Interferometric Swath Radar Altimetry for the study of the Cryosphere

Noel Gourmelen[1]

Amaury Dehecq[1], Luca Foresta[1], Paul Tepes[1], Flora Weissgerber[1], Livia Jakob[2], Albert Garcia-Mondejar[3], Maria Jose Escorihuela[3], Jan Wuite[4], Martin Ewart[2], Jonathan Alford[2], Alex Horton[2], Julia Bizon[2], Carolyn Michael[2], Johanna Kauffert[2], Pete Nienow[1], Thomas Nagler[4], Monica Roca[3], Andrew Shepherd[5], David Brockley[6], Steven Baker[6], Michele Scagliola[7], Lisa Recchia[7], Rob Cullen[8], Mark Drinkwater[8], Stephen Plummer[8], Jerome Bouffard[8], Alessandro Di Bella[8], Diego Fernandez[8]

1 University of Edinburgh, UK
2 Earthwave, UK
3 isardSAT, SP
4 ENVEO, AT
5 University of Leeds / CPOM, UK
6 UCL / CPOM, UK
7 Aresys
8 ESA

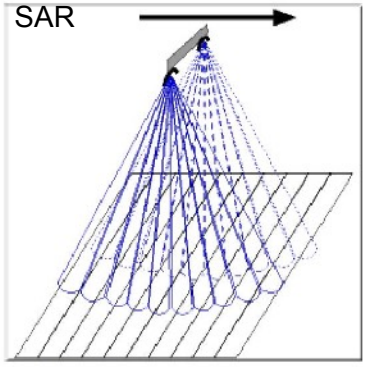
CryoSat

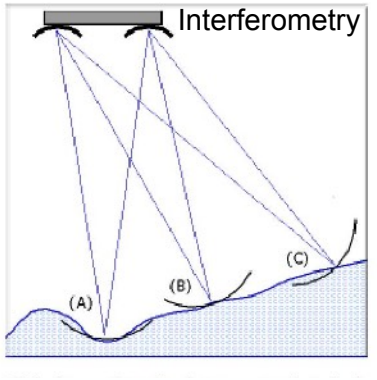
Mission's primary objectives

- determine regional trends in Arctic perennial **sea-ice** thickness and mass
- determine the contribution that the Antarctic and Greenland **ice sheets** are making to mean global rise in sea level.

Mission's secondary objectives

- the variation in the thickness of the Earth's **ice caps** and **glaciers**.
- …





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Mission's secondary objectives

