Combination of satellite remote sensing with glaciological and geodetic field methods for the study of mountain glaciers

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Bavarian glaciers

Bavarian glacier report

- published together with the Bavarian State Ministry of the Environment and Consumer Protection
- released in April 2021
- 5 glaciers at Zugspitze and Berchtesgaden Alps

Bavarian glaciers

■ Glacier ▲ Peak ■ City

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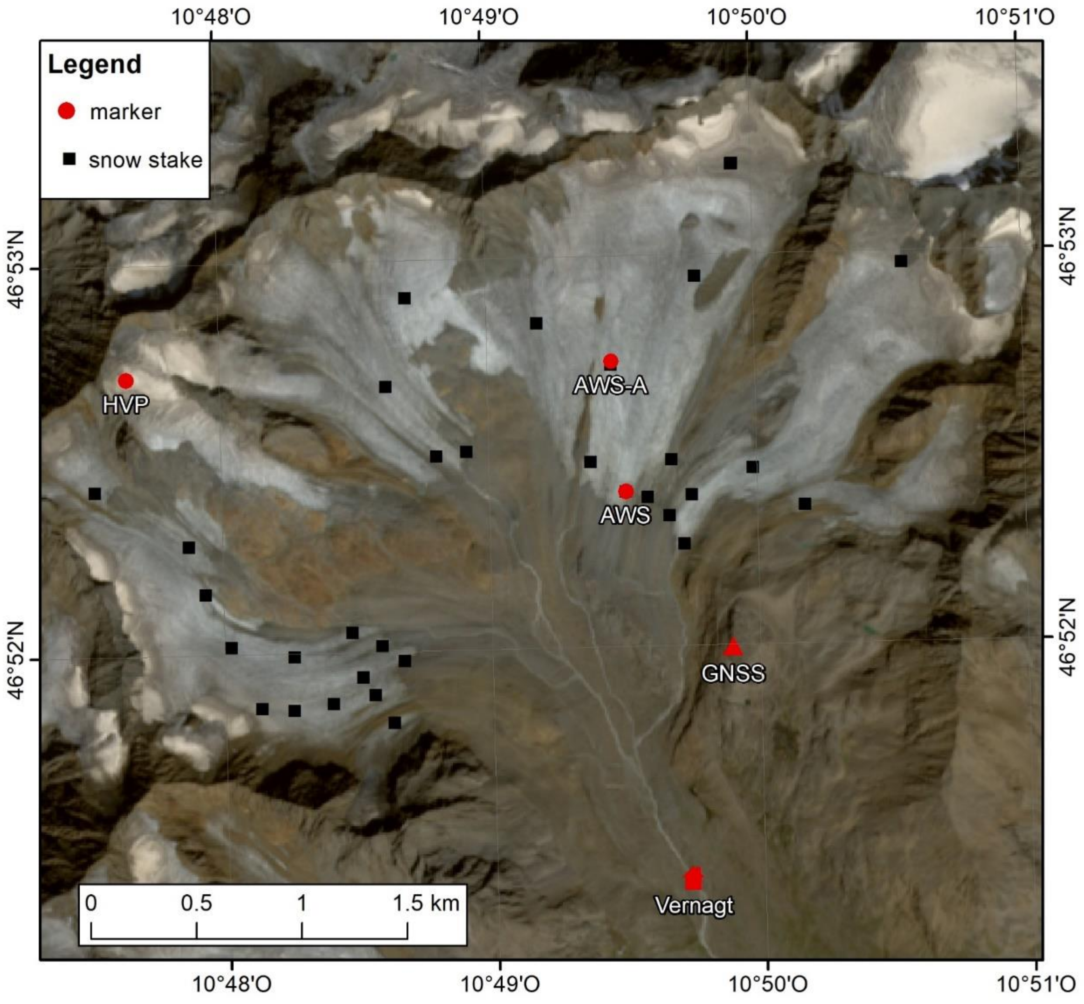
Balance year 2022

- less winter snow
- Sahara dust in spring
- long and hot summer
- ➢ Southern Schneeferner downgraded to perennial ice patch and taken out of the observing system

➢ only 4 German glaciers

Vernagtferner, Oetztal Alps, Austria



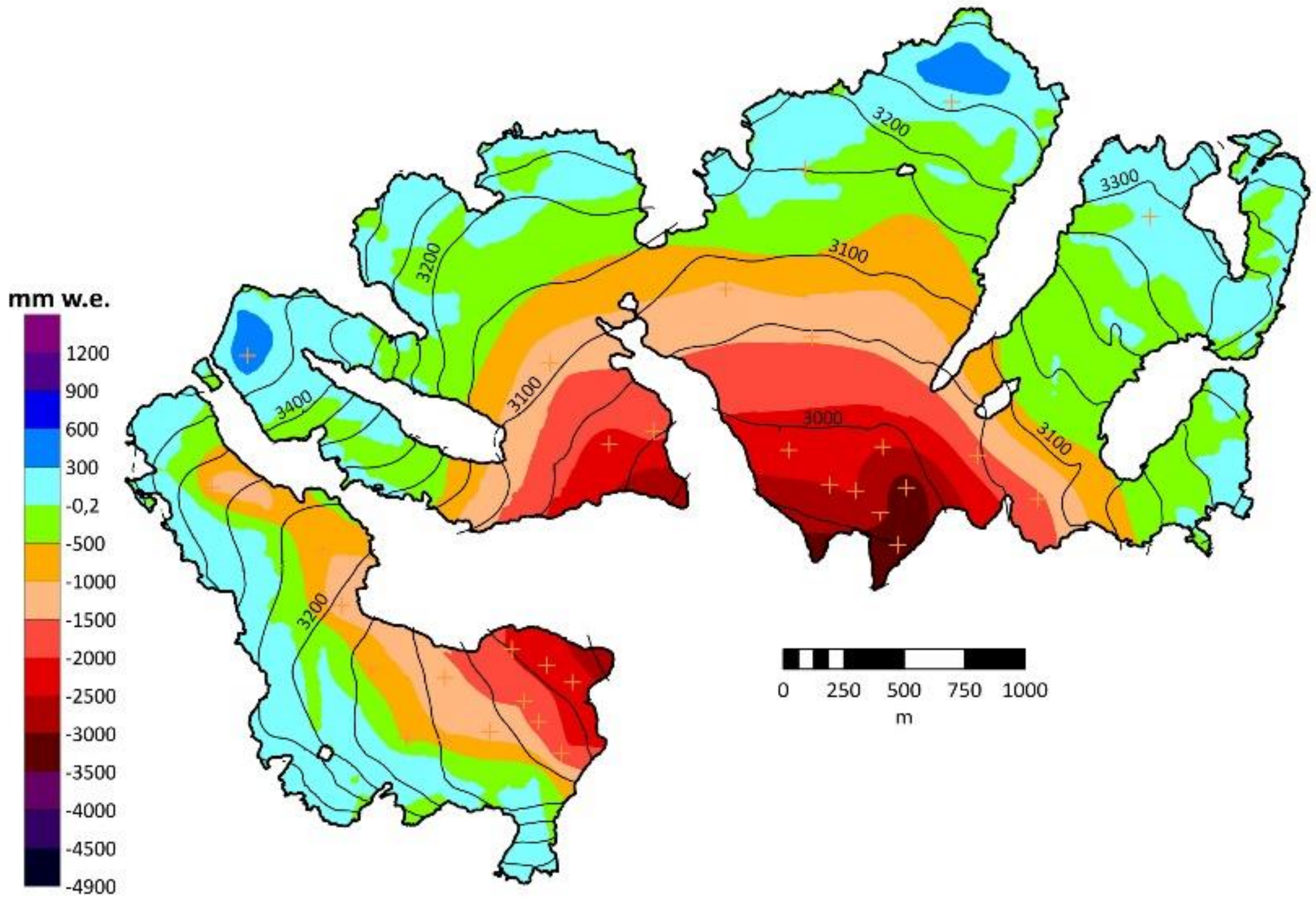
Copernicus Sentinel 2 (2022-08-29)

- First topographic map in 1889
- mass balance program since 1964
- 3 automatic weather stations
- permanent GNSS station

- research station with permanent meteorological and hydrological measurements
- base for field campaigns

Reference glacier of the World Glacier Monitoring Service (WMO, UNESCO, UN Environment)
Data archived in WGMS and PANGÄA
reported to GCOS

Vernagtferner, Oetztal Alps, Austria



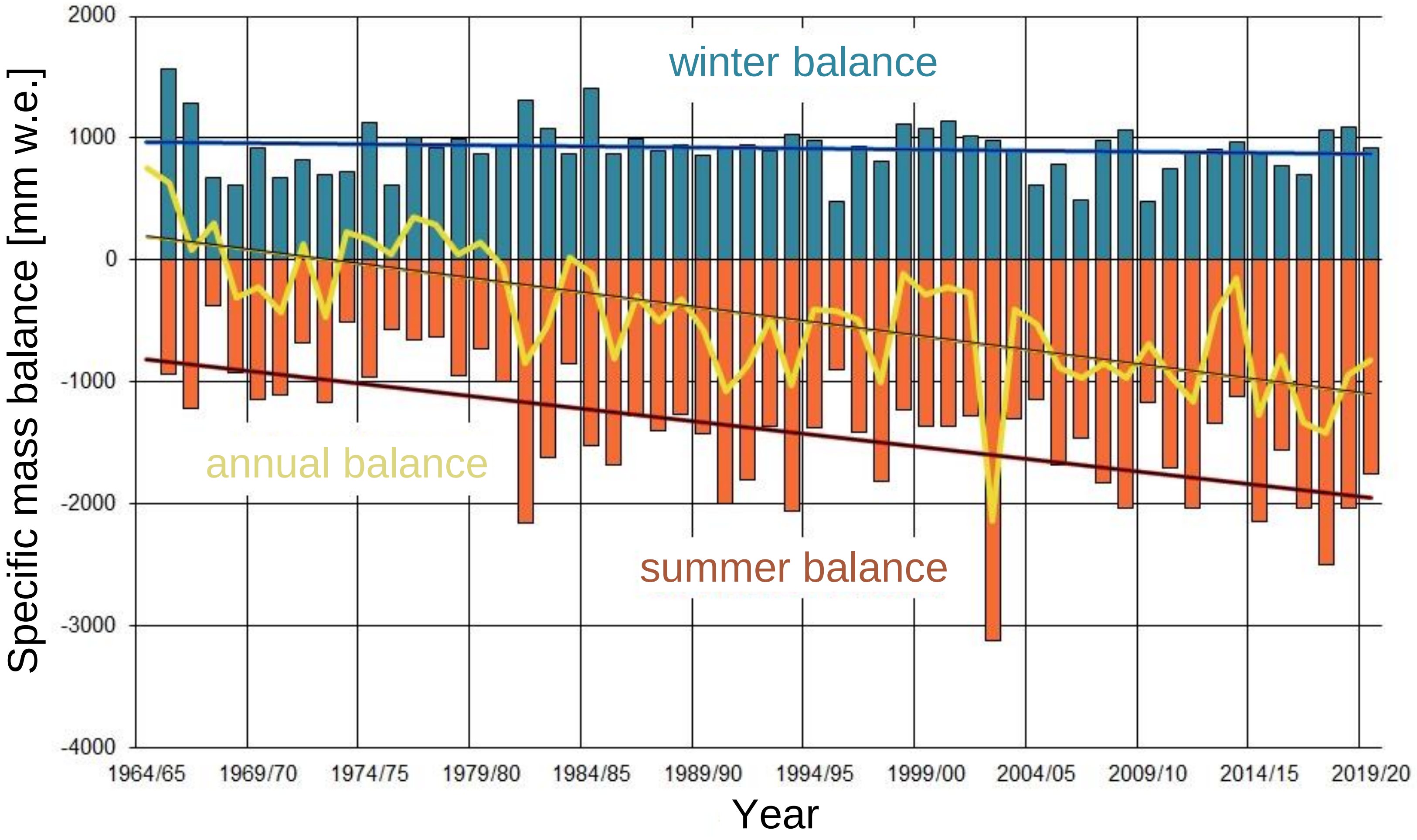
Mass balance year 2020/21

b: -593 mm w.e.
AAR: 24%
ELA: 3248 m

Mass balance year 2021/22

b: < - 2000 mm w.e.
AAR: 0%
ELA: > 3600 m

Vernagtferner, Oetztal Alps, Austria

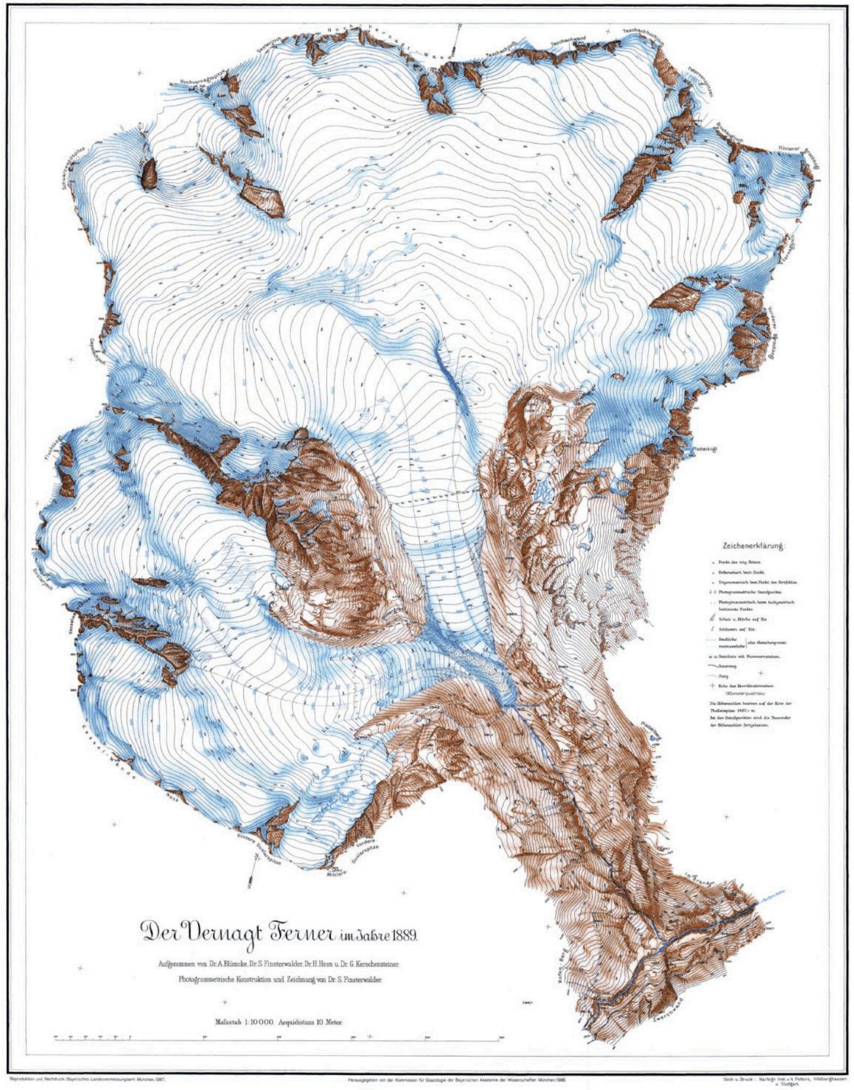


Glaciological mass balance time series

winter balance: constant
summer balance: decreasing

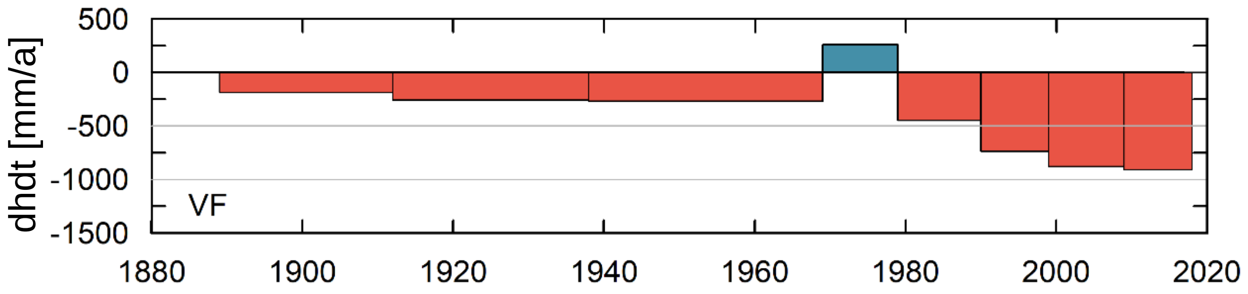
→ Continuous mass loss starting in the 1980s

