Remote sensing of Svalbard mass balance, 2011-2017

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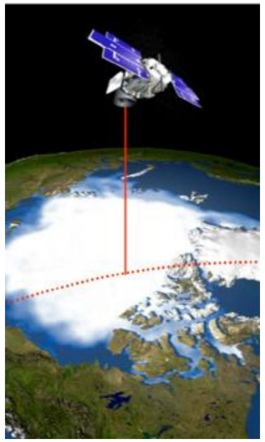
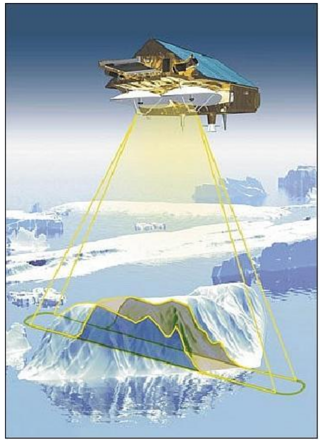
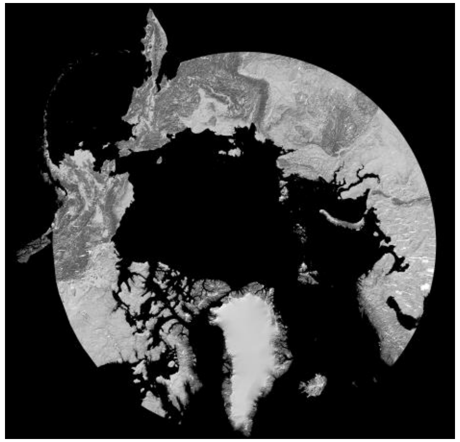
SVALBARD INTEGRATED ARCTIC EARTH OBSERVING SYSTEM

The Research Council of Norway | uOttawa | UiO : Universitetet i Oslo | esa | Norsk Romsenter Norwegian Space Agency | Copernicus Bretjeneste Norge

Remote Sensing Webinar #2
24th April 2020

Photo: Nordenskiöldbreen, Thorben Dunse



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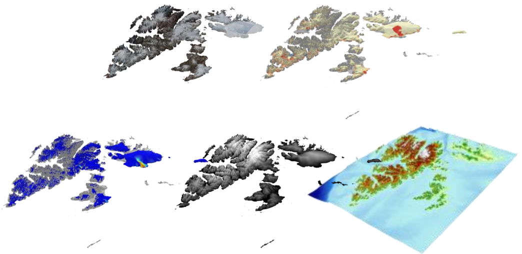

ICESat-1 Laser Altimeter (2003-2009)

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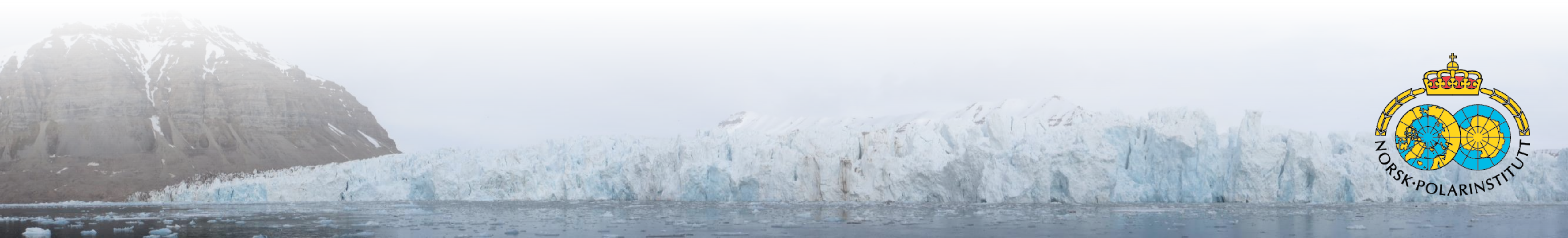
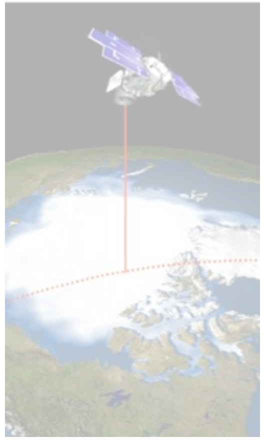
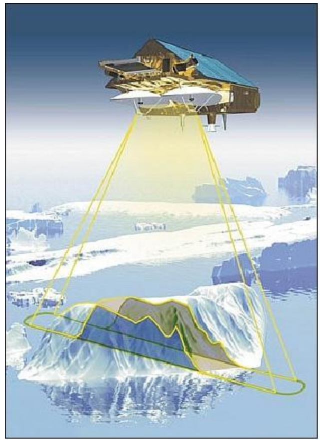
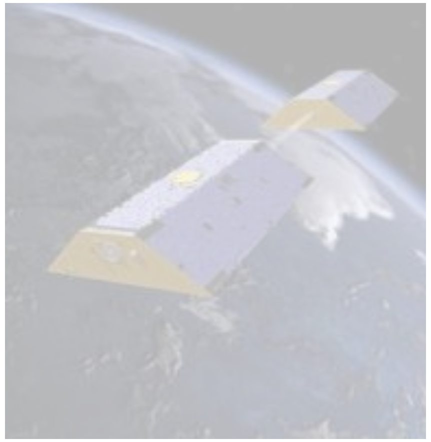
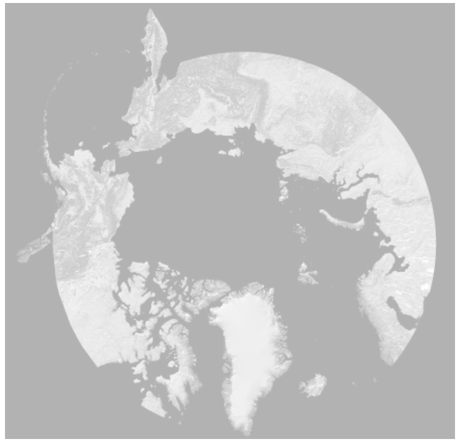
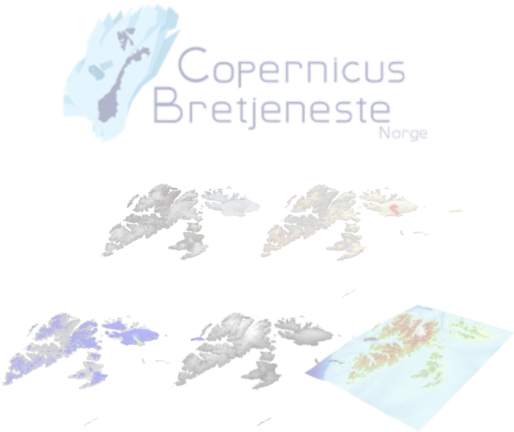
GRACE satellite gravimetry (2002-2017)



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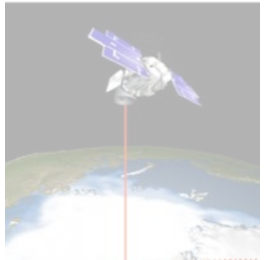

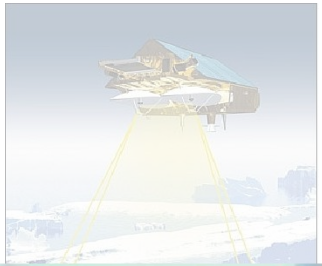

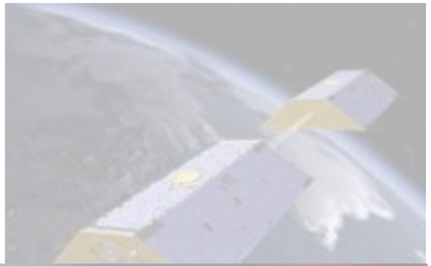

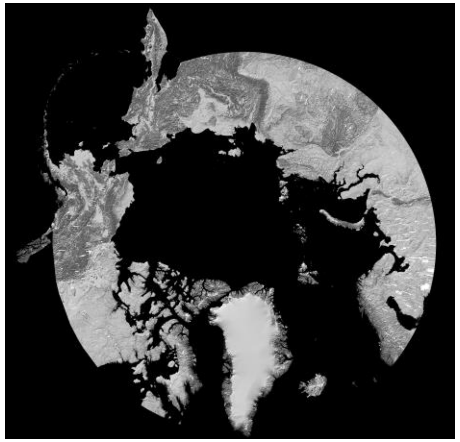

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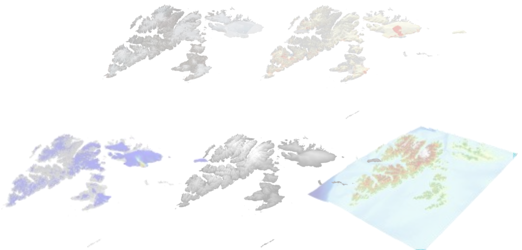

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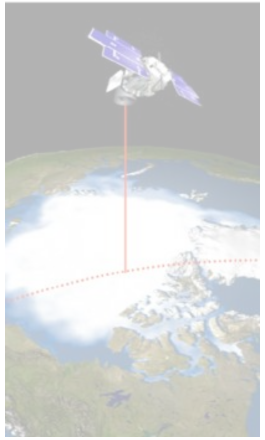
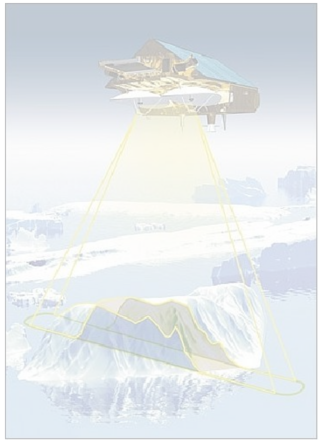
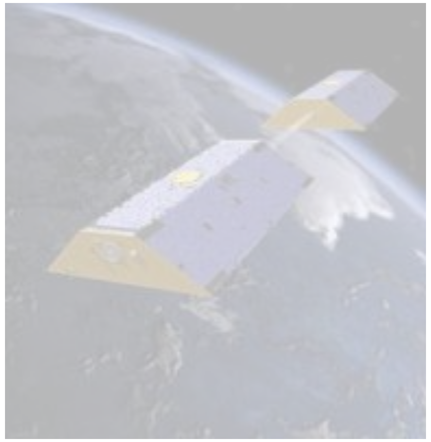
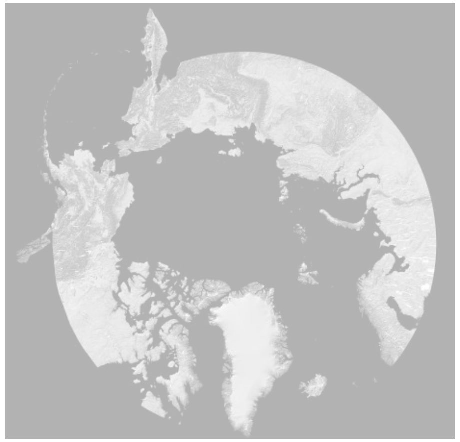

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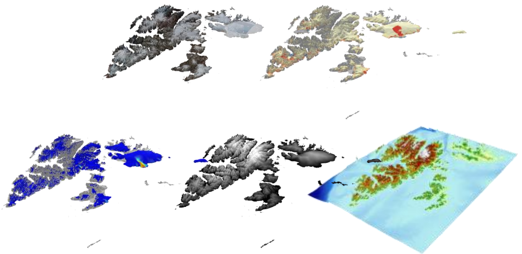

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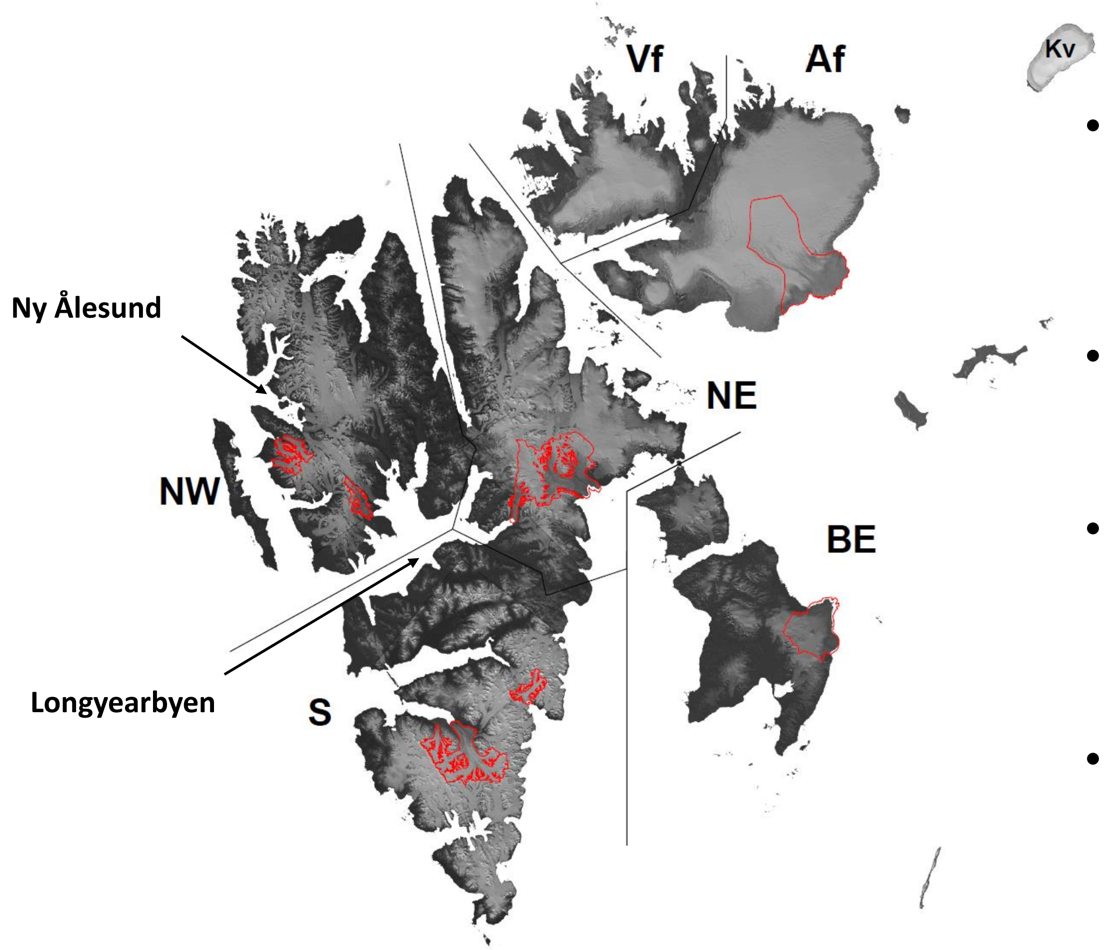
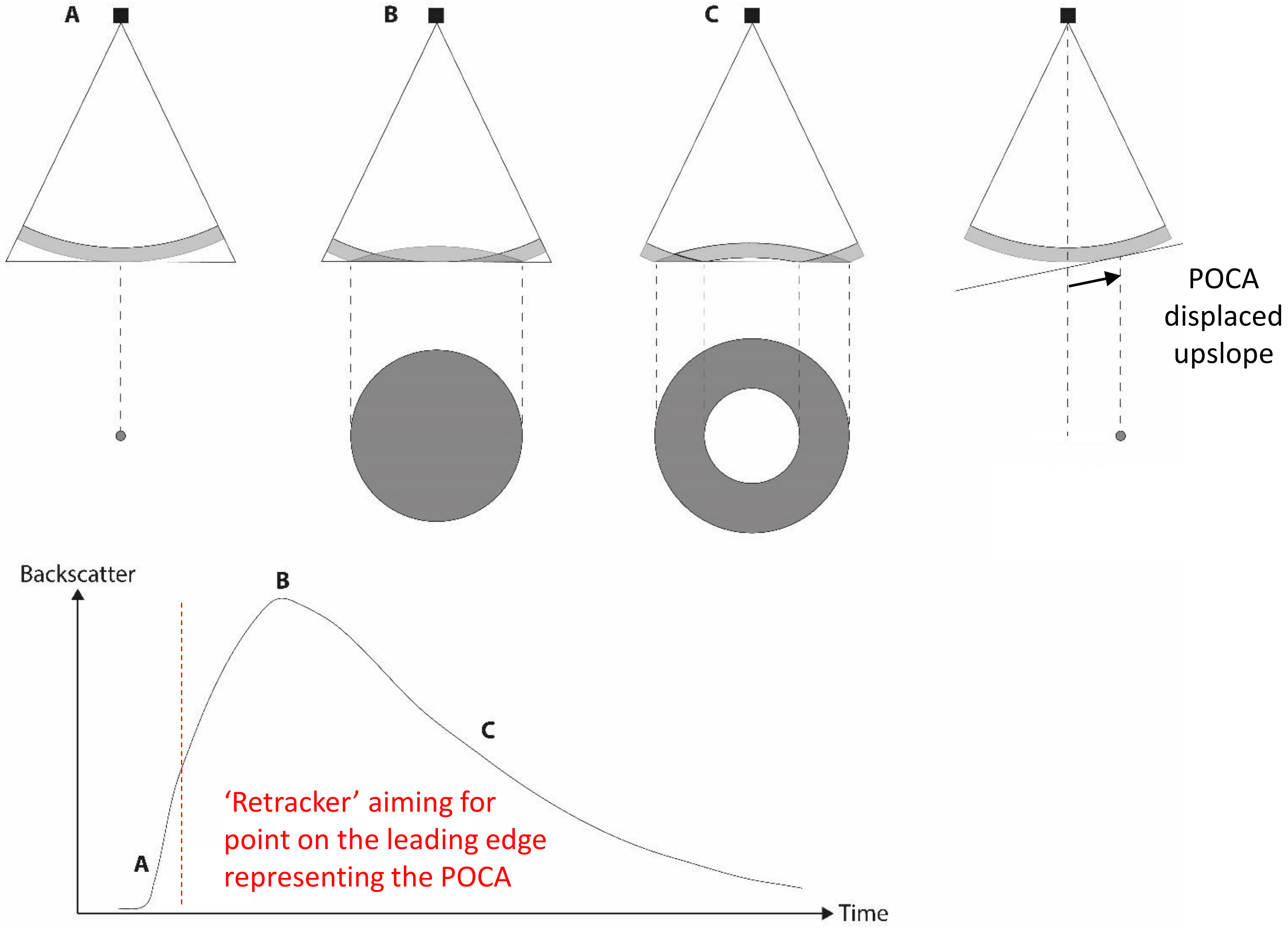


- Svalbard located in the **most rapidly warming area of the Arctic**, at the interface of Atlantic and Arctic air and ocean masses.
- This leads to **strong gradients** in temperature and precipitation across the archipelago.
- ~34,000 km² of glacier cover, varying from cirques, valley glaciers and icefields on Spitsbergen, to ice caps on the eastern islands.
- Numerous **surging glaciers** including Nathorstbreen and Storisstraumen, the largest surges since the 1930s.



- Radar altimetry illuminates large area of the surface, producing a 'waveform'.
- **'Retracker'** used to locate 'Point of closest approach' (**POCA**).
- POCA displaced upslope. *A priori* knowledge of subsatellite topography required for geolocation.
- **Penetration** of signal into dry snowpack.

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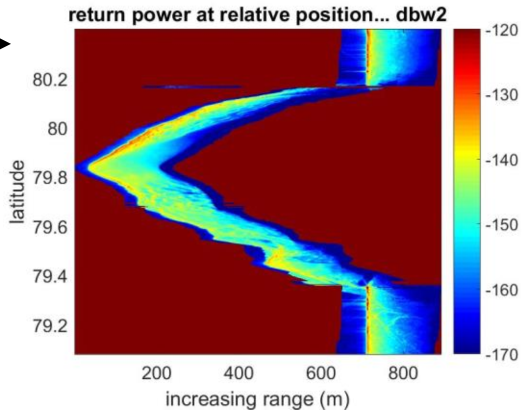
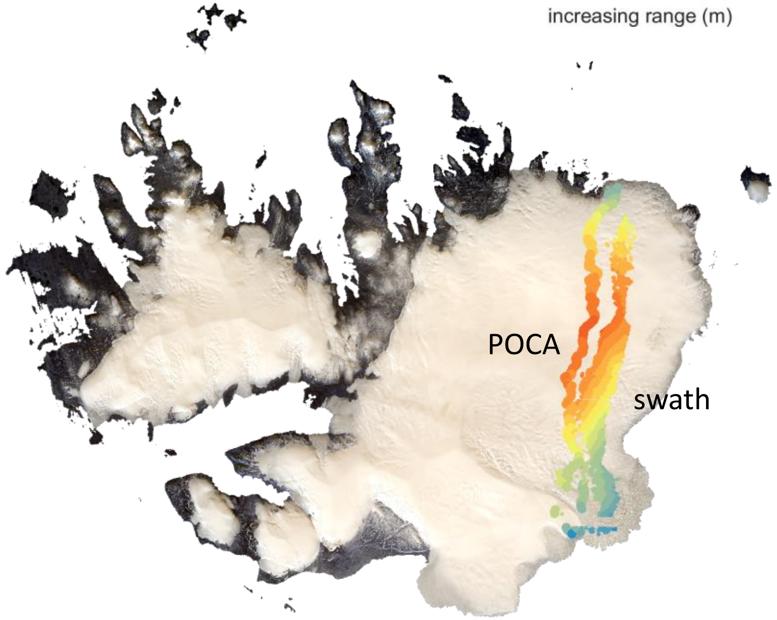
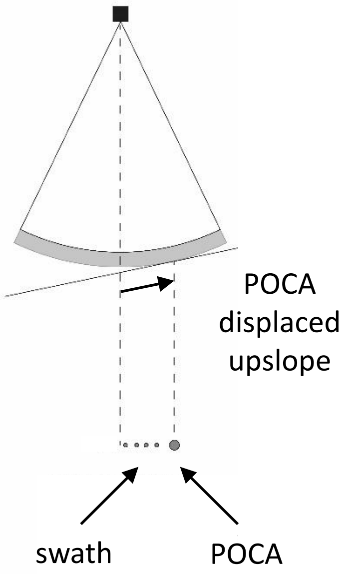
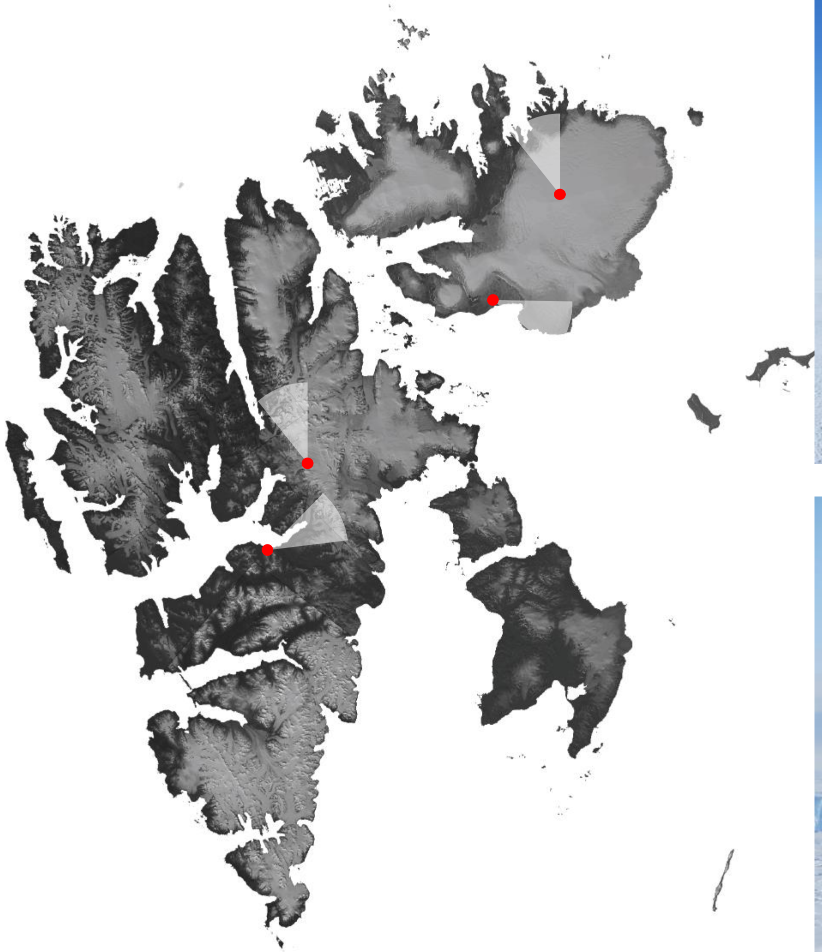
Waveforms for each 300 m strip, backscatter power shown by colourbar, shifted by range from satellite relative to minimum. Descending pass over eastern Austfonna.

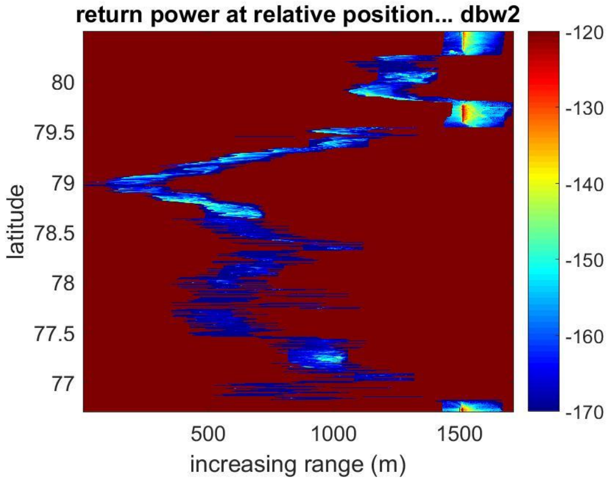


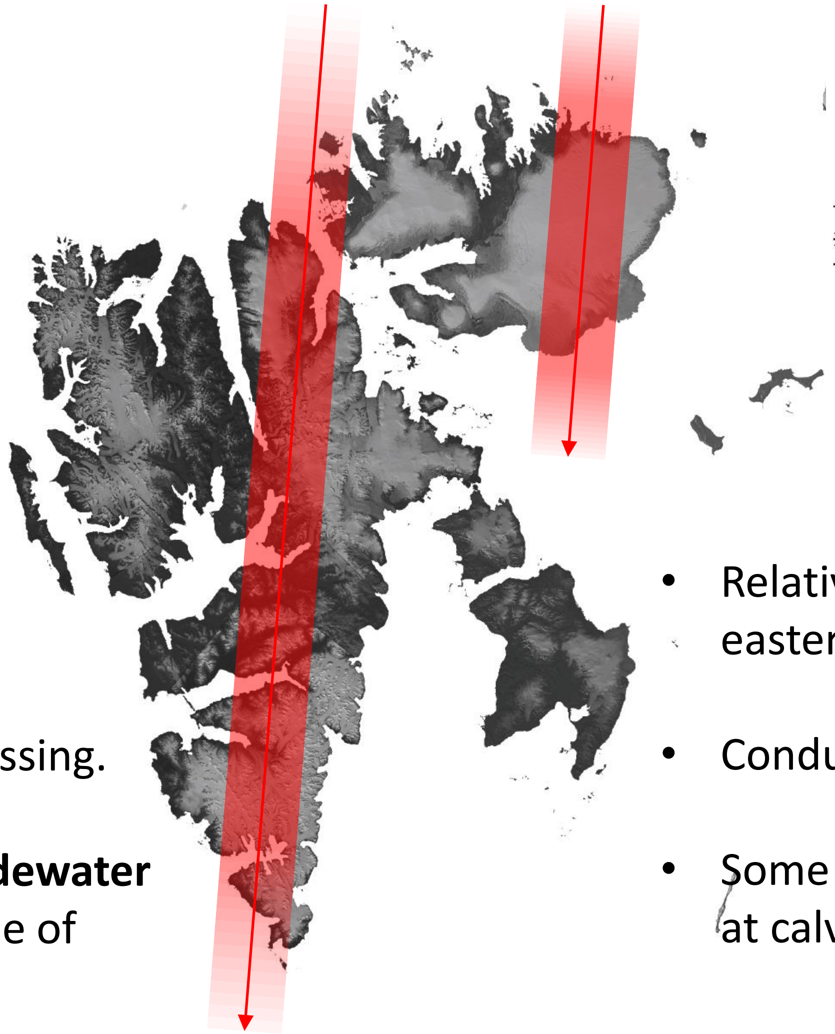


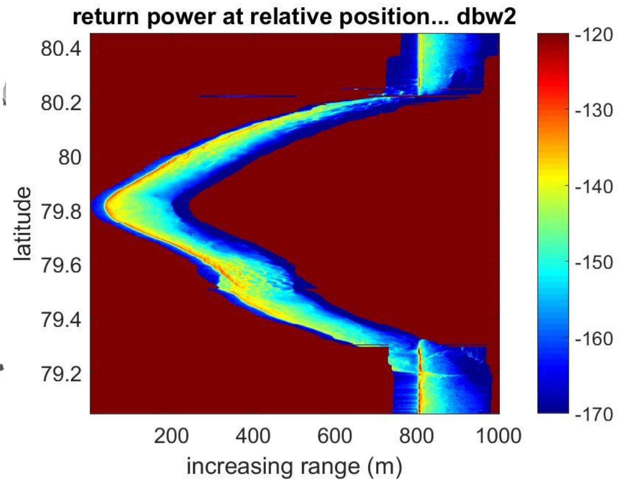


- **CryoSat-2** specifically designed to address the shortcomings of radar altimetry over **glaciers, ice caps, and the margins of the ice sheets**.
- **Doppler shift** used to split the footprint into ~300 m along-track strips.
- **Dual receiving antenna** positioned across- track. **Phase shift** used to locate POCA in across-track direction.
- Where are across-track slope is within a suitable range, can retrieve additional **swath points**.