- the variation in the thickness of the Earth's **ice caps** and **glaciers**.
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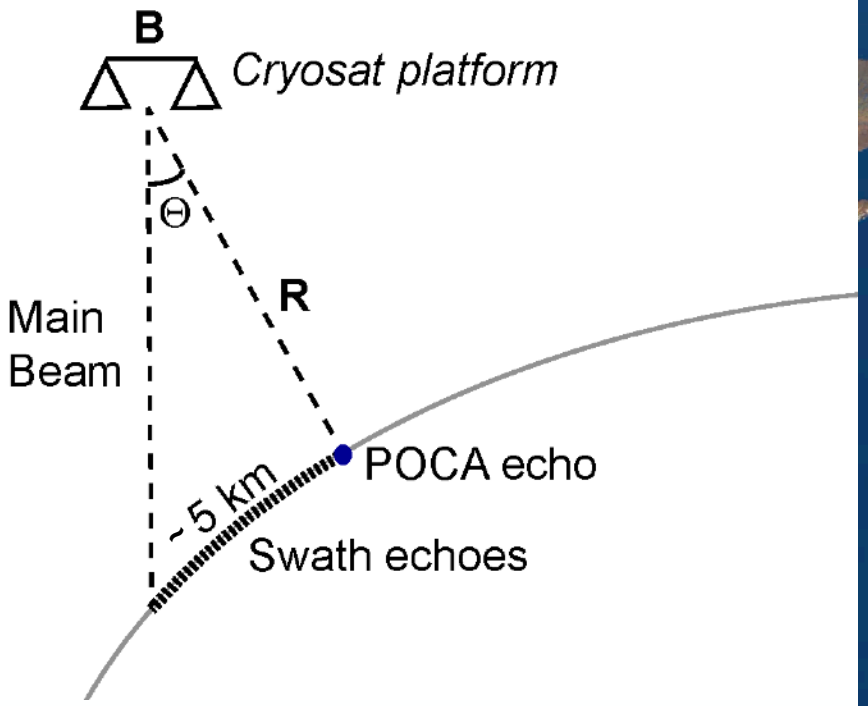
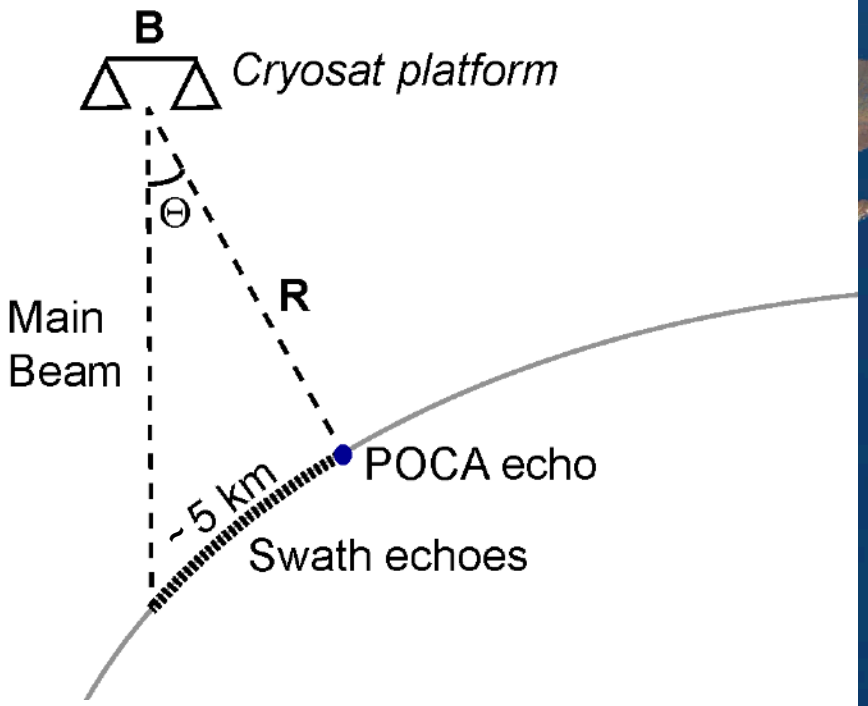
A final aspect that forms part of the validation is **to determine the performance over regions of complex ice cap and glacier geometries**. The orbit and payload have been designed to observe the large, polar ice sheets. Nonetheless, SARInM data will be collected over all of the Earth's ice bodies (Section 2.5) in order that, at least experimentally, the performance of the SIRAL instrument over these ice bodies may be evaluated. As noted at the end of Section 3.2, **when surface slopes exceed 0.8", the echo loses its leading edge and the geometry becomes similar to that of a sideways-looking SAR interferometer**. Specific experiments are planned in regions of glaciated Svalbard to compare "**swath-mode**" retrievals of elevation from SIRAL echoes with that of airborne laser surveys. **Should these prove successful, it is planned to develop, post-launch, verified algorithms for use in the operational environment.**

