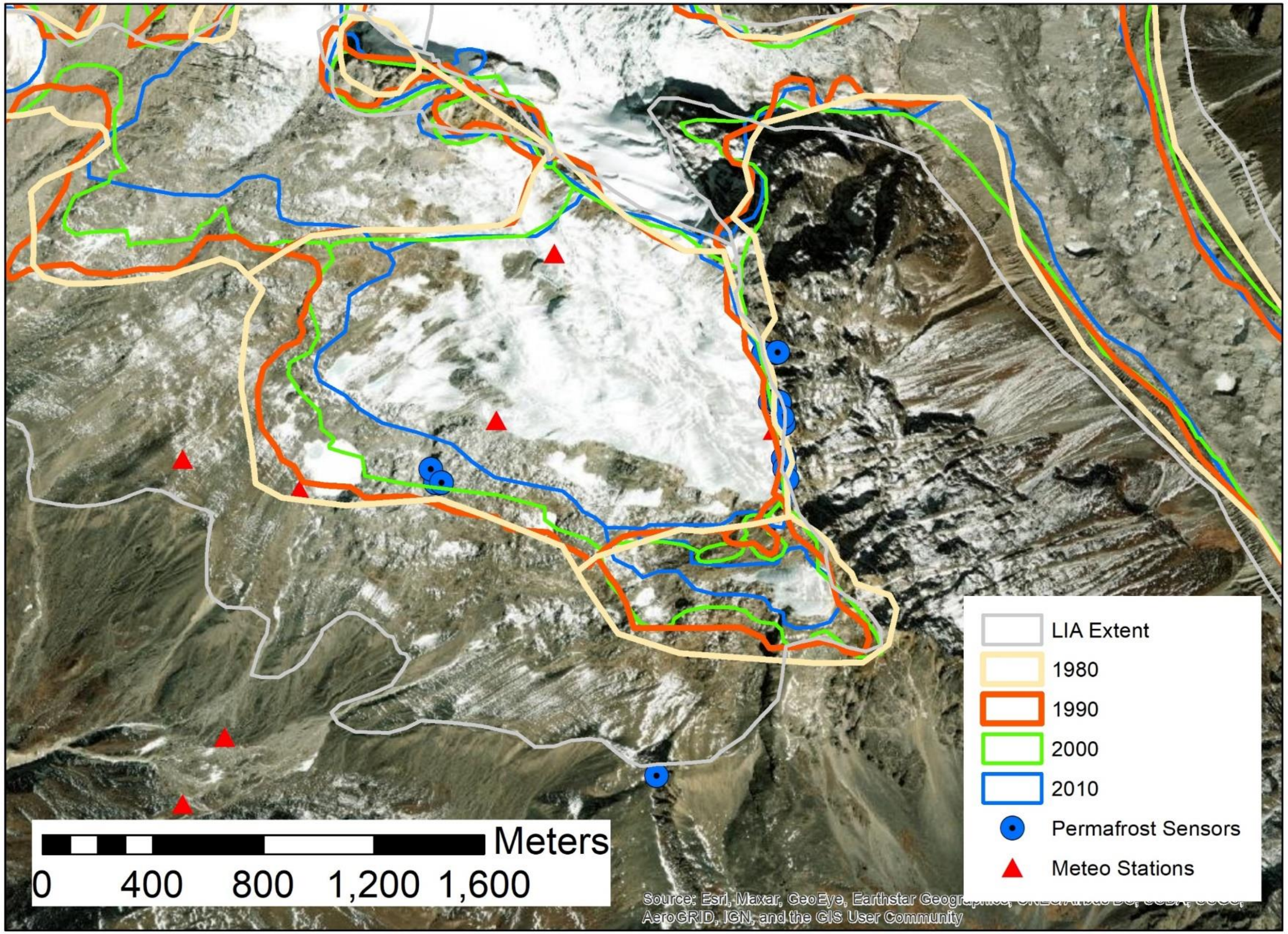
Stoffel et al., 2024



Draebing et al., 2022

Incre

- Wh


LIA Extent
1980
1990
2000
2010
Permafrost Sensors
Meteo Stations
Meters
0 400 800 1,200 1,600
Source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Inc

