Remote sensing of Svalbard mass balance, 2011-2017

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Photo: Nordenskiöldbreen, Thorben Dunse

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**Svalbard glacier mass balance derived from annual Arctic DEMs, 2013-2017**

Copernicus Glacier Service (2013-)

CryoSat-2 Radar Altimeter (2010-)

Arctic DEM (2013-2018)

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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.
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.
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• 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.
\[
\begin{align*}
    f(x, y, z) &= c_1 x + c_2 y + \frac{dh}{dt} t + v \\
 \end{align*}
\]

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.
1.08 ± 1.57 Gt/yr

-3.34 ± 1.72 Gt/yr

-4.47 ± 2.62 Gt/yr

4.50 ± 1.93 Gt/yr

0.58 ± 0.54 Gt/yr

-0.94 Gt/yr (non-surge)

-1.93 ± 0.74 Gt/yr

(non-surge)
Spikes caused by raising of radar reflection horizon at the onset of melt.
ICESat data from Moholdt et al., 2010

- +0.44±0.46 Gt/yr
- -2.89±1.26 Gt/yr
- -0.70±0.80 Gt/yr
- -0.33±0.21 Gt/yr
- +0.52±0.37 Gt/yr
- -0.39±0.26 Gt/yr
*Northeast*

2003-2008  \(+0.44\pm0.46\) Gt/yr  
2011-2017  \(-1.08\pm1.57\) Gt/yr

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

Northwest
2003-2008  -2.89±1.26 Gt/yr
2011-2017  -3.34±1.72 Gt/yr

Rapid mass loss during both periods.
**Northeast**

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.

**Northwest**

2003-2008  -2.89±1.26 Gt/yr  
2011-2017  -3.34±1.72 Gt/yr  

Rapid mass loss during both periods.

**South**

2003-2008  -0.70±0.80 Gt/yr  
2011-2017  -4.47±2.62 Gt/yr  

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

**Vestfonna**
2003-2008  -0.33±0.21 Gt/yr
2011-2017  -0.58±0.54 Gt/yr

Moderate mass loss in both periods.
Northeast
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.

Northwest
2003-2008  -2.89±1.26 Gt/yr
2011-2017  -3.34±1.72 Gt/yr
Rapid mass loss during both periods.

South
2003-2008  -0.70±0.80 Gt/yr
2011-2017  -4.47±2.62 Gt/yr
Switch from slight thickening to rapid thinning on eastern (Storfjorden) coast.

Vestfonna
2003-2008  -0.33±0.21 Gt/yr
2011-2017  -0.58±0.54 Gt/yr
Moderate mass loss in both periods.

Austfonna
2003-2008  +0.52±0.37 Gt/yr
2011-2017  -4.50±1.93 Gt/yr
Non surge  -0.94 Gt/yr
Rapid mass loss from surging Storisstrømen and southern margin. Slight thickening at high elevations.
Northeast
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.

Northwest
2003-2008  -2.89±1.26 Gt/yr
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Rapid mass loss during both periods.

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2003-2008  -0.70±0.80 Gt/yr
2011-2017  -4.47±2.62 Gt/yr
Switch from slight thickening to rapid thinning on eastern (Storfjorden) coast.

Vestfonna
2003-2008  -0.33±0.21 Gt/yr
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Moderate mass loss in both periods.

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2003-2008  +0.52±0.37 Gt/yr
2011-2017  -4.50±1.93 Gt/yr
Non surge  -0.94 Gt/yr
Rapid mass loss from surging Storisstraumen and southern margin. Slight thickening at high elevations.

Barentsøya-Edgeøya
2003-2008  -0.39±0.26 Gt/yr
2011-2017  -1.93±0.74 Gt/yr
Increased melt and surge of Stonebreen.
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

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

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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-surfing -10.99 Gt/yr
Excellent agreement between satellite gravimetric and altimetric mass loss time-series.

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

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

Barents Sea margins: Increase in glacier thinning and mass loss from southeastern Spitsbergen, Barentsøya-Edgeøya, and southern Austfonna.
CryoSat-2
2011-2017
(Gt/yr)

-15.9±4.1 Gt/yr

CS-2 v ICESat-1
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Svalbard total:
-17.0 ± 0.2 km³/a
-0.60 ± 0.01 m/a

CS-2 v ArcticDEM

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• **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.
Atlantic water inflow into Fram Strait (West Spitsbergen Current)

Svalbard: Continued mass loss from west coast, spread of mass loss to Barents Sea margins.

Barents Sea: Rapid regional warming (Screen and Simmonds, 2010), ‘Atlantification’ (Lind et al., 2018) and sea ice decline.

Franz Josef Land: Greatest thinning in southwest, lowest in northeast (Zheng et al., 2018).

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 (Ciraci et al., 2018).