CryoSat swath altimetry

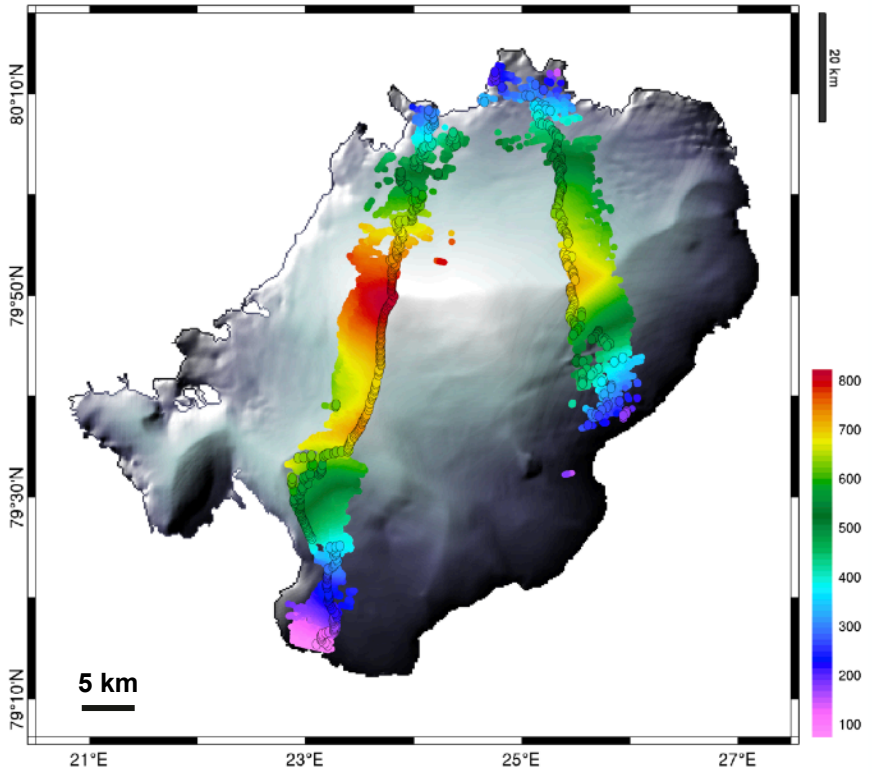


CryoSat swath altimetry



CryoSat swath altimetry

Increased spatial coverage



Gourmelen et al., 2018

CryoSat swath altimetry

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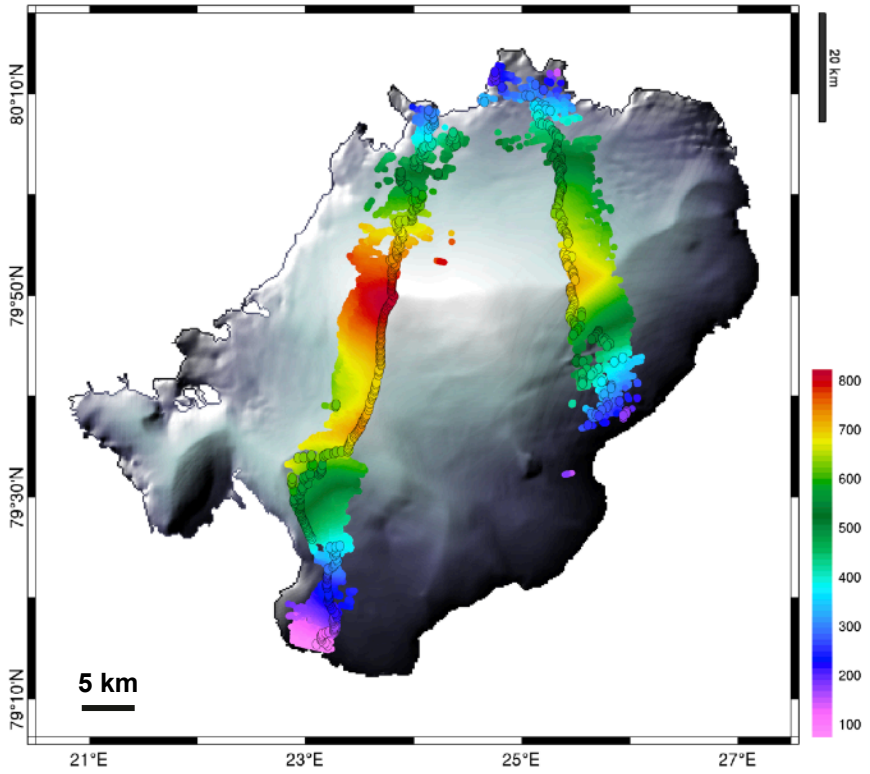
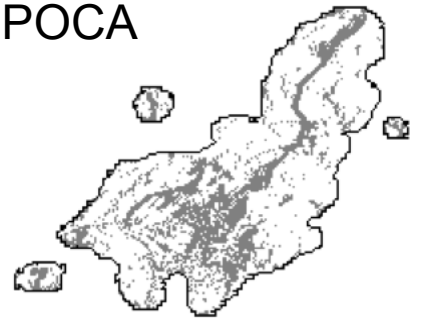
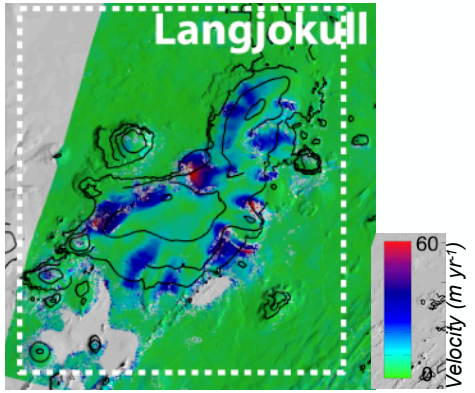