• W

Effects downstream – debris flows

Destabilization of frozen soil

Beyond the glaciers – cryosphere hazards

Snow avalanches

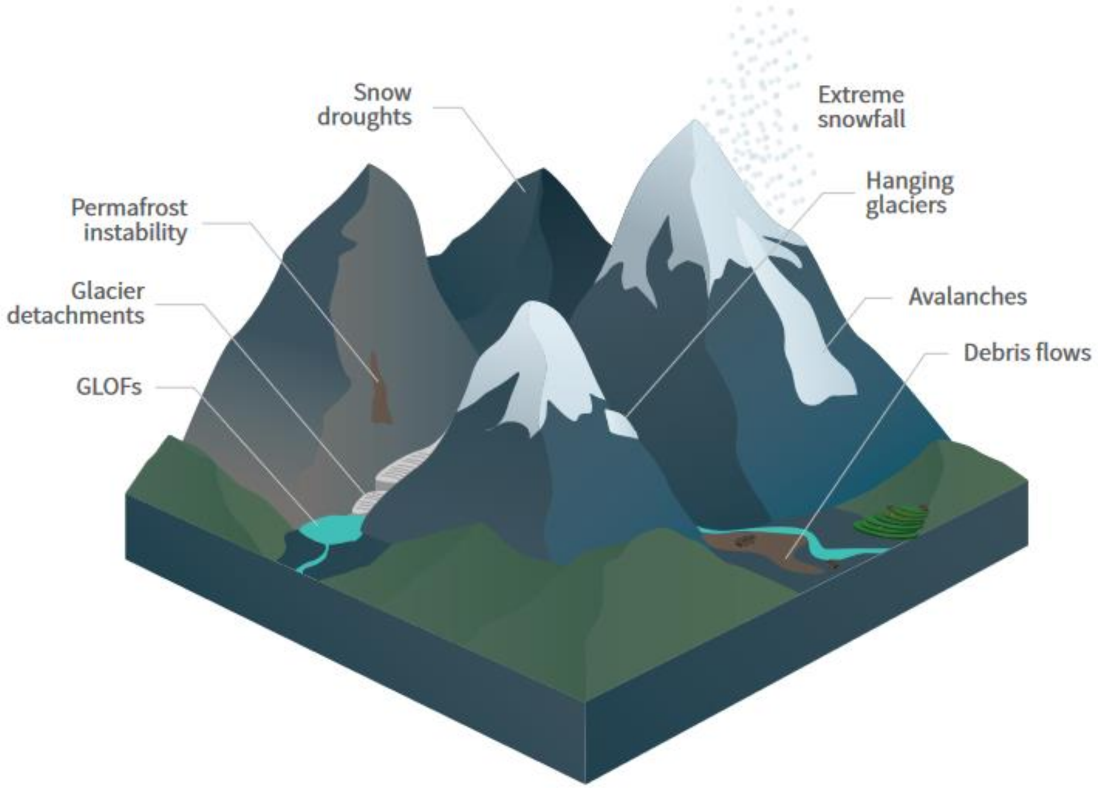
Snow drought

Unstable slopes due to permafrost thaw

Debris flows/landslides as a result of unstable slopes

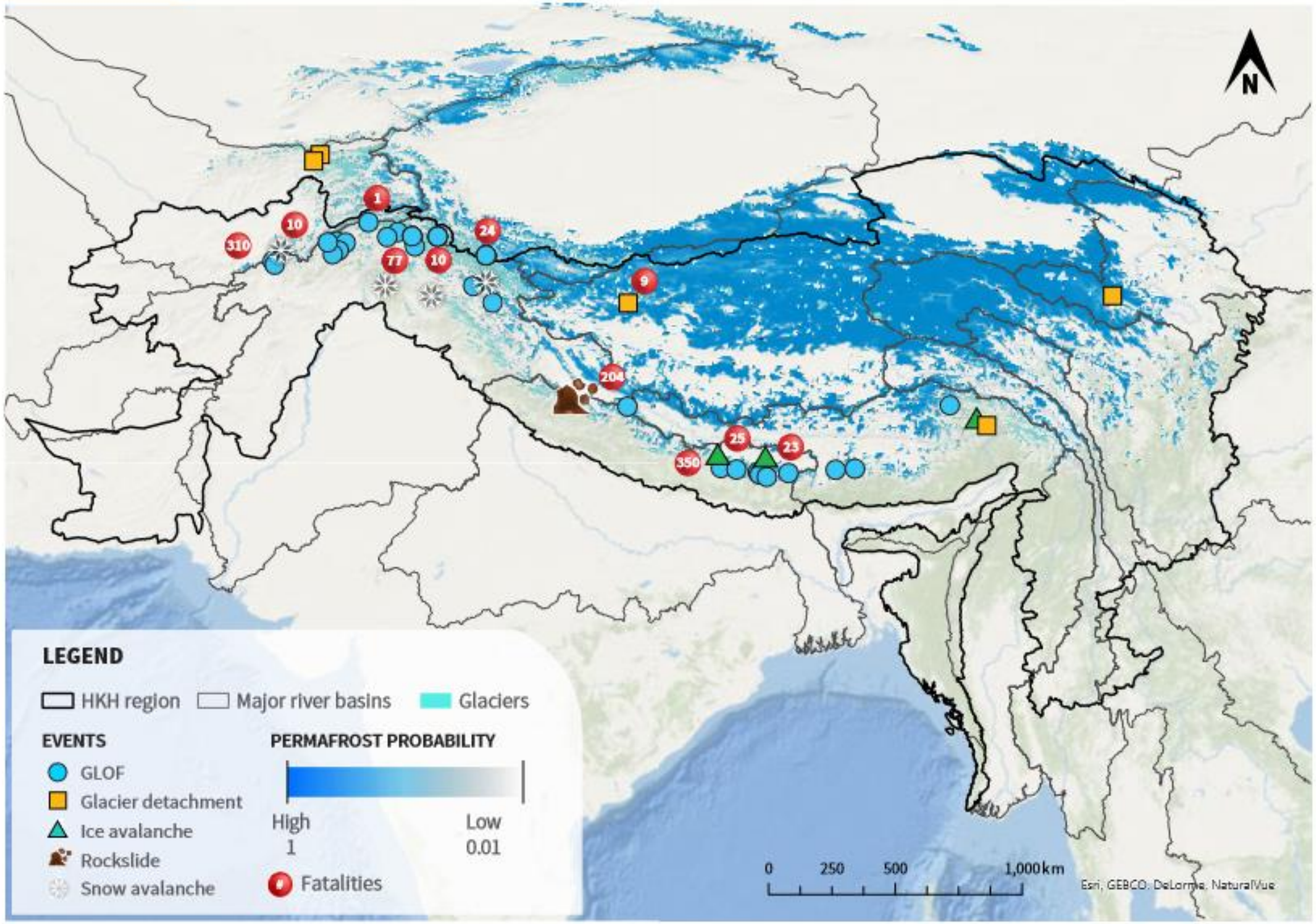
Methane emissions as a result of permafrost thaw

FIGURE 3.5 **A SCHEMATIC REPRESENTATION OF THE DOCUMENTED HAZARDS RELATED TO THE CRYOSPHERE AND HYDROSPHERE IN THE HKH**



Nepal, Steiner et al. (2023)

FIGURE 3.6 OVERVIEW OF ALL RECORDED CRYOSPHERE-RELATED EVENTS IN THE HKH SINCE 2015



Notes: Events are coloured and symbolised by type. Numbers indicated are fatalities for individual events. Permafrost probability is based on data from Obu (2021). The bold black outline marks the HKH outline, permafrost extent is shown in blue, glacier outlines are shown in cyan.

Topics

Terminology: Hazards. Risks. Mitigation.