Vernagtferner, Oetztal Alps, Austria

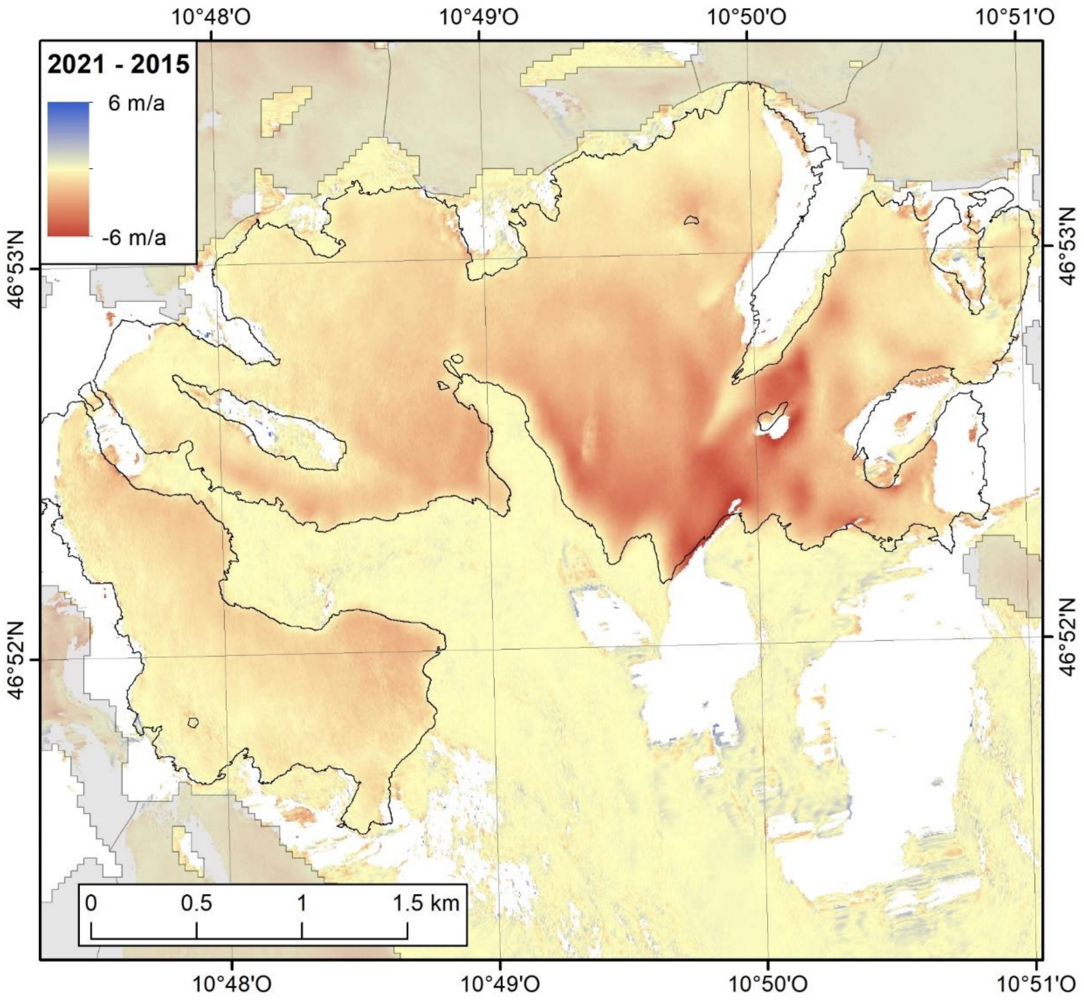


Geodetic mass balance

Volume changes from DEM differencing since 1889



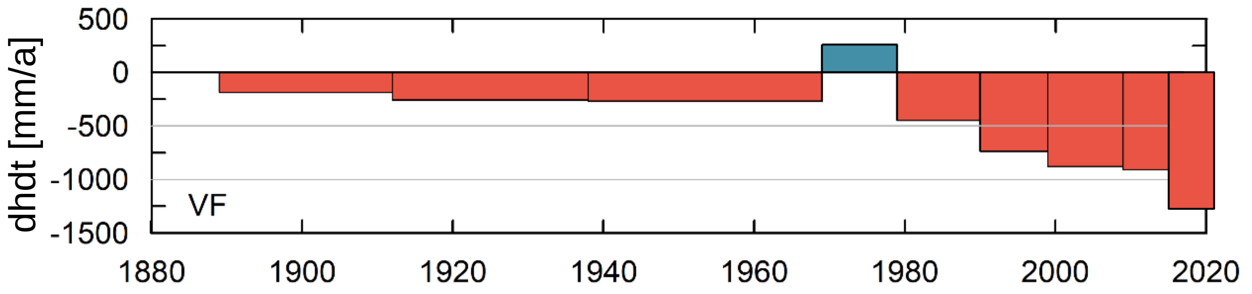
Vernagtferner, Oetztal Alps, Austria



TanDEM-X © DLR 2015, 2021

Geodetic mass balance

Volume changes from DEM differencing since 1889



Elevation change rates from InSAR

- TanDEM-X

IACS working group (International Association of Cryospheric Sciences)

Glacier volume change intercomparison experiment

- compute volume changes for a validation period using either ASTER or TDX DEMs
- test sites: e.g. Hintereisferner, Baltoro (Pakistan)

Challenges:

- timing close to reference date
- resolution, coverage
- InSAR: surface penetration

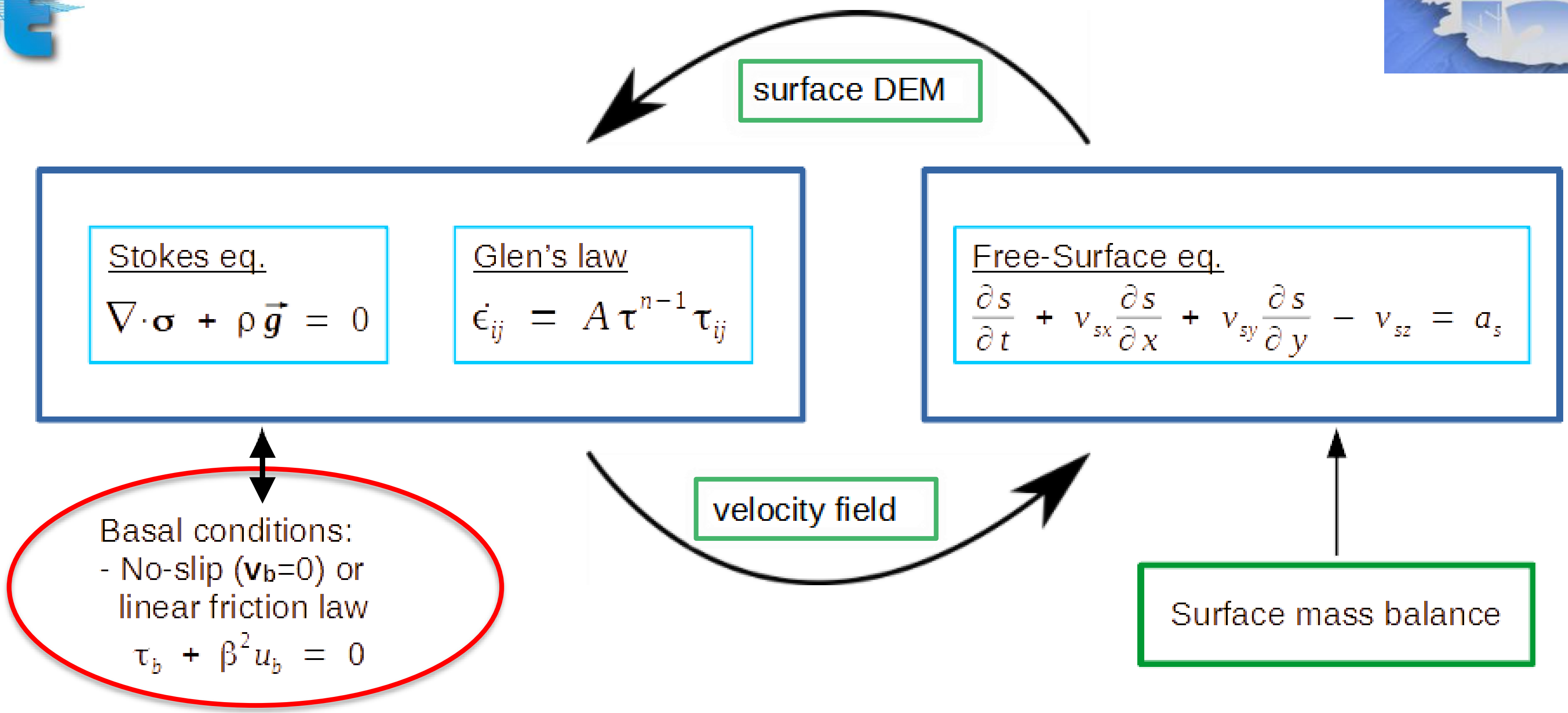
Advantage:

- global observations

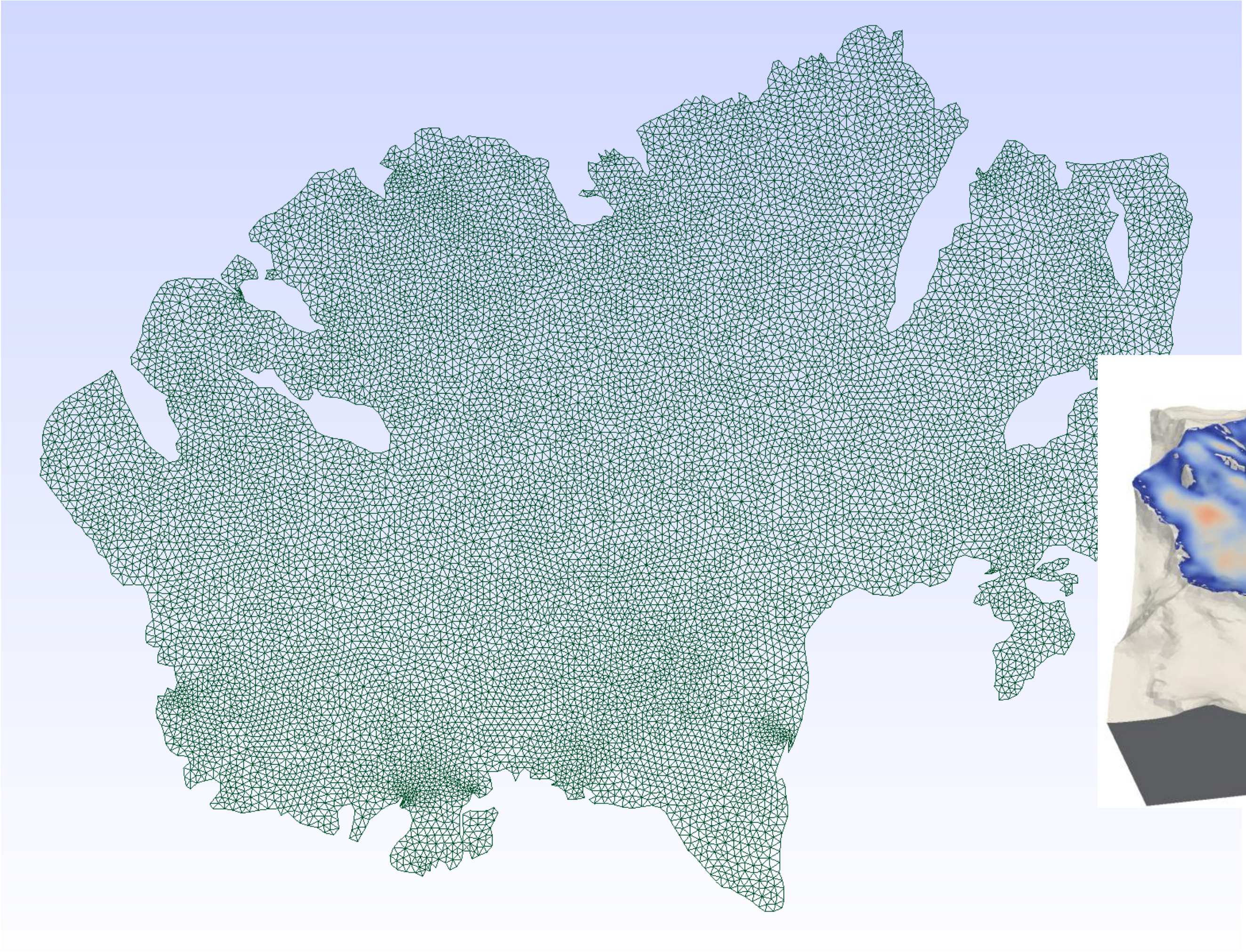
→ Community efforts to agree on corrections and define best practice

BAdW

Ice flow modelling



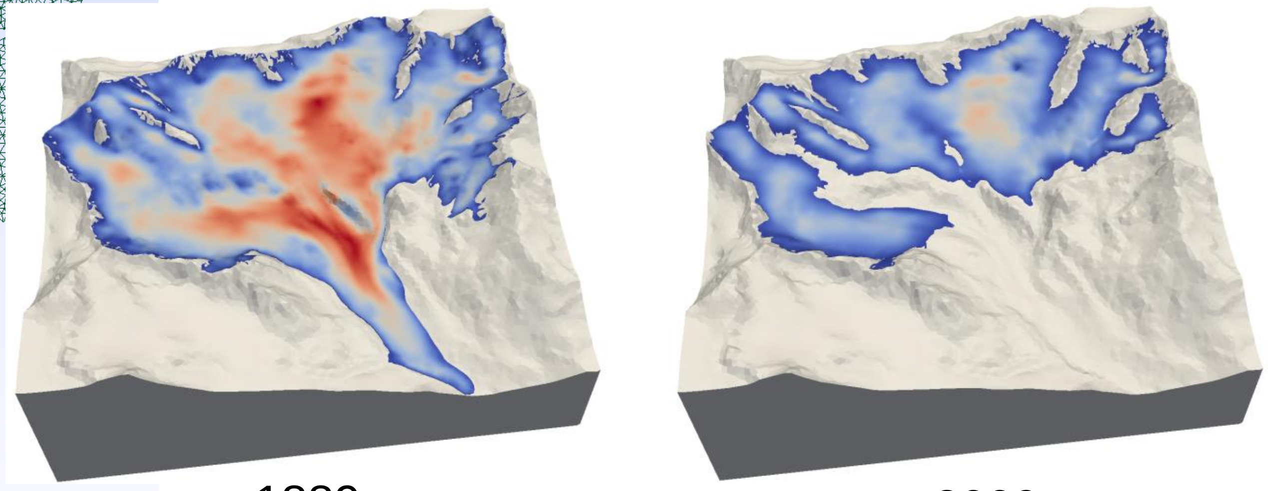
Ice flow modelling



Elmer/Ice on 50 m mesh

→ Sliding dominates over internal deformation

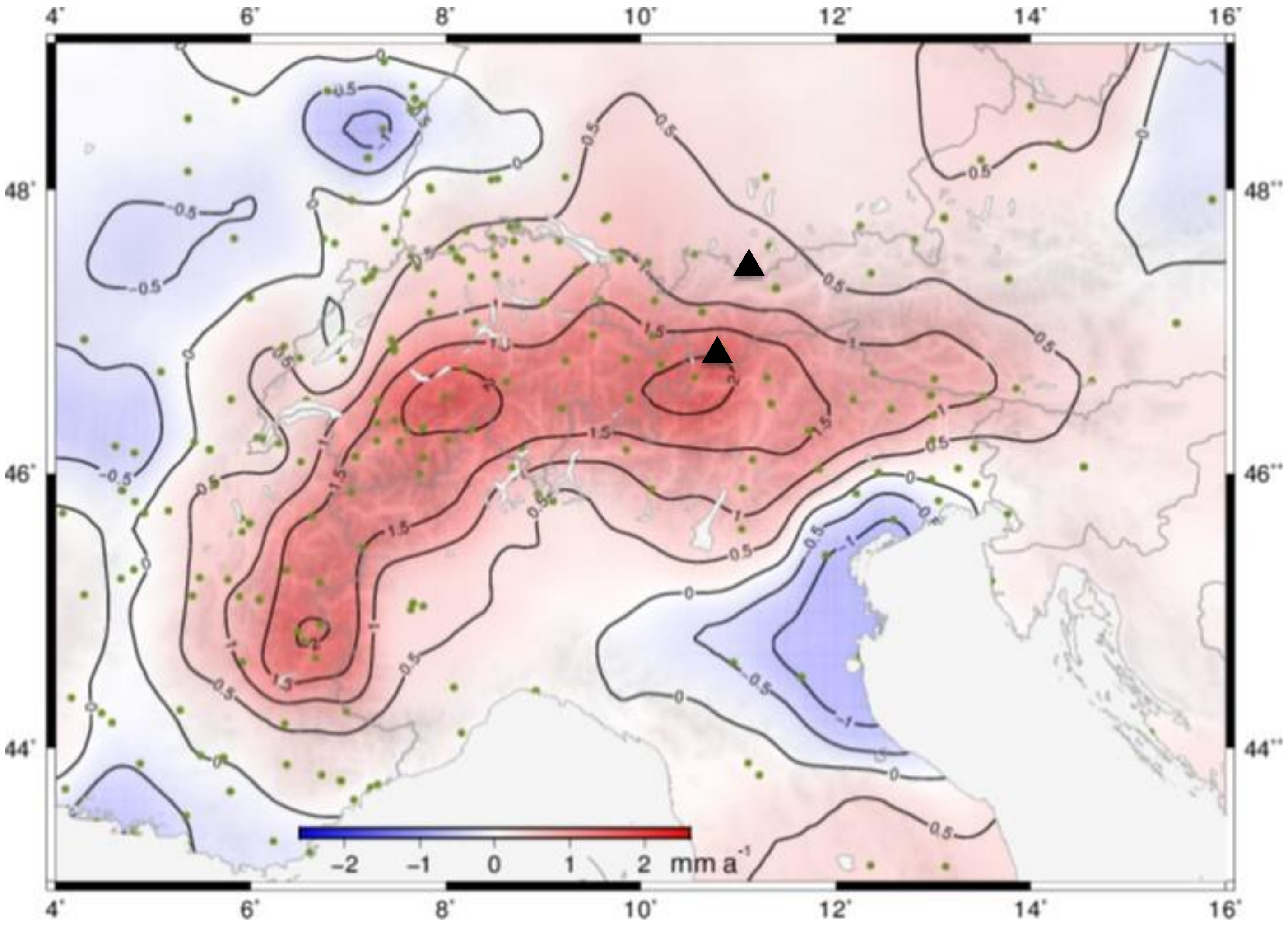
→ Reconstruct observed past glacier changes