Gourmelen et al., 2018

More homogeneous topographic sampling

POCA





Foresta et al., 2016; Gourmelen et al., 2011

CryoSat swath altimetry

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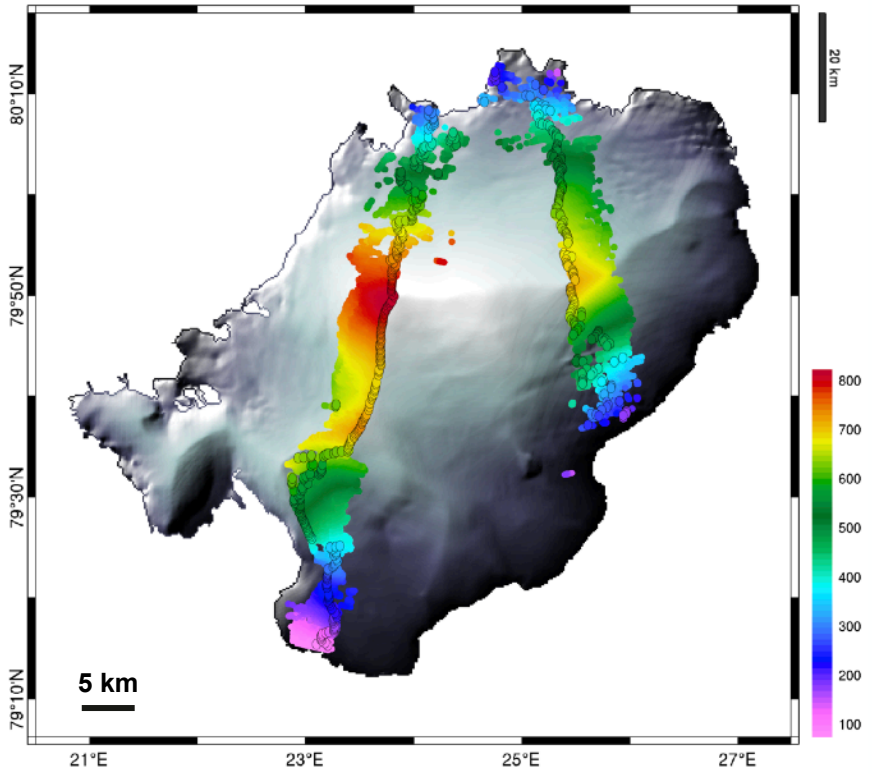

Gourmelen et al., 2018

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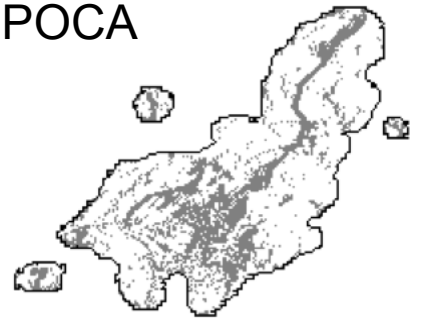

SWATH

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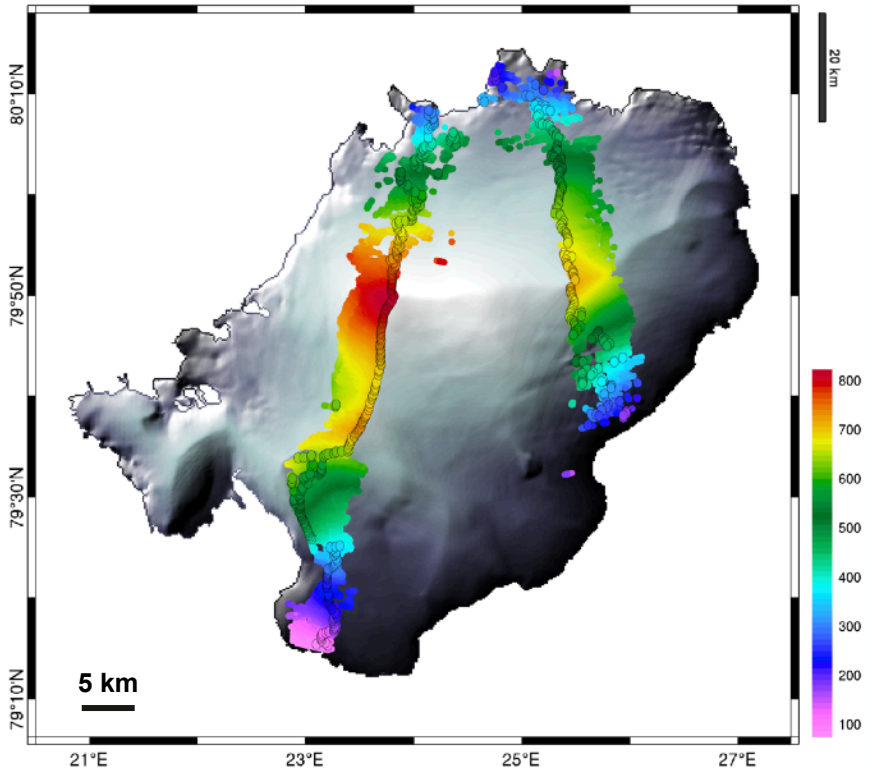

