



# Glacial Hazards

# Risk Assessment and Mitigation

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Hazards and Risk Assessment



# Topics

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

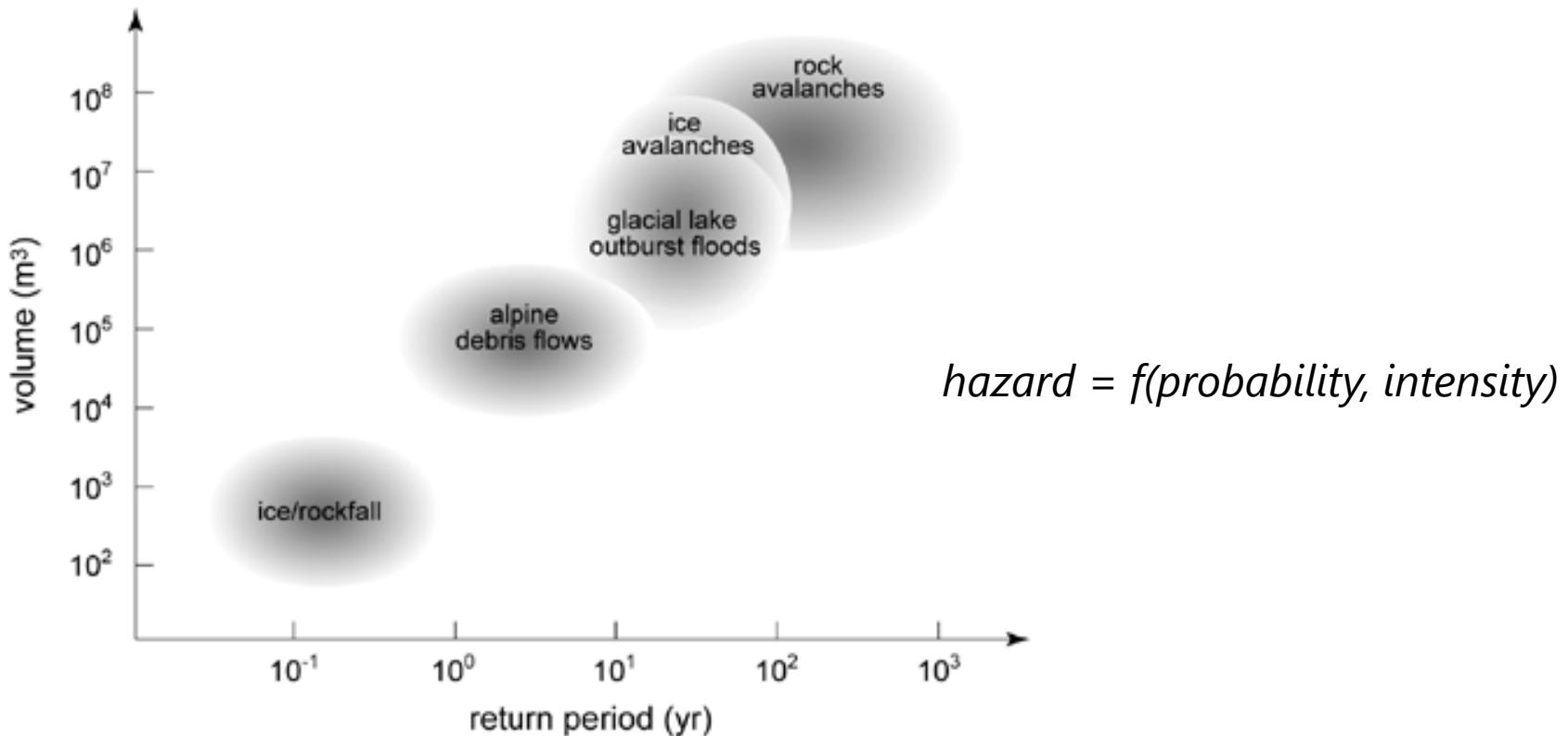


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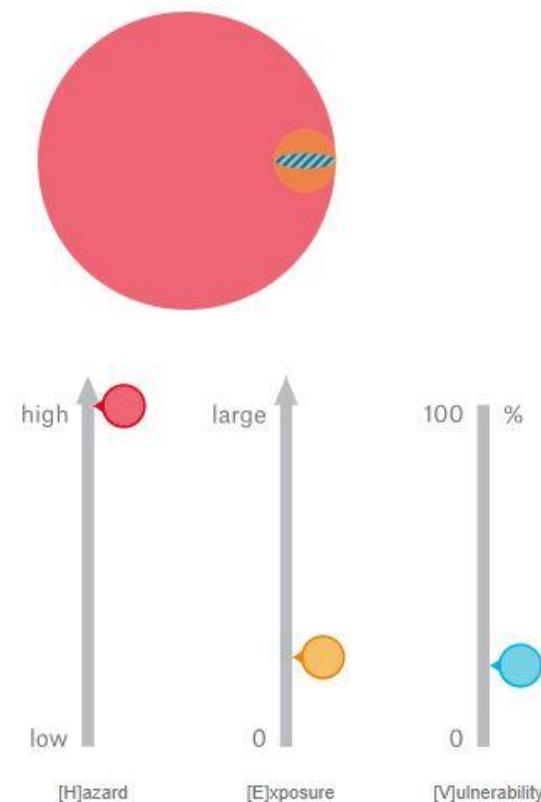
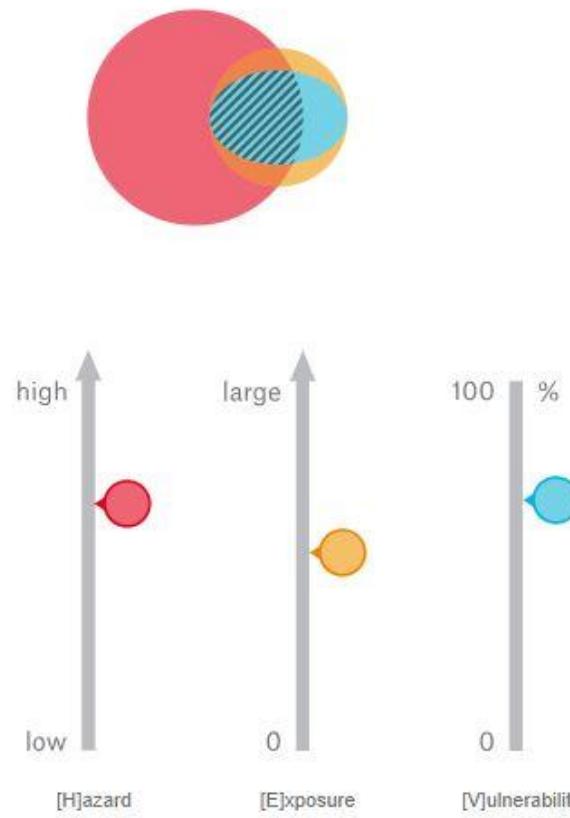


# Return periods vs. volumes





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





# Topics

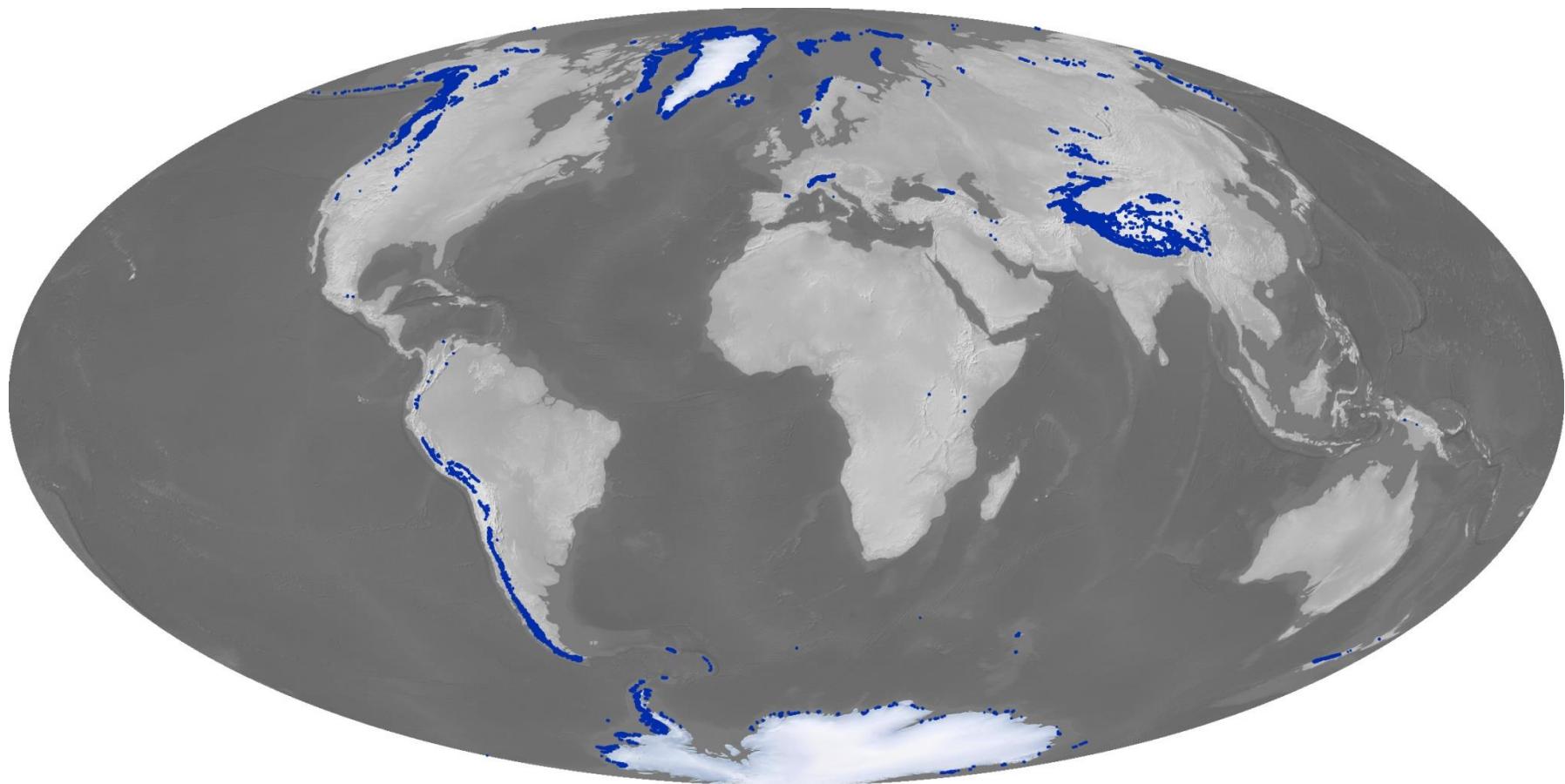
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# Glaciers Globally

## Total Area:

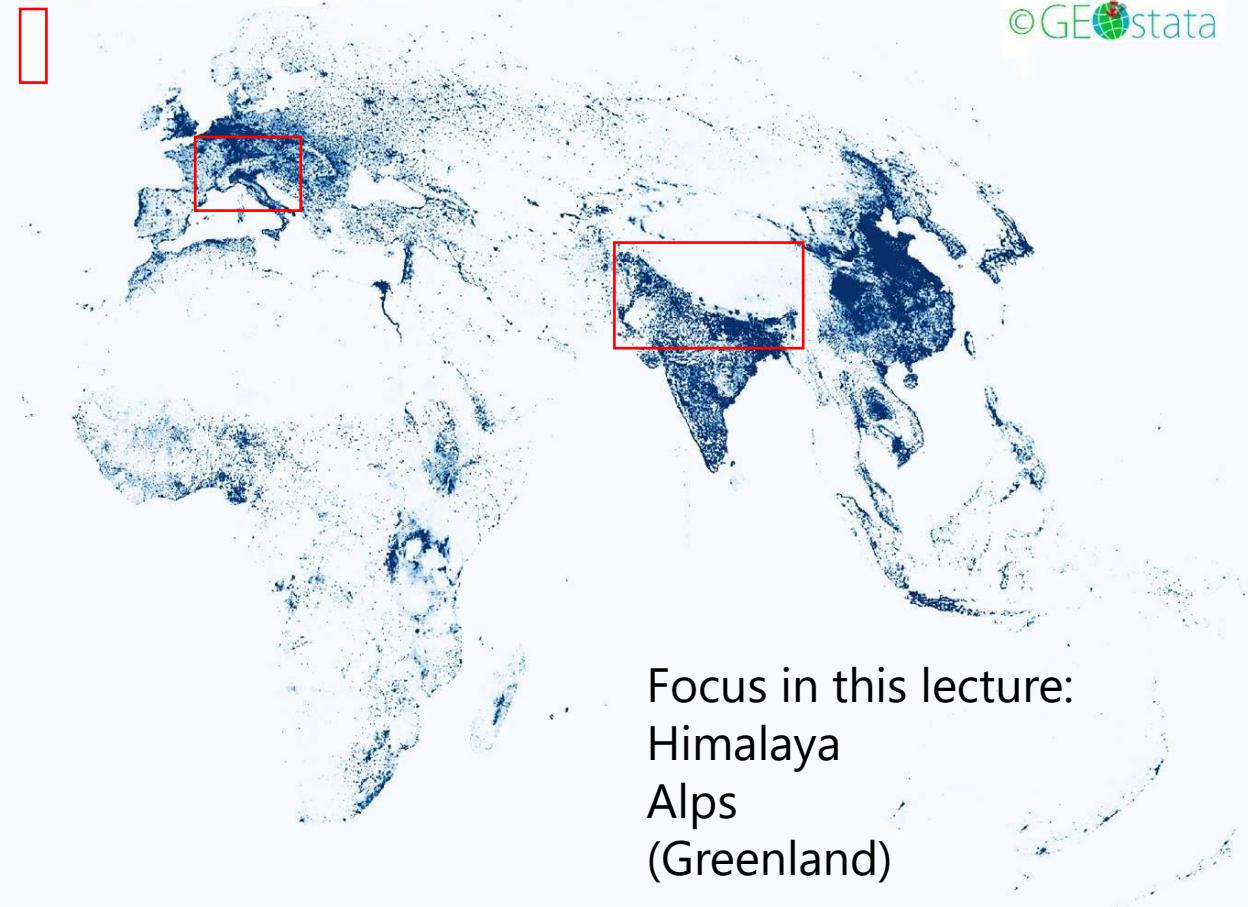
RGI: 734 933 km<sup>2</sup>  
WGI: 747 688 km<sup>2</sup>



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



WORLD POPULATION DENSITY MAP - 2015

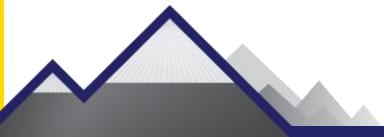


Data source: Freire, Sergio; Pesaresi, Martino (2015): GHS population grid, derived from GPW4, multitemporal (1975, 1990, 2000, 2015). European Commission, Joint Research Centre (JRC).  
PID: [http://data.europa.eu/89h/jrc-ghs1-ghs\\_pop\\_gpw4\\_globe\\_r2015a](http://data.europa.eu/89h/jrc-ghs1-ghs_pop_gpw4_globe_r2015a)



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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)