Atlantic water inflow into Barents Sea
Does CryoSat-2 see it?
Does CryoSat-2 see it?

SMB-driven mass change
Does CryoSat-2 see it?

SMB-driven mass change

Dynamically-driven mass change

Dynamic thinning (thickening) due to faster (slower) flow
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Calving front retreat (or advance during surge)

Does CryoSat-2 see it?

<table>
<thead>
<tr>
<th>SMB-driven mass change</th>
<th>Dynamically-driven mass change</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
Altimetry gives geodetic mass balance, not total.

Need to integrate additional datasets to measure the total mass balance (including due to advance and retreat).

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

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1 Wyższa Szkoła Zawodowa, Uniwersytet Śląski, Roździeś 60, 41-200 Szczecin, Poland
2 Institute of Geophysics PAN, Kraków Janiszewa 64, 30-432 Kraków, Poland
3 Department of Geosciences, University of Oslo, P.O. Box 147 Blindern, N-0316 Oslo, Norway

Abstract: The purpose of this study is to describe the current state of tidewater glaciers in Svalbard as an extension of the inventory of Błaszczyszyn et al. (1993). The ice masses of Svalbard cover an area of c. 36,600 km² and more than 60% of the glacial area are glaciers which terminate in the sea at calving ice-cliffs. Recent data on the geometry of glacier termini, 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 167 Svalbard glaciers are of tidewater type (having contact with the ocean) and the total length of their calving ice-cliffs is 880 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 pattern and flow velocity: (1) very slow or stagnant glaciers, (2) slow-flowing glaciers, (3) fast-flowing glaciers, and (4) retreating glaciers (on 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 Kongsfjorden is estimated to be 3.0–4.4 km³ yr⁻¹ (water equivalent; w.e.), with a mean value of 3.75 ± 1.34 km³ yr⁻¹ (w.e.). Thus, ablation due to calving contributes as much as 17–25% with a mean value of 20% to the overall mass loss from Svalbard glaciers. By implication, the contribution of Svalbard iceberg flux to seaward the amount is of 0.62 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.

Keywords: 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.
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.

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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.
Datasets: Ice velocity

- Velocity from NASA GoLIVE and ITS_LIVE and feature tracking of sentinel imagery (Adrian Luckman at Swansea University.)
Datasets: Ice surface DEM

- Discharge calculations currently implemented with fixed ice surface DEM (NP DEM).
- Working on implementing annual DEMs from ArcticDEM
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.
• 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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1990 Inventory

1930 Inventory

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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

2015
2016
2017
2018
2019

Advance/retreat (m/yr)

<20
20 - 40
40 - 60
60 - 80
80 - 100
100 - 150
150 - 200
>200

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### Results: Mass loss due to retreat

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

- 60-90% of tidewater glaciers retreat annually, but surging may lead to net area gain (2015,2019).
### Results: Geodetic and total mass balance

<table>
<thead>
<tr>
<th>Year</th>
<th>Geodetic (Gt/yr)</th>
<th>Total (Gt/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013-2014</td>
<td>-14.3</td>
<td>-13.0</td>
</tr>
<tr>
<td>2014-2015</td>
<td>-14.3</td>
<td>-12.2</td>
</tr>
<tr>
<td>2015-2016</td>
<td>-18.5</td>
<td>-24.6</td>
</tr>
<tr>
<td>2016-2017</td>
<td>-25.7</td>
<td>-29.4</td>
</tr>
</tbody>
</table>

- Combine with mass change due to advance/retreat to give total mass change.
Results: Geodetic and total mass balance

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Geodetic (Gt/yr)</th>
<th>Total (Gt/yr)</th>
<th>Frontal ablation (Gt/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>-14.3</td>
<td>-13.0</td>
<td>12.7</td>
</tr>
<tr>
<td>2015</td>
<td>-14.3</td>
<td>-12.2</td>
<td>12.5</td>
</tr>
<tr>
<td>2016</td>
<td>-18.5</td>
<td>-24.6</td>
<td>23.2</td>
</tr>
<tr>
<td>2017</td>
<td>-25.7</td>
<td>-29.4</td>
<td>23.2</td>
</tr>
</tbody>
</table>
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).

ERAS 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. Field campaigns on Austfonna are a collaboration between the Norwegian Polar Institute and the University of Oslo, funded by ESA PRODEX and CryoVEx programs. Trond Eiken at the University of Oslo processed the GNSS data. Thanks also to Thorben Dunse, Thomas Schuler and others who have participated in the field campaigns.

Airborne laser altimeter data were provided by Sebastian Simonsen at the Technical University of Denmark and NASA’s Operation IceBridge. Photograph of Nordenskioldbreen by Thorben Dunse.

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Thanks to Geir for slides!


Acknowledgements & References