Towards an EO-based freshwater budget of the Greenland ice sheet

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Session: From ice sheets to oceans: a comprehensive view of Arctic freshwater fluxes

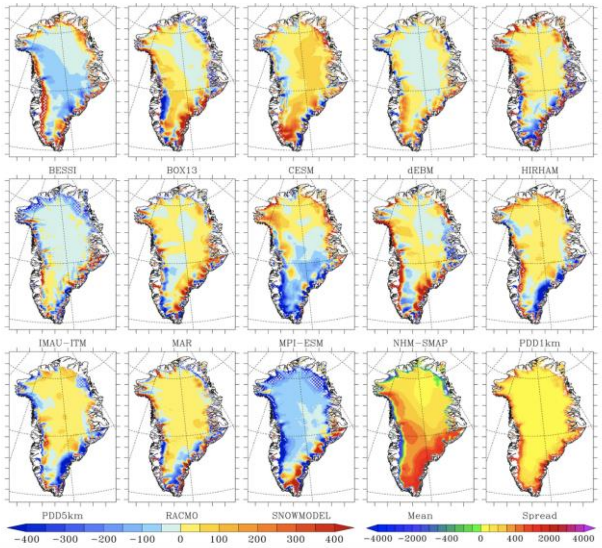
Motivation

Mapping and understanding the hydrology in Greenland is important because it affects e.g.

- Sea Level Rise.
- Glacier dynamics.
- Fjord dynamics.
- Ocean circulation.
- Marine ecosystems.
- Sedimentation rates.

Earth Observation is important because:

- Advance our understanding of the hydrology of the ice sheet.
- Regional Climate Models and Re-analysis includes currently little or no data
- There is a large spread in e.g. ice sheet runoff from models… can EO data help to constrain or validate?
- Advance our understanding of the ice sheet response to e.g. extreme events



[Fettweis et al., 2021]

The 4DGreenland project (phase 1)

4DGreenland

- Maximize the use of Earth Observation in characterizing the different components of the hydrological system of the Greenland Ice Sheet.
- Advance our understanding of the Greenland hydrology.

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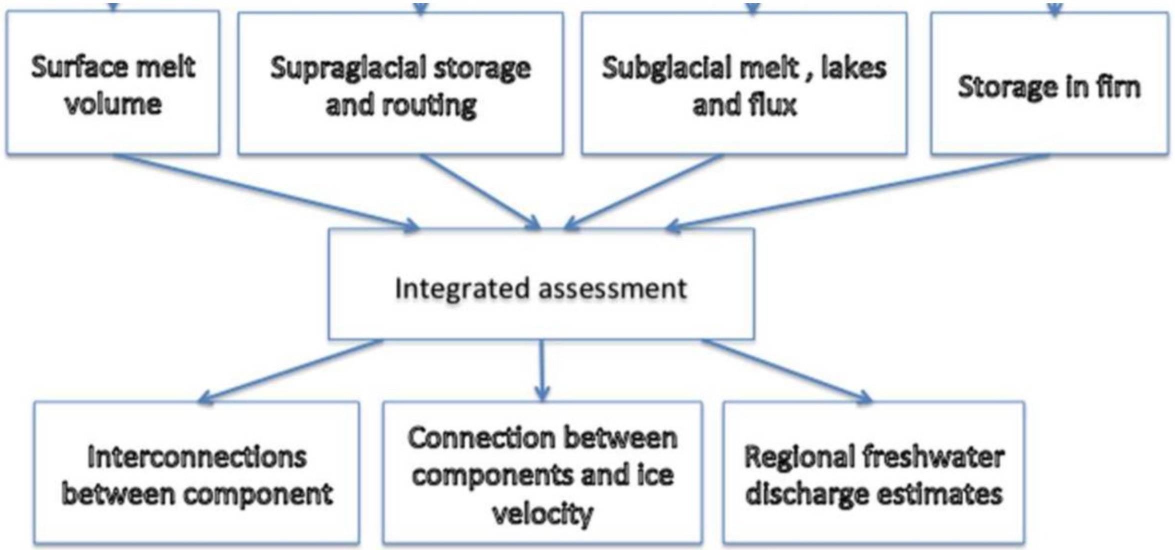
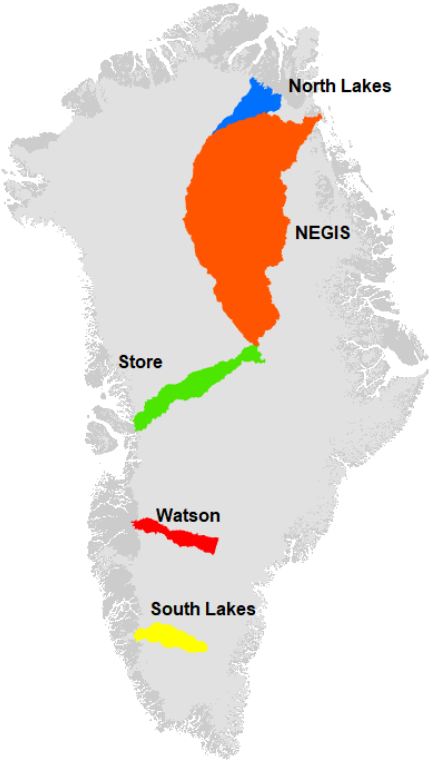




Surface melt

- How much meltwater is generated at the surface of the ice sheet? And when/where?
- Earth Observation data can provide an indication of melt presence and intensity – but not volume.
- Regional Climate Models (RCMs) are therefore widely used for surface mass balance and runoff assessments – but there is a wide spread in model output!

