REMOTE MONITORING OF IMPENDING OUTBURST FLOODS AT KYAGAR GLACIER, CHINESE KARAKORAM

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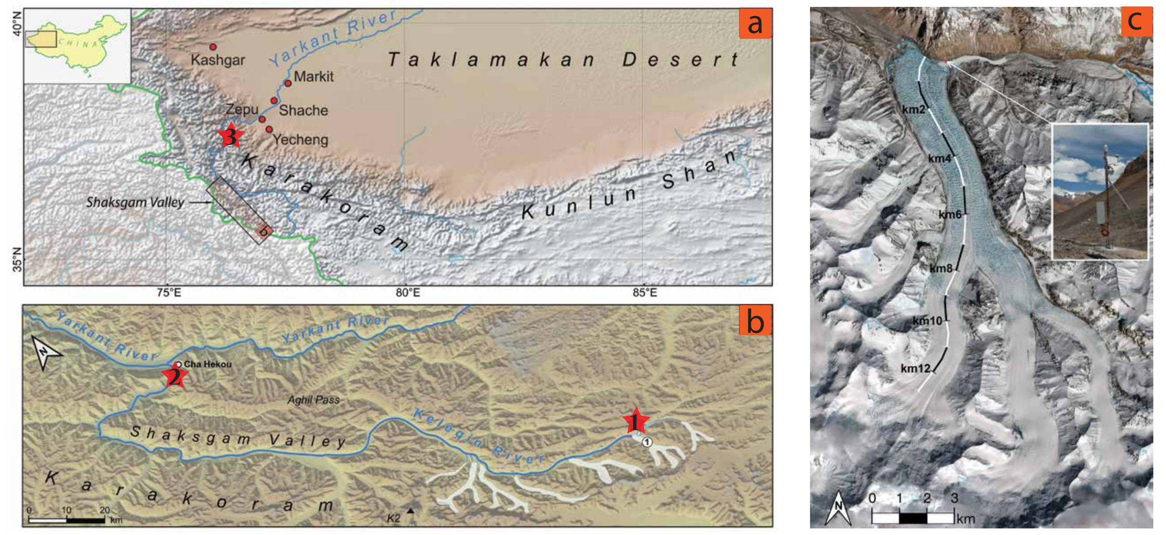
BACKGROUND

What: Kyagar Glacier experienced a **dramatic glacier surge** in 2014 which caused 60 meters thickening at the glacier terminus and the **formation of an ice dam.** The ice dam blocks the main river and impounds a large lake prone to rapid **outburst floods.**

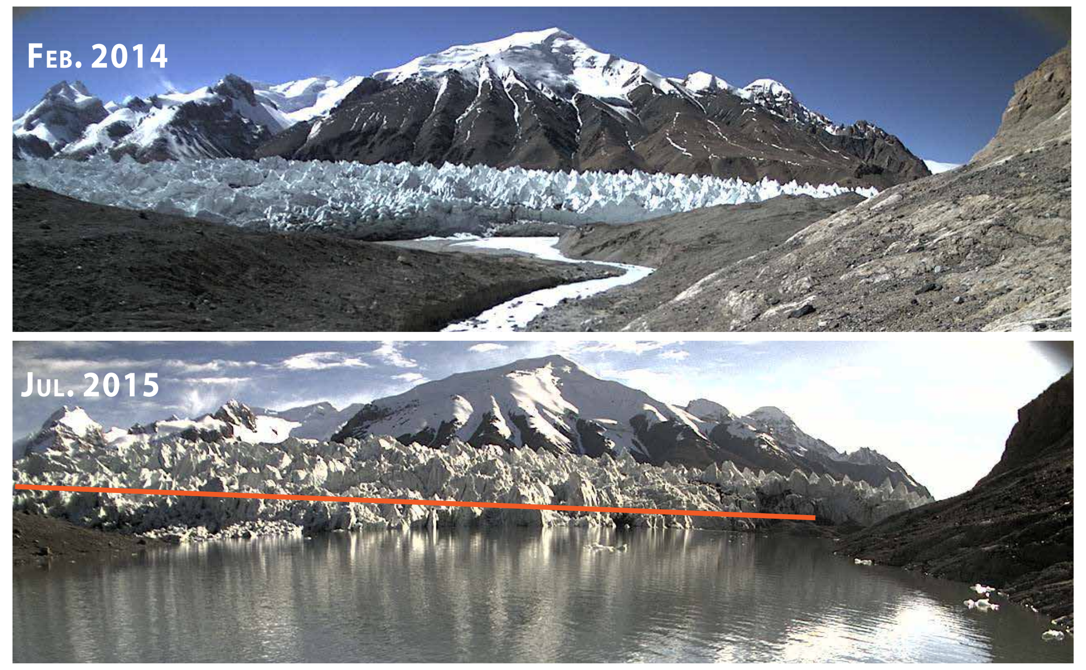
Where: Kyagar Glacier is located in the **Chinese Karakoram Mountains**, at an elevation of 4800-7000 m a.s.l. It is extremely remote and access is restricted for political reasons.