1889 2009

→ Forward modelling under different PRCs (representative concentration pathways)

Tectonic uplift of the Alps



Sánchez et al., 2018

>300 permanent GNSS stations
time span 2004 – 2016

average uplift of 1.8 mm a^{-1}
largest uplift rates >2 mm a^{-1} e.g. near Vernagtferner
lower rates towards the margins

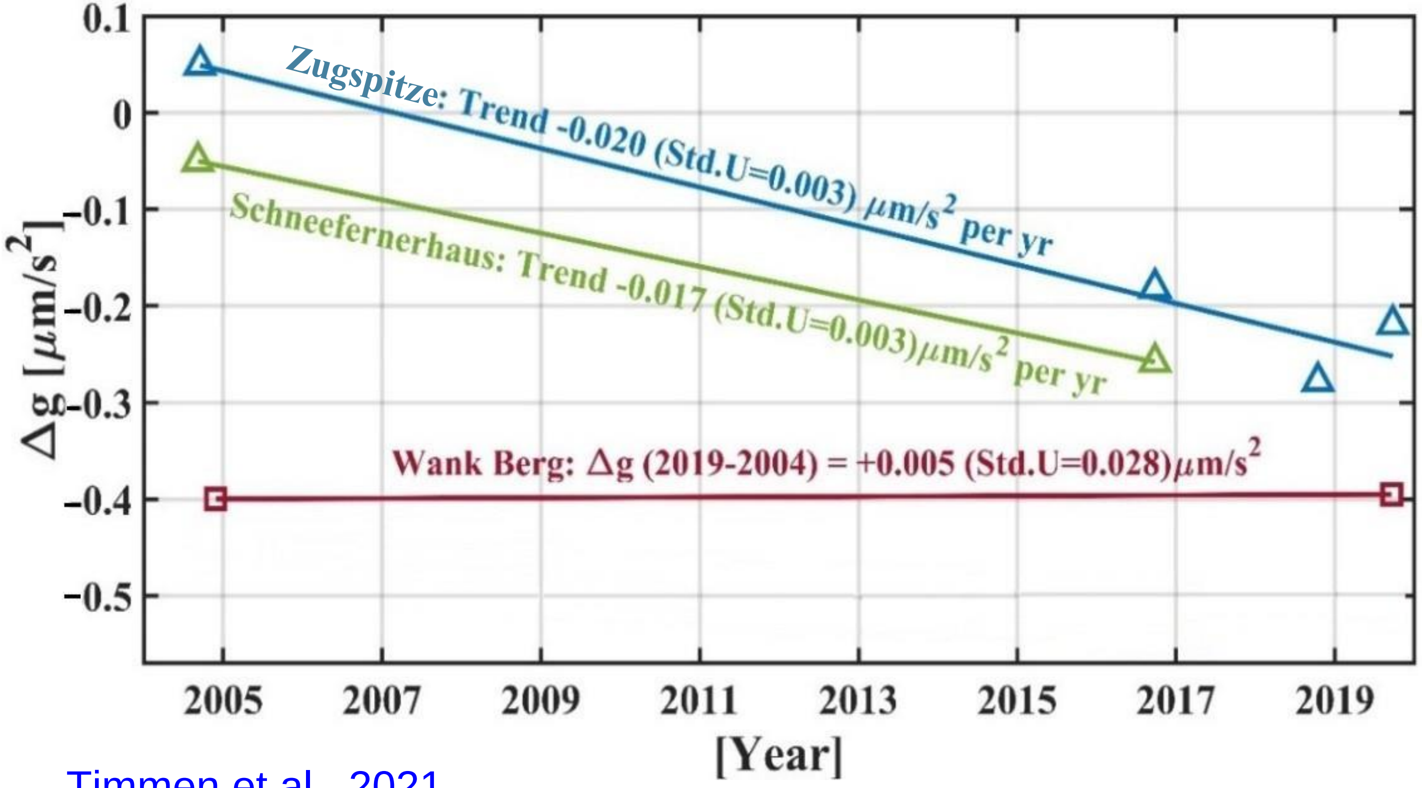
Absolute gravimetry at Zugspitze

Absolute gravity measurements
2004 - 2019

- Zugspitze and Schneefernerhaus
- Nearby non-glacierized mountain Wank

Timmen et al., 2021

Absolute gravimetry at Zugspitze



Timmen et al., 2021

Absolute gravity measurements 2004 - 2019

- Zugspitze and Schneefernerhaus
- Nearby non-glacierized mountain Wank

Wank:

no vertical movement
no gravity change

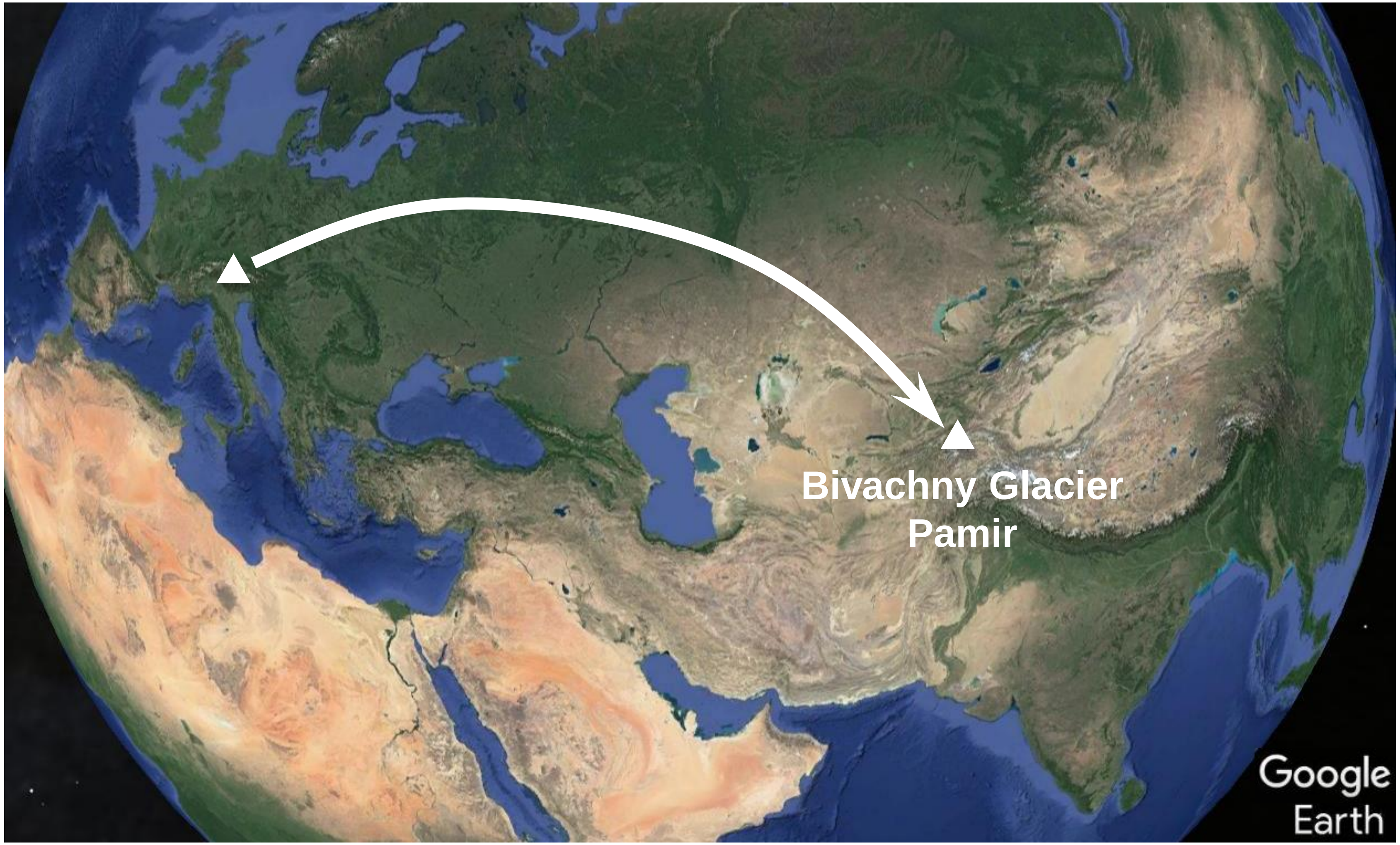
Zugspitze:

gravity change due to vertical movement: <15 %
gravity change due to glacier retreat: 75 %

permafrost processes, local hydrology: ?

→ superconducting gravimeter installed by GFZ in 2018

Surge-type glaciers



Glaciers are climate indicators

because:

Glaciers act as a low pass filter to changes in climate

BUT:

Some glaciers show mass changes independent from climate changes

→ Surge-type glaciers

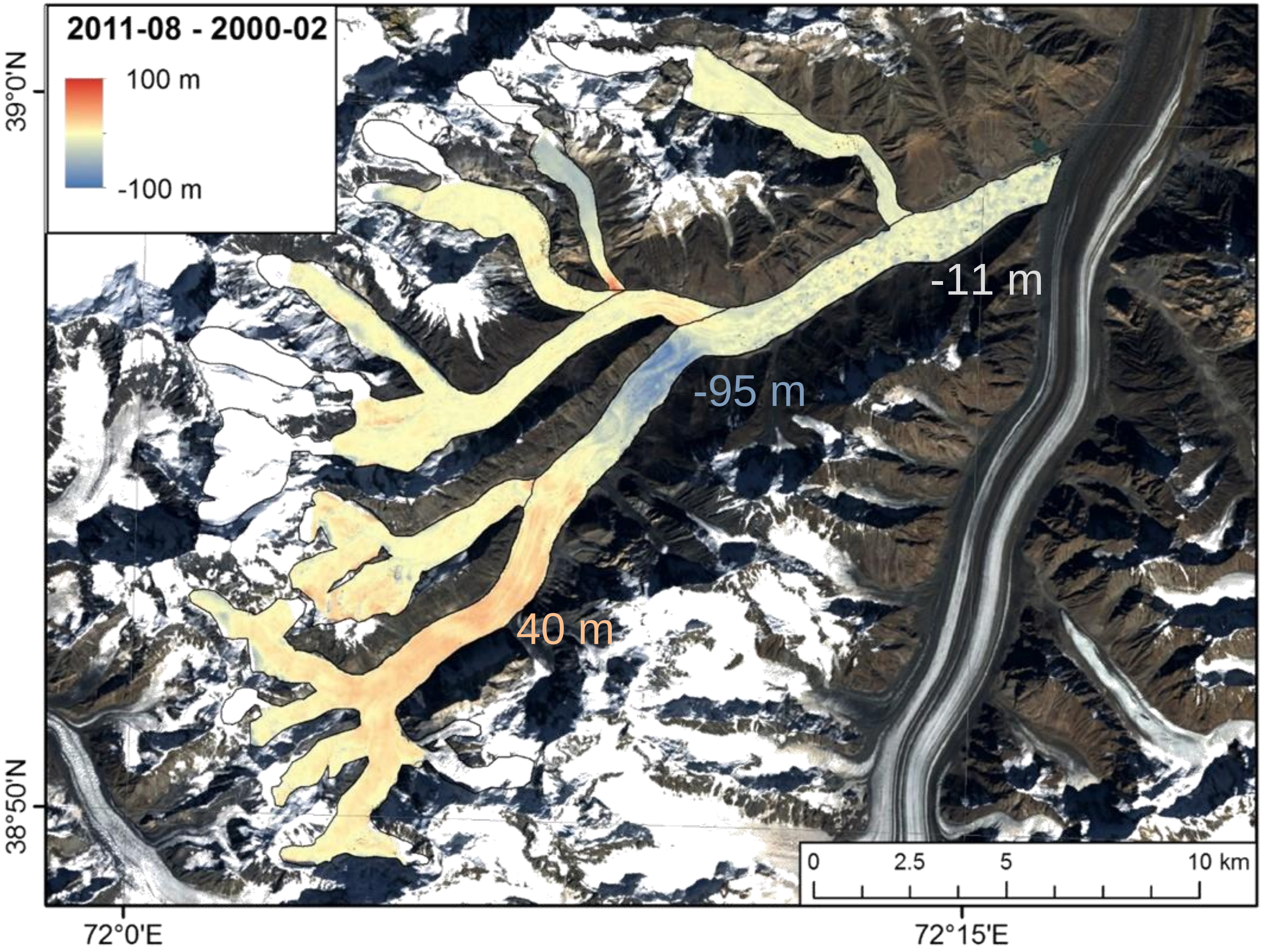
Bivachny Glacier, Pamir Mountains, 2011 - 2015

[Wendt et al., 2017](#)

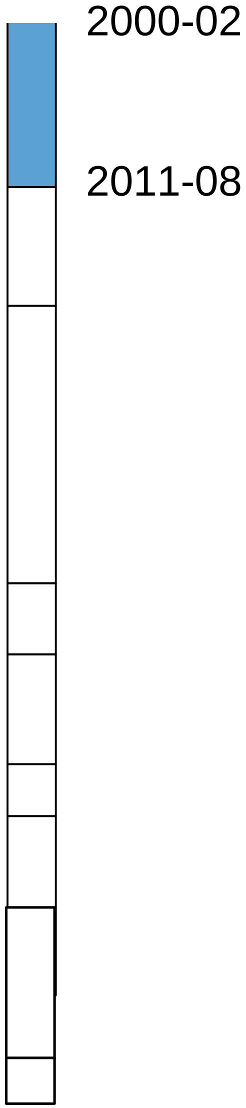
Surge-type glaciers:

- quiescent and active phase
- sudden advance with increase of speed
- mass transport from a reservoir area to lower glacier
- lasts for months to years
- Different theories of surge mechanisms:
  - related to a switch in subglacial water discharge
  - based on coupled mass and enthalpy budgets (Benn et al, 2019)