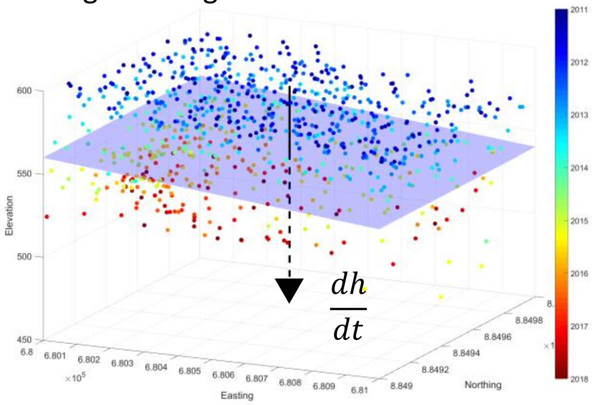


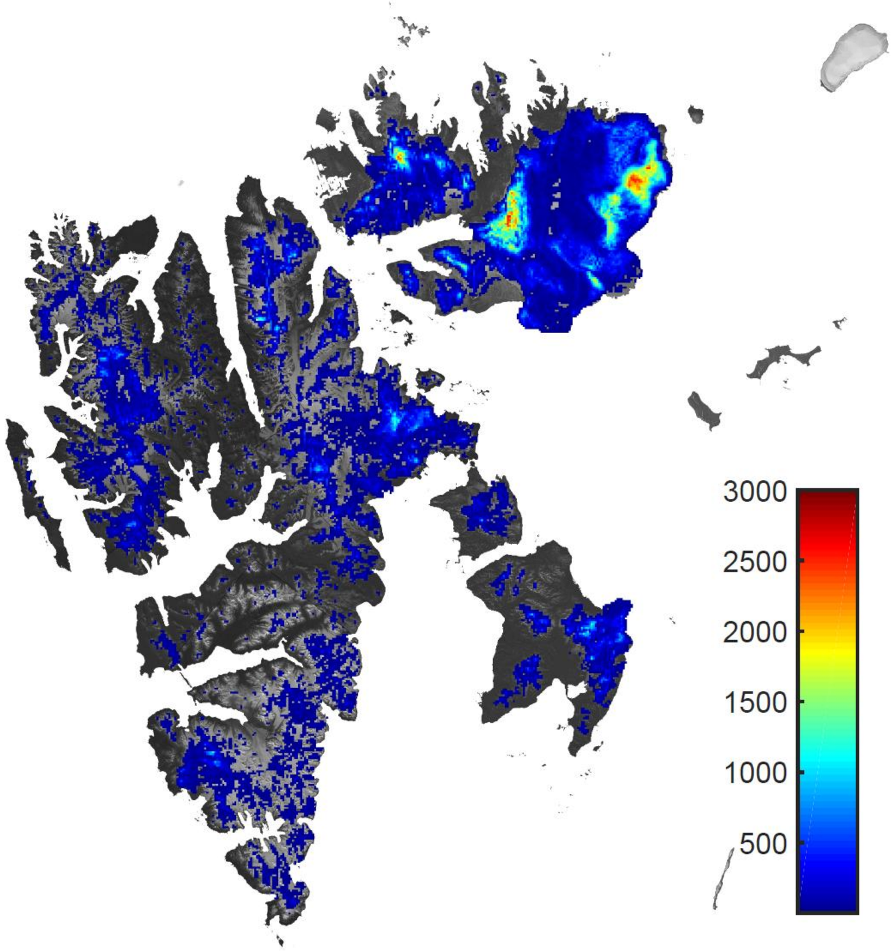
- **Mountainous topography** in Spitsbergen. 'Loss of lock'.
- Less conducive to swath processing.
- Potentially rapidly changing **tidewater glaciers undersampled** because of fjord walls

- Relatively **simple topography** on the eastern islands.
- Conducive to swath processing.
- Some problems for ascending passes at calving cliffs.

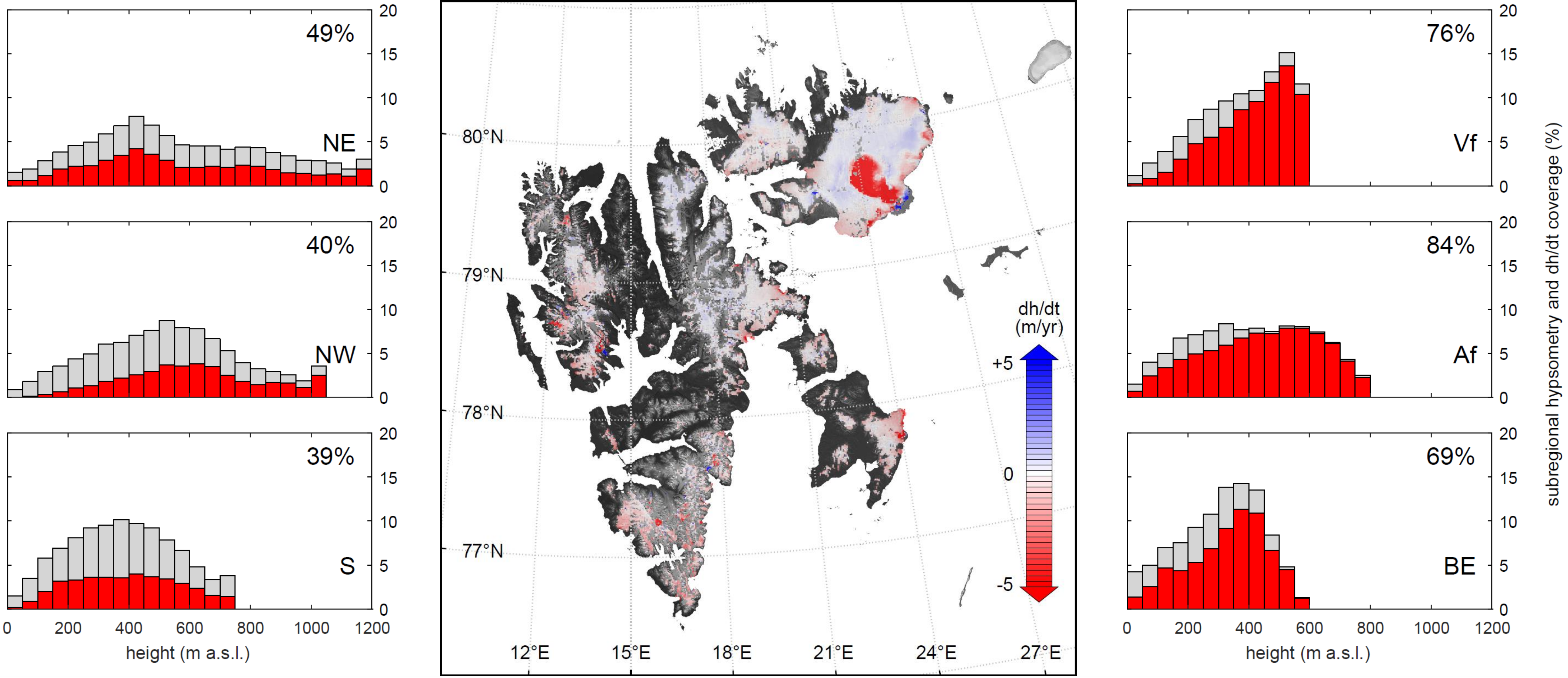
$$f(x, y, z) = c_1 x + c_2 y + \frac{dh}{dt} t + v$$

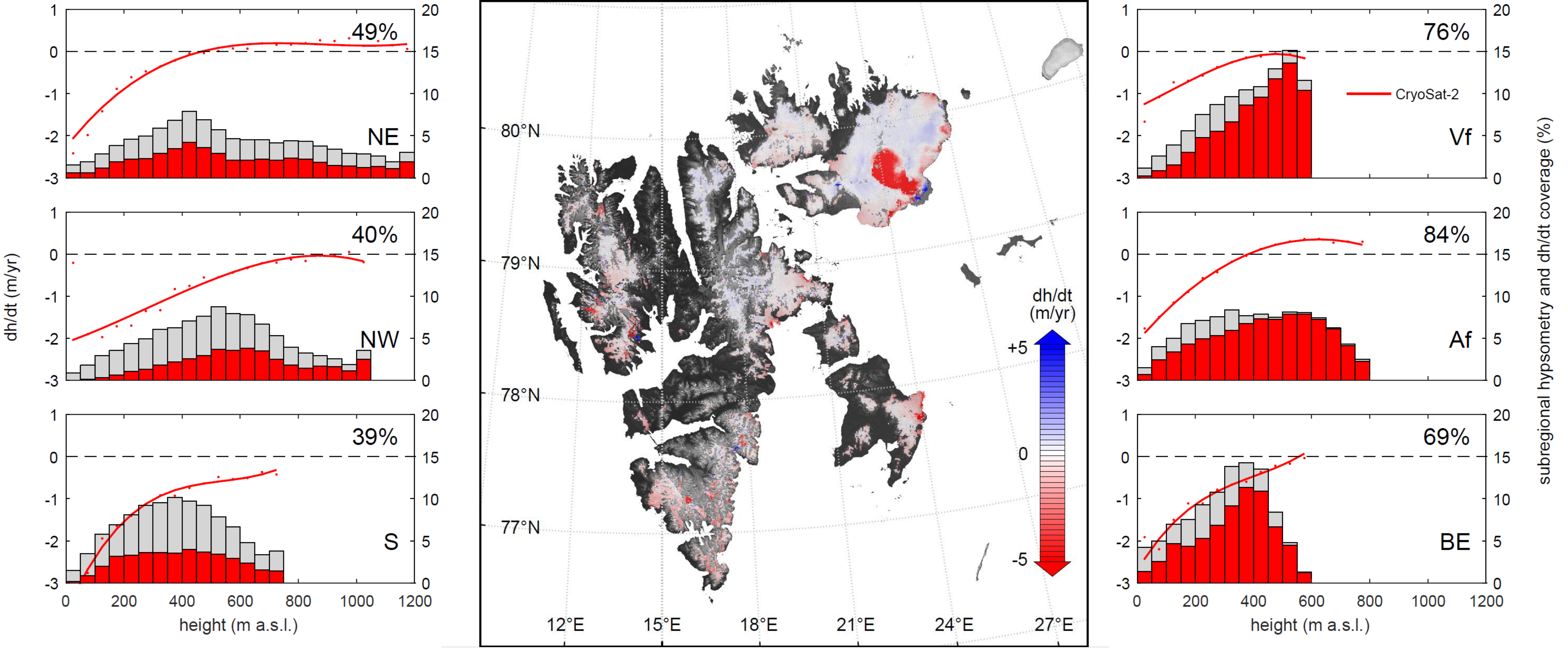
Single 1km² grid cell:





- Almost complete coverage on eastern islands, less extensive coverage on Spitsbergen.
- **Least-squares plane-fitting** technique used to calculate rate of elevation change in 1km² grid cell.
- **Residuals** stored and used later to add in seasonality and interannual variability.


49%
NE
40%
NW
39%
S
height (m a.s.l.)
80°N
79°N
78°N
77°N
12°E
15°E
18°E
21°E
24°E
27°E
dh/dt
(m/yr)
+5
0
-5
76%
Vf
84%
Af
69%
BE
height (m a.s.l.)
subregional hypsometry and dh/dt coverage (%)

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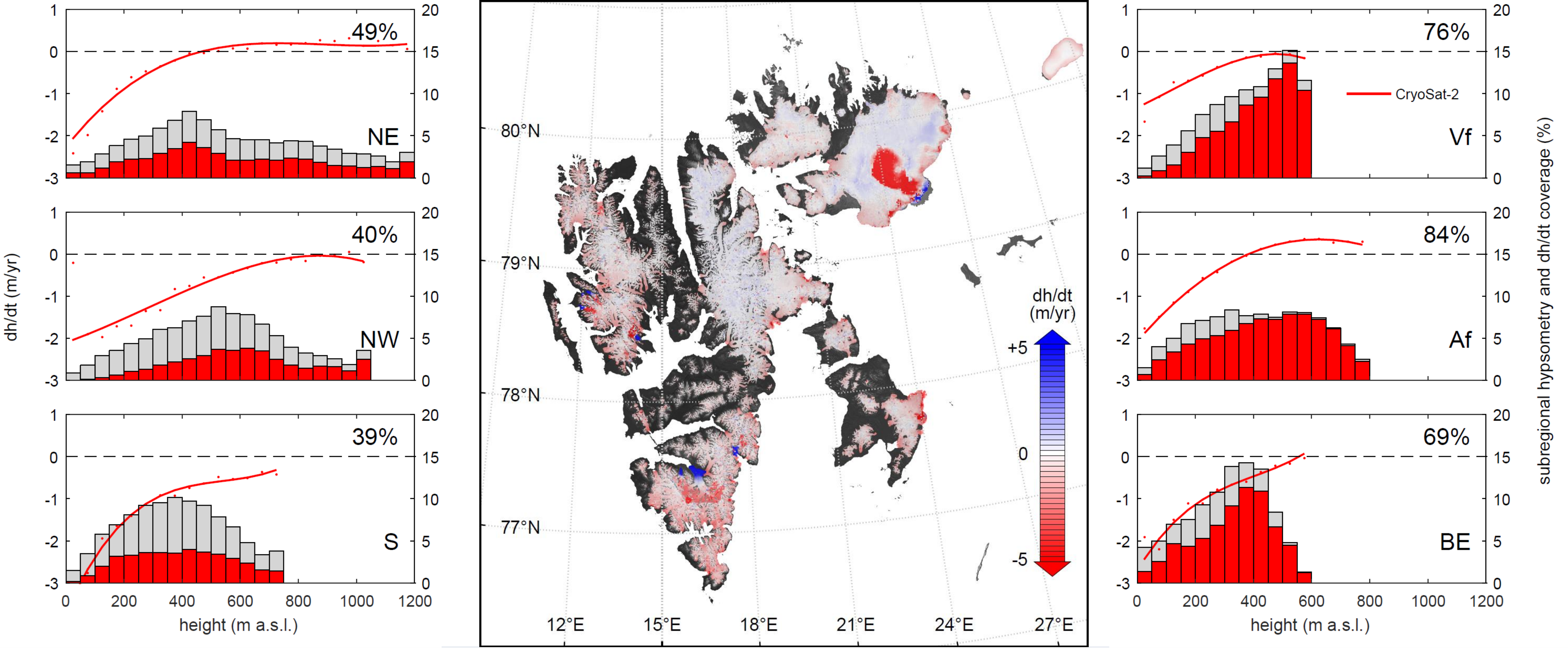
dh/dt (m/yr)
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49%
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CryoSat-2
height (m a.s.l.)
height (m a.s.l.)
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dh/dt
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+5
0
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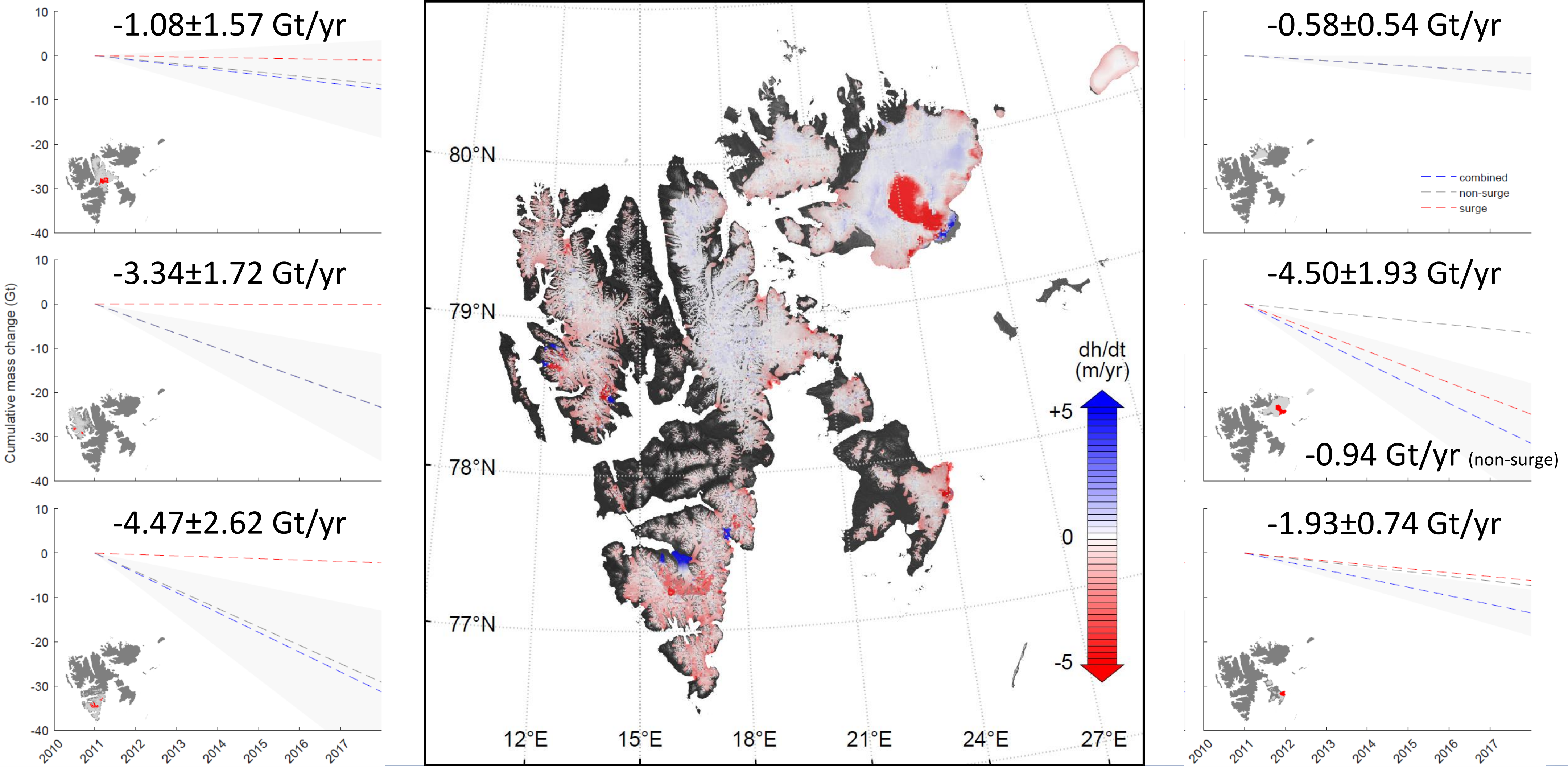
-1.08±1.57 Gt/yr
-3.34±1.72 Gt/yr
-4.47±2.62 Gt/yr
Cumulative mass change (Gt)
10
0
-10
-20
-30
-40
2010
2011
2012
2013
2014
2015
2016
2017
80°N
79°N
78°N
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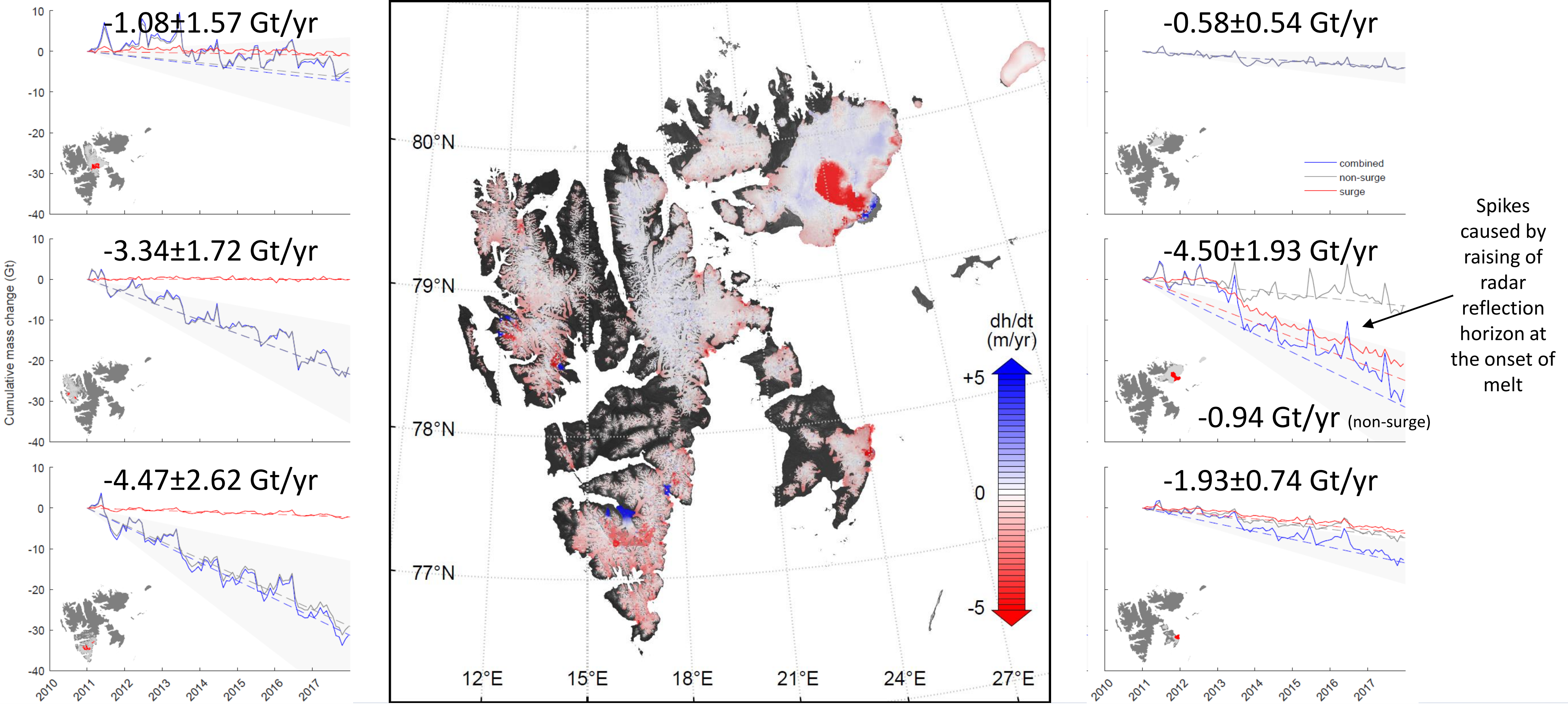
12°E
15°E
18°E
21°E
24°E
27°E
dh/dt
(m/yr)
+5
0
-5
-0.58±0.54 Gt/yr
combined
non-surge
surge
-4.50±1.93 Gt/yr
-0.94 Gt/yr (non-surge)
-1.93±0.74 Gt/yr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Spikes caused by raising of radar reflection horizon at the onset of melt


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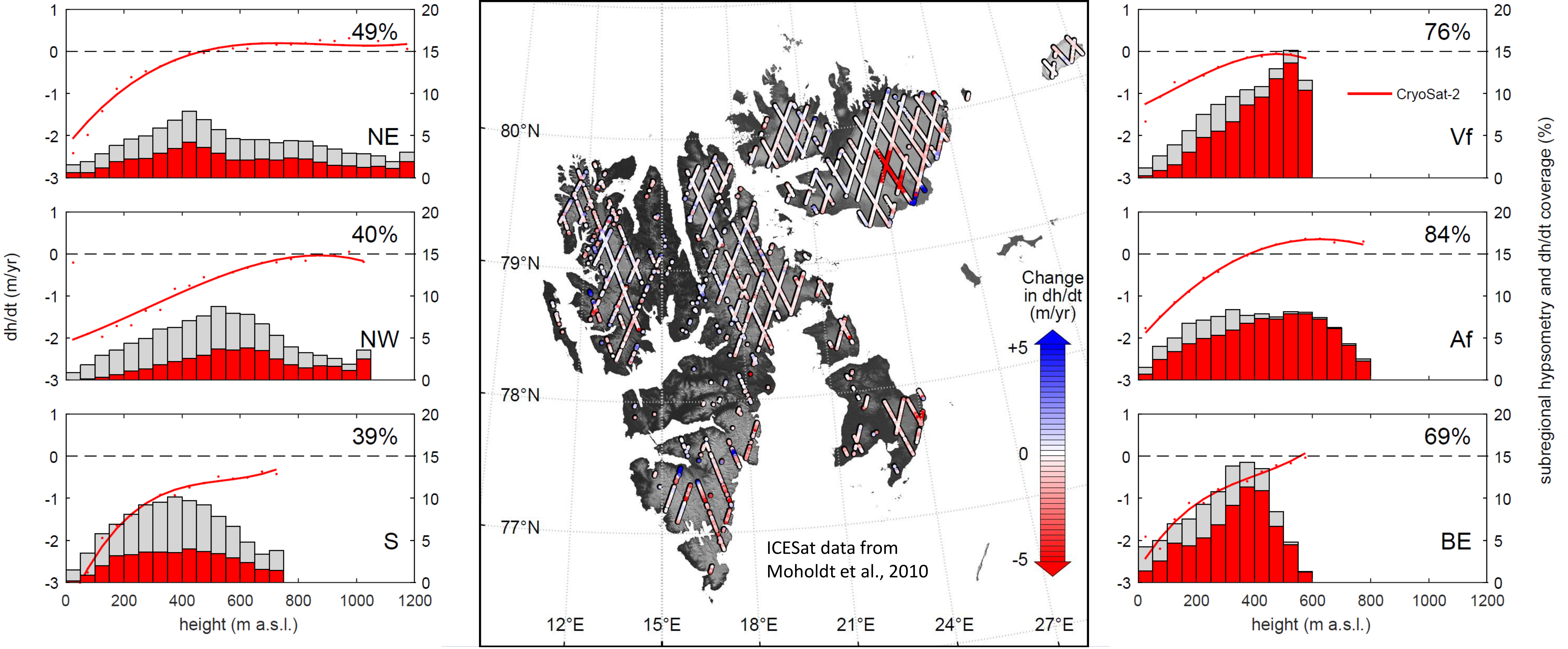

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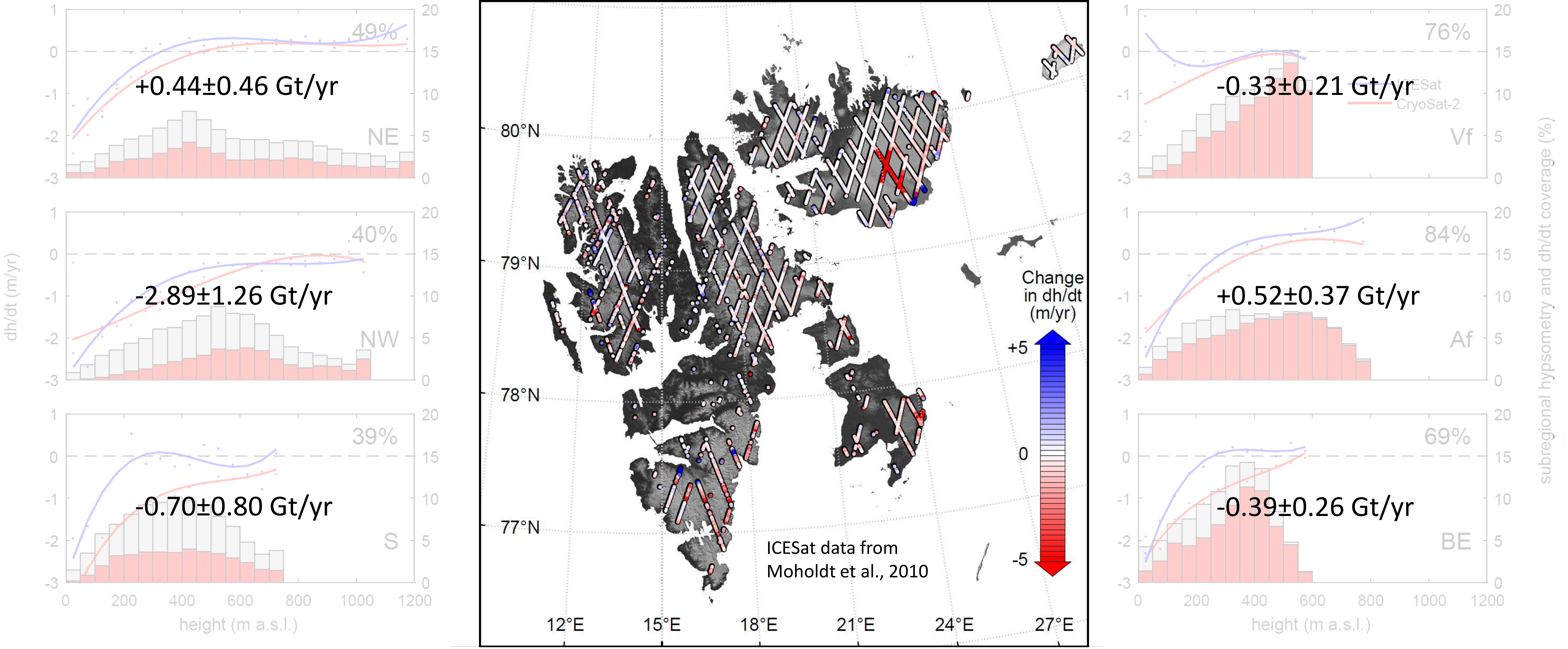
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dh/dt (m/yr)
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79°N
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12°E
15°E
18°E
21°E
24°E
27°E
Change in dh/dt (m/yr)
+5
0
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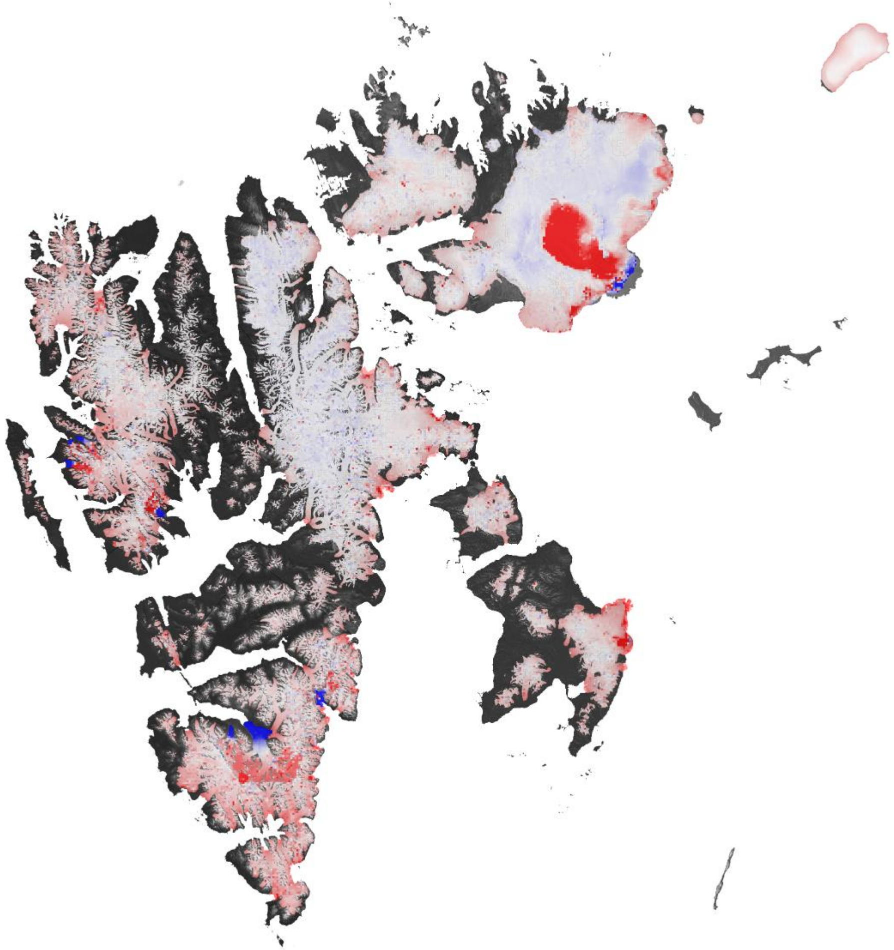

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2003-2008 +0.44±0.46 Gt/yr

2011-2017 -1.08±1.57 Gt/yr

Increased thinning for low elevation areas.
Slight thickening at highest elevations.