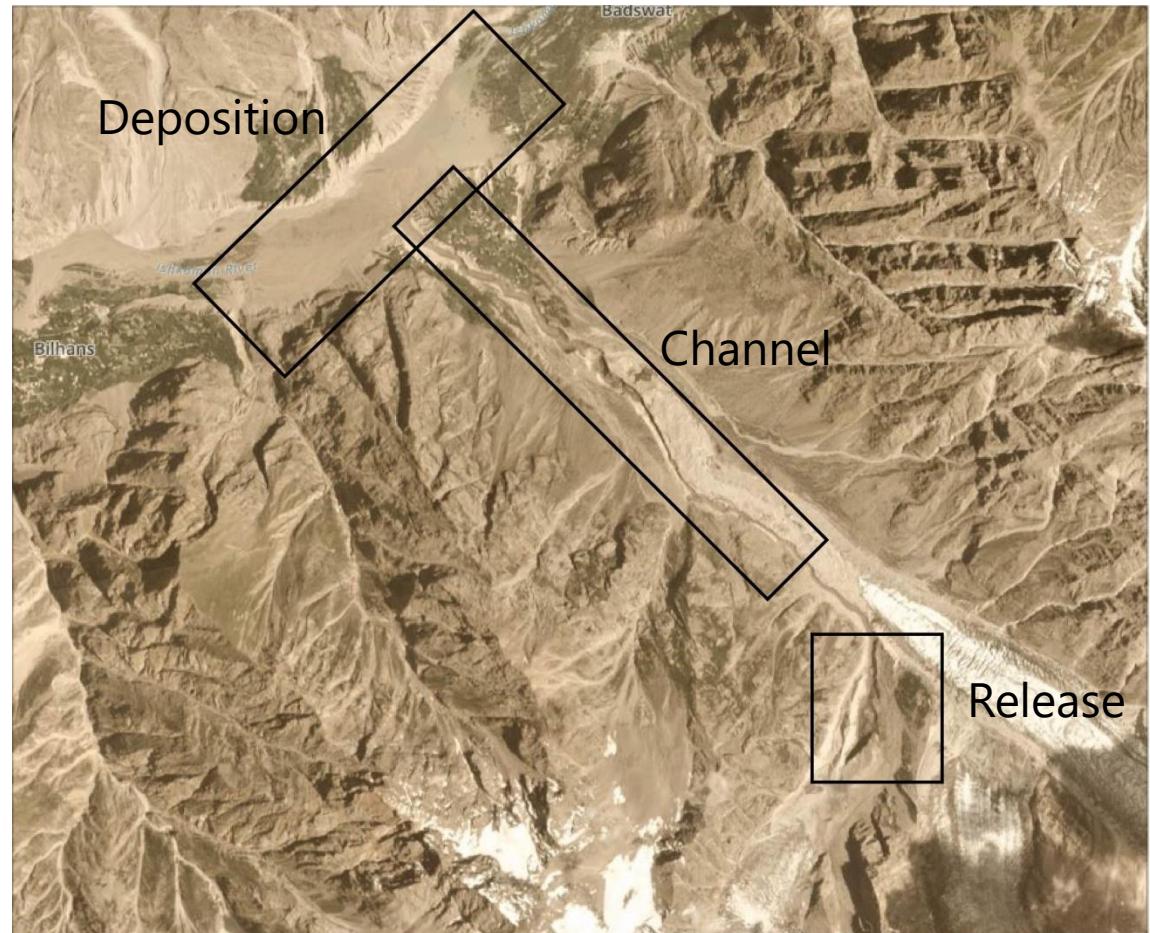


British Columbia  
Canada

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*



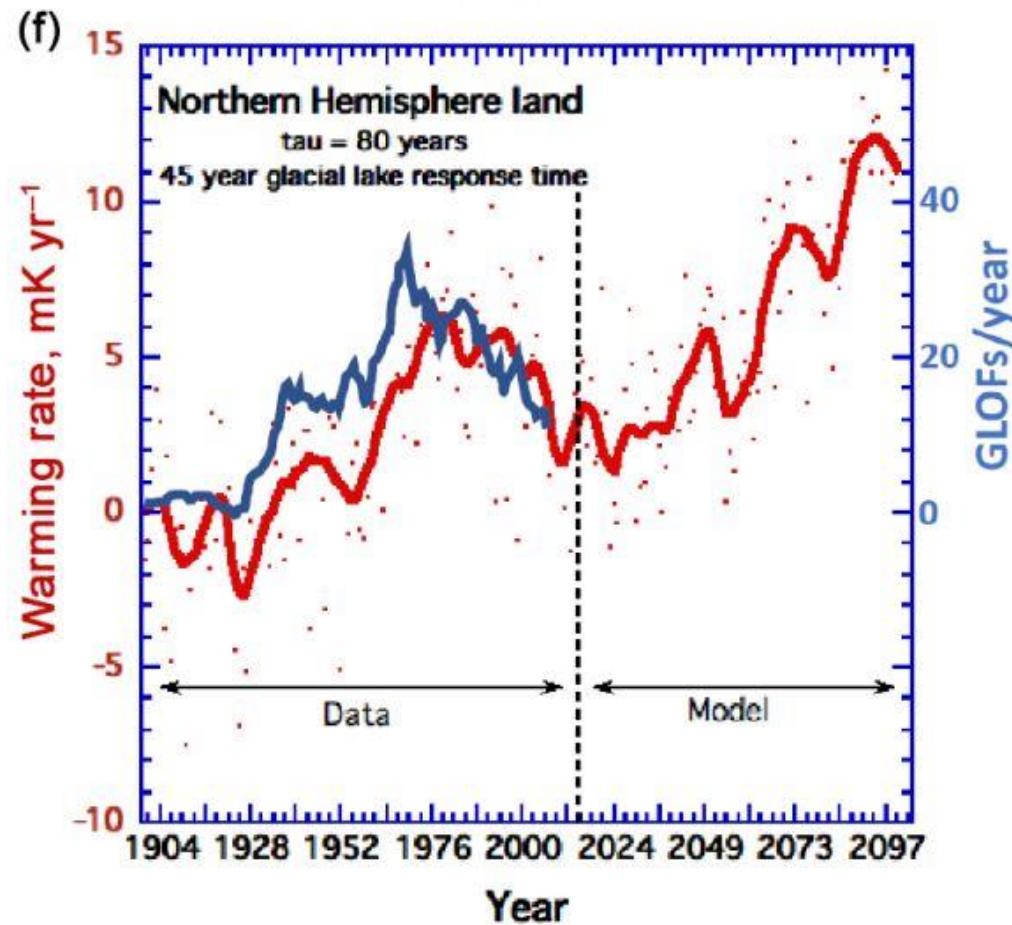
# Glacier Lake Outburst Floods - *Causes*

- 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)



# Glacier Lake Outburst Floods - *Causes*

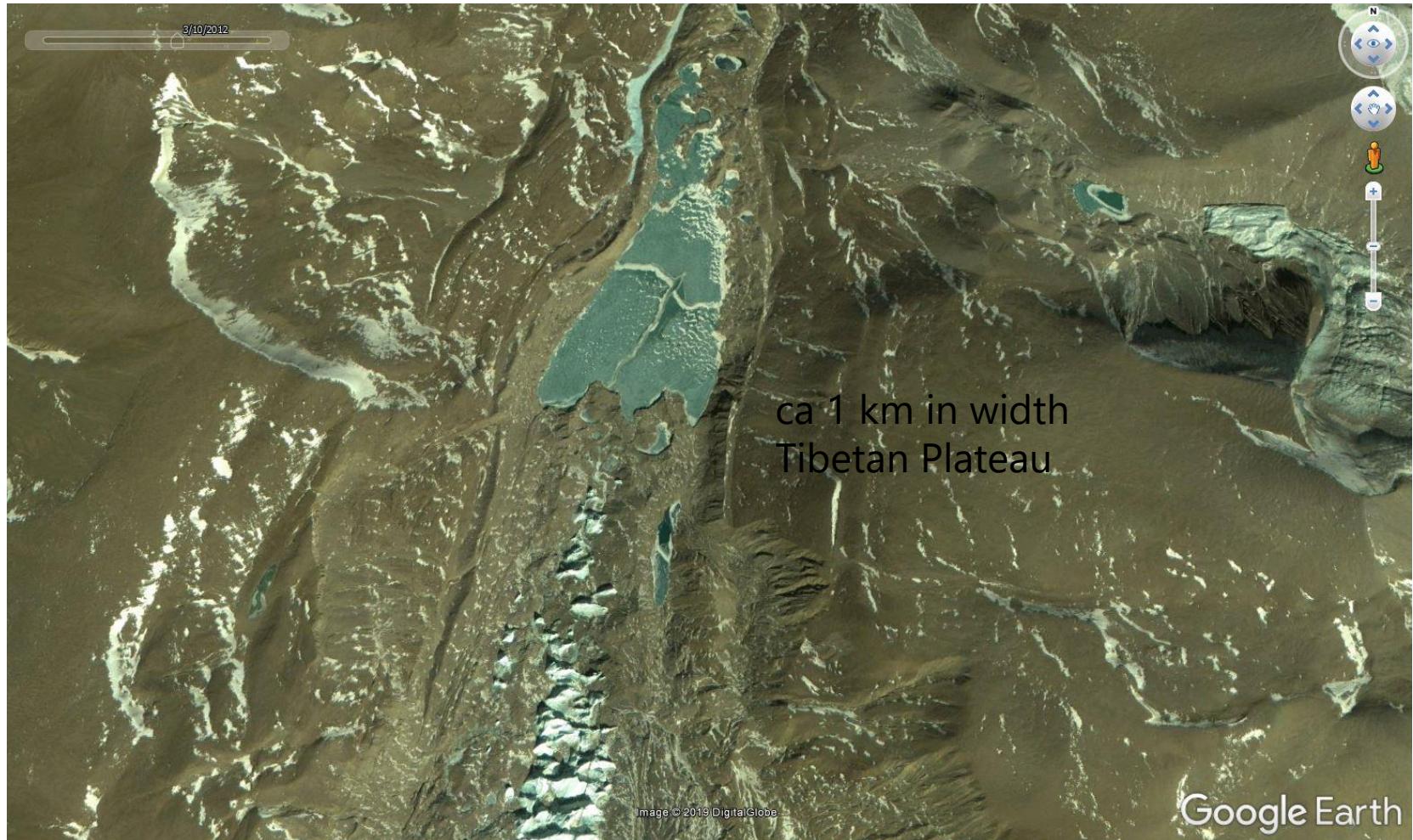
- Link to climate change?
  - Seems very plausible and some indications
  - Difficult to proof with very little data
  - Data bias towards more observations in recent years