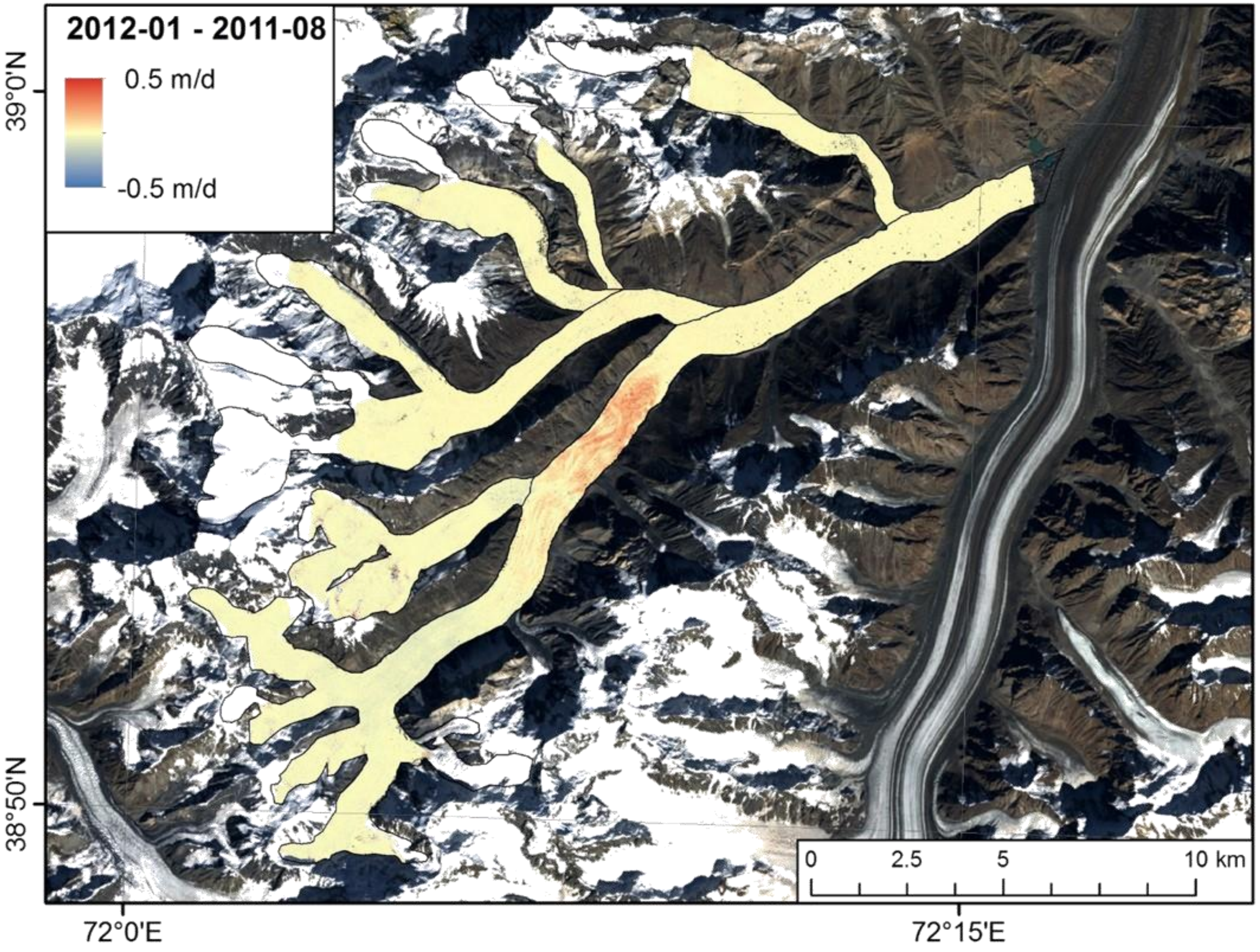
Pre-surge elevation changes 2000 - 2011

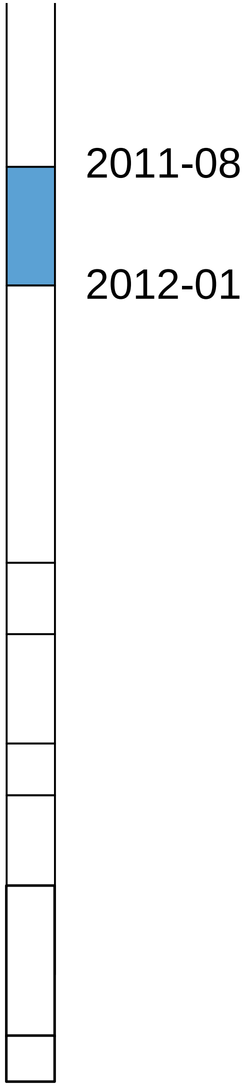


SRTM, TanDEM-X © DLR 2015, 2021



Elevation change rates during the surge





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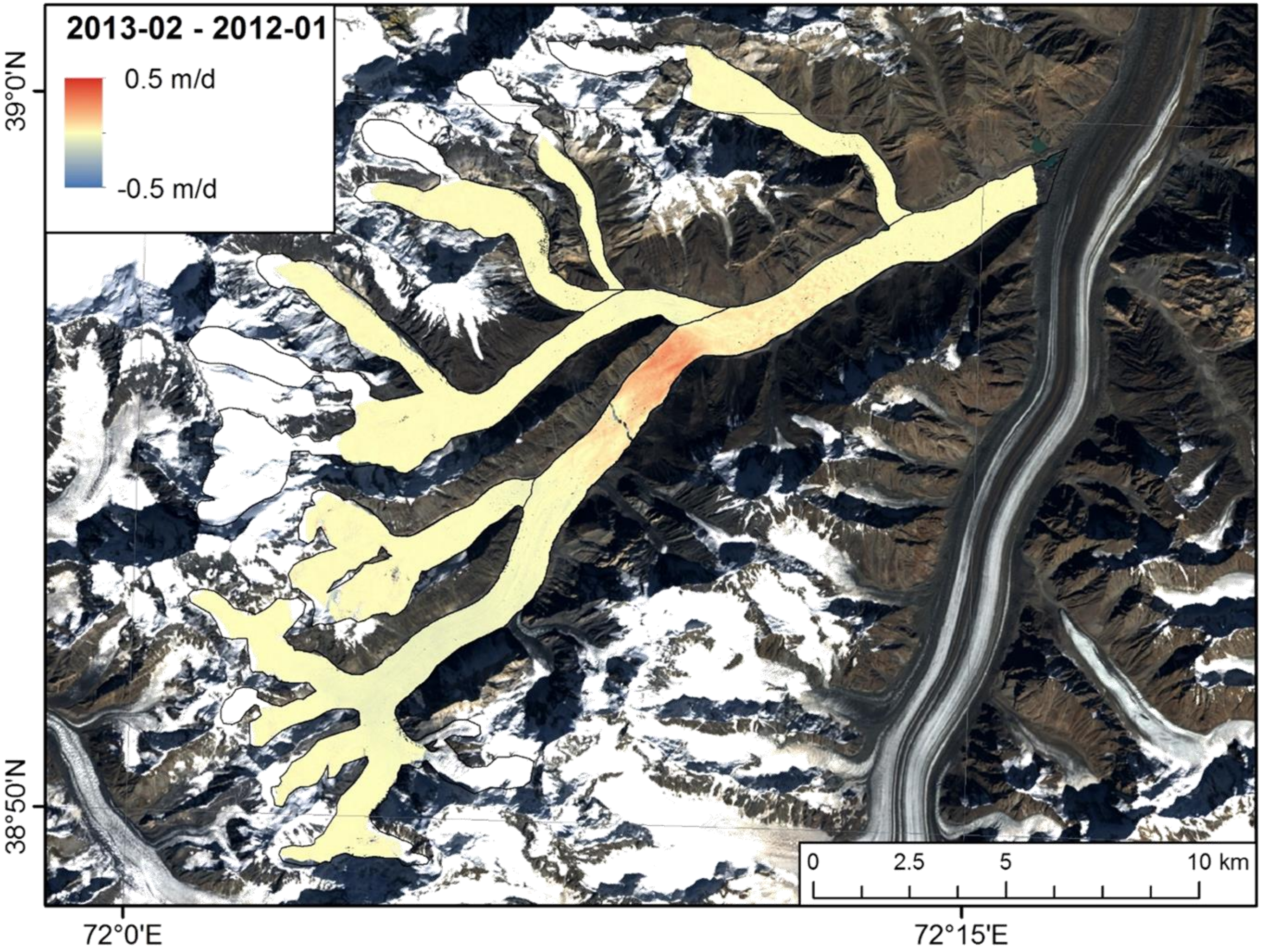
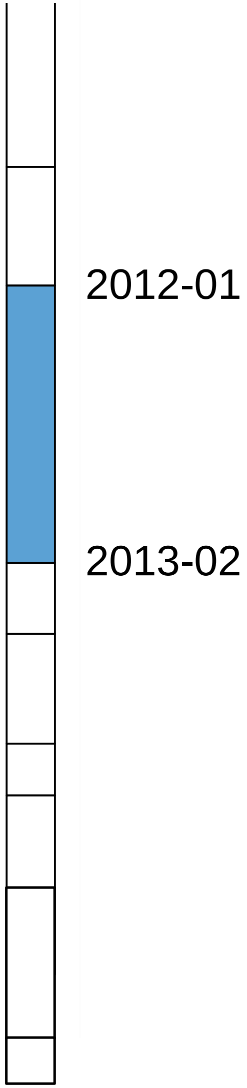
Elevation change rates during the surge





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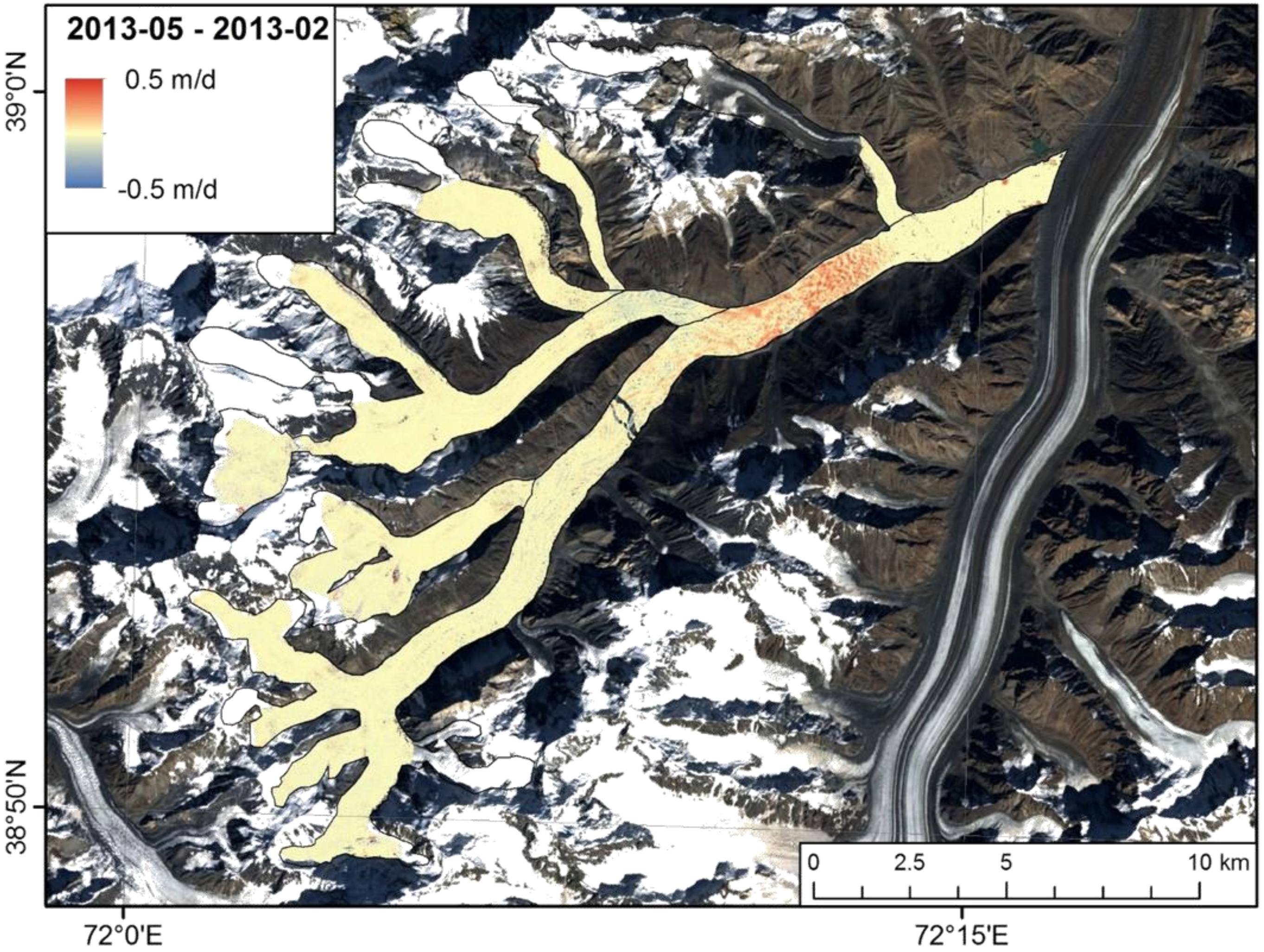
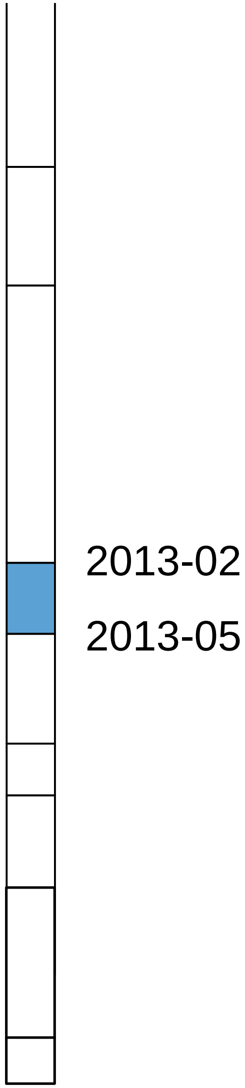
Elevation change rates during the surge



TanDEM-X © DLR 2011-2015



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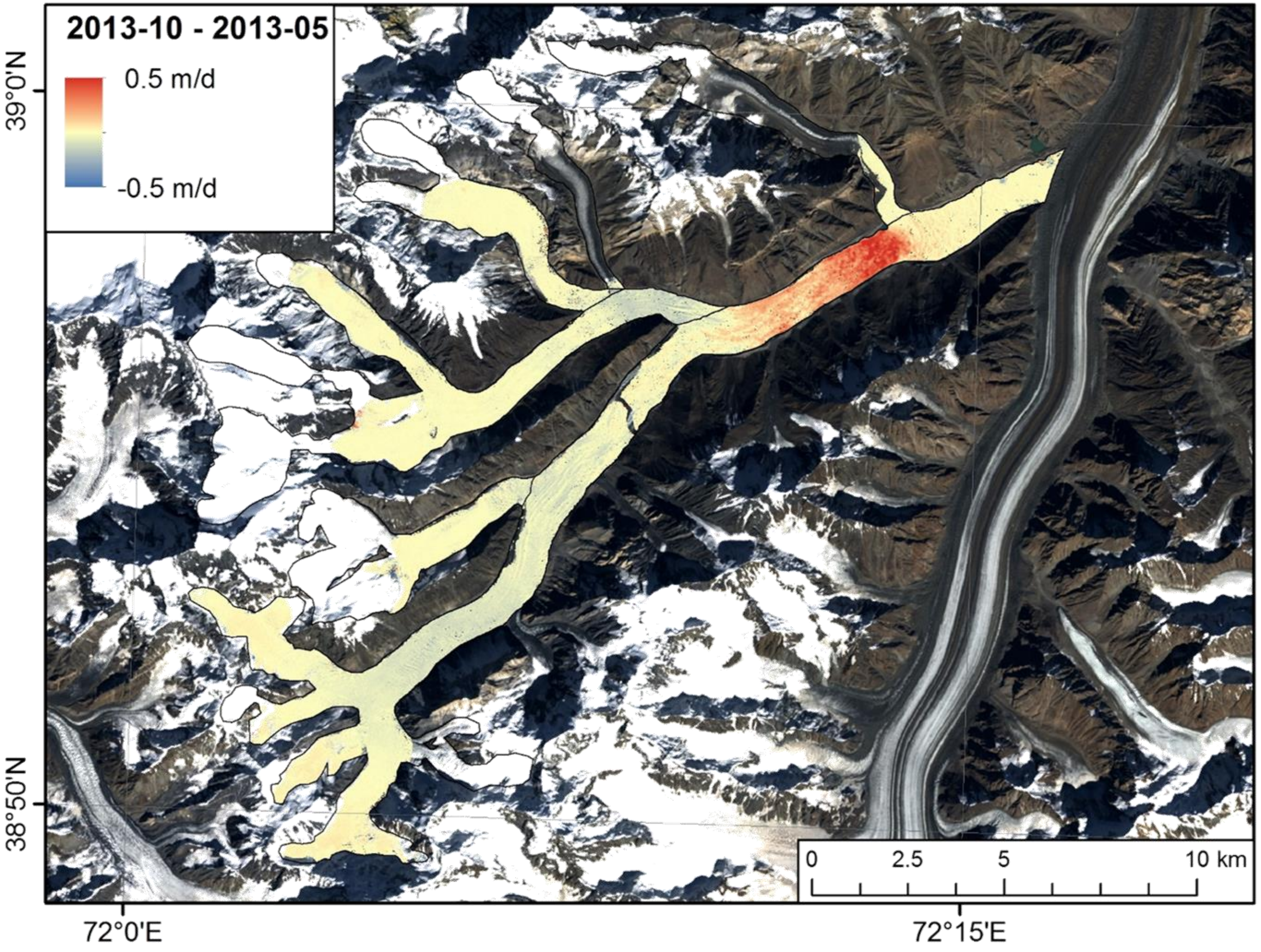