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Switch from slight thickening to rapid thinning on eastern (Storfjorden) coast.

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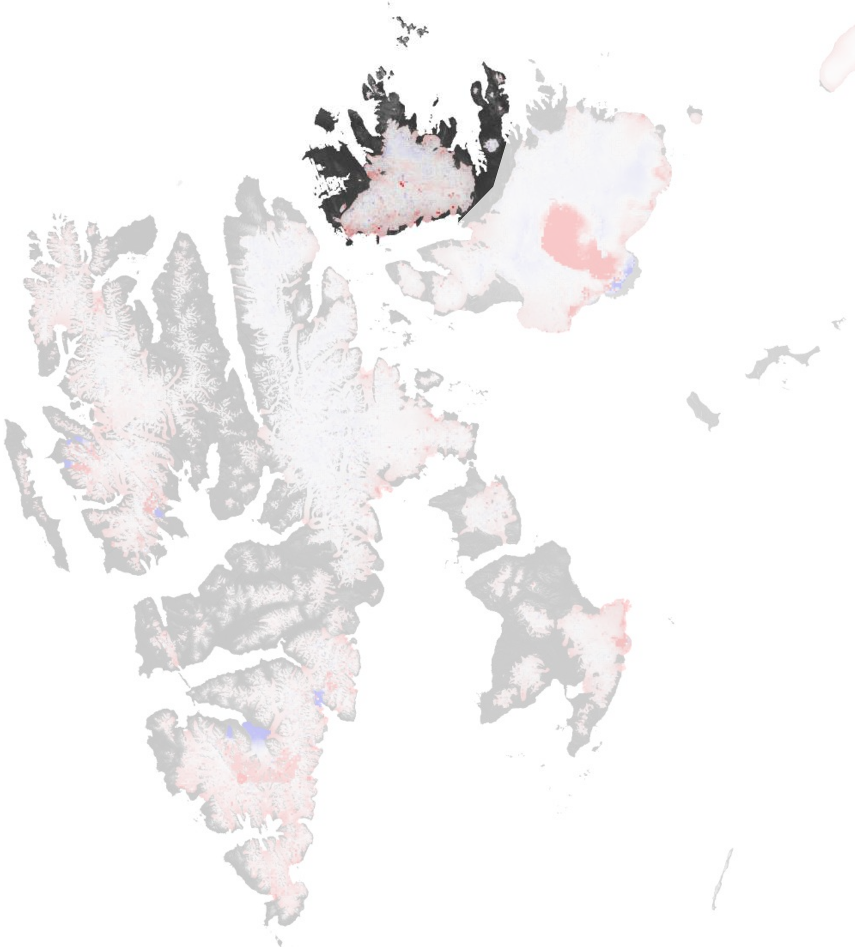

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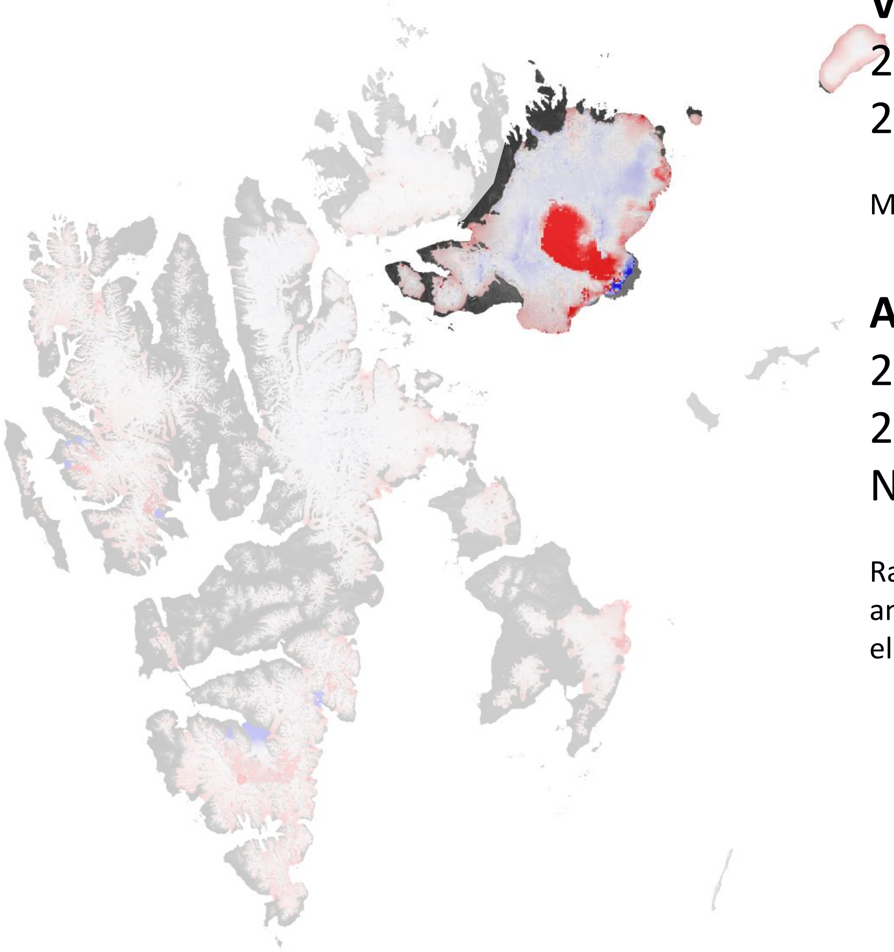

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Non surge -0.94 Gt/yr

Rapid mass loss from surging Storisstraumen and southern margin. Slight thickening at high elevations

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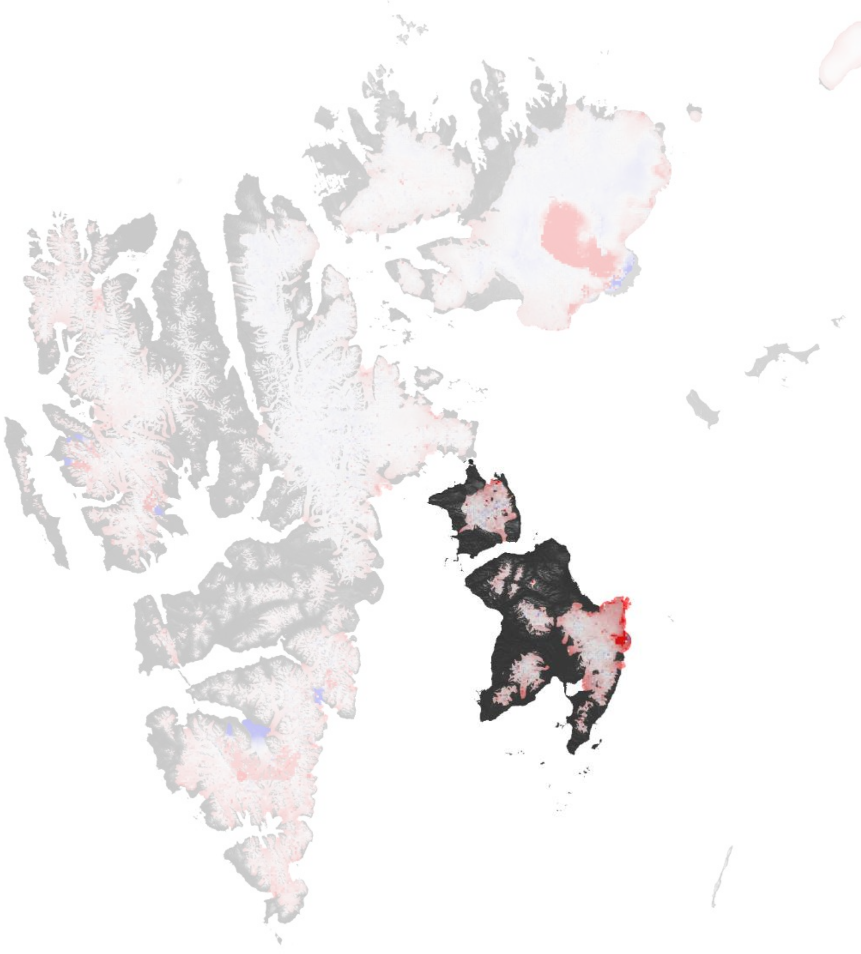

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Barentsøya-Edgeøya

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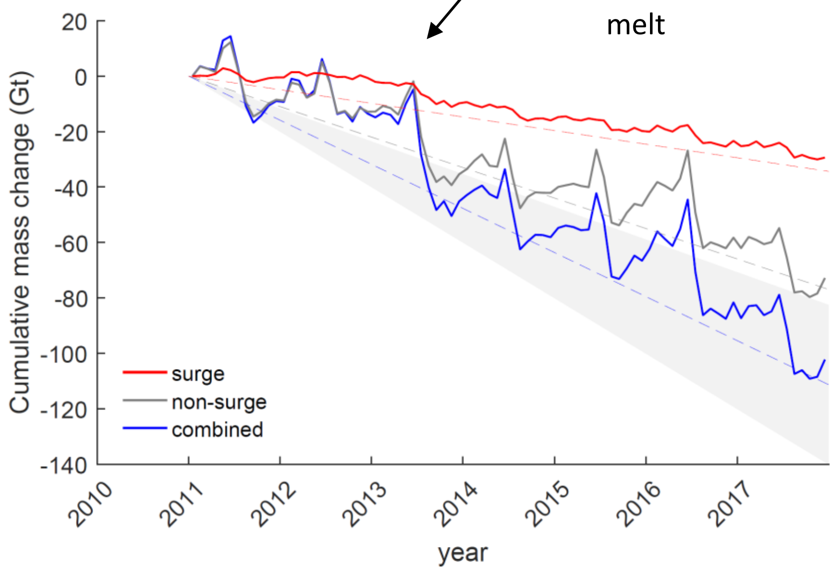
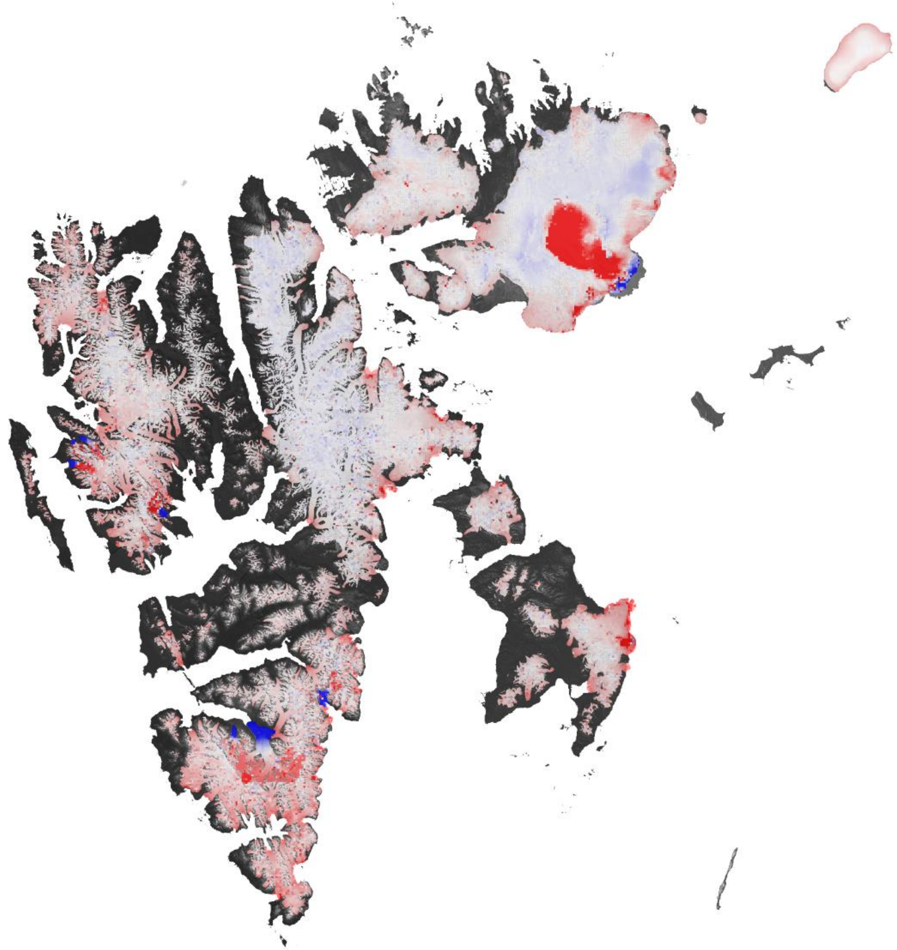
Increased melt and surge of Stonebreen.

Reminder! Spikes caused by raising of radar reflection horizon at the onset of melt



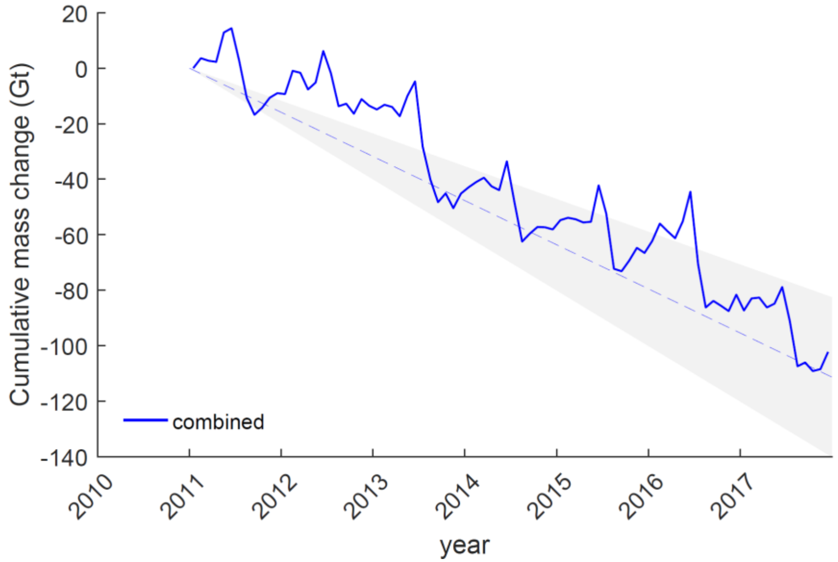


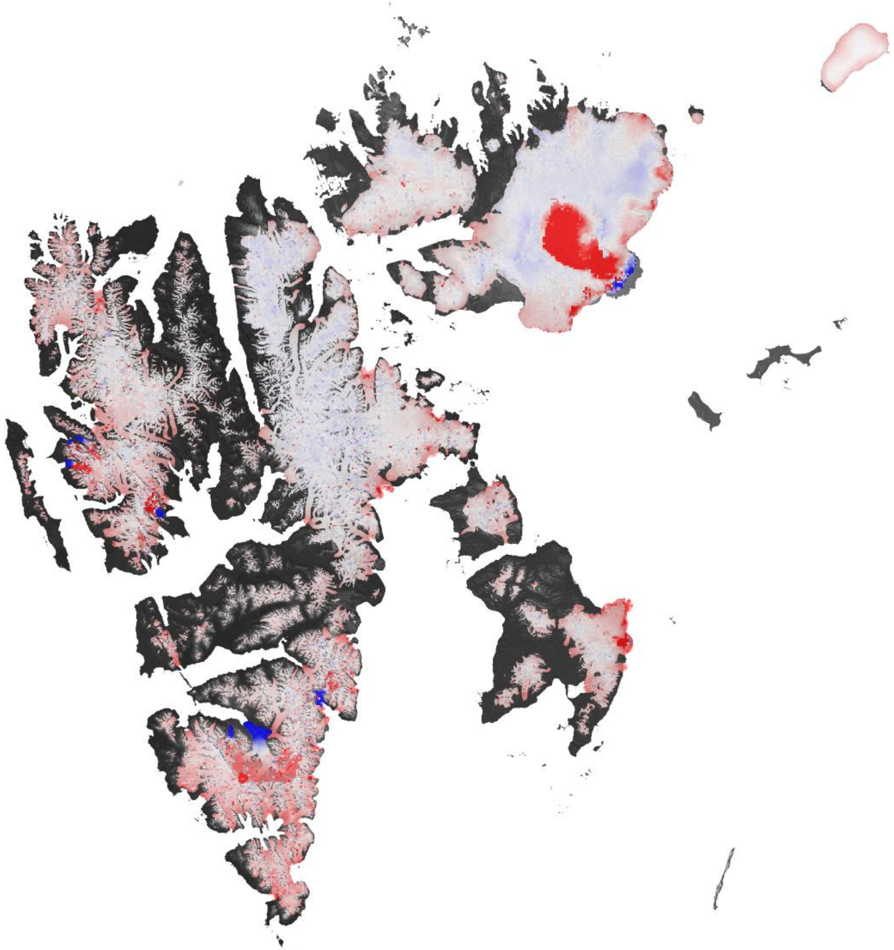
Svalbard
ICESat
(2003-2008)
-3.4±1.6 Gt/yr

CryoSat-2
(2011-2017)
-15.9±4.1 Gt/yr

Surging
-4.91 Gt/yr

Non-surging
-10.99 Gt/yr





Svalbard
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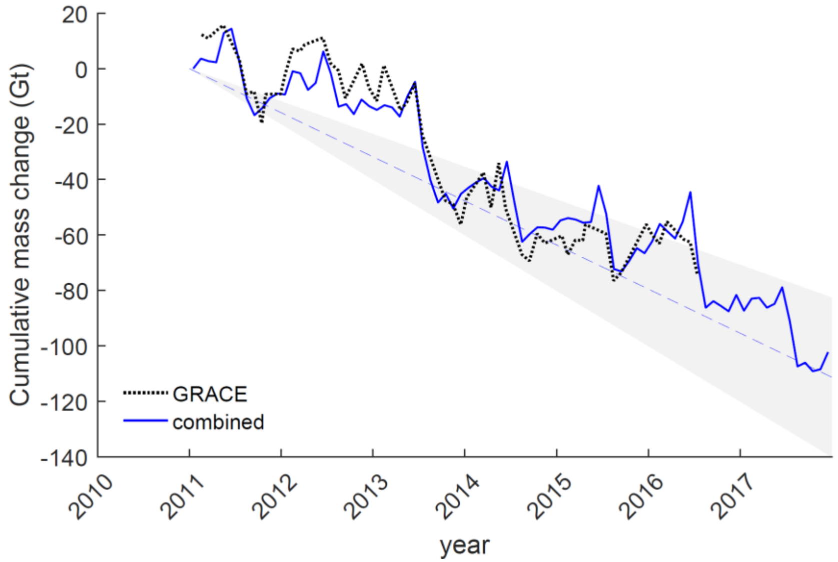
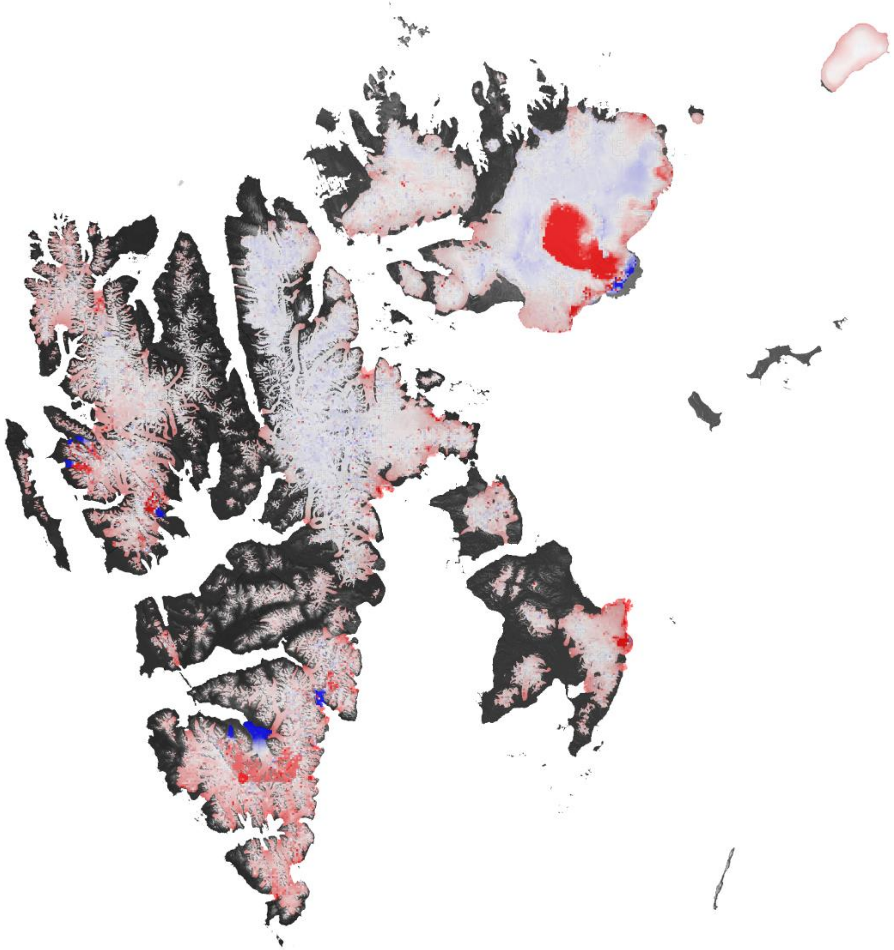
Surging
-4.91 Gt/yr

Non-surging
-10.99 Gt/yr

Excellent agreement between satellite gravimetric and altimetric mass loss time-series





Svalbard
ICESat
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-3.4±1.6 Gt/yr

CryoSat-2
(2011-2017)
-15.9±4.1 Gt/yr

Surging
-4.91 Gt/yr

Non-surging
-10.99 Gt/yr

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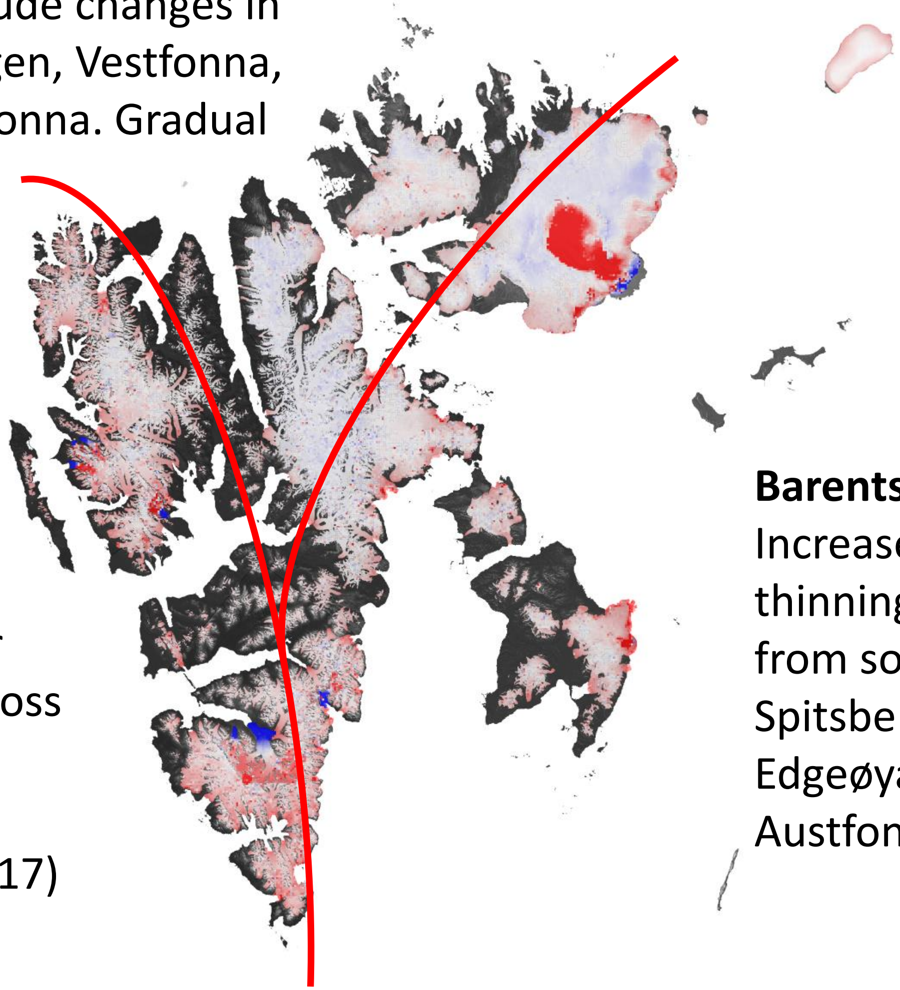
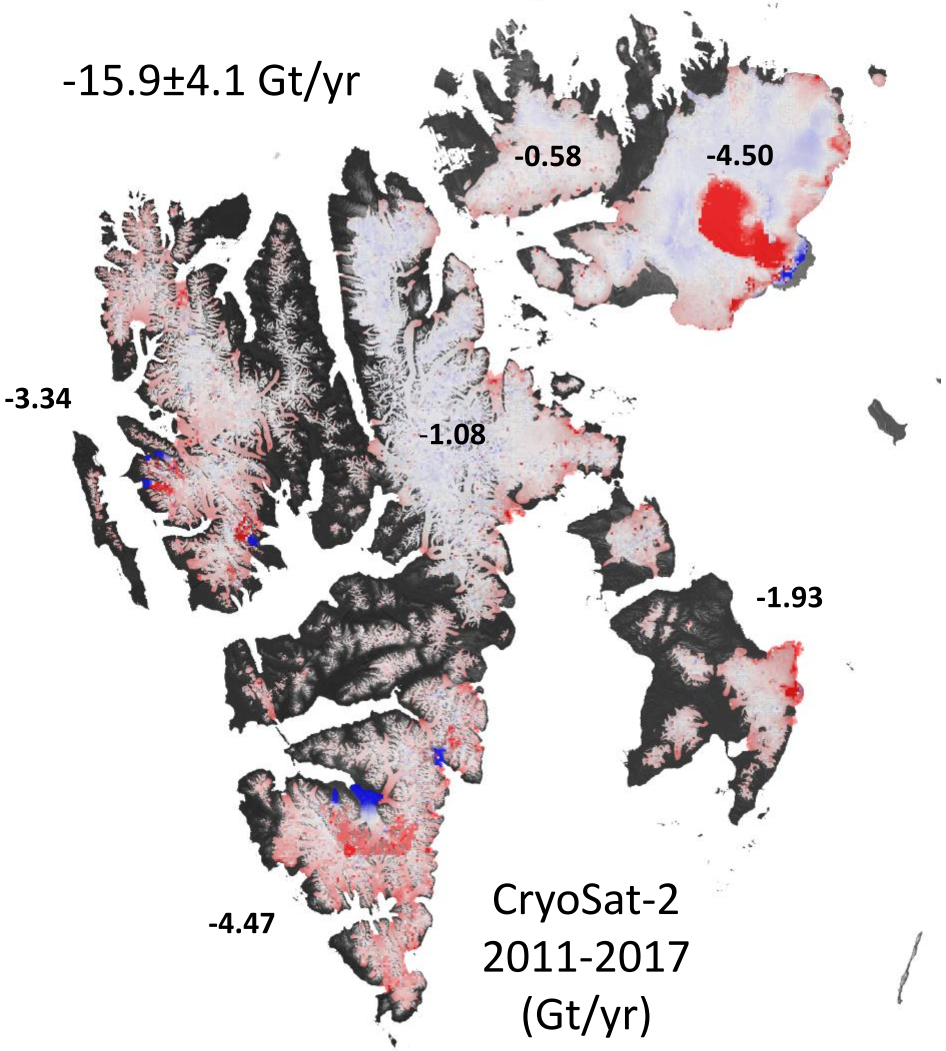
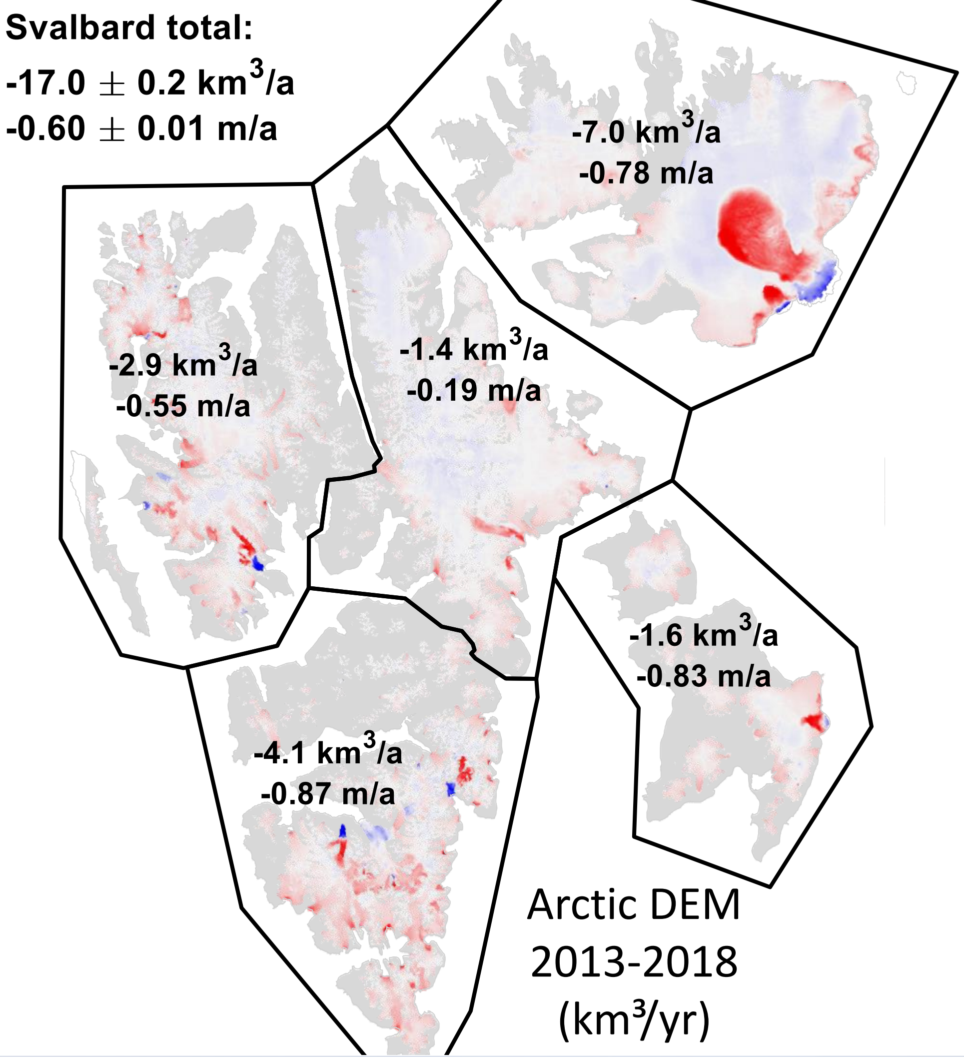
North: Low magnitude changes in northeast Spitsbergen, Vestfonna, and northern Austfonna. Gradual thickening at high altitude.