Global ice and exposure to hazards

Types of glacial hazards

Hazard Assessment: Mapping and Modelling

Monitoring and risk mitigation

Hazard Mapping

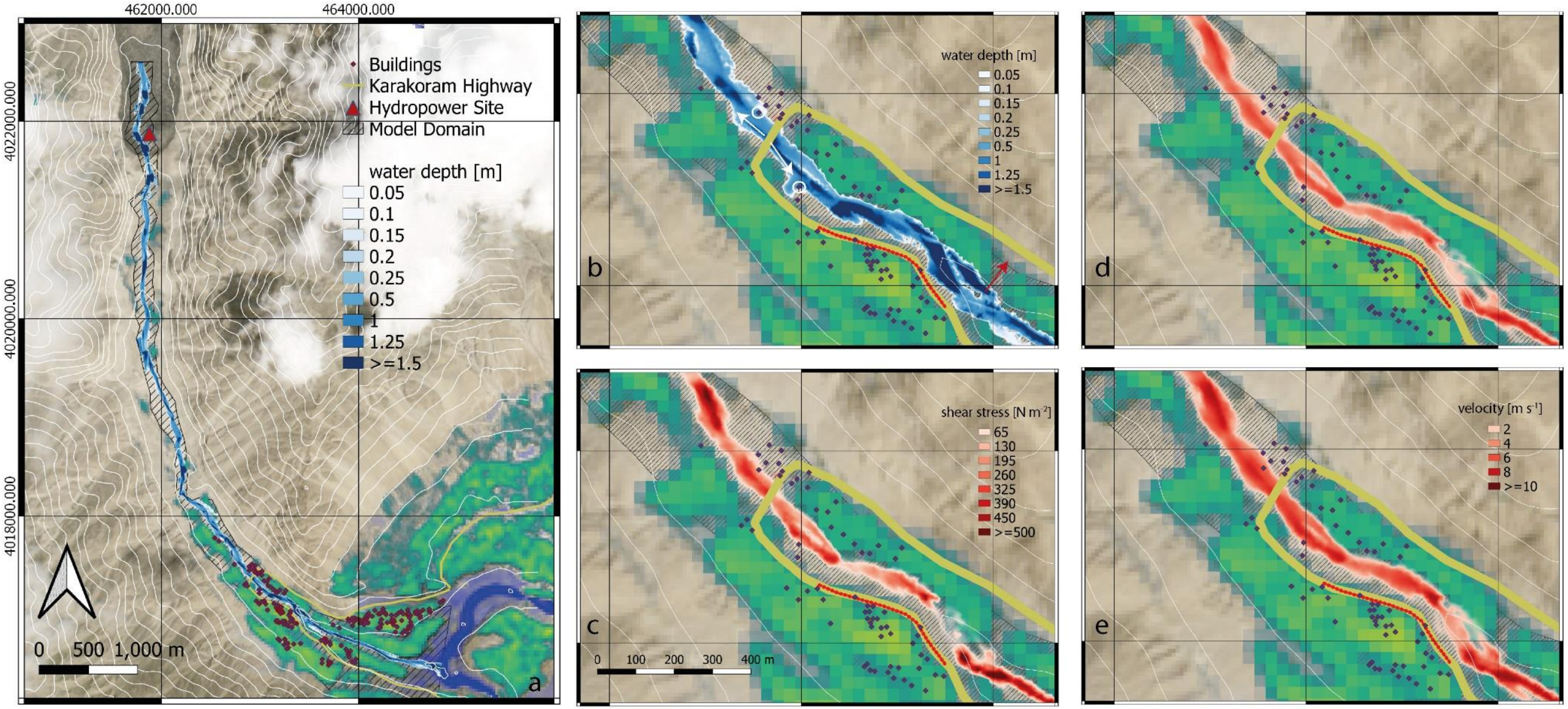
Remote sensing

- Maps of potential instable areas
- Identification of weak moraines/ice cores/rapid surface changes on glaciers
- Slope maps + exposure to solar radiation (freeze thaw cycle)
- Exposure maps

Field based

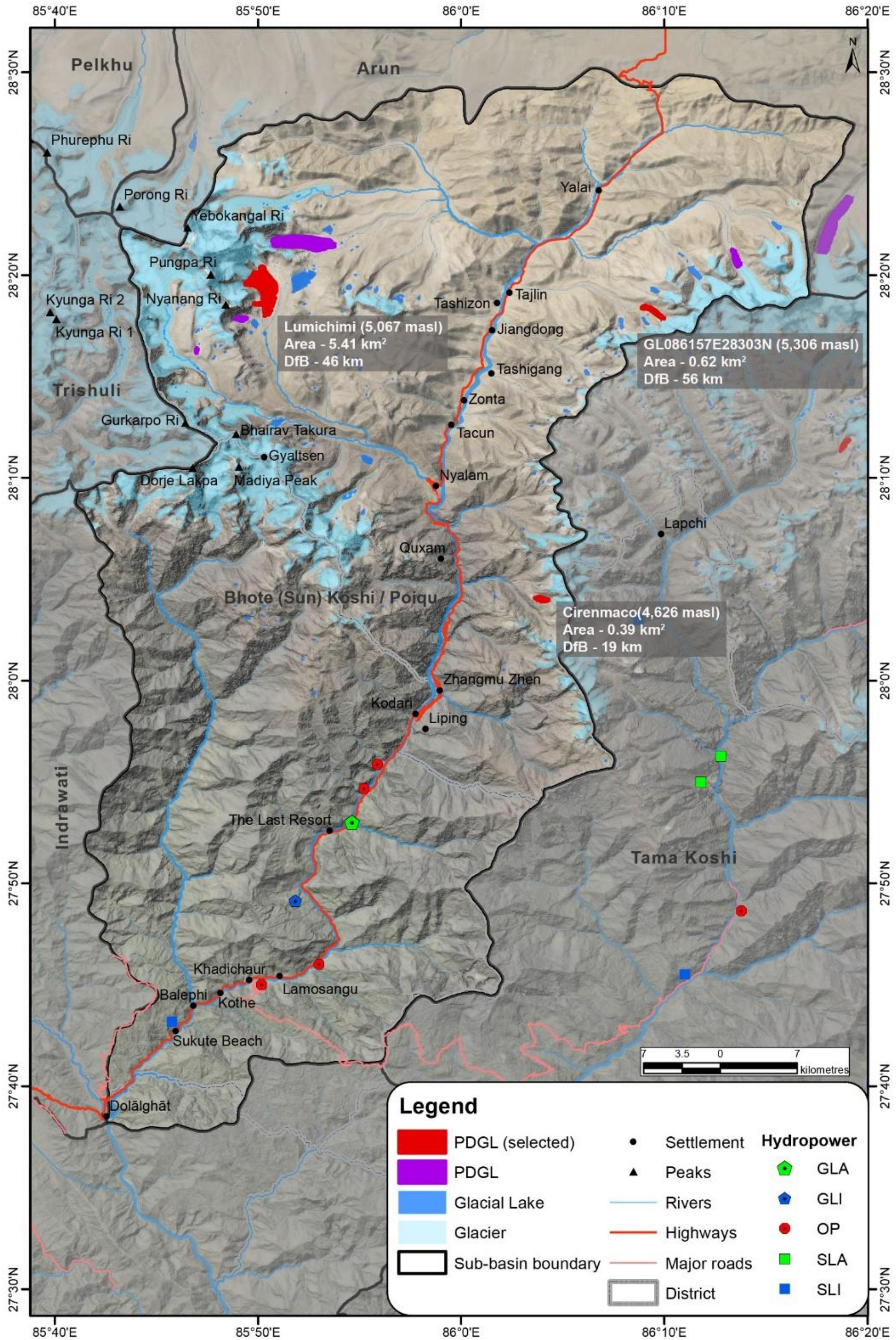
- Runout lengths
- Damage classification (pressure, inundation)
- Interviews