[Fettweis et al., 2021]

[Fettweis et al., 2021]

13 models to estimate present-day SMB 1980–2012.

Models differ in physical complexity, resolution, topographies etc.

All forced with the same ERA-Interim reanalysis forcing fields

Conclusion: Wide spread. The ensemble mean was found to yield the best estimate of the present-day SMB when compared to observational data.

	Runoff		
	Mean	SD	Trend
BESSI	134	52	4.2
BOX13	508	118	9.1
CESM	276	66	4.0
dEBM	280	108	8.6
HIRHAM	491	123	8.2
IMAU-ITM	382	122	9.5
MAR	302	107	8.0
MPI-ESM	336	70	4.0
NHM-SMAP	260	79	6.1
PDD1km	230	87	7.0
PDD5km	278	97	7.5
RACMO	306	90	6.7
SNOWMODEL	469	171	13.4
ENSEMBLE	331	102	8.0

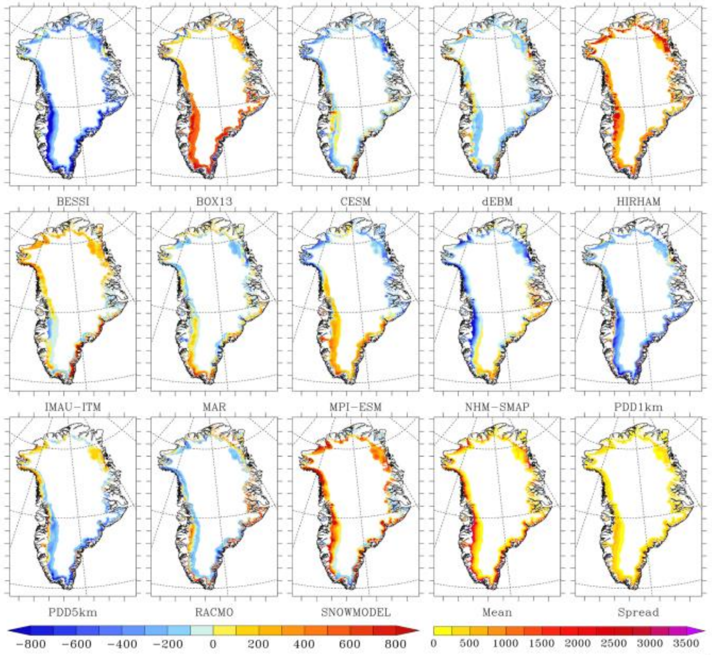
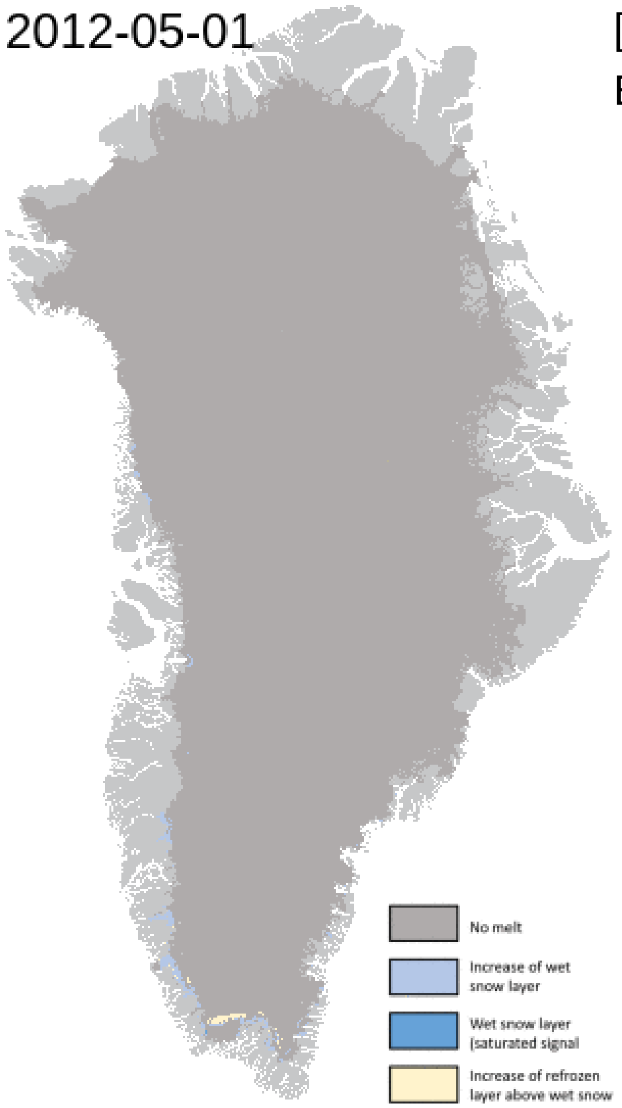


Figure 3. Same as Fig. 2 but for the modelled runoff. The ensemble mean and model spread around the mean are also shown in mm w.e. yr^{-1} in the two last plots. Finally it is important to note that only the area where the runoff of the ensemble mean is higher than 100 mm w.e. yr^{-1} is shown here.