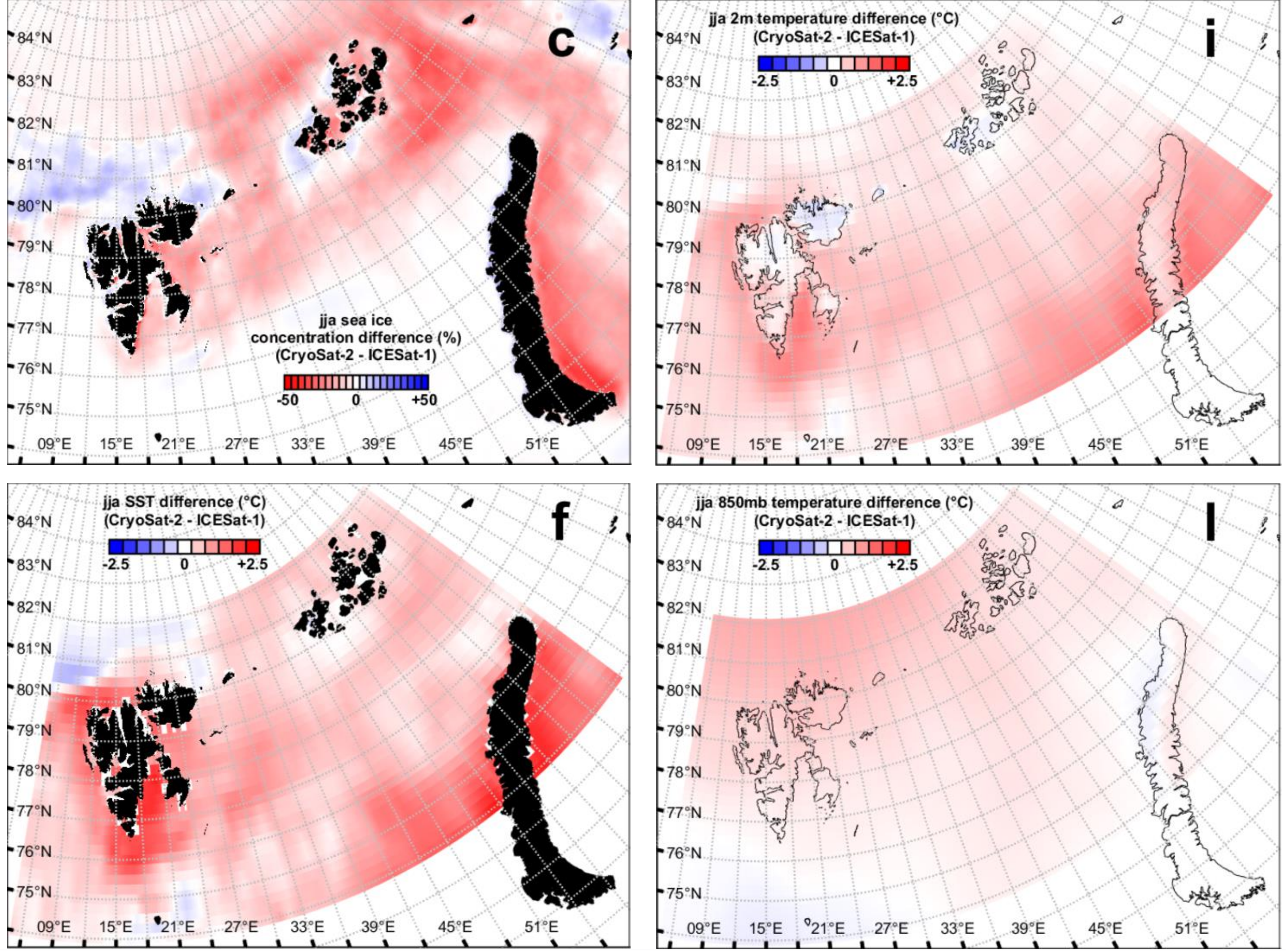
West Coast: Glacier thinning and mass loss during both ICESat (2003-2008) and CryoSat-2 (2011-2017) periods.

Barents Sea margins: Increase in glacier thinning and mass loss from southeastern Spitsbergen, Barentsøya-Edgeøya, and southern Austfonna.

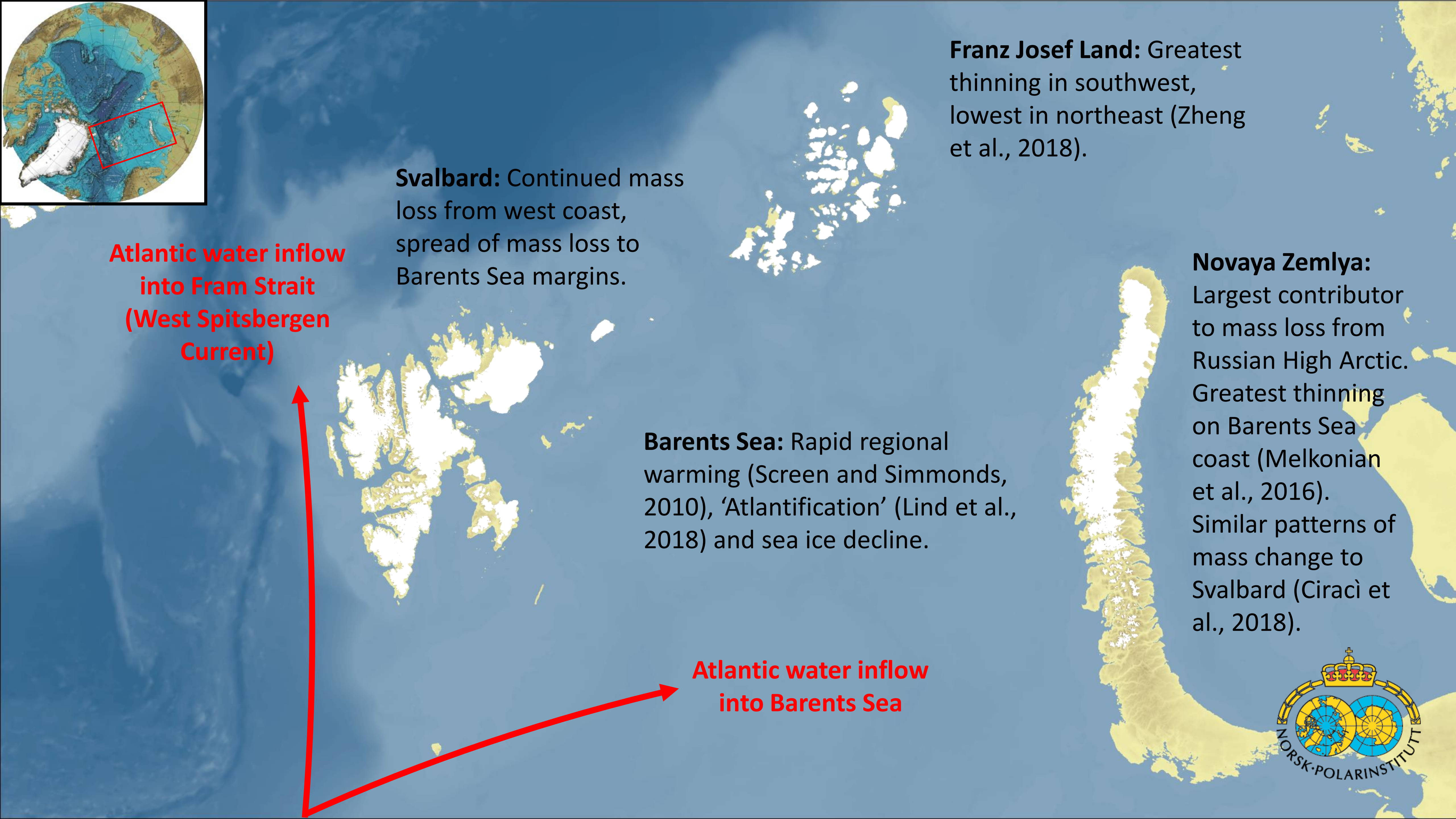

-15.9±4.1 Gt/yr
-0.58
-4.50
-3.34
-1.08
-1.93
-4.47
CryoSat-2
2011-2017
(Gt/yr)


Svalbard total:
-17.0 ± 0.2 km³/a
-0.60 ± 0.01 m/a
-7.0 km³/a
-0.78 m/a
-2.9 km³/a
-0.55 m/a
-1.4 km³/a
-0.19 m/a
-1.6 km³/a
-0.83 m/a
-4.1 km³/a
-0.87 m/a
Arctic DEM
2013-2018
(km³/yr)

- **Sea ice decline** in northern Barents Sea.
- **Subsurface** (Lind et al., 2018) and **surface ocean warming.** Strong SST warming in Storfjorden.
- 2 m temperature warming pattern reflects SSTs.
- 850 mb warming greatest to the north of Svalbard.



Sea ice concentration maps were obtained from the University of Bremen (https://seaice.uni-Bremen.de/sea-ice-concentration).
ERA5 climate reanalysis data were obtained through the EU's Copernicus program (https://climate.Copernicus.eu/climate-reanalysis).


Franz Josef Land: Greatest thinning in southwest, lowest in northeast (Zheng et al., 2018).
Svalbard: Continued mass loss from west coast, spread of mass loss to Barents Sea margins.
Atlantic water inflow into Fram Strait (West Spitsbergen Current)
Novaya Zemlya: Largest contributor to mass loss from Russian High Arctic. Greatest thinning on Barents Sea coast (Melkonian et al., 2016). Similar patterns of mass change to Svalbard (Ciracì et al., 2018).
Barents Sea: Rapid regional warming (Screen and Simmonds, 2010), 'Atlantification' (Lind et al., 2018) and sea ice decline.
Atlantic water inflow into Barents Sea
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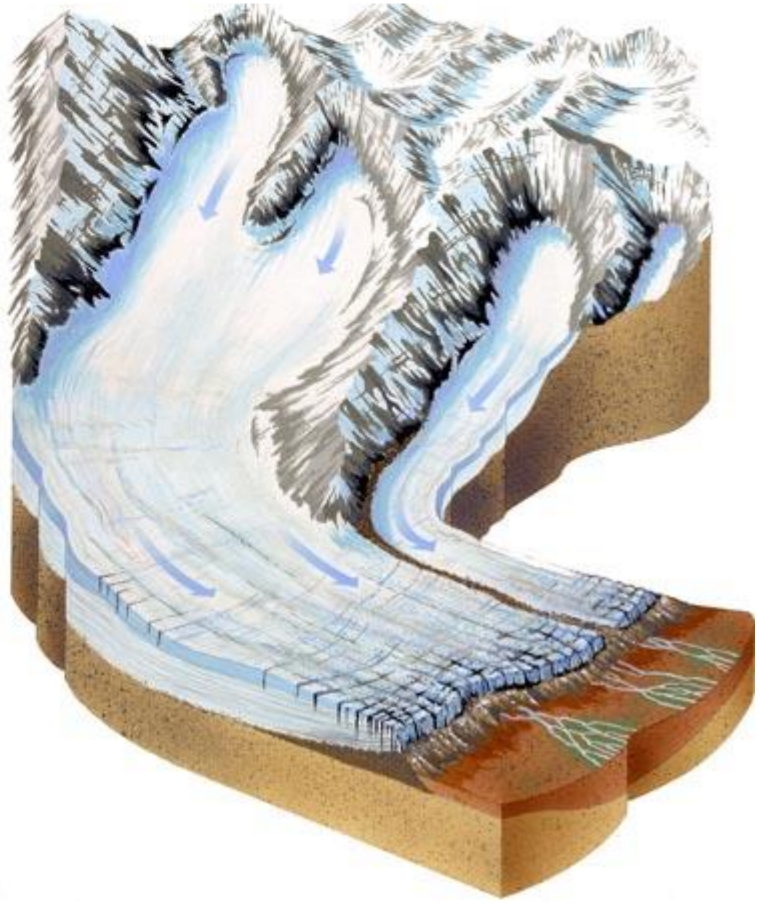
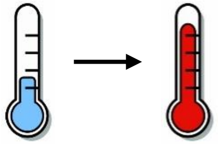
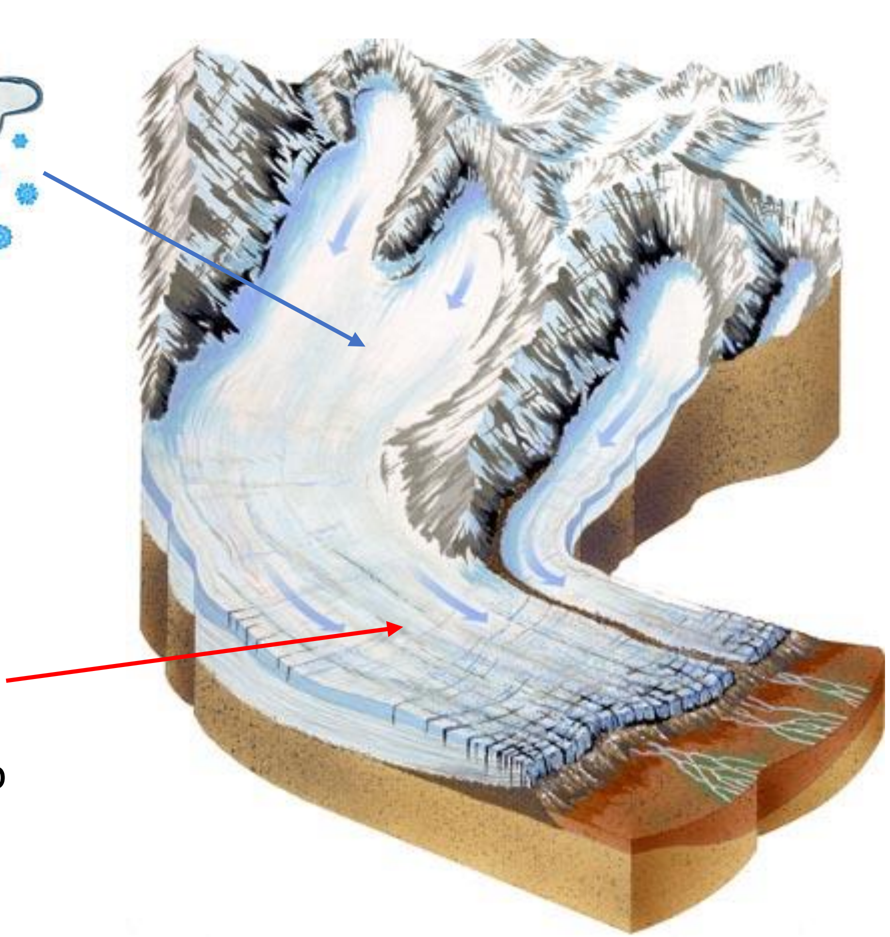


Does CryoSat-2 see it?

Thickening due to increased snowfall

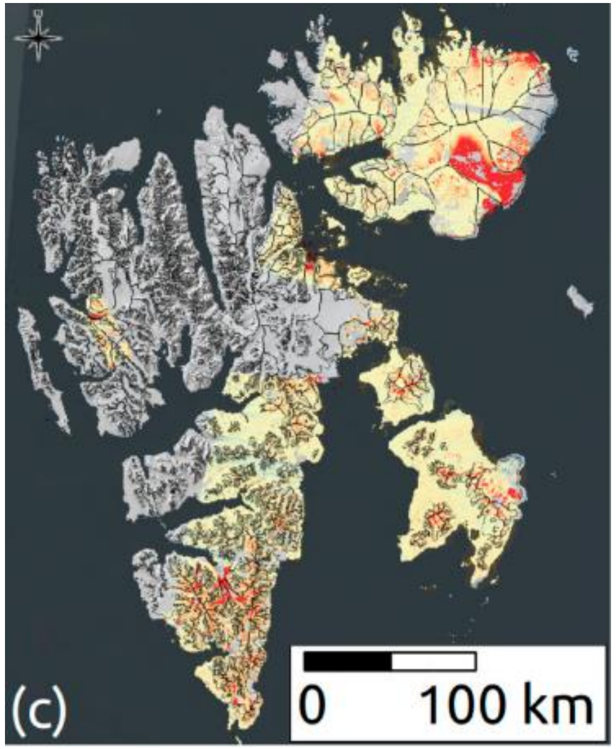


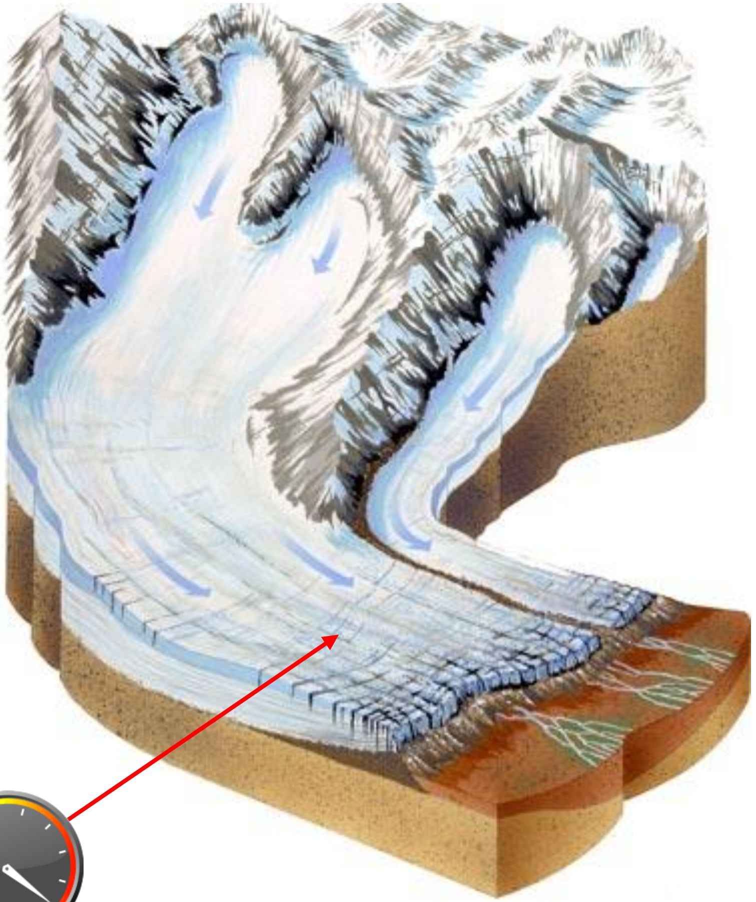
Thinning due to increased melt



Does CryoSat-2 see it?

SMB-driven mass change ✓



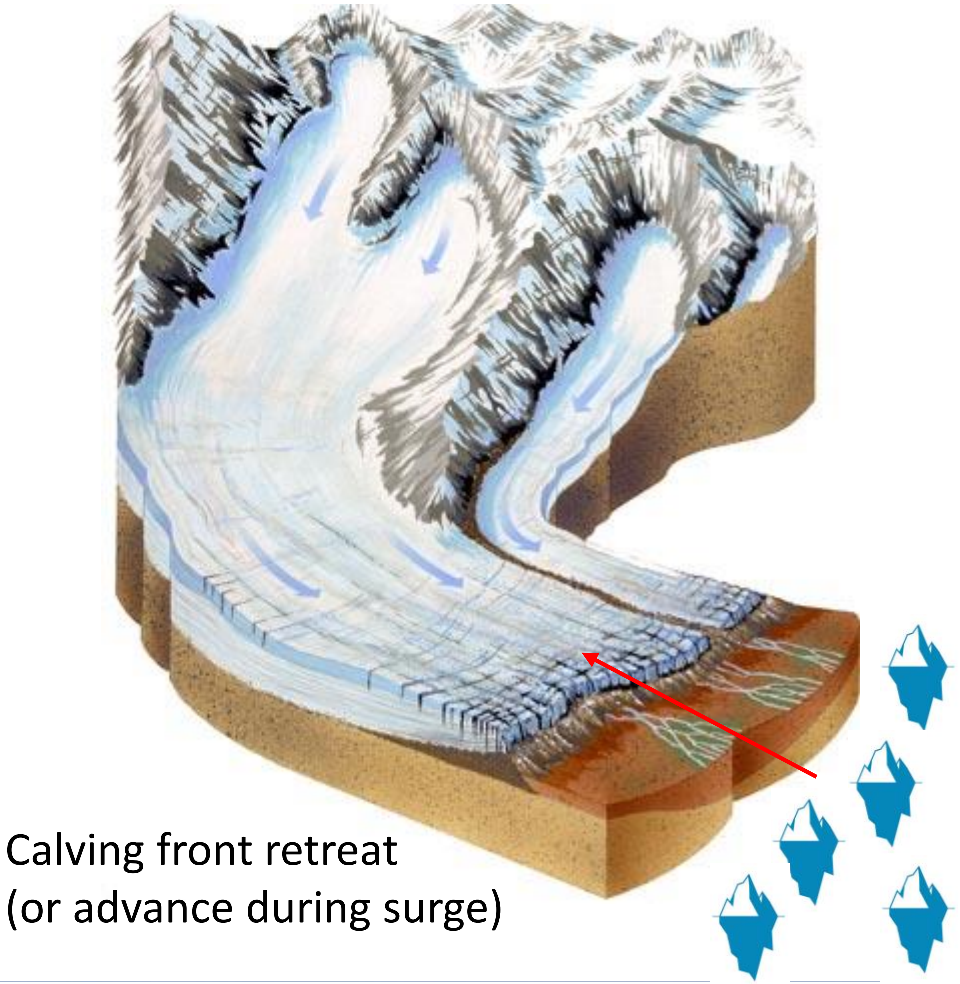


Dynamic thinning (thickening) due to faster (slower) flow

Does CryoSat-2 see it?

SMB-driven mass change ✓

Dynamically-driven mass change ✓

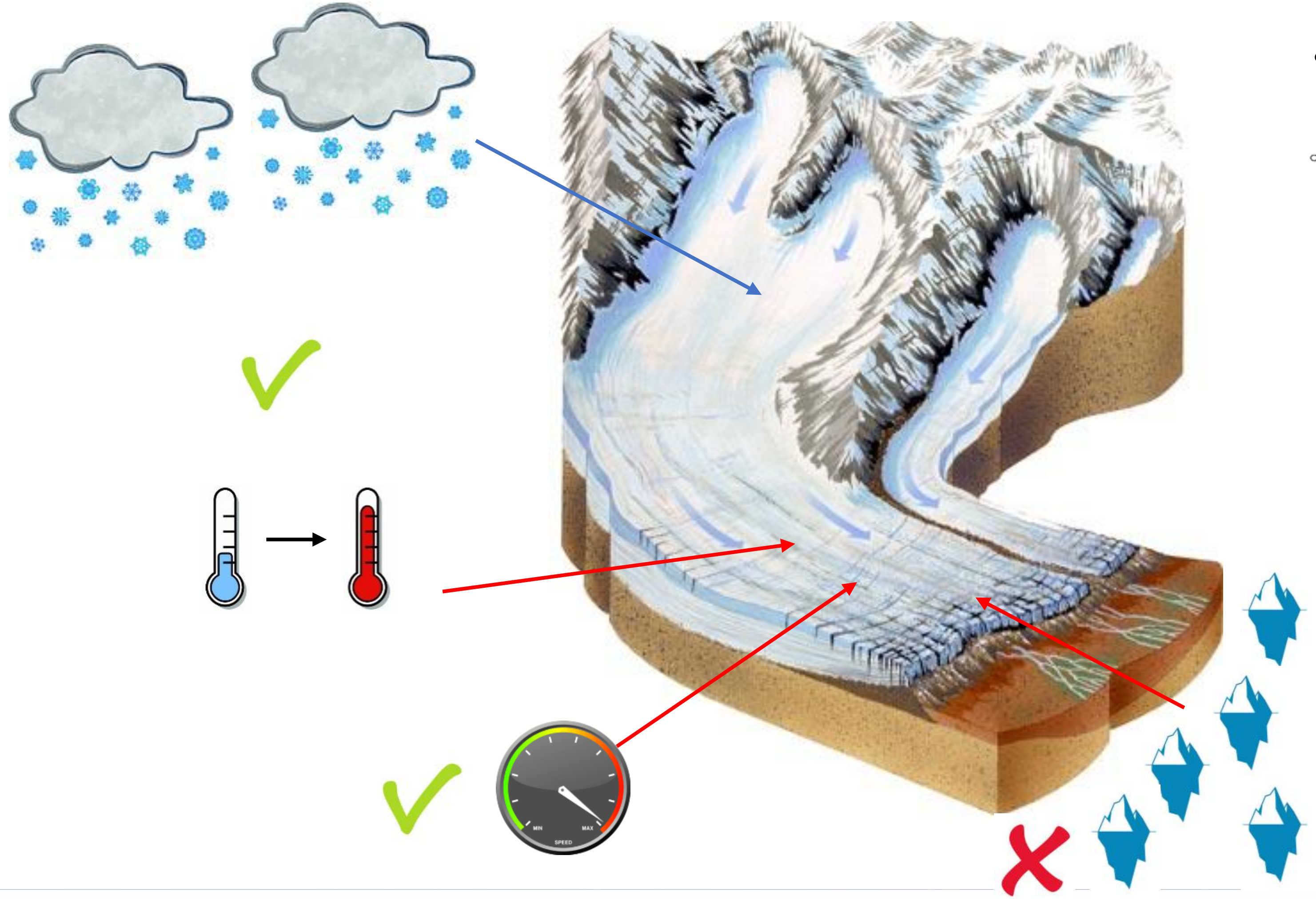


Does CryoSat-2 see it?