Harrison et al., 2018

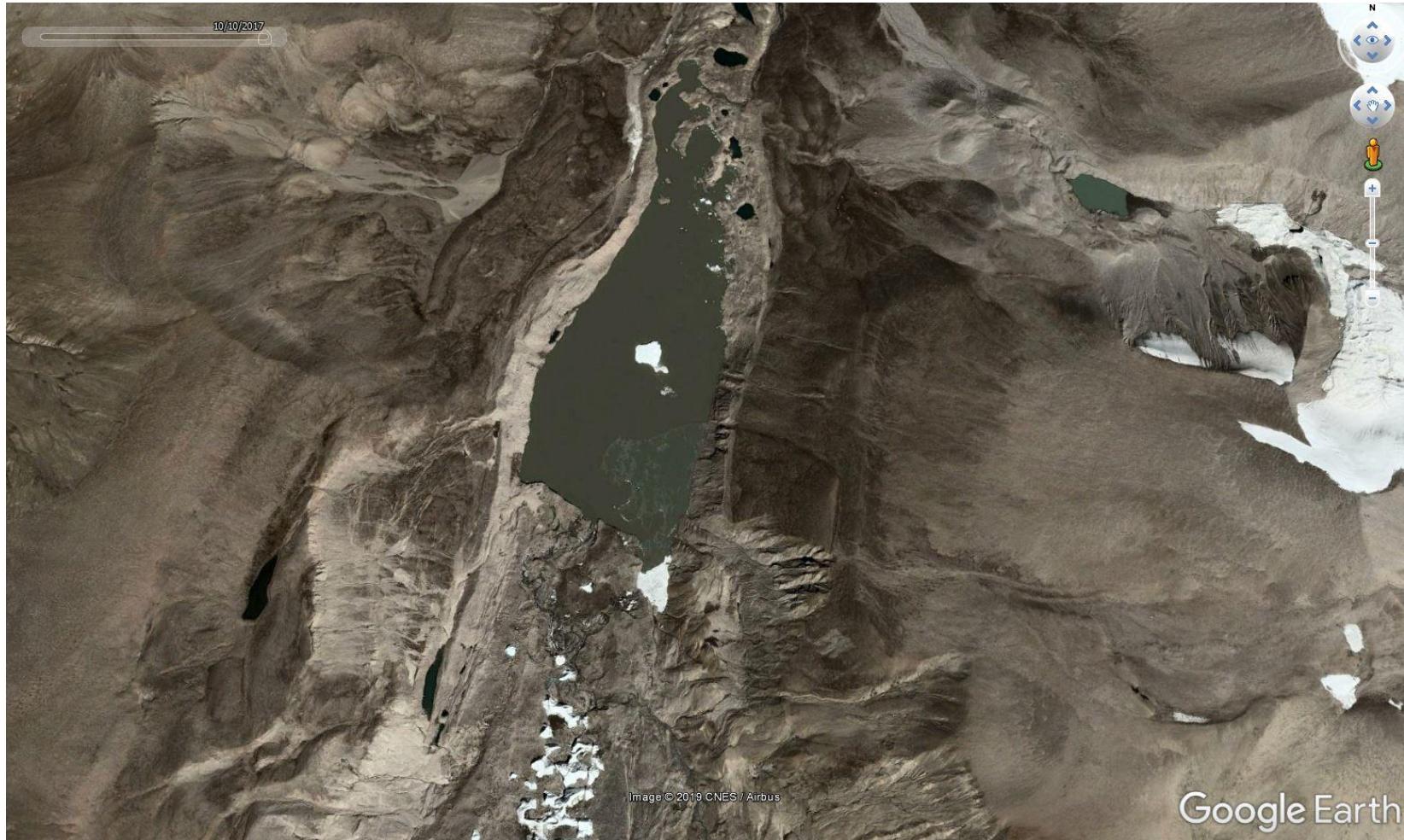


# Growth of terminal lakes (2012)





# Growth of terminal lakes (2017)



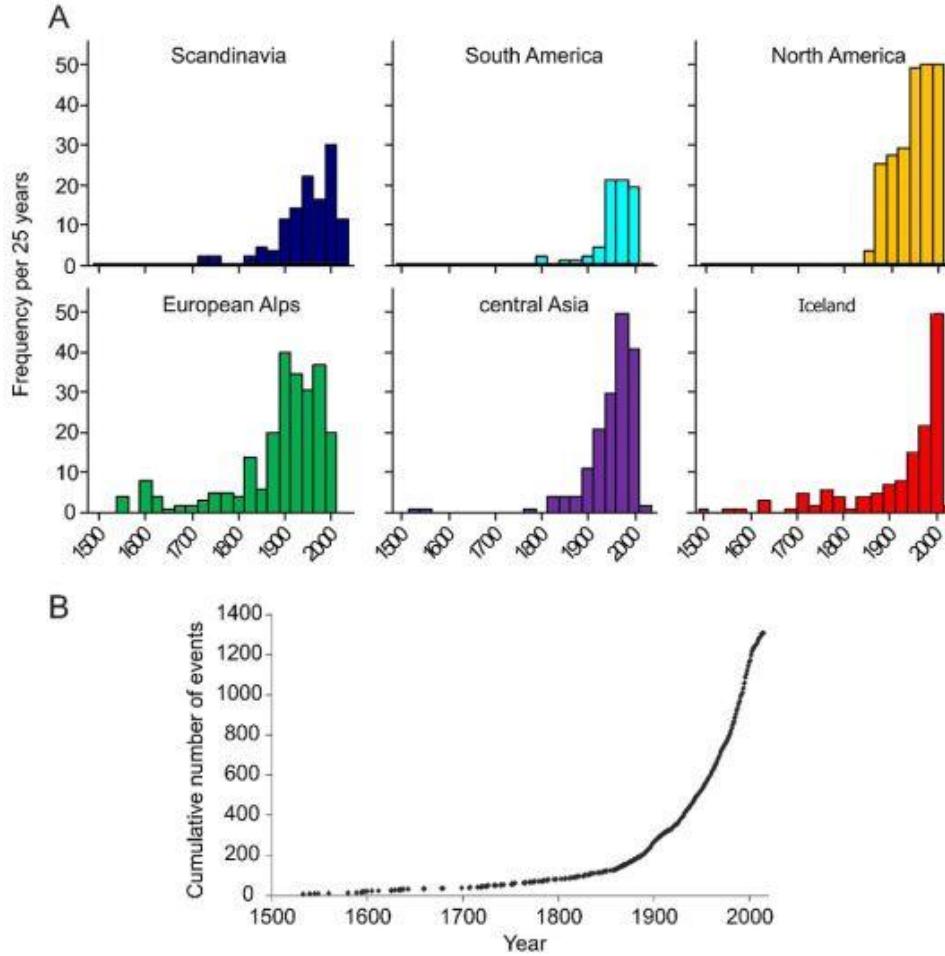


# Surging glaciers



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

# Glacier Lake Outburst Floods - *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*

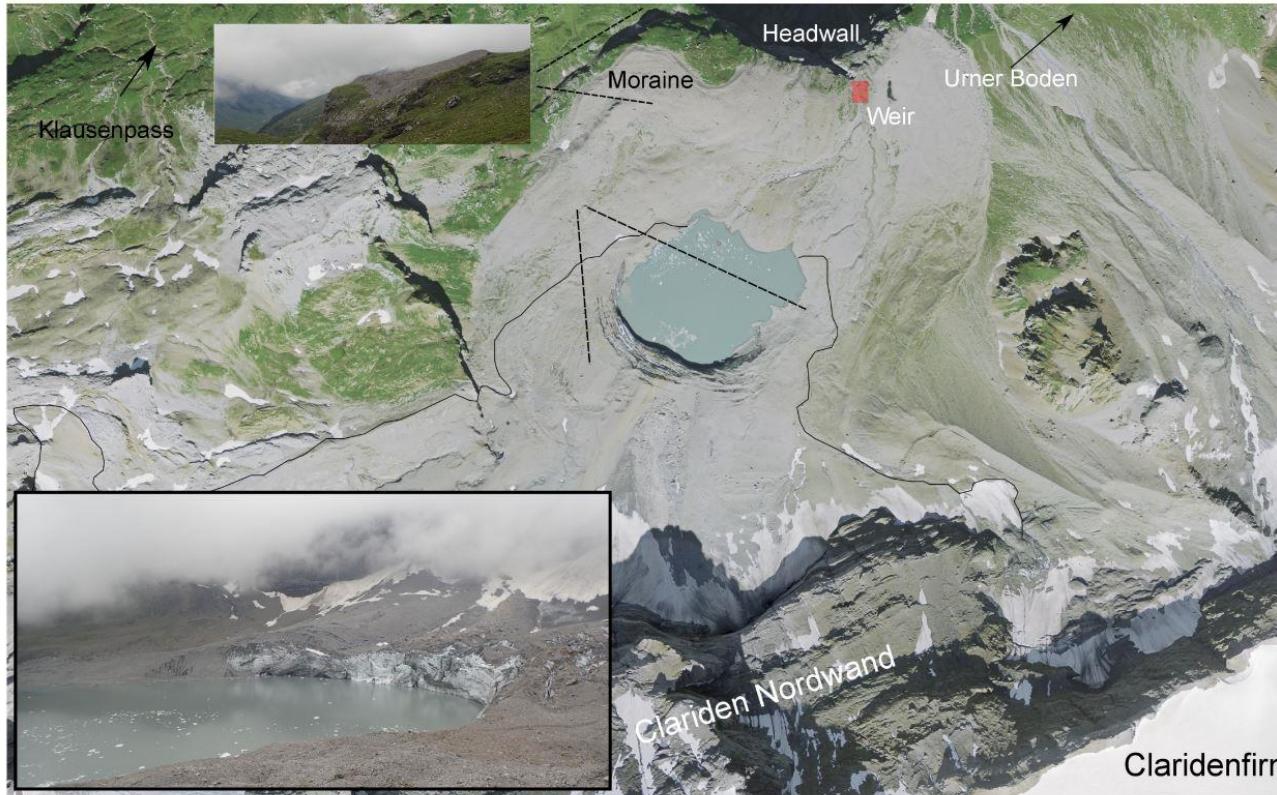


Figure 1: Griessseeli in an orthophoto from 2013 (main frame, swisstopo). The calving front as well as the frontal moraine of the glacier are shown in insets taken in August 2016 by the authors.

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



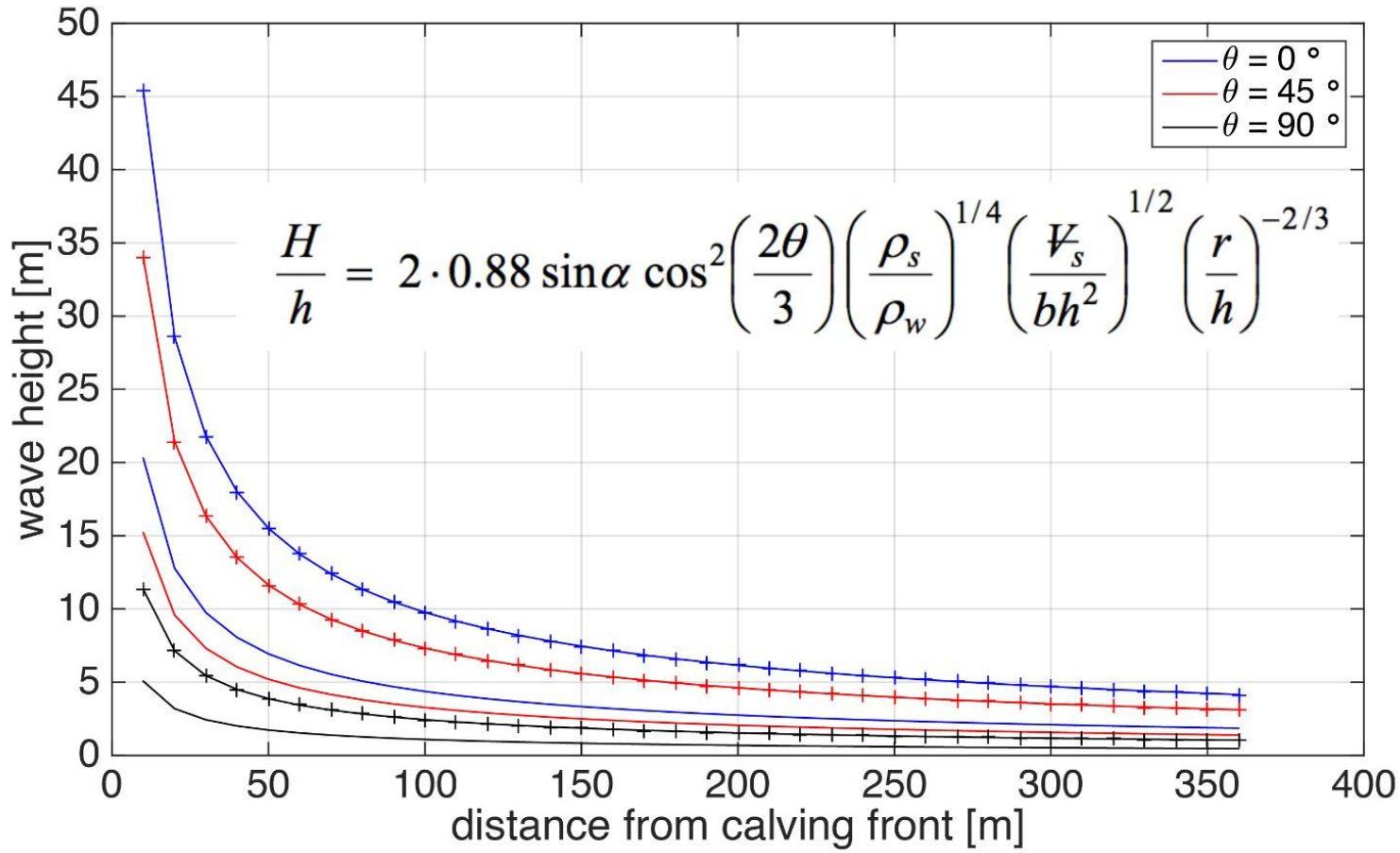
# Impact waves

- 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.

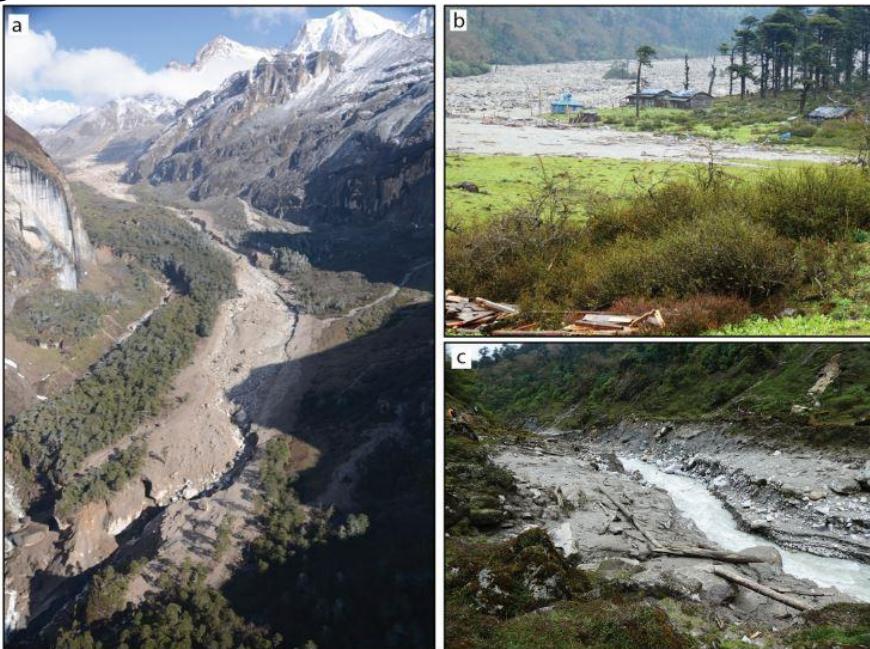
# Impact waves





# 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



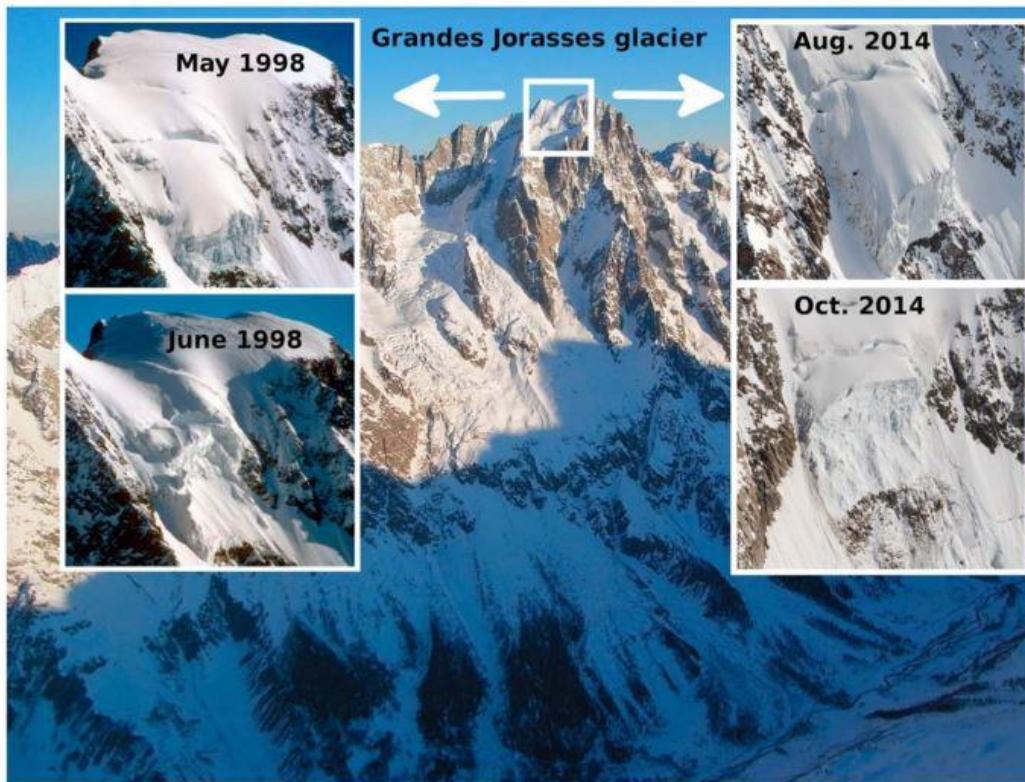
# Glacier related hazards

- 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

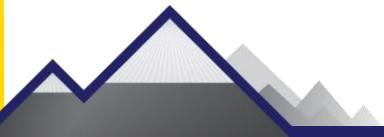


**Figure 7.** South side of the Grandes Jorasses and the Italian Val Ferret. (left inset) Evolution of the hanging glacier from May to June 1998. (right inset) Evolution of the hanging glacier from August to October 2014.

Faillettaz et al., 2015



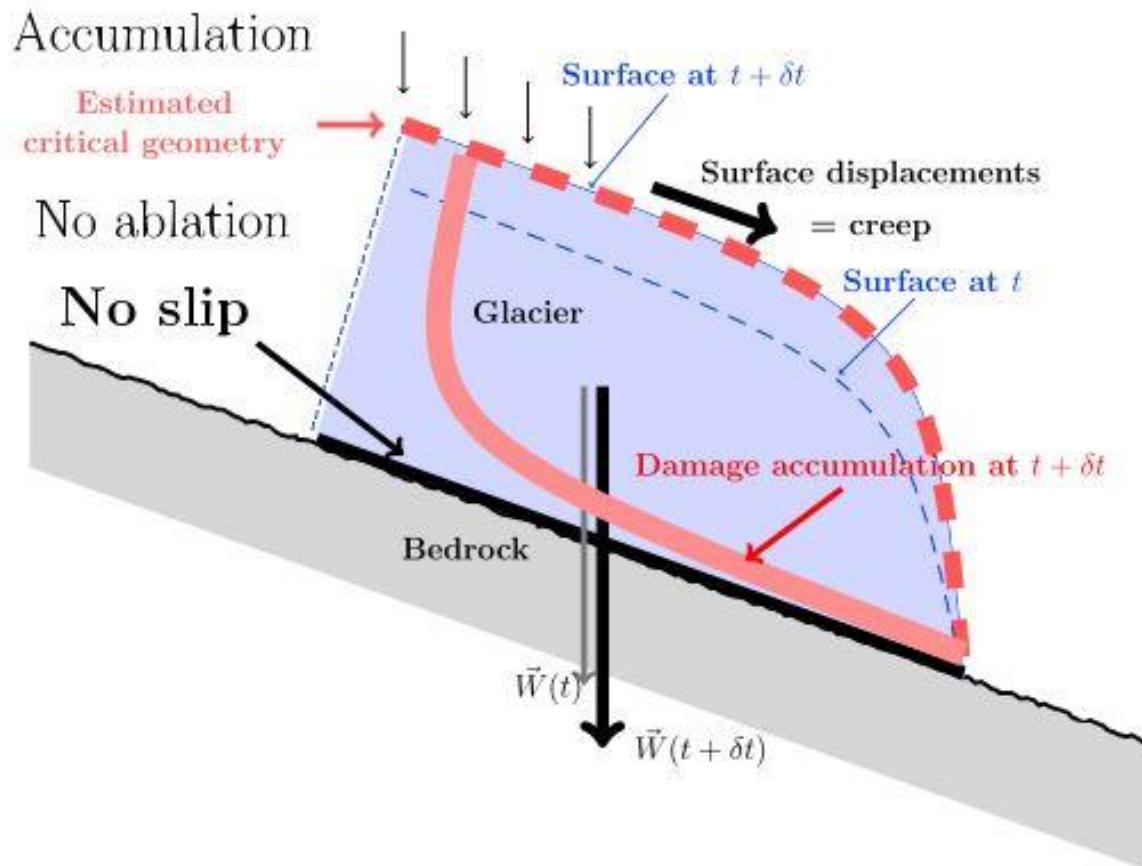
# Ice break offs + collapsing glaciers





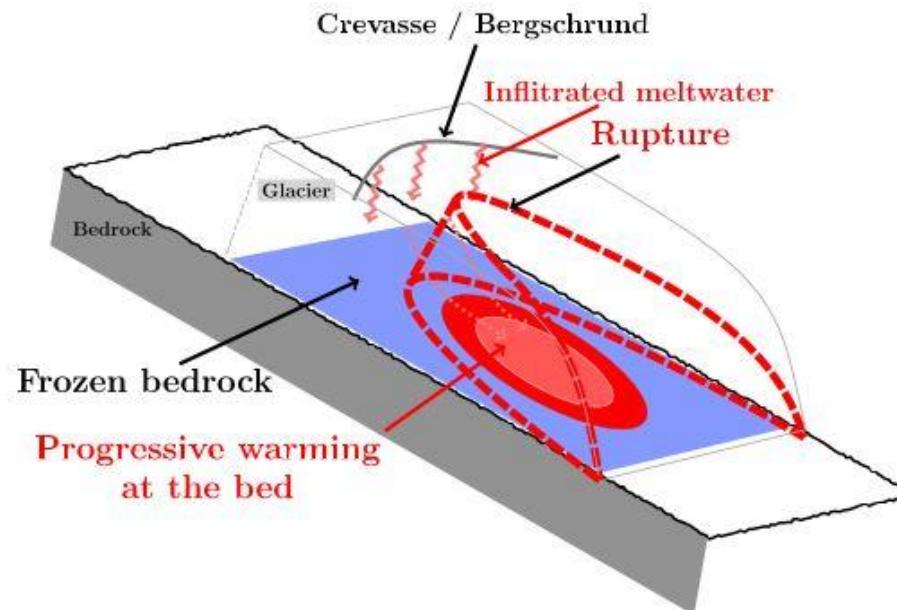
# Causes – *cold based; damage propagation*