Surface melt

- Can EO data help? Several datasets exist.
- Resolution-enhanced active microwave measurement from Advanced SCATterometer (ASCAT) (Lindsley and Long, 2010).
- (Nagler et al. 2024) identify melt phases by applying a hierarchical decision tree using dynamic thresholds based on the first- and second-time derivatives of σ^0
- Apply a snowline mask (Box et al. 2012) to areas where ASCAT persistently cannot correctly detect the presence of liquid water
- Only melt extent not melt volume

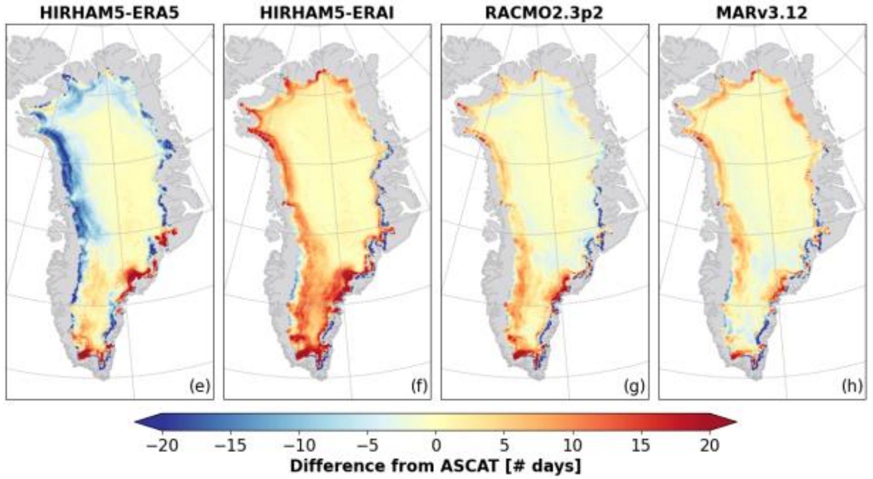
[Credit: ENVEO]



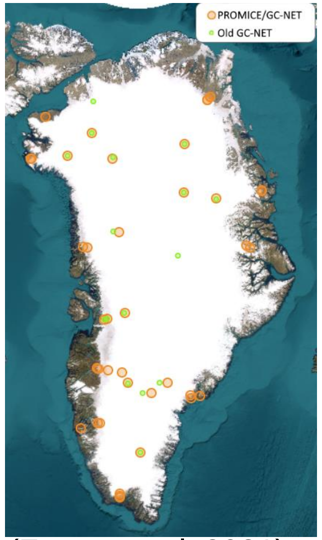
Surface melt

[Puggaard et al., 2024]

- ASCAT provides a valuable tool for evaluating the performance of RCMs
- Melting thresholds found in the RCMs when compared to AWS
- In some cases one RCM can represent present-day melt extent across the entire ice sheet more effectively than the ensemble mean, as variability among models does not appear to be random variations.
- Models that had MODIS data into the surface albedo scheme appears to produce more accurate meltwater estimates.



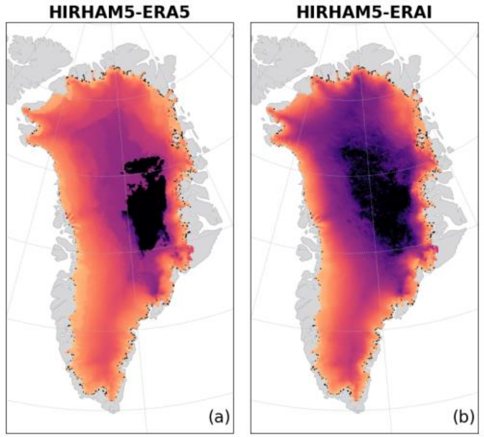
In-situ AWS observations

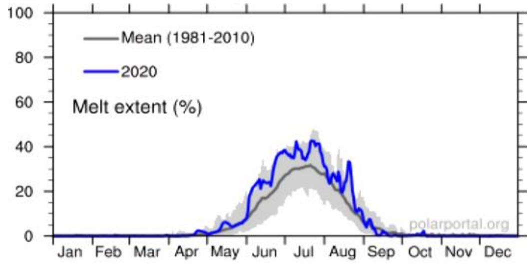


(Fausto et al. 2021)

	Thresholds [mm w.e. day^{-1}]
HIRHAM5-ERA5	4.1
HIRHAM5-ERAI	0.4
RACMO2.3p2	0.7
MARv3.12	1.0
PROMICE GC-net	–

Regional climate models





(Polar Portal, 2024)

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(Puggaard et al, 2024)

Storage in meltwater lakes

In RCMs, excess meltwater is assumed to produce instantaneous runoff.

Some meltwater is stored temporarily in meltwater lakes on the ice surface.

For more accurate runoff estimates at higher temporal resolution we can use EO data to assess water volumes in lakes.

Not trivial!

Also, how much is stored during winter?