Example GLOFs – *Impact*



Muhammad et al., 2021

- Transboundary multi-hazard and risk assessment
- China-Nepal border



Local and Indigenous knowledge

- Focus Group Workshops
- Interviews
- Awareness Raising

Shimshal, Pakistan

Melamchi, Nepal

Local and Indigenous knowledge

- How do we turn local knowledge into (western) scientific data?

Acharya et al., 2023

Topics

Terminology: Hazards. Risks. Mitigation.

Global ice and exposure to hazards

Types of glacial hazards

Hazard Assessment: Mapping and Modelling

Monitoring and risk mitigation

Monitoring and hazard mitigation

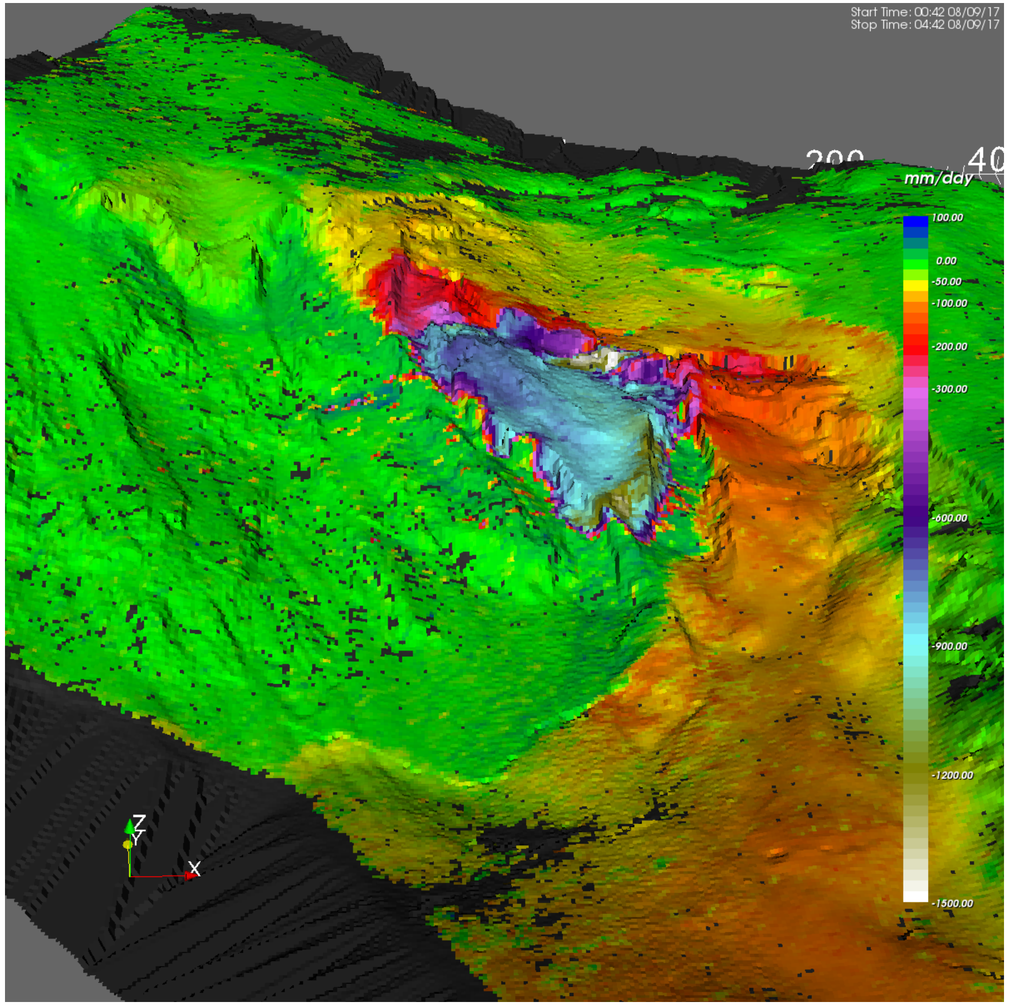
Remote Sensing

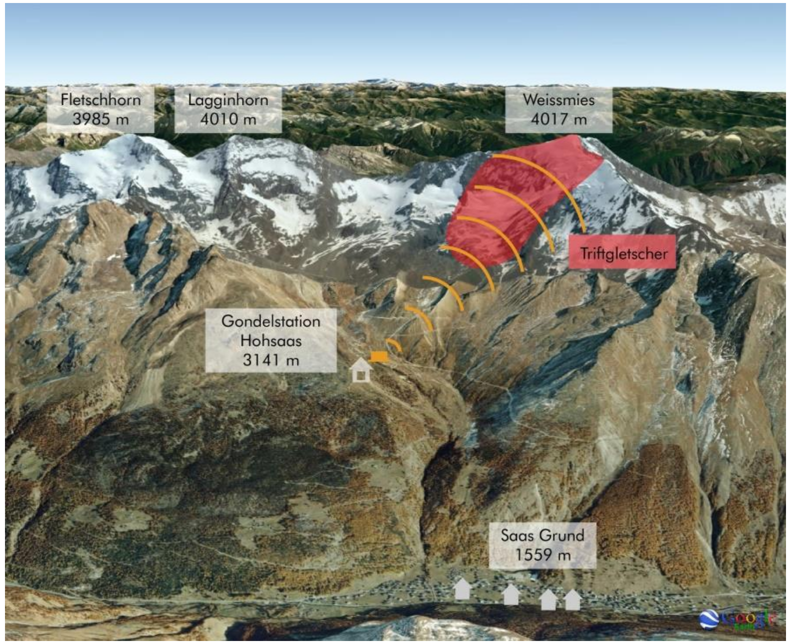
- new near real-time products for observations (Planet, Sentinel, new Radar satellites …)
- Temperature/Precipitation products