*Location of Kyagar Glacier in the Upper Shaksgam Valley (b), to the south west of the Taklamakam Desert (a). Flooding impacts occur where the Yarkant River enters the plains. The inset in (c) shows the **monitoring station** at the glacier terminus.*

Impacts: **Floodwaters** from the outburst of Kyagar Glacier lake (★) threaten **>1 million inhabitants**, agricultural land and expanding infrastructure 500km downstream (★), where the Yarkant River leaves the mountains at the edge of the Taklamakan Desert.

Monitoring station: From mid 2012 to mid 2015, an automated station operated upstream of the glacier terminus, monitoring lake volumes and ice dam height. It captured the glacier suge arriving at the terminus in 2014, but was **destroyed by lake formation** in 2015.



Views of the glacier terminus and ice-dammed lake, from the monitoring station upstream of the terminus. The camera was drowned shortly after. The line on the July 2015 image represents the ice level in Feb. 2014, highlighting the ice dam growth.

Early warning system: Two river stations downstream of Kyagar glacier (★★) provide ~22 h warning if a flood wave is approaching.

Previous works:

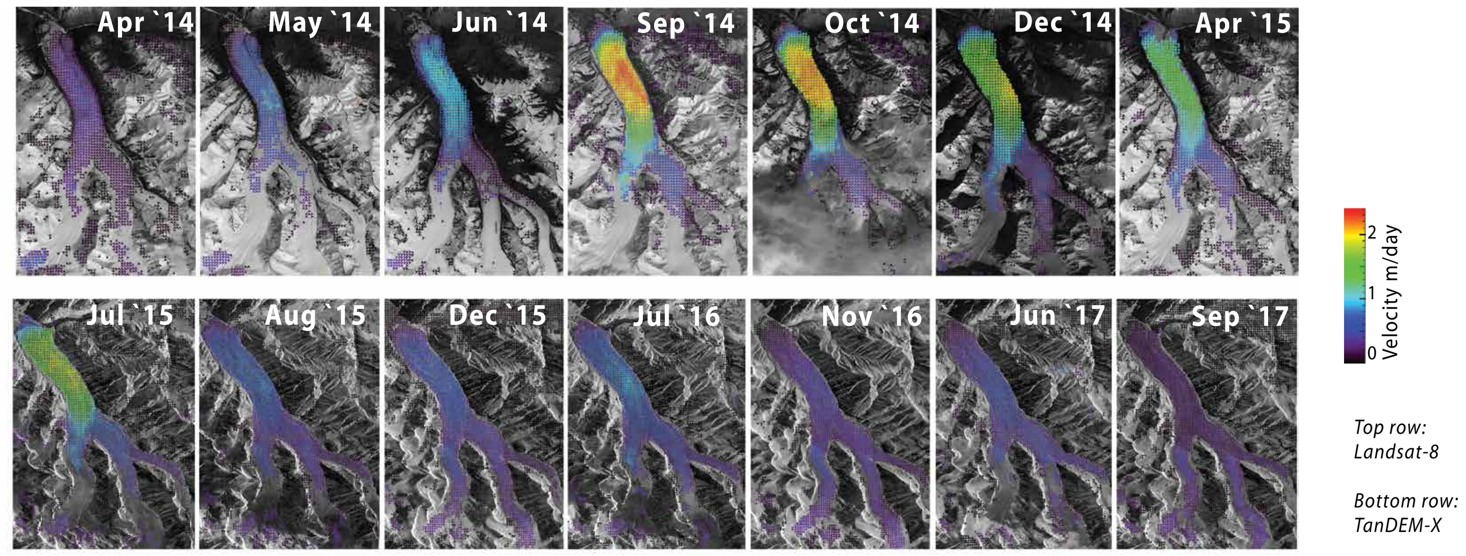
Round et al, 2016, Surge dynamics and lake outbursts of Kyagar Glacier, Karakoram, *The Cryosphere*, 11