Gourmelen et al., 2018

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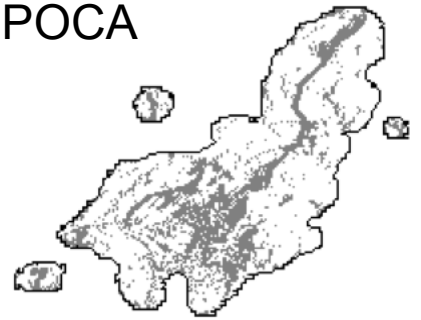
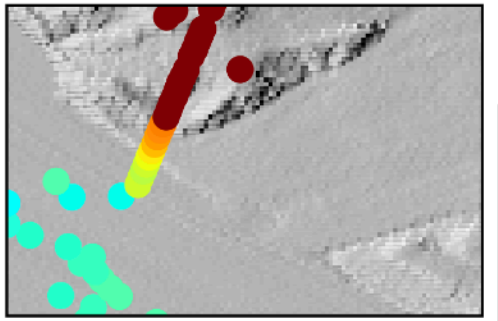


SWATH

Retrieval where retracking fails

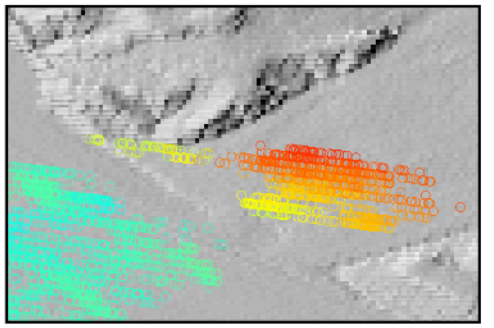
POCA

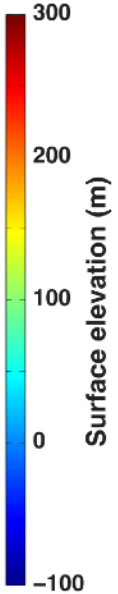
a)



SWATH

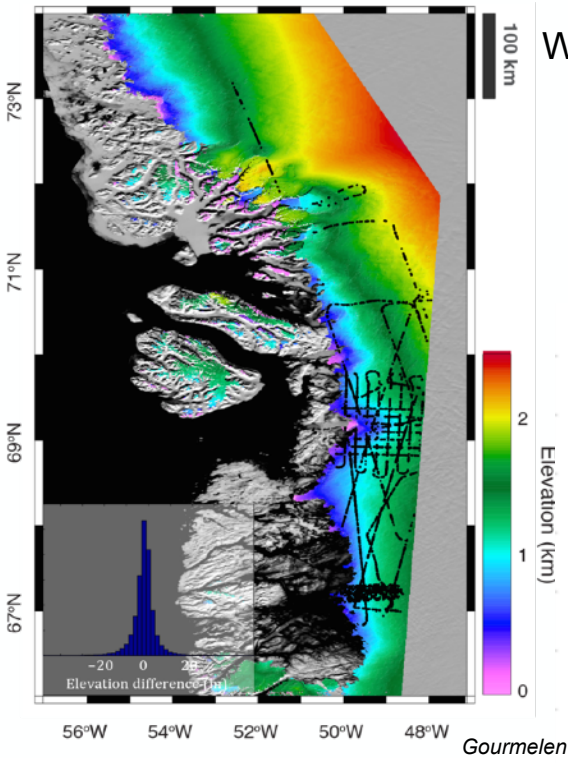
b)