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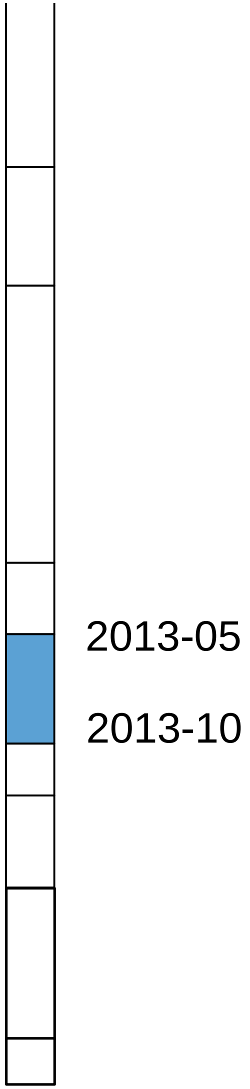
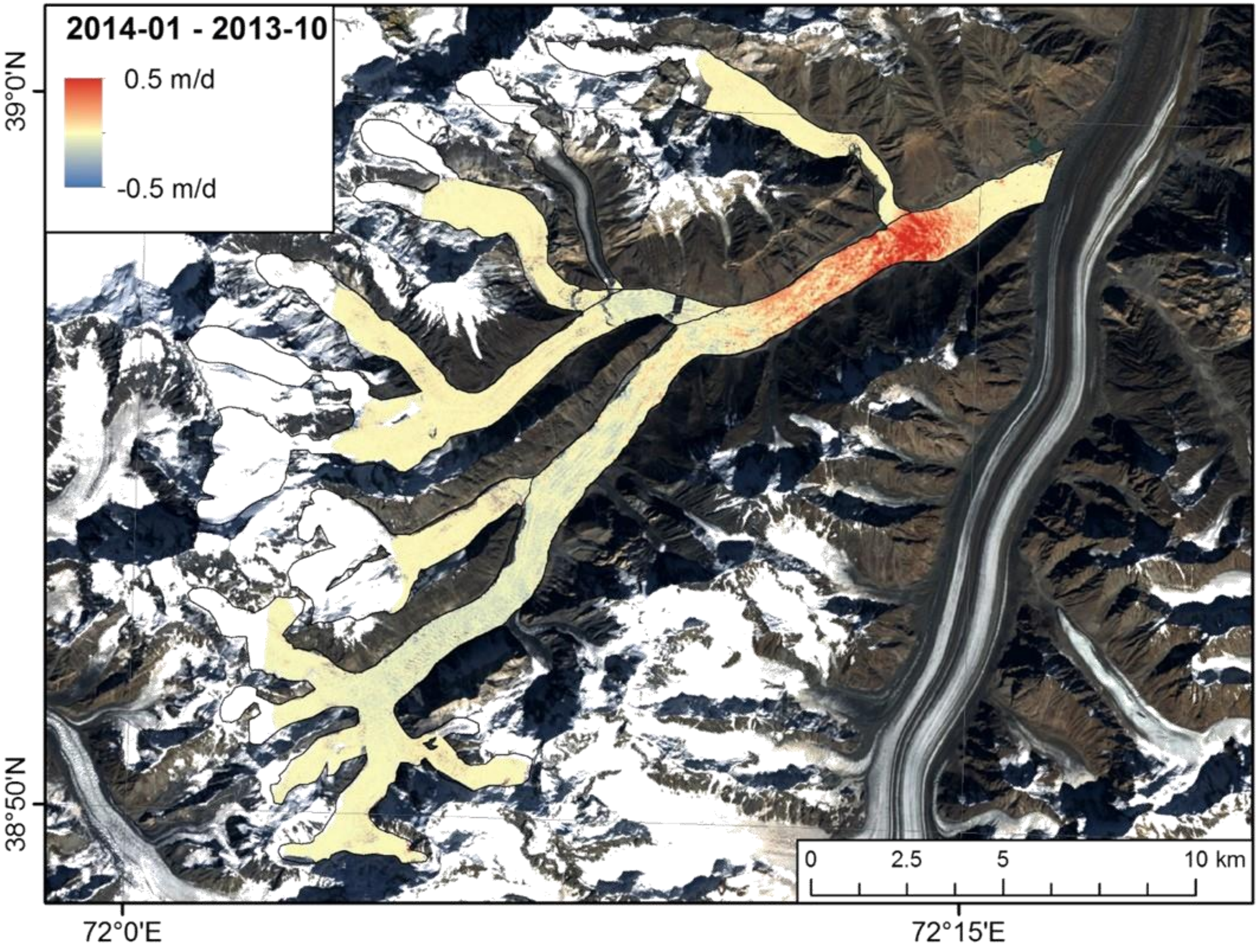
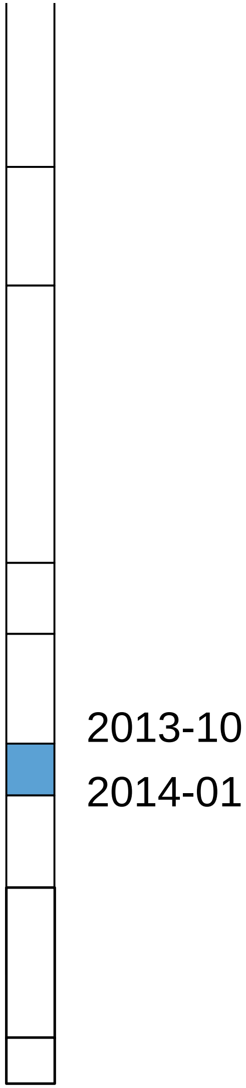


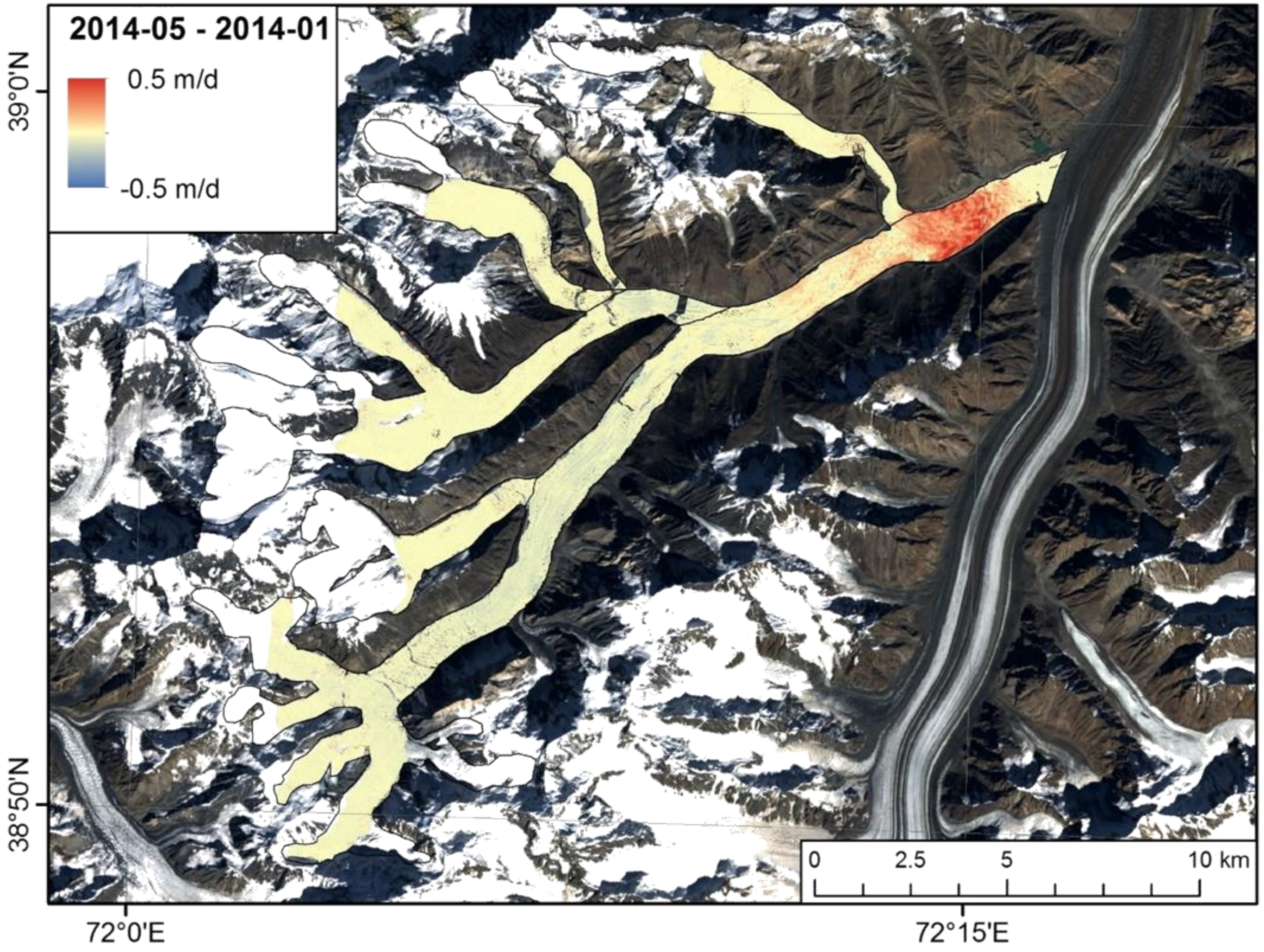
Elevation change rates during the surge



TanDEM-X © DLR 2011-2015



Elevation change rates during the surge



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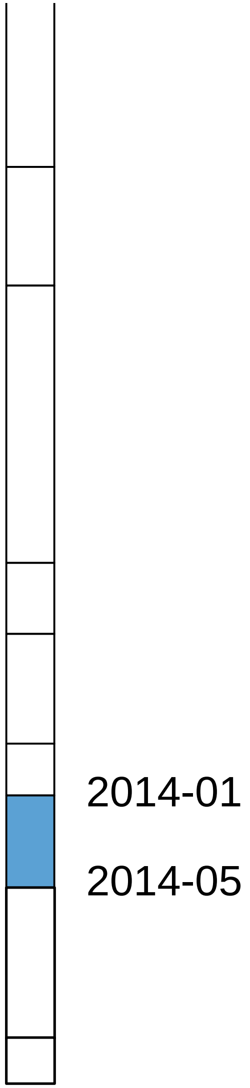
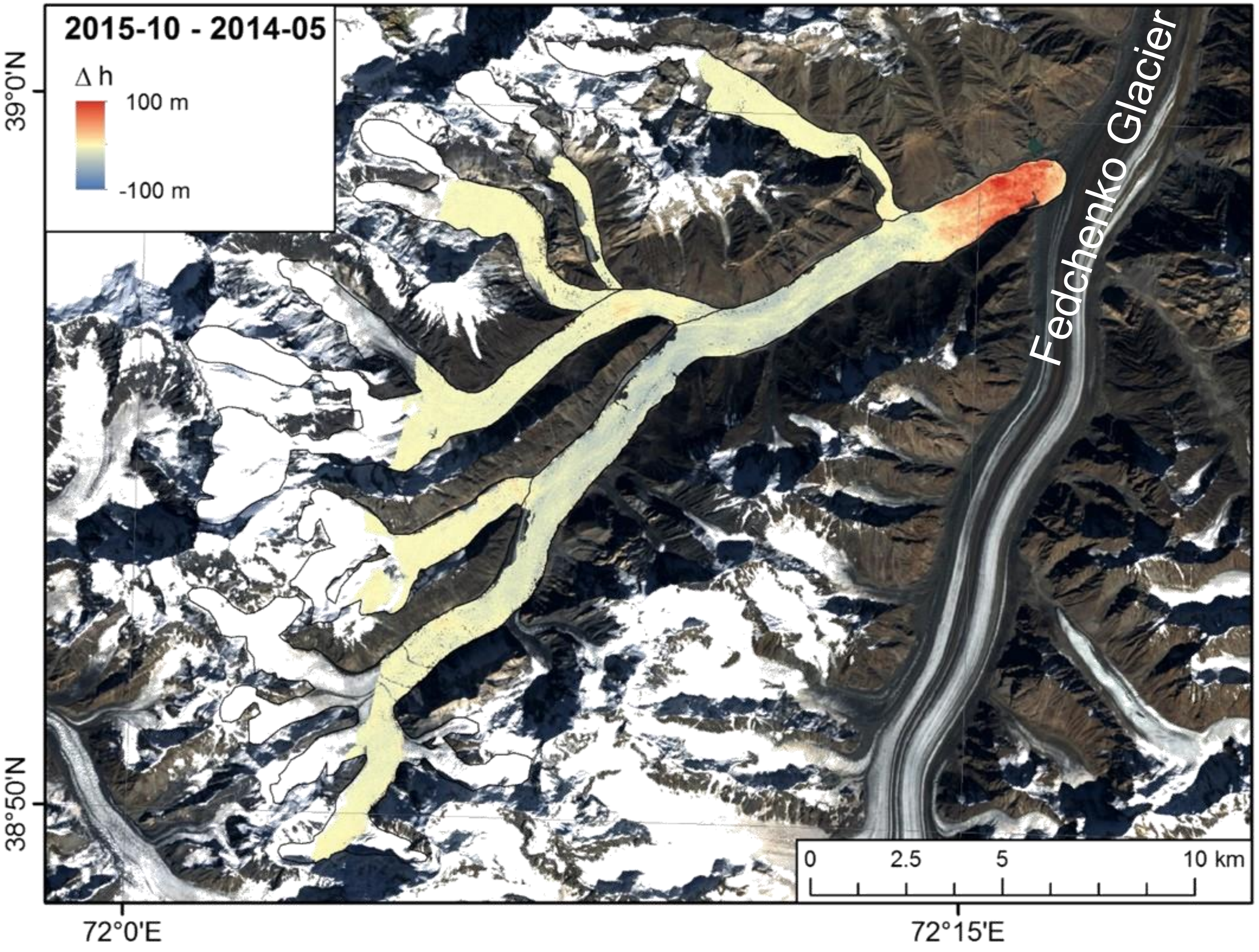


BAdW

Elevation change rates during the surge



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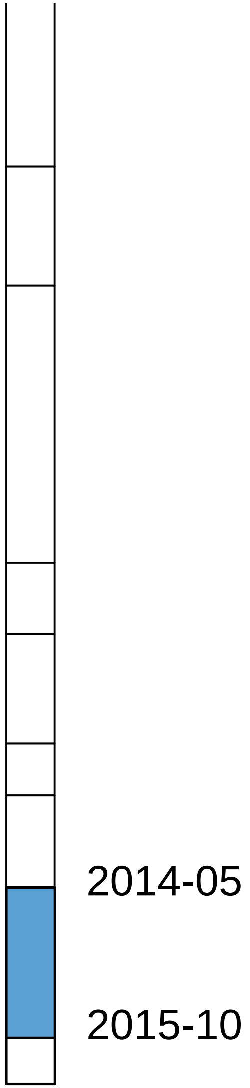
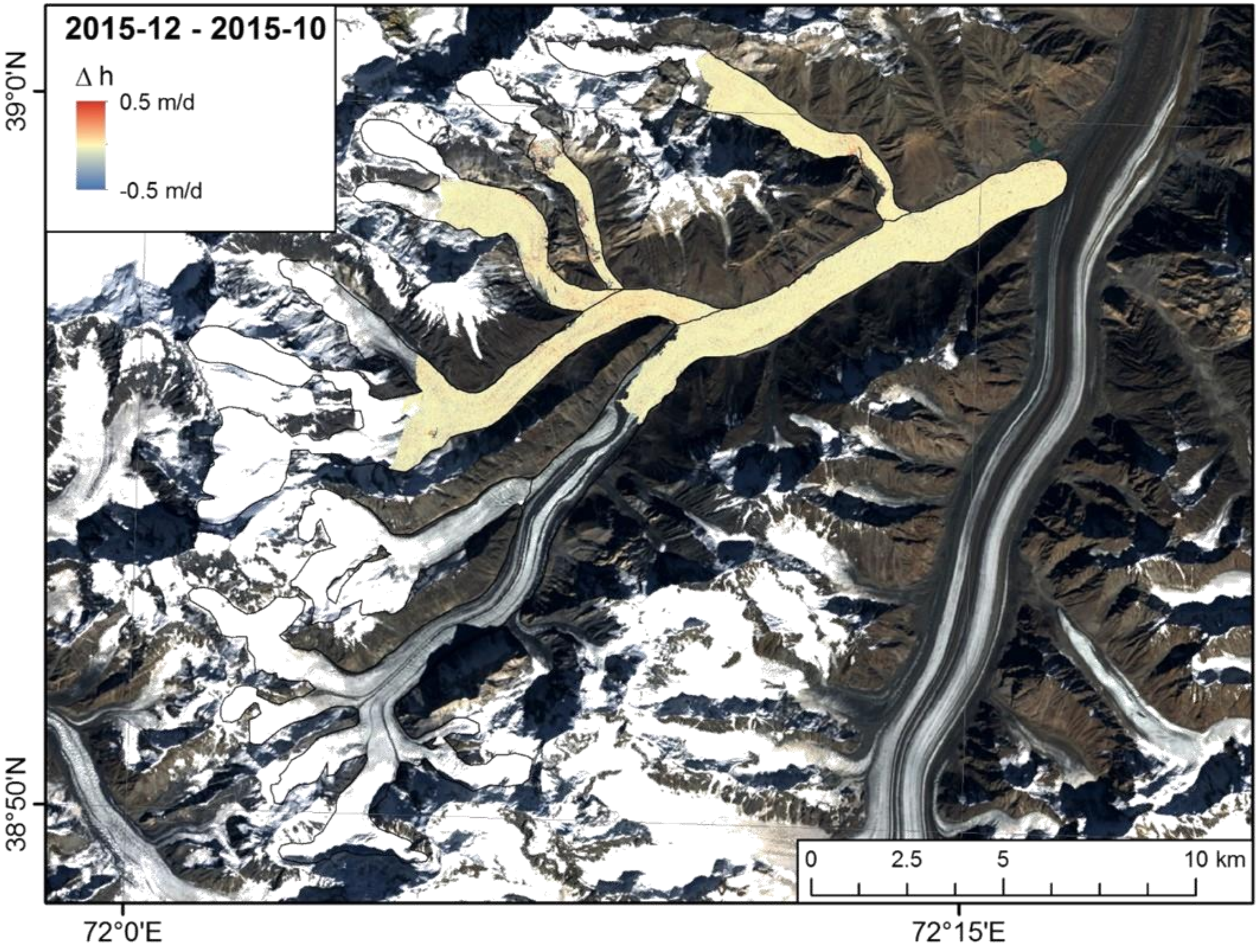
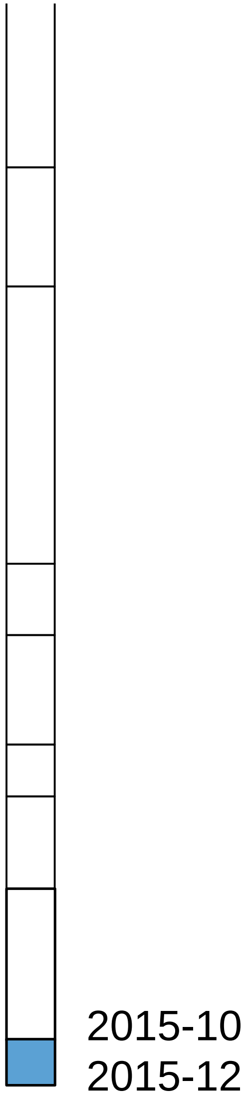