SMB-driven mass change ✓

Dynamically-driven mass change ✓

Advance/retreat-driven mass change ✗



- Altimetry gives geodetic mass balance, not total

POLISH POLAR RESEARCH
vol. 30, no. 2, pp. 85–142, 2009

Tidewater glaciers of Svalbard: Recent changes and estimates of calving fluxes

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[2] Instytut Geofizyki PAN, Księcia Janusza 64, 01-452 Warszawa, Poland

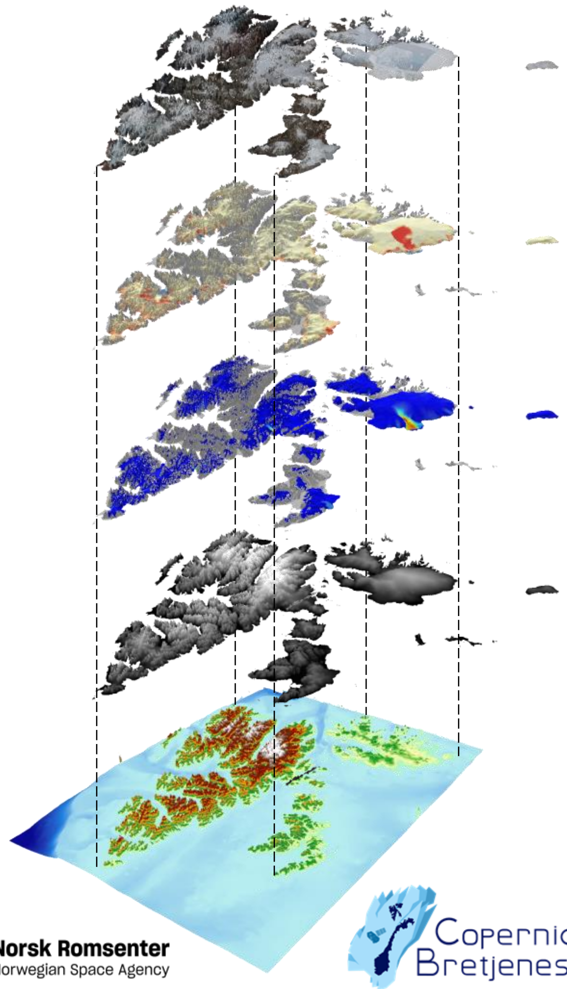
[3] Department of Geosciences, University of Oslo, POBox 1047 Blindern, N-0316 Oslo, Norway <joh@geo.uio.no>

Abstract: The purpose of this study is to describe the current state of tidewater glaciers in Svalbard as an extension of the inventory of Hagen *et al*. (1993). The ice masses of Svalbard cover an area of *ca* 36 600 km^2 and more than 60% of the glaciated areas are glaciers which terminate in the sea at calving ice-cliffs. Recent data on the geometry of glacier tongues, their flow velocities and front position changes have been extracted from ASTER images acquired from 2000–2006 using automated methods of satellite image analysis. Analyses have shown that 163 Svalbard glaciers are of tidewater type (having contact with the ocean) and the total length of their calving ice-cliffs is 860 km. When compared with the previous inventory, 14 glaciers retreated from the ocean to the land over a 30–40 year period. Eleven formerly land-based glaciers now terminate in the sea. A new method of assessing the dynamic state of glaciers, based on patterns of frontal crevassing, has been developed. Tidewater glacier termini are divided into four groups on the basis of differences in crevasse patterns and flow velocity: (1) very slow or stagnant glaciers, (2) slow-flowing glaciers, (3) fast-flowing glaciers, (4) surging glaciers (in the active phase) and fast ice streams. This classification has enabled us to estimate total calving flux from Svalbard glaciers with an accuracy appreciably higher than that of previous attempts. Mass loss due to calving from the whole archipelago (excluding Kvitøya) is estimated to be 5.0–8.4 $km^3\ yr^{-1}$ (water equivalent – w.e.), with a mean value 6.75 ± 1.7 $km^3\ yr^{-1}$ (w.e.). Thus, ablation due to calving contributes as much as 17–25% (with a mean value 21%) to the overall mass loss from Svalbard glaciers. By implication, the contribution of Svalbard iceberg flux to sea-level rise amounts to *ca* 0.02 $mm\ yr^{-1}$. Also calving flux in the Arctic has been considered and the highest annual specific mass balance attributable to iceberg calving has been found for Svalbard.

Key words: Arctic, Svalbard, tidewater glaciers, calving flux, ASTER.

- Data from the increasing constellation of Earth observation satellites, combined with bedrock and bathymetry datasets allow the monitoring of all components of Svalbard glacier mass balance at annual resolution.

- **Aim**: to combine Sentinel-2 optical imagery, CryoSat-2 radar altimetry, ice velocity maps, and digital elevation models of ice surface, bedrock and bathymetry and potentially additional datasets to monitor calving front advance and retreat (and resulting mass change), geodetic mass balance, total mass balance, sea level rise contribution, tidewater glacier discharge, surging, and freshwater flux; and make result available to glaciologists and the wider Svalbard scientific community.



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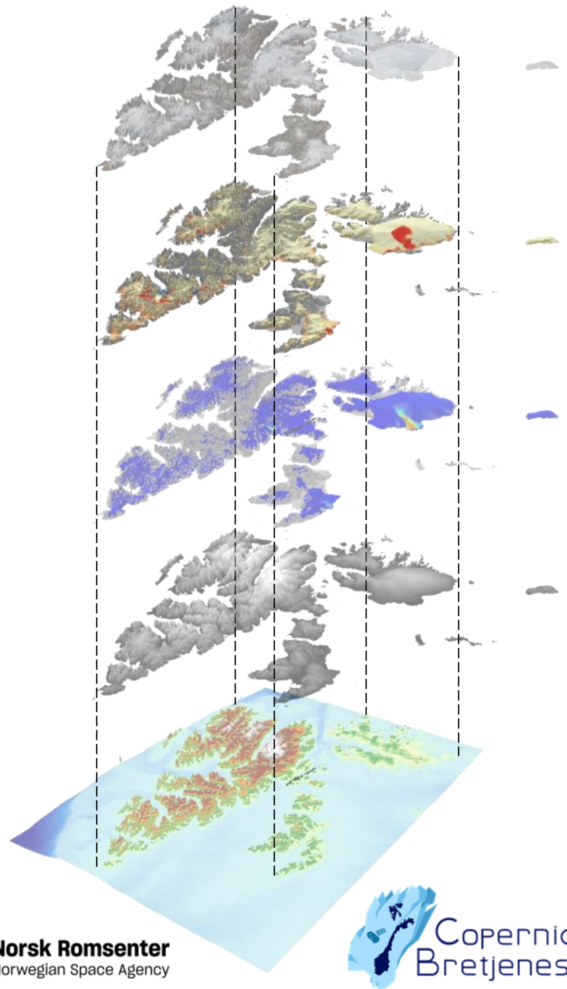

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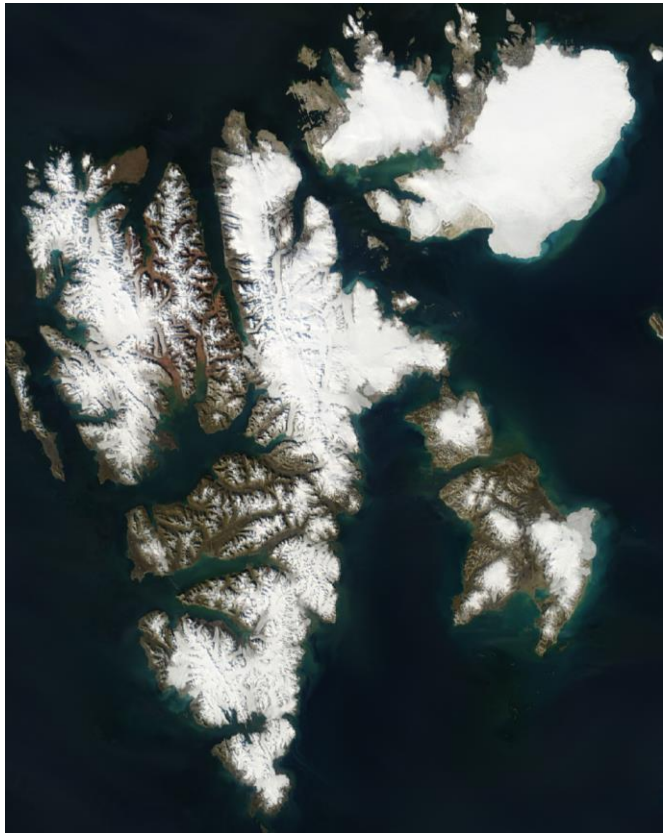
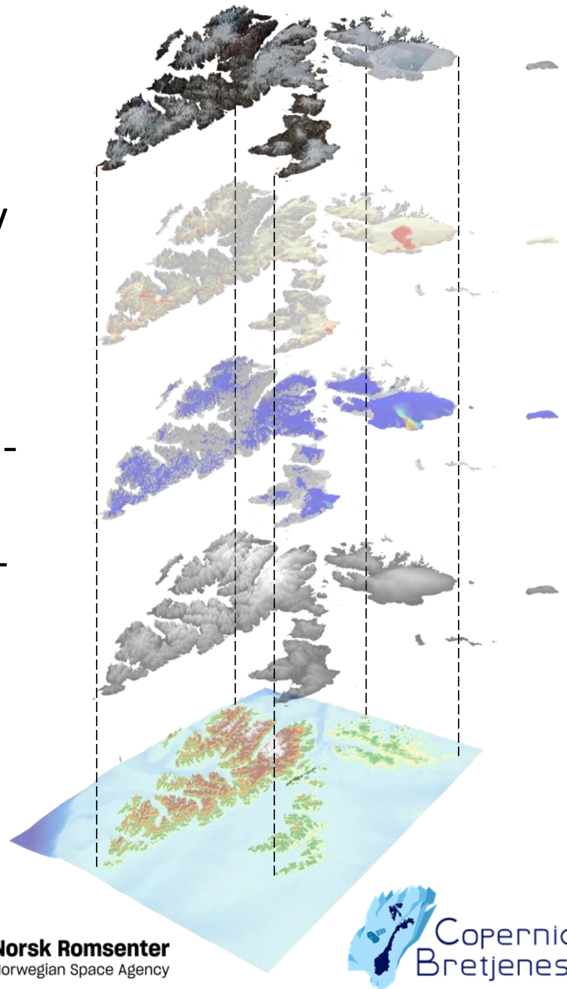
Datasets: Sentinel-2 optical imagery



- Polar night and frequent cloud cover limits availability of scenes for digitising calving front position.
- Short revisit time of Sentinel-2 A/B increases likelihood of acquisition of a suitable late-summer cloud-free image.
- Supplemented by Landsat-8 OLI imagery.



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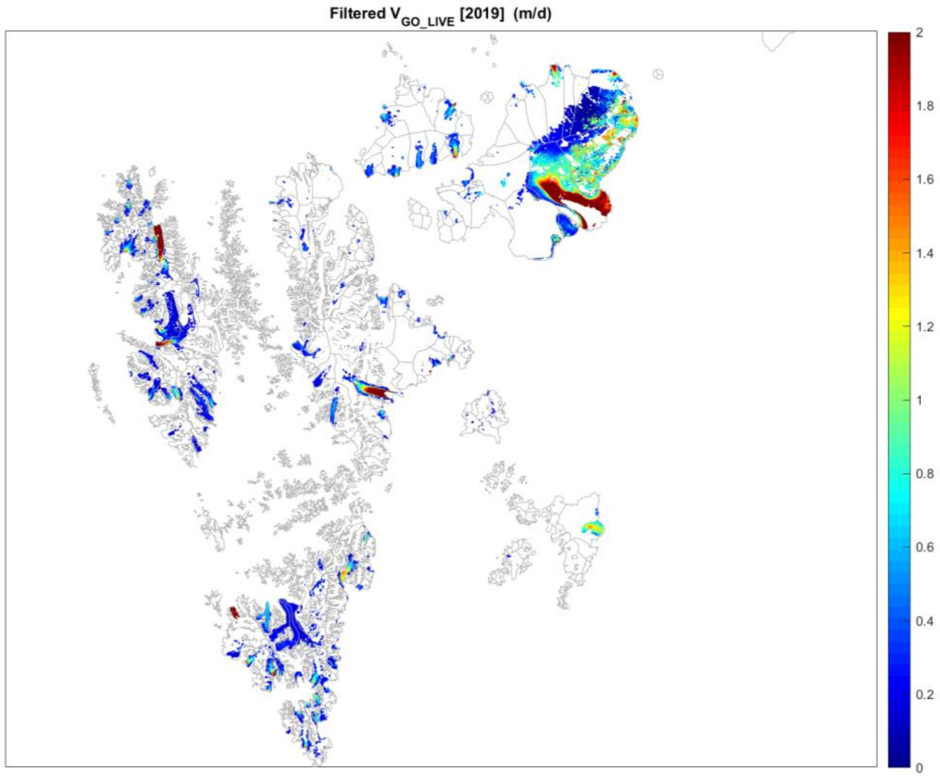
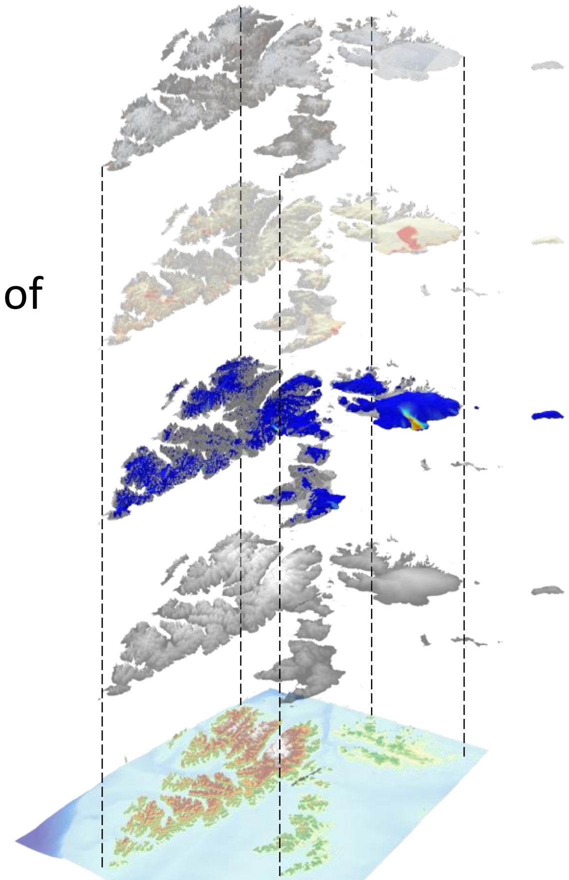
Datasets: Ice velocity



- Velocity from NASA GoLIVE and ITS_LIVE and feature tracking of sentinel imagery (Adrian Luckman at Swansea University.



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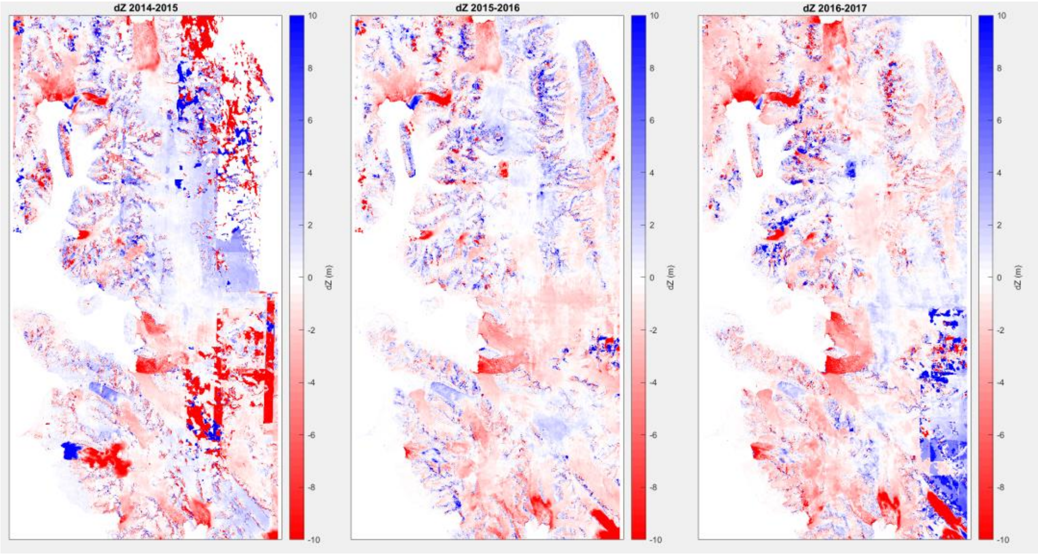
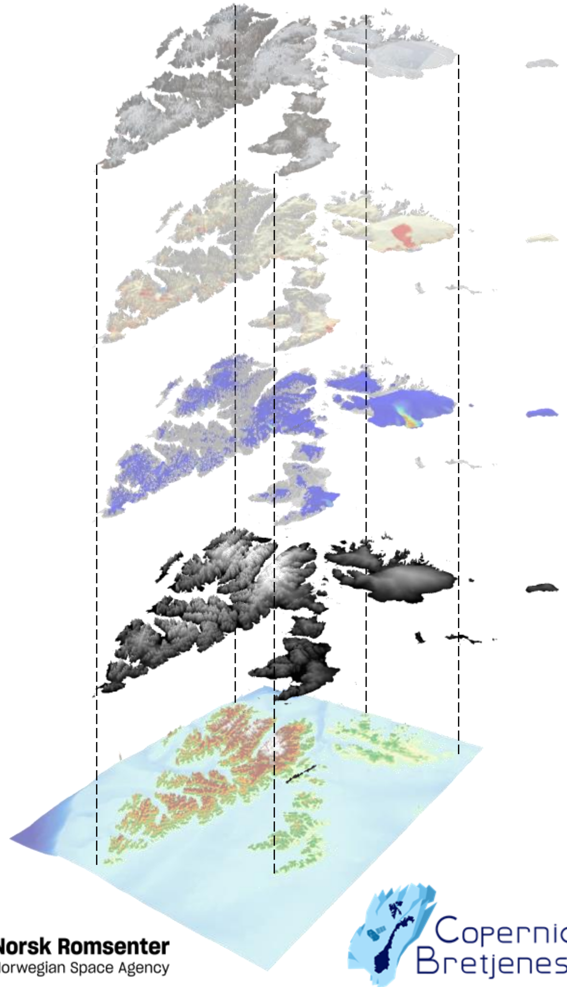
Datasets: Ice surface DEM

- Discharge calculations currently implemented with fixed ice surface DEM (NP DEM).
- Working on implementing annual DEMs from ArcticDEM





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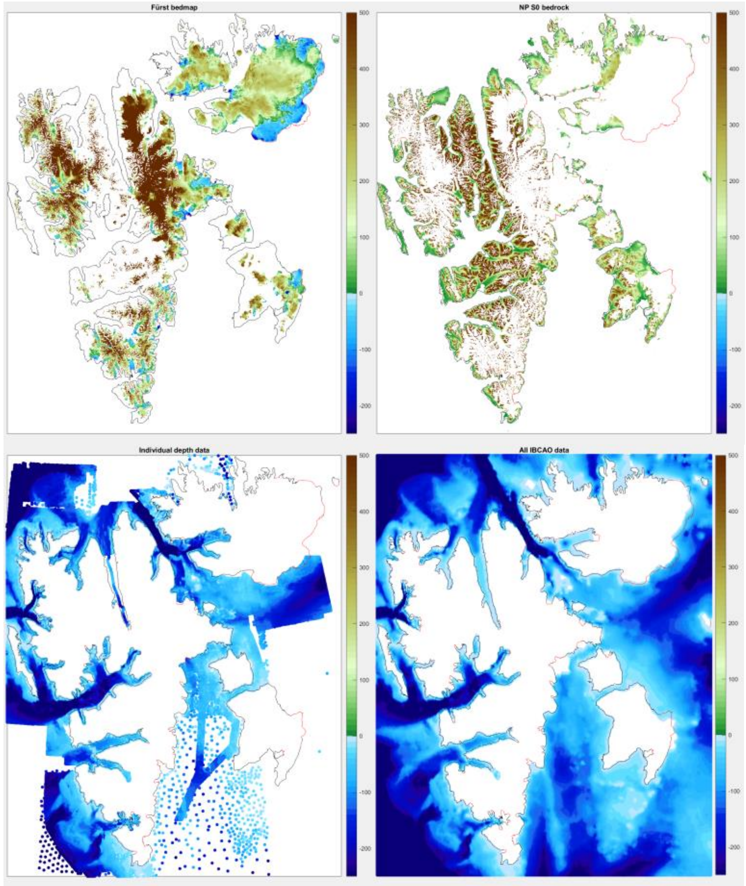
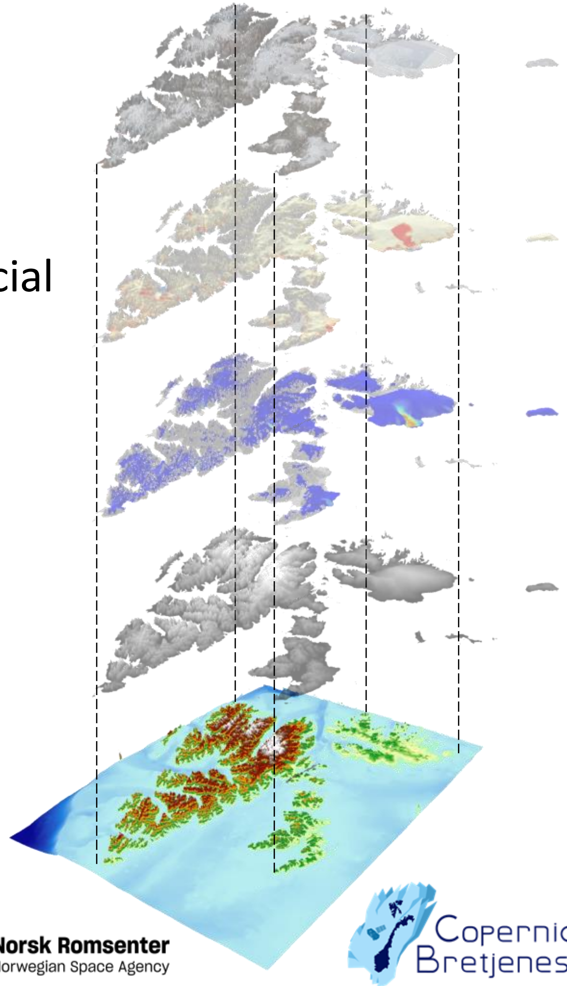
Datasets: bedrock and bathymetry DEM



- (near calving front) thickness of Svalbard tidewater glaciers until recently poorly constrained. Crucial in estimating discharge.
- Combined Fürst et al. (2018) ice free topography with fjord bathymetric observations supplemented by International Bathymetric Chart of the Arctic Ocean.
- Realistic terminus/flux gate thickness estimates.



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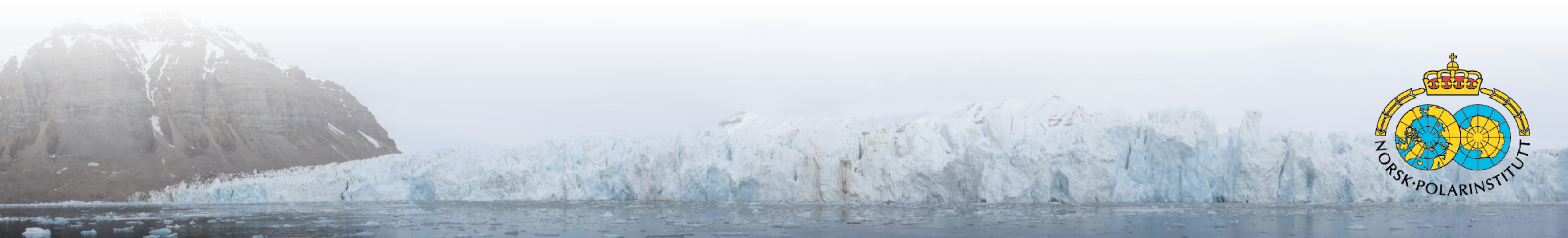

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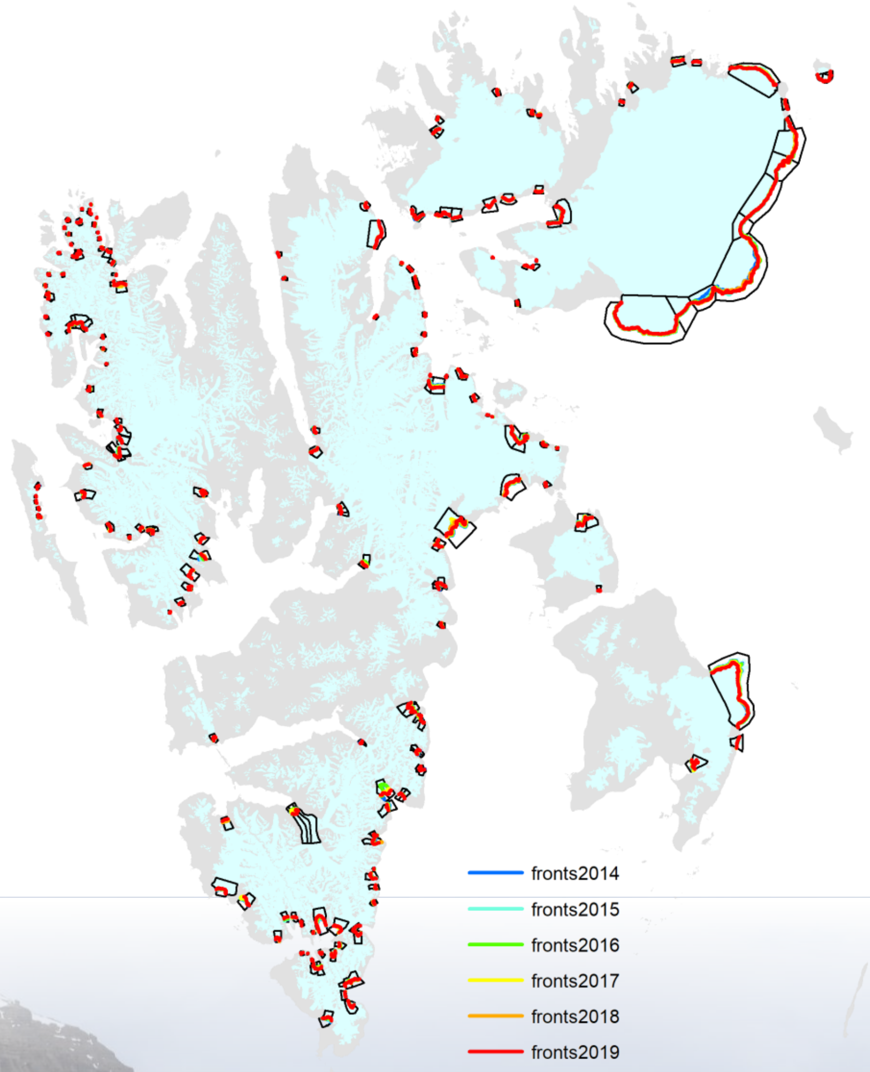
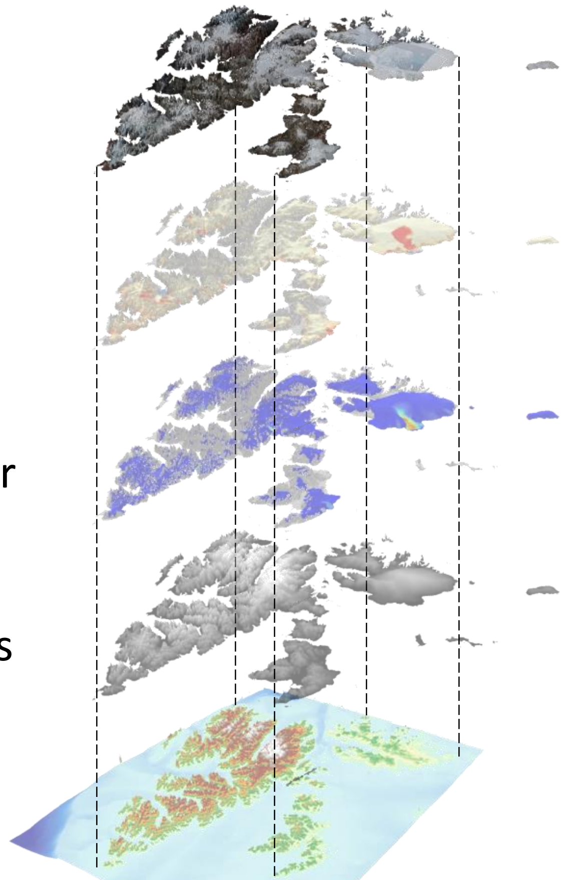
Results: Calving front advance/retreat



- Defined polygons for all ~800km of calving fronts around the archipelago.
- Digitised late-summer calving front positions for all glaciers 2013-2019.
- Retreat rate calculated as area change divided by glacier width.