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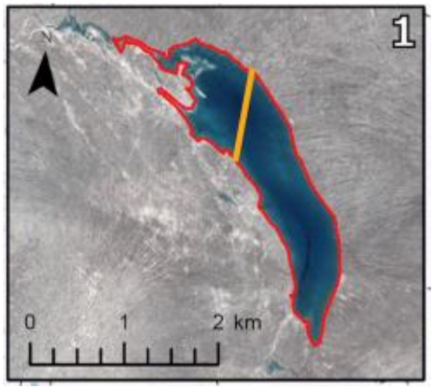
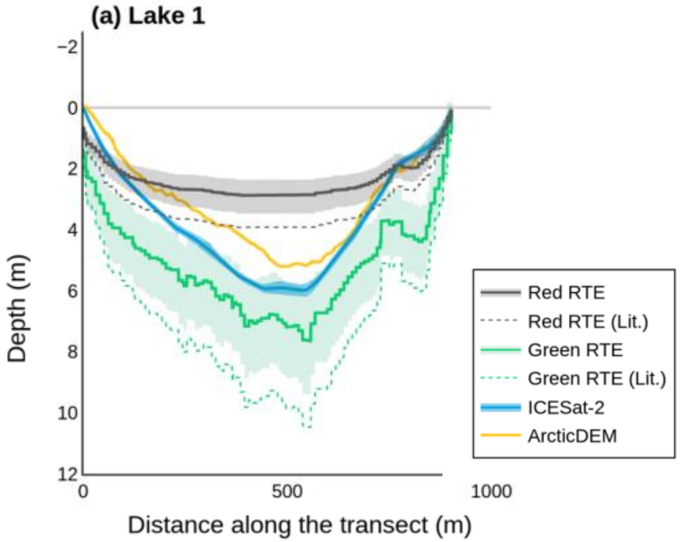


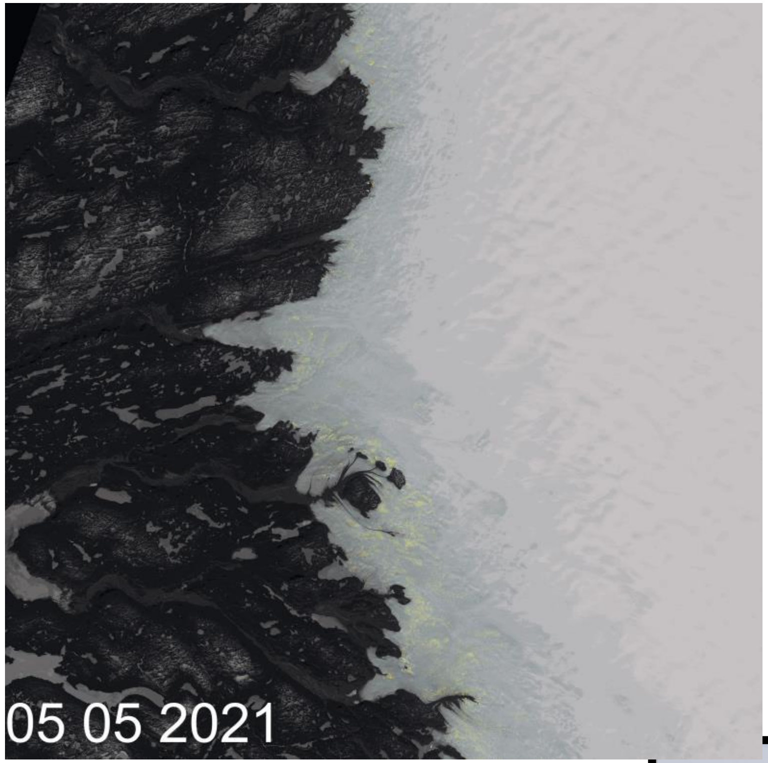


Radiative Transfer Equation to derive depth from optical imagery does not agree with other observations - especially for deeper supraglacial lakes.

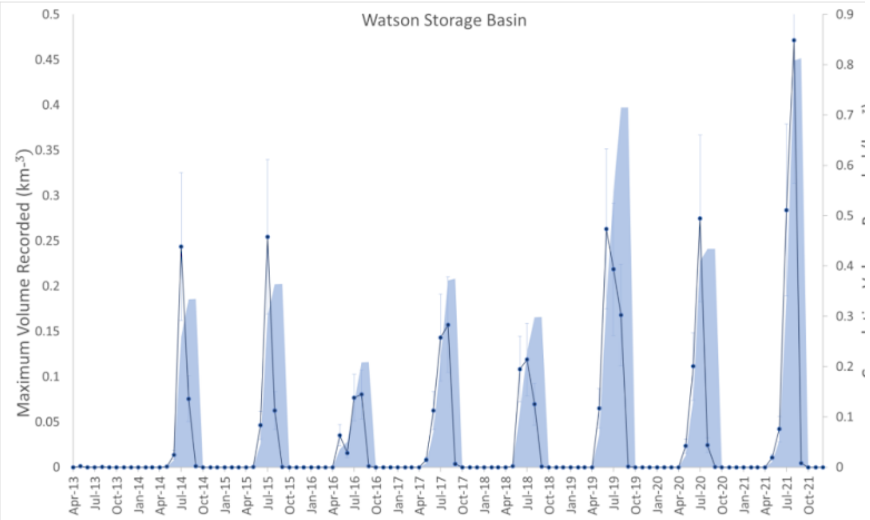
(Melling et al., 2024)

Storage in meltwater lakes

- Supraglacial hydrology features can be easily identified by the eye in optical satellite imagery.
- Automated approaches to mapping these features are needed.
- Machine learning algorithms have yet to be exploited fully.
- This example uses Random Forrest to map supraglacial hydrology on the ice sheet surface from Sentinel-2 and Landsat-8 optical imagery.