Haemmig et al, 2014, Hazard assessment of glacial lake outburst floods from Kyagar glacier, Karakoram Mountains, China, *Ann. Glaciology*, 55

OVERVIEW

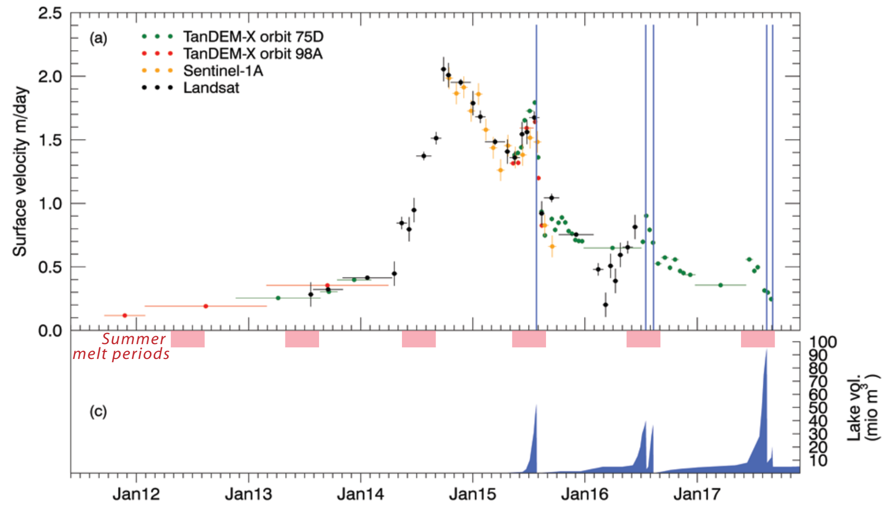
We present an overview of the **glacier surge** and hazardous ice-dammed **lake oubursts** at Kyagar Glacier. Since the surge ended in 2015, outburst floods occurred each summer. In 2017 the lake was its **largest since 2002**, and according to our records the 5th largest since 1950. Remote sensing is our only way of **monitoring** the glacier surge, the **development of the lake** and **lake drainage mechanisms**. We create time series of **digital elevation models** to assess the height of the ice dam and **potential future lake volume**.