BAdW

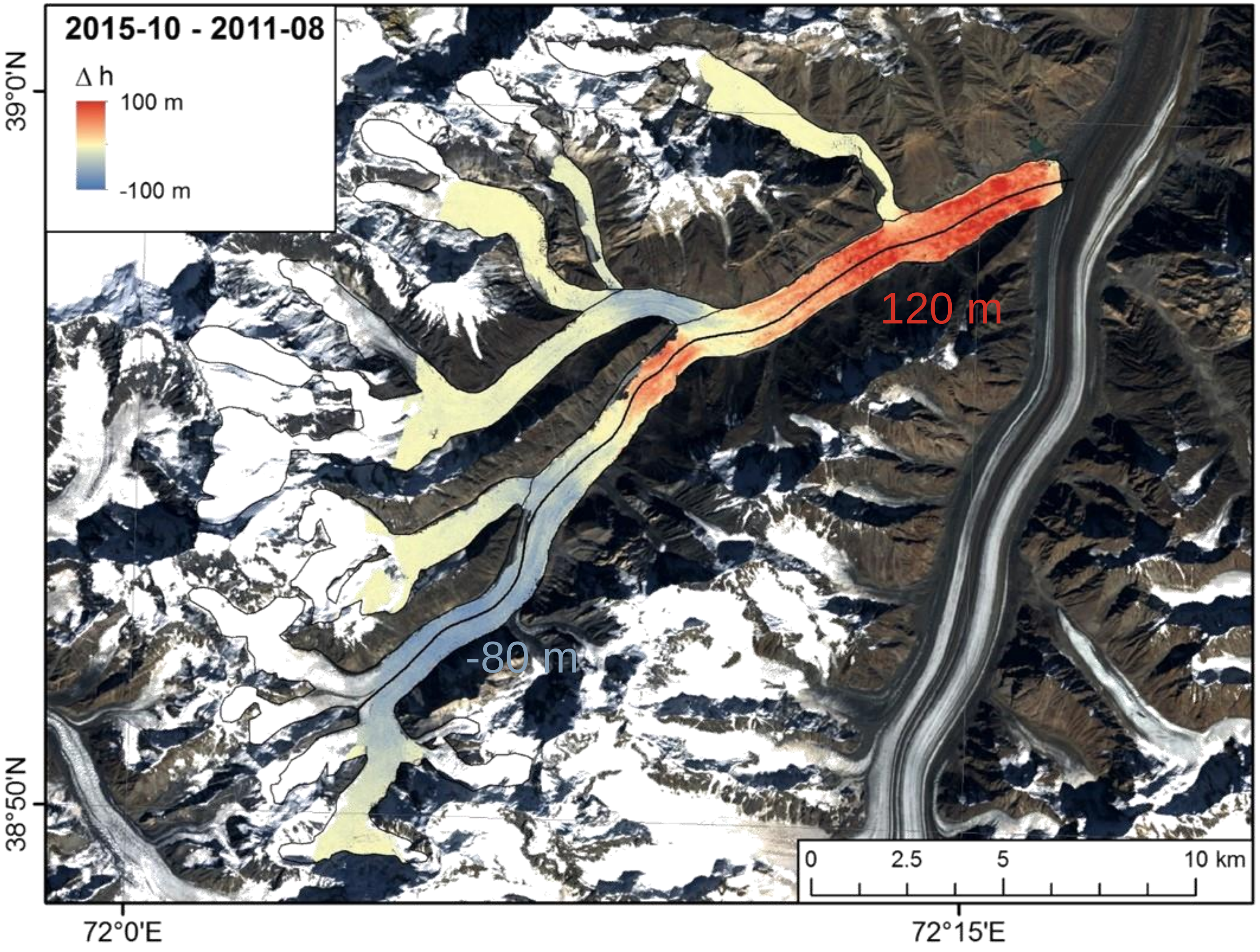
Elevation change after the surge



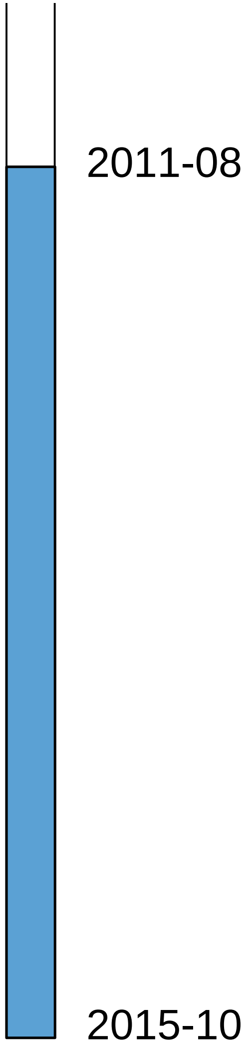


TanDEM-X © DLR 2011-2015

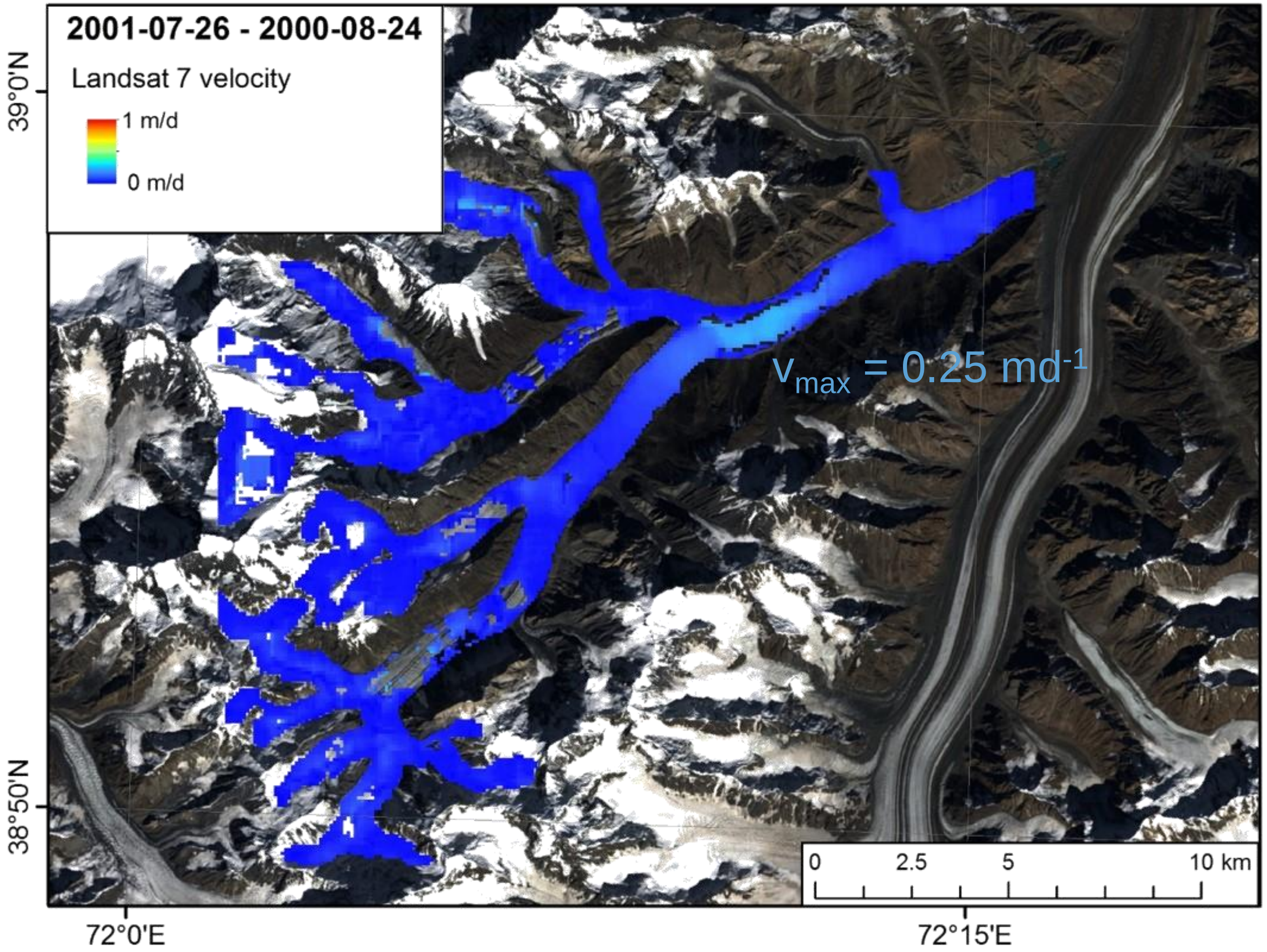
Total elevation change during the surge

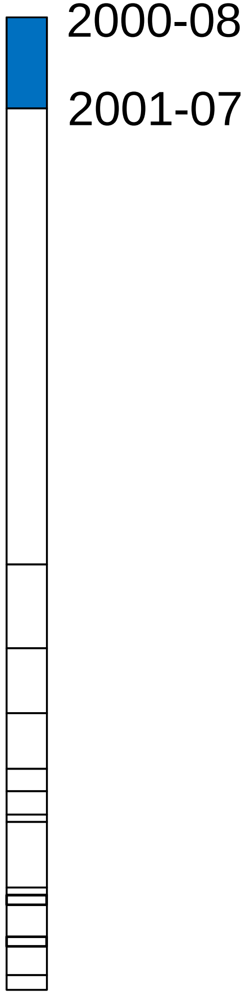


TanDEM-X © DLR 2011-2015

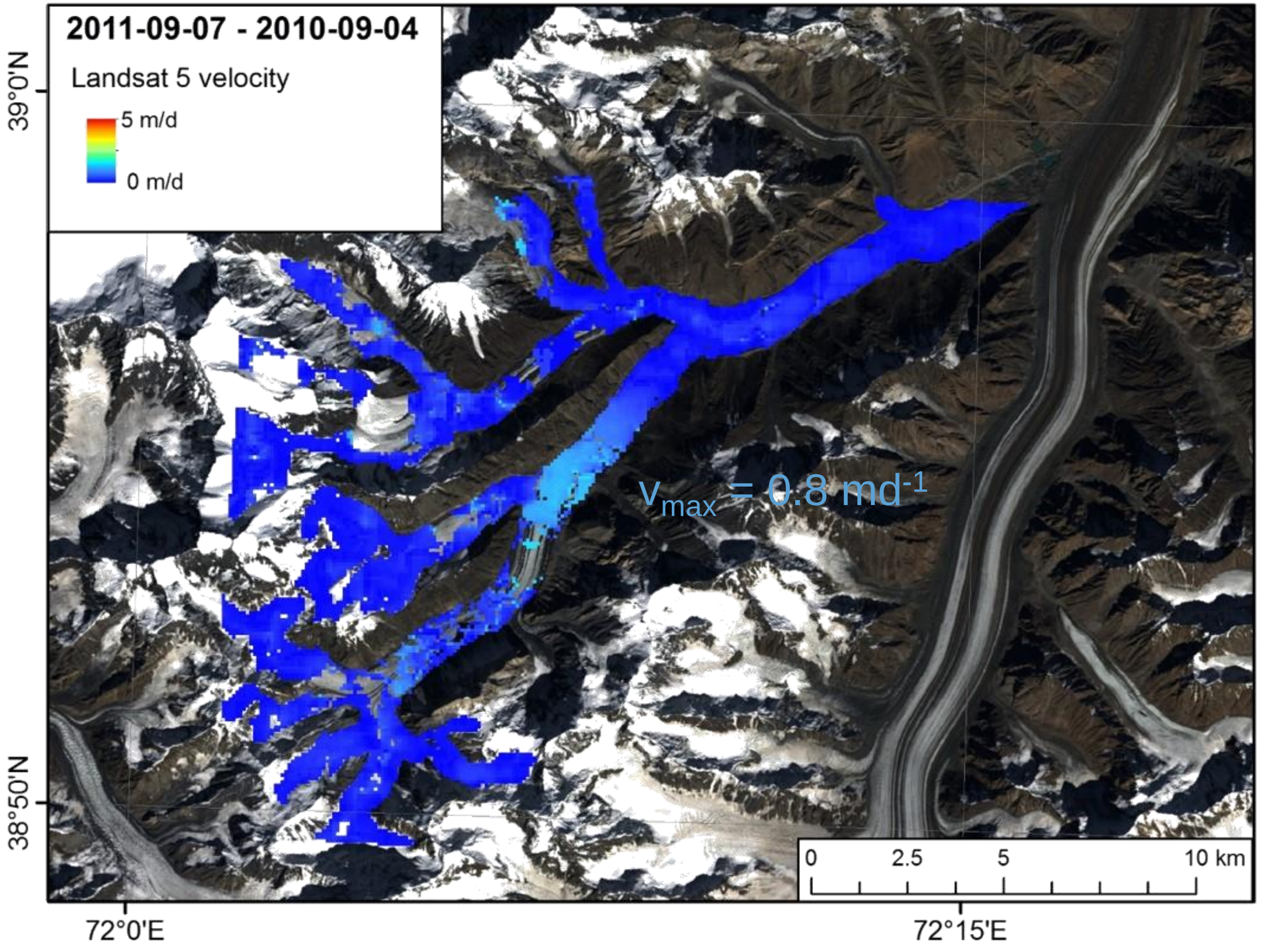


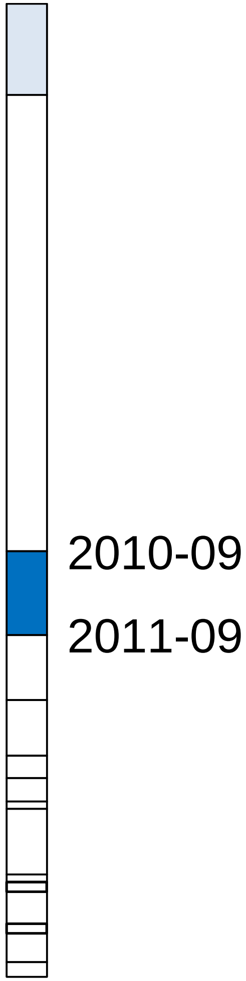
Annual flow velocities 2000/2001



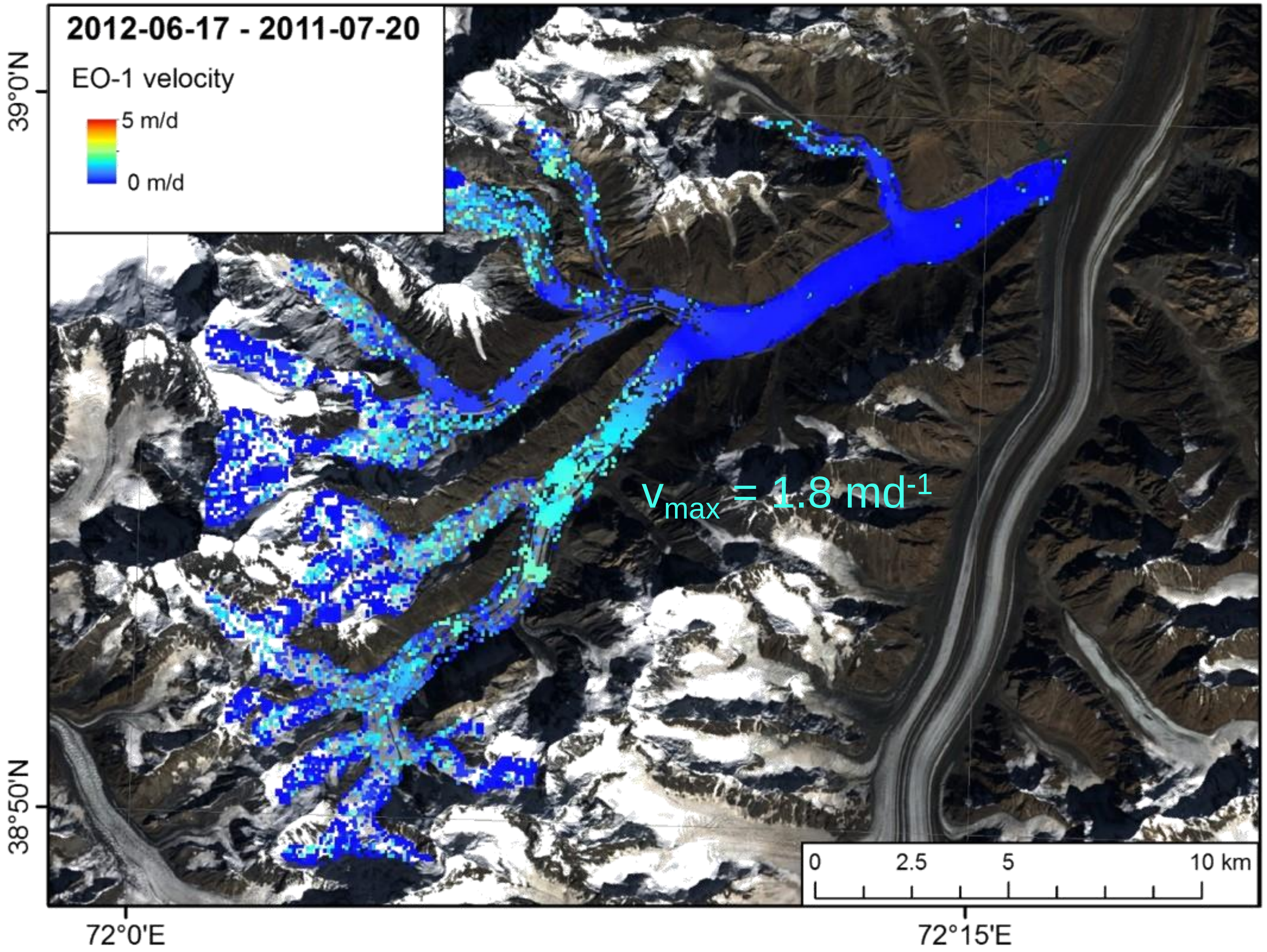


Annual flow velocities 2010/2011





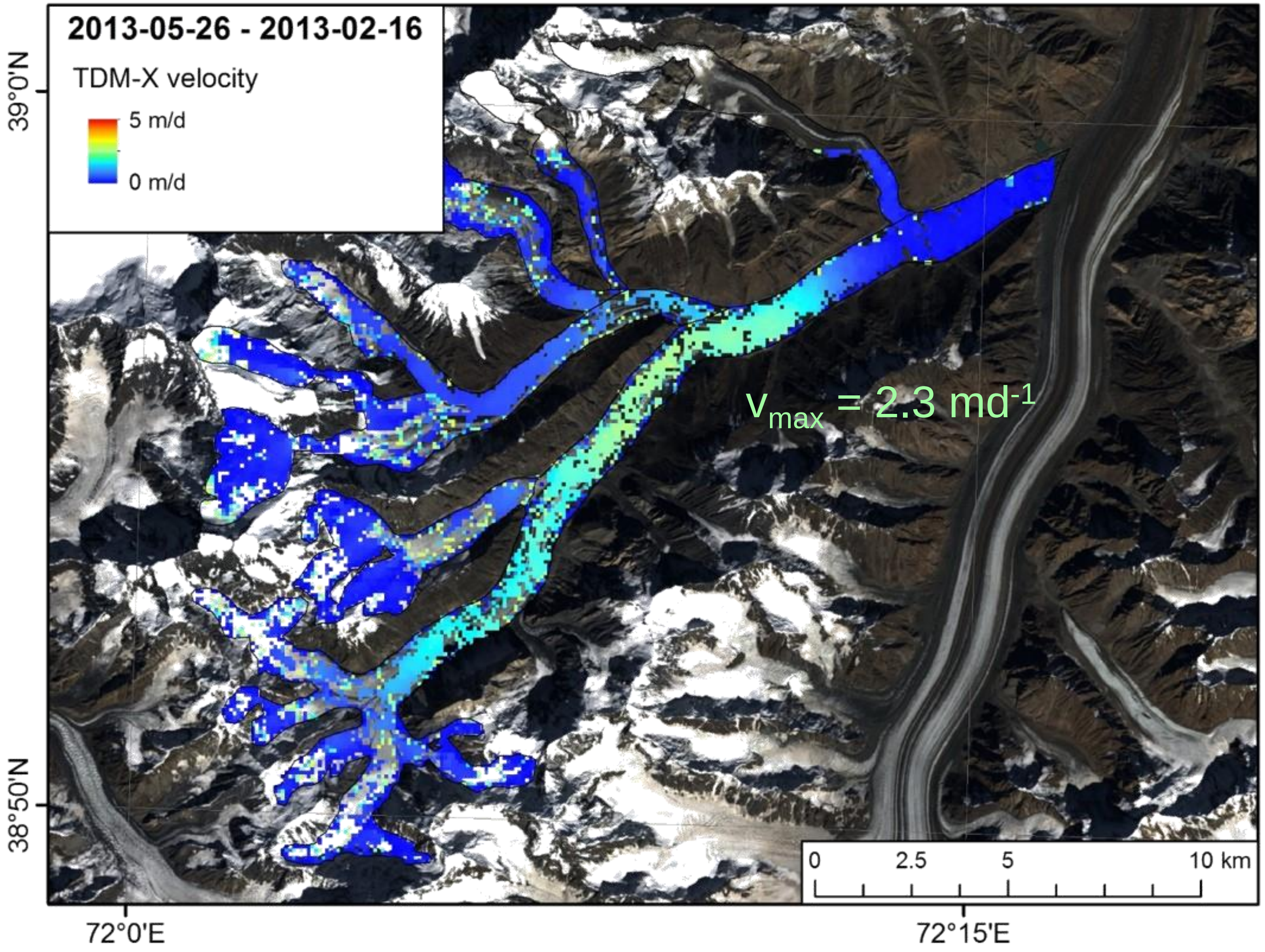
Annual flow velocities 2011/2012

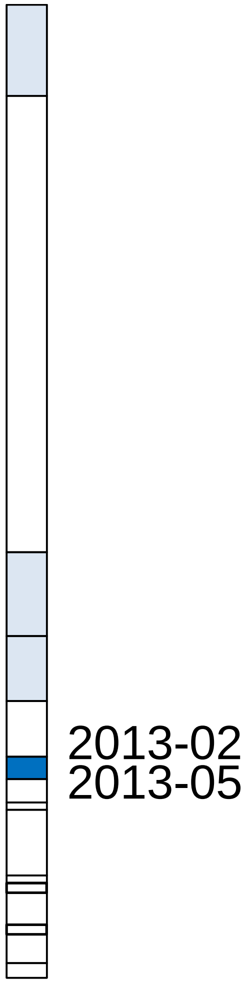


2011-07

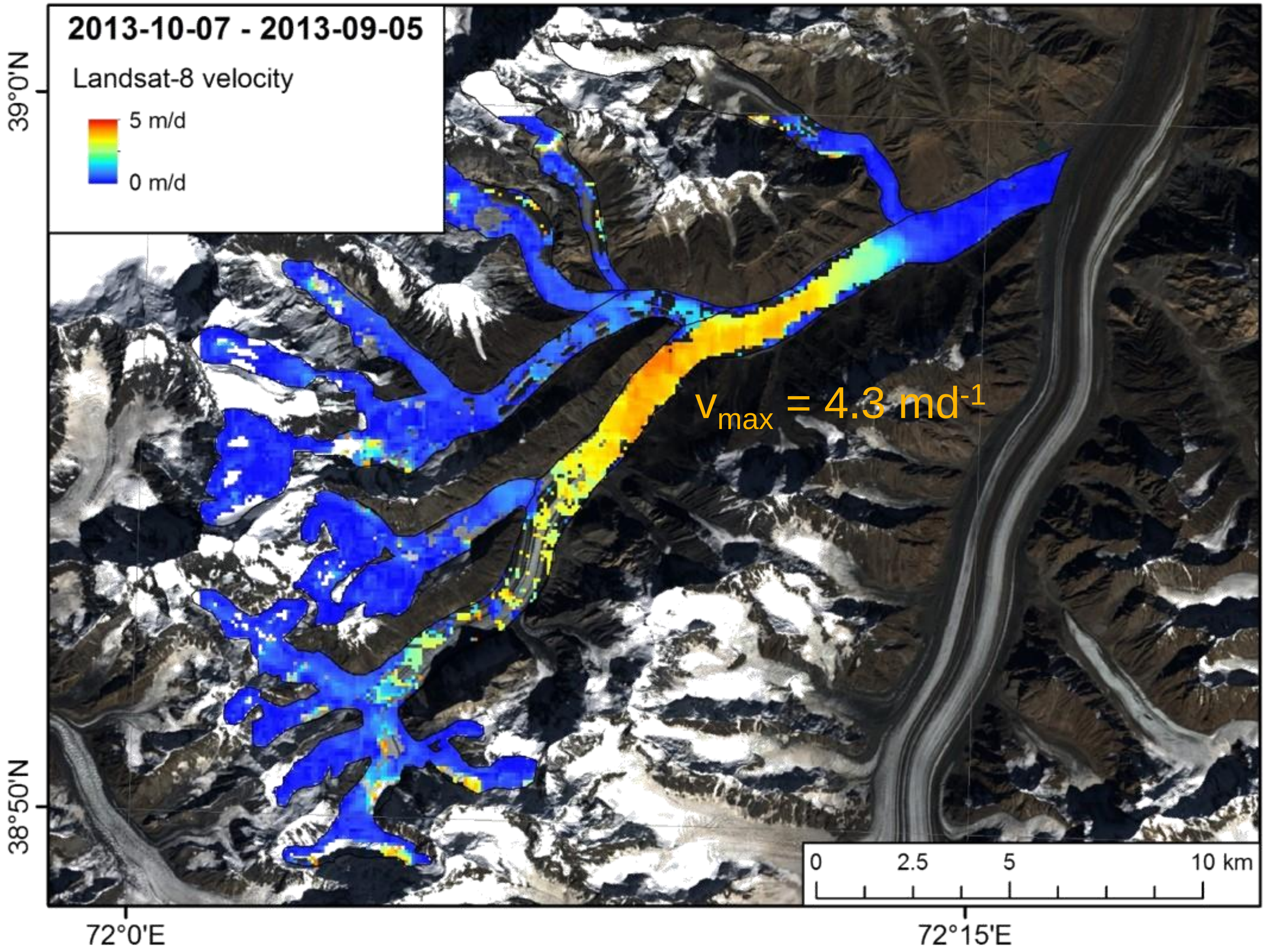
2012-06

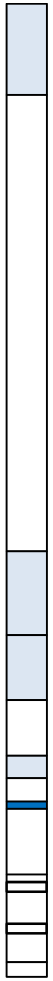
Flow velocities 2013-02/2013-05



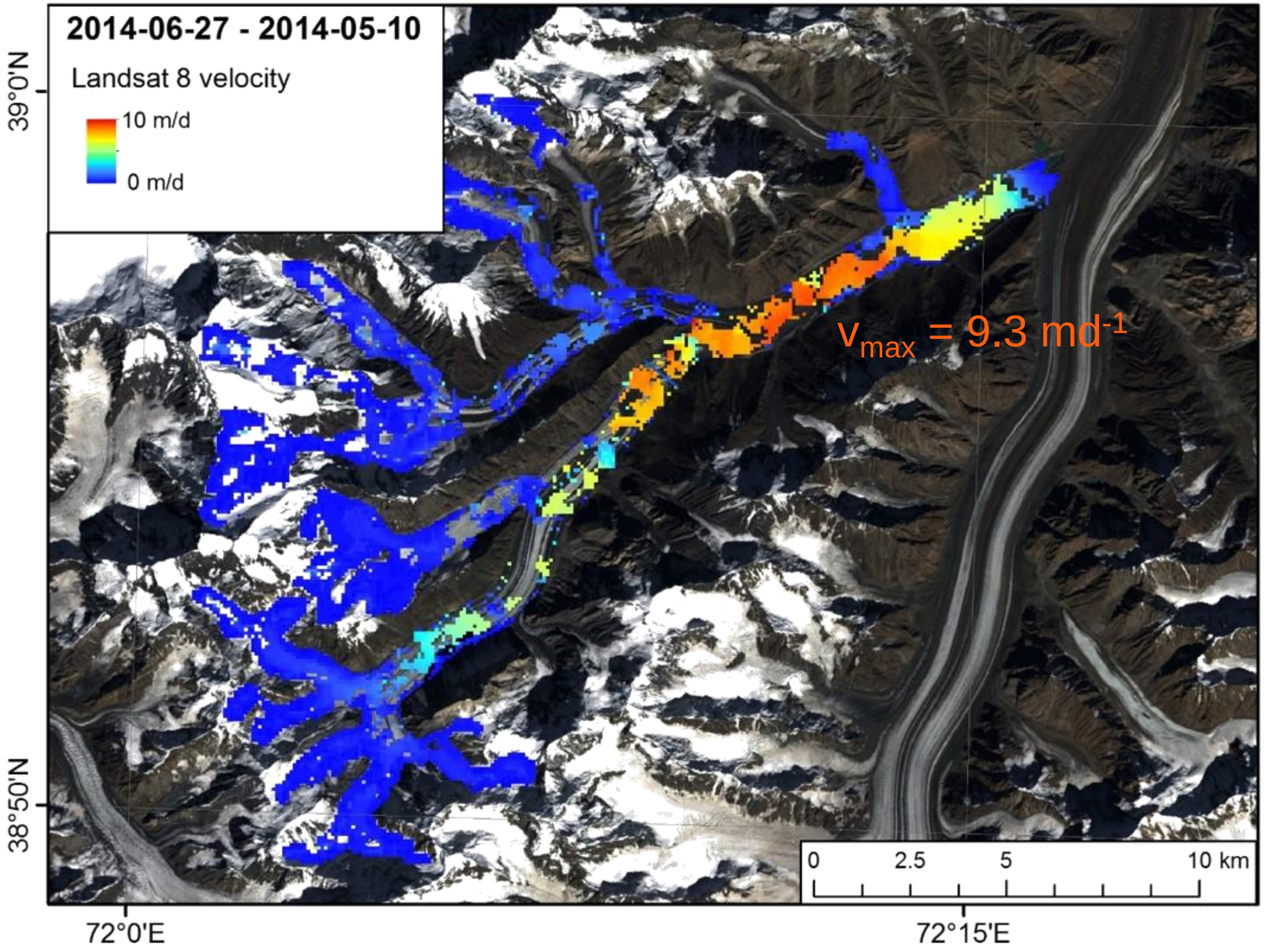


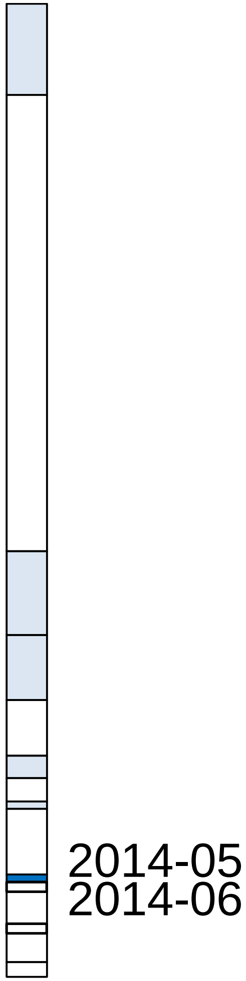
Flow velocities 2013-09/2013-10



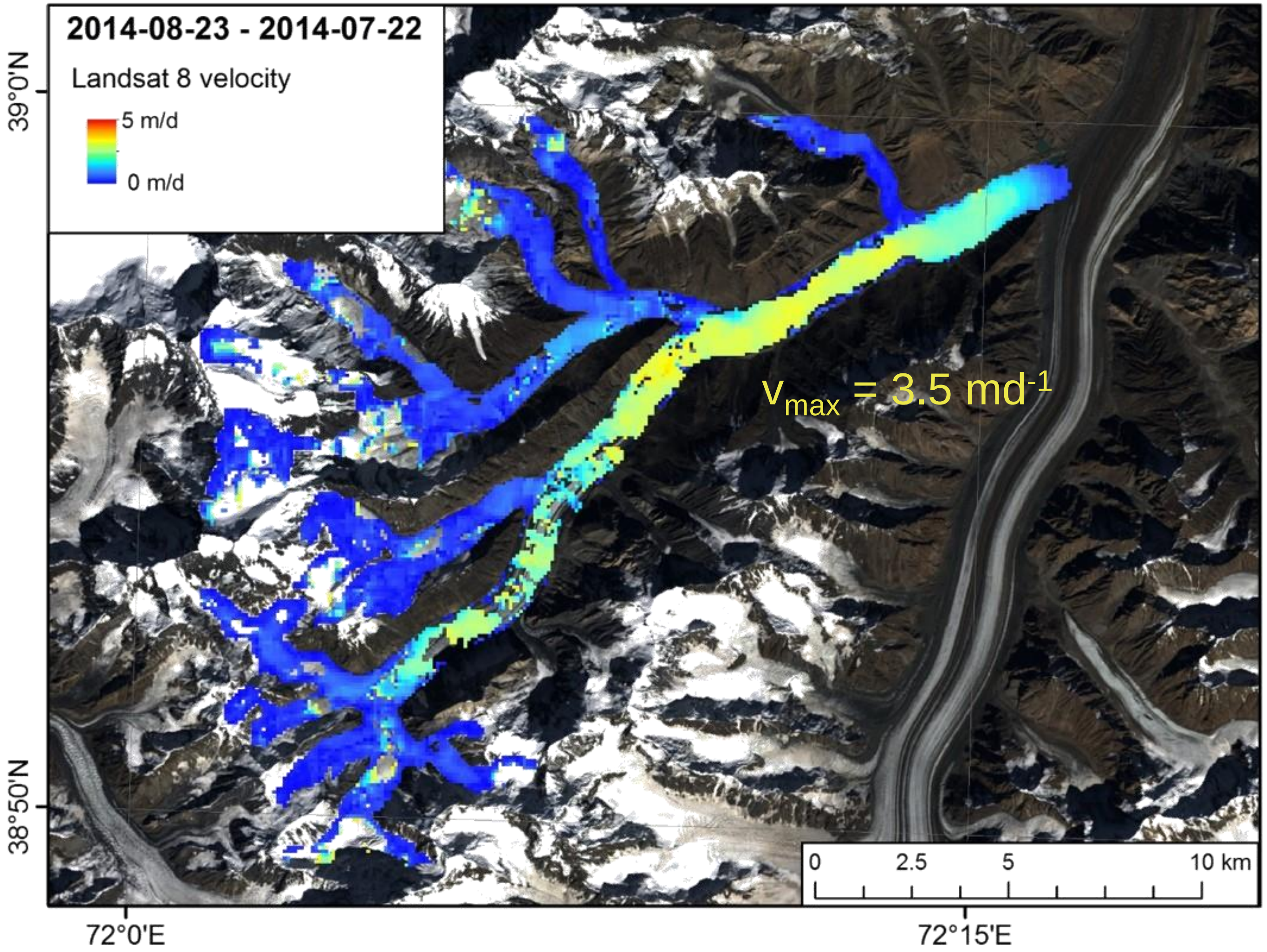


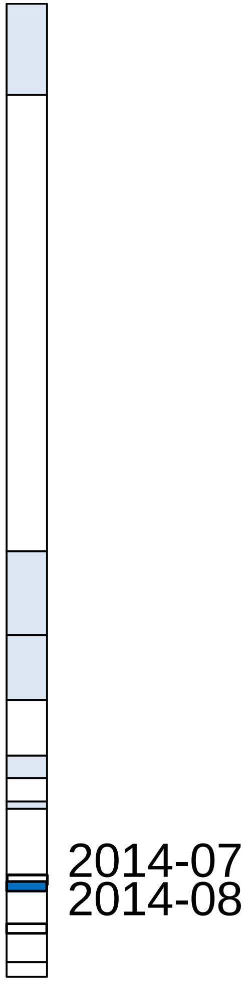
Flow velocities 2014-05/2014-06



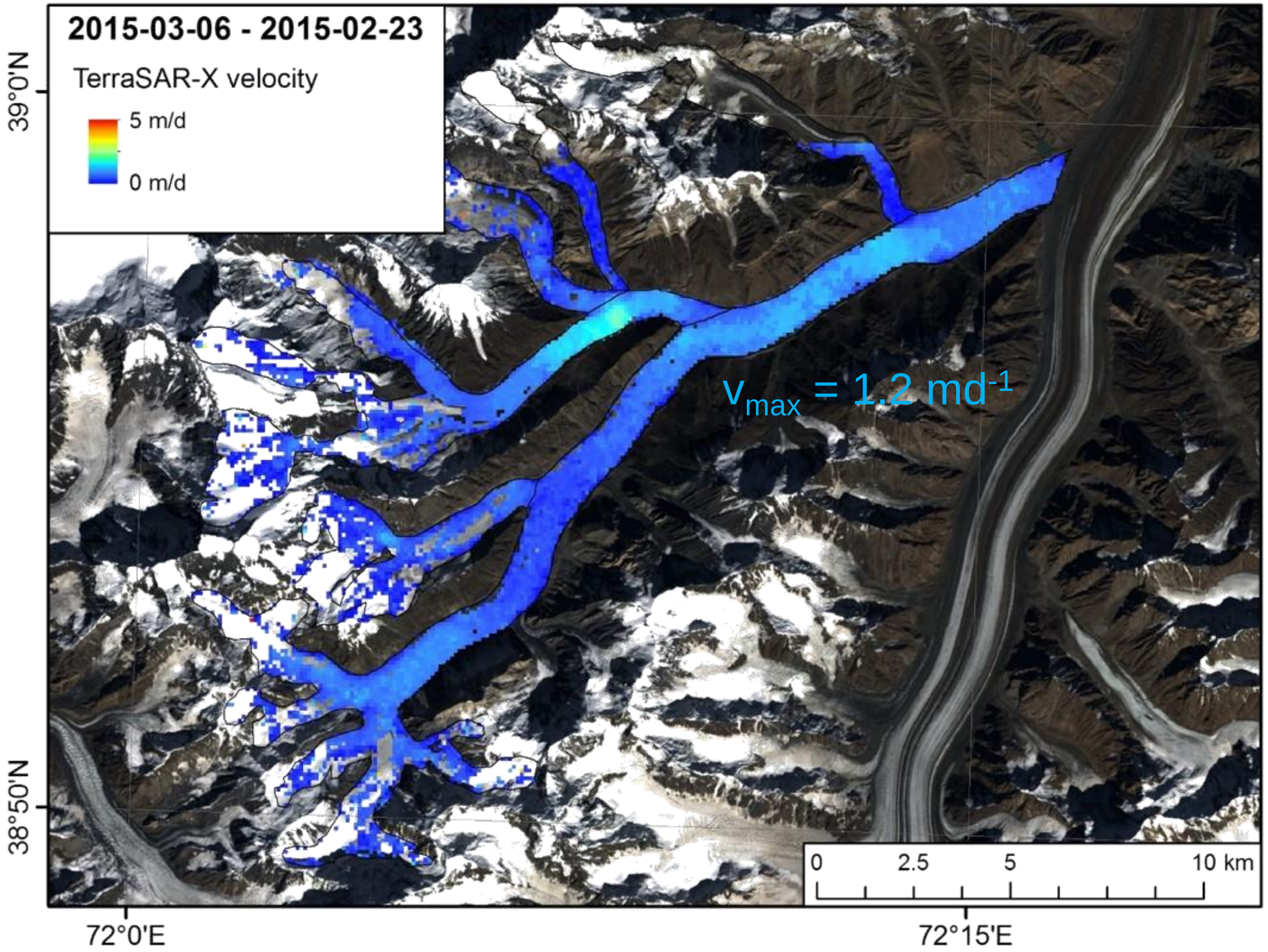


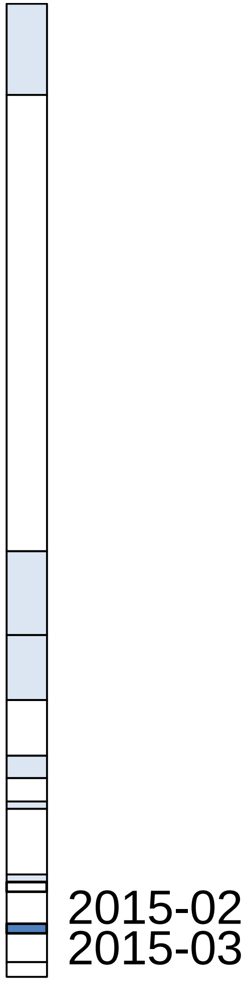
Flow velocities 2014-07/2014-08



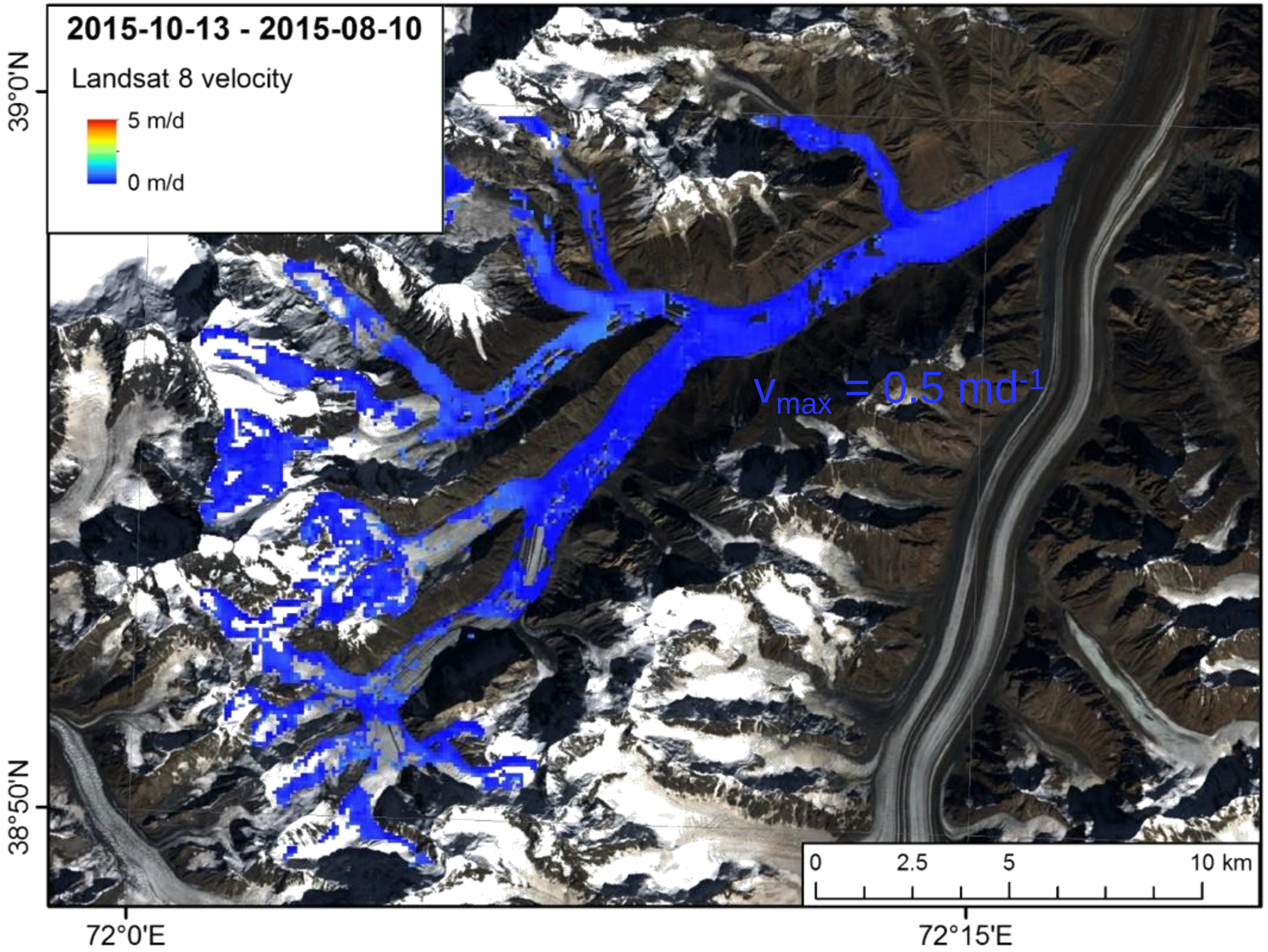


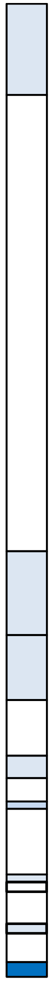
Flow velocities 2015-02/2015-03



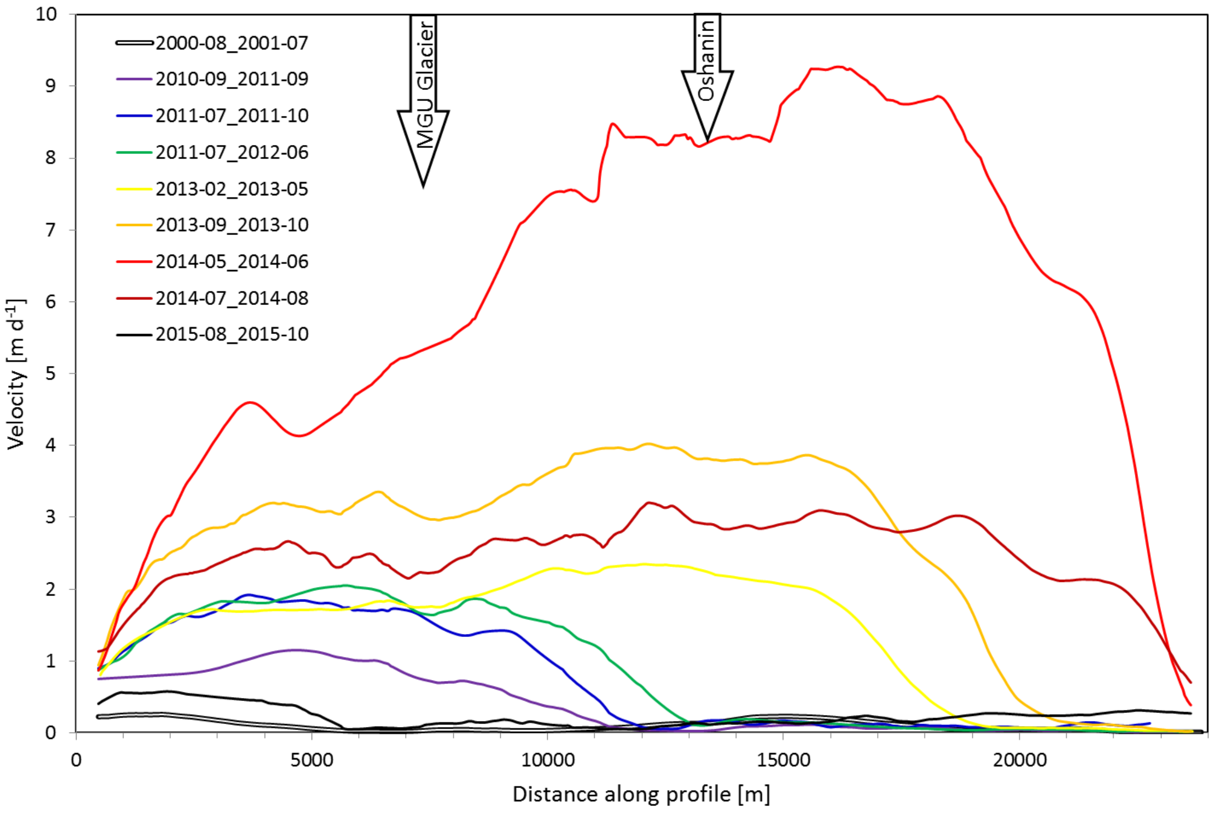


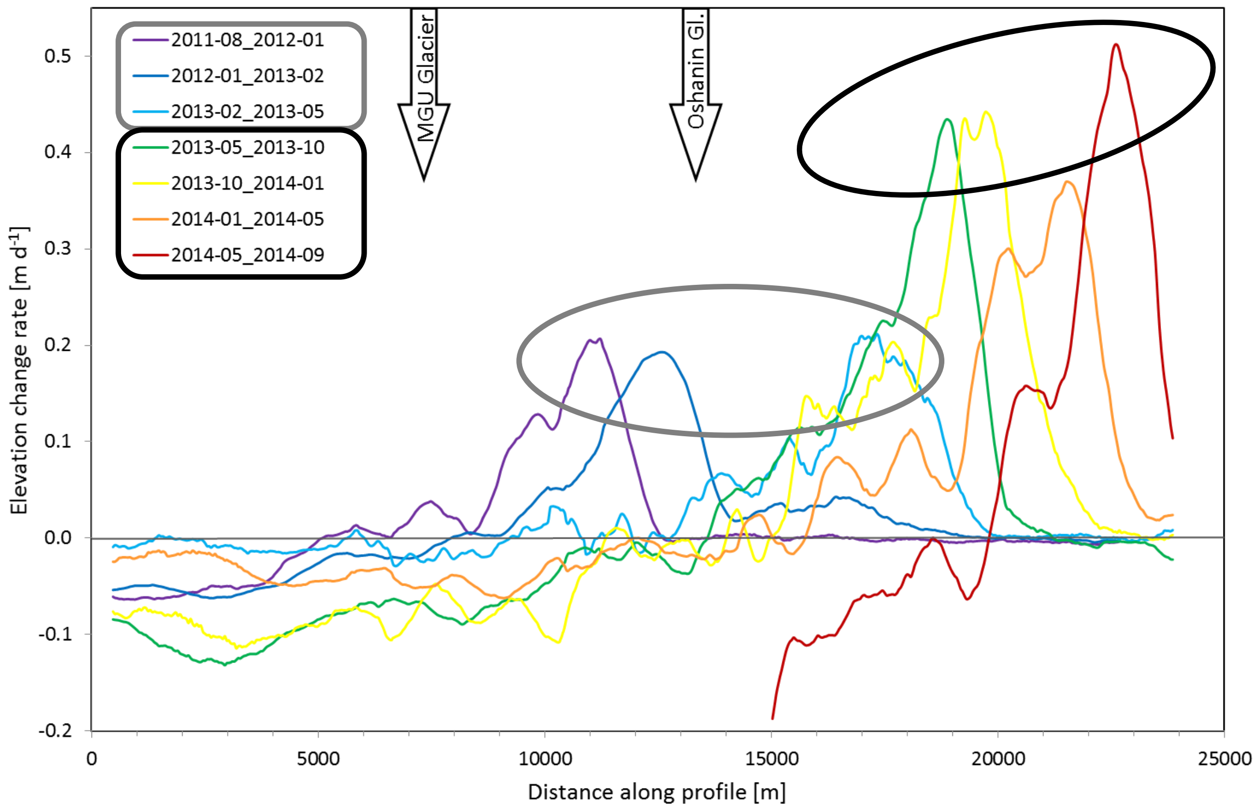
Flow velocities 2015-08/2015-10





Flowline profiles of velocity and elevation





→ Satellite monitoring of elevation and velocity changes in high temporal resolution

BAdW

Summary

- Glaciers are subject to unprecedented changes due to climate change but can also show quick changes due to dynamic processes.
- Long-term observations are important to document trends.
- Satellite observations offer the opportunity to observe glaciers in remote areas and also globally.
- Field measurements stay important for validating satellite data.