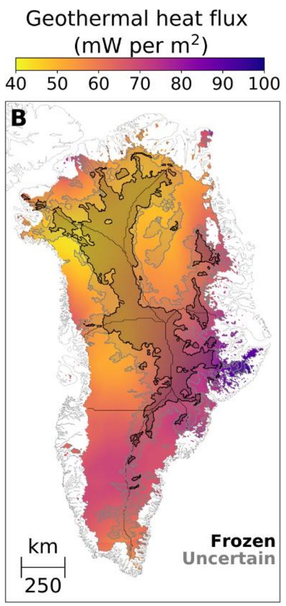
Lake depth / m



(Credit: Corr, 2022)

How much is stored during winter?

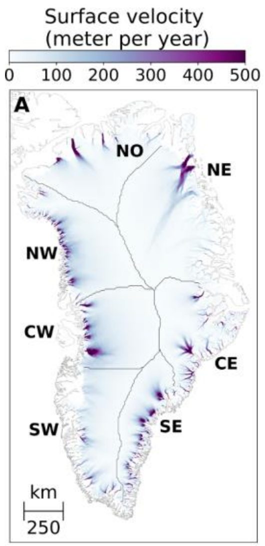
Subglacial melt



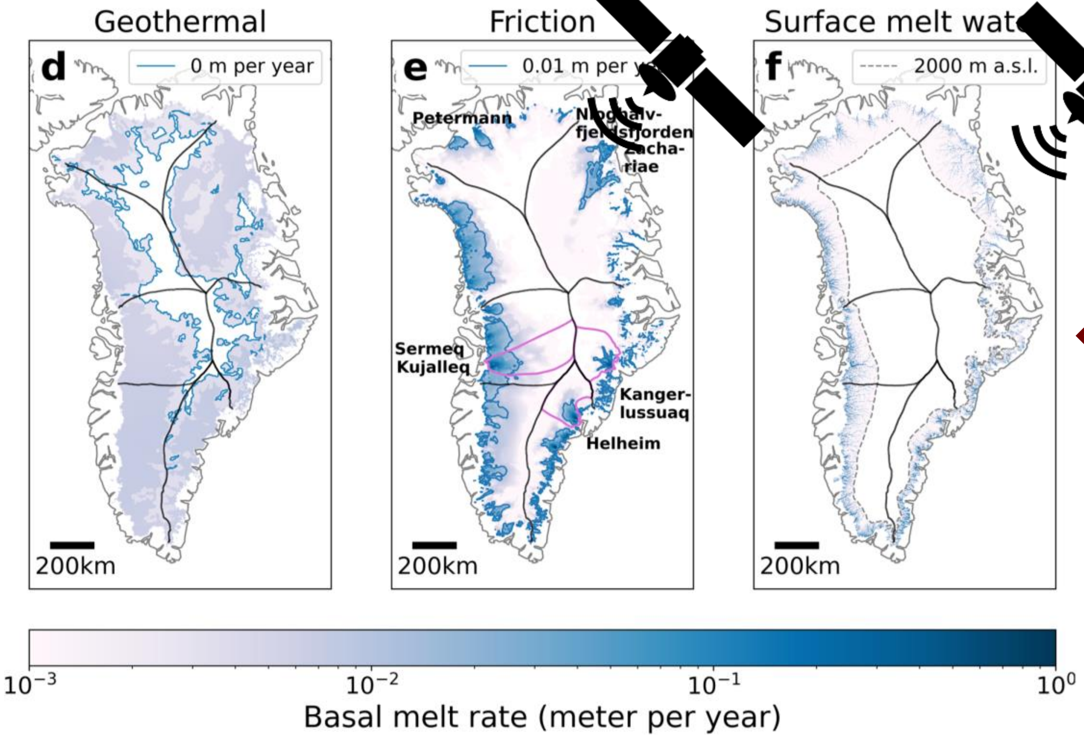
Geothermal flux:

The average of three heat maps:

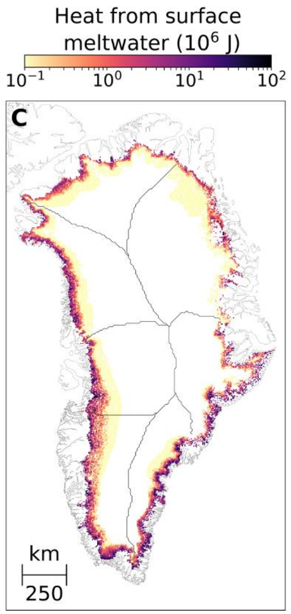
Shapiro & Ritzwoller (2014), Fox Maule et al. (2009) and Martos et al. (2018)



Elmer/Ice model (Gillet-Chaulet et al., 2012) tuned to assimilate observed surface velocities produces an estimate of friction heat.