GLACIER SURGE: SURFACE VELOCITIES



Top row: Landsat-8

Bottom row: TanDEM-X

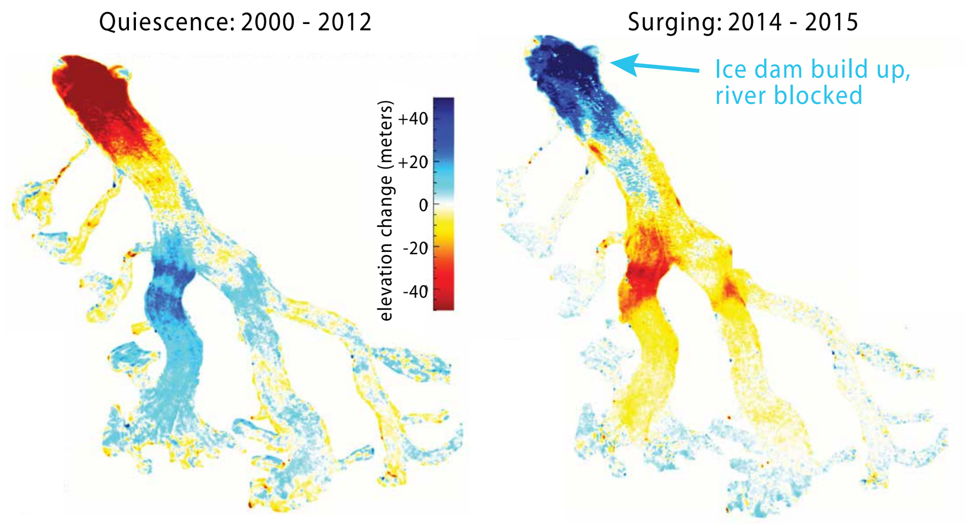


Surface velocities clearly show a surge event which peaked in Sep. 2014 and stopped abruptly in August 2015.

Since then, velocity has kept decreasing gradually, with slight summer accelerations.

Lake formation follows the glacier surge. Rapid glacier **deceleration is linked to lake outbursts** (vertical blue lines).

GLACIER SURGE: SURFACE ELEVATION CHANGES



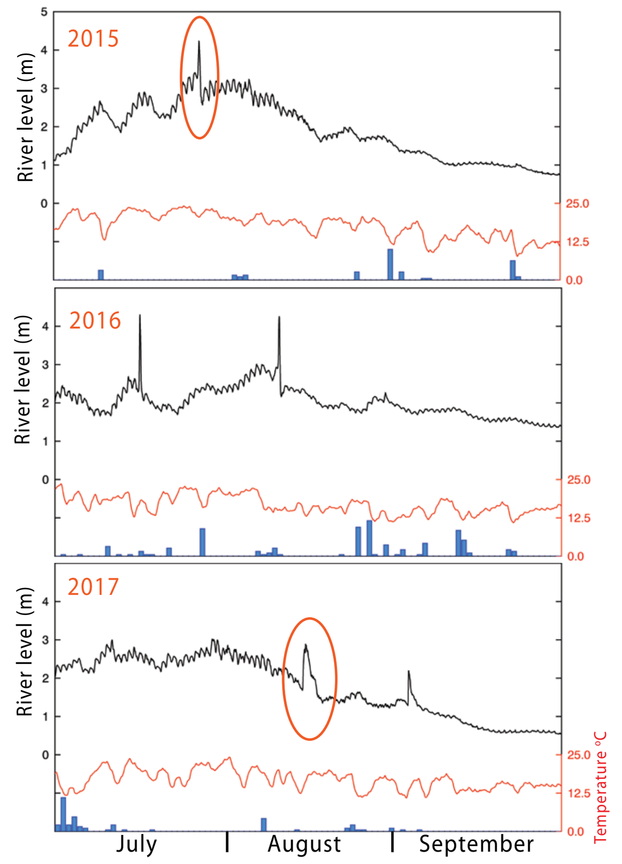
In the **quiescence period before a surge**, mass is lost from the glacier tongue through melting, whilst higher on the glacier mass accumulates.

This pattern can help us to **anticipate a surge.**

During a surge, ice is rapidly transported down the glacier. At Kyagar Glacier, this caused the glacier terminus to thicken by >60m, blocking the river.