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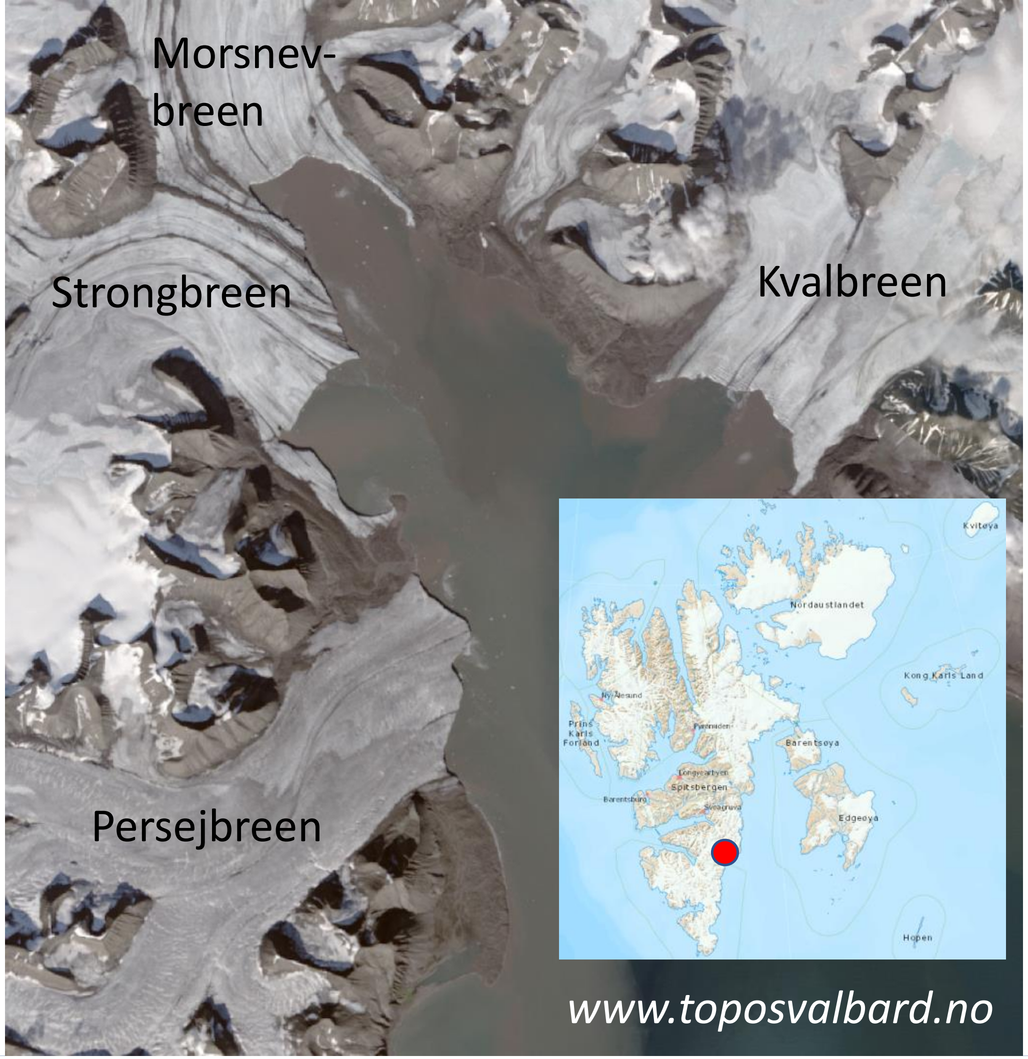
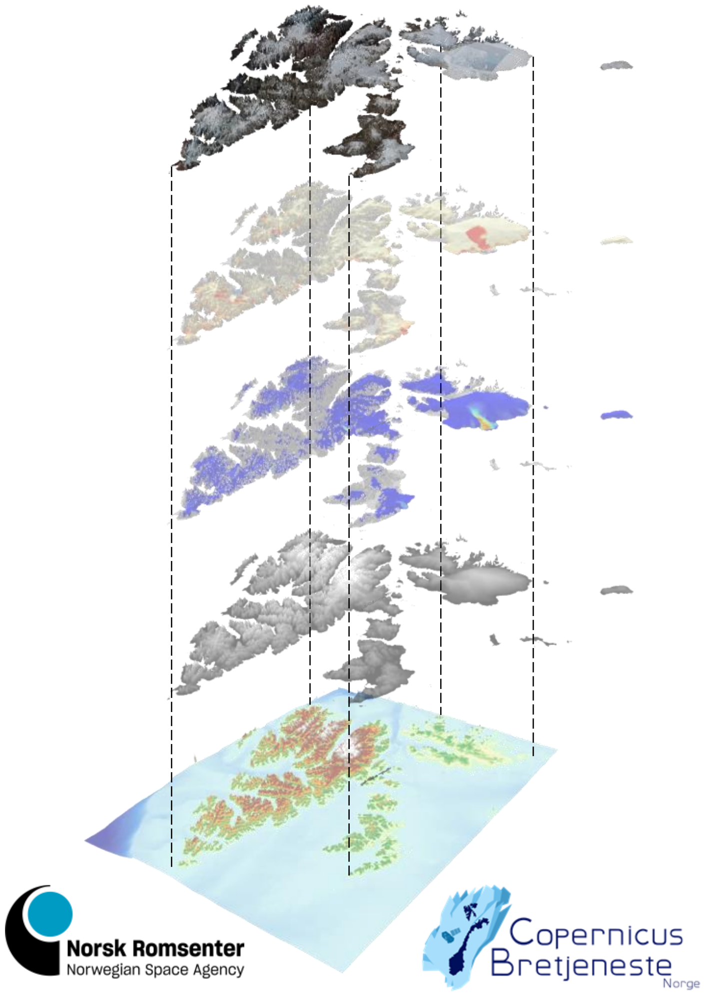


Morsnev-
breen
Strongbreen
Kvalbreen
Persejbreen
Kvitøya
Nordaustlandet
Kong Karls Land
Barentsøya
Spitsbergen
Edgeøya
Hopen
www.toposvalbard.no



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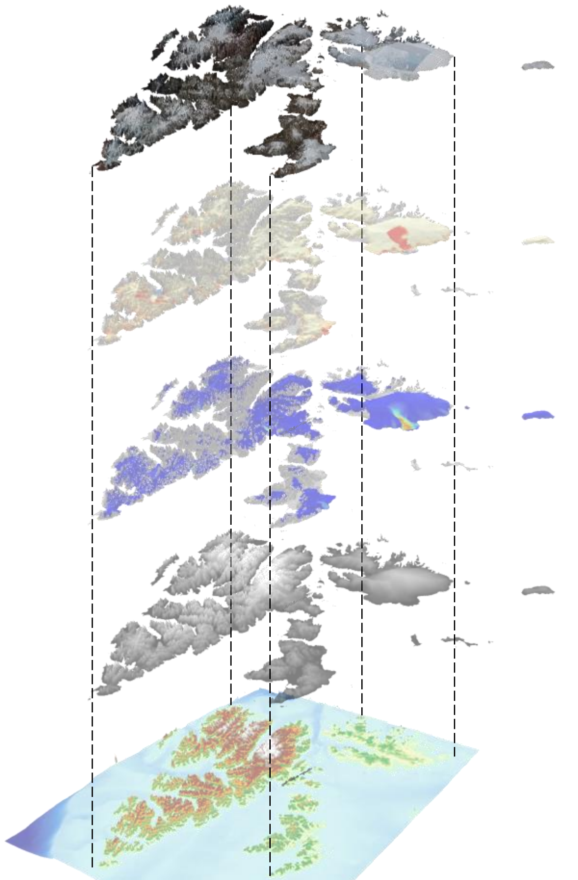

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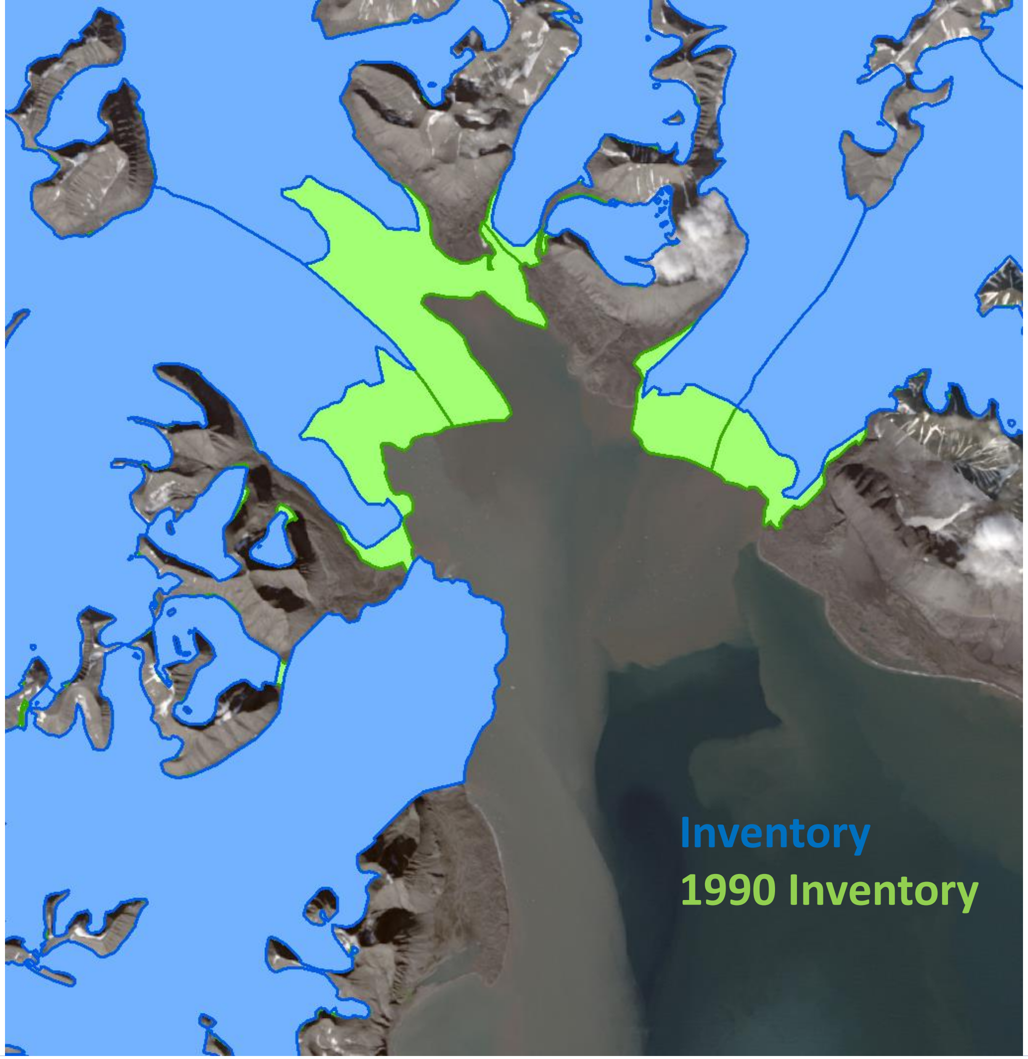

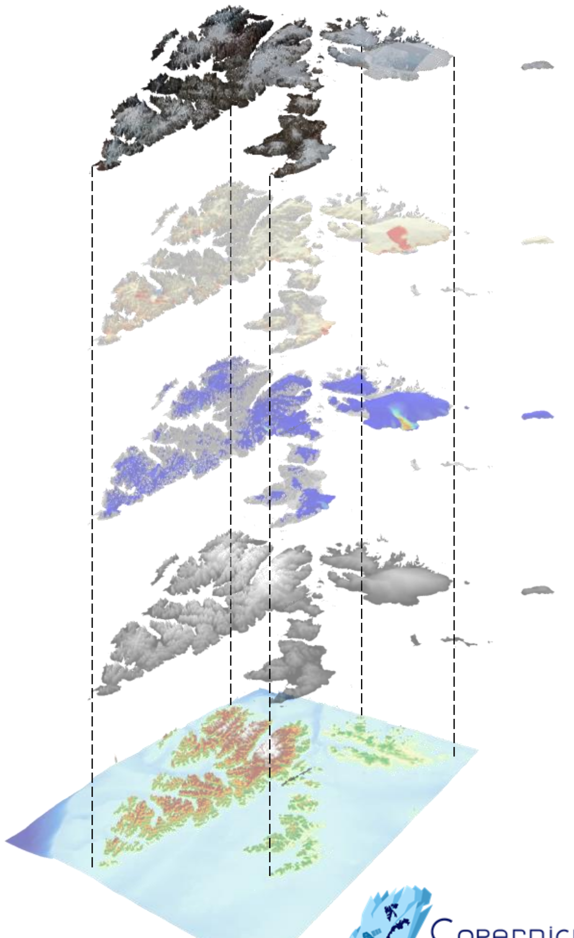

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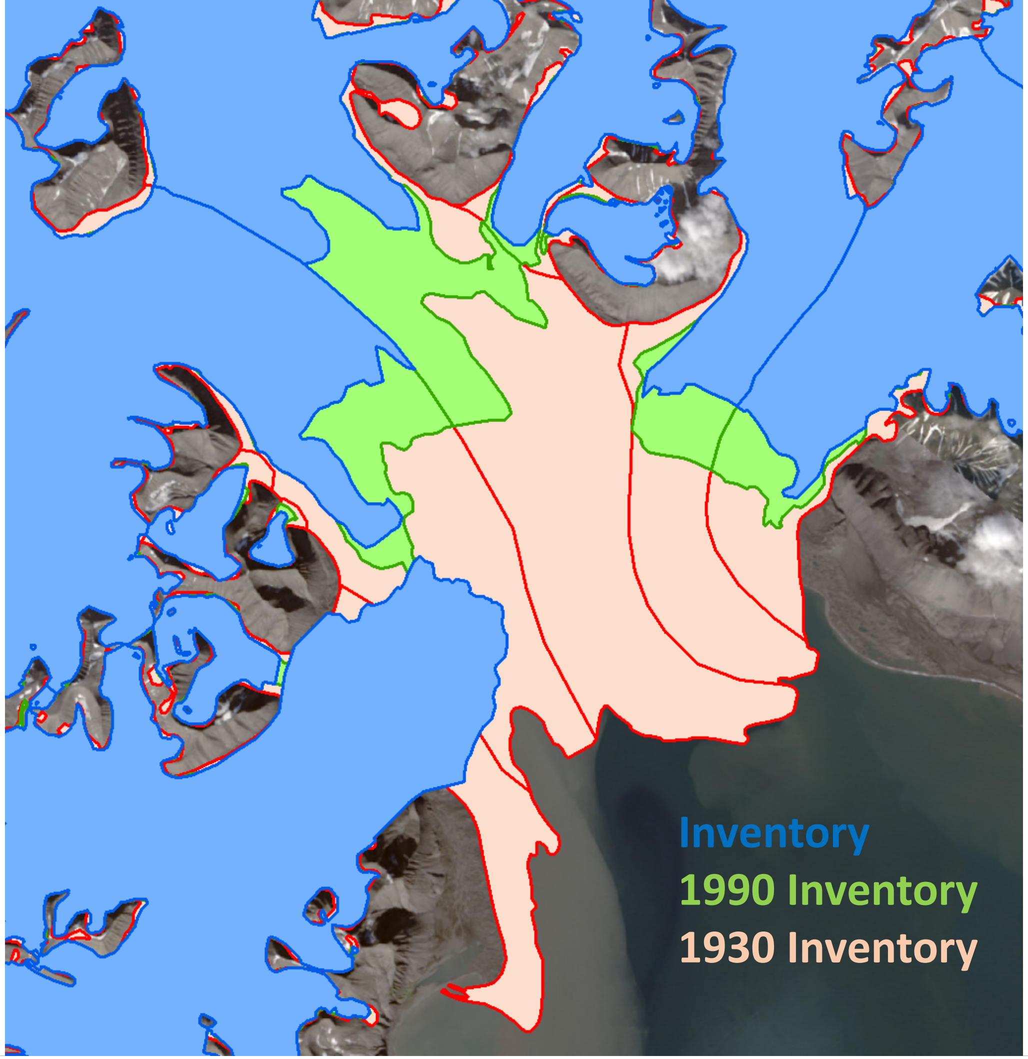

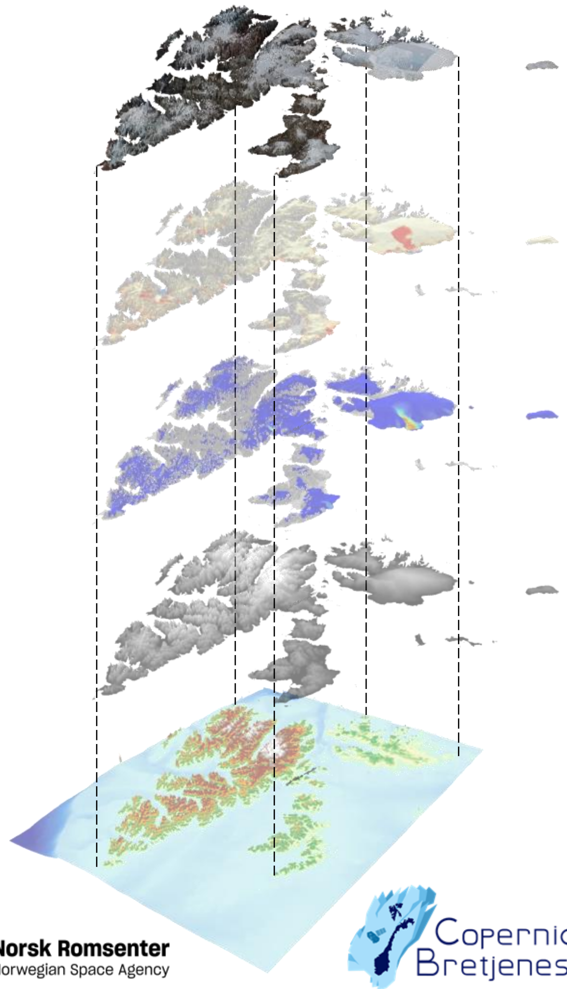

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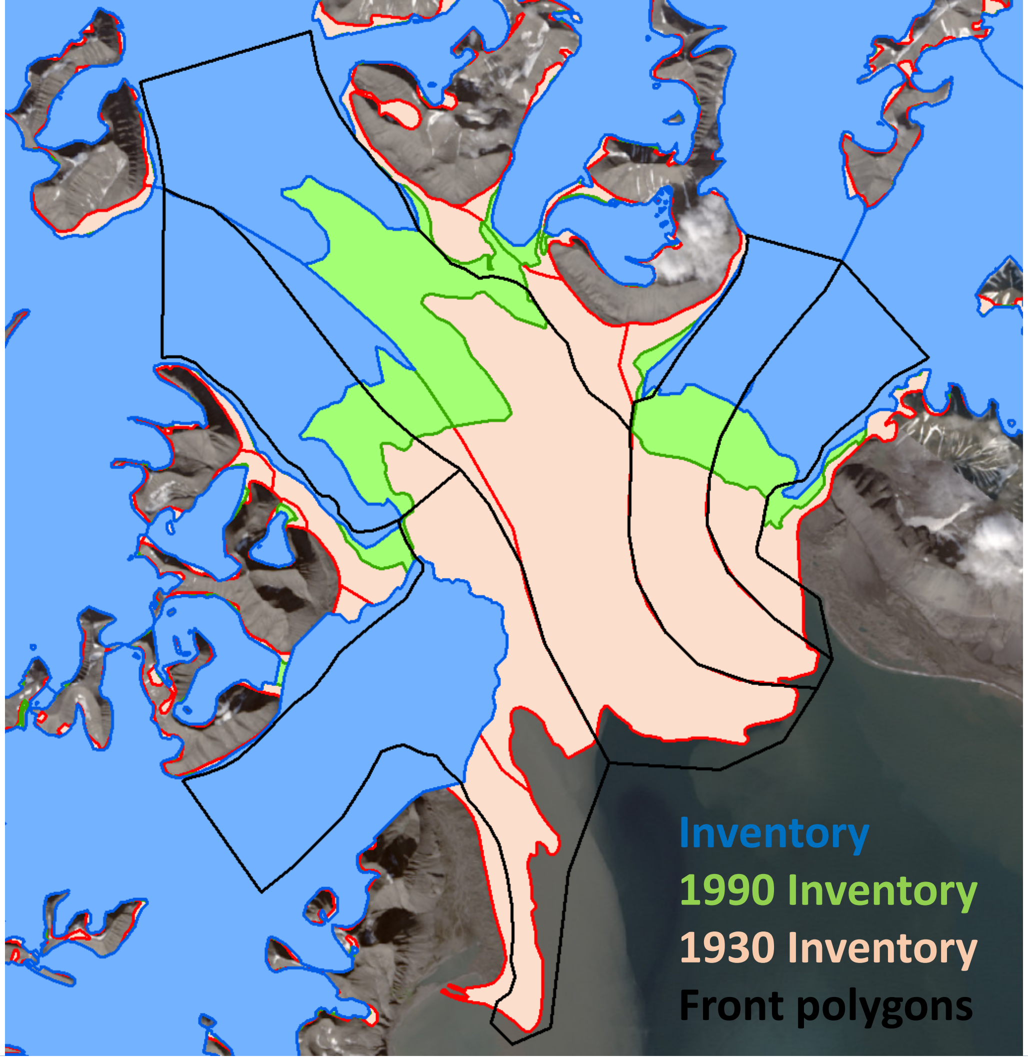

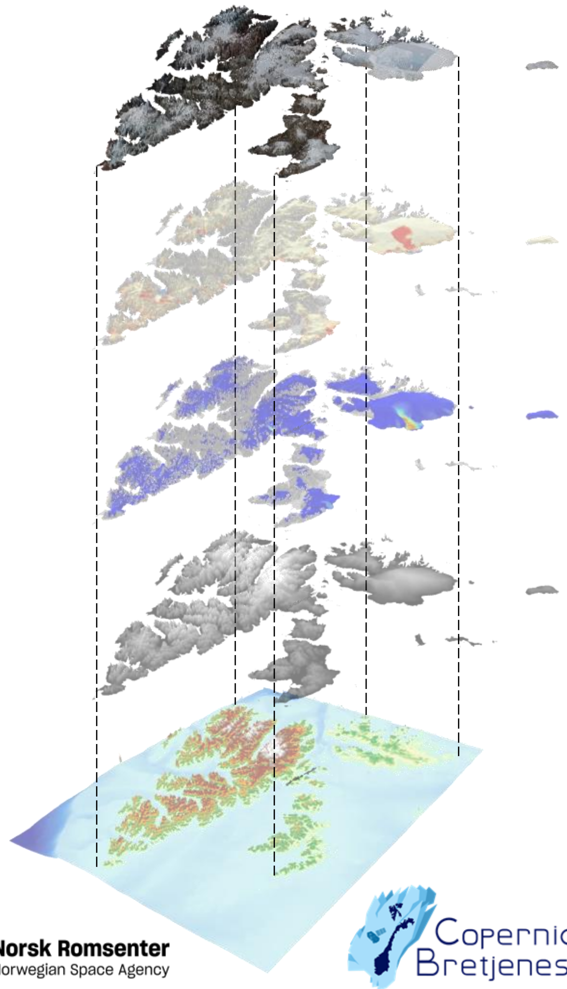

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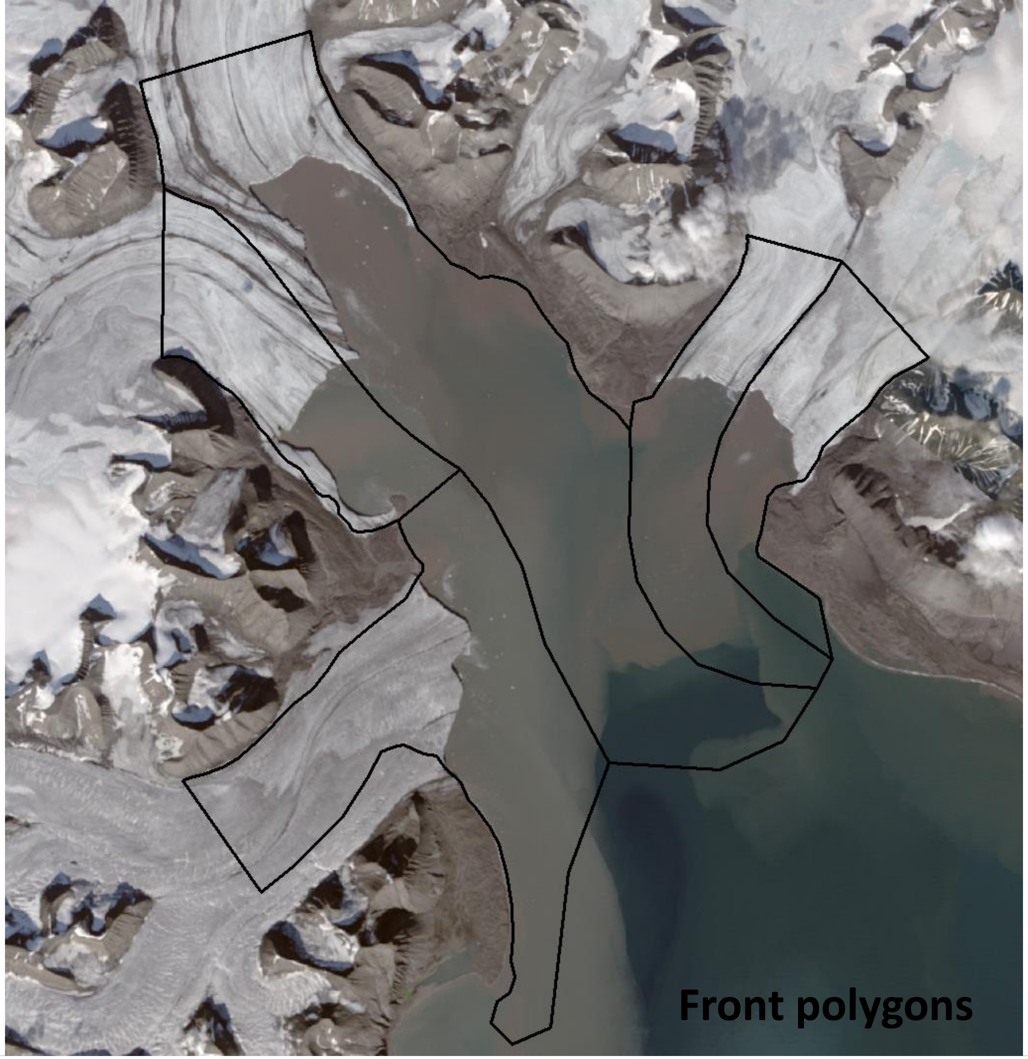
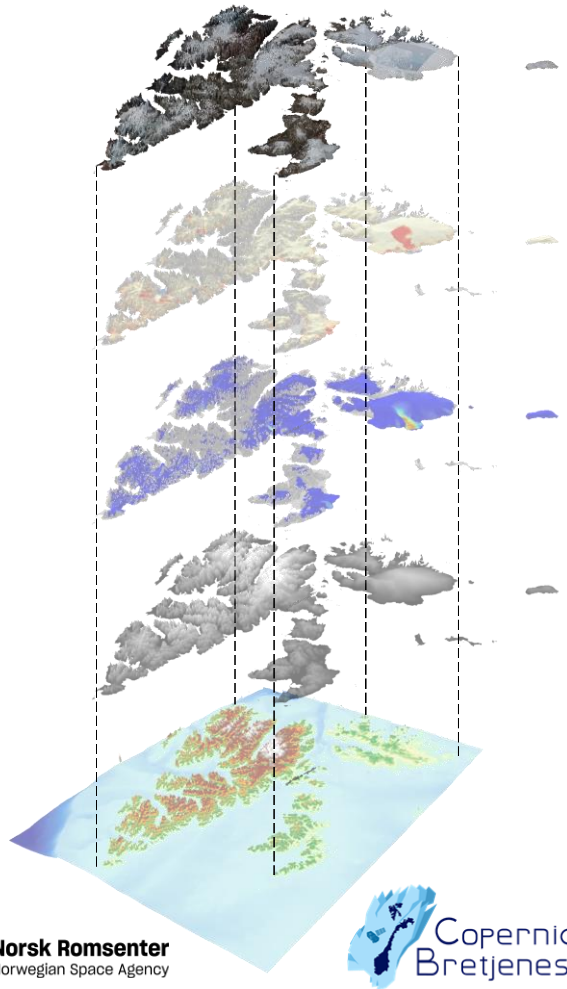

Front polygons



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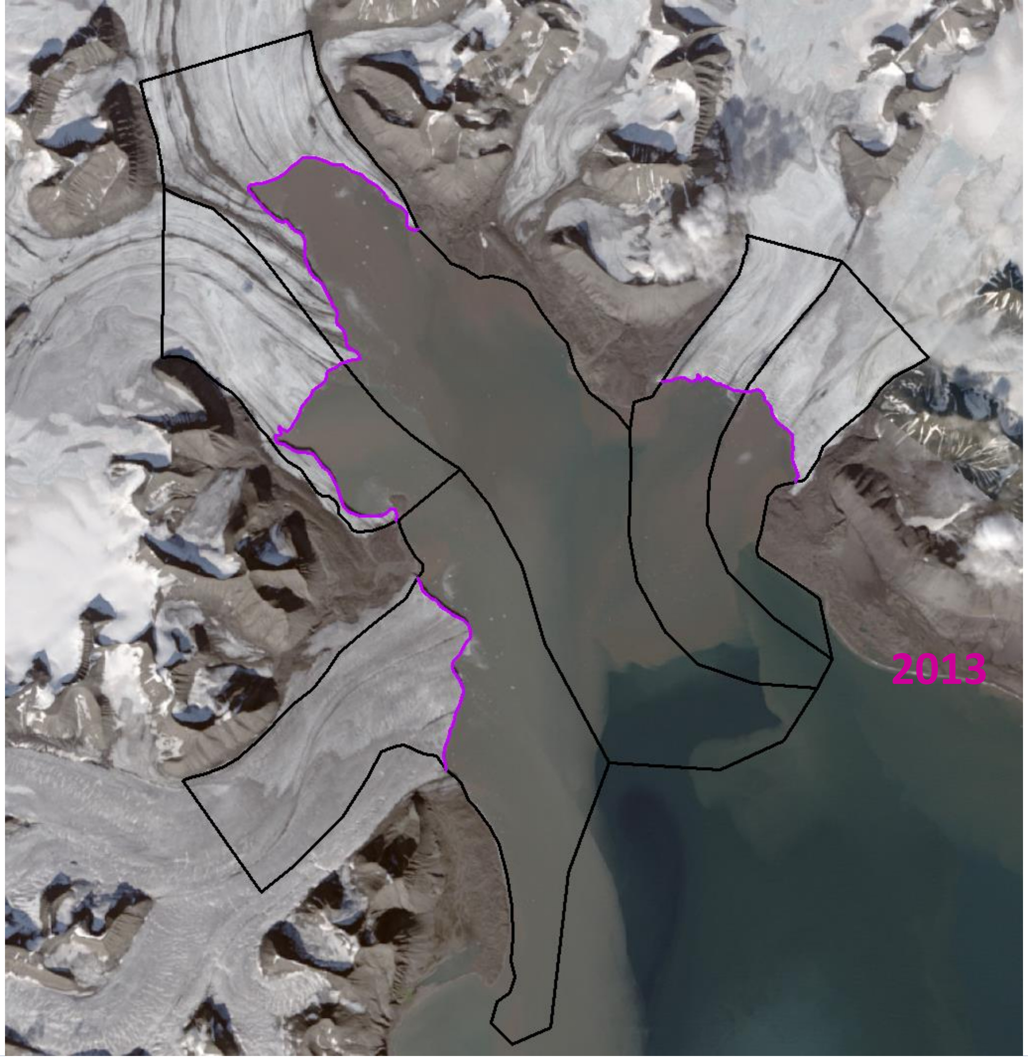