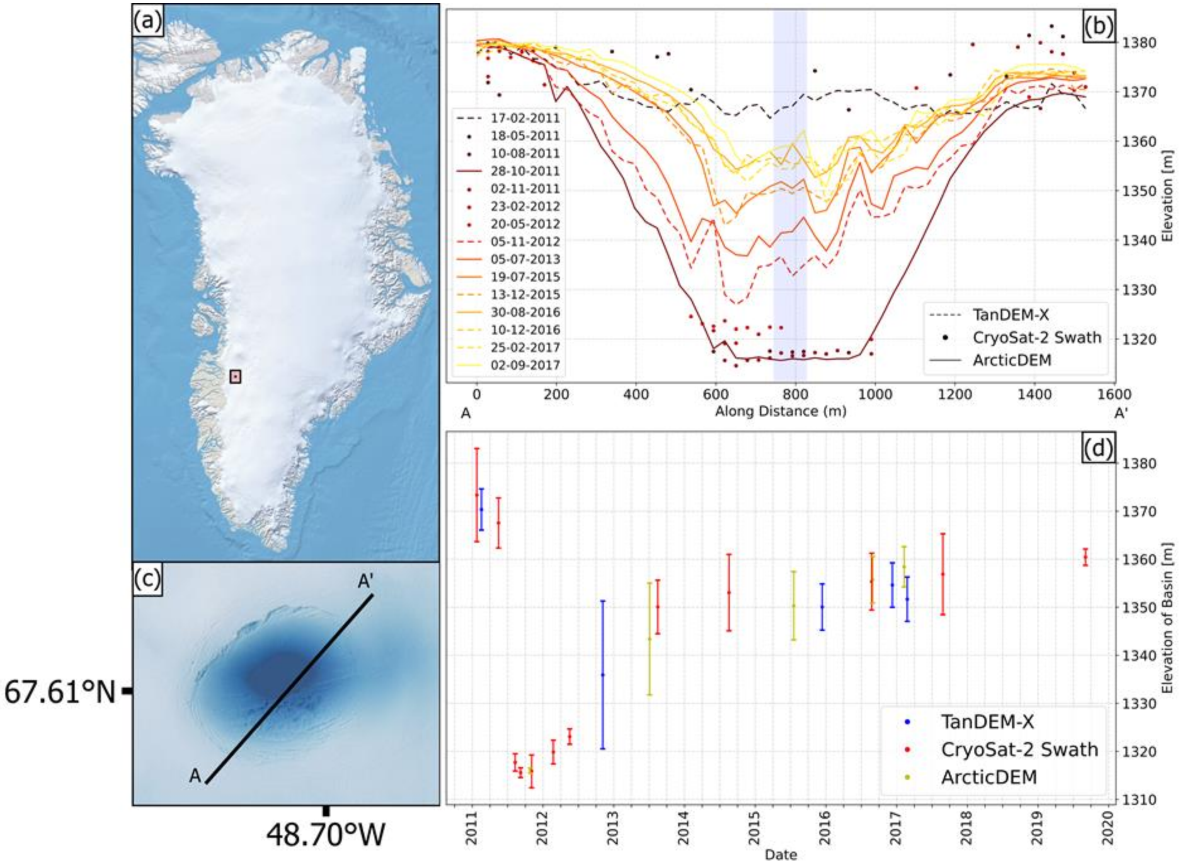
(Karlsson et al., 2021)



Viscous heat from surface meltwater (Mankoff et al., 2017; 2020) is routed through the subglacial system.

Subglacial lakes – drainage and refilling

- Active subglacial lakes impacts the timing of runoff.
- In Greenland there are not many sublacial lakes.
- CryoSat-2 and ICESat-2 data can be applied in monitoring
- ArcticDEM and TanDEM-X DEMs as well.
- Subglacial lake activity can inform us about basal melt production.



(Sørensen et al., 2024)