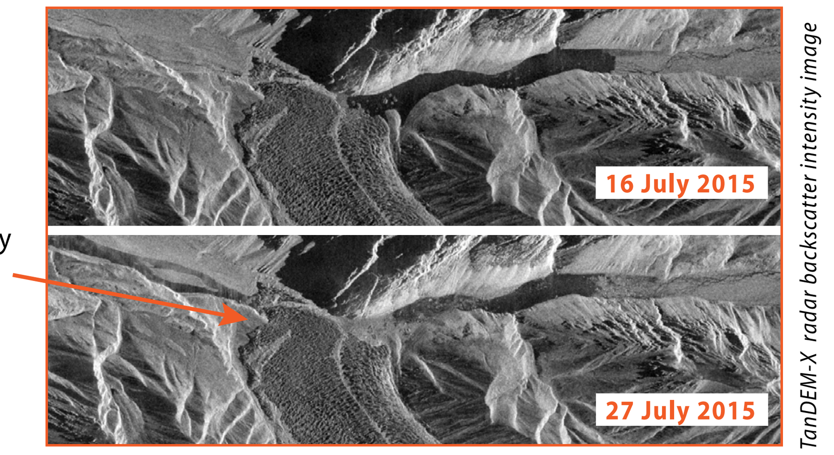
RECENT GLACIER LAKE OUTBURST FLOODS

Glacier lake outbursts occurred each summer since the surge in 2014. In 2015 and 2016 outbursts were rapid and caused **steep peaks in river levels** downstream. In **2017** the total lake volume was larger but is **drained over a longer time**, meaning **lower peak flood levels**.

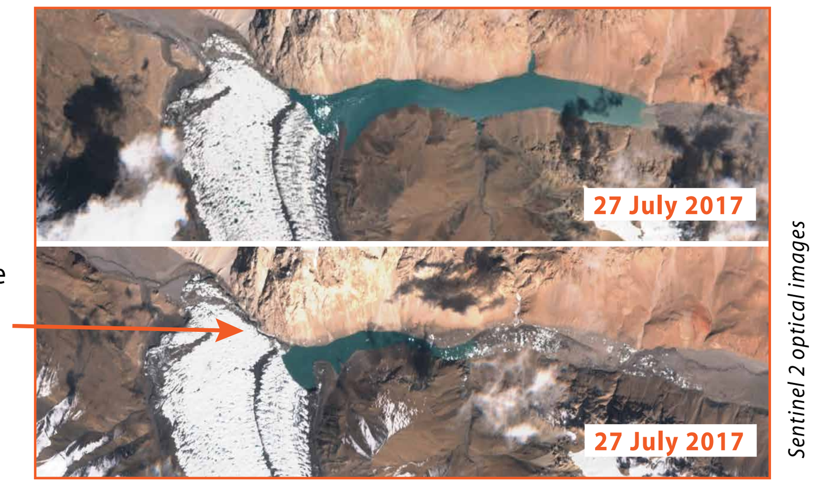


River level and metorological data from Cha Hekou monitoring station, 200km dosntream of Kyagar Glacier lake.

In 2015 the ice-dammed lake drained completely and rapidly through **subglacial channels.**



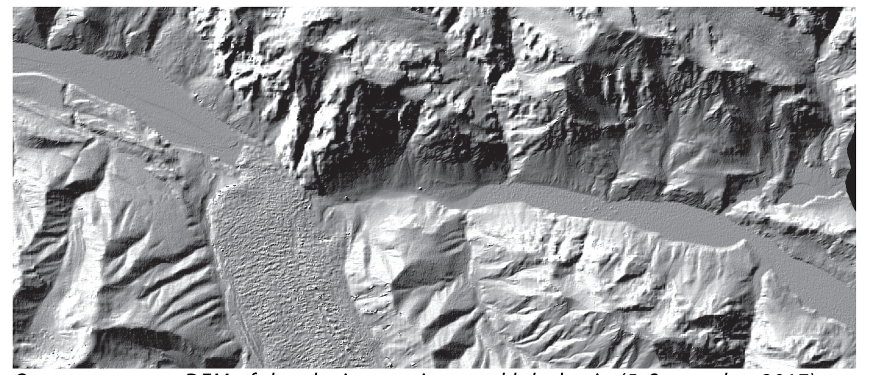
In 2017, drainage was incomplete, occured more slowly. It appears that the **lake topped over the ice** dam, forming a channel between the glacier ice and mountain flank.