Field based

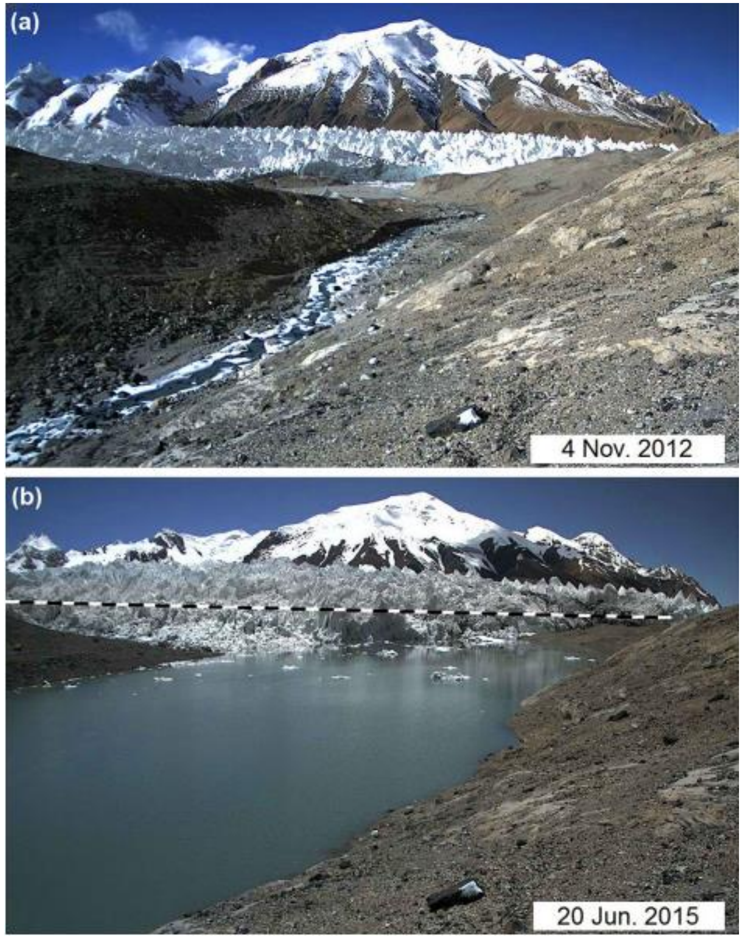
- climate and discharge monitoring
- radar monitoring