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



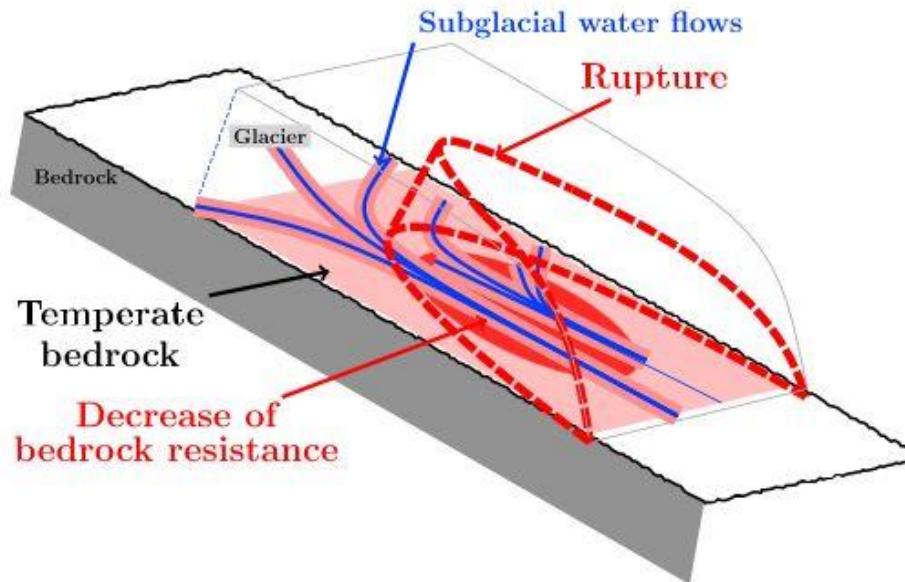
Faillietaz et al., 2015

# 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.

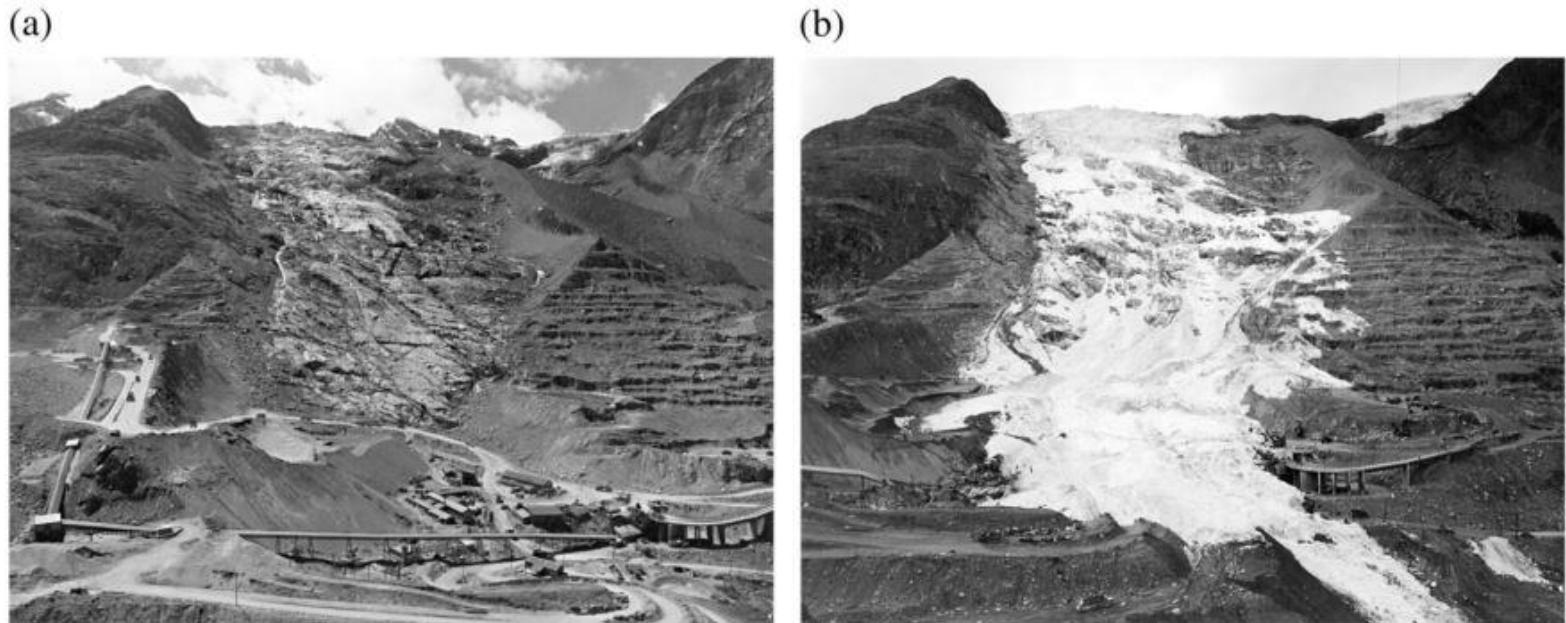
# Causes – *warm based; hydraulic slip*



**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 (Switzerland)



**Figure 13.** The Mattmark disaster:  $2 \times 10^6 \text{ m}^3$  of ice broke off on 30 August 1965 (archive VAW).



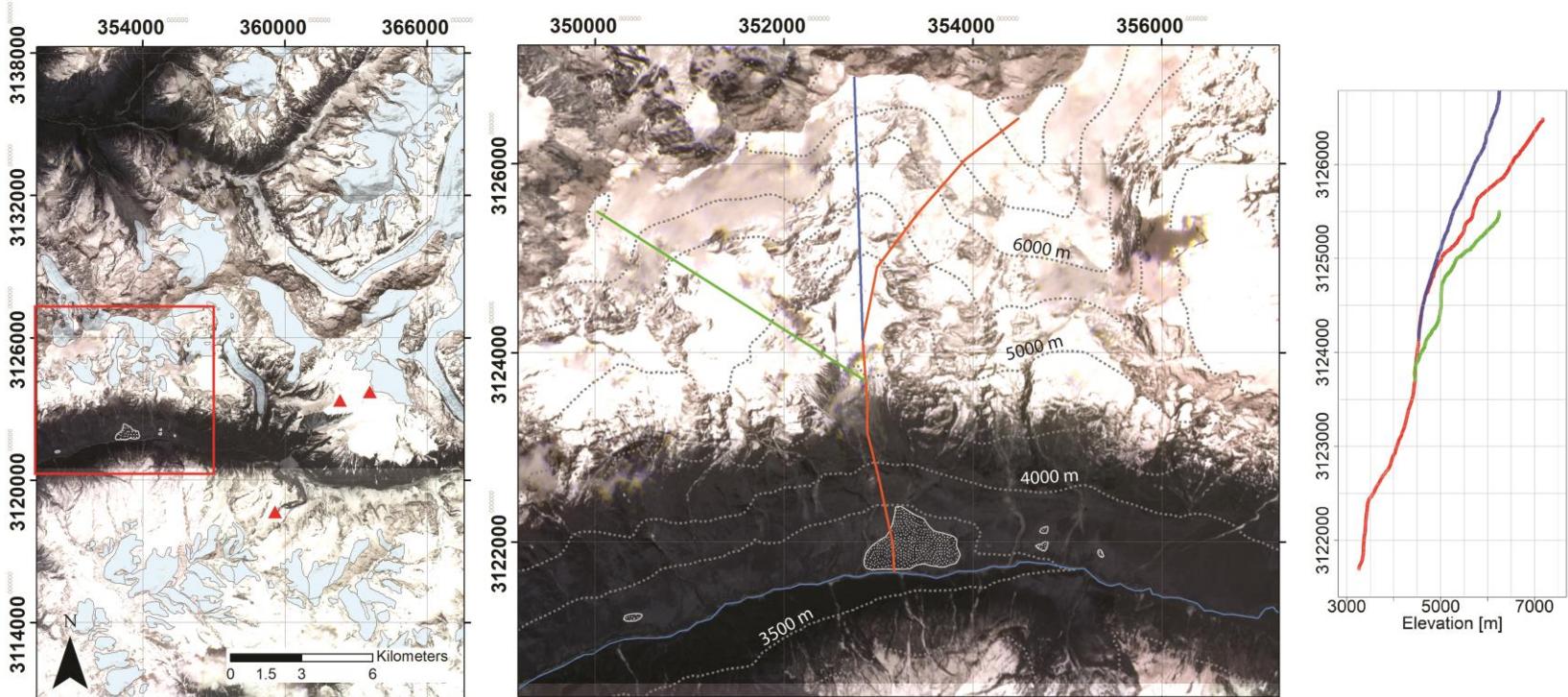
# Results – co-seismic events

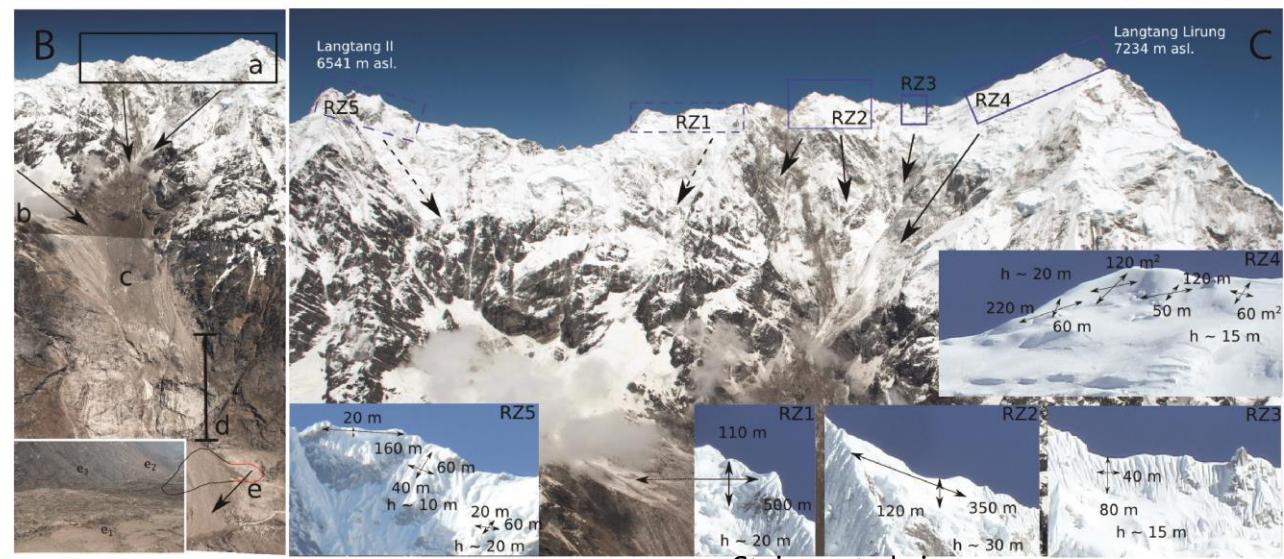
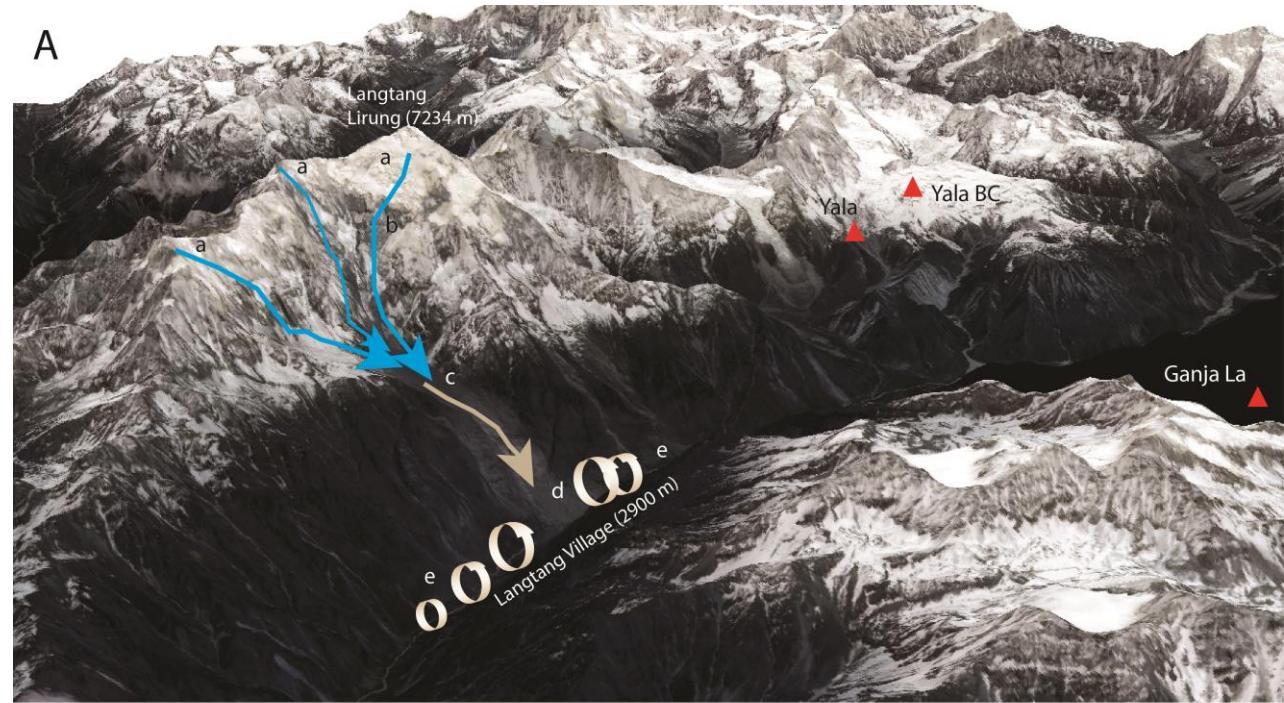
- Gorkha earthquake 2015 in Nepal
- >4000 co-seismic landslides
- Ice-break offs that caused deposits of up to 100 m depth
- Multi-hazard (ice break off + avalanche + debris flow)



Kargel et al., 2016

# Results – co-seismic events

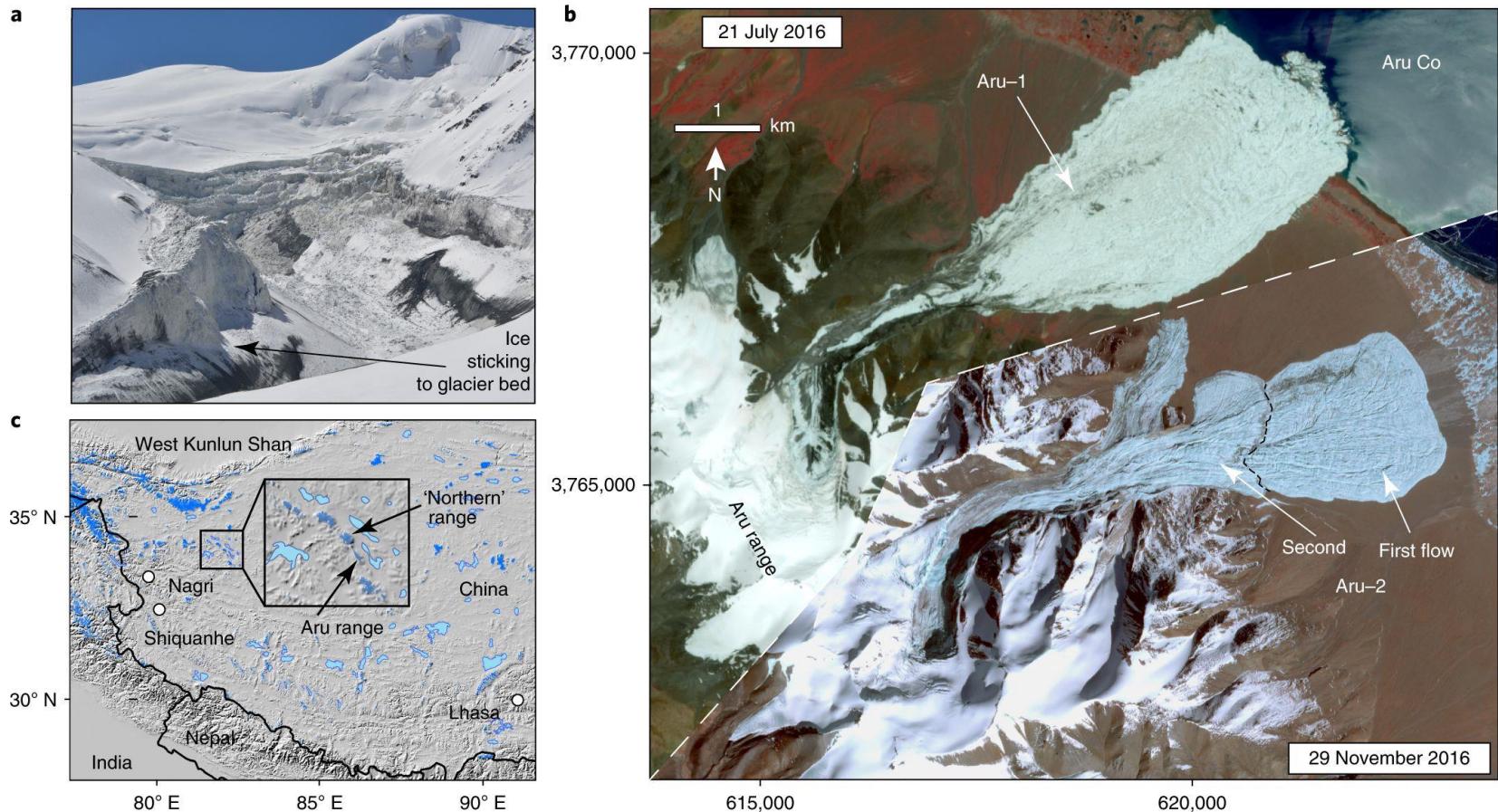




Steiner et al., in prep.

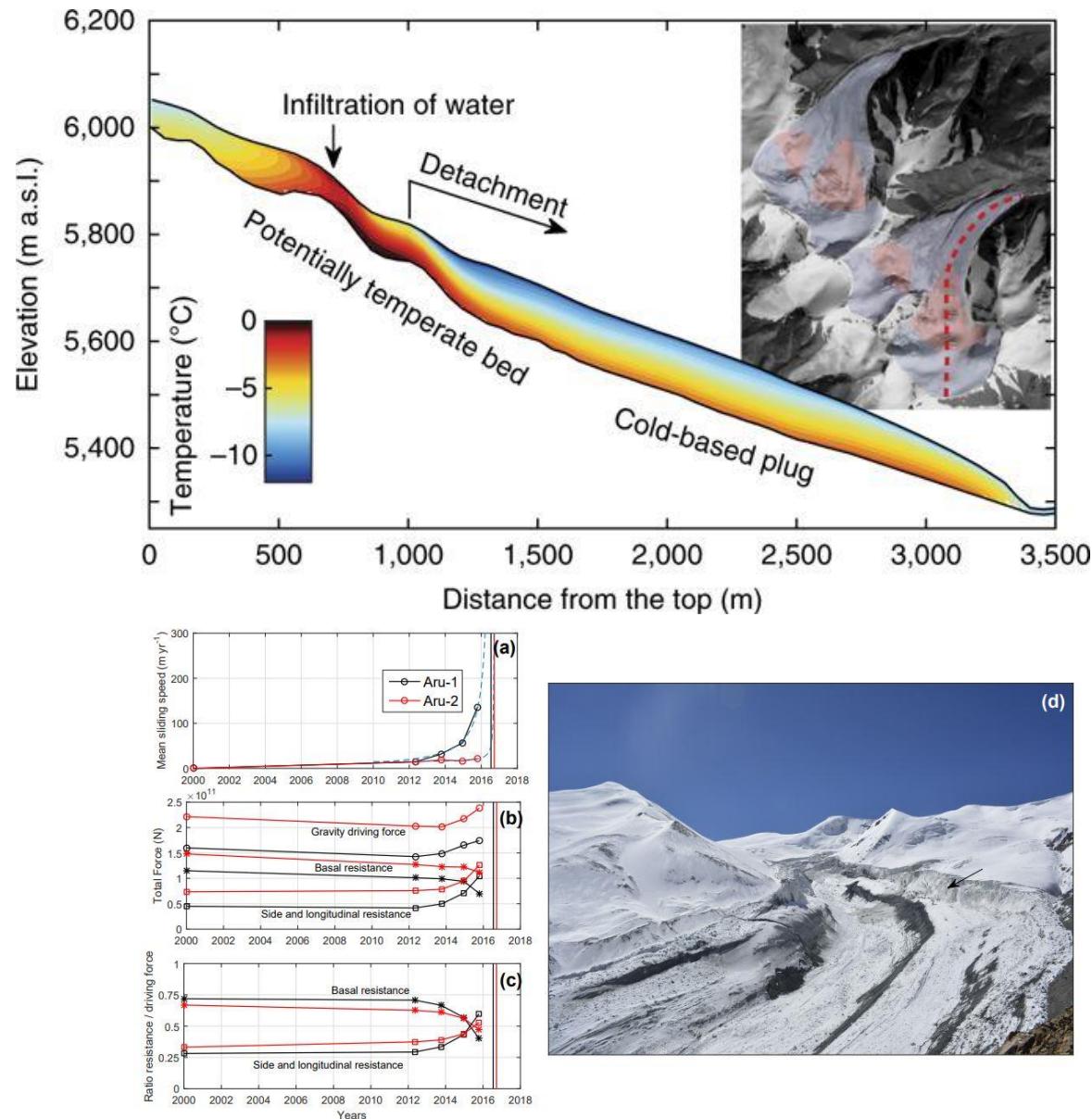


# Results – Internal glacier collapse





- 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)



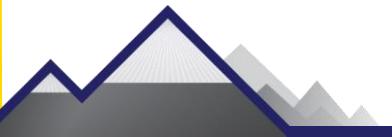
Kaab et al., 2018

Gilbert et al., 2018



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- ice break offs (+ resulting events) / collapsing glaciers
- glacier length variations
- destabilization of frozen soils/slopes



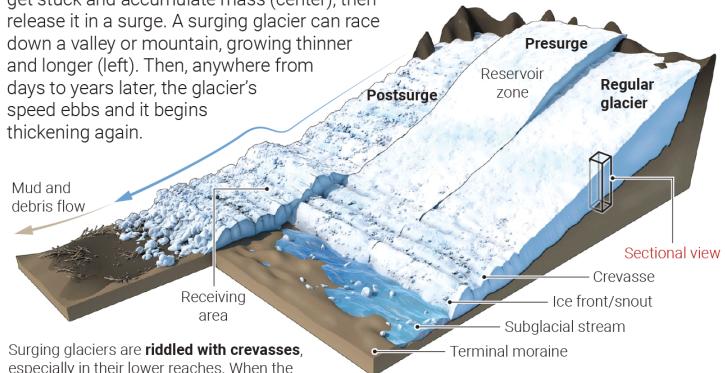


# Glacier length variations surges

- 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

## A glacier unleashed

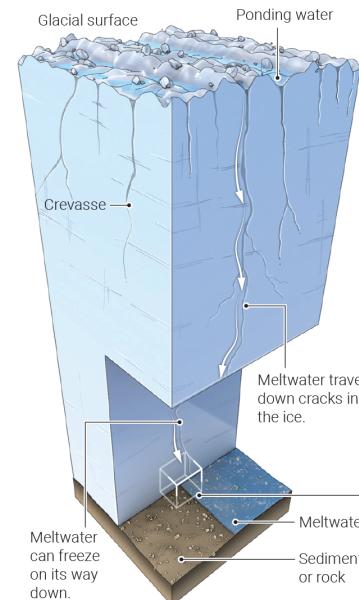
Glaciers gain mass in their upper reaches, where snowfall is heavier, and lose it at their snouts, where the ice breaks up and melts (right). Most glaciers flow steadily, but some get stuck and accumulate mass (center), then release it in a surge. A surging glacier can race down a valley or mountain, 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.

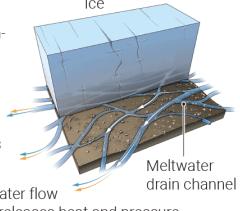
## Trickling down

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.



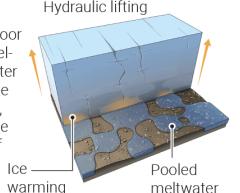
## Steady state

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



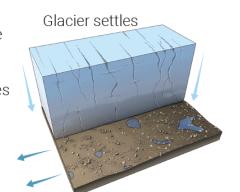
## Buildup to a surge

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



## Aftermath

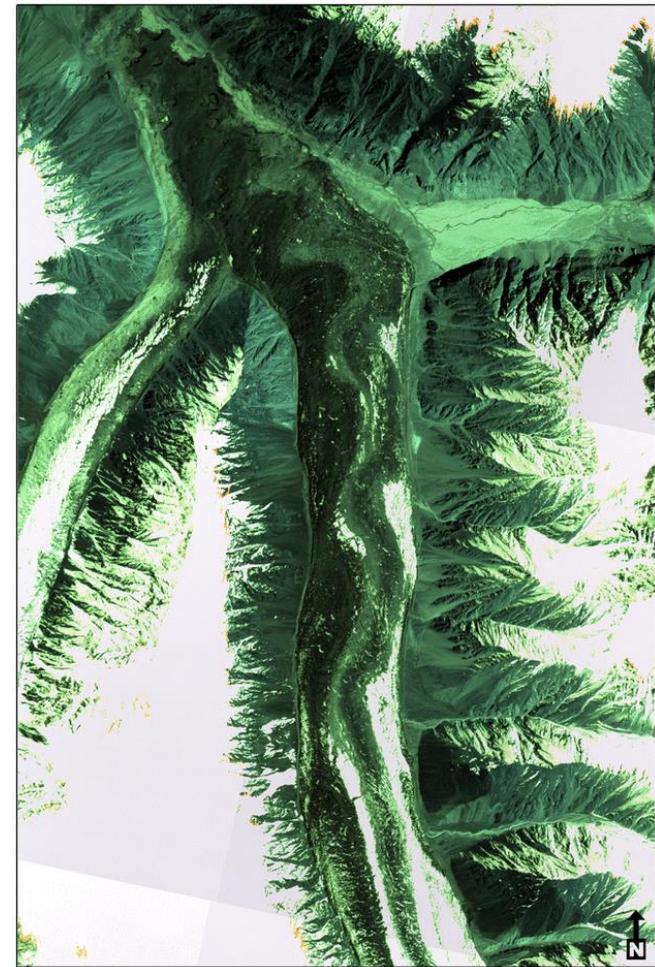
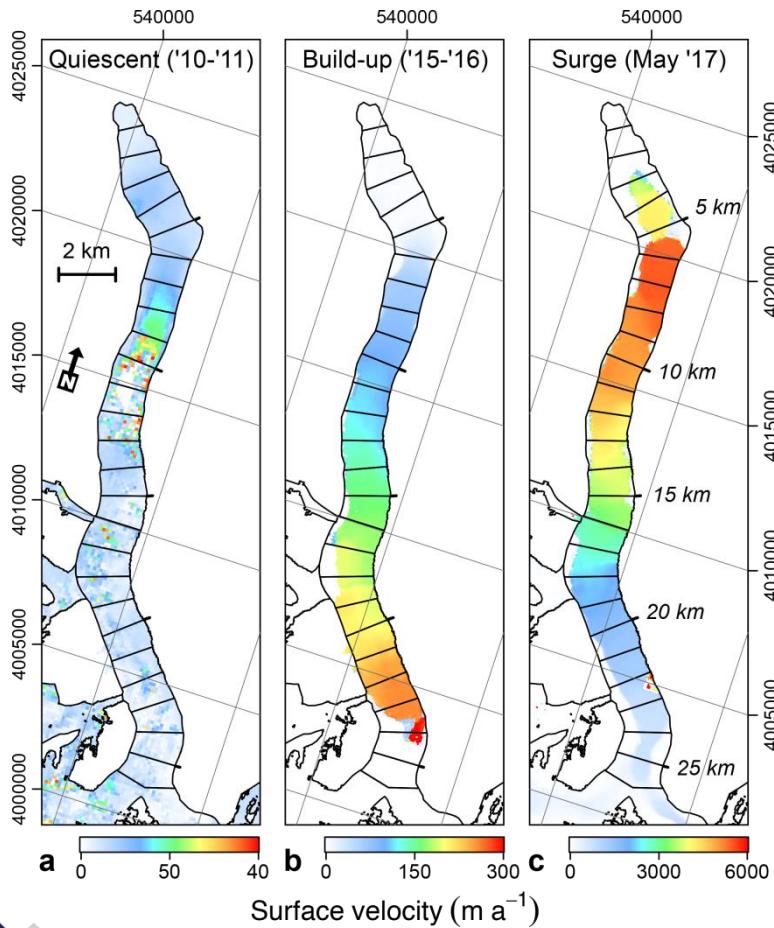
Once the surge releases the meltwater, the glacier subsides onto its bed, and the cycle begins again.



CREDITS: (GRAPHIC) C. BICKEL/SCIENCE

# Surge in Karakoram 2017

- Glacier velocities from remote sensing





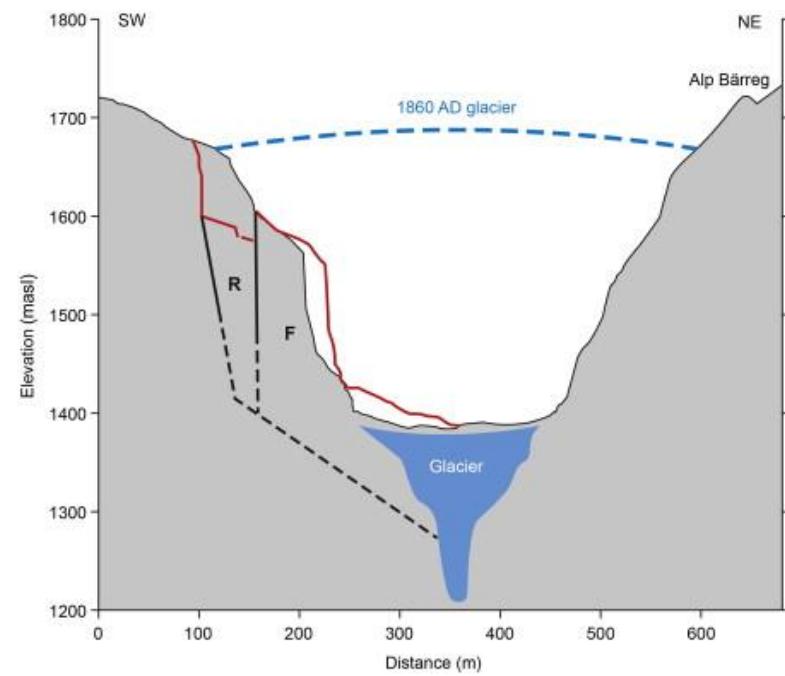
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# Destabilization of frozen soil

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

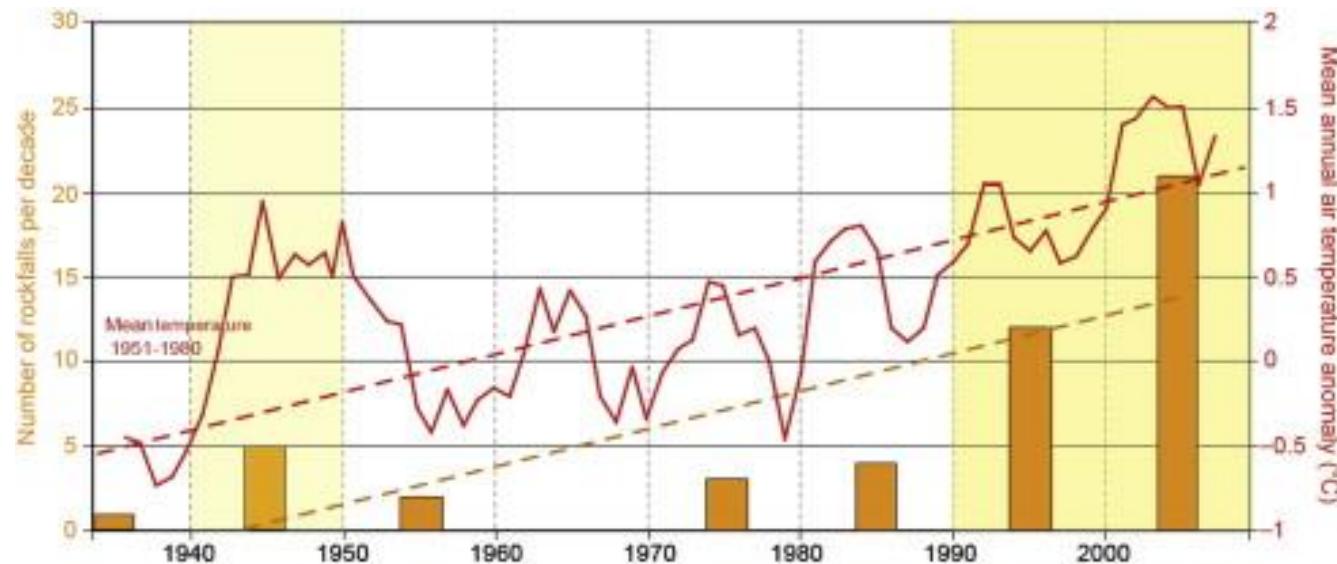
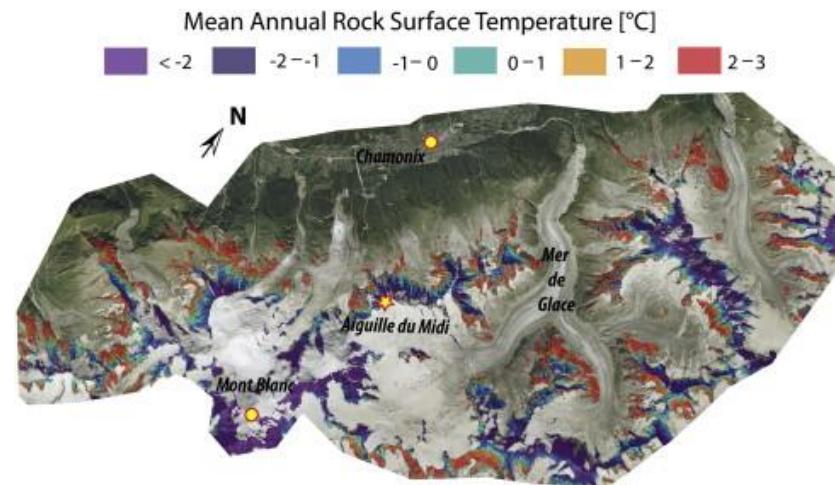


Deline et al., 2015



# Destabilization of frozen soil

- Likely direct link with increasing temperatures



Deline et al., 2015



# Destabilization of frozen soil

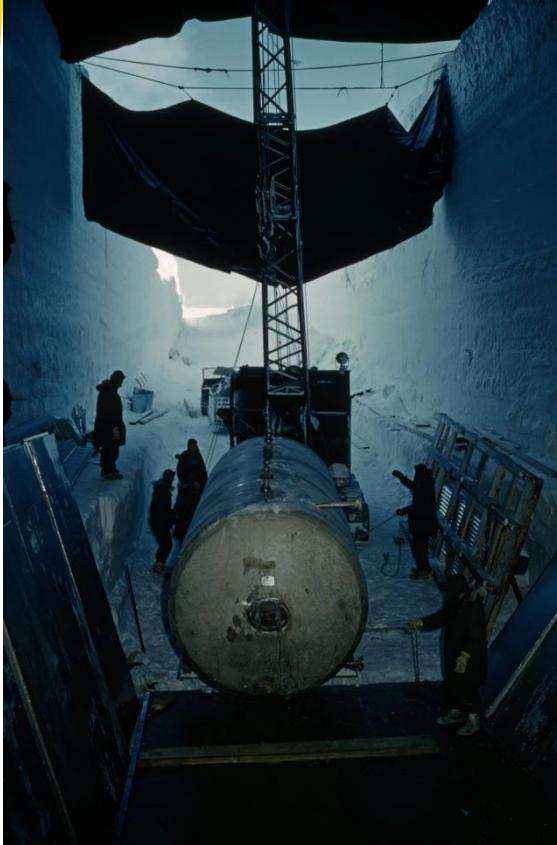


- <https://www.youtube.com/watch?v=RYRfPrhCWzs>
- <https://www.youtube.com/watch?v=BcXsJzzINNk>

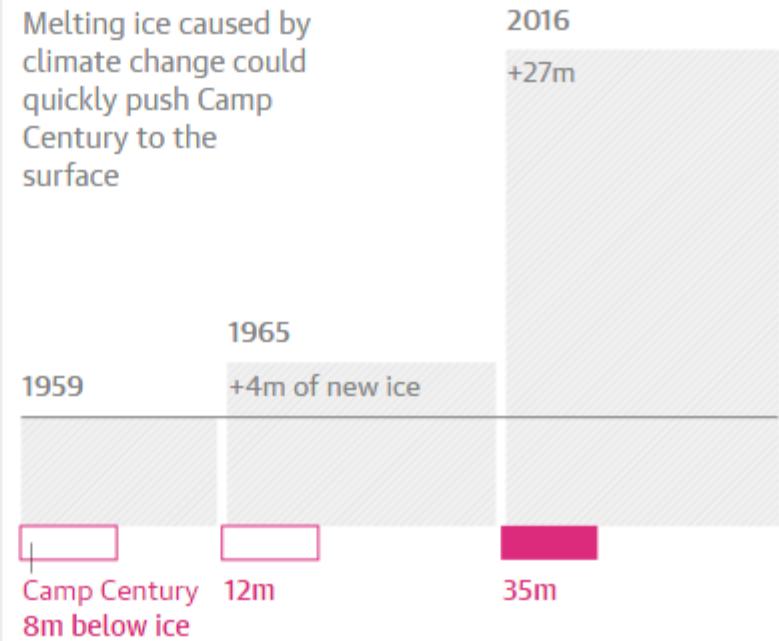


# Hazards of deglaciation on ice sheets

- Deglaciation over hazardous materials

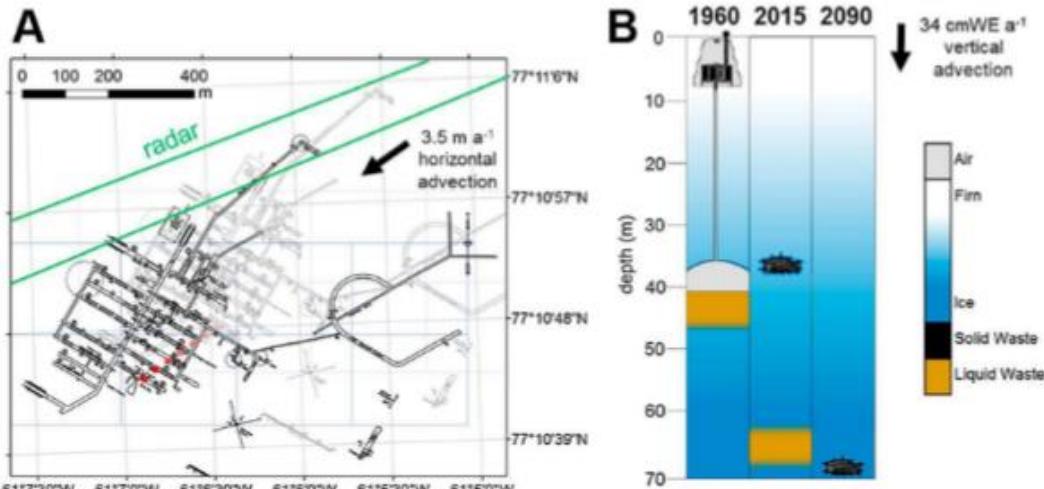


Melting ice caused by climate change could quickly push Camp Century to the surface



Graphic: The Guardian, 27/09/2016

- 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?

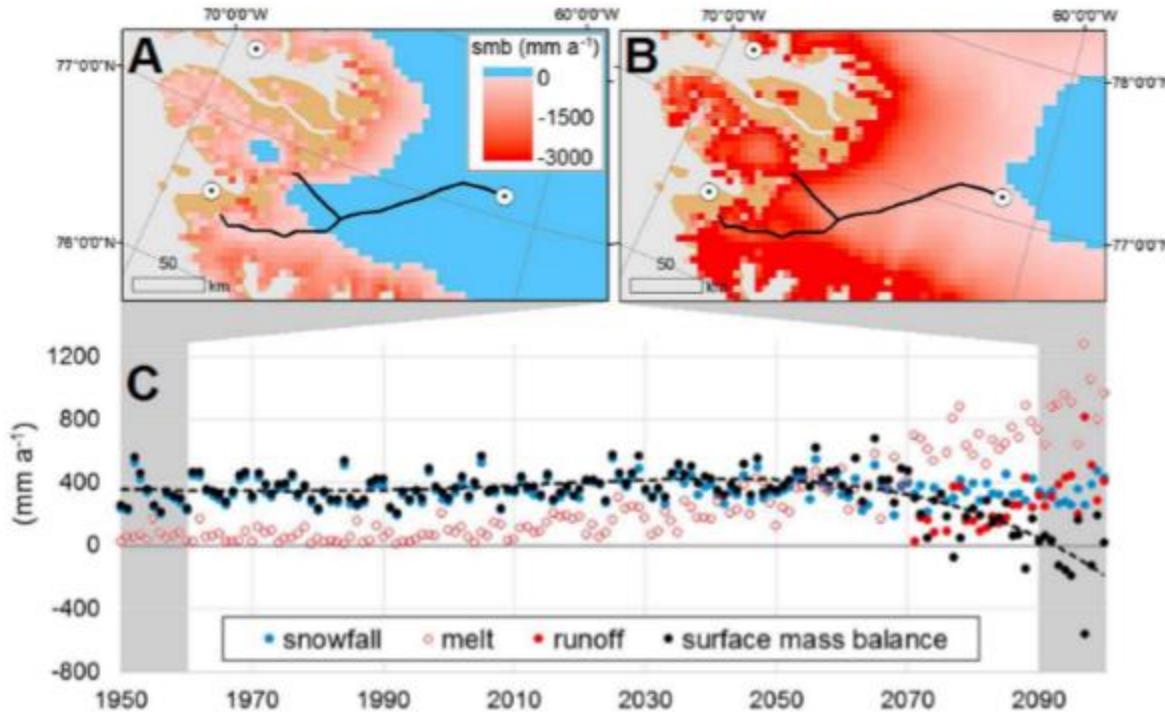


**Figure 2.** (a) Camp Century "as built" map georeferenced to 1960 (grey) and 2020 (black) locations [Kovacs, 1970], based on past surveys of the borehole location and horizontal advection associated with ice flow (Supplementary Methods). The red points denote decadal borehole location from 1960 to 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

# Future Ice melt in a changing climate ...



**Figure 4.** (a) Surface mass balance in Northwest Greenland during the 1950s (1950–1959) and (b) 2090s (2090–2099) as simulated by MAR v3.5 forced by CanESM2 under RCP8.5 [Fettweis et al., 2013]. The color bars saturate at minimum and maximum values. The blue shading denotes the accumulation area where surface mass balance is positive. (c) Surface mass balance, and its components, at Camp Century during 1950–2100 as simulated by MARv3.5 and forced by CanESM2. The dashed line denotes polynomial trend. The NorESM1 simulation is shown in Figure S2.

Colgan et al., 2016, GRL

*... what about horizontal movement?*

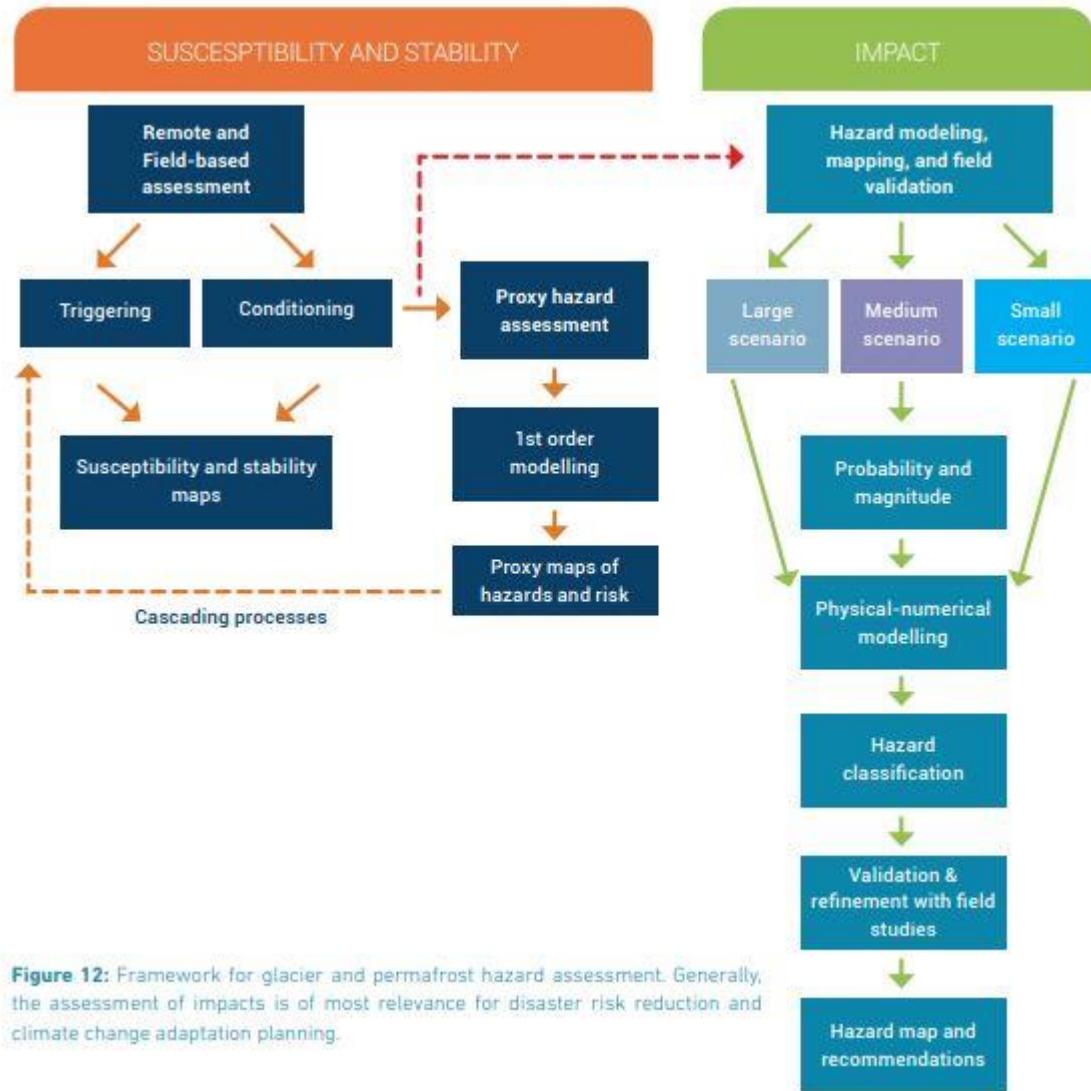


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# Hazard Assessment

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



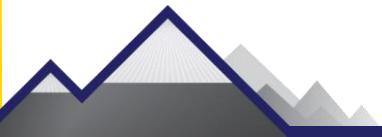
Allen et al., 2017, GAPHAZ

**Figure 12:** Framework for glacier and permafrost hazard assessment. Generally, the assessment of impacts is of most relevance for disaster risk reduction and climate change adaptation planning.



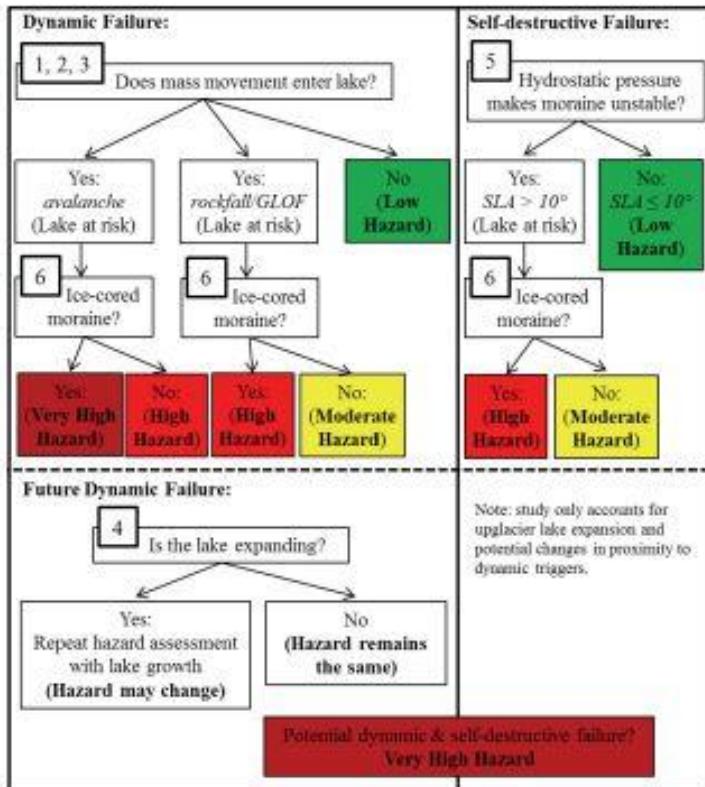
# Hazard Mapping

- 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



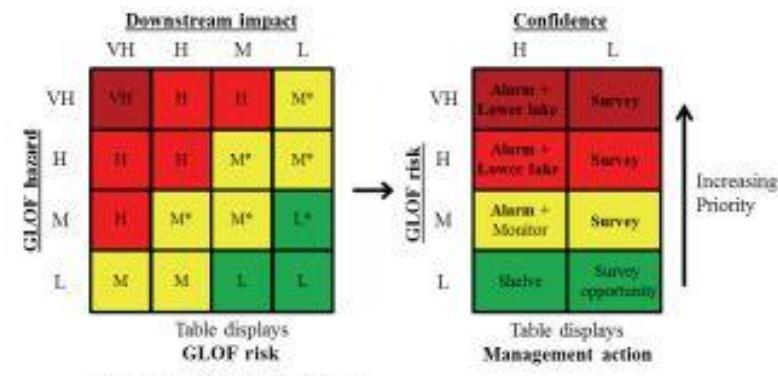


# Example GLOFs – *Susceptibility*



**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

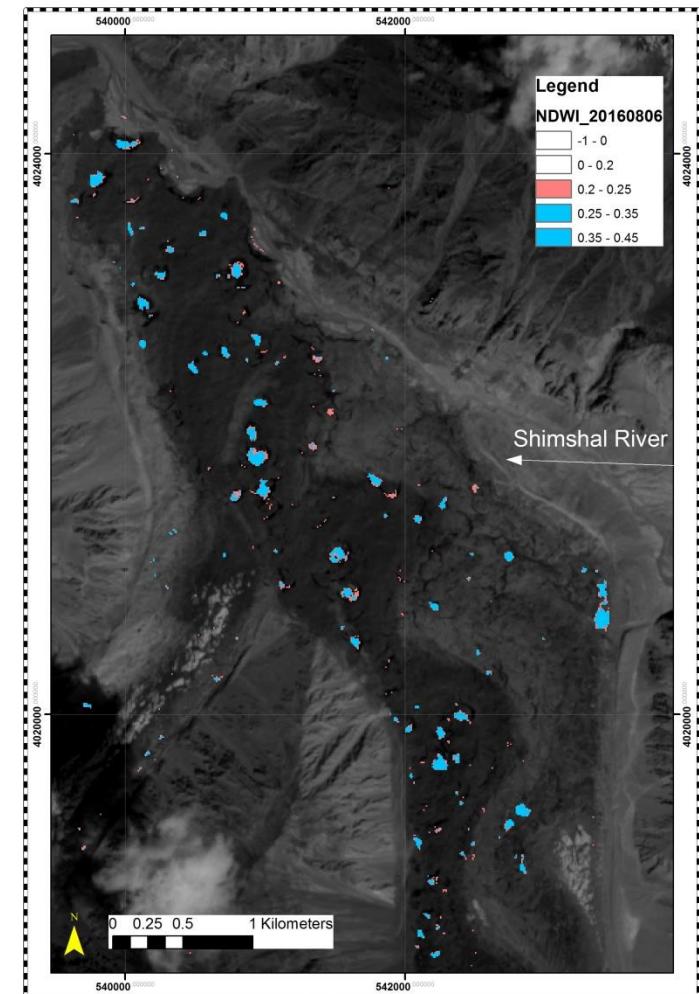


**Figure 5.** Risk management and action framework. Left table: GLOF risk is a function of the hazard and downstream impact. Right table: the recommended course of action for a given glacial lake based on the type of assessment.



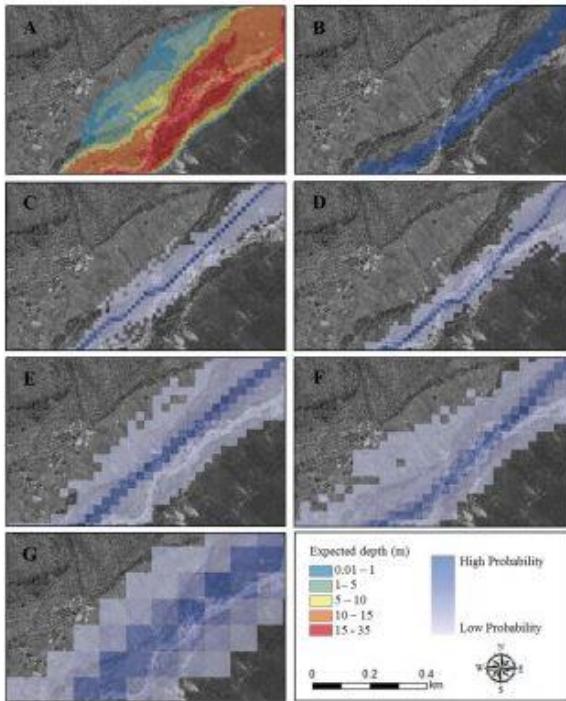
# Example GLOFs – *Proxy Hazard Assessment*

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





# Example GLOFs – *Impact*



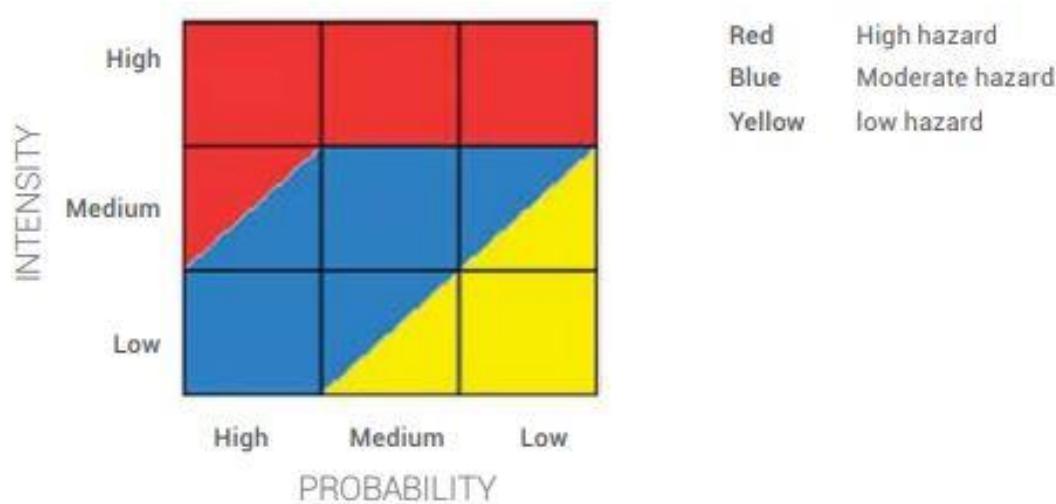
**Figure 3.** Inundated areas at Dingboche for a GLOF from Imja Tsho using (a) FLO2D (Somos-Valenzuela et al., 2015), (b) the MSF model using the GDEM, and (c–g) the MC-LCP model with various DEMs and pixel sizes: (c) SRTM 90 m resampled 15 m, (d) GDEM 30 m resampled 15 m, (e) SRTM 90 m resampled 30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





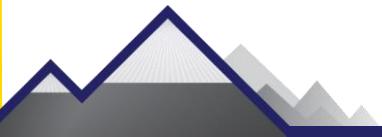
# Topics

- 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?



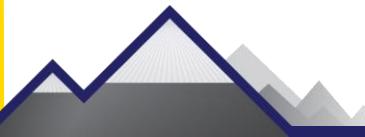


# Grindelwald Switzerland

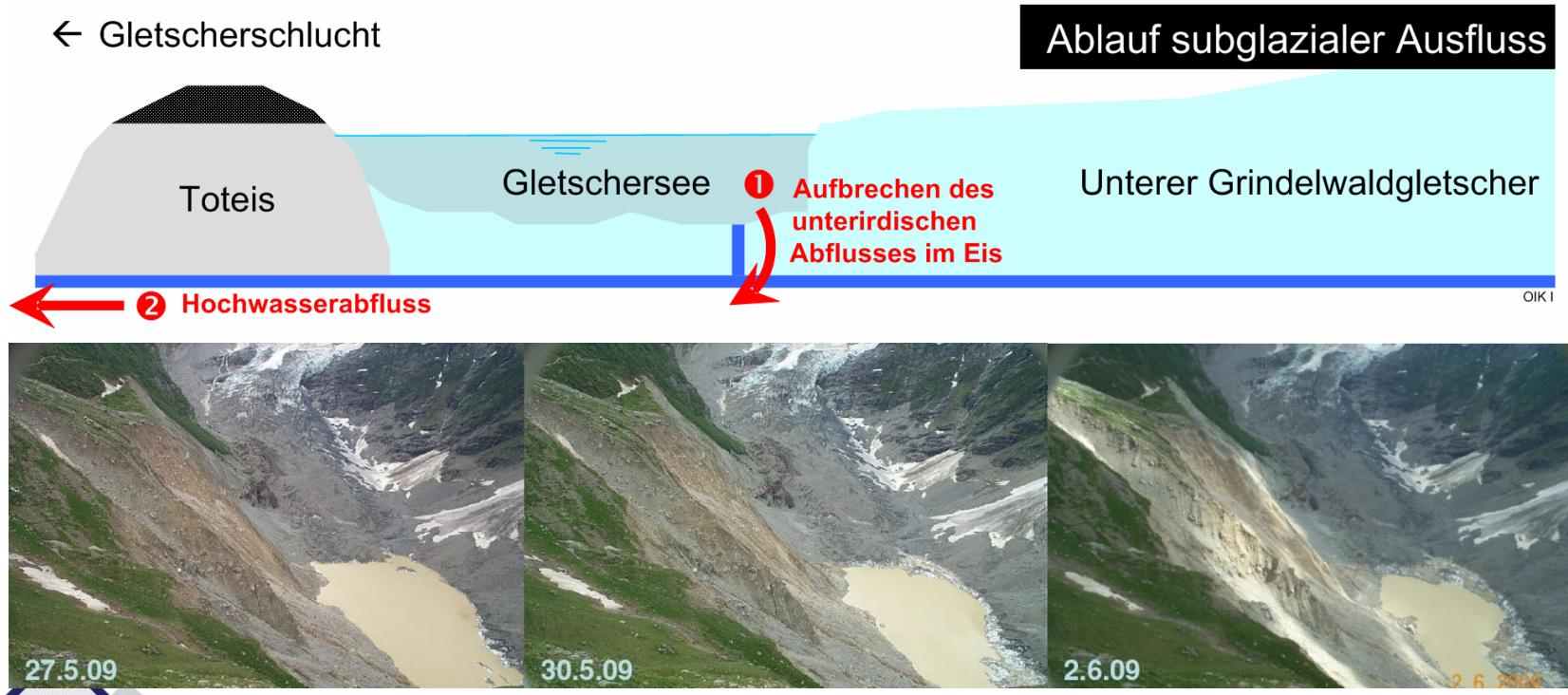
- Glacial lake formed repeatedly
- Concerns about possible downstream damages
- Classical compound event
- Who decides? Who pays?



# Grindelwald Switzerland



# Formation of a glacial lake



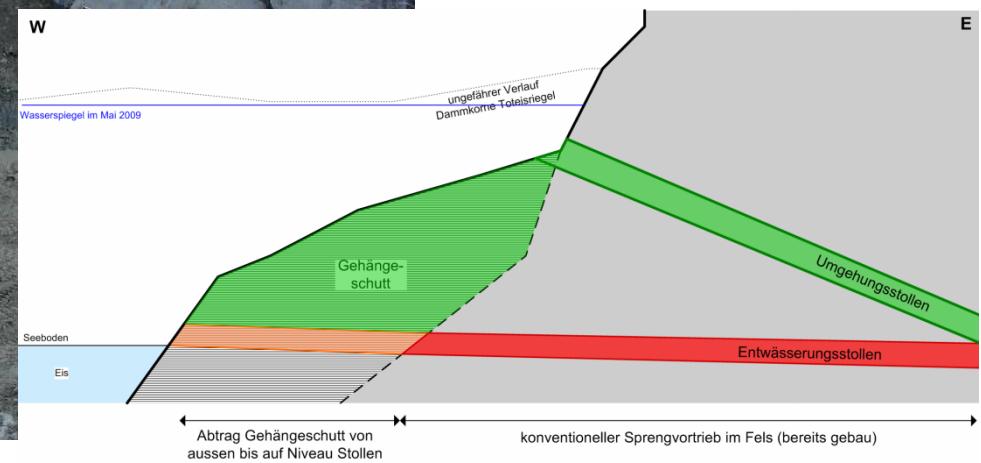


# Slumping moraines and rockfall





# Decision to build a tunnel ...





... and then the lake emptied naturally





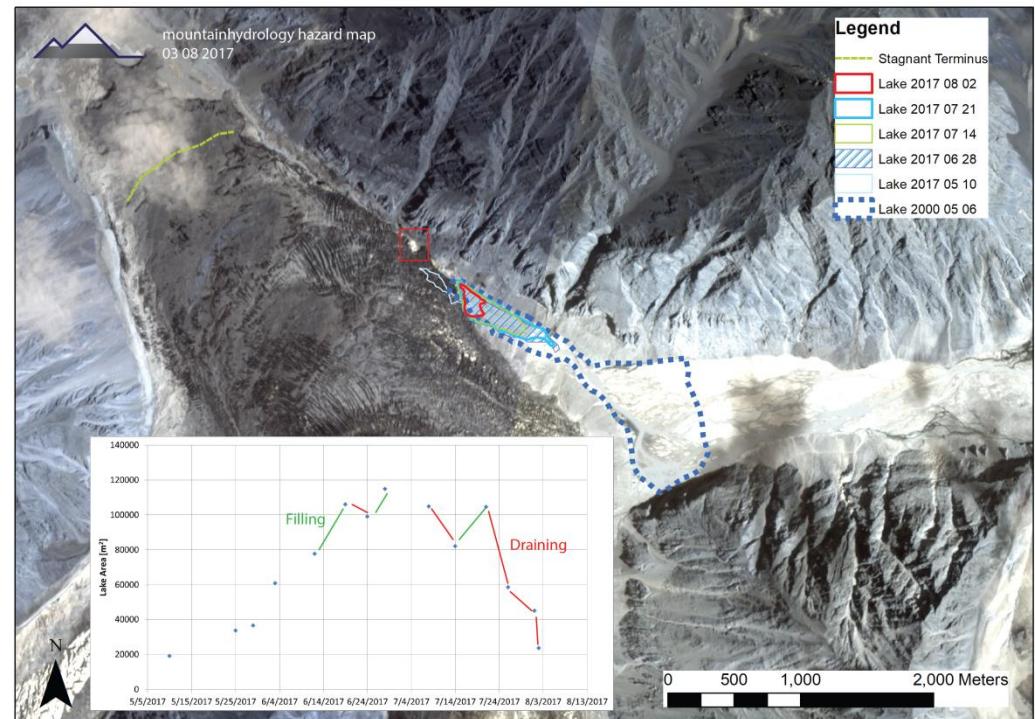
# Shimshal Glacial Lake (Pakistan)

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



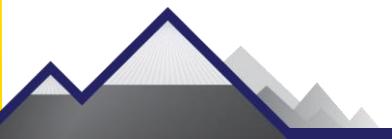
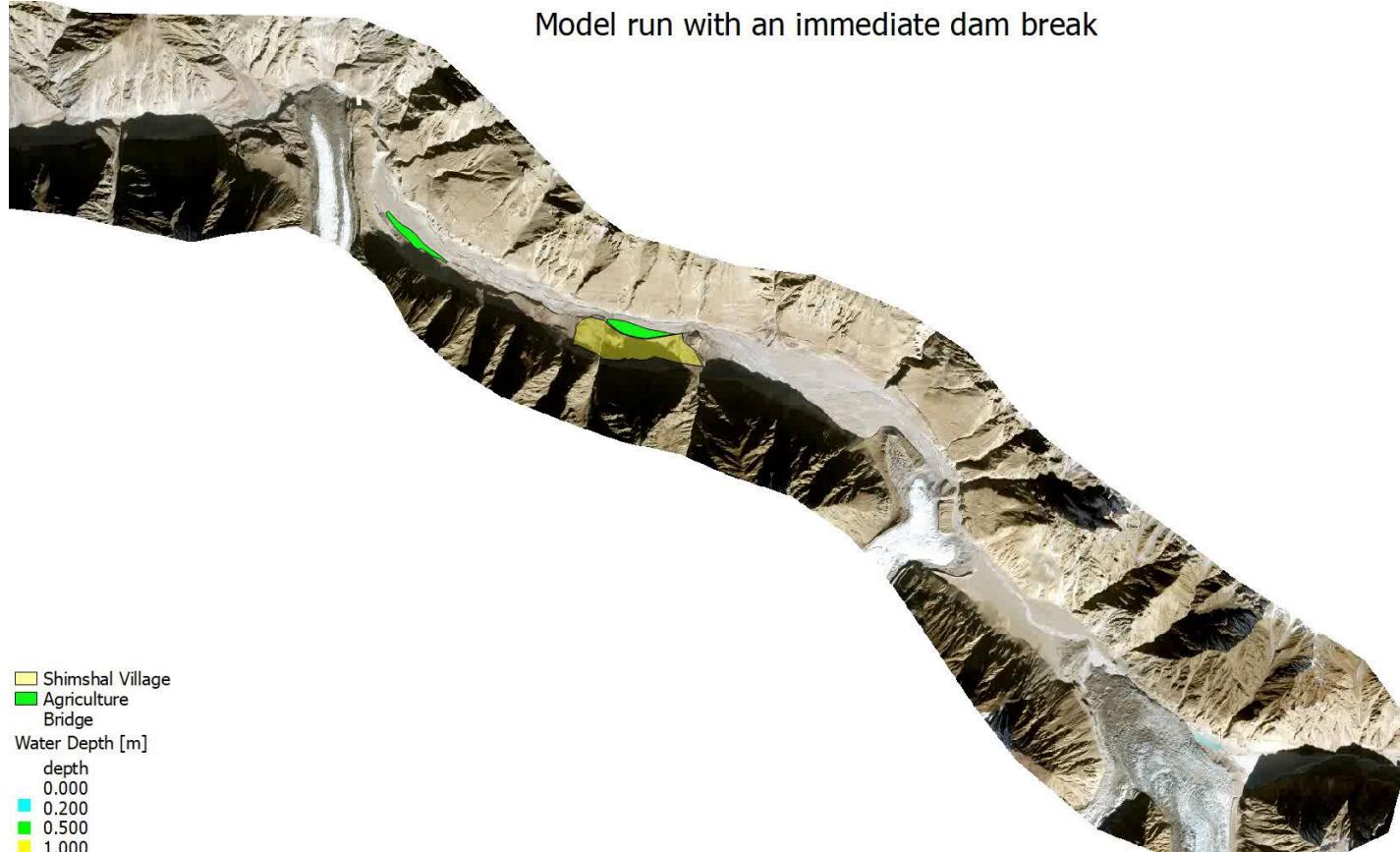
# Scenarios

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

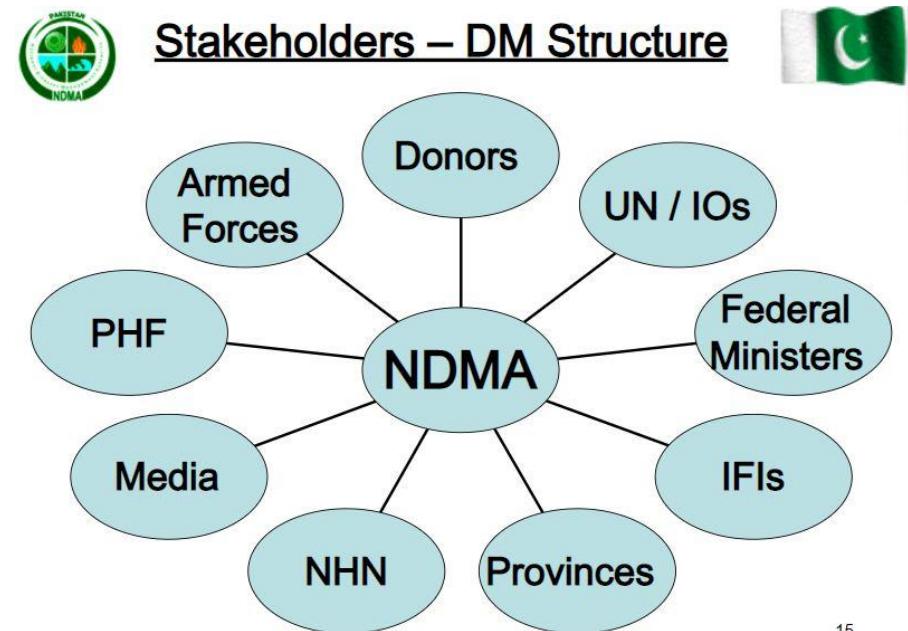
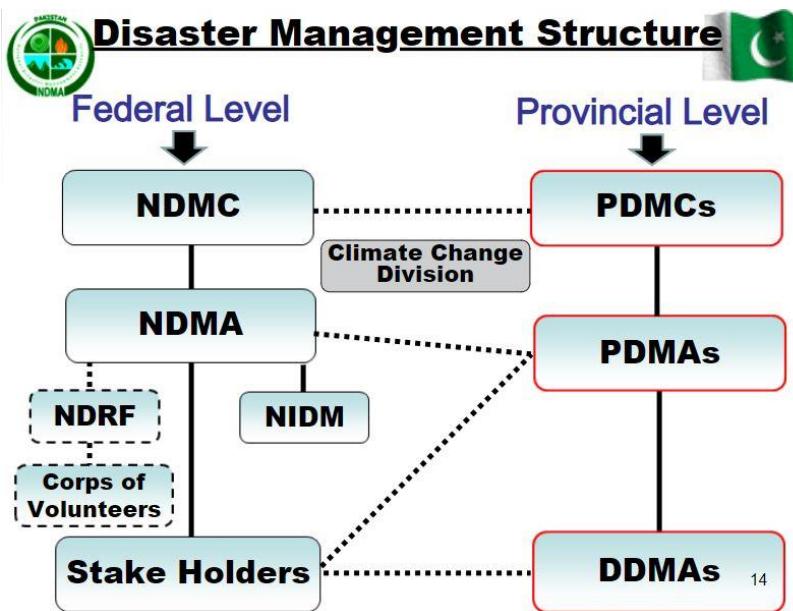




# Hydrodynamic Modelling



# Institutional challenge





## **Cost Implications and Interventions** **- NDMP**

### Cost Implication

<u>Component</u>	Estimated Cost (Ten Yrs)	
	US\$ (million)	PKR (million)
Main Volume: NDMP	774.1	6,843.04
Volume-I HRD	64.3	568.41
Volume-II EWS	188.5	1,666.34
Volume-III CBDRM	14.00	123.73
<b>Total Cost</b>	<b>1,040.90</b>	<b>9,201.52</b>

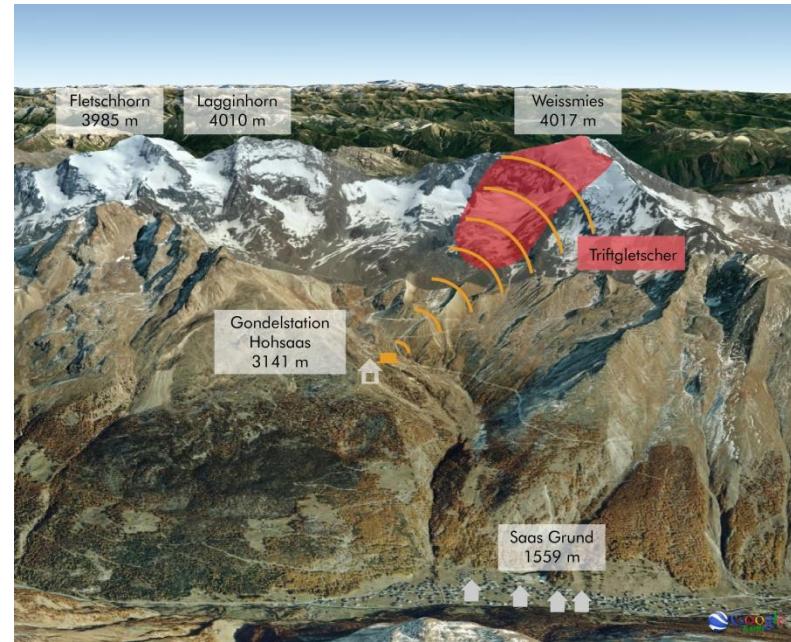
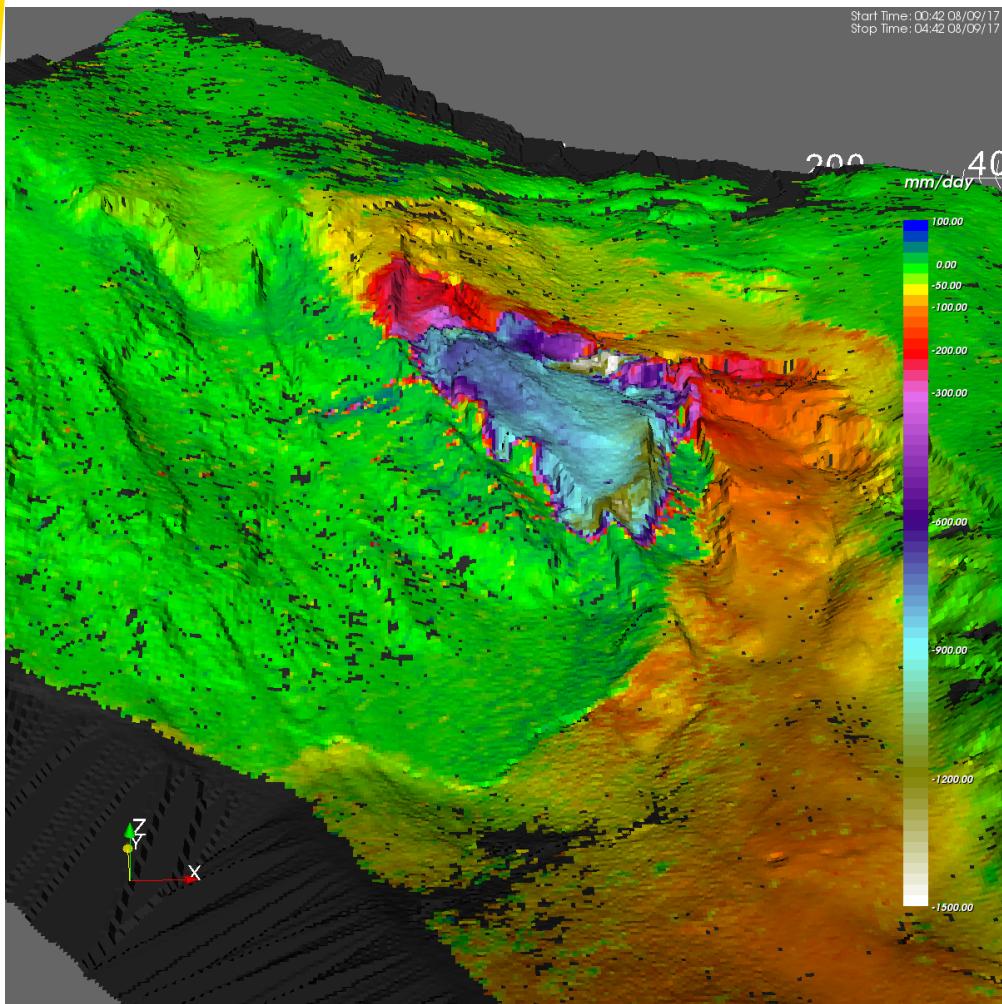


# Monitoring and Risk Mitigation

- 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