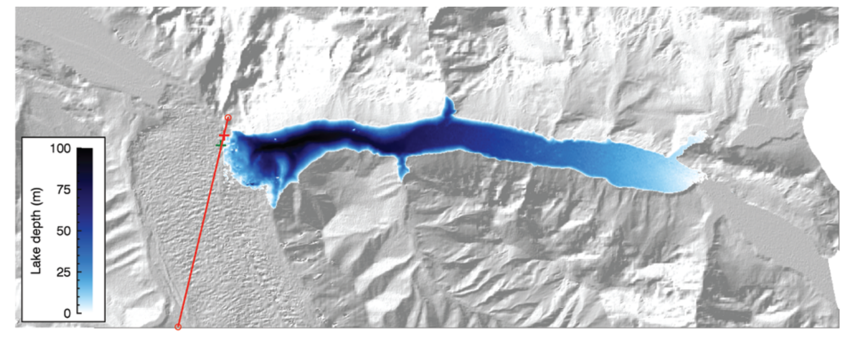
MONITORING IMPENDING OUTBURST FLOODS

We monitor the volume of the lake during the summer to **identify the GLOF hazard** level by **anticipating how large** an outburst flood could be.

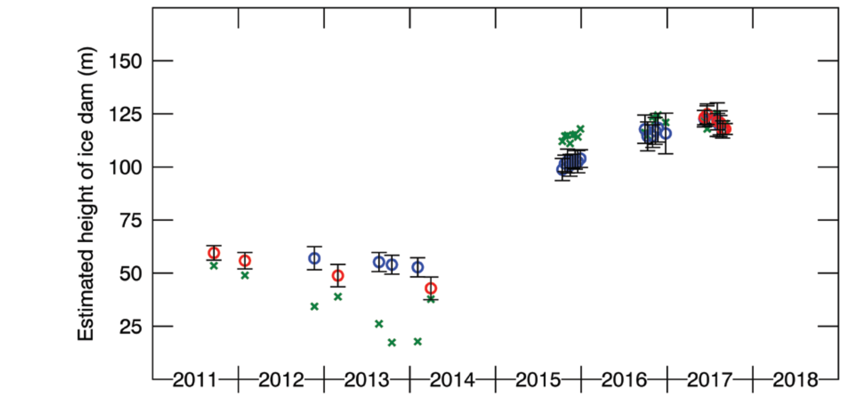
For this we use a digital elevation model of the lake basin and the most **recent available satellite images**. For future volumes we need to

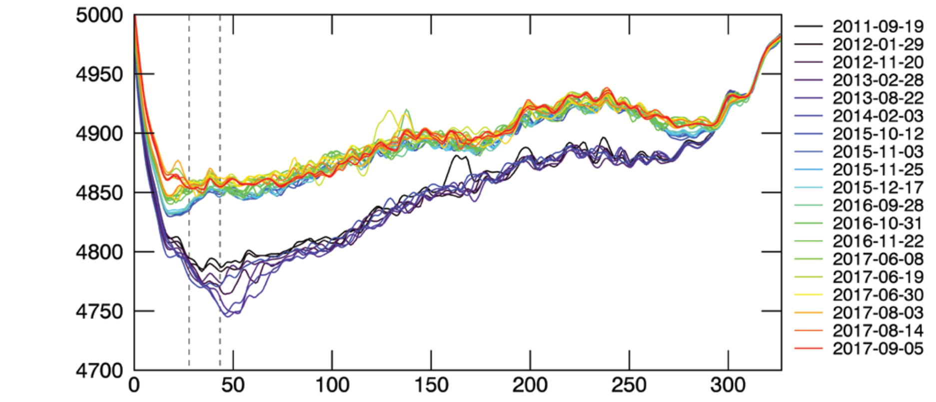


Our most recent DEM of the glacier terminus and lake basin (5. September 2017), from TanDEM-X data, filled with the ALOS DEM where coherence was too low.