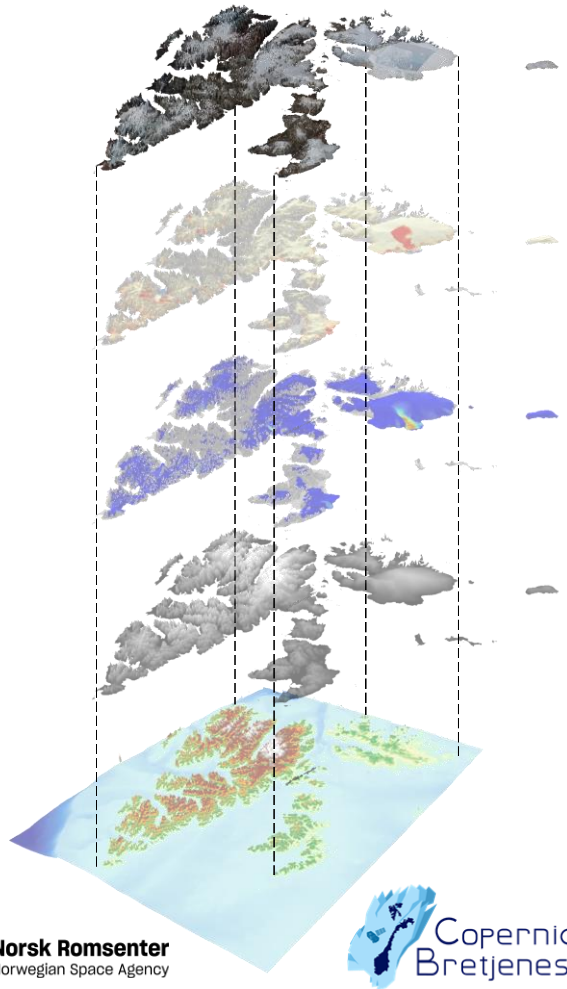

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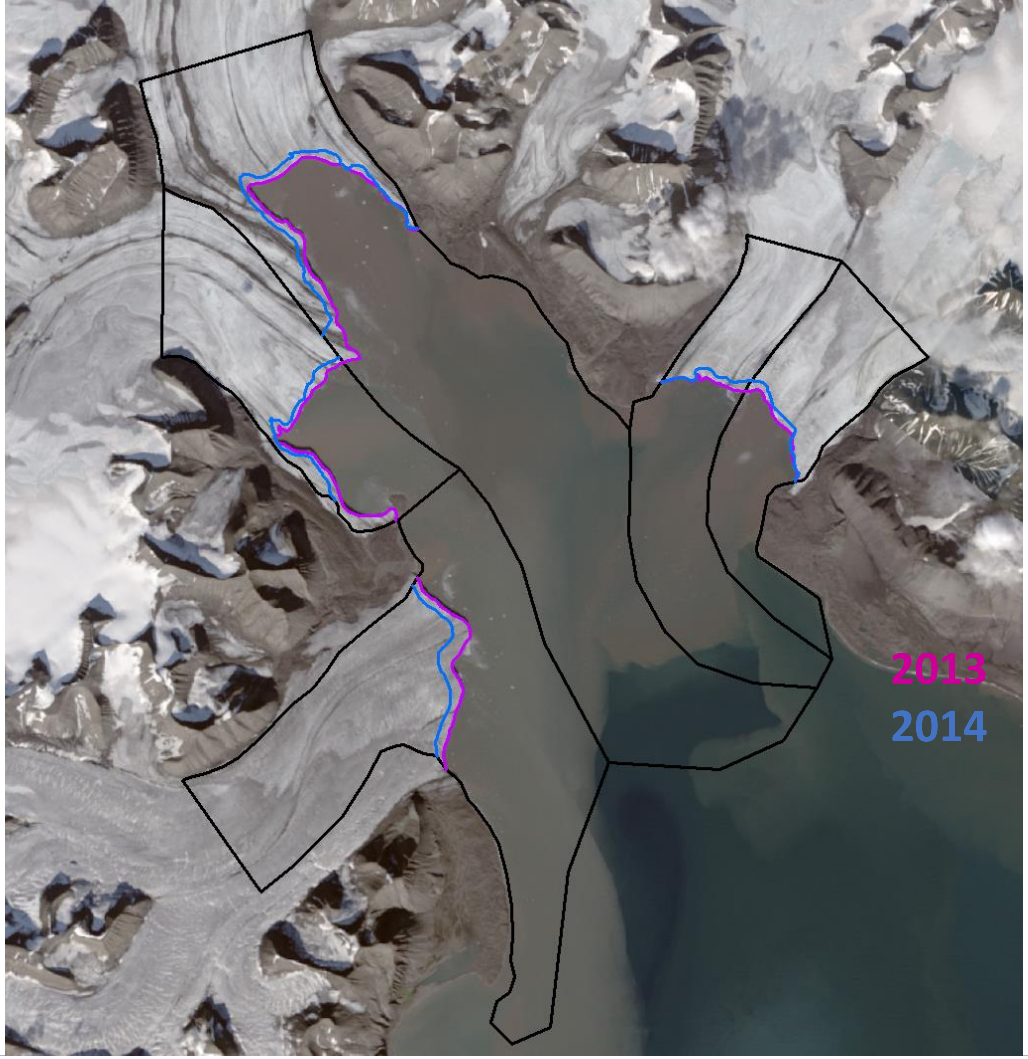

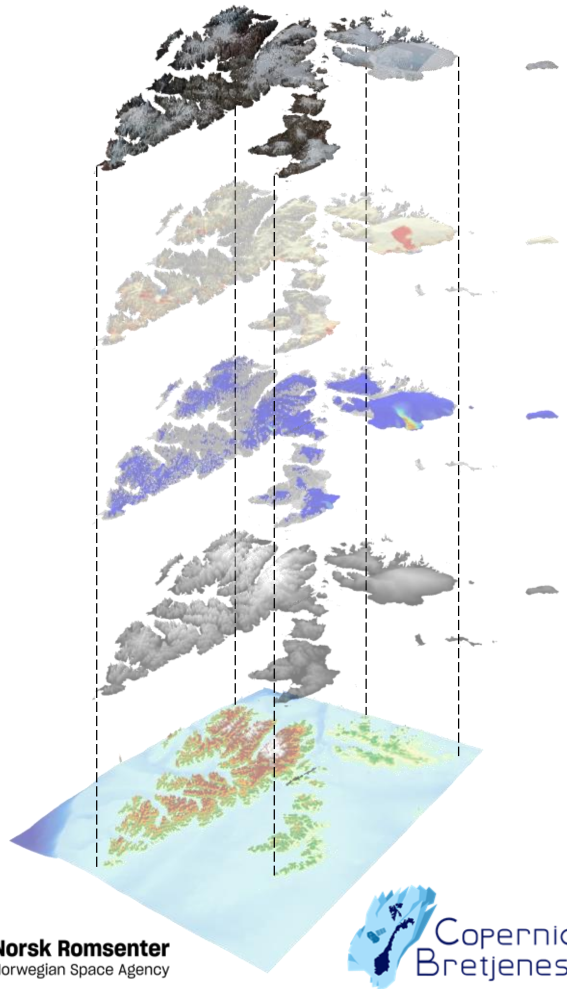

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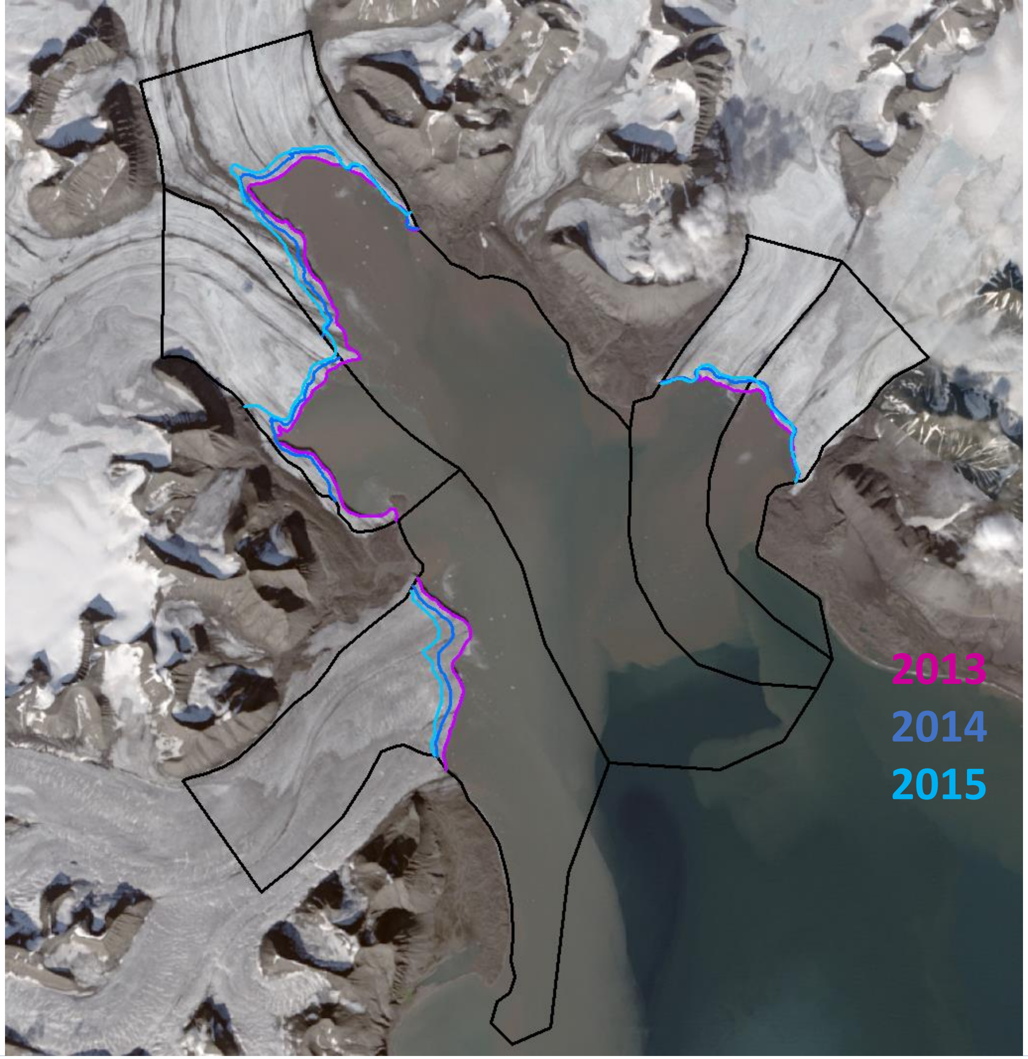

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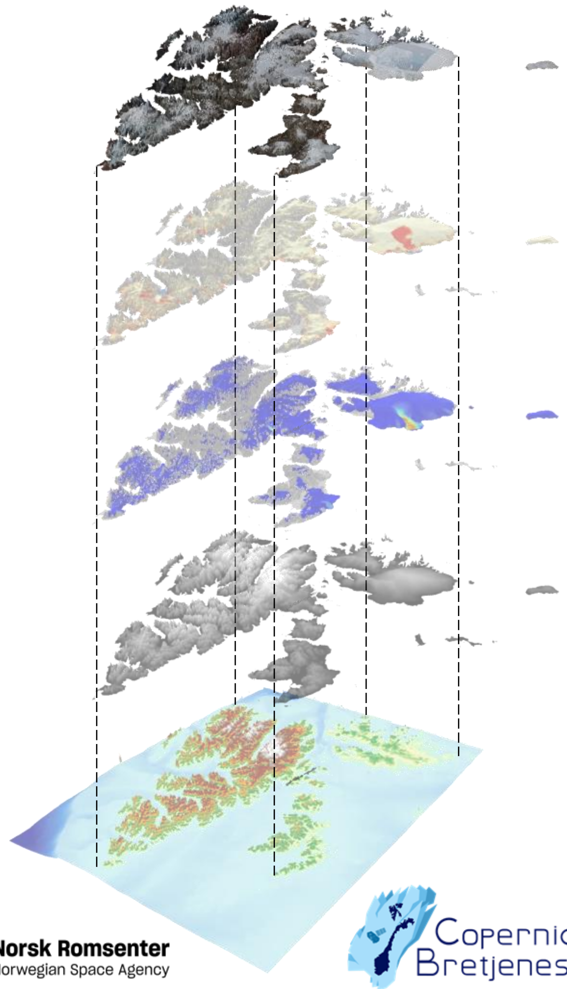
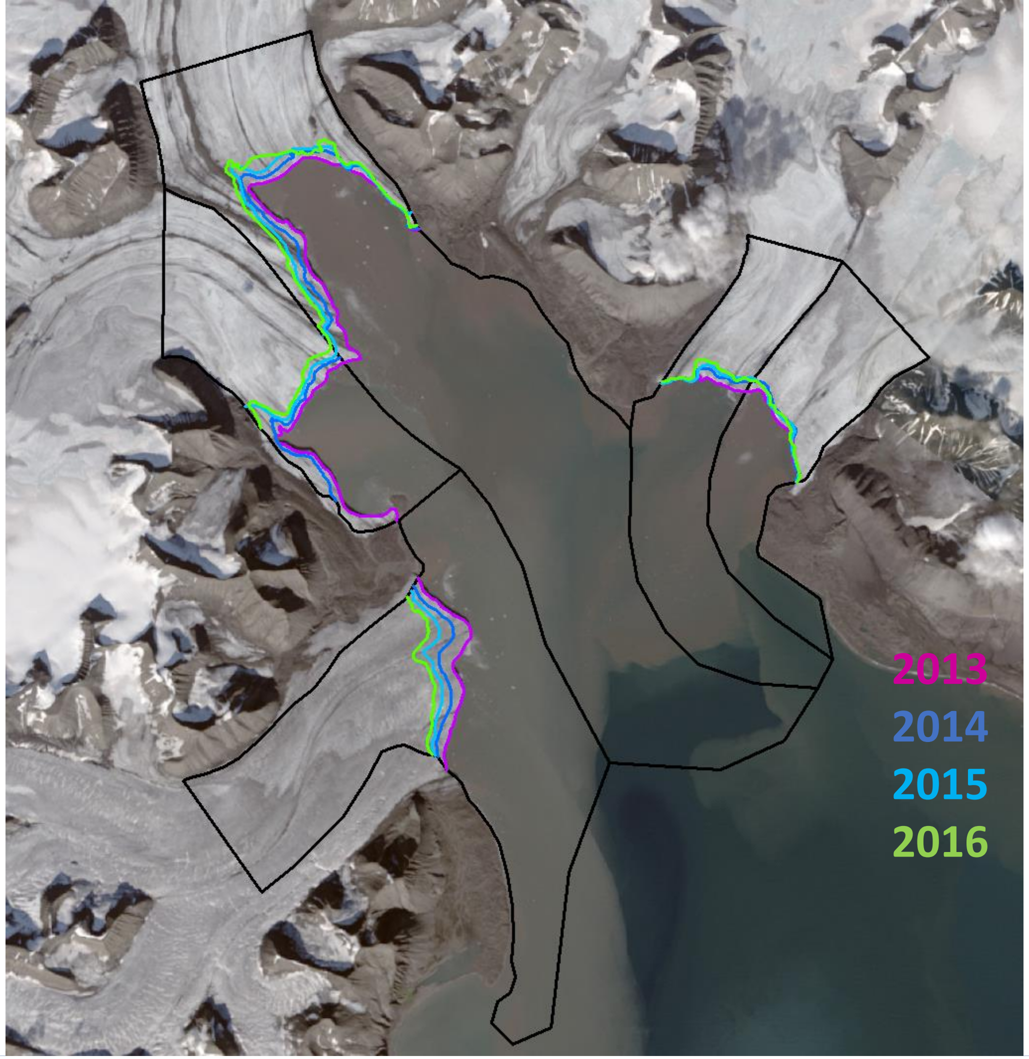
2015

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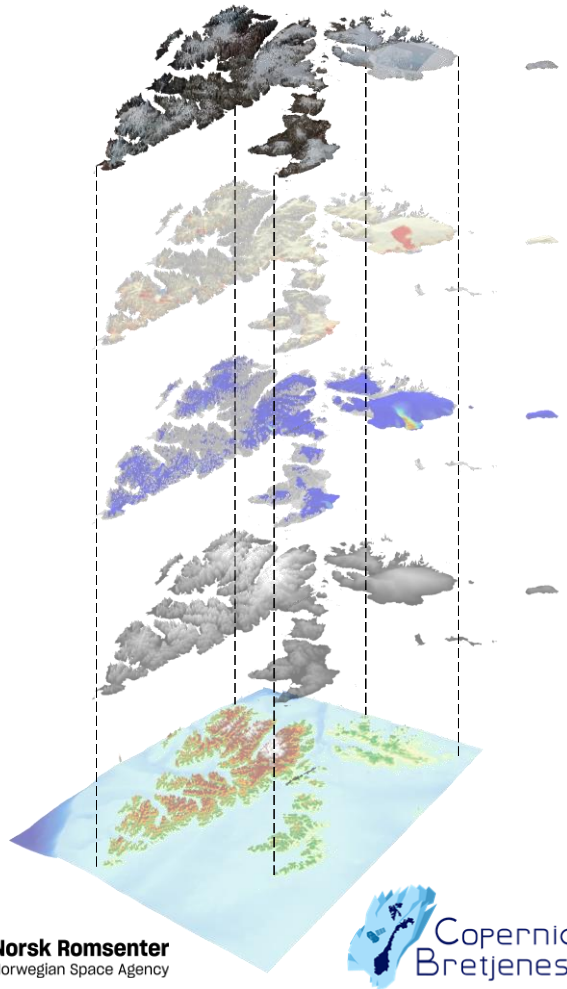

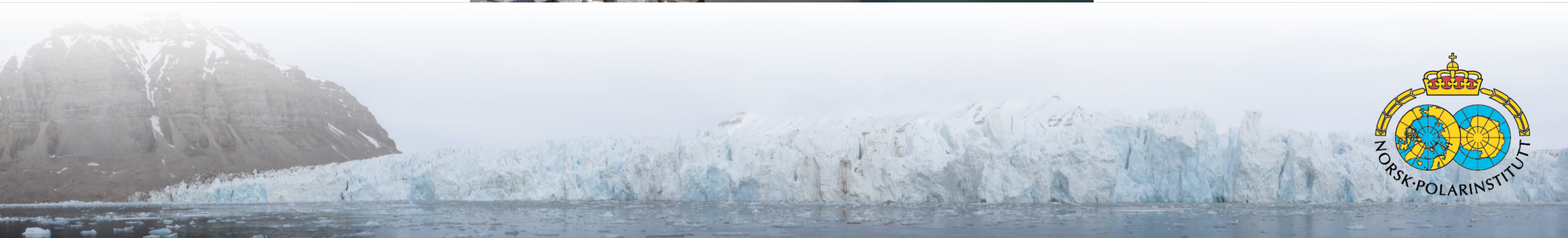

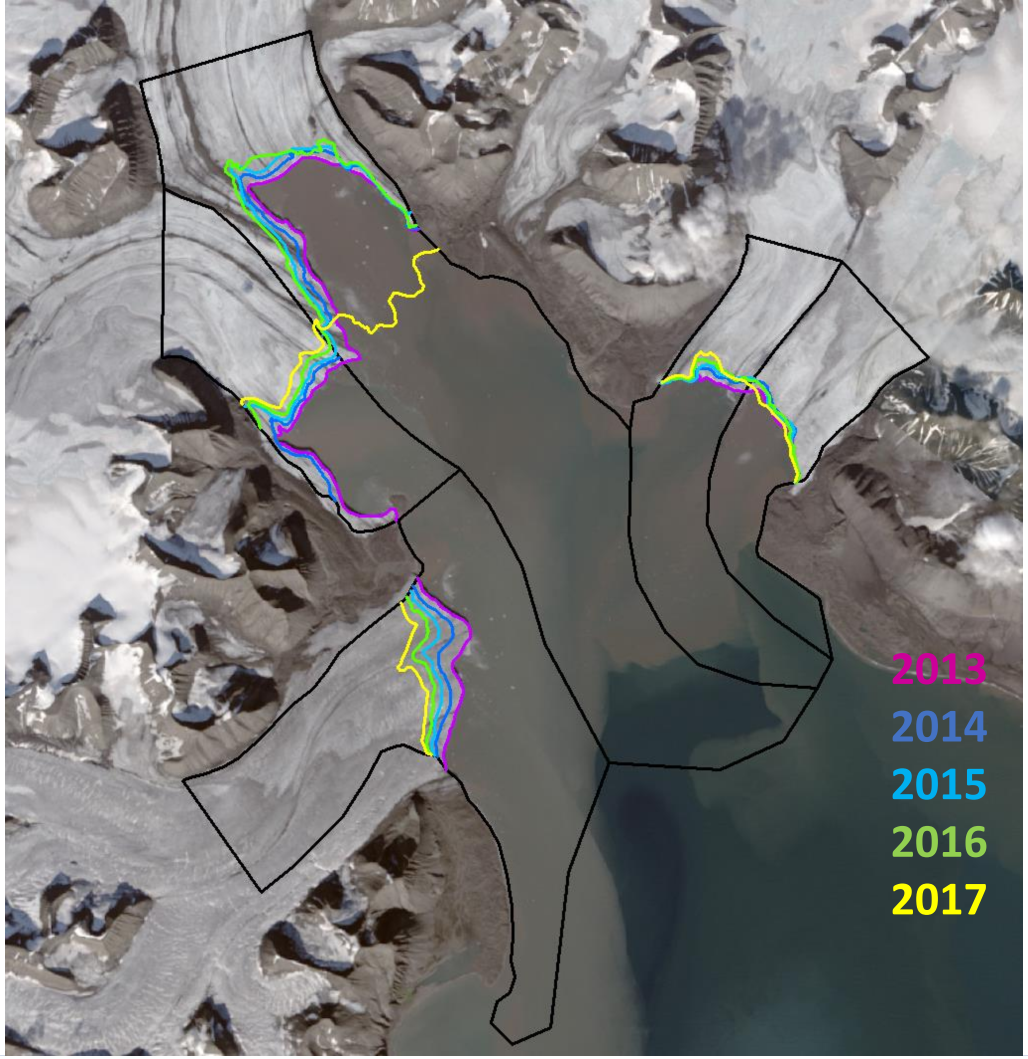
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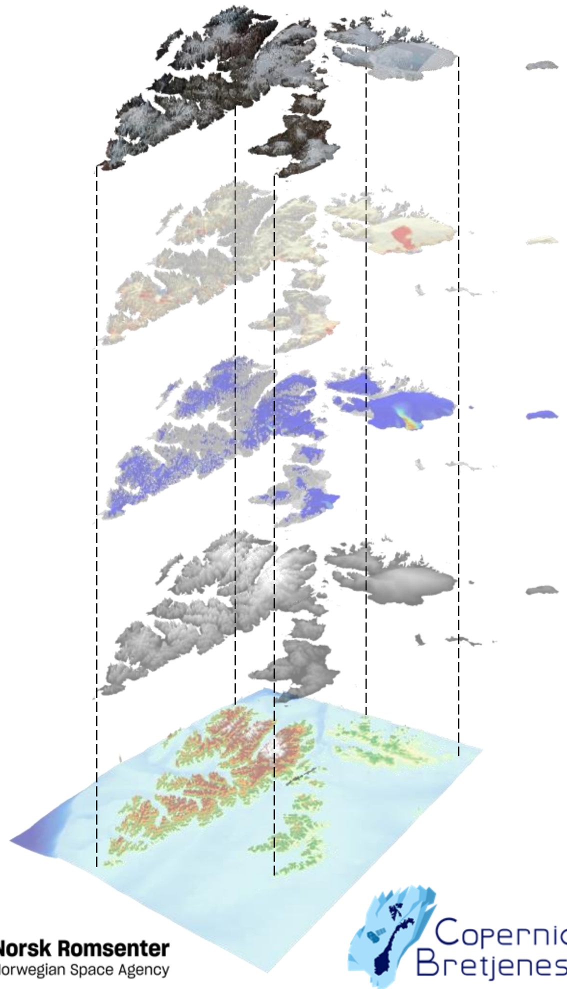
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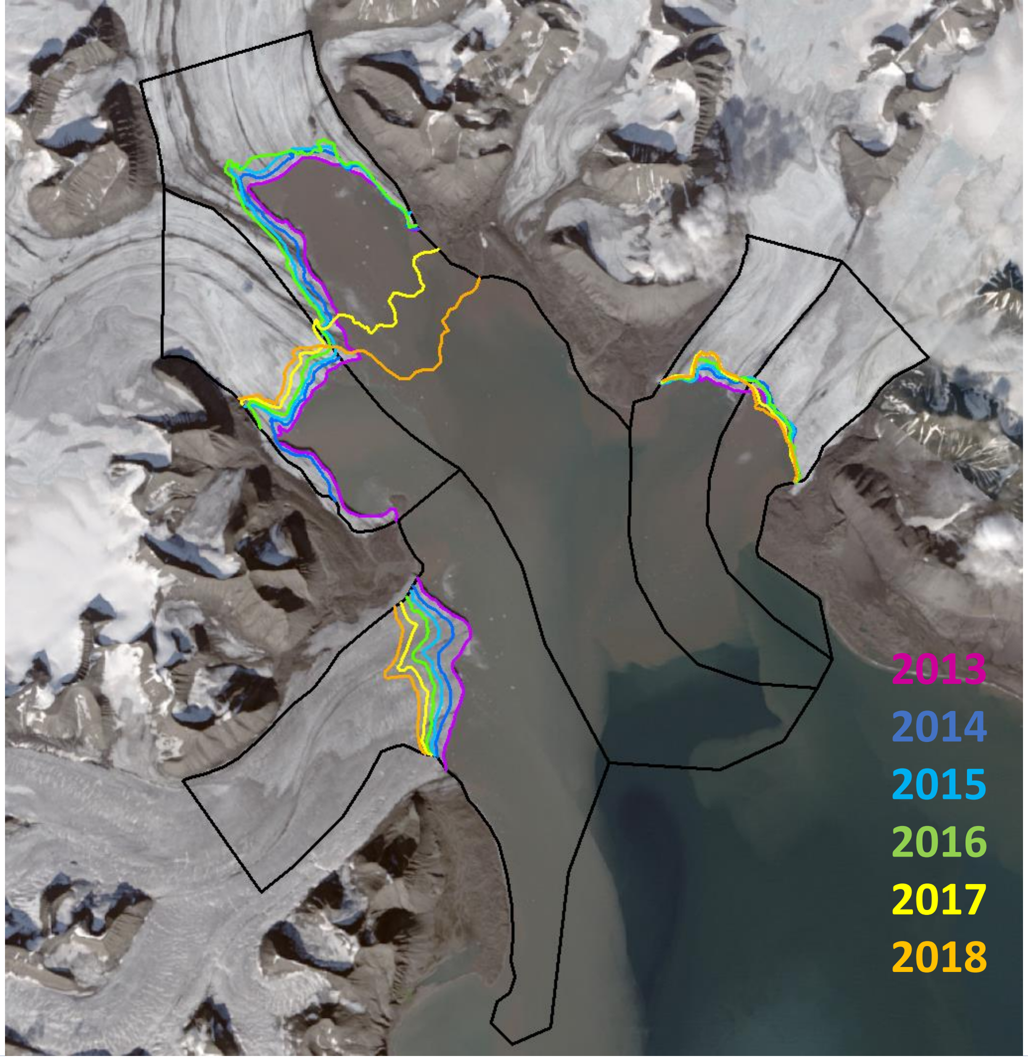

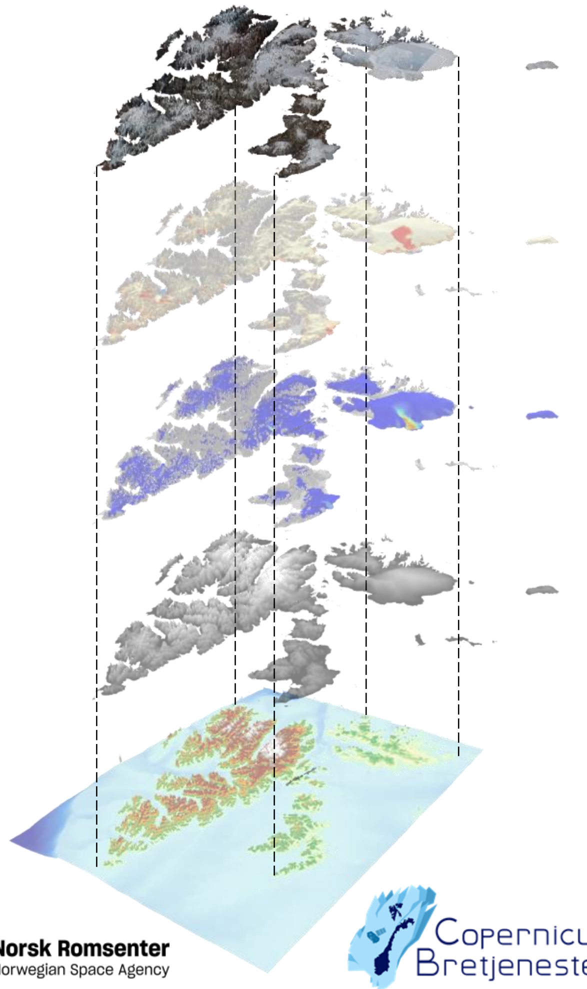

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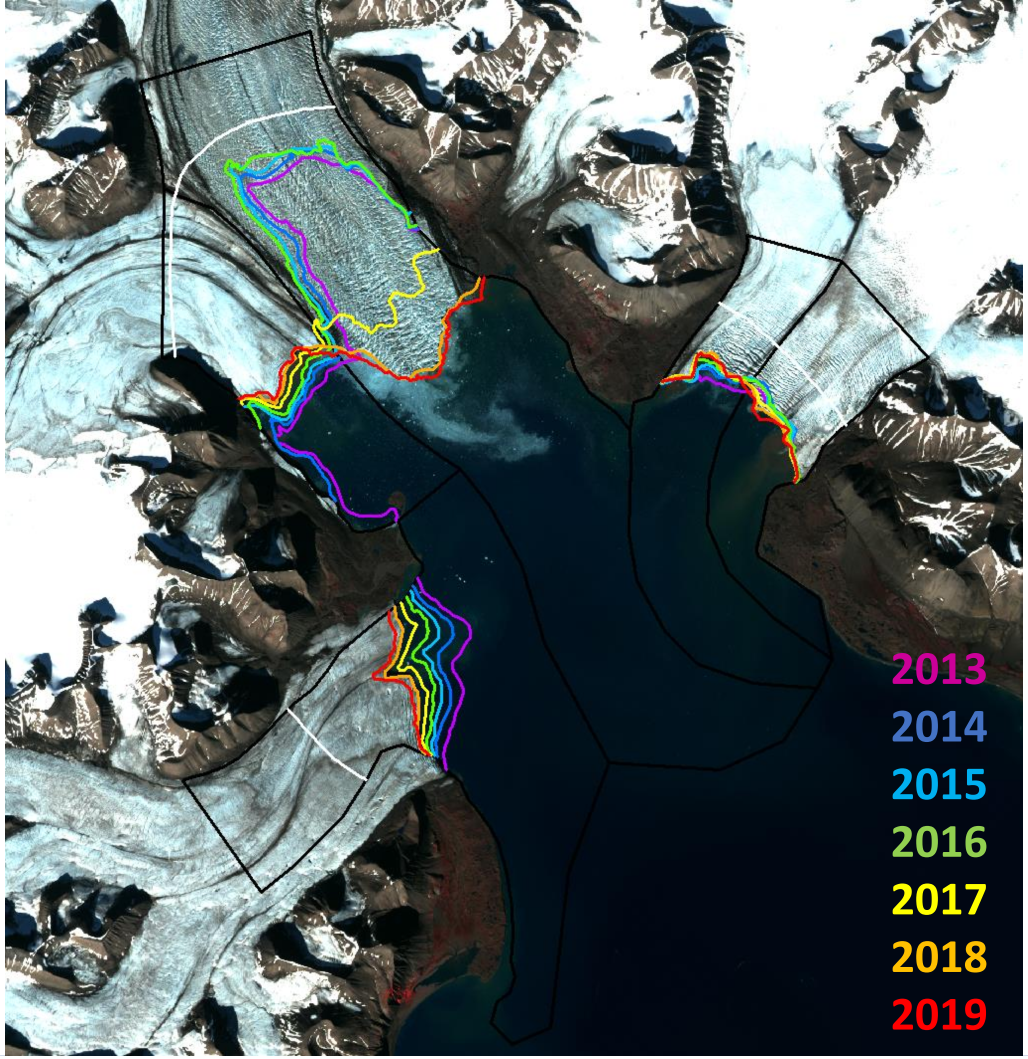