Monitoring ice falls

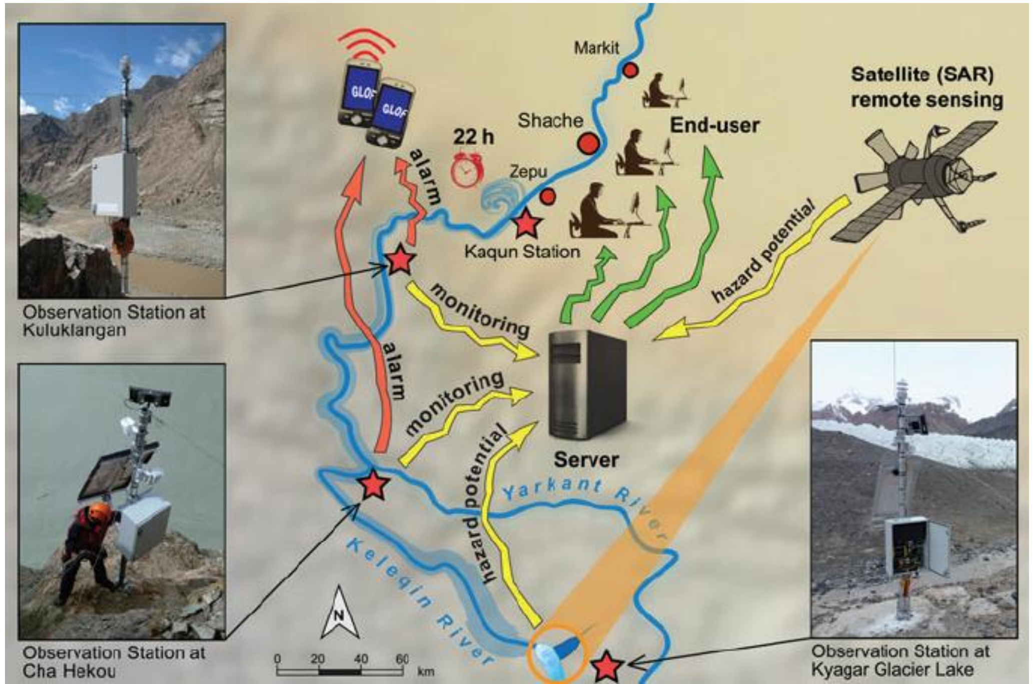




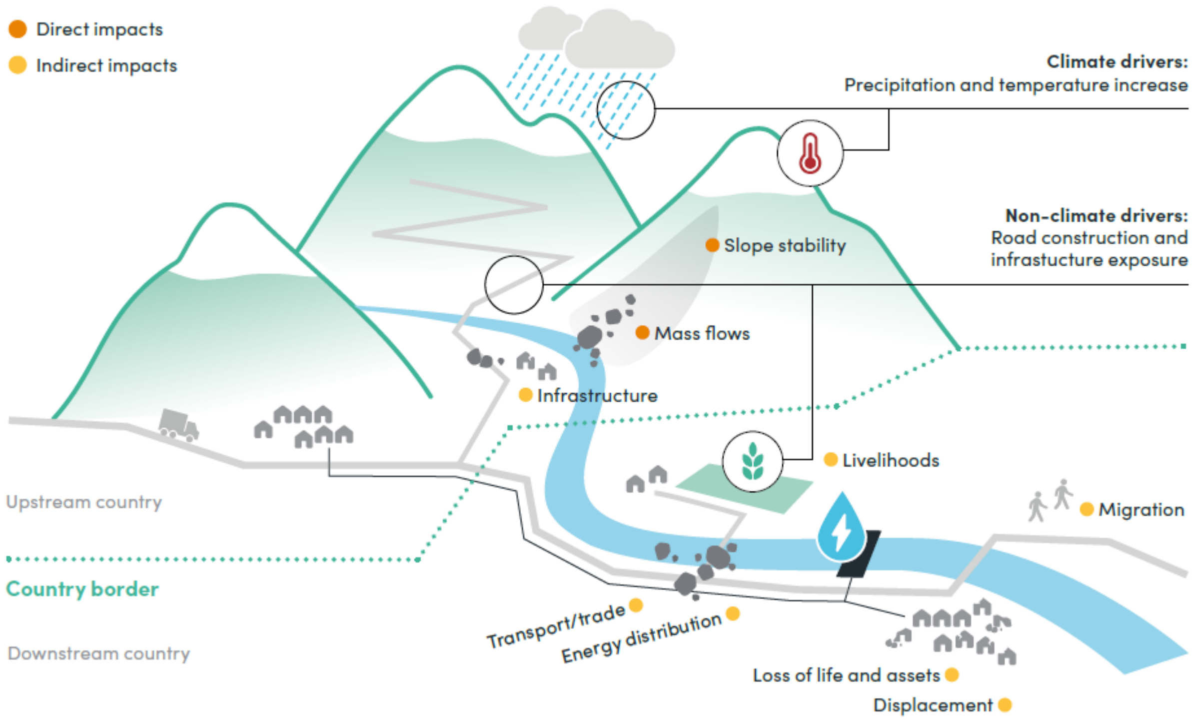
Monitoring a glacier lake




DCP
Tipping Bucket
RLS
Volumetric Water Content Sensor
Siren


Markit
Shache
Zepu
22 h
Kaqun Station
End-user
Satellite (SAR) remote sensing
hazard potential
alarm
monitoring
alarm
monitoring
hazard potential
Server
Yarkant River
Keleqin River
Observation Station at Kuluklangan
Observation Station at Cha Hekou
Observation Station at Kyagar Glacier Lake
0 20 40 60 km

Risk



Steiner et al., 2023

Upstream – downstream linkage

Cascading hazards and risks (*knock on effects*)

Transboundary risk

Local challenges – Alps vs Himalaya

- Similar glacial hazards
- Population in relatively remote areas directly exposed
- Expensive infrastructure (Nepal/Pakistan: trade to China; India: connection to tourism areas; Switzerland: everything is expensive …)
- (Geo-)Politics? Willingness/ability to pay? Institutional development?

Grindelwald Switzerland

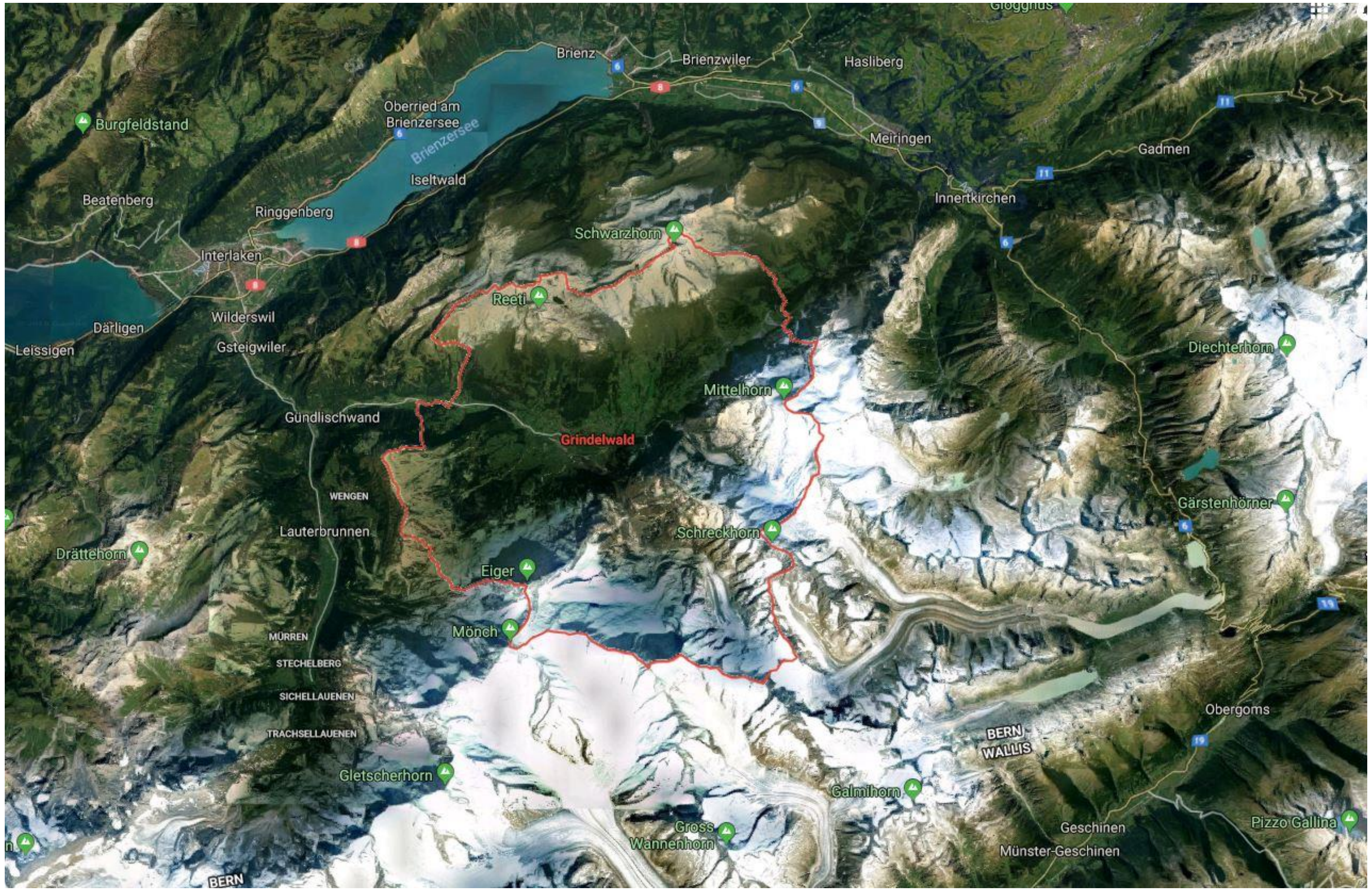
Glacial lake formed repeatedly

Concerns about possible downstream damages

Classical compound event

Who decides? Who pays?

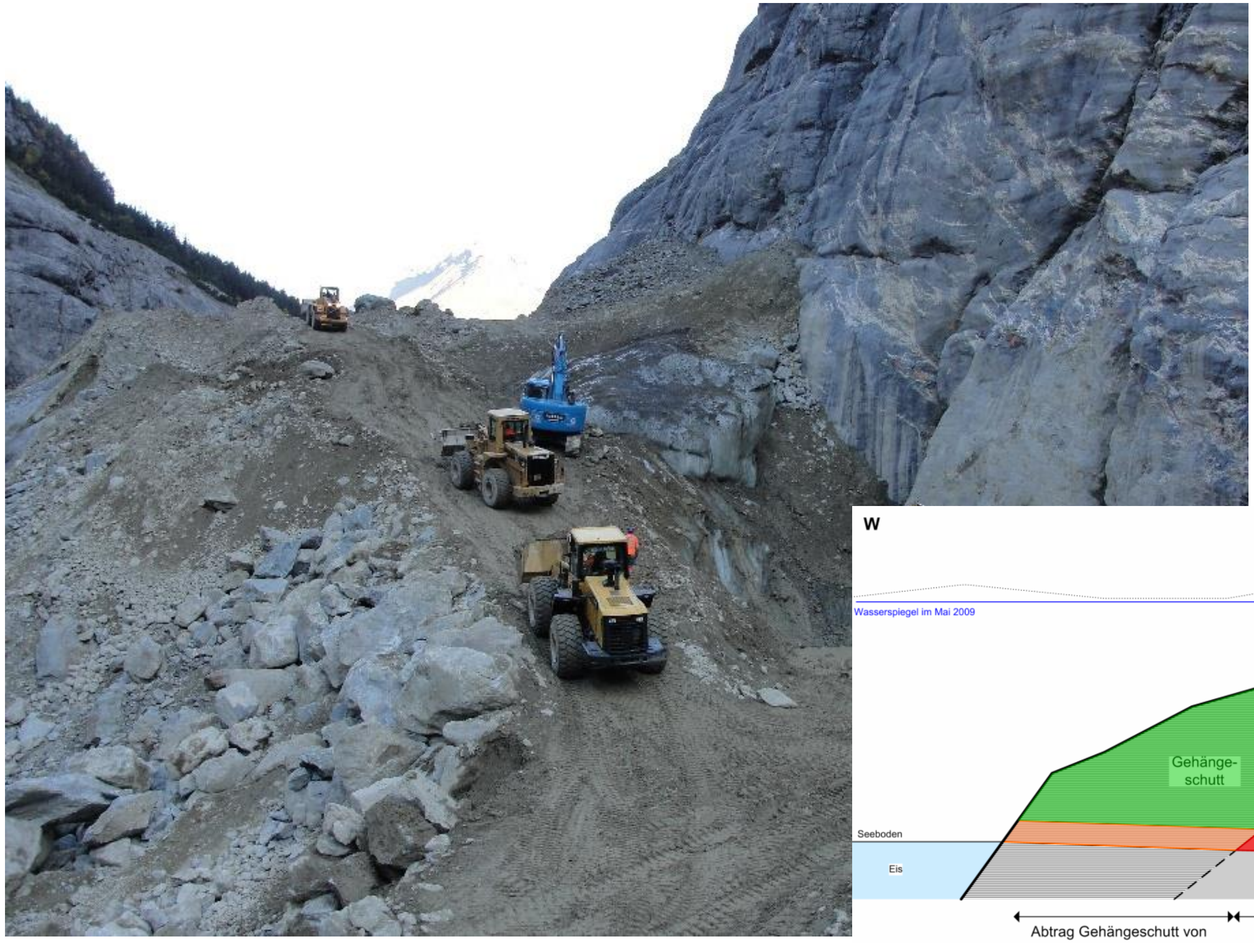
Grindelwald Switzerland

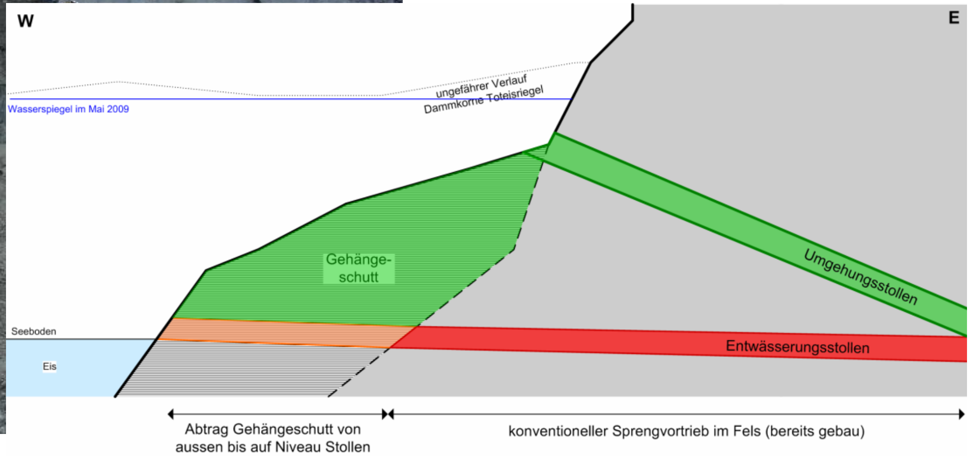


Formation of a glacier lake

Slumping moraines and rockfall

Decision to build a tunnel …





… and then the lake emptied naturally

Shimshal glacier lake (Pakistan)

Lake forms as a result of a glacier surge

Damages to local roads and agriculture

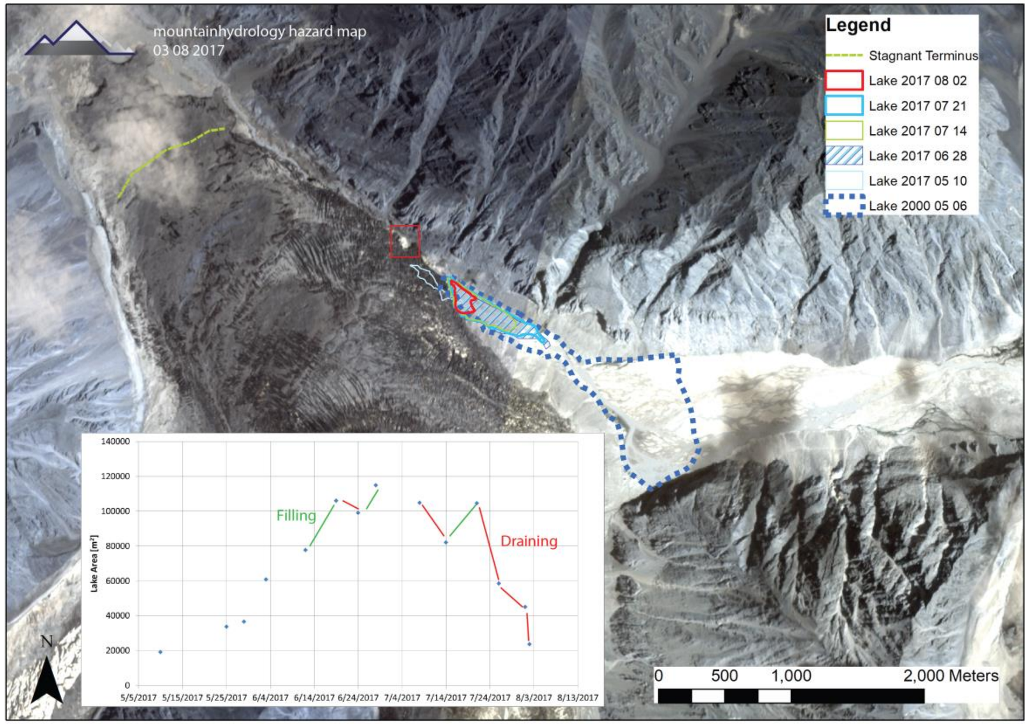
Politically instable

Difficult to access (no telephone, bad roads)

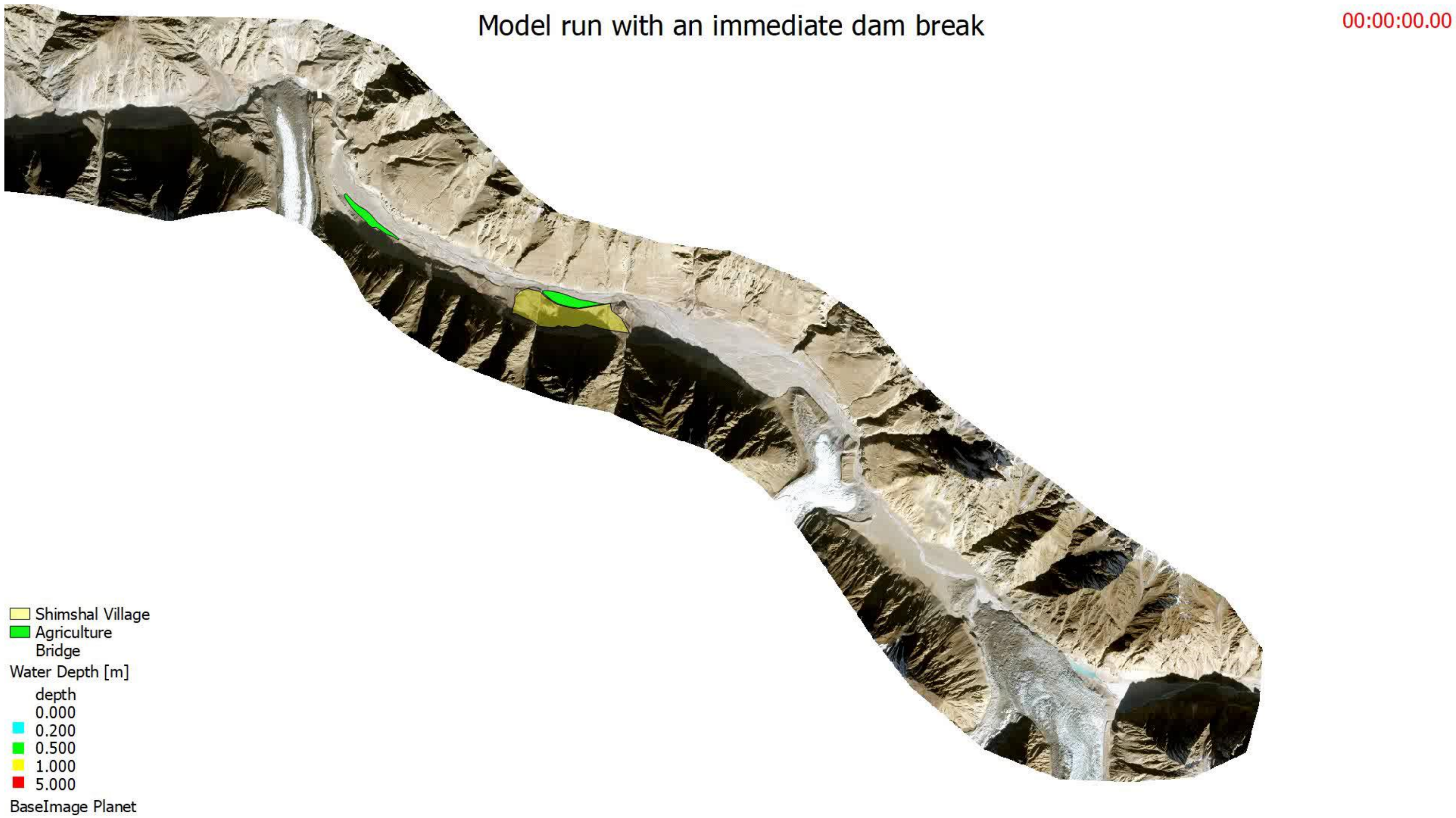
Scenarios

Volume = f(Area)

Discharge = f(Volume, dam break scenario)



Hydrodynamic modelling



Institutional challenge