*Using the **minimum height** of the ice dam (red cross) we can model the potential lake volume which could be impounded (shaded in blue).*





*The **height evolution** of the ice dam, at the minimum height (top), and along a profile (red line in left figure) through the terminus (x-axis - distance in meters)*

DATA AND METHODS

Satellite systems and application

TanDEM-X	SAR*	~2 m	Surface **elevation** and velocity
Sentinal 1-A	SAR	10 m	Surface velocities
Sentinel 2-A	Optical	10 m	Visual observations
Landsat 8	Optical	15 m	Surface velocities

*SAR = Synthetic Aperture Radar

Glacier surface velocities : repeat pass offset tracking

1) All scenes co-registered to a common master scene (subpixel accuracy)
2) Cross-correlation function applied to corresponding patches from image pairs from different dates
   » Intensity correlation for SAR images
   » Phase correlation for optical images
3) 0.08 pixel accuracy for absolute shift (15-120cm depending on resolution)

Digital elevation models: single pass SAR interferometry

1) TanDEM-X supplies pairs of radar images, captured from satellites flying in tandem
2) The interferometric phase difference between the images is unwrapped to height
   » The 30m resolution DEM "ALOS World 3D" (AW3D30) is used to aid phase unwrapping and for orthorectification
3) Satelite baselines >200m cause decorrelation over the pinnacled glacier surface
5) Vertical errors estimated at <2 meters, including signal penetration

OUTLOOK

Since the glacier surge, we have recorded five glacier lake outbursts with volumes from 20 - 90 million m^3, draining through both subglacial drainage and dam overtopping. The largest observed lake occured in 2017 but the flood impacts were minimised because of slower and incomplete drainage and low baseflow of Yarkant River.

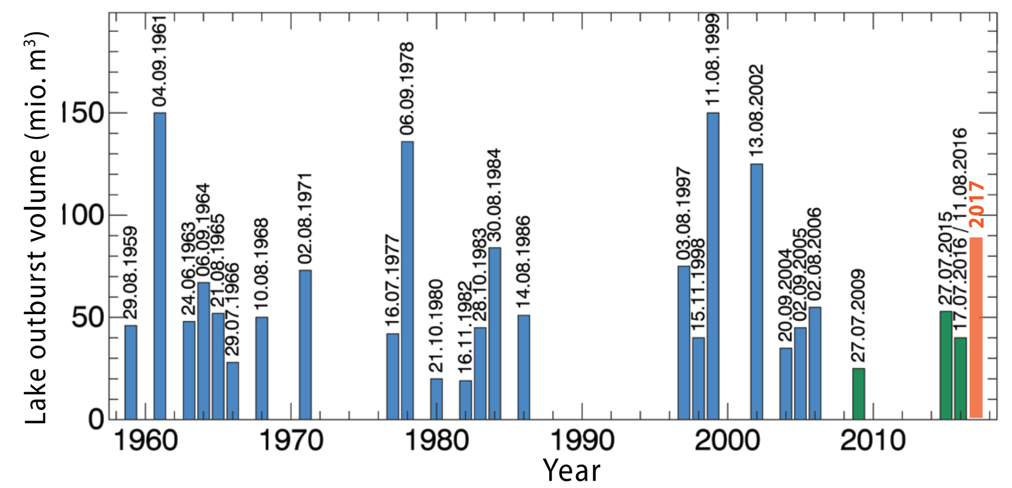
Factors which need to be understood to anticipate future hazard:

» How will the ice dam height evolve in time? For this, timely DEMs are crucial.

» Velocity tracking continues to be useful to assess mass transport to the terminus, when we don't have DEMs.

» Will we see a large rapid outburst again or slower, incomplete drainages like 2017?

» Outburst floods during times of high river baseflow are much more hazardous. 2017 was lucky in this respect!



Historically, largest outburst floods have followed in the years after surging. The lake outbursts of the last three years have not been as large as in the past, but there is potential for such big events in the next few summers.