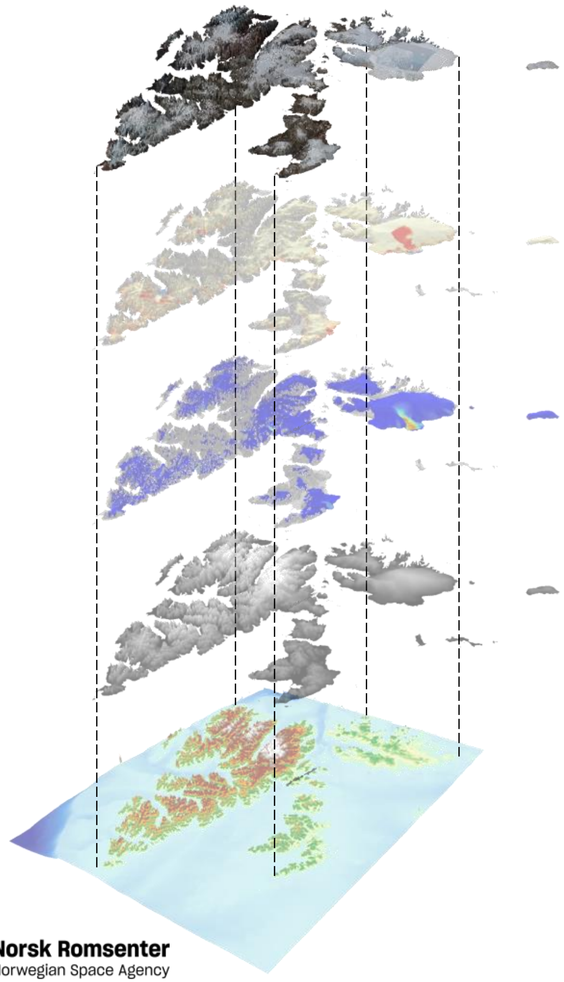

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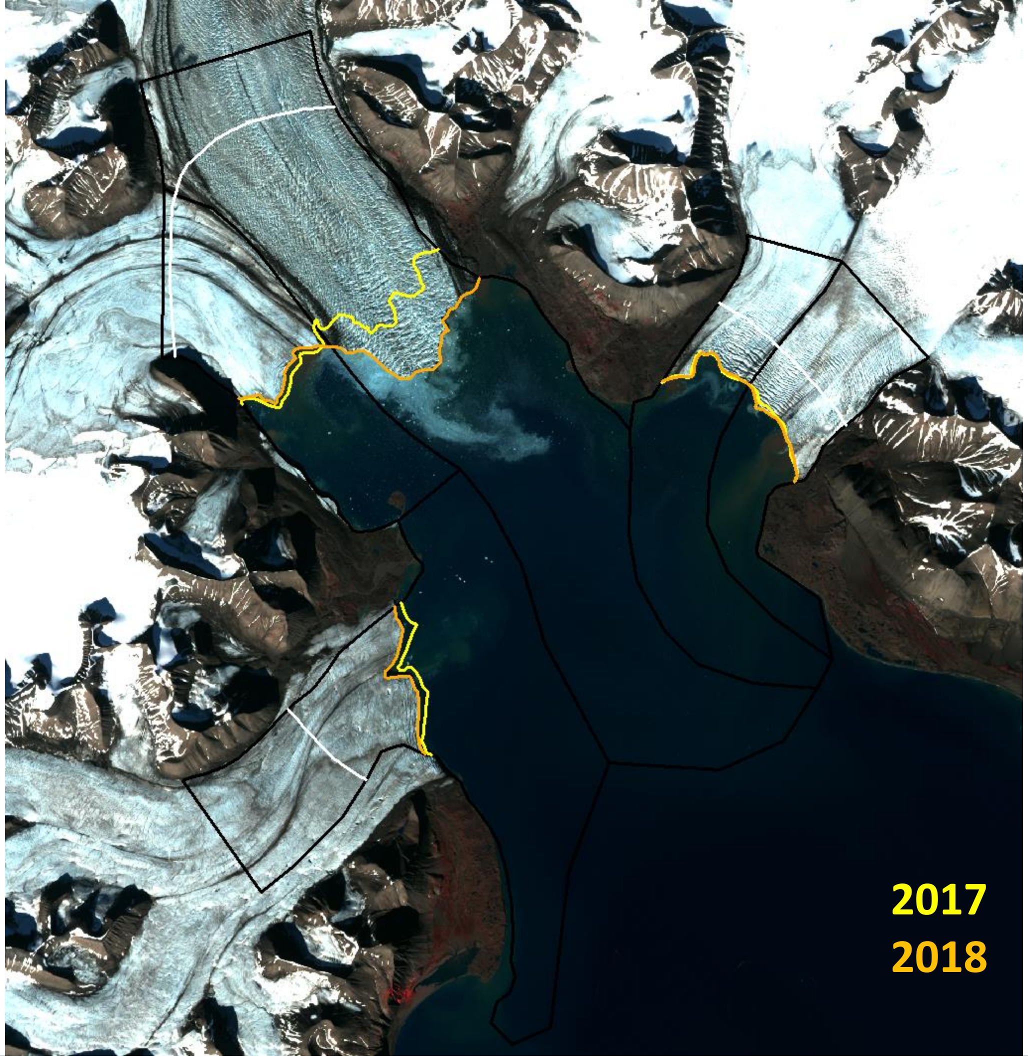

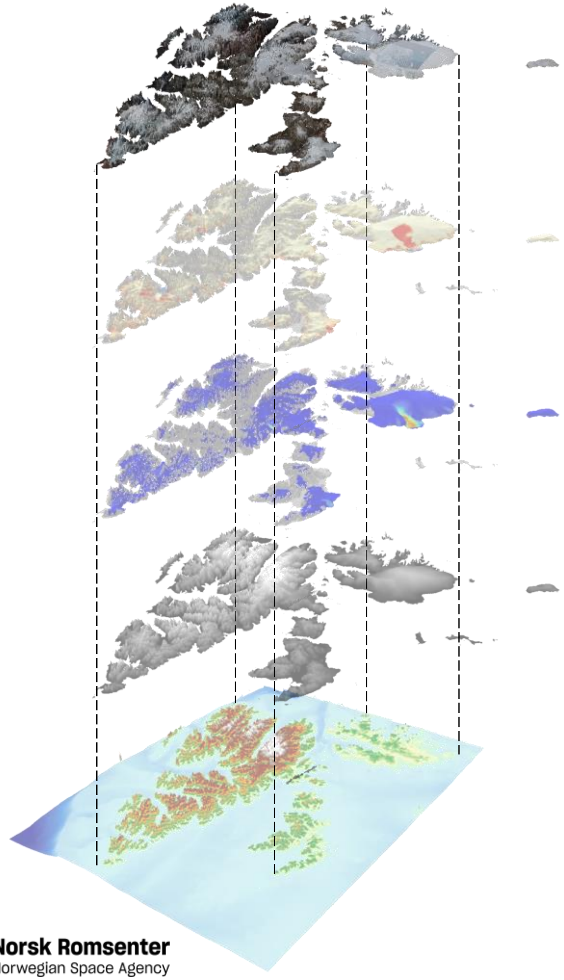

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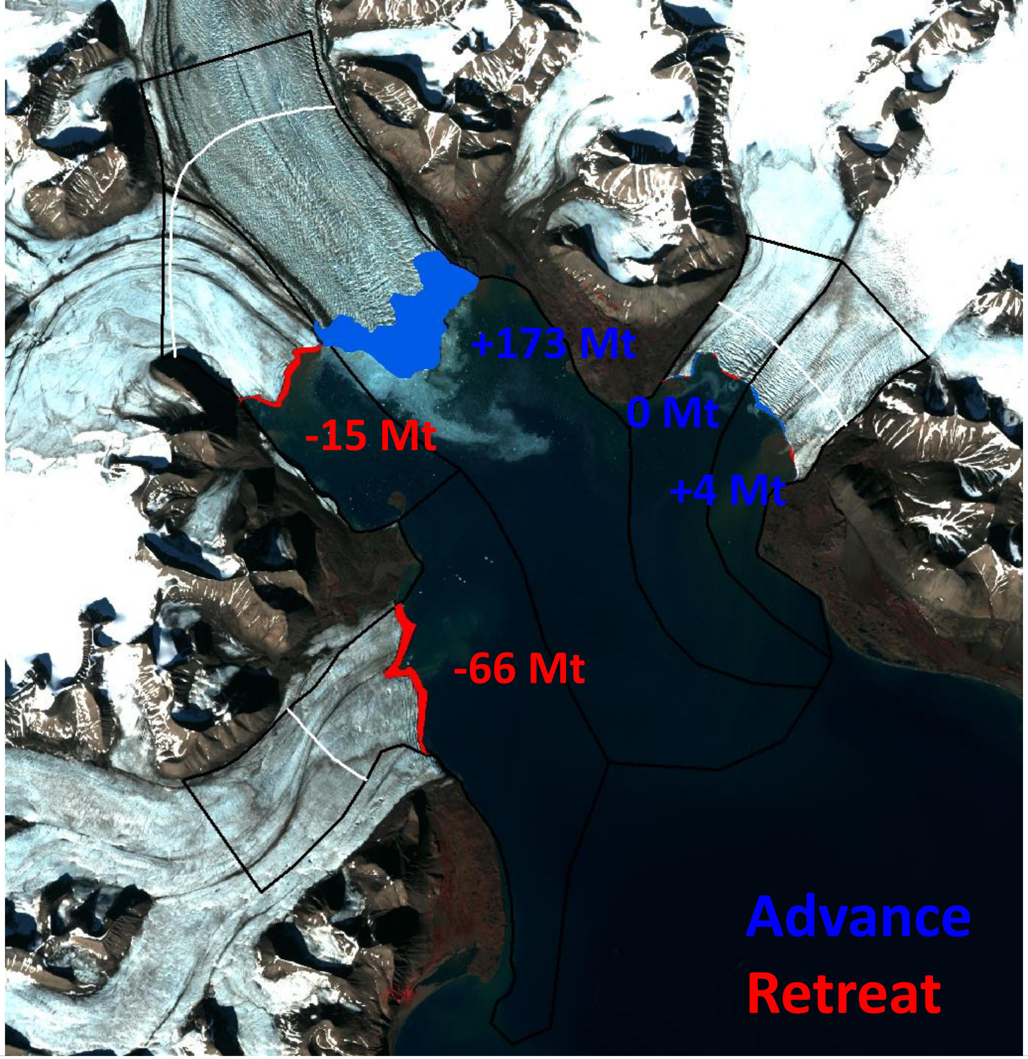
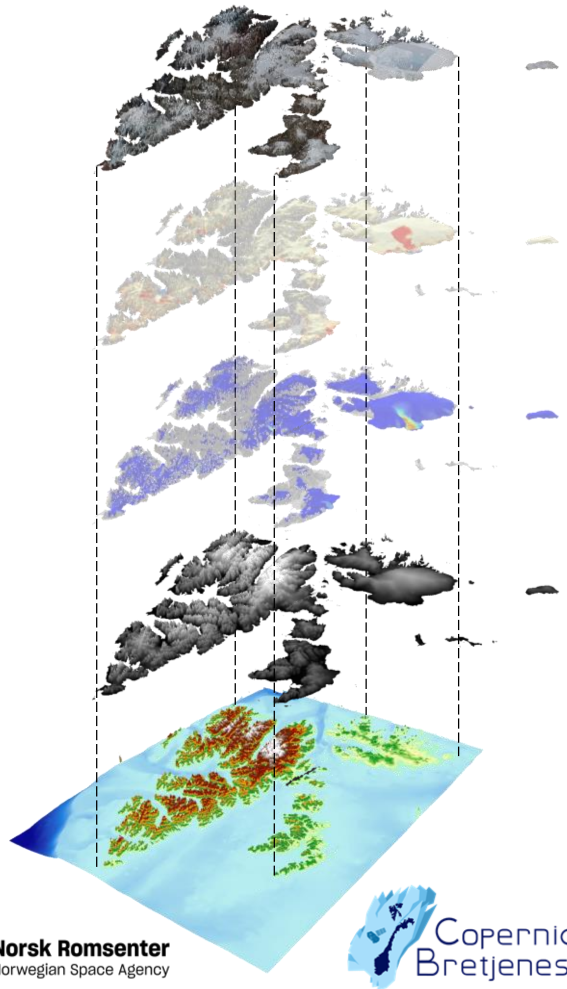
Multiply area by ice thickness (surface DEM – bed DEM) and convert volume to mass





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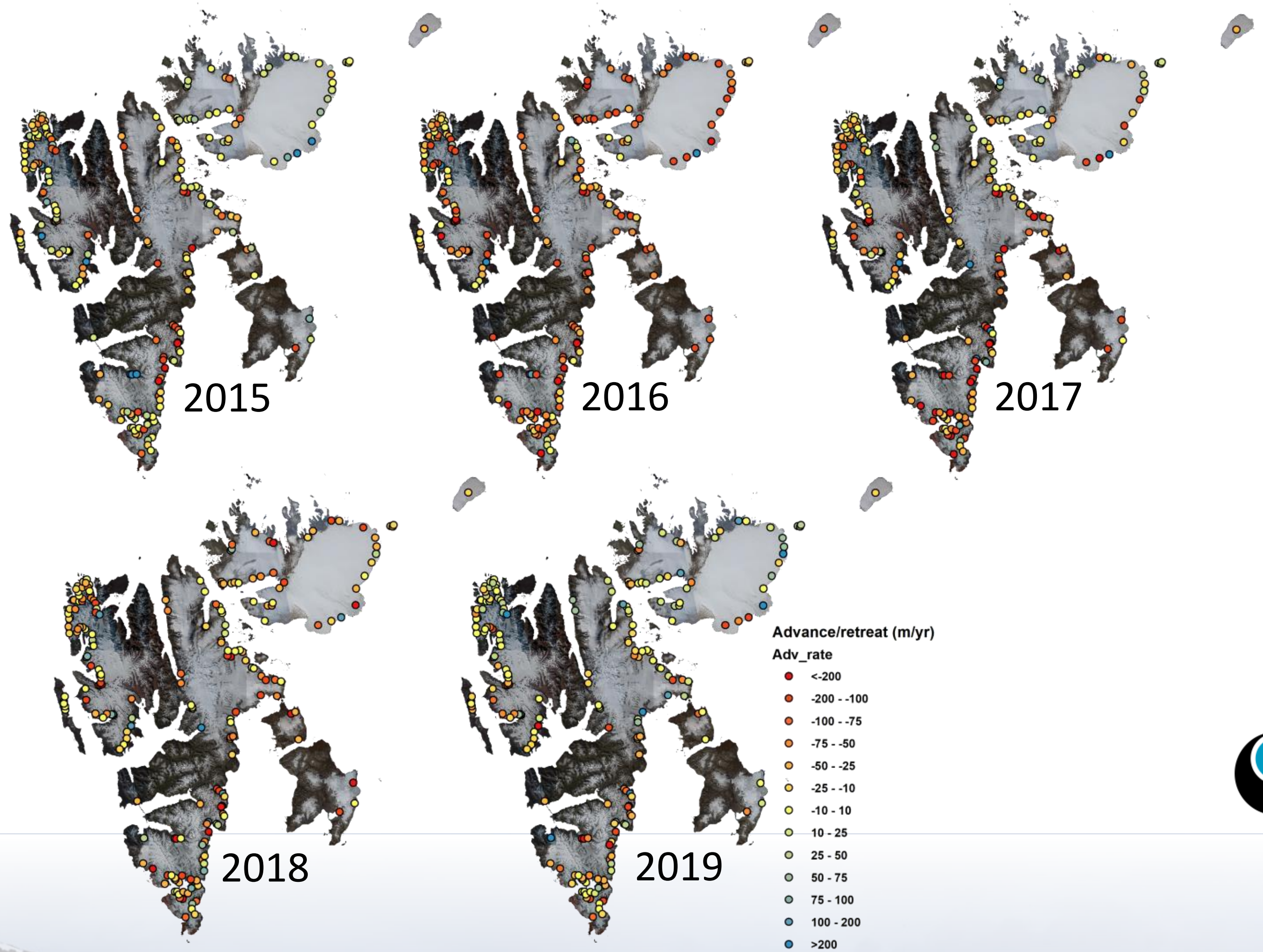
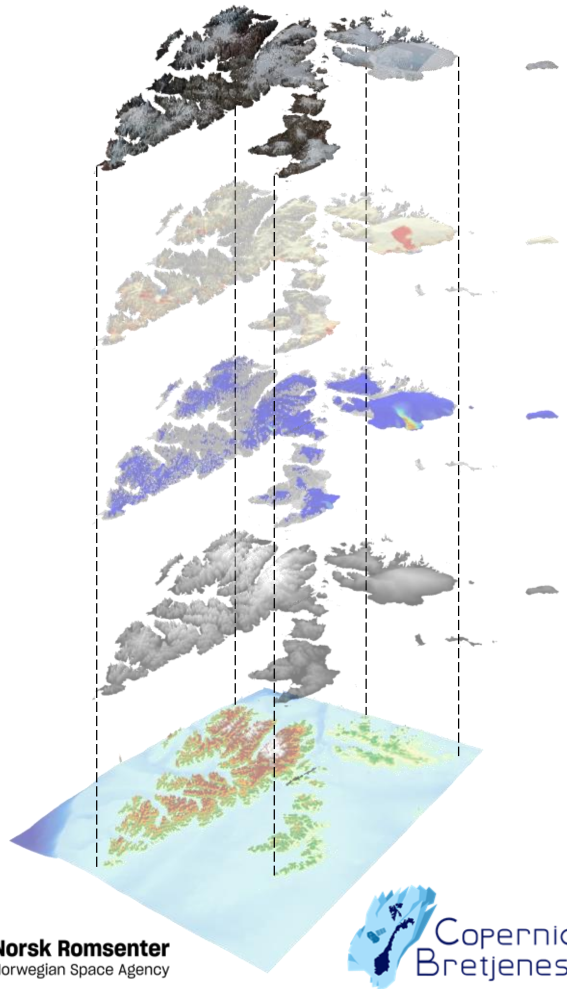
Results: Calving front advance/retreat





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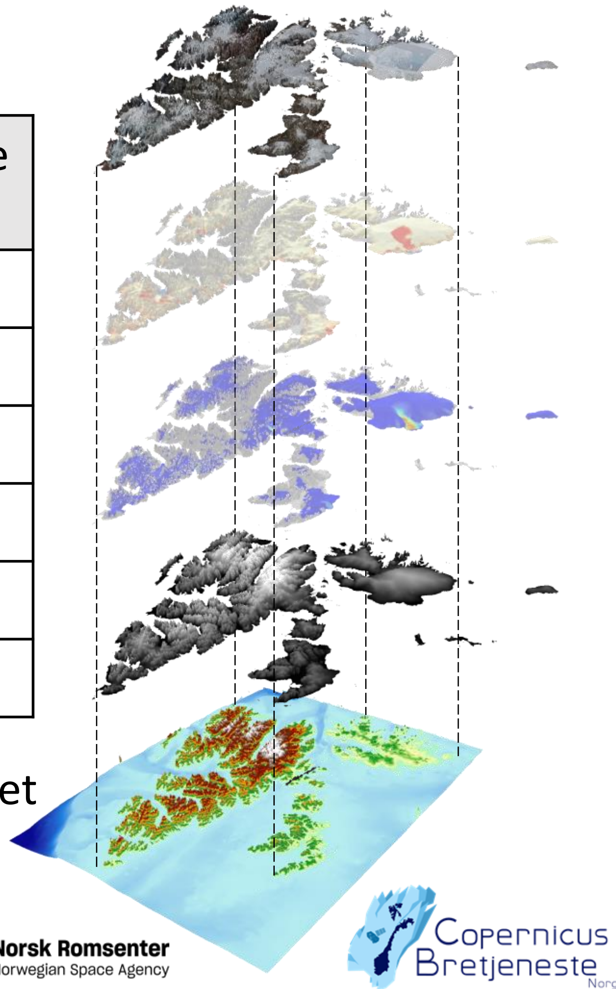
Results: Mass loss due to retreat

Year	Area (km²/yr)	retreat (m/yr)	% retreating	Mass (Gt/yr)	Non-surge (Gt/yr)
2014	-5.1	-23.9	72	1.3	-3.3
2015	20.4	-9.3	62	2.1	-1.2
2016	-70.5	-52.8	90	-6.1	-6.8
2017	-35.5	-17.8	74	-3.7	-4.9
2018	-45.7	-23.4	77	-5.0	-5.6
2019	9.4	-4.8	58	0.8	-2.1

- 60-90% of tidewater glaciers retreat annually, but surging may lead to net area gain (2015,2019).



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Introduction
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CryoSat-2 Results
CS-2 v ICESat-1
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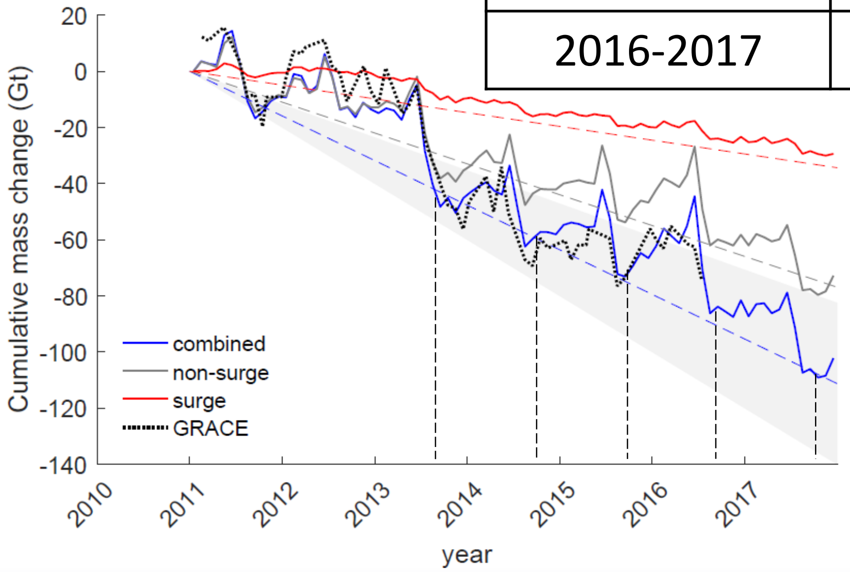
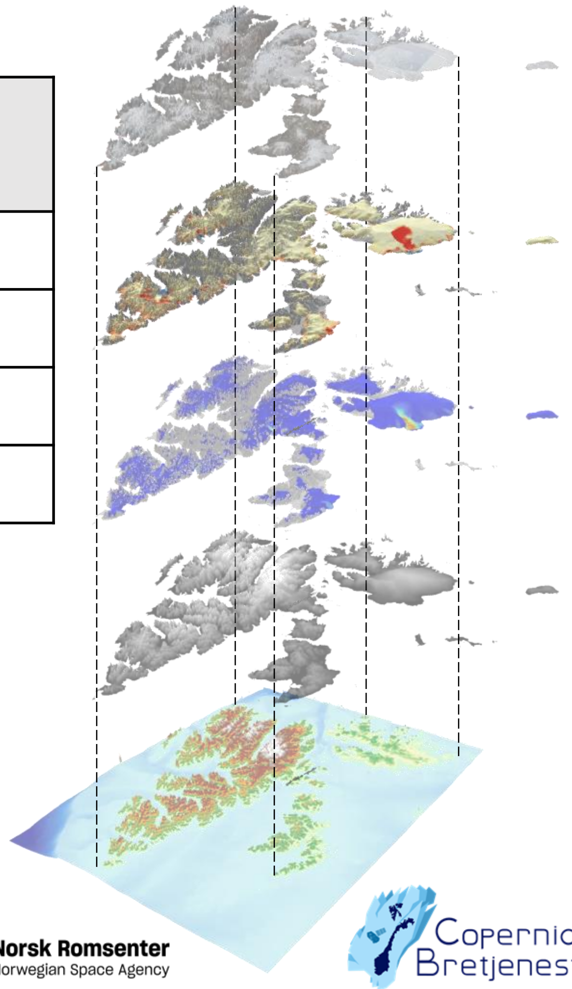
Copernicus glacier service
Advance/retreat
Total mass balance
Acknowledgements & References

Results: Geodetic and total mass balance

Year	Geodetic (Gt/yr)	Total (Gt/yr)
2013-2014	-14.3	-13.0
2014-2015	-14.3	-12.2
2015-2016	-18.5	-24.6
2016-2017	-25.7	-29.4



- Combine with mass change due to advance/retreat to give total mass change.



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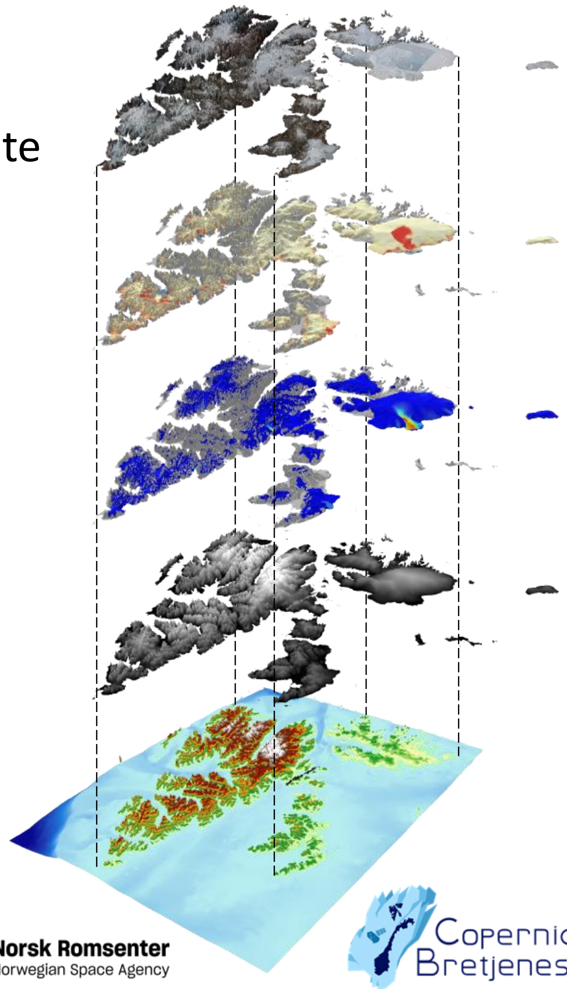
Results: Geodetic and total mass balance

- Combine discharge and mass changes due to advance/retreat to calculate **frontal ablation.**

Year	Geodetic (Gt/yr)	Total (Gt/yr)	Frontal ablation (Gt/yr)
2014	-14.3	-13.0	12.7
2015	-14.3	-12.2	12.5
2016	-18.5	-24.6	23.2
2017	-25.7	-29.4	23.2



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Conclusions

- Large reduction in geodetic mass balance between the ICESat-1 and CryoSat-2 periods. Persistent mass loss from west Spitsbergen coast, increase in mass loss from southeastern Spitsbergen Barentsøya-Edgeøya, southern Austfonna. Northern Austfonna, Vestfonna and Northeastern Spitsbergen closer to balance.
- Strong surface mass balance-driven mass loss in 2013.
- CryoSat-2 results consistent with ArcticDEM and GRACE derived mass change estimates.
- Discharge losses dominate for large (and surging) glaciers, retreat losses dominate for small glaciers.
- Retreat losses more variable than discharge losses (except surges).
- Increase in geodetic mass loss and frontal ablation around 2016. Step change in Svalbard mass loss?

CryoSat-2 L1b and STR mispointing angles data provided by the European Space Agency.
L. Gray wrote the retracking and swath processing software.
The dataset will be made available through the Norwegian Polar Data Centre (data.npolar.no/home).
GRACE Mascon data available from http://grace.jpl.nasa.gov, supported by the NASA MEaSUREs Program.
Sea ice concentration maps were obtained from the University of Bremen (https://seaice.uni-Bremen.de/sea-ice-concentration).
ERA5 climate reanalysis data were obtained through the EU's Copernicus program (https://climate.Copernicus.eu/climate-reanalysis).
Landsat-8 OLI data available from the U.S. Geological Survey (https://earthexplorer.usgs.gov).
Bathymetry of the Barents Sea from International Bathymetric Chart of the Arctic v3.0.
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Photograph of Nordenskioldbreen by Thorben Dunse.

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