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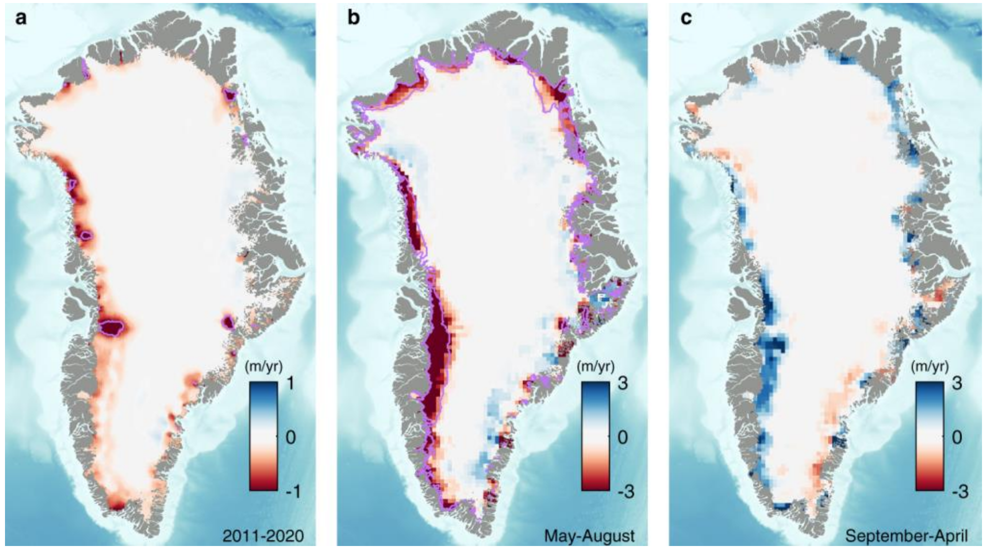
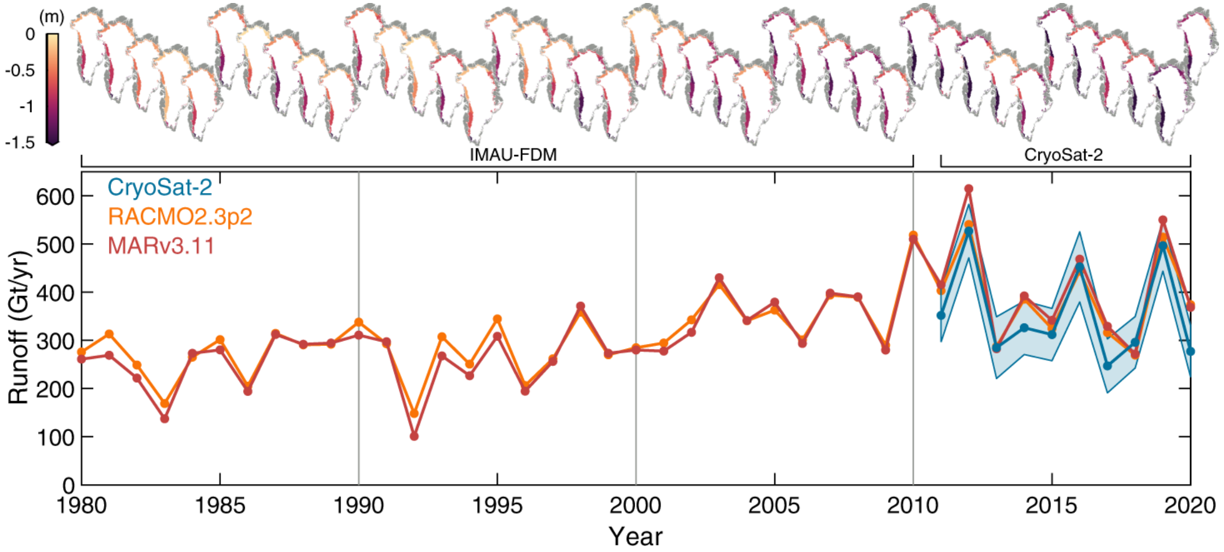
Runoff from altimetry

CryoSat-2 satellite altimetry has been used to produce independent and direct measurements of Greenland’s runoff variability, based on seasonal changes in the ice sheet’s surface elevation.

Agrees well with models.

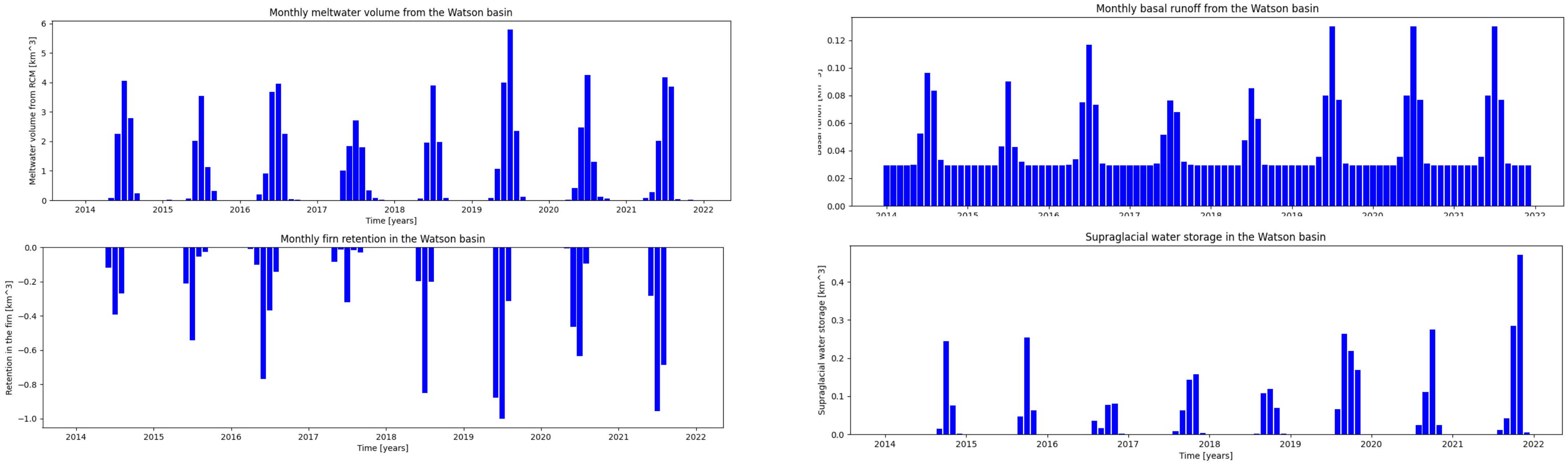
Difficult in highly dynamic regions.

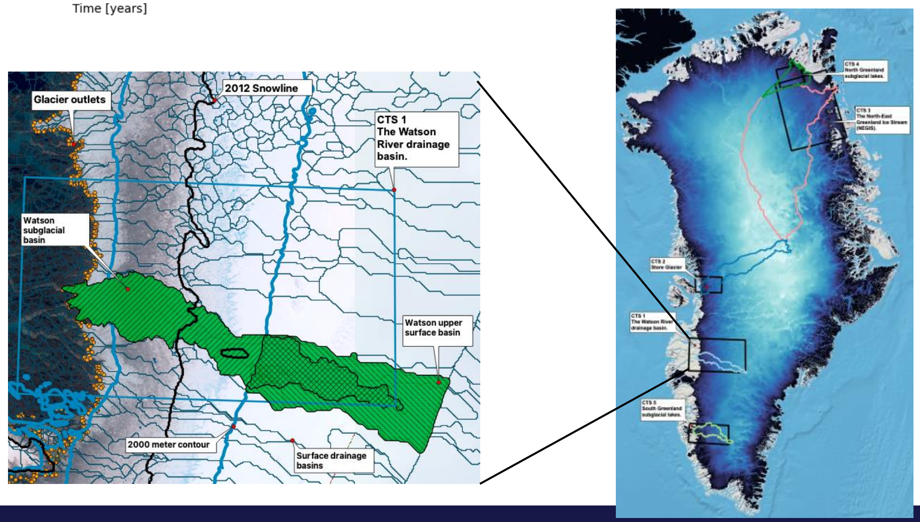




(Slater et al., 2021)

Monthly runoff – (partly constrained by EO)





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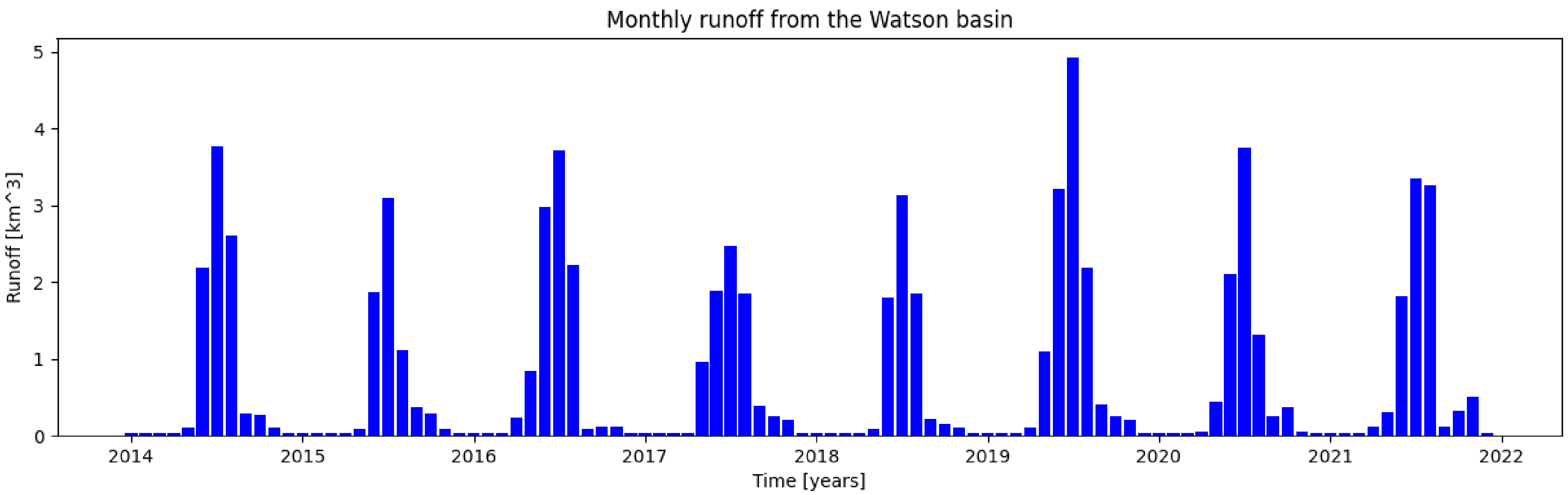

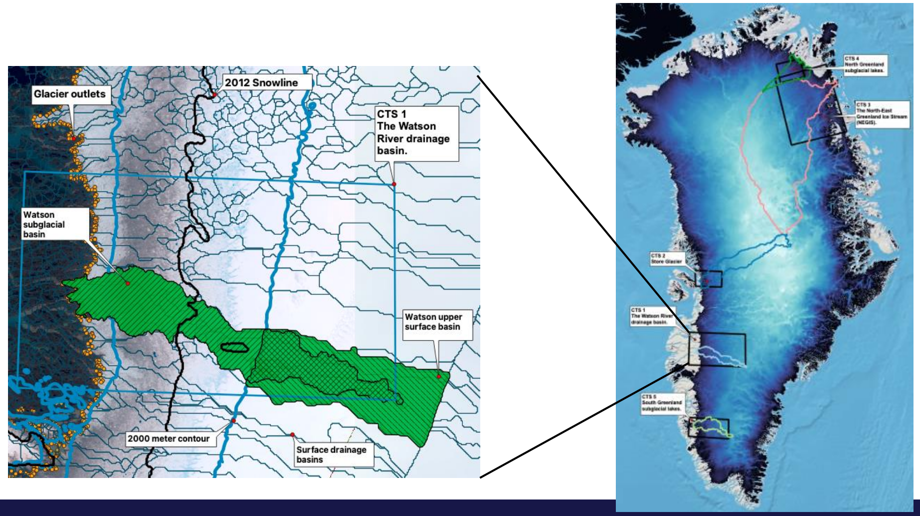

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Outlook

- Data assimilation into models. Great potential – still a long way to go.
- Full ice-sheet wide analysis.
- Large datasets - Further develop ML methods.
- Dynamic EO datasets for assessing basal melt.
- Operationalize
- More R&D needed