

Pan-arctic glacier volume change 1975-2019

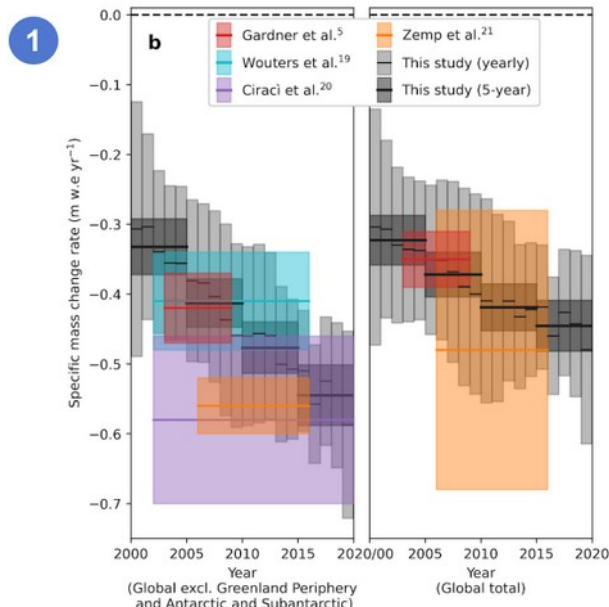
Amaury Dehecq^{1,2,3}, Alex Gardner⁴, Romain Hugonnet^{2,3,5}, Erik Mannerfelt^{2,3}, Joaquin M.C. Belart^{6,7}

1. Institut des Geosciences de l'Environnement (IGE), Université Grenoble Alpes, IRD, Grenoble, France
2. Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, Switzerland
3. Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland
4. NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
5. LEGOS, Université de Toulouse, CNES, CNRS, IRD, UPS, F-31400 Toulouse, France
6. National Land Survey of Iceland, Akranes, Iceland
7. Institute of Earth Sciences, University of Iceland, Reykjavík, Iceland

I. Introduction - Context

- 1 Over the past few years, the number of observations of global glacier volume changes has increased drastically! (Gardner et al., 2013; Wouters et al. 2019; Zemp et al., 2019; Ciraci et al., 2020; Hugonnet et al., 2021)
- 2 However, prior to 2000, observations are limited to a few hundred in situ observations (Zemp et al., 2019) or scattered local geodetic mass balance (Maurer et al., 2019; Girod et al., 2018; Belart et al. 2019 and many others...)

⇒ We need more consistent, global DEMs of glaciers prior to 2000.



Hugonnet et al. (2021)

2

Extended Data Table 1 | Overview of new geodetic volume changes

Region	DEMs used	SP
Alaska	ASTER, ArcticDEM, IPY-Spirit	2000–17
Greenland	TanDEM-X, AeroDEM	1985–12
Iceland	ASTER, ArcticDEM, IPY-Spirit	2000–17
Svalbard	ASTER, ArcticDEM, IPY-Spirit	2000–17
Scandinavia	ASTER, ArcticDEM	2000–17
Russian Arctic	ASTER, ArcticDEM, IPY-Spirit	2000–17
Caucasus	ASTER	2000–17
Africa	ASTER	2000–17
Central Asia	ASTER, HMA DEMs	2000–17
New Zealand	ASTER	2000–18

Zemp et al. (2019)

Extended Data Table 2 | Spatial clusters used to analyse temporal variability from glaciological samples

Cluster	1 st and 2 nd order regions	N
C01: Alaska & British Columbia	ALA, WNA-02	19
C02: Western Canada	WNA-01, WNA-03	3
C03: Western USA	WNA-04, WNA-05	24
C04: Canadian Arctic	ACN, ACS	10
C05: Greenland	GRL	8
C06: Iceland	ISL	14
C07: Svalbard & Russian Arctic	SJM, RUA	17
C08: Scandinavia North	SCA-01	17
C09: Scandinavia South-West	SCA-02	17
C10: Scandinavia South-East	SCA-03	6
C11: Northern Asia	ASN-01-03,-05-06	10
C12: Russian Altay	ASN-04	4
C13: Central Europe	CEU	59
C14: Caucasus	CAU	11
C15: Central Asia South-West	ASW, ASC-01-03,-05	25
C16: Central Asia South-East	ASE, ASC-04,-06-09	22
C17: Low Latitudes	TRP-01	11
C18: Southern Andes	SAN	12
C19: New Zealand	NZL	6
C20: Antarctic & Subantarctic	ANT	10

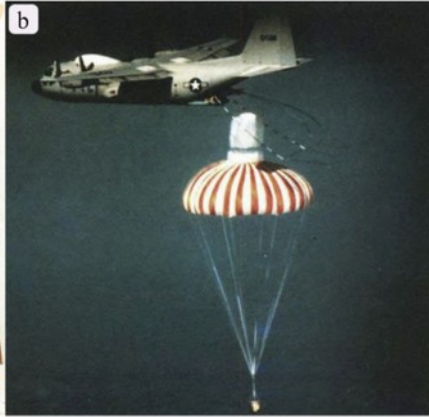
II. Data - Hexagon (KH-9) satellite images

The declassified American reconnaissance satellite program **Hexagon (KH-9)** at a glance:

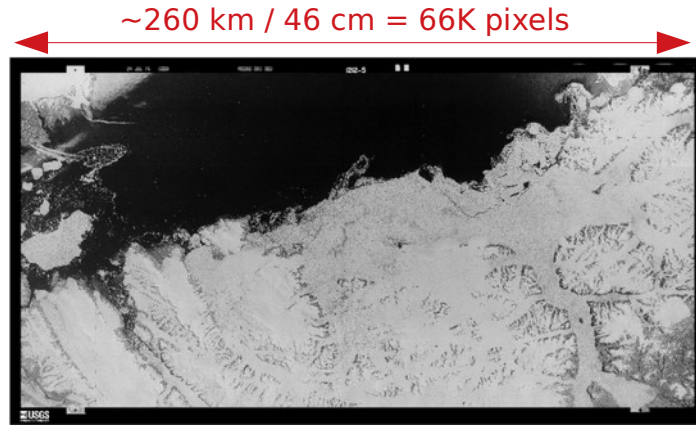
- Period: 1973-1986 – 20 satellites/missions
- Main payload : 2 panoramic cameras - 0.6 m resolution → currently only available over US
- 12/20 missions included a frame **mapping camera (MC)** - 6-9 m resolution → focus of this study
- Photos printed on film → 4 re-entry capsules ("buckets") snatched mid-air



KH-9 vehicle



Aerial recovery of the film
Maurer et al. (2015)



Example of a KH-9 MC film (46 x 23 cm²)
over the Canadian Arctic

More info:

- *Burnett et al. (2012)*
- *Surazakov & Aizen(2010)*
- *Maurer et al. (2015)*

Challenges:

- Large (~ 2 GB) images scanned in **2 pieces** + **film distortion** → heavy preprocessing
- Images **crudely geolocated**, no ground control points available
- Satellite position + lens characteristics poorly known or classified

II. Data - KH-9 DEMs

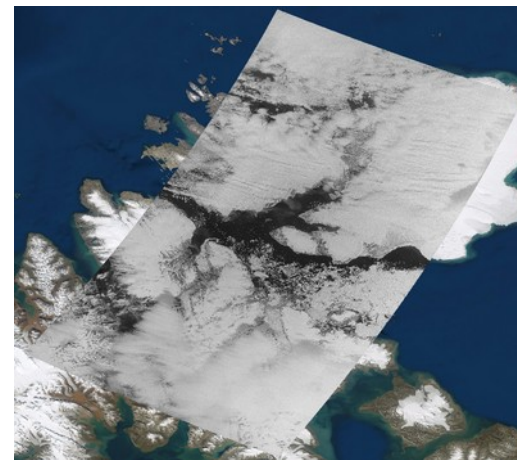
DEMs generated from ~250 KH-9 images - Period 1974-1980 - 24 m resolution
using methodology of [Dehecq et al. \(2020\)](#)

KH-9 images coverage



Extensive coverage of Arctic glaciers, but...

- Many images are extremely cloudy or have fresh snow/saturation
- Thus, most areas have at most one “good” acquisition
- The Greenland ice sheet/periphery is not covered



Roughly geolocated KH-9 image over Svalbard featuring clouds and saturation

II. Data - 2019 DEMs

DEMs generated from interpolation of ASTER/ArcticDEM time series - date 01/09/2019 - 100 m res

From [Hugonnet et al. \(2021\)](#) (Published April 28 at 16:00 London time)

2019 DEM coverage (gray hillshade)



- Nearly complete coverage of Arctic glaciers
- Unique acquisition date
- Not biased by radar penetration

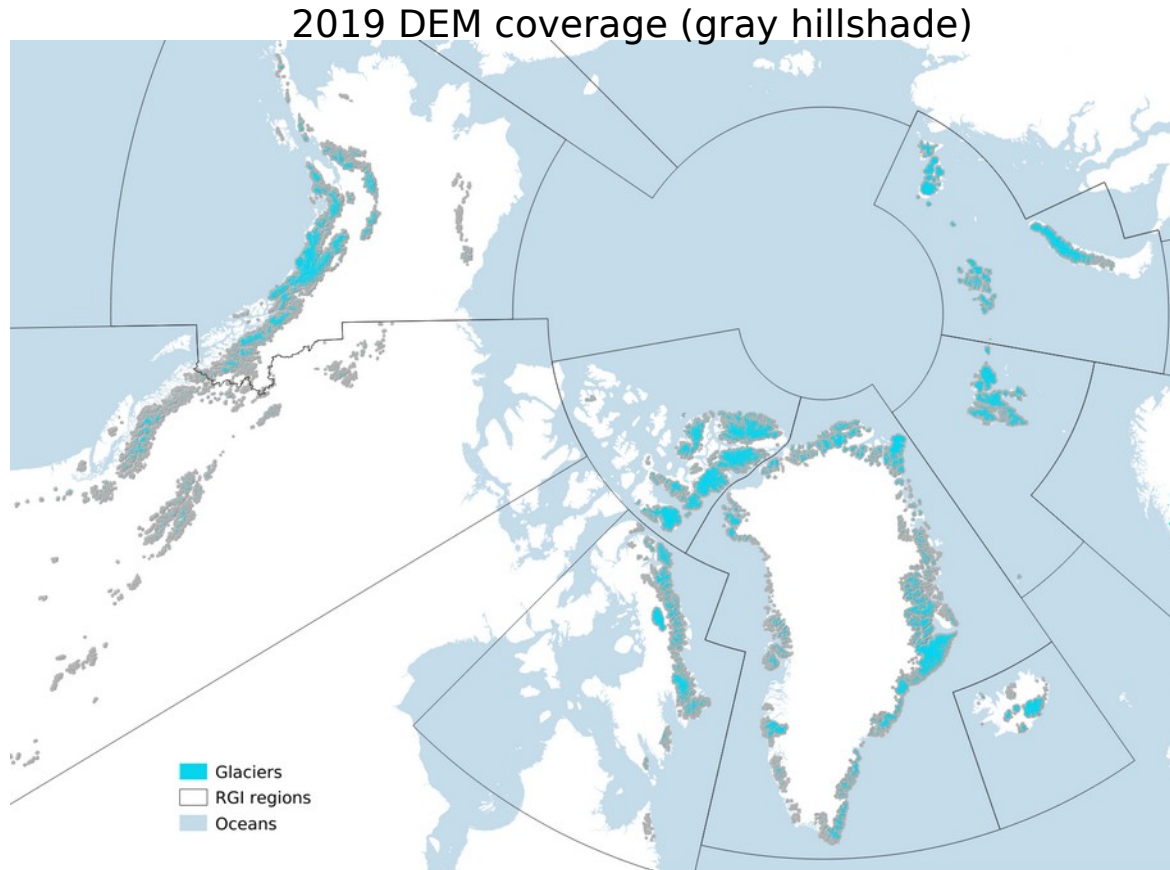


Zoom over N. Ellesmere Island, Canada

II. Data - 2019 DEMs

DEMs generated from interpolation of ASTER/ArcticDEM time series - date 01/09/2019 - 100 m res

From [Hugonnet et al. \(2021\)](#) (Published yesterday in Nature!)



Note on the choice of the date:

The end date was chosen to match the period of Hugonnet et al. (2021), which is 01/01/2000 - 31/12/2019.

It would be more interesting to have a DEM for year 2000, to be able to provide two independent estimates: 1975-2000 and 2000-2019, but the DEM time series is poorly constrained in 2000 (few ASTER DEMs, no ArcticDEM).

Thus the idea is to subtract the 2000-2019 estimates from the 1975-2019 estimates to get a 1975-2000 estimate.

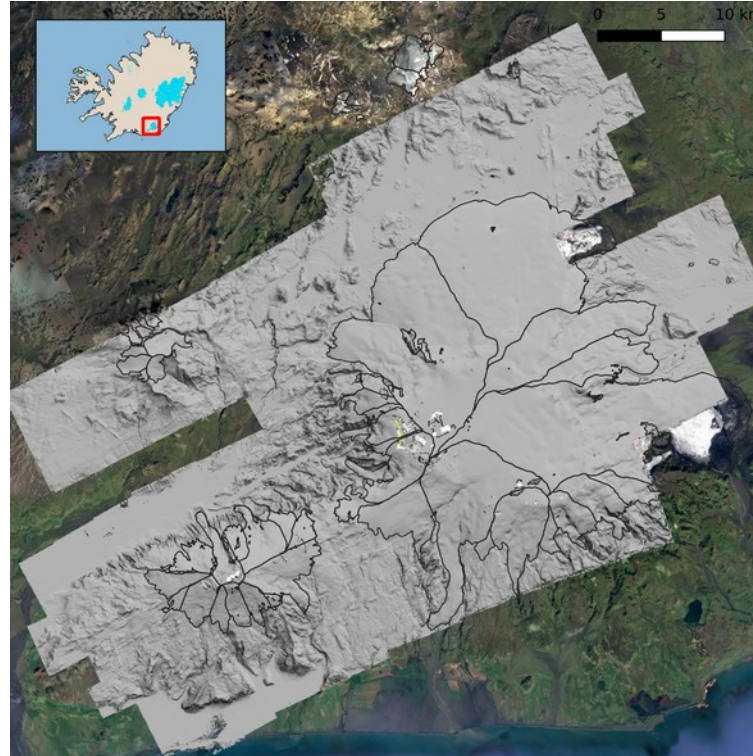
Other suggestions welcome!



II. Data - Icelandic aerial DEM

DEM on Icelandic Myrdalsjökull ice cap, from aerial images
acquired on 28/07/1980, < 1 month apart from KH-9 acquisitions

From [Belart et al. \(2019\)](#)



II. Methods - Overview

Largely following standard methods for geodetic mass balance calculation:

- Calculate elevation difference $dh = h_{2019} - h_{KH9}$
- Convert to elevation change rate $dhdt$ (m/yr) using individual KH-9 acquisition date
- Calculate median $dhdt$ in each pixel, from the multiple stereo pairs
- Filter outliers
- Fill gaps
- Integrate elevation changes over glacier area (currently using RGI outlines), to estimate volume change
- Volume to mass conversion using the *magic* number of 850 kg/m³ ([Huss et al. 2013](#)).

Hopefully Matthias will be able to tell us how to do better in his [EGU presentation!](#) Similar work also under way with JPL's mass balance model GEMB.

Figures to come on the following slides...

II. Methods - Outlier filtering

Issue: A large number of outliers are present in the elevation data due to mismatches, presence of clouds or low image contrast. These are/will be filtered using several steps:

- **Low coherence threshold** - Done

During stereo processing, image matching is performed both ways (“left” to “right”, “right” to “left”) and pixels where the two results disagree are discarded → removes most blunders in areas of low contrast (Dehecq et al. (2020))

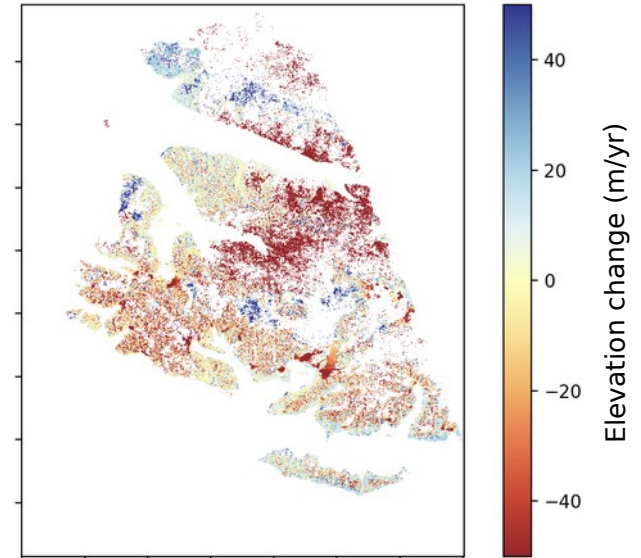
- **Elevation range filtering** - Done

Pixels where $\text{abs}(\text{dh}) > 1000$ m are removed. Some marine terminating glaciers such as Columbia thinned more than 800 m !!
But some low elevation clouds can remain...

- **Spatial filtering** - To be implemented

Idea: Filter pixels for which the elevation falls below/above the reference elevation within a given radius, similar to Hugonnet et al. (2021). To be applied for various disk sizes and deviation thresholds.

Other suggestions welcome!



DEM difference (KH-9 - ArcticDEM) over Svalbard for a cloudy scene
(Sorry, didn't have time to make a nice map!)

II. Methods - Gap filling

Issue: Most elevation change maps present large gaps => How to best derive regional mass balance from incomplete observations? Instead of using a single approach, we sequentially apply several methods (see [McNabb et al. 2019](#) for a summary):

- **Inverse Distance Weighting interpolation**

for small gaps (max search distance of 500 m) - using `gdal_fillnodata.py` + removal of extrapolated points

- **Local hypsometric filling**

Missing values are replaced by the mean value of the elevation bin from a single glacier.

For glaciers with > 20 % coverage and minimum of 10 pixels per elevation bin, i.e. 0.1 km² (parameters to be further tested)

- **Local hypsometric extrapolation** - To be implemented

Idea: adjust a glacier hypsometric curve to fit the regional hypsometric curve. Needed for gaps at high elevation.

- **Regional hypsometric filling**

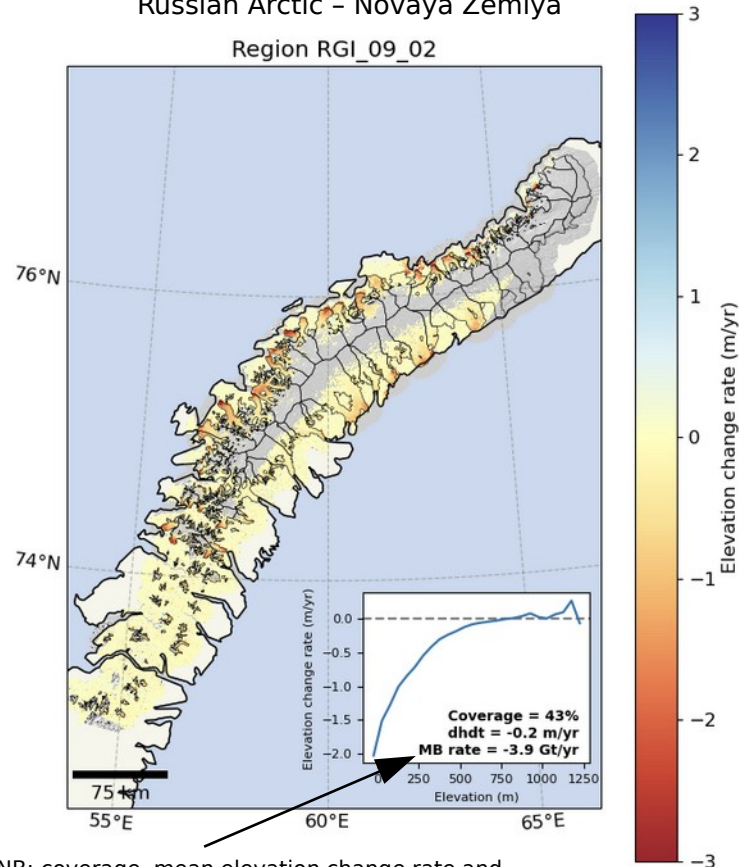
Missing values are replaced by the mean value of the elevation bin from all glaciers in the region.

For remaining glaciers with little/no observation.

Raw elevation change map

Russian Arctic - Novaya Zemlya

Region RGI_09_02



NB: coverage, mean elevation change rate and regional mass balance displayed for each case

II. Methods - Gap filling

Issue: Most elevation change maps present large gaps => How to best derive a regional mass balance from incomplete observations? Instead of using a single approach, we sequentially apply several methods (see [McNabb et al. 2019](#) for a summary):

- **Inverse Distance Weighting (IDW) interpolation**

for small gaps (max search distance of 500 m) – using `gdal_fillnodata.py` + removal of extrapolated points

- **Local hypsometric filling**

Missing values are replaced by the mean value of the elevation bin from a single glacier.

For glaciers with > 20 % coverage and minimum of 10 pixels per elevation bin, i.e. 0.1 km² (parameters to be further tested)

- **Local hypsometric extrapolation** – To be implemented

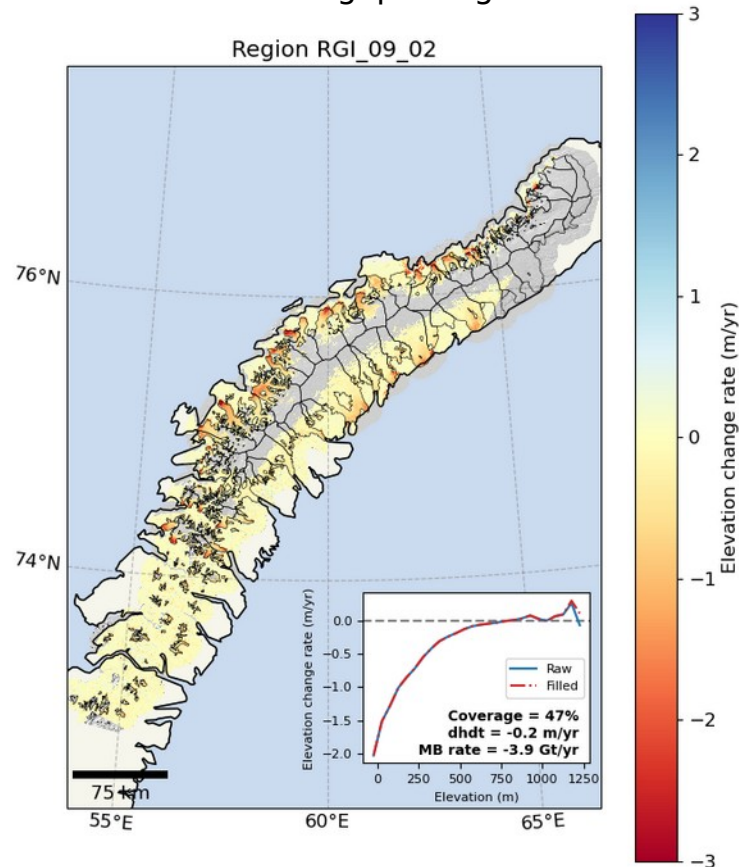
Idea: adjust a glacier hypsometric curve to fit the regional hypsometric curve. Needed for gaps at high elevation.

- **Regional hypsometric filling**

Missing values are replaced by the mean value of the elevation bin from all glaciers in the region.

For remaining glaciers with little/no observation.

After IDW gap filling



II. Methods - Gap filling

Issue: Most elevation change maps present large gaps => How to best derive a regional mass balance from incomplete observations? Instead of using a single approach, we sequentially apply several methods (see [McNabb et al. 2019](#) for a summary):

- **Inverse Distance Weighting (IDW) interpolation**

for small gaps (max search distance of 500 m) – using `gdal_fillnodata.py` + removal of extrapolated points

- **Local hypsometric filling**

Missing values are replaced by the mean value of the elevation bin from a single glacier.

For glaciers with > 20 % coverage and minimum of 10 pixels per elevation bin, i.e. 0.1 km² (parameters to be further tested)

- **Local hypsometric extrapolation** – To be implemented

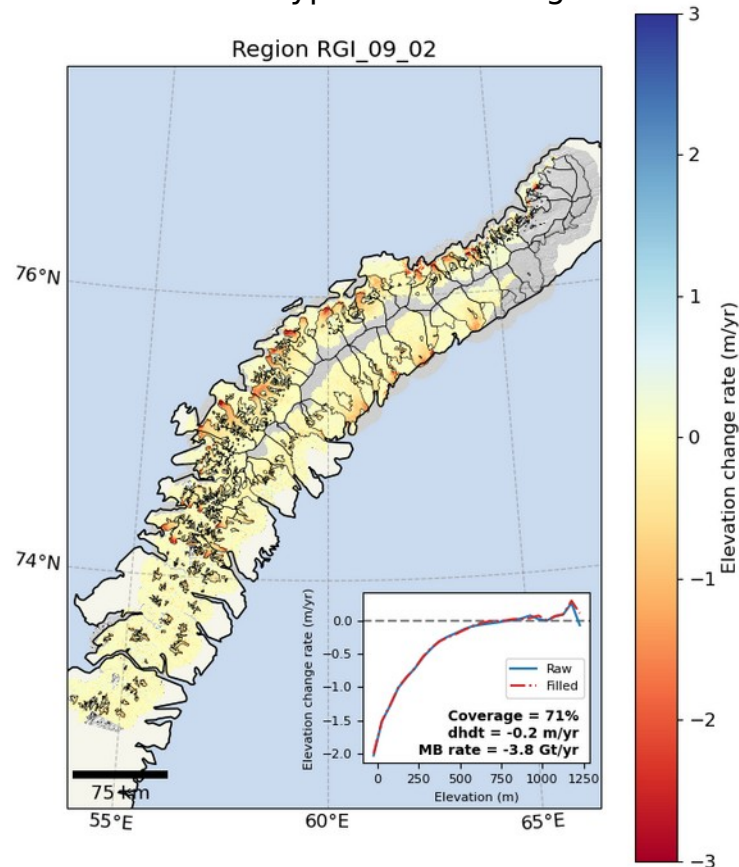
Idea: adjust a glacier hypsometric curve to fit the regional hypsometric curve. Needed for gaps at high elevation.

- **Regional hypsometric filling**

Missing values are replaced by the mean value of the elevation bin from all glaciers in the region.

For remaining glaciers with little/no observation.

After local hypsometric filling



II. Methods - Gap filling

Issue: Most elevation change maps present large gaps => How to best derive a regional mass balance from incomplete observations? Instead of using a single approach, we sequentially apply several methods (see [McNabb et al. 2019](#) for a summary):

- **Inverse Distance Weighting (IDW) interpolation**

for small gaps (max search distance of 500 m) – using `gdal_fillnodata.py` + removal of extrapolated points

- **Local hypsometric filling**

Missing values are replaced by the mean value of the elevation bin from a single glacier.

For glaciers with > 20 % coverage and minimum of 10 pixels per elevation bin, i.e. 0.1 km² (parameters to be further tested)

- **Local hypsometric extrapolation** – To be implemented

Idea: adjust a glacier hypsometric curve to fit the regional hypsometric curve. Needed for gaps at high elevation.

- **Regional hypsometric filling**

Missing values are replaced by the mean value of the elevation bin from all glaciers in the region.

For remaining glaciers with little/no observation.

After local hypsometric filling

To be implemented

II. Methods - Gap filling

Issue: Most elevation change maps present large gaps => How to best derive a regional mass balance from incomplete observations? Instead of using a single approach, we sequentially apply several methods (see [McNabb et al. 2019](#) for a summary):

- **Inverse Distance Weighting (IDW) interpolation**

for small gaps (max search distance of 500 m) – using `gdal_fillnodata.py` + removal of extrapolated points

- **Local hypsometric filling**

Missing values are replaced by the mean value of the elevation bin from a single glacier.

For glaciers with > 20 % coverage and minimum of 10 pixels per elevation bin, i.e. 0.1 km² (parameters to be further tested)

- **Local hypsometric extrapolation** – To be implemented

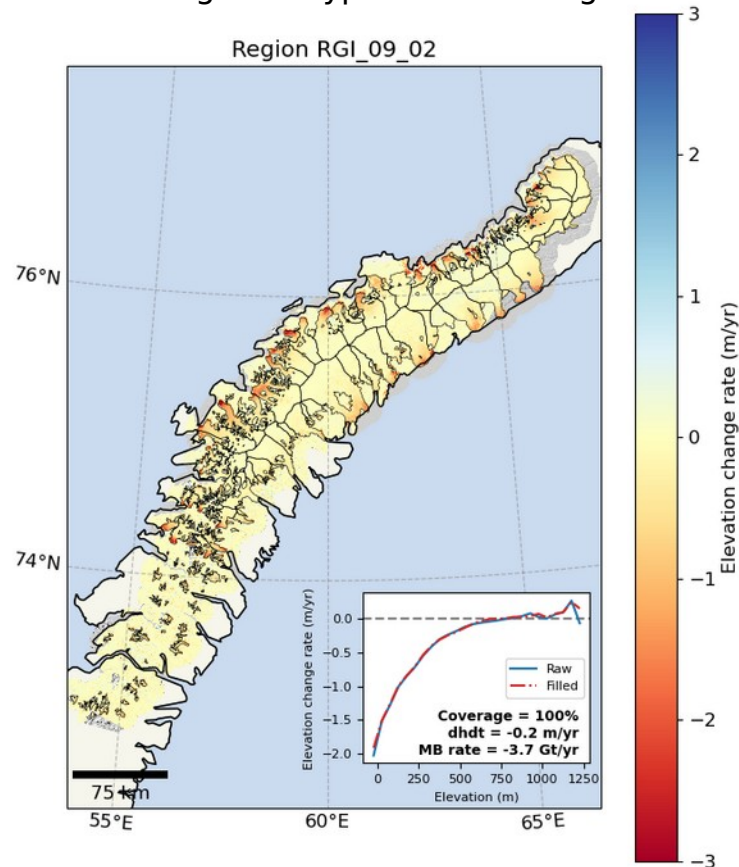
Idea: adjust a glacier hypsometric curve to fit the regional hypsometric curve. Needed for gaps at high elevation.

- **Regional hypsometric filling**

Missing values are replaced by the mean value of the elevation bin from all glaciers in the region.

For remaining glaciers with little/no observation.

After regional hypsometric filling



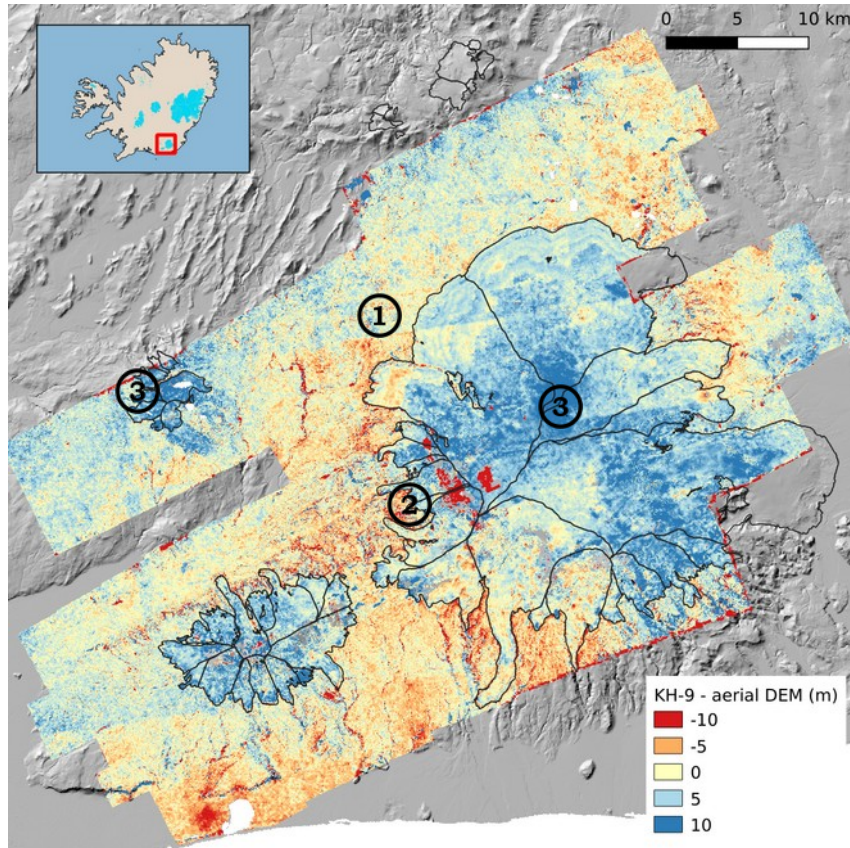
Results



South coast of Alaska - KH-9 image

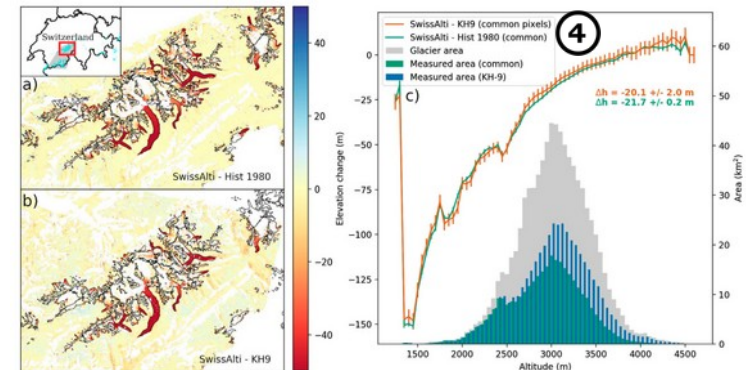
III. Results - Iceland validation

- Comparison of the KH-9 vs aerial DEM acquired in summer 1980 over Myrdalsjökull icecap



- ① Some artifacts (steps) present in KH-9 DEM introduced during scanning and/or preprocessing.
- ② Photogrammetric blunders in aerial DEM.
- ③ Systematic elevation bias of up to 10 m in high altitude => It is still unclear whether the bias are present in the KH-9 DEMs or aerial DEM. This requires further investigation.

- The overall difference is within expected DEMs uncertainty, **i.e. 5-10 m vertically**. Similar comparison in the Alps showed very satisfactory results (see [Dehecq et al., 2020](#) + figure below)
- ④

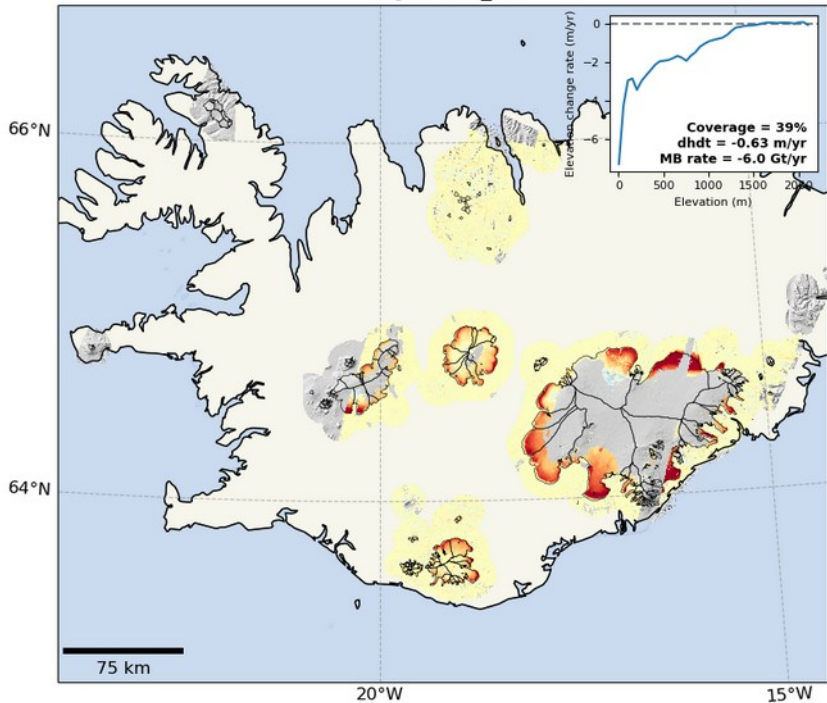


III. Results - Iceland

~1975 - 2019 elevation change rate - preliminary results!

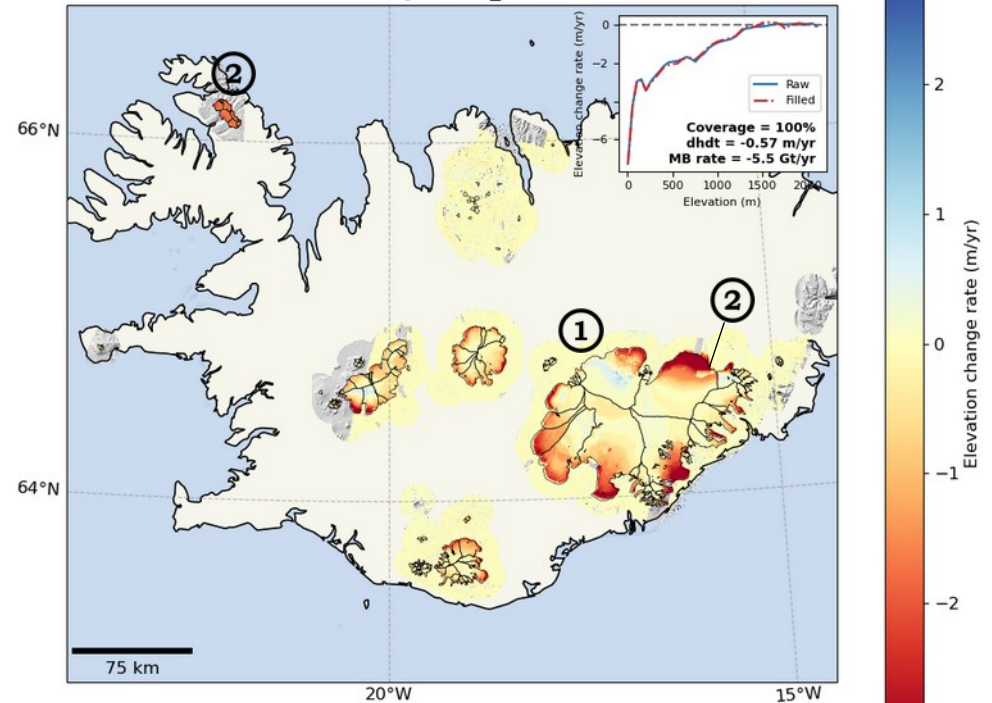
Raw dhdt

Region RGI_06



After gap filling

Region RGI_06



- ① Likely surge of Dyngjökull basin
- ② Interpolation/extrapolation issues...

III. Results - Iceland

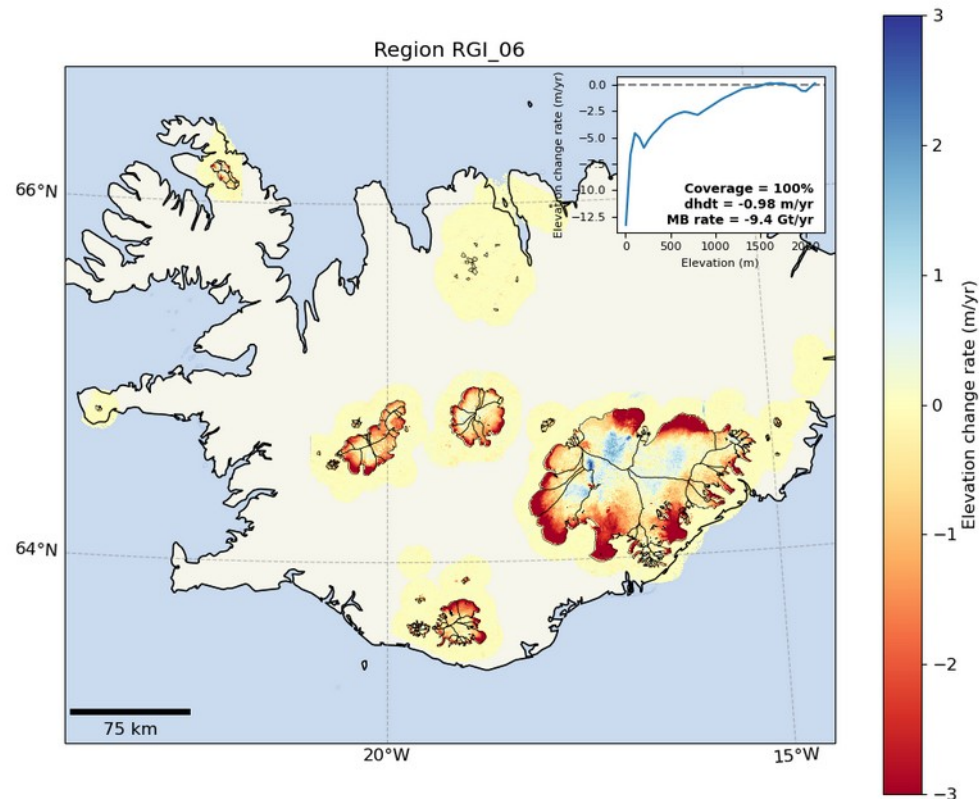
2000 - 2019 elevation change rate - from [Hugonnet et al. \(2021\)](#)

Observations:

- Elevation change patterns are consistent between the two time periods
- Strikingly similar profile with elevation!
- Thinning nearly doubled during 2000-2019 compared to 1975-2019

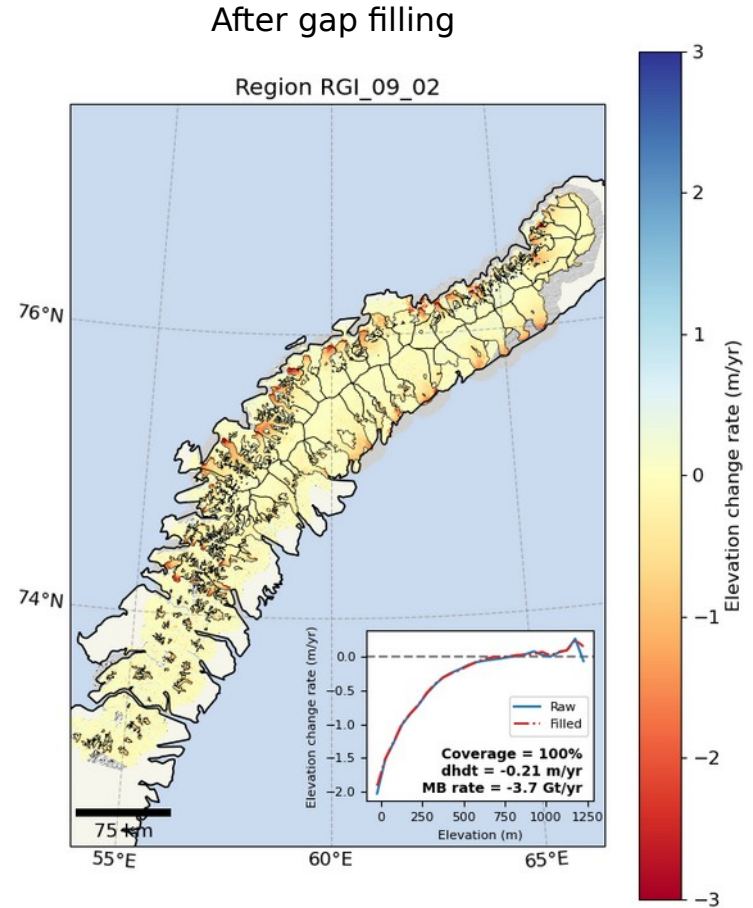
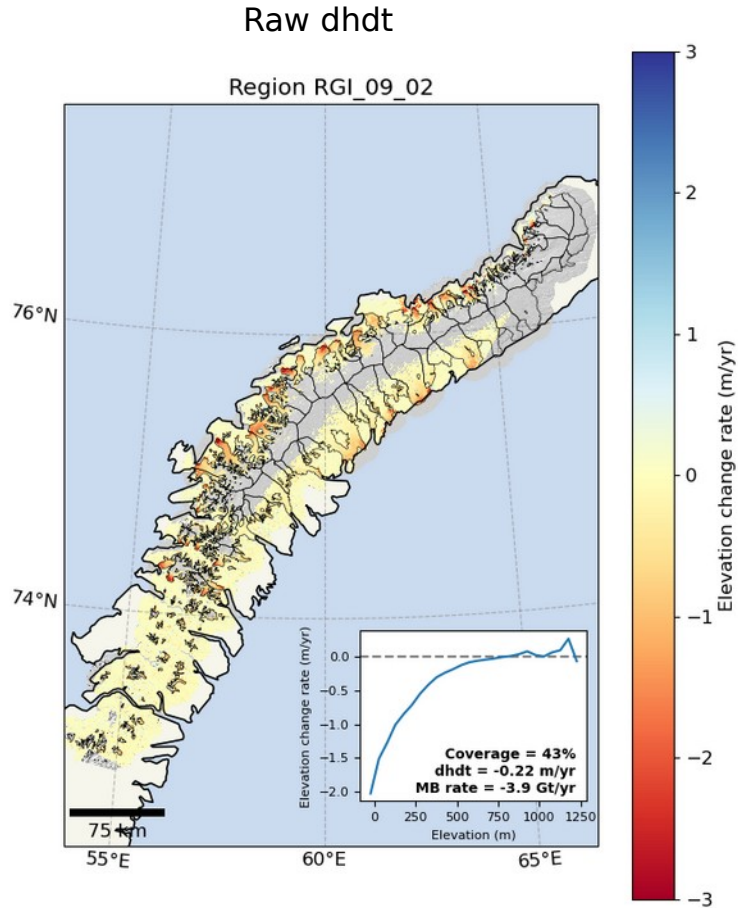


I welcome any validation data set or reference around the period 1974-1980 in all glacier regions!



III. Results - Russian Arctic

~1975 - 2019 elevation change rate - preliminary results!

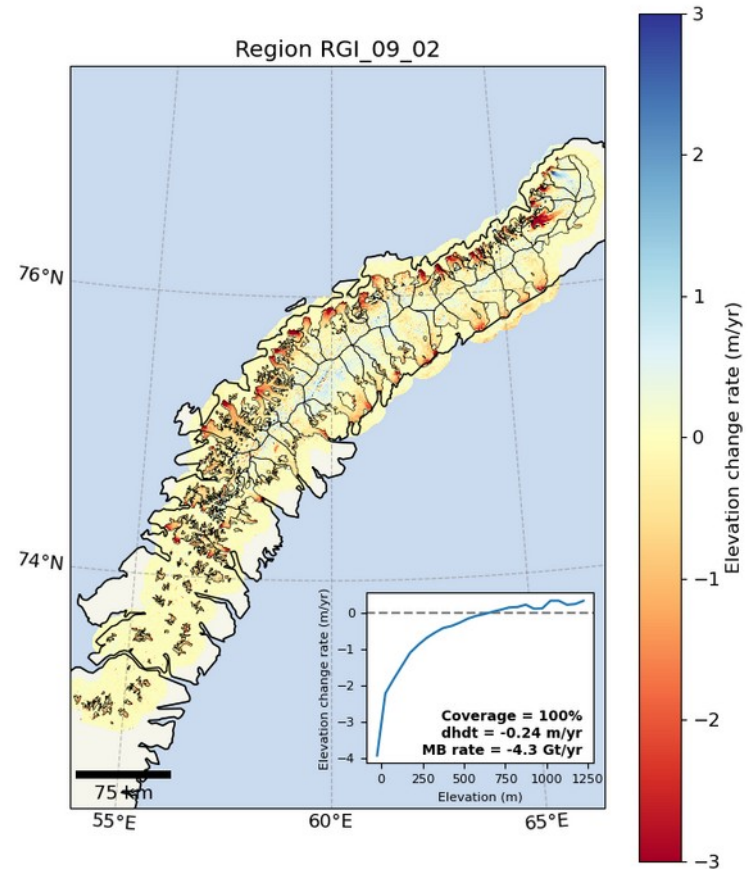


III. Results - Russian artic

2000 - 2019 elevation change rate - from [Hugonnet et al. \(2021\)](#)

Observations:

- Elevation change patterns are consistent between the two time periods
- Stronger (x2) thinning at low elevation for the later period
- Despite this, the average thinning seem to be relatively stable over the two time periods. Thickening in high altitude over 2000-2019?



III. Results - Other regions

For more maps, come chat during the EGU session!

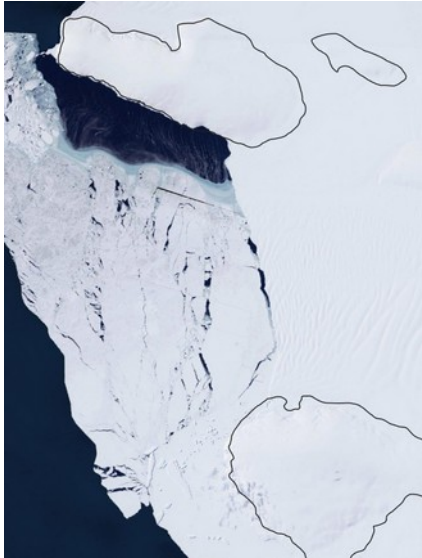
IV. Issues and next steps



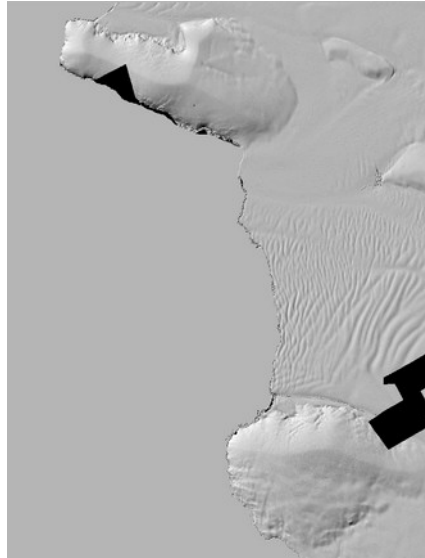
- **DEM coregistration:** how to align the KH-9 DEMs to a reference, when there is no stable terrain to tie to? For scenes covered with glaciers and/or clouds and/or ocean...

Example of the Antarctic periphery

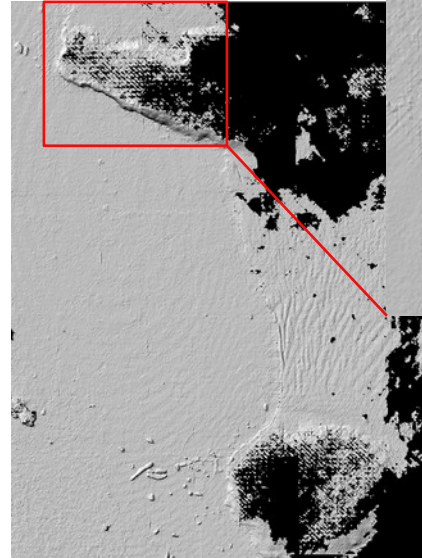
Satellite image



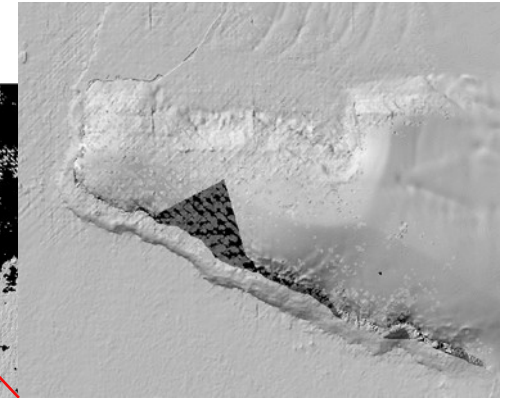
REMA DEM



KH-9 DEM



Both overlaid with transparency

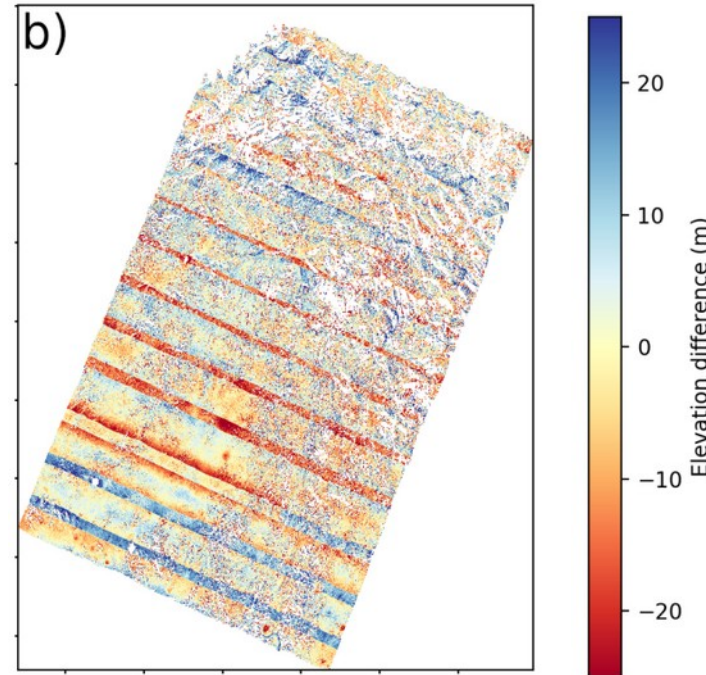


IV. Issues and next steps



- **DEM coregistration:** how to align the KH-9 DEMs to a reference, when there is no stable terrain to tie to? For scenes covered with glaciers and/or clouds and/or ocean...
- **Bias correction:** some KH-9 DEMs are highly affected by scanning artifacts

Elevation difference KH9 - SRTM over High Mountain Asia

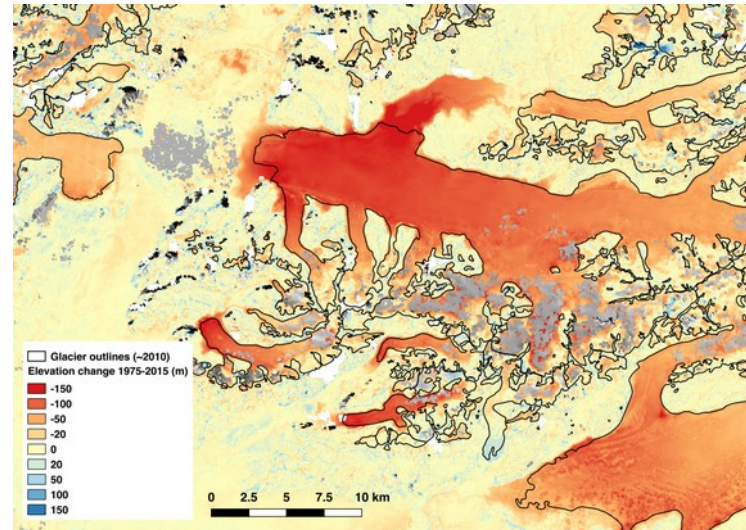


IV. Issues and next steps



- **DEM coregistration:** how to align the KH-9 DEMs to a reference, when there is no stable terrain to tie to? For scenes covered with glaciers and/or clouds and/or ocean...
- **Bias correction:** some KH-9 DEMs are highly affected by scanning artifacts
- **Glacier retreat** since 1975: the mass balance should be calculated on all glacier surfaces, but no global outlines exist for 1975 and many of those retreated until the RGI.

St Elias range, Alaska - KH-9 vs ArcticDEM



IV. Issues and next steps



- **DEM coregistration:** how to align the KH-9 DEMs to a reference, when there is no stable terrain to tie to? For scenes covered with glaciers and/or clouds and/or ocean...
- **Bias correction:** some KH-9 DEMs are highly affected by scanning artifacts
- **Glacier retreat** since 1975: the mass balance should be calculated on all glacier surfaces, but no global outlines exist for 1975 and many of those retreated until the RGI.
- **Time homogeneity:** KH-9 DEMs spans a period of ~ 7 years. The values will be reported for the median date, but the current approach assumes a linear trend over this period.
- **Uncertainty quantification:**
 - pixel-wise elevation uncertainty, regional-wise elevation uncertainty (largely discussed in Dehecq et al. 2020)
 - uncertainty related to data gaps – need to test the sensitivity to the interpolation/extrapolation methods
 - uncertainty related to glacier retreat – how a wrong glacier outline will affect the total mass change?
- **And many more!**

Conclusions

- Using a combination of declassified and modern satellite images, we are able to provide a clear picture of glacier volume changes for most of the Arctic for a > 40 years period.
- Preliminary results show a consistent spatial pattern of glacier thinning, with an expected acceleration of thinning at lower elevations.
- Spy satellites are great... when we find out about them 40 years later!



If you have any feedback, suggestions or ideas, please come chat during the EGU session or send me an email!

amaury.dehecq@univ-grenoble-alpes.fr

