



Glacial Hazards

Risk Assessment and Mitigation

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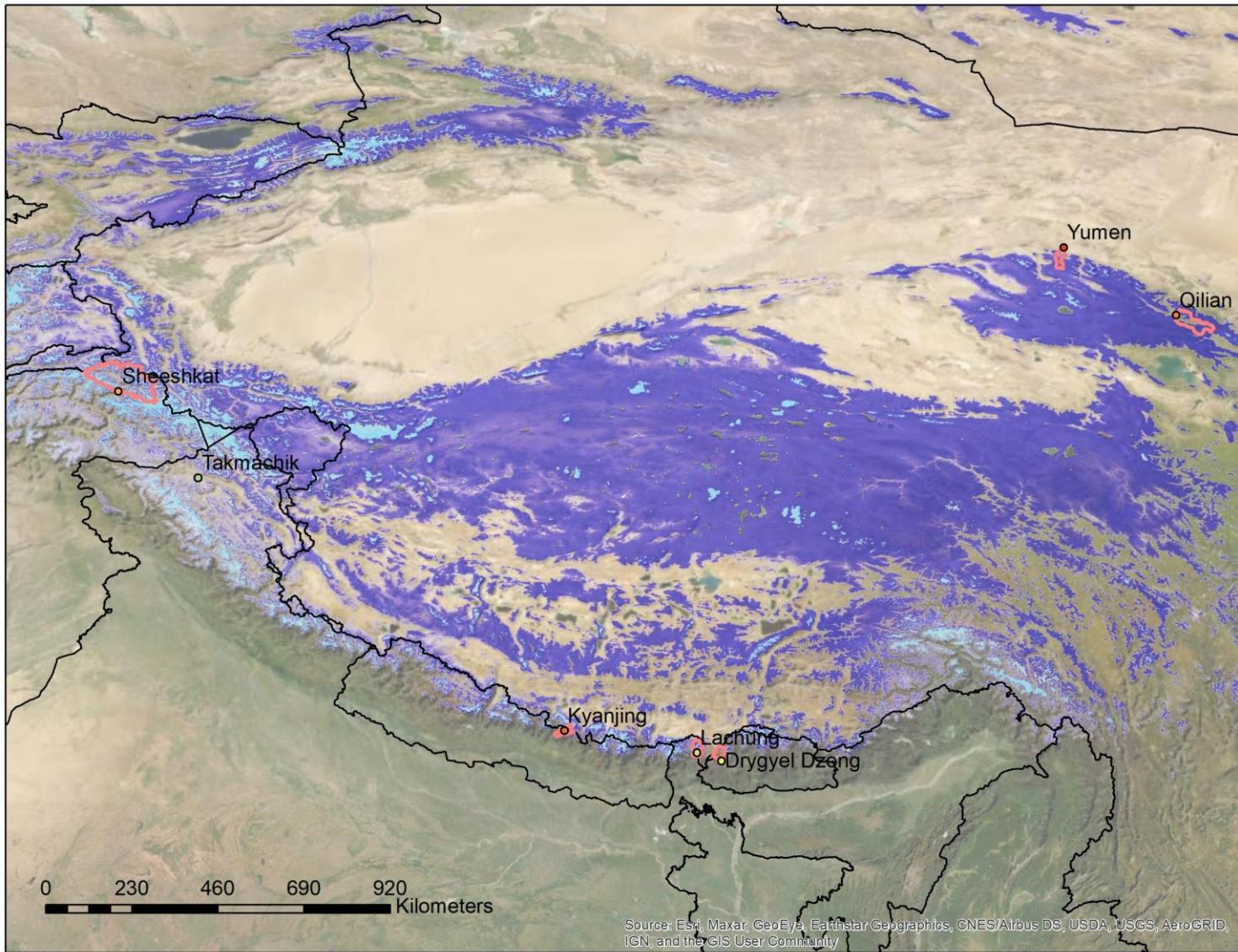
Hazards and Risk Assessment



IPCC AR6 WGII

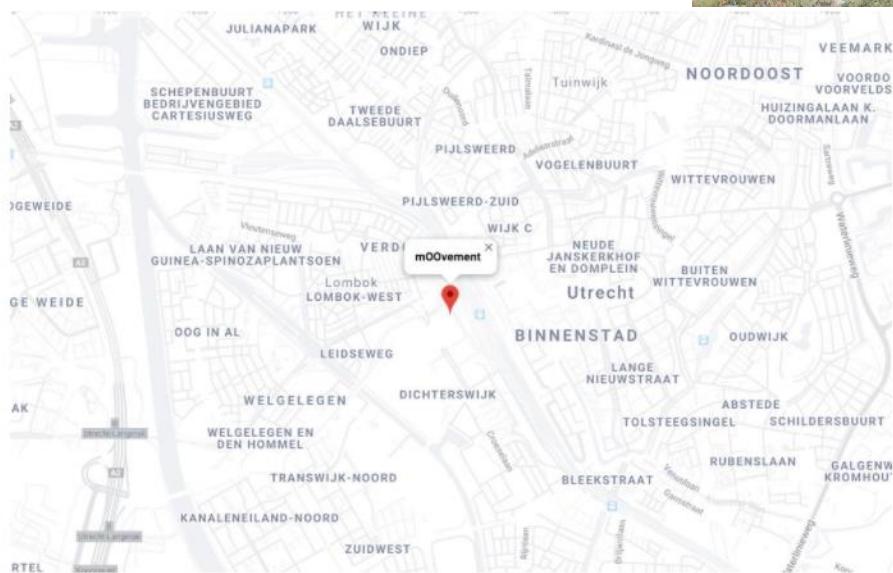


Figure CCP5.4: Synthesis of detection and attribution of impacts of anthropogenic climate change on different natural and human systems in mountain regions. For each system and region assessed, the level of confidence for detection and for attribution to anthropogenic climate change is indicated. Also indicated is how strong the contribution of climate change is to the observed changes, considering climatic and non-climatic causal factors. Observed impacts were analysed in terms of negative impacts (e.g. economic or non-economic damages, losses, contribution to increasing risks for society), where the numbers refer to the percentage of references indicating negative impacts for a given impact. The percentage of local community perception indicates the percentage of all literature references for a given system and region that account for local knowledge. The number of references refers to the total number of literature references considered for an impact to a specific system and region. “Not assessed” refers to *limited evidence* in the literature (see SMCCP5.2 and Table SMCCP5.5-5.14).





Yak tracking



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Topics

- Terminology: Hazards. Risks. Mitigation.
- *Global ice and exposure to hazards*
- *Types of glacial hazards*
- *Hazard Assessment: Mapping and Modelling*
- *Monitoring and risk mitigation*

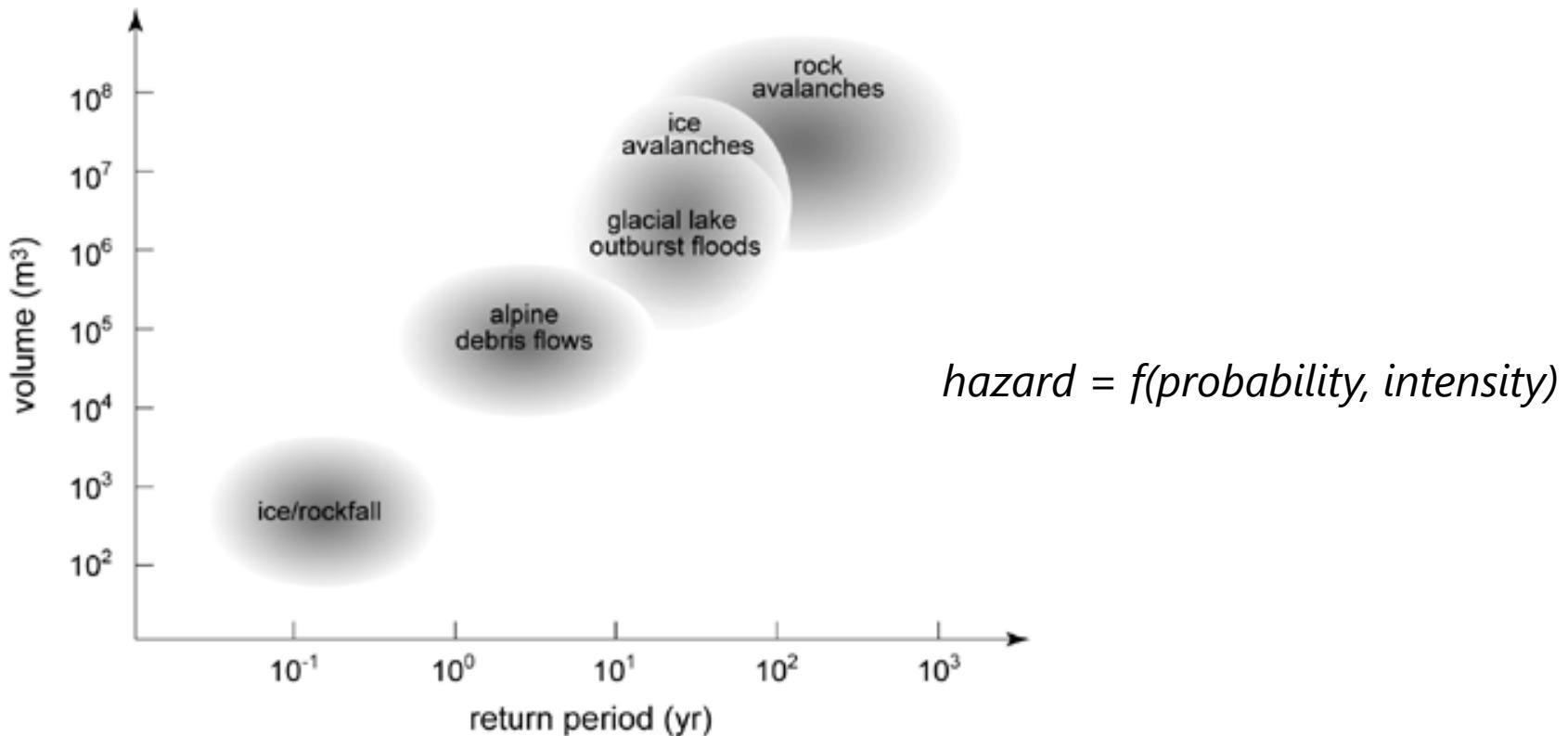


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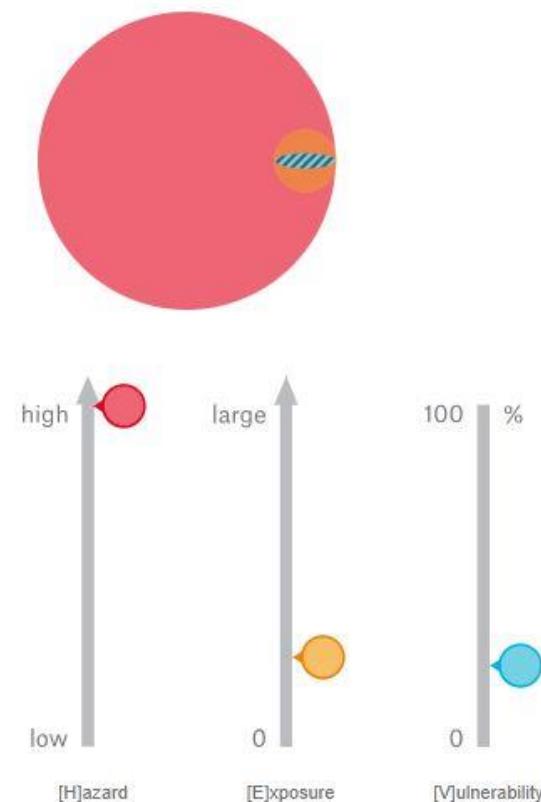
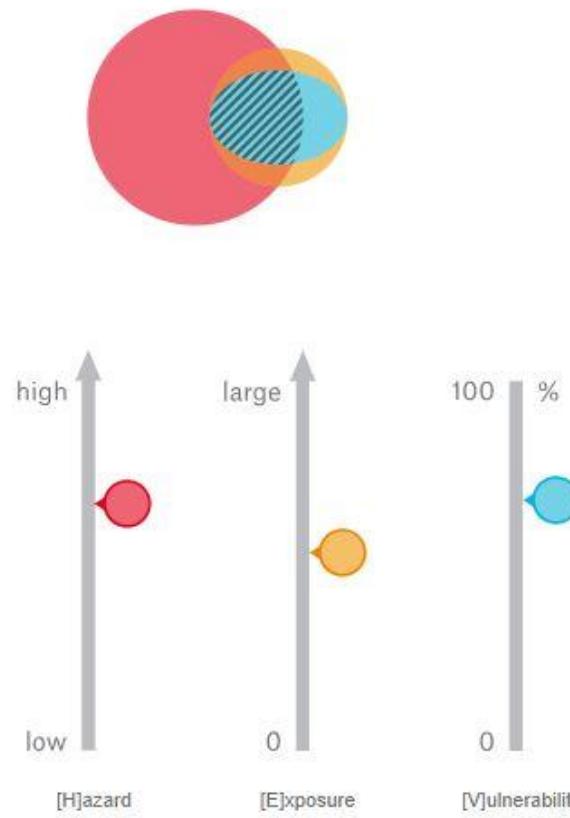


Return periods vs. volumes





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





Topics

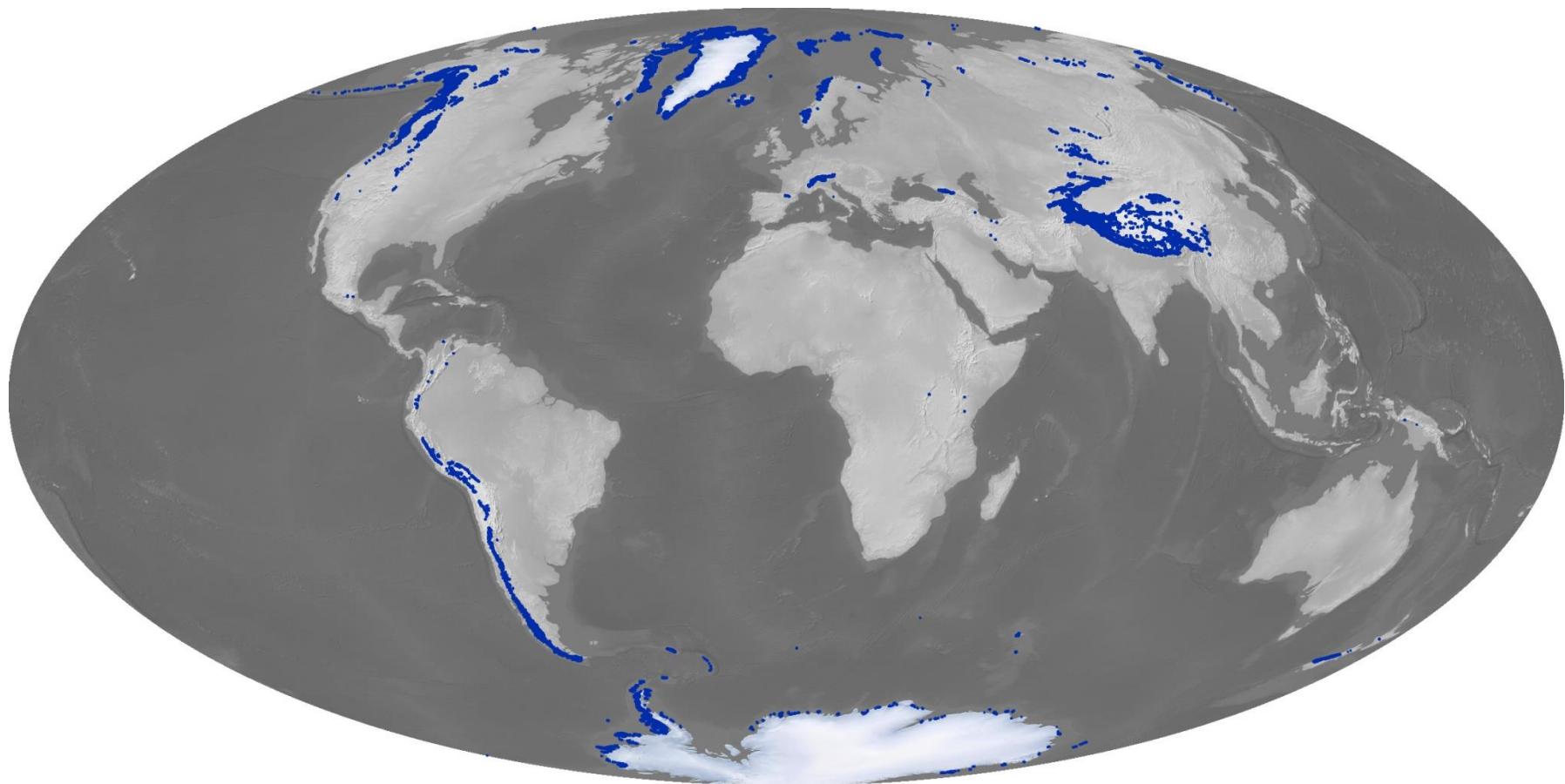
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Glaciers Globally

Total Area:

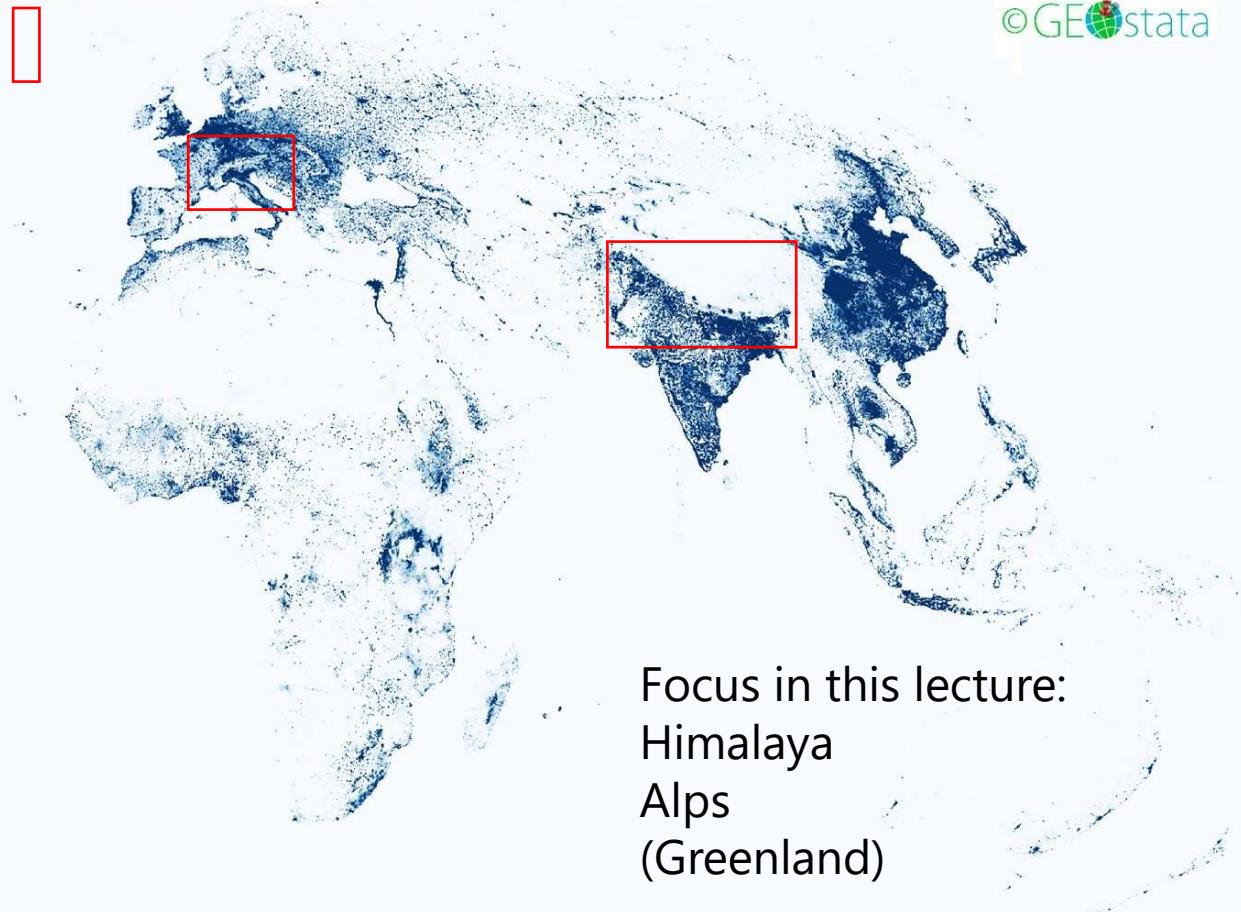
RGI: 734 933 km²
WGI: 747 688 km²



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



WORLD POPULATION DENSITY MAP - 2015



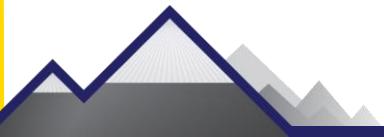
Focus in this lecture:
Himalaya
Alps
(Greenland)

Data source: Freire, Sergio; Pesaresi, Martino (2015): GHS population grid, derived from GPW4, multitemporal (1975, 1990, 2000, 2015). European Commission, Joint Research Centre (JRC).
PID: http://data.europa.eu/89h/jrc-ghs1-ghs_pop_gpw4_globe_r2015a



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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

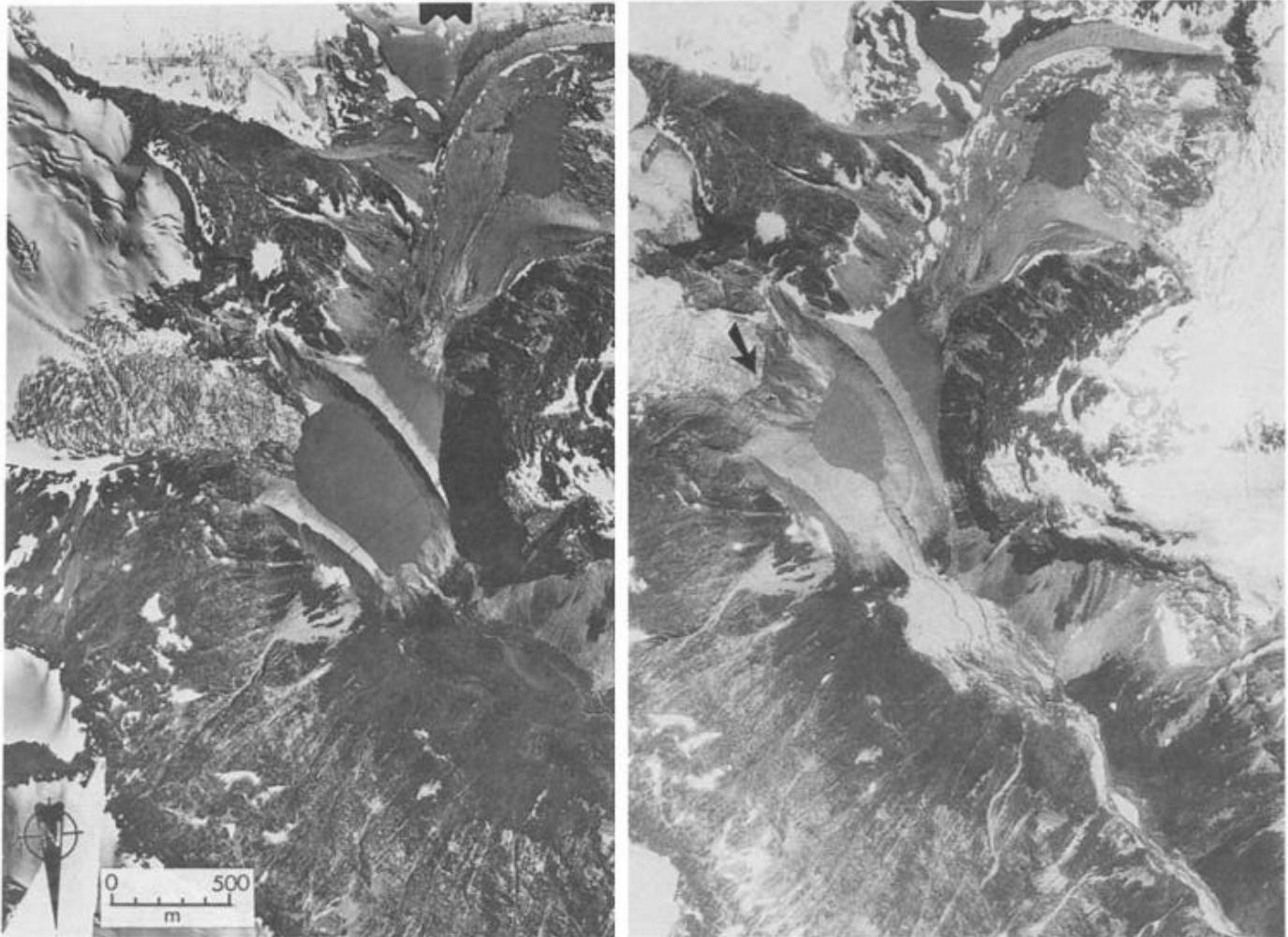


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Glacier Lake Outburst Floods (1)

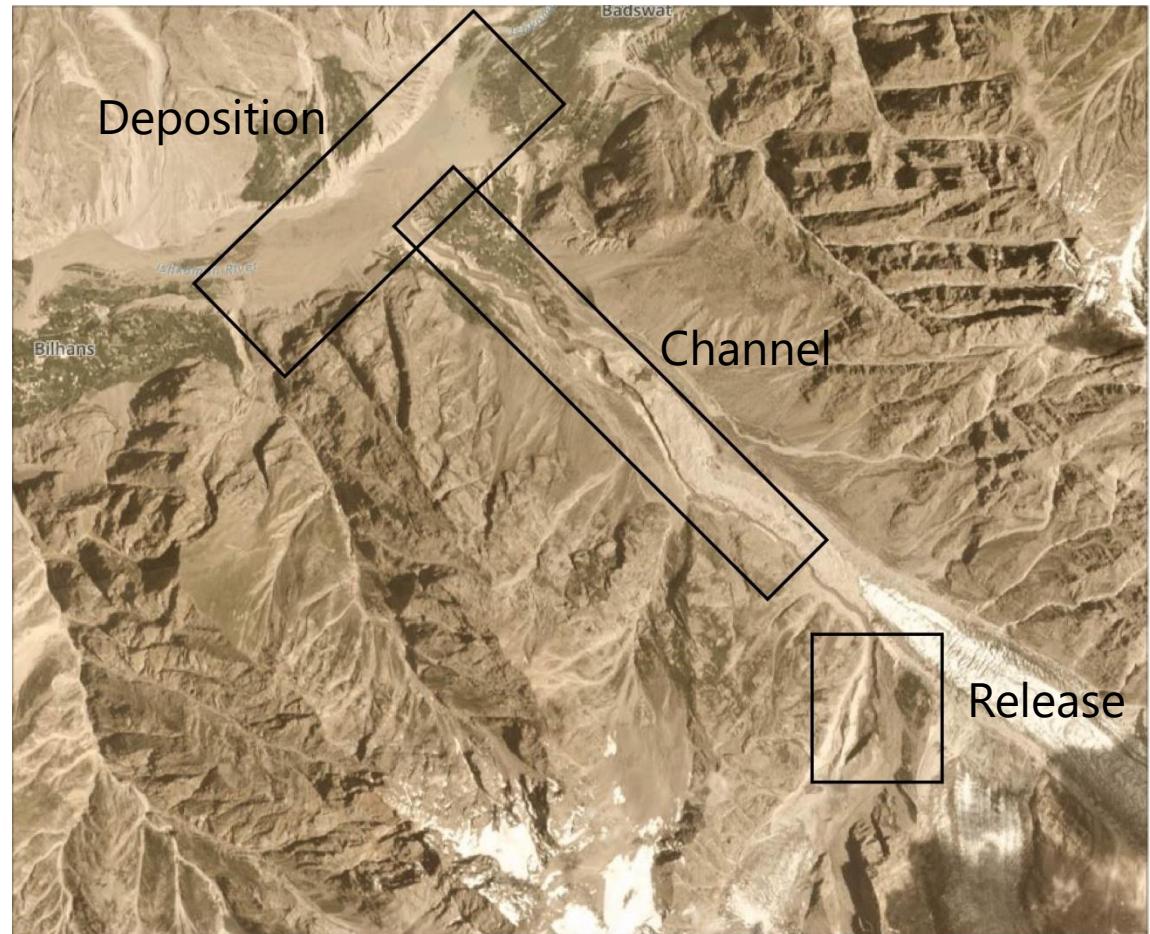


British Columbia
Canada

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.



Glacier Lake Outburst Floods (2)

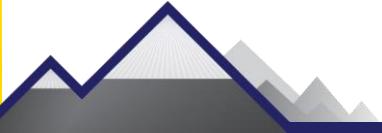


Helicopter Image/Pakistan Army; Sat image Planet



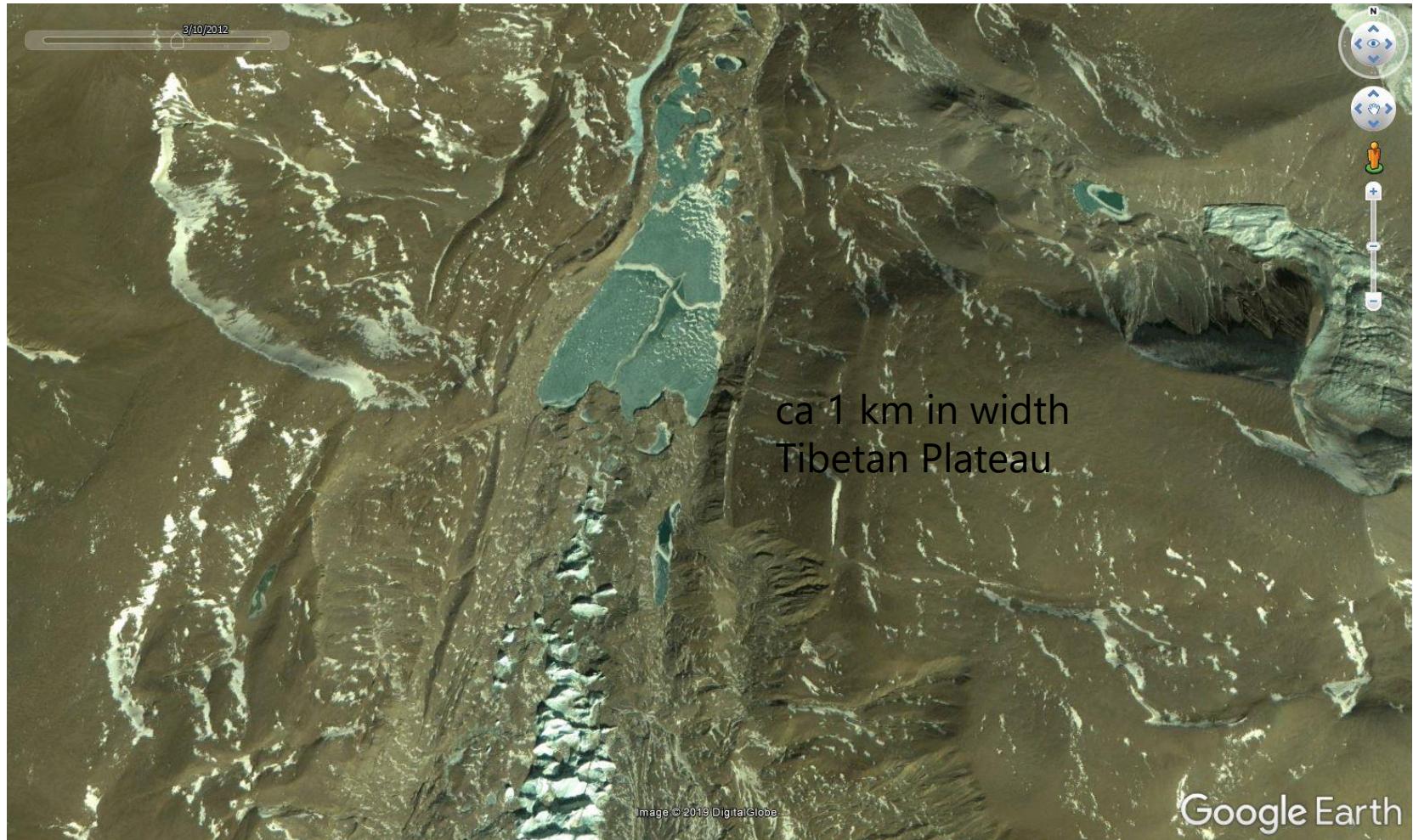
Glacier Lake Outburst Floods - *Causes*

- 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 internal lake (**internal melt**)
- Intense melt/rainfall



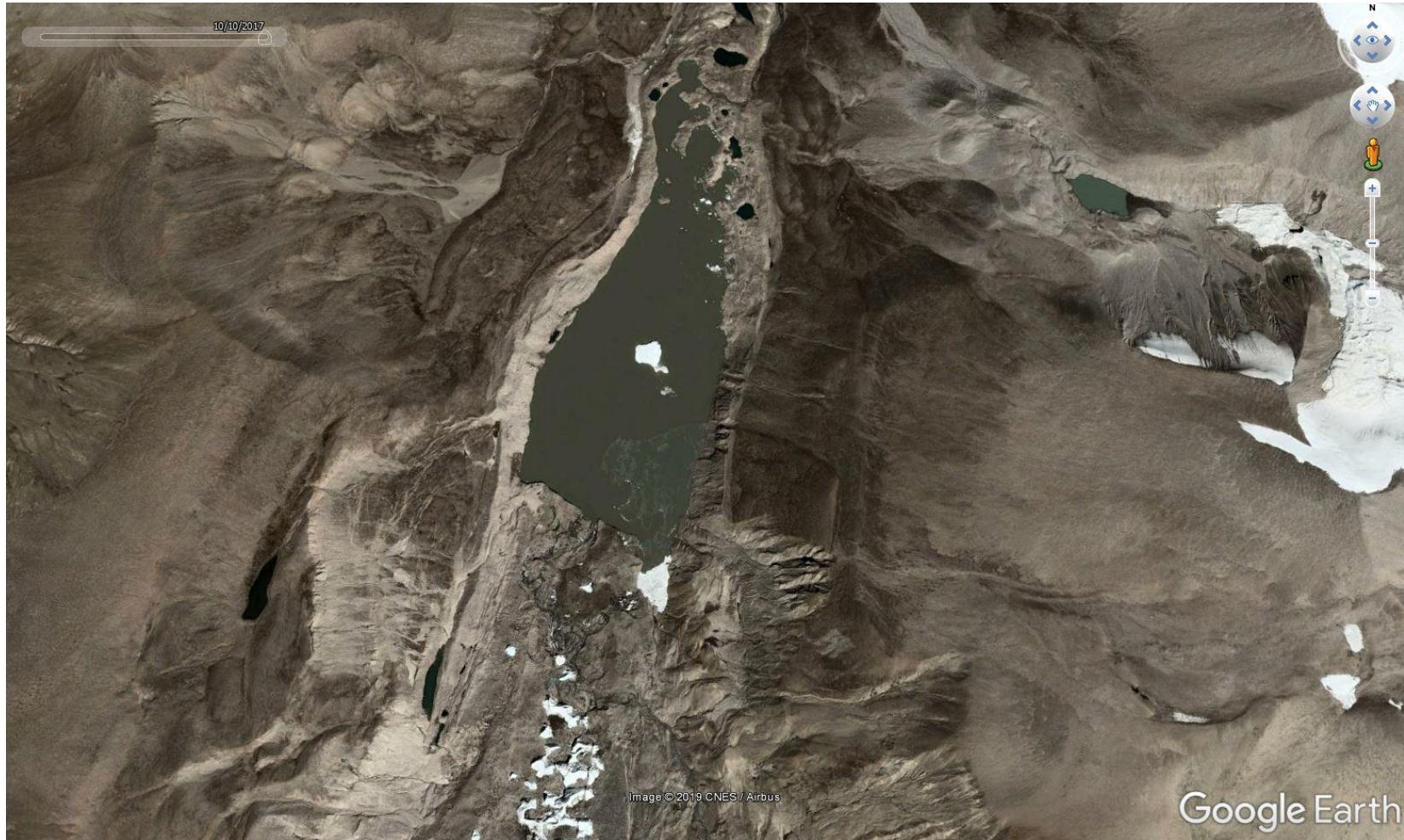


Growth of terminal lakes (2012)





Growth of terminal lakes (2017)





Surging glaciers

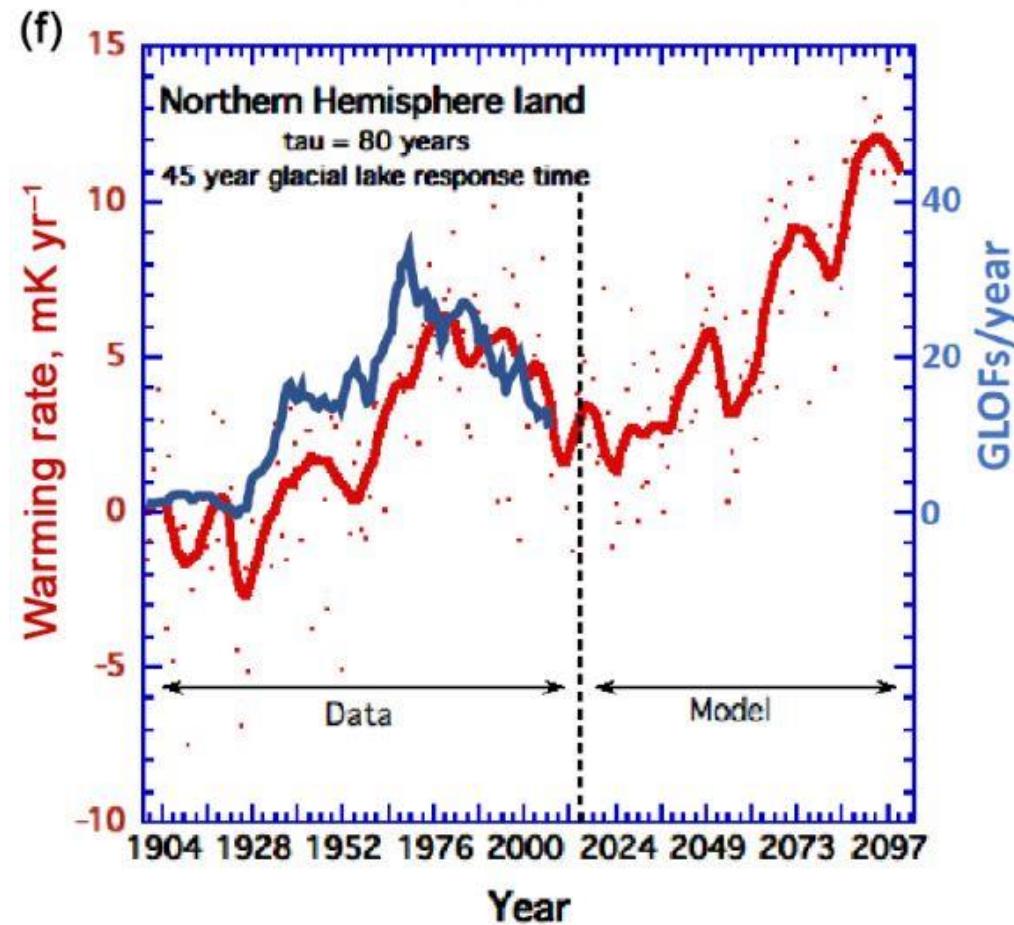


- Rapidly advancing glaciers block rivers
- Potentially hazardous lakes
- Interference with water supply
- Karakoram, Svalbard, Andes, Alaska



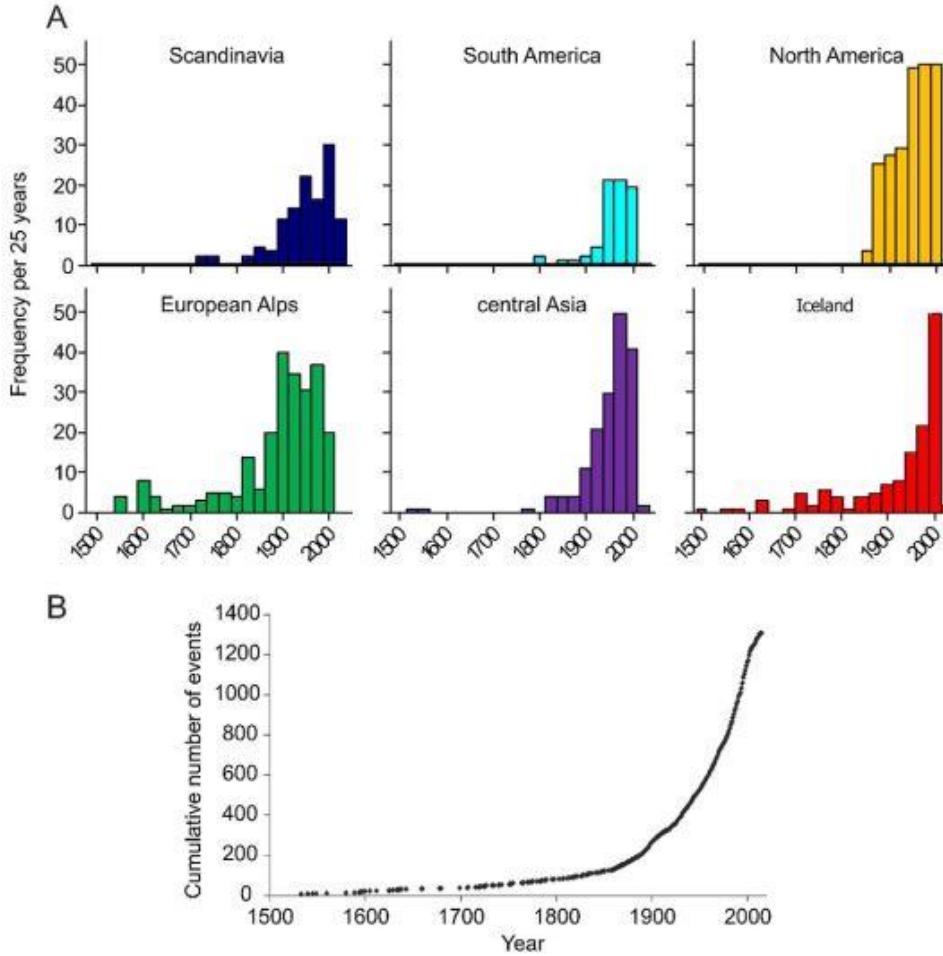
Glacier Lake Outburst Floods - *Causes*

- 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

Glacier Lake Outburst Floods - *Results*



- ca 1500 GLOFs since 1500
- ca 15 000 deaths
- Trend?
Observation bias?
- <https://www.youtube.com/watch?v=e83ONilzyK8&list=PLD585D2210775E1CD>

Fig. 3. Number of glacier outburst floods per 25 years by major region (A) and as a global cumulative total (B). Note that for clarity the x-axis is limited to displaying records from the last 500 years.

Carriwick and Tweed, 2016



Glacier Lake Outburst Floods - *Results*

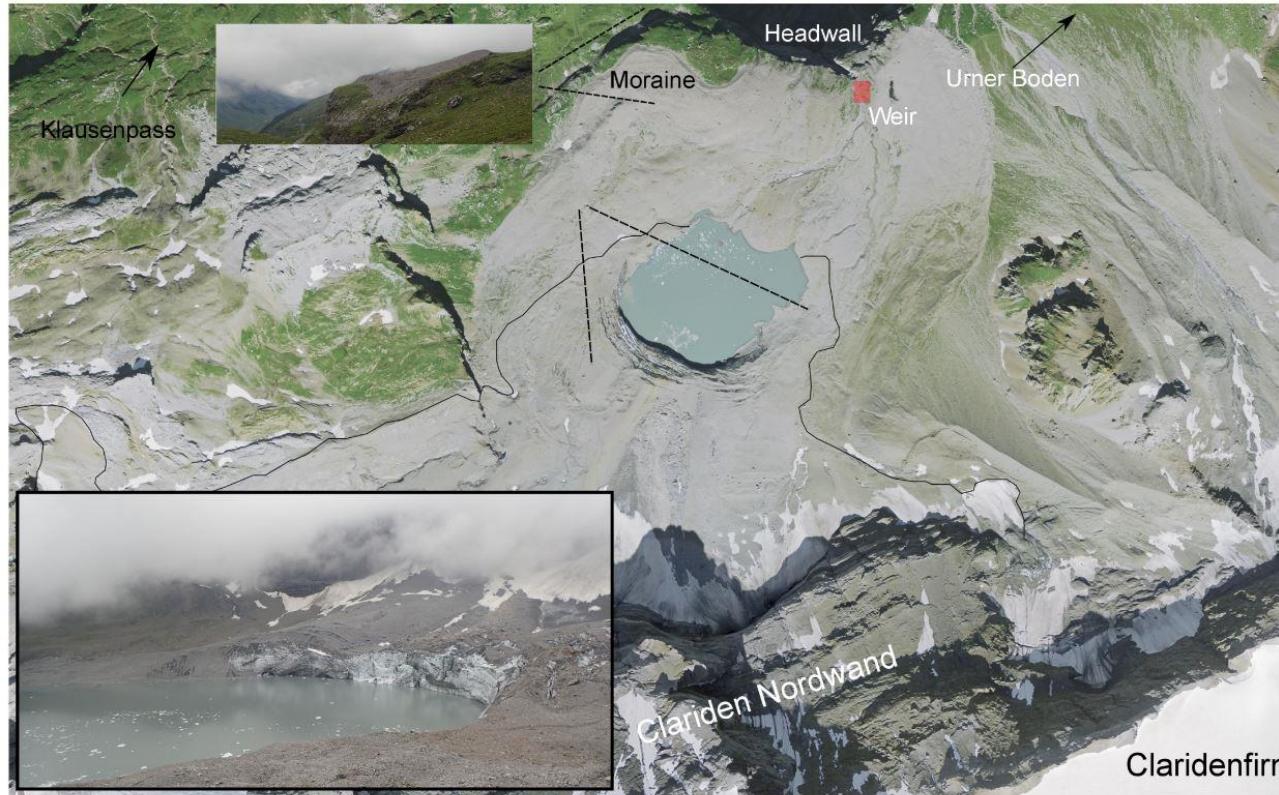


Figure 1: Griessseeli in an orthophoto from 2013 (main frame, swisstopo). The calving front as well as the frontal moraine of the glacier are shown in insets taken in August 2016 by the authors.

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



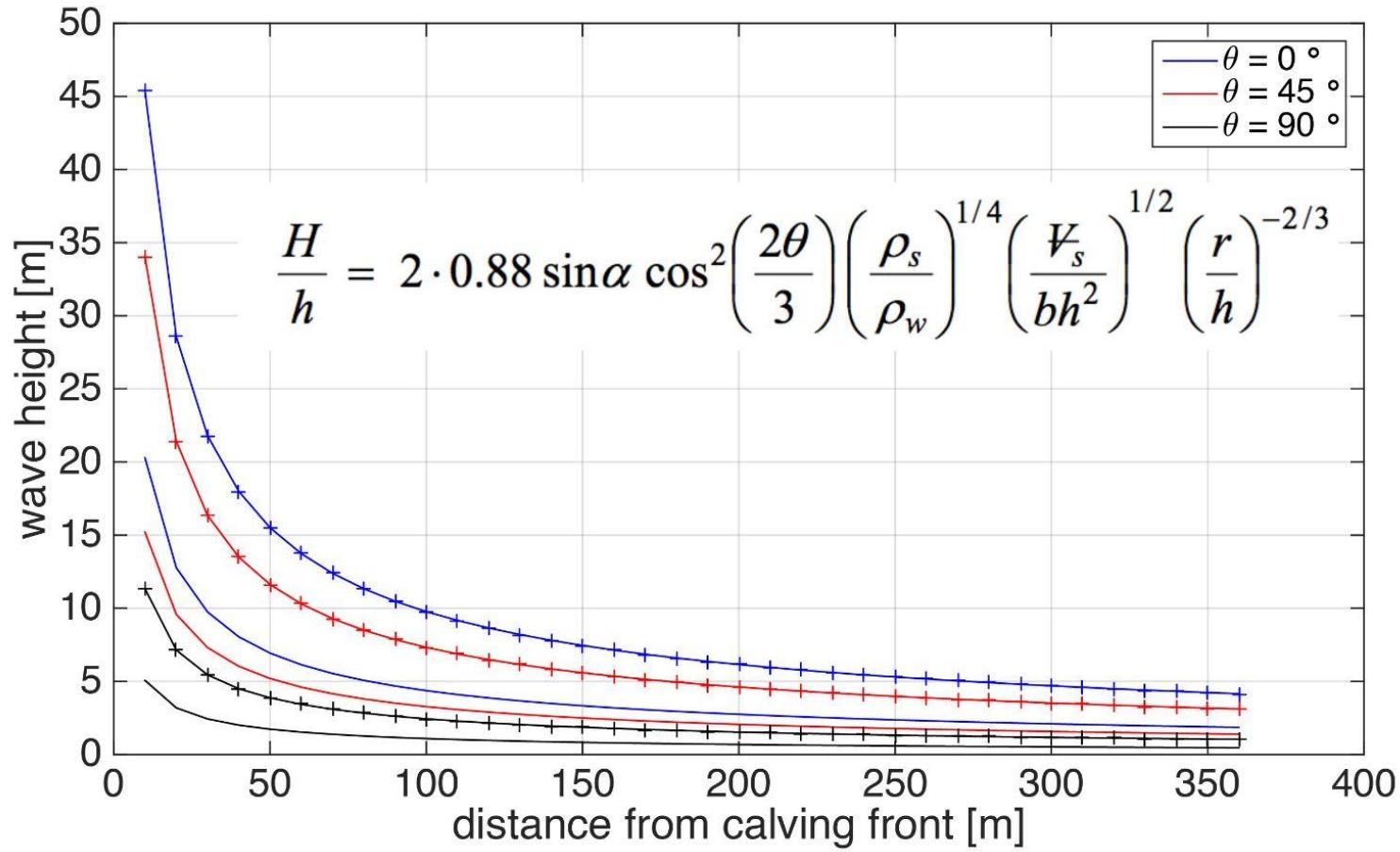
Impact waves

- 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.

Impact waves





Glacier Lake Outburst Floods - *Results*

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

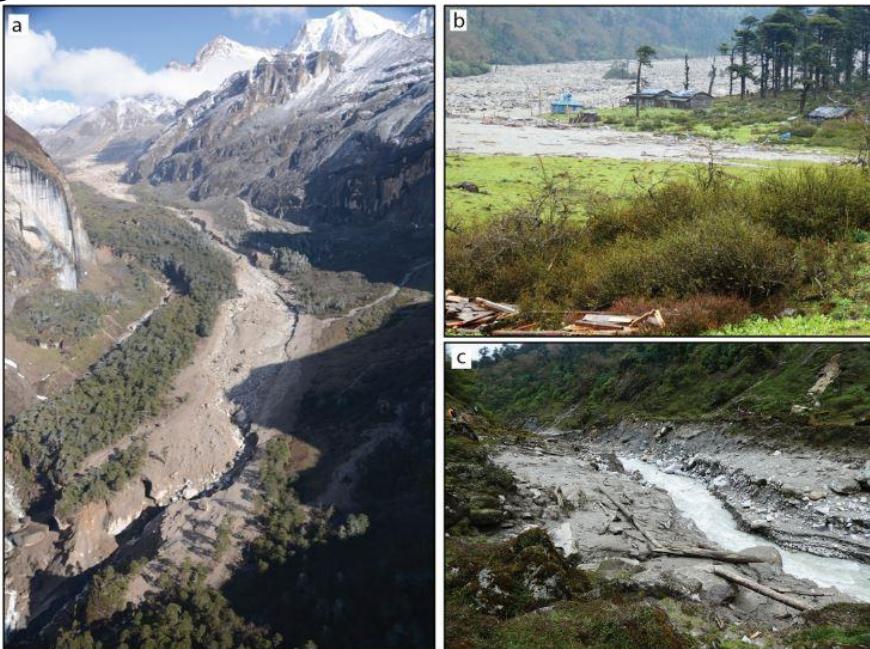


Fig. 13 a The flood path from the air. b The destruction at Yangle Kharka, where four buildings were destroyed. c The narrowed flood channel below Yangle Kharka



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

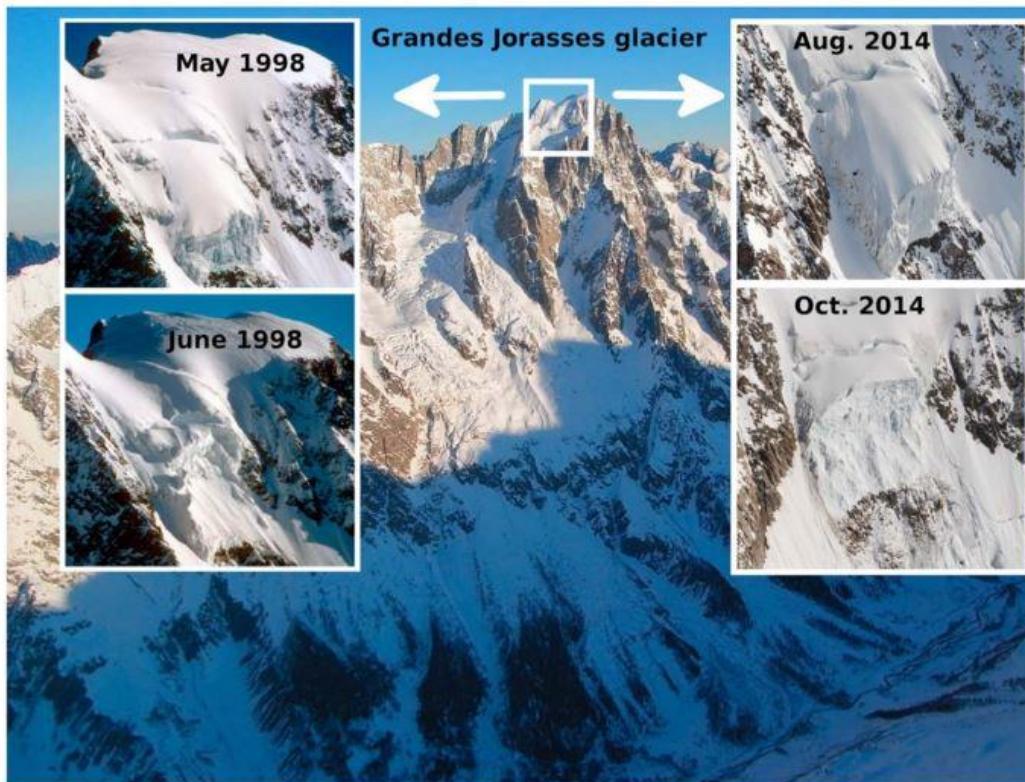
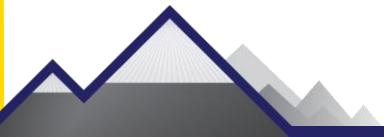


Figure 7. South side of the Grandes Jorasses and the Italian Val Ferret. (left inset) Evolution of the hanging glacier from May to June 1998. (right inset) Evolution of the hanging glacier from August to October 2014.

Failliettaz et al., 2015



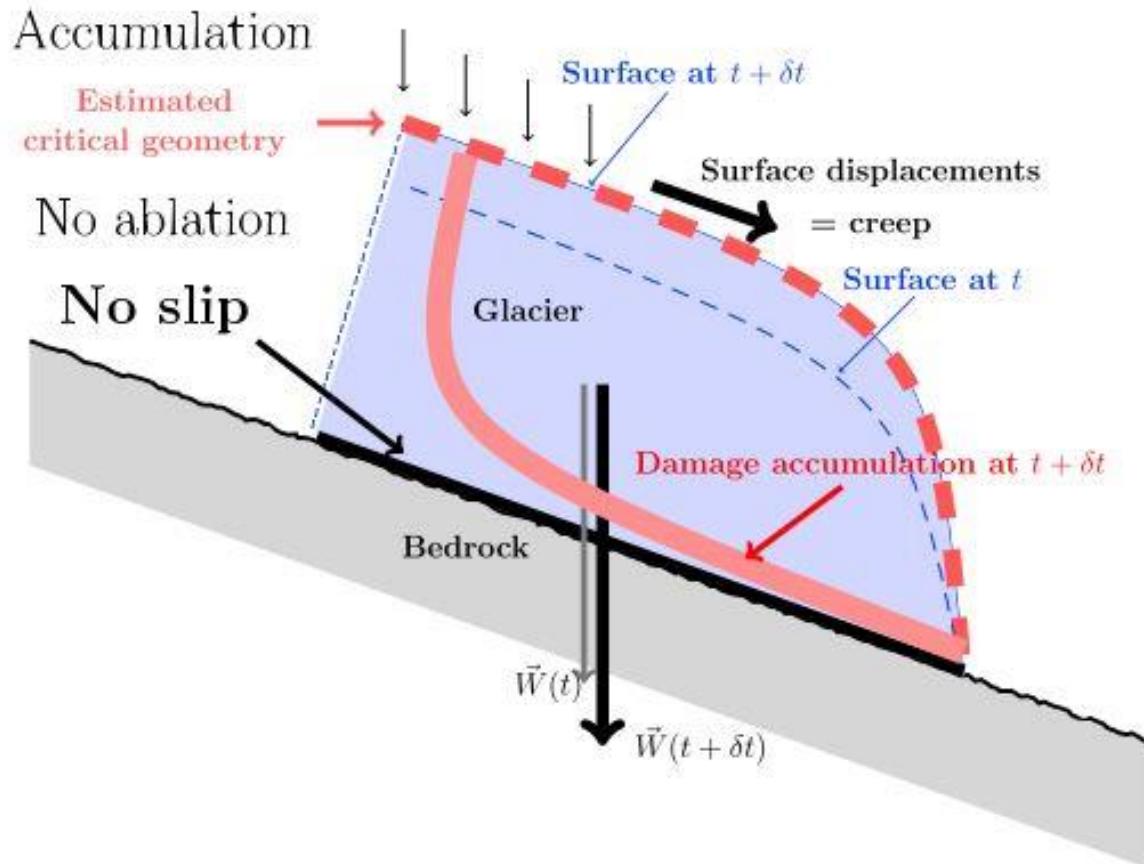
Ice break offs + collapsing glaciers





Causes – *cold based; damage propagation*

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



Faillietaz et al., 2015



Causes – *transition from cold to warm based*

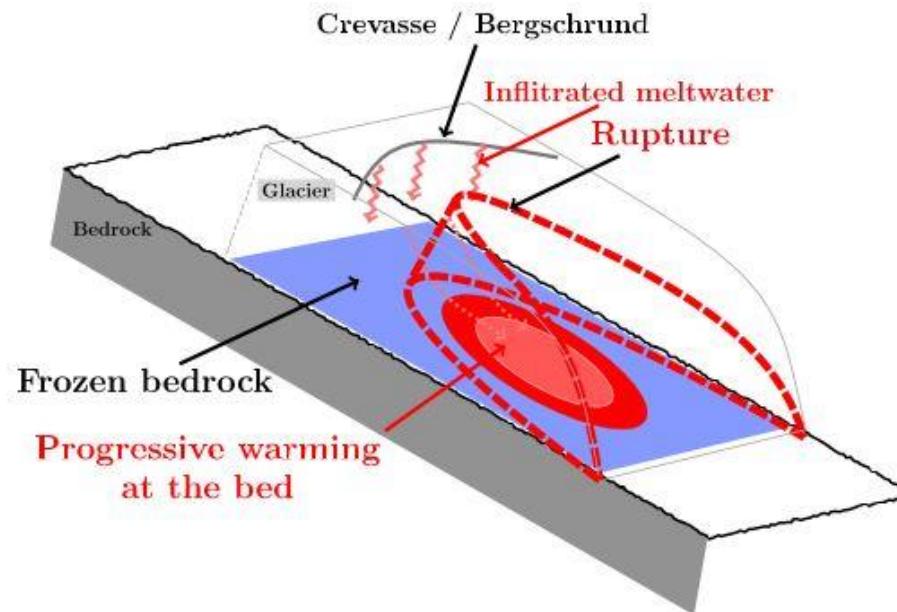


Figure 12. Schematic evolution of the instability initiated by a rapid localized warming at the ice-bedrock interface.

Causes – *warm based; hydraulic slip*

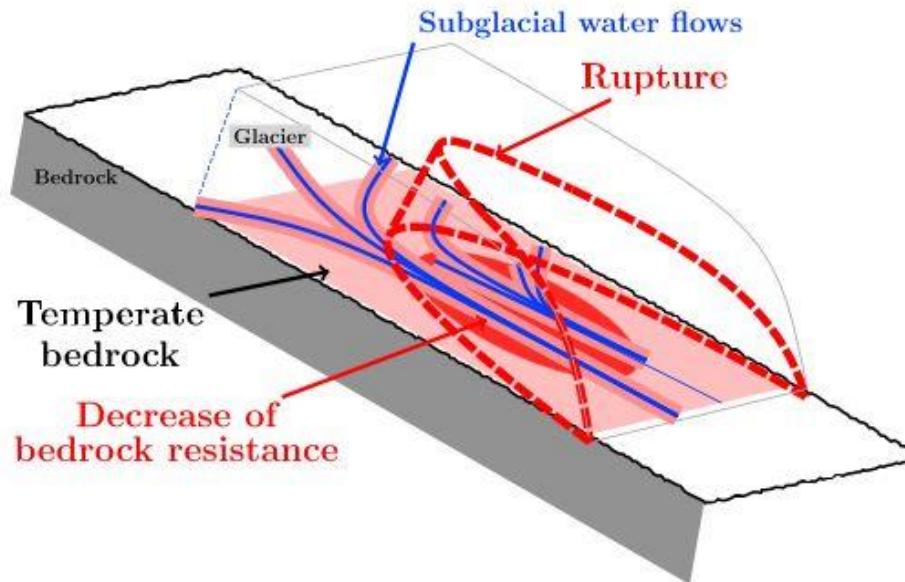


Figure 16. Schematic evolution of the instability for the case of a balanced glacier with a decreasing basal resistance due to increasing subglacial water pressure.



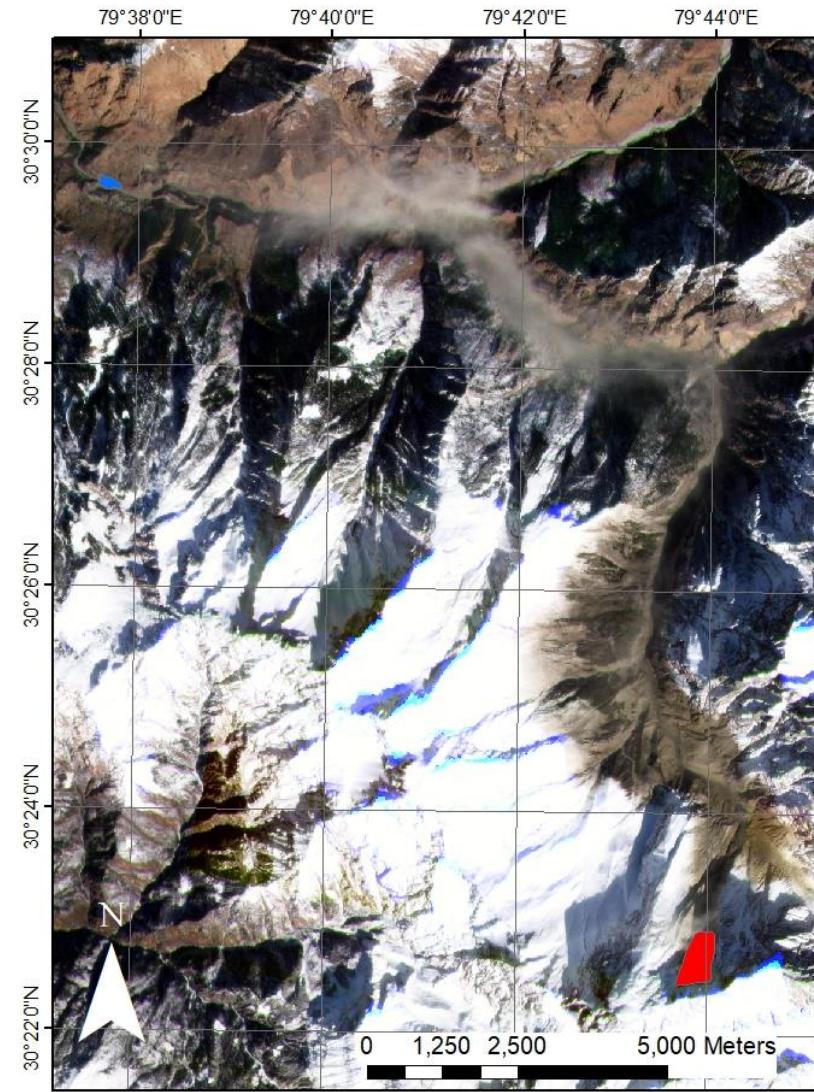
Results – accidents in remote locations (Uttrakhand, India, 7 February 2021)

- 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
- >100 people missing
- <https://www.youtube.com/watch?v=6ucU0Rcx5n4>



Results – Uttrakhand rock fall/debris flow

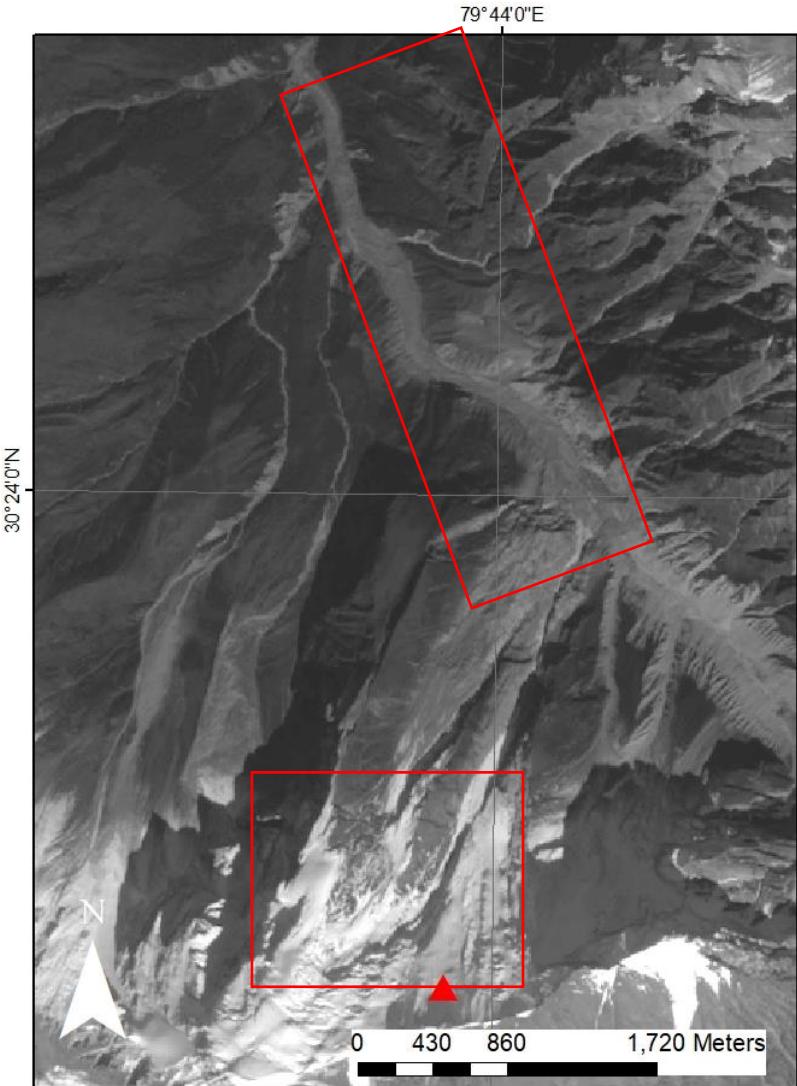
- rockfall mixed with ice
- mobilization of deposited debris
- Transition into debris flow





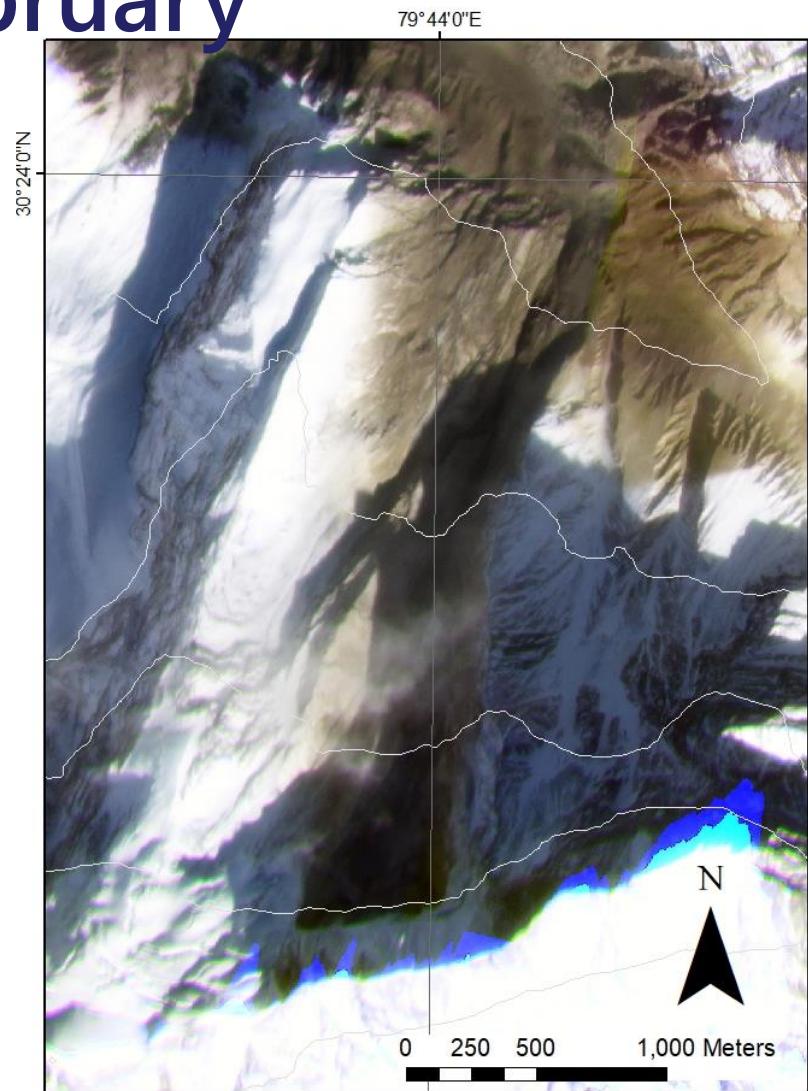
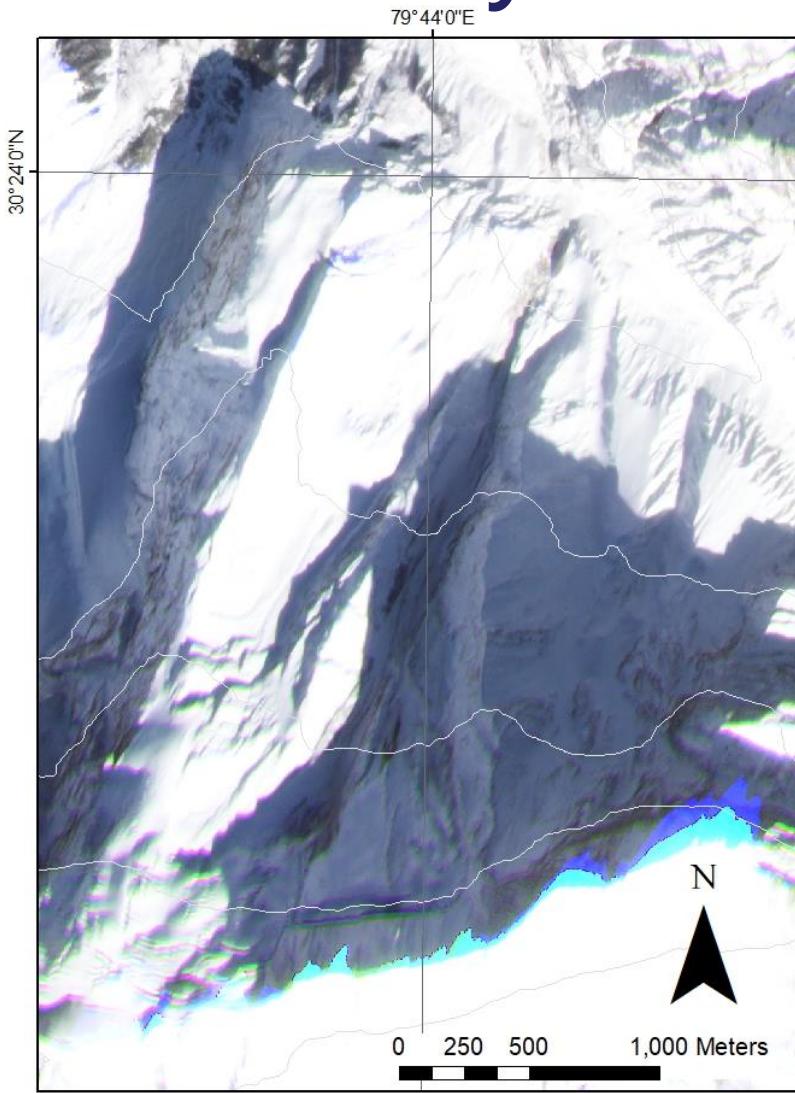
Climate change? Bad luck?

- Previous ice avalanche in 2016
- Ice/debris deposited in valley below





6 February vs 9 February





Calculating the impacts

- Impact energy:

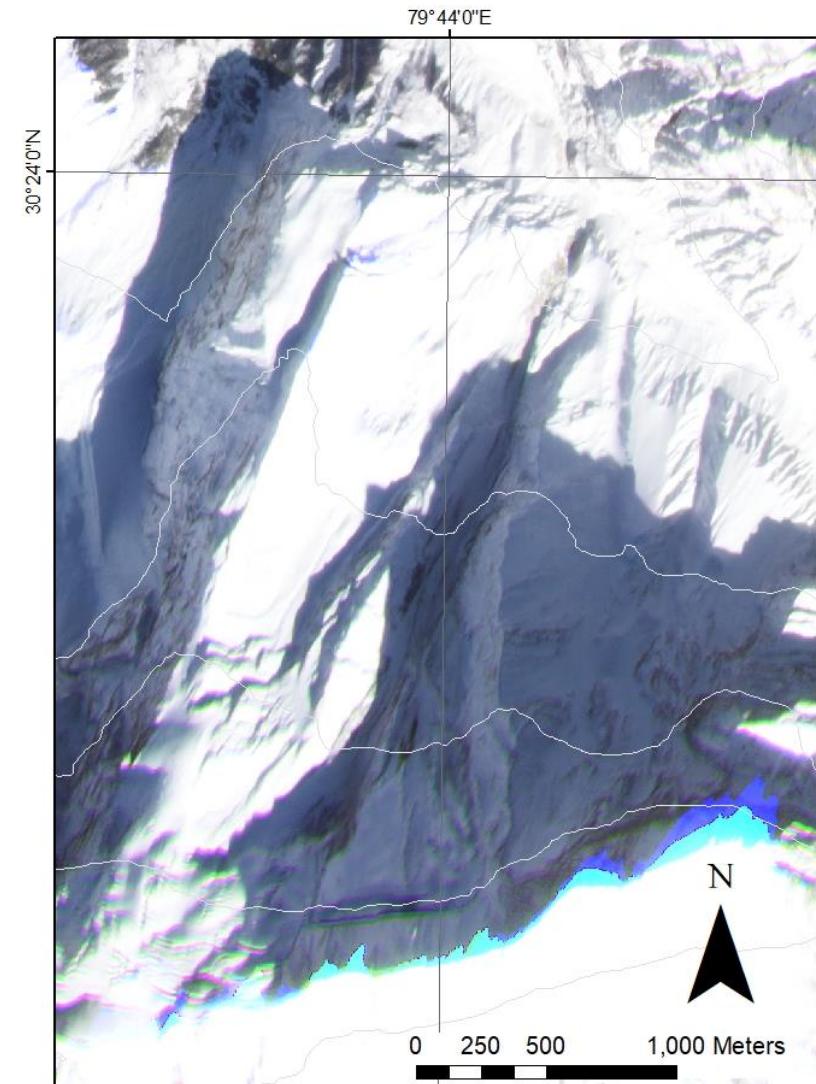
$$E [J] = mgh$$

$m = \sim 52000$ mio kg of rock/ice

$h = 1600$ m

$$E = 9.7 * 10^{14} \text{ J}$$

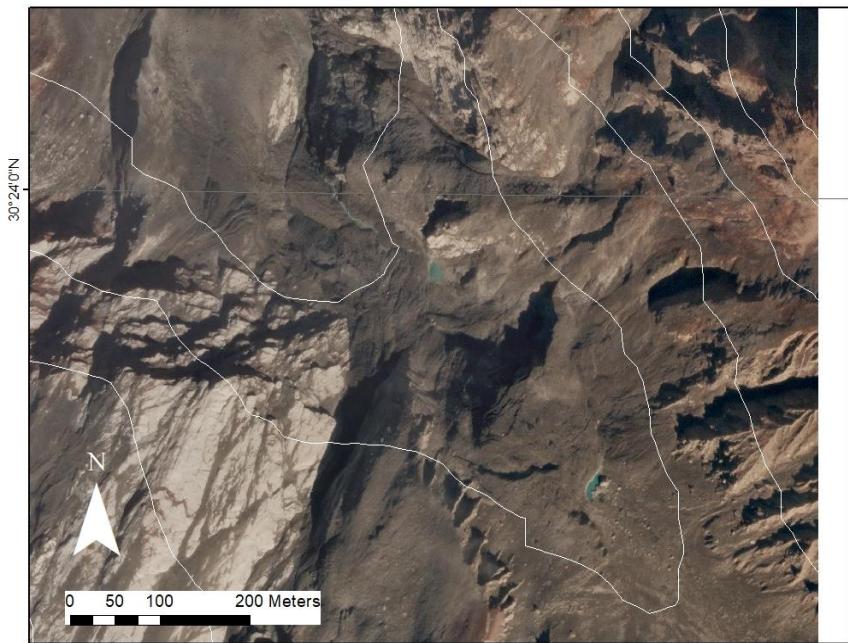
($10 \times$ Little Boy Hiroshima,
 $1 \times$ Chelyabinsk meteor)





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)





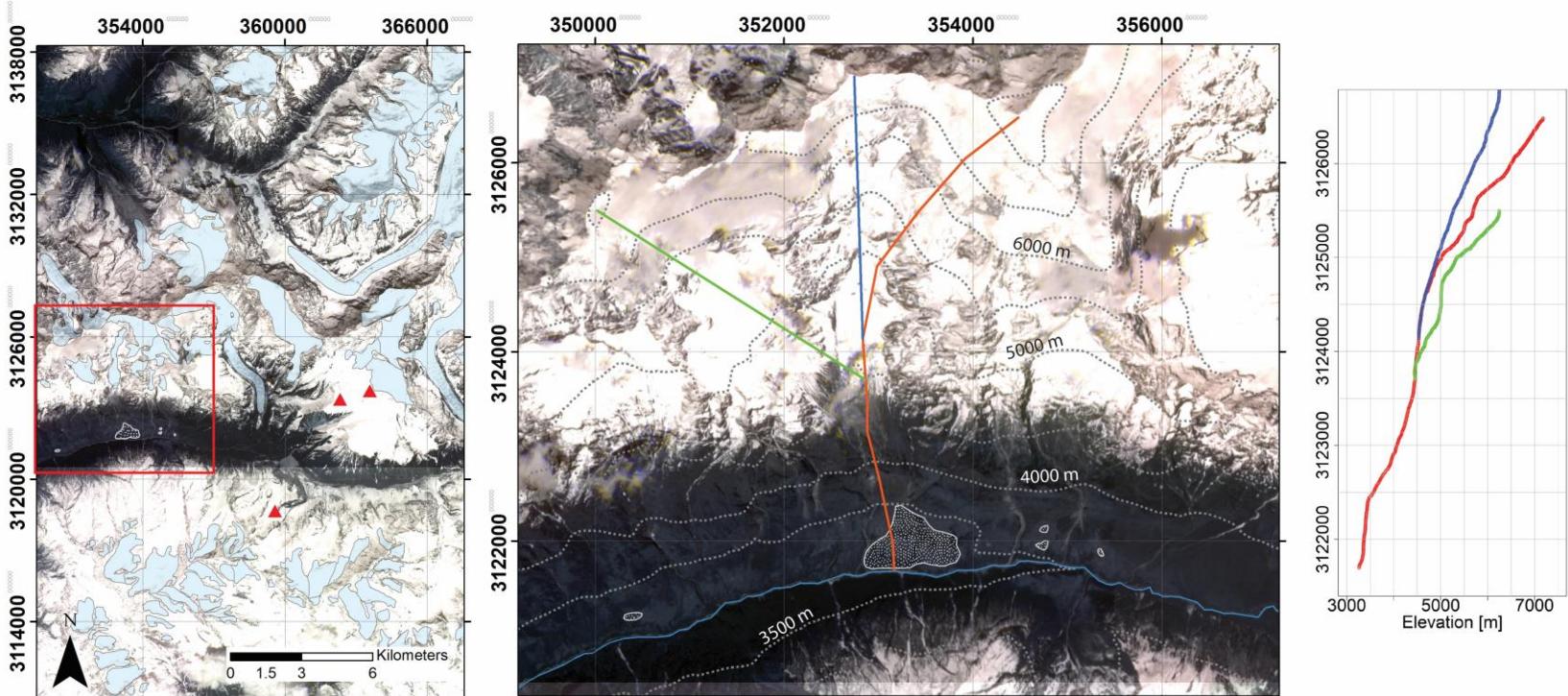
Results – co-seismic events

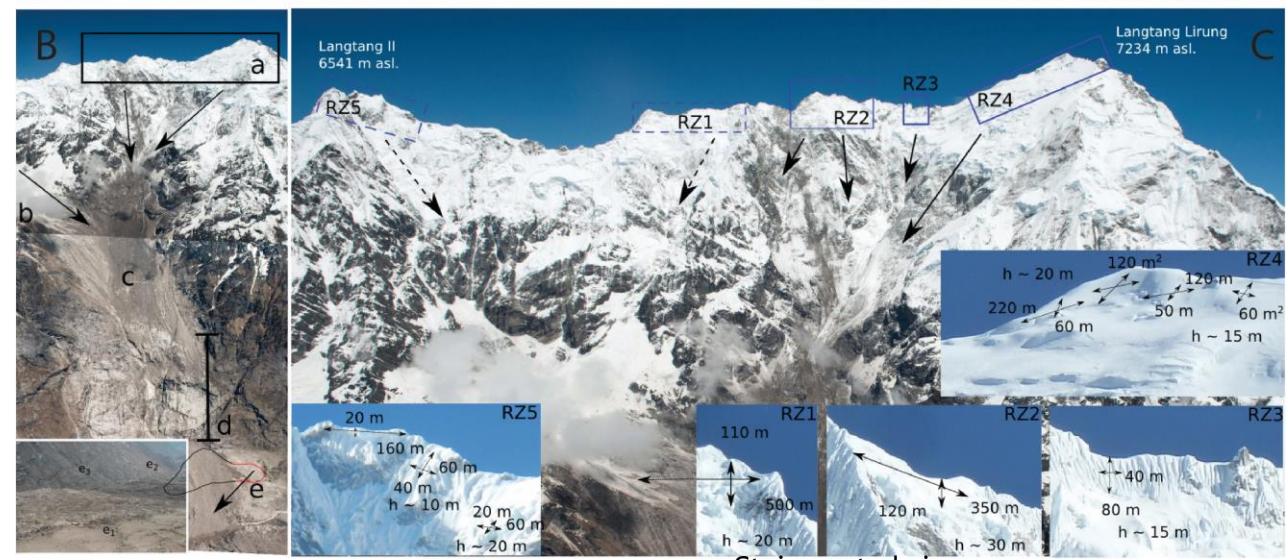
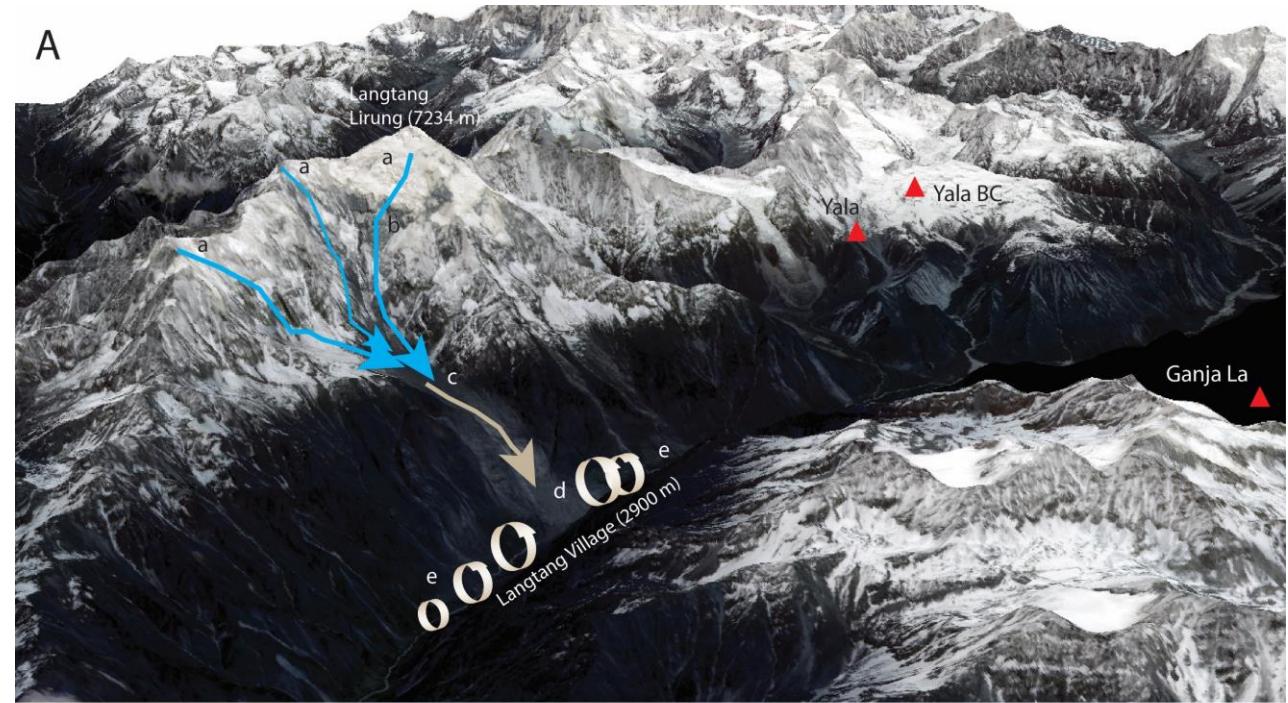
- Gorkha earthquake 2015 in Nepal
- >4000 co-seismic landslides
- Ice-break offs that caused deposits of up to 100 m depth
- Multi-hazard (ice break off + avalanche + debris flow)



Kargel et al., 2016

Results – co-seismic events

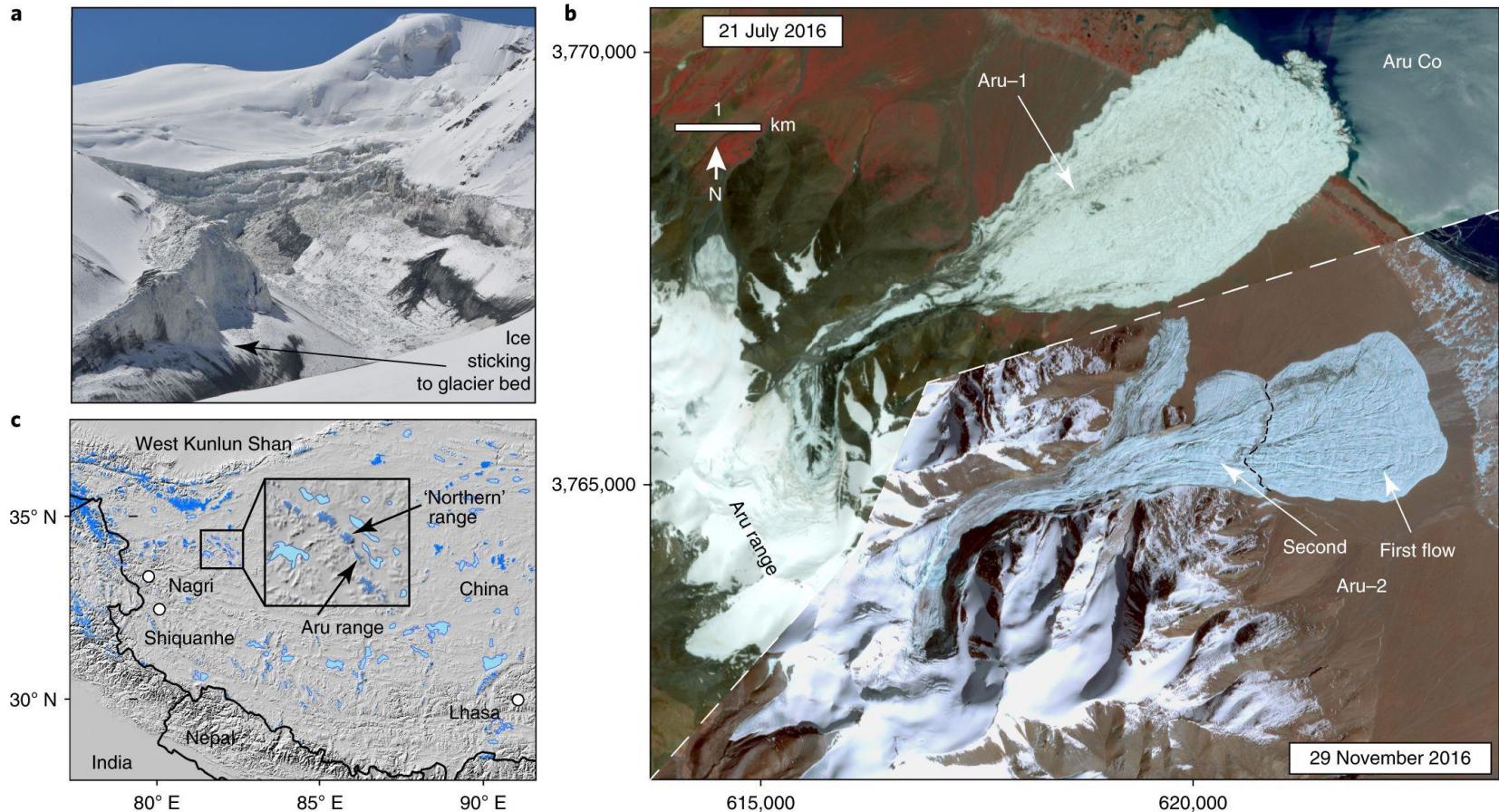




Steiner et al., in prep.

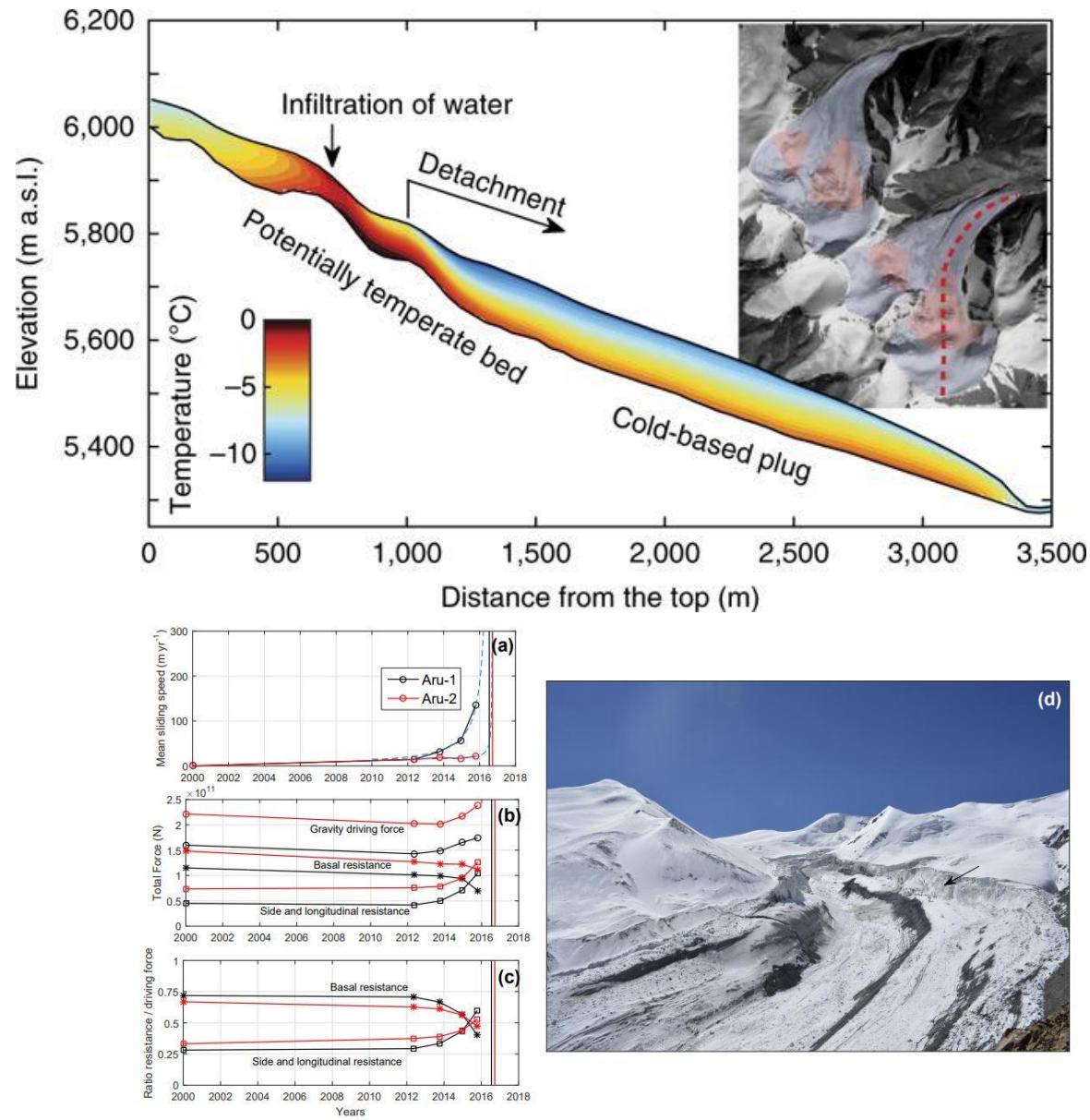


Results – Internal glacier collapse





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



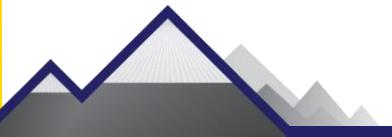
Kaab et al., 2018

Gilbert et al., 2018



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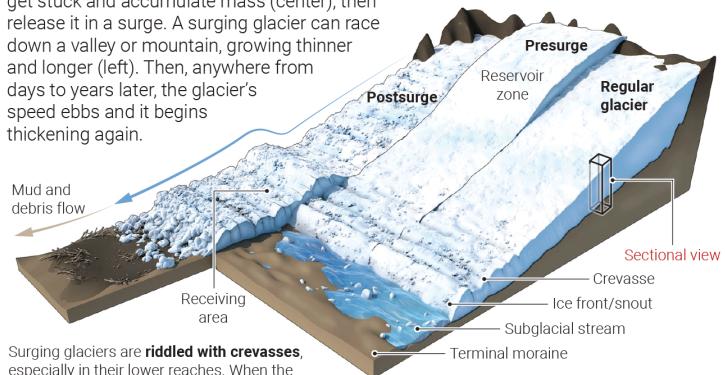


Glacier length variations surges

- 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

A glacier unleashed

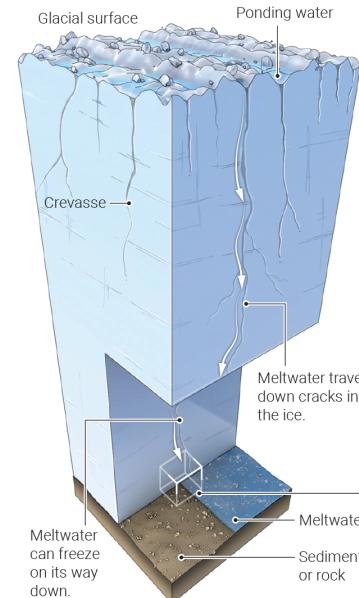
Glaciers gain mass in their upper reaches, where snowfall is heavier, and lose it at their snouts, where the ice breaks up and melts (right). Most glaciers flow steadily, but some get stuck and accumulate mass (center), then release it in a surge. A surging glacier can race down a valley or mountain, growing thinner and longer (left). Then, anywhere from days to years later, the glacier's speed ebbs and it begins thickening again.



Surging glaciers are **riddled with crevasses**, especially in their lower reaches. When the surge ends, meltwater that built up under the glacier before the surge may sweep mud and debris from its snout.

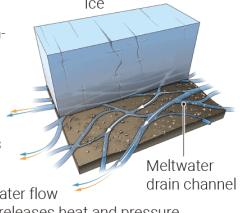
Trickling down

Meltwater plays a key role in triggering surges. Pooling on the glacier's surface, it can seep down into crevasses. There it can refreeze, releasing heat that softens the ice; it can also pool at the base of the ice.



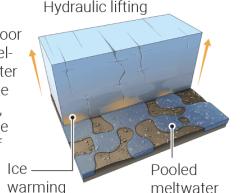
Steady state

In a "normal" glacier, meltwater drains efficiently from its base, carrying away heat and leaving the ice anchored to its bed.



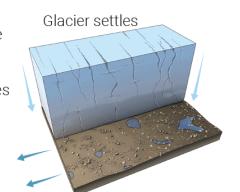
Buildup to a surge

If drainage is poor or melting accelerates, meltwater can accumulate under a glacier, warming the ice and lifting it off the ground.



Aftermath

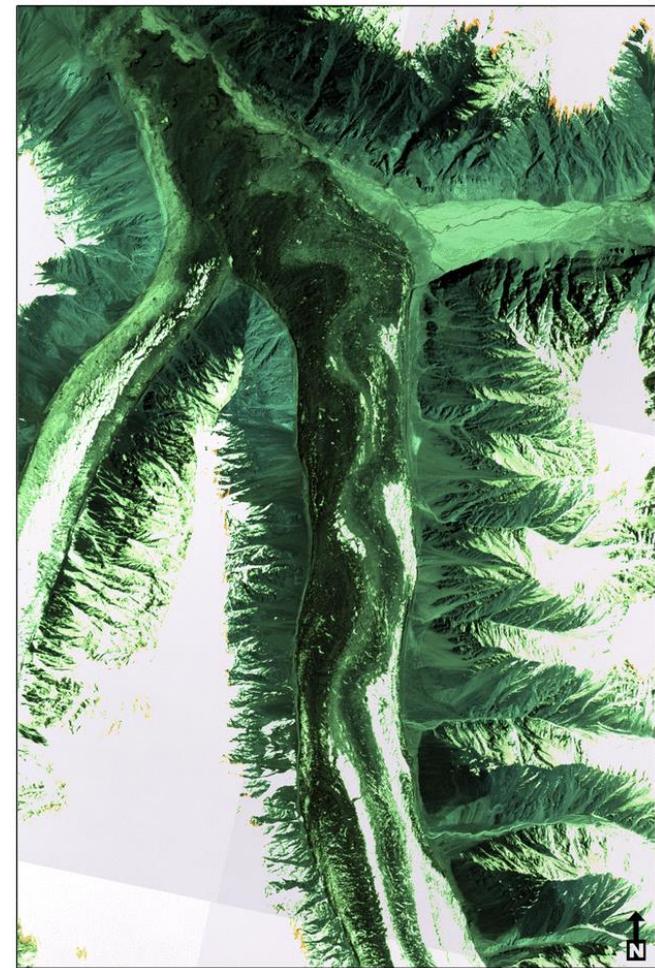
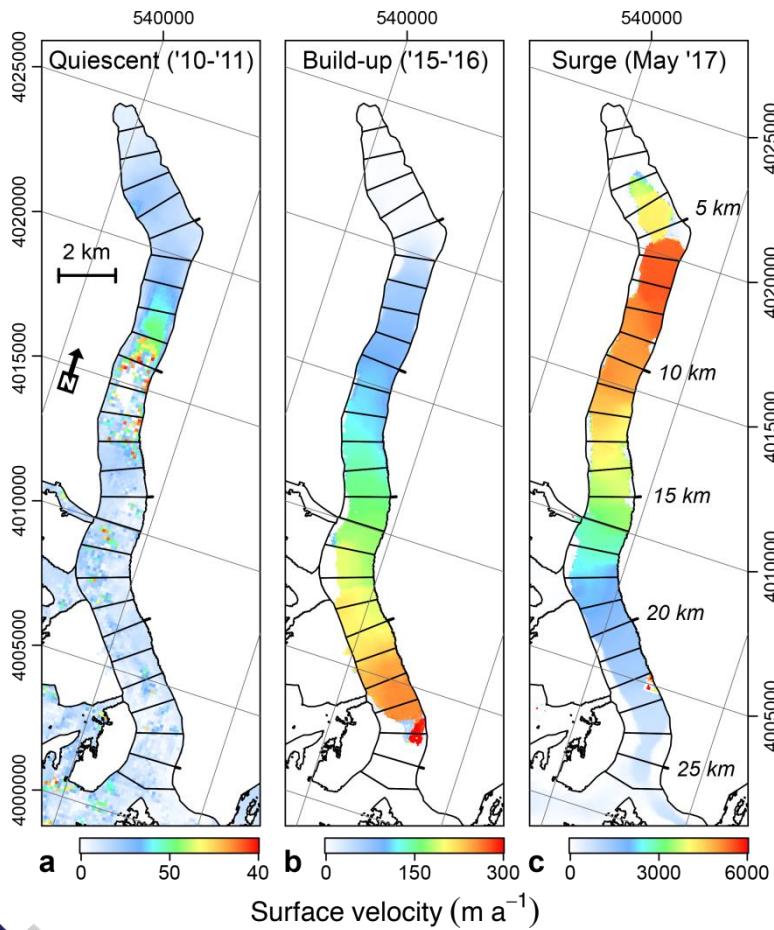
Once the surge releases the meltwater, the glacier subsides onto its bed, and the cycle begins again.



CREDITS: (GRAPHIC) C. BICKEL/SCIENCE

Surge in Karakoram 2017

- Glacier velocities from remote sensing





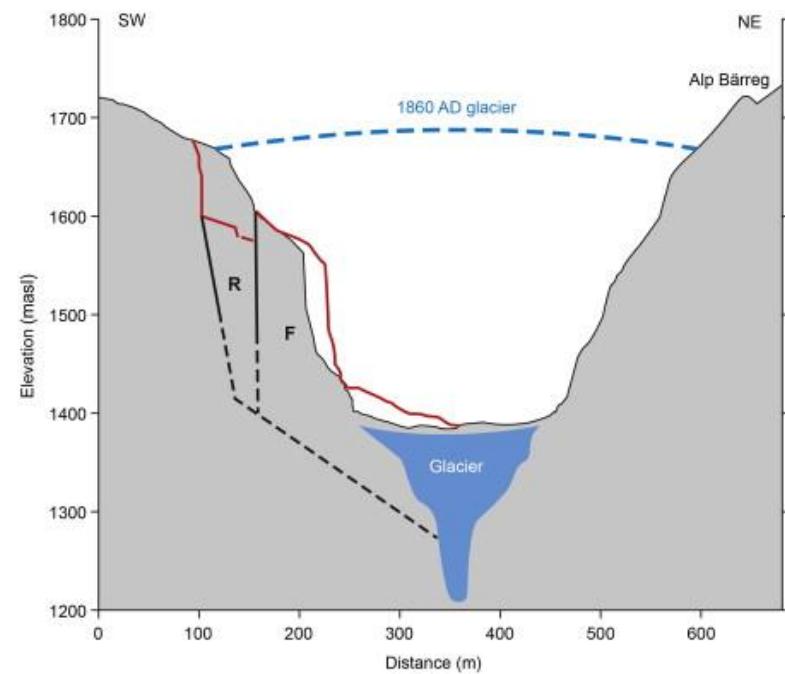
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Destabilization of frozen soil

- Increased rock slope failure in post-glaciated environments
- Dependent on geology
- Freeze-thaw within rock cracks
- Isostatic rebound after deglaciation

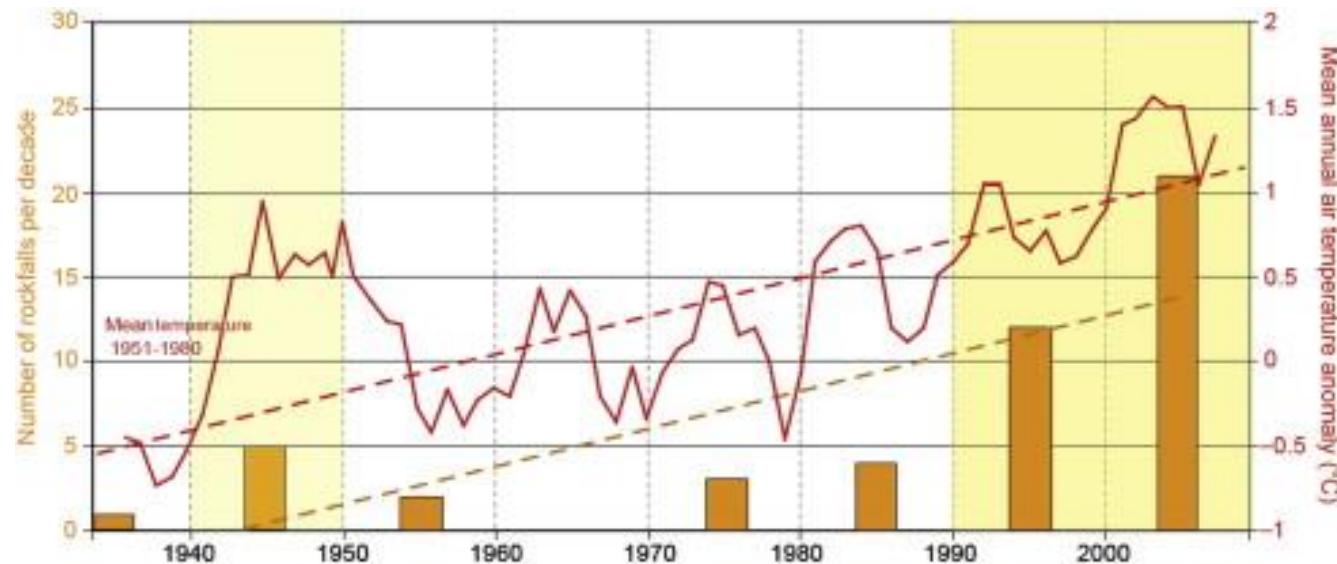
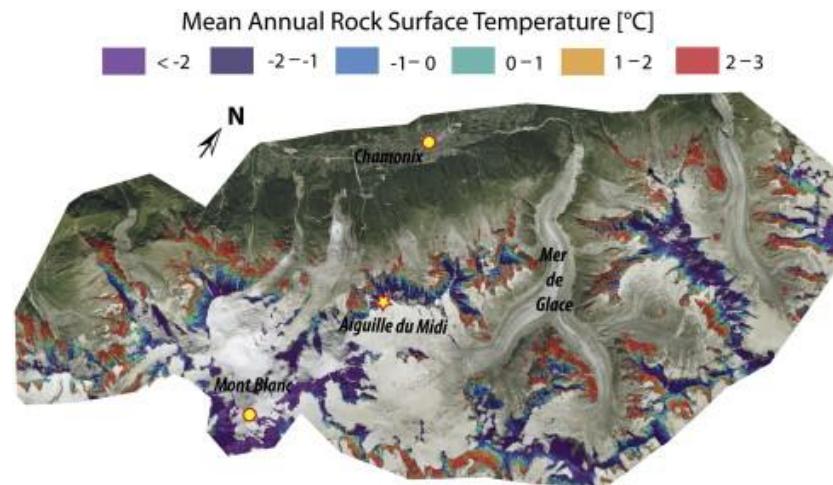


Deline et al., 2015



Destabilization of frozen soil

- Likely direct link with increasing temperatures





Destabilization of frozen soil



- [https://www.youtube.com/
watch?v=RYRfPrhCWzs](https://www.youtube.com/watch?v=RYRfPrhCWzs)

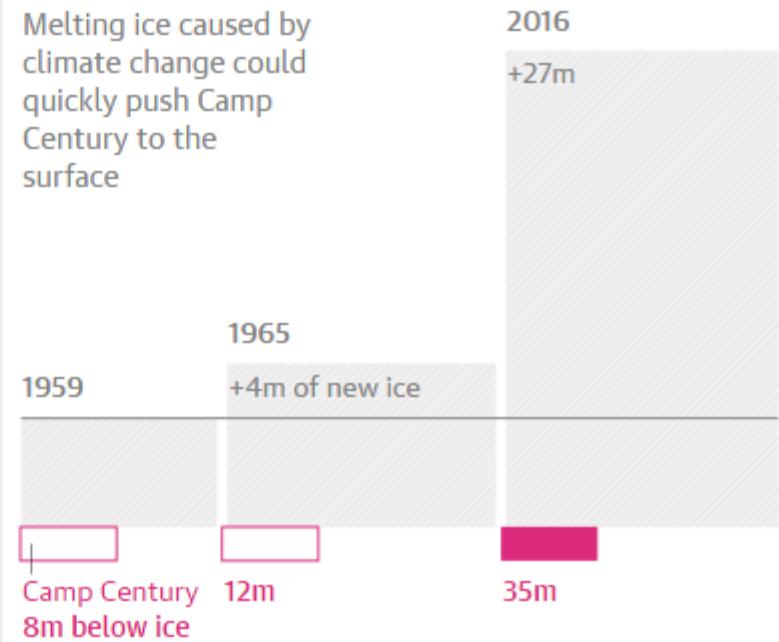


Hazards of deglaciation on ice sheets

- Deglaciation over hazardous materials



Melting ice caused by climate change could quickly push Camp Century to the surface



- Nuclear waste originally deposited 10 m below the surface in the accumulation area
- Today >30 m below the ice
- Change in ice density/weight
- In future?

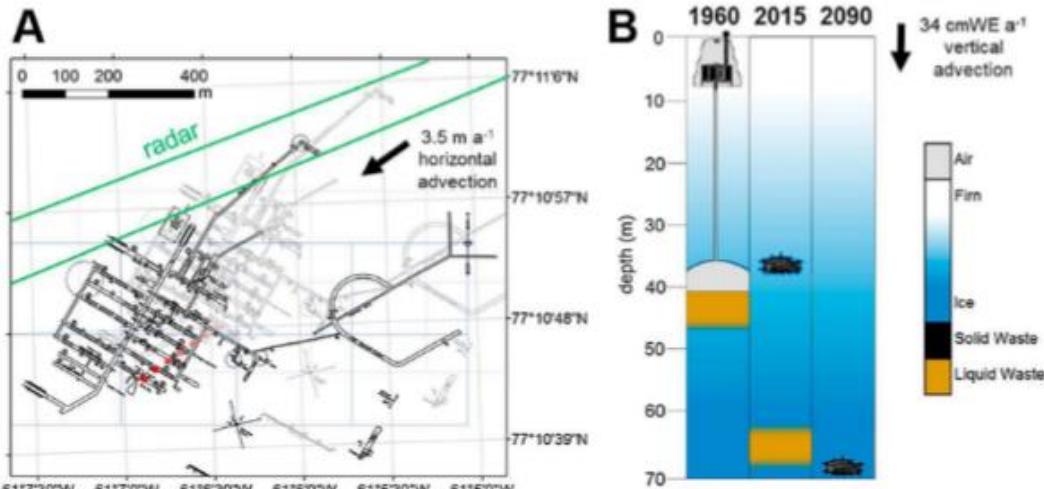


Figure 2. (a) Camp Century "as built" map georeferenced to 1960 (grey) and 2020 (black) locations [Kovacs, 1970], based on past surveys of the borehole location and horizontal advection associated with ice flow (Supplementary Methods). The red points denote decadal borehole location from 1960 to 2020. The green lines denote radar profiles shown in Figure 3. (b) Estimated Camp Century solid and refrozen liquid waste depths in 1960, 2015, and 2090, based on vertical advection rates (Figure S3). The horizontal extent of the liquid waste, while large relative to tunnel width, is small relative to camp width.



Colgan et al., 2016, GRL

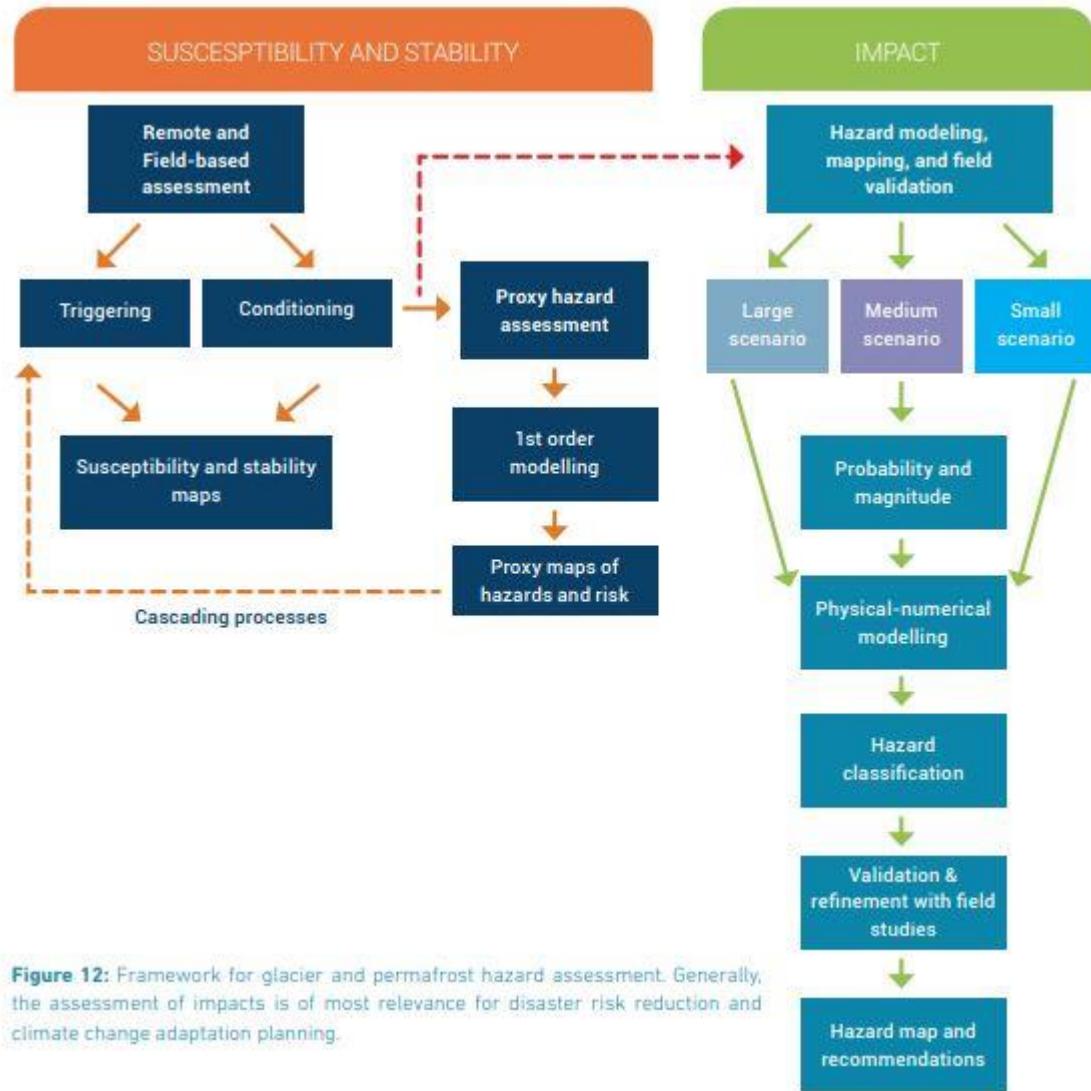


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Hazard Assessment

- 2 tier assessment procedure
- Rapid and long-term assessment
- Communication to affected population (alertness vs unnecessary fear)

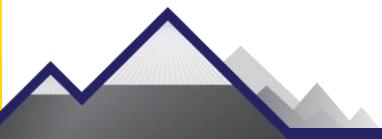


Allen et al., 2017, GAPHAZ



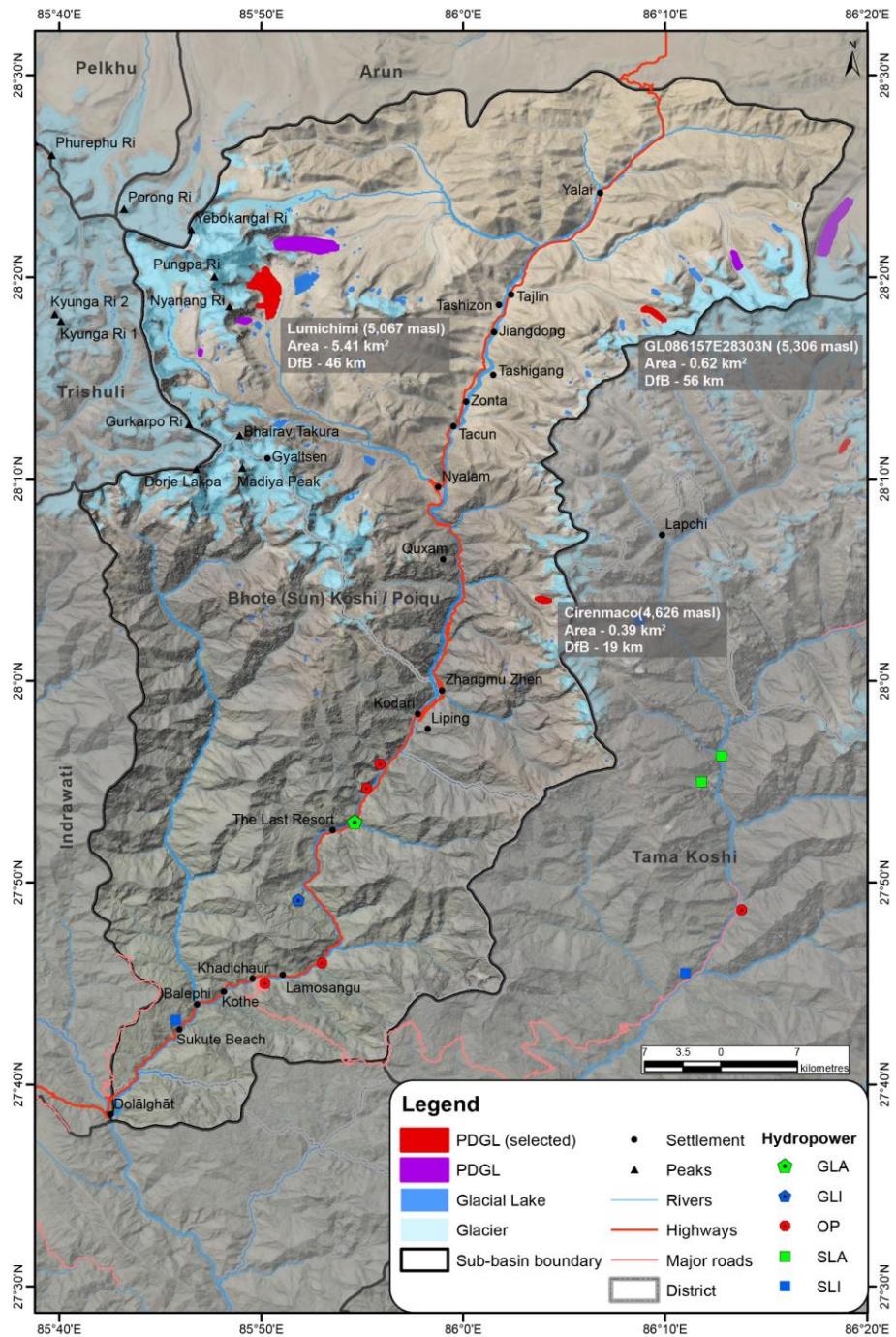
Hazard Mapping

- 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





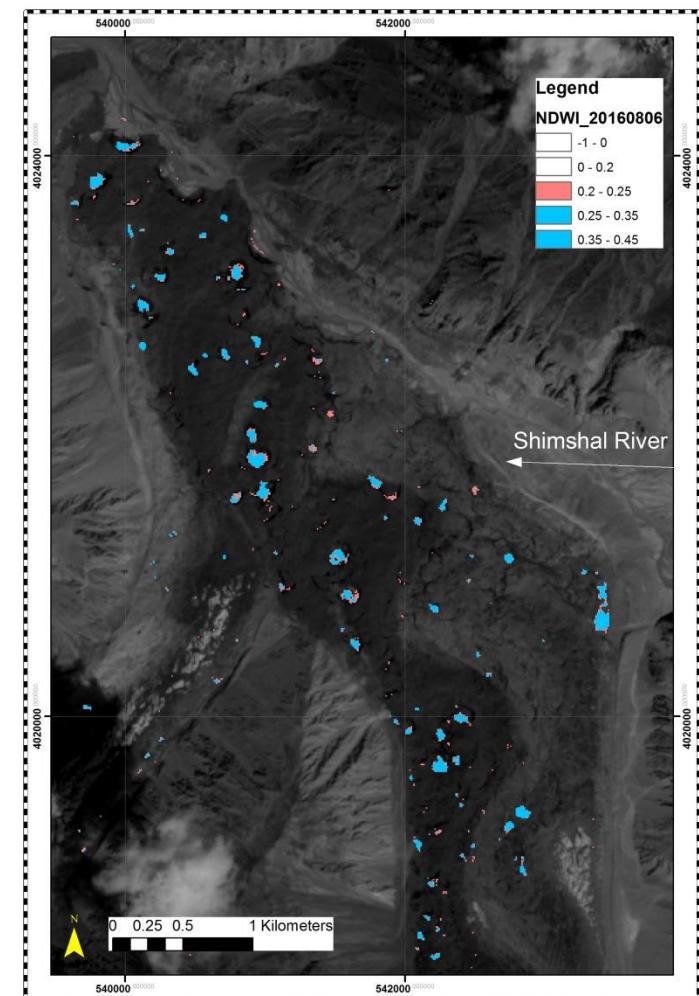
- Transboundary multi-hazard and risk assessment
- China-Nepal border





Example GLOFs – *Proxy Hazard Assessment*

- Accumulating water (using e.g. Landsat)
- Increasing velocities (using optical imagery)



Example GLOFs – *Susceptibility + Risk*

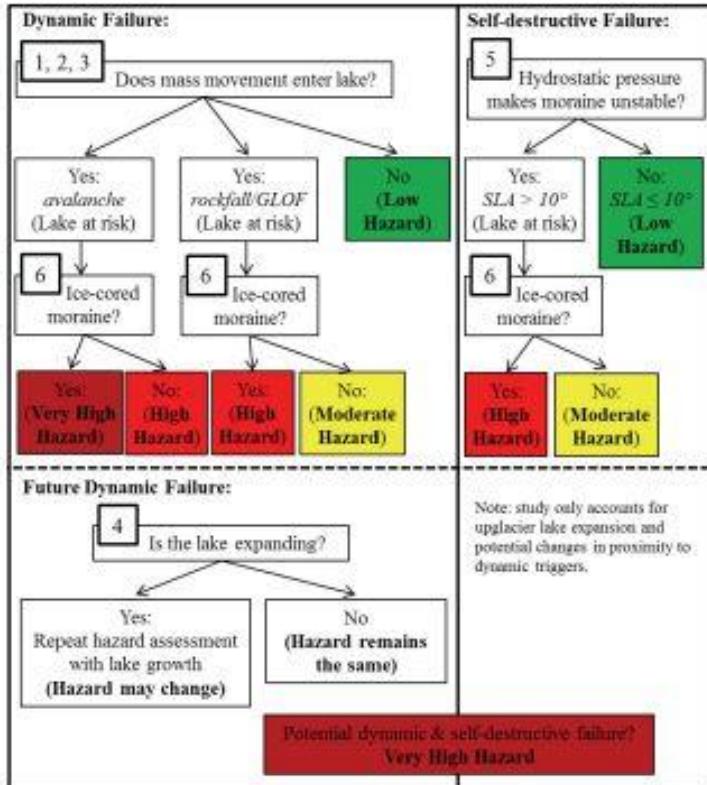


Figure 4. Hazard classification flow chart for determining the hazard associated with a glacial lake (numbers refer to hazard parameters in Fig. 2).

Rounce et al., 2015

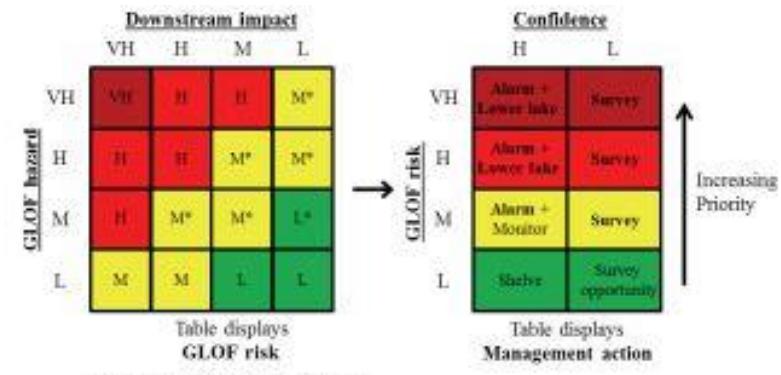


Figure 5. Risk management and action framework. Left table: GLOF risk is a function of the hazard and downstream impact. Right table: the recommended course of action for a given glacial lake based on the type of assessment.



Example GLOFs – *Impact*

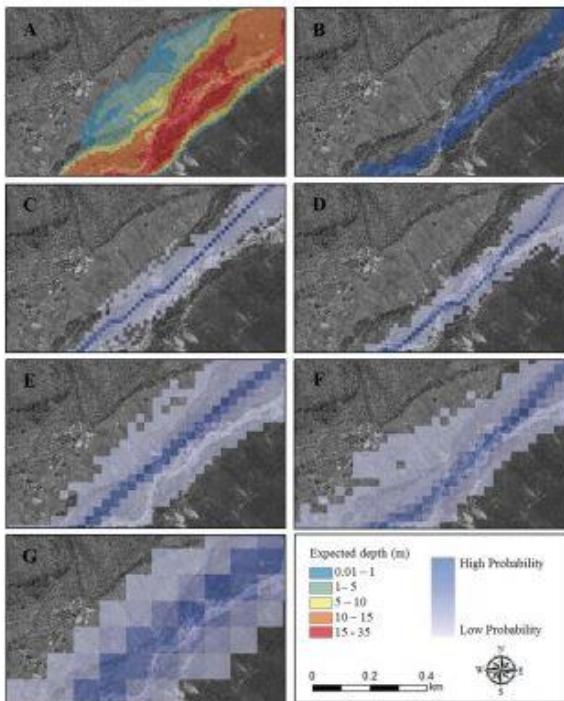


Figure 3. Inundated areas at Dingboche for a GLOF from Imja Tsho using (a) FLO2D (Somos-Valenzuela et al., 2015), (b) the MSF model using the GDEM, and (c–g) the MC-LCP model with various DEMs and pixel sizes: (c) SRTM 90 m resampled 15 m, (d) GDEM 30 m resampled 15 m, (e) SRTM 90 m resampled 30 m, (f) GDEM 30 m, and (g) SRTM 90 m.

Table 4. Descriptions of downstream impact classifications.

Classification	Description of downstream impact
Very high	Potential loss of life with no warning (lodges/buildings) <i>and</i> the loss of costly infrastructure (e.g., hydropower)
High	Potential loss of life with no warning (lodges/buildings) <i>or</i> the loss of costly infrastructure (e.g., hydropower)
Moderate	Damage that is disruptive, which includes agricultural lands, bridges, trails, etc.
Low	No impact on humans, infrastructure, or other projects



Final Assessment

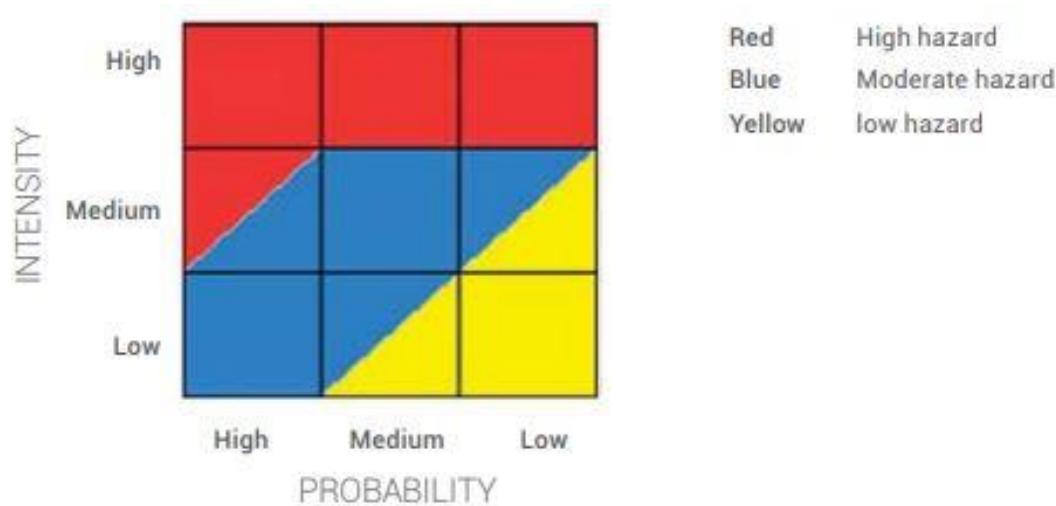


Table 1. Indicative values for the intensity classification for various high mountain hazards as used in Swiss practice (after; Hürlimann et al., 2006; Raetzo et al., 2002). E Kinetic energy; v Velocity; h flow depth or height of the deposit.

Phenomena	Low intensity	Medium intensity	High intensity
Rockfall	$E < 30 \text{ kJ}$	$30 < E < 300 \text{ kJ}$	$E > 300 \text{ kJ}$
Rock avalanche			$E > 300 \text{ kJ}$
Landslide	$v \leq 2\text{cm/year}$	$v: \text{dm/year}$ $(>2\text{cm/year})$	$v > 0.1 \text{ m/day}$ for shallow landslides; displacement $> 1\text{m}$ per event
Debris flow (single parameter)		$h < 1 \text{ m}$	$h > 1 \text{ m}$
Debris flow (multiple parameter)		$h < 1 \text{ m}$ or $v < 1\text{m/s}$	$h > 1 \text{ m}$ and $v > 1\text{m/s}$



Impact

- Focus Group Workshops
- Interviews
- Awareness Raising





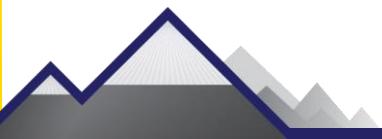
Topics

- Terminology: Hazards. Risks. Mitigation.
- *Global ice and exposure to hazards*
- *Types of glacial hazards*
- *Hazard Assessment: Mapping and Modelling*
- *Monitoring and risk mitigation*



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?



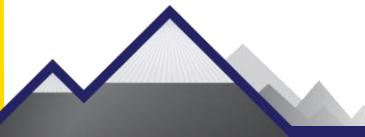


Grindelwald Switzerland

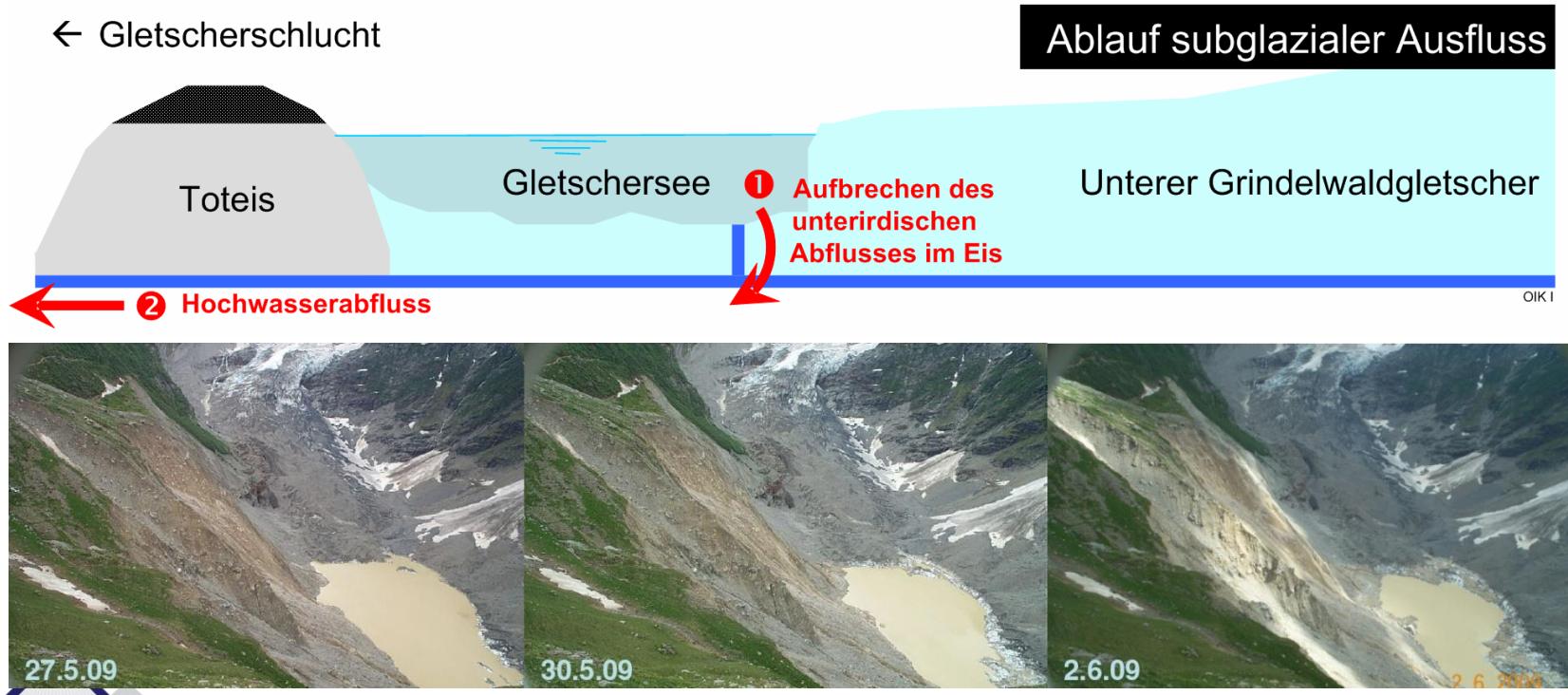
- Glacial lake formed repeatedly
- Concerns about possible downstream damages
- Classical compound event
- Who decides? Who pays?



Grindelwald Switzerland



Formation of a glacial lake



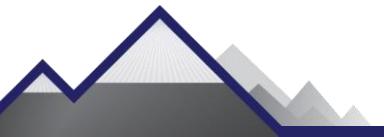
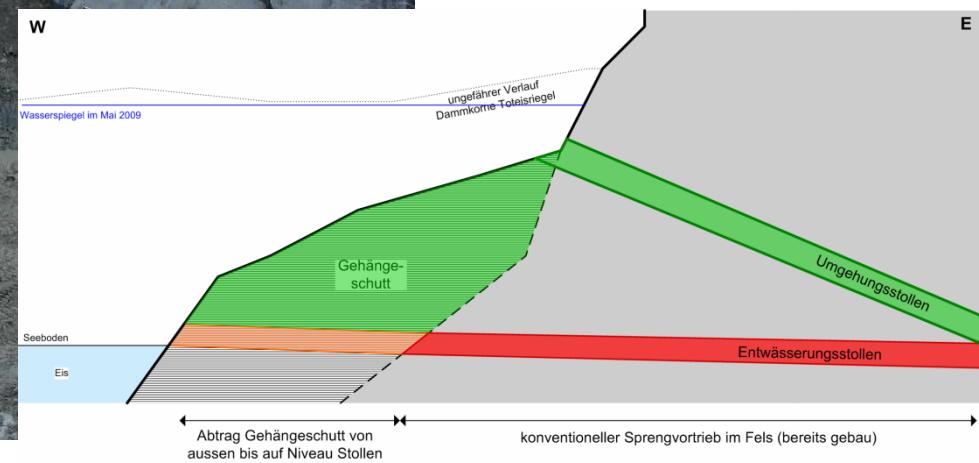


Slumping moraines and rockfall





Decision to build a tunnel ...





... and then the lake emptied naturally





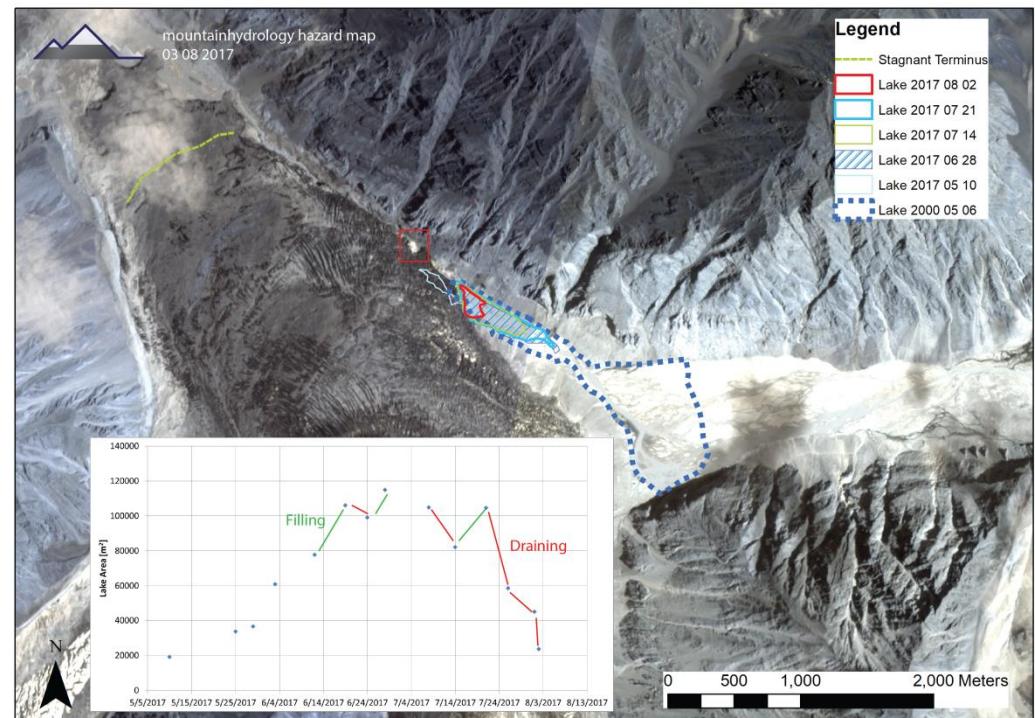
Shimshal Glacial Lake (Pakistan)

- Lake forms as a result of a glacier surge
- Damages to local roads and agriculture
- Politically unstable
- Difficult to access (no telephone, bad roads)



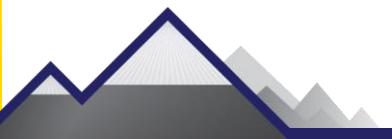
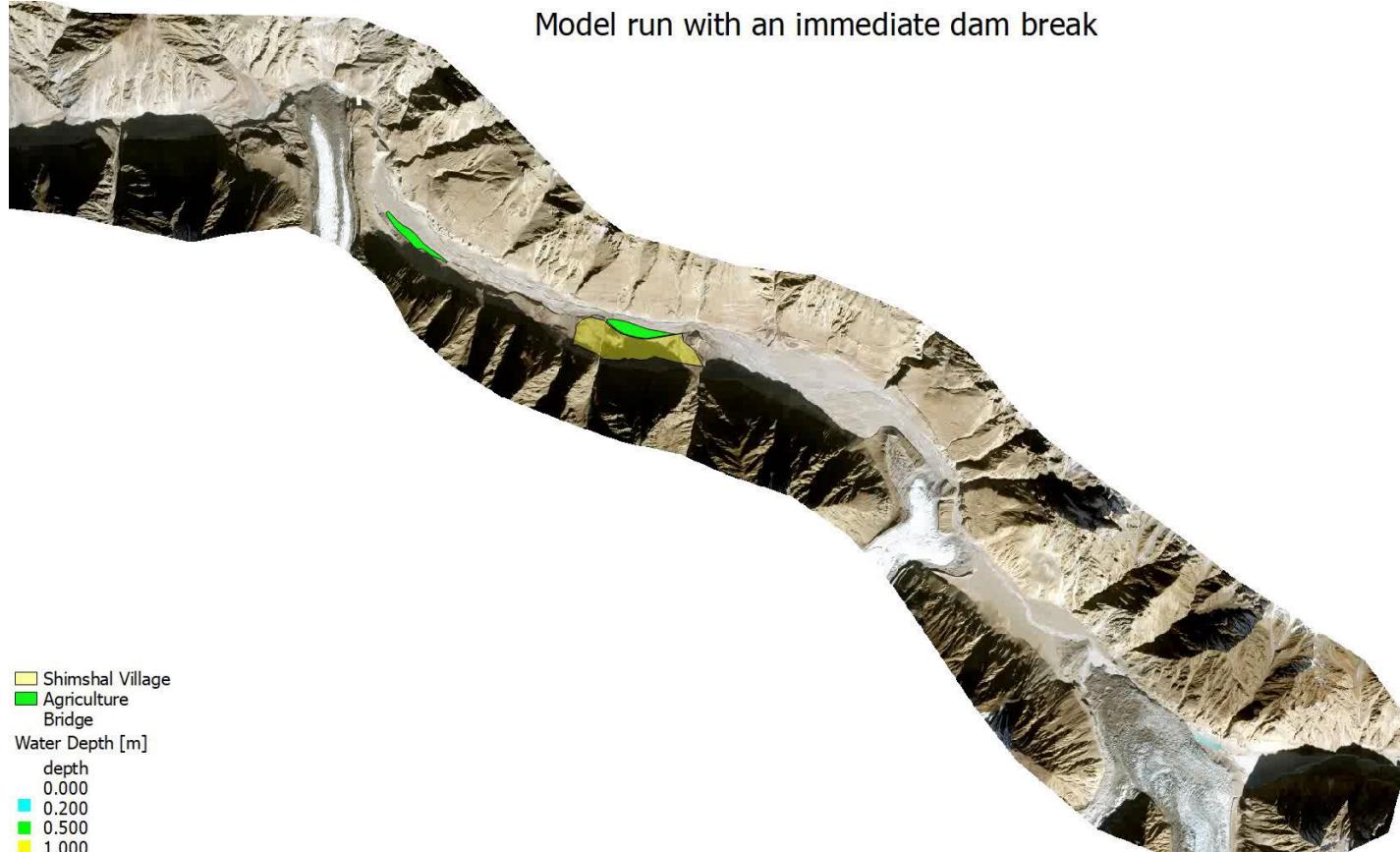
Scenarios

- Volume = $f(\text{Area})$
- Discharge = $f(\text{Volume}, \text{dam break scenario})$

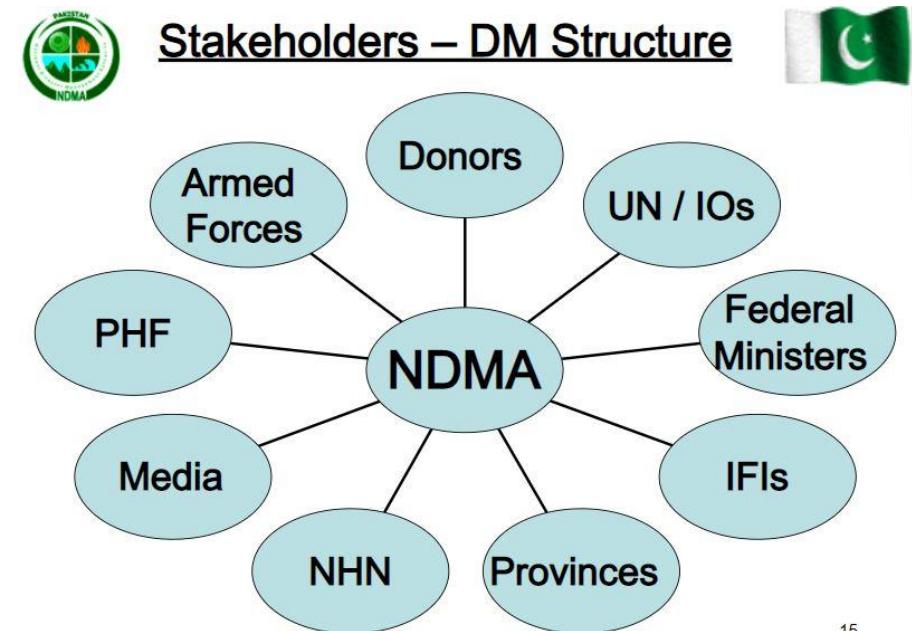
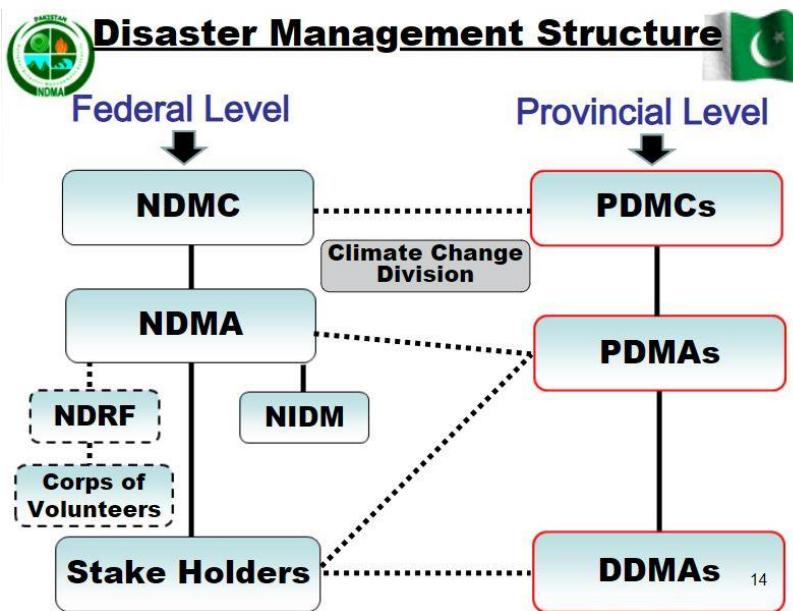




Hydrodynamic Modelling



Institutional challenge



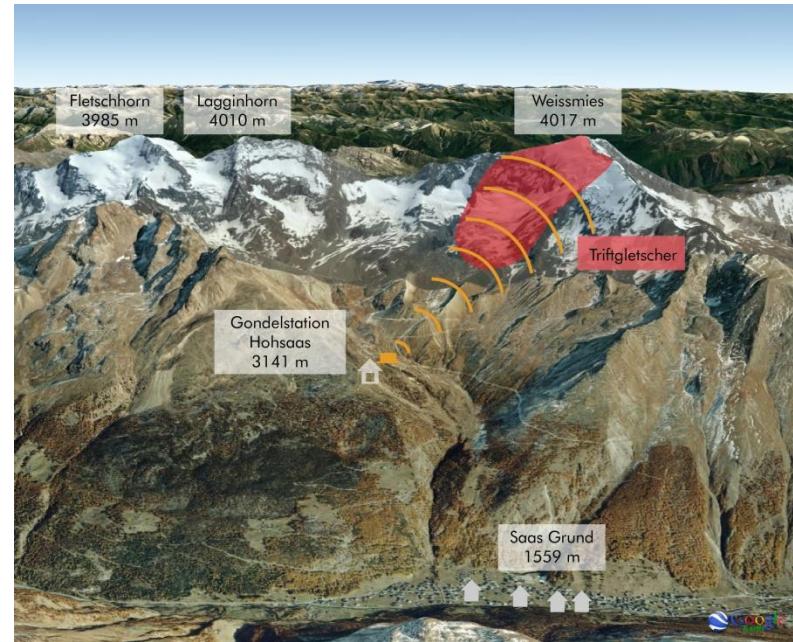
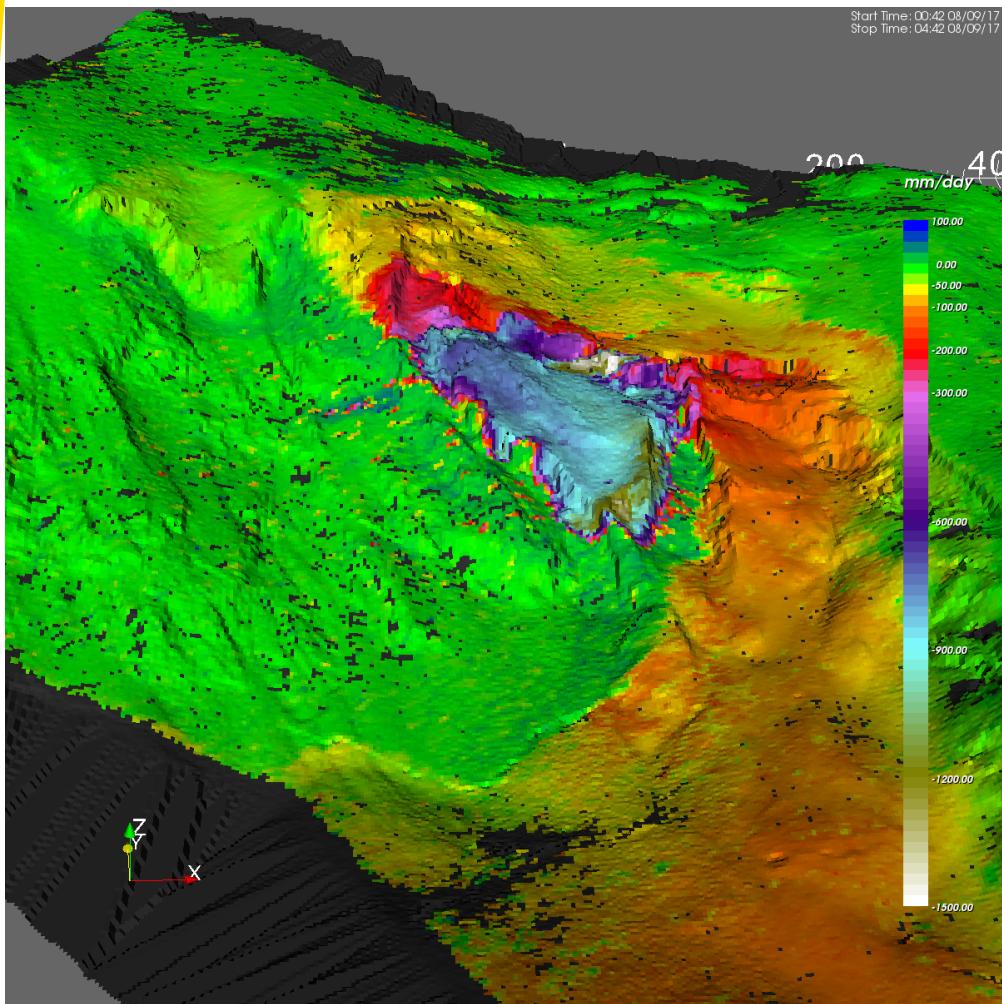


Monitoring and Risk Mitigation

- Remote Sensing
 - new near real-time products for observations
(Planet, Sentinel)
 - Temperature/Precipitation products
- Field based
 - climate and discharge monitoring
 - radar monitoring



Monitoring ice falls





Monitoring Glacial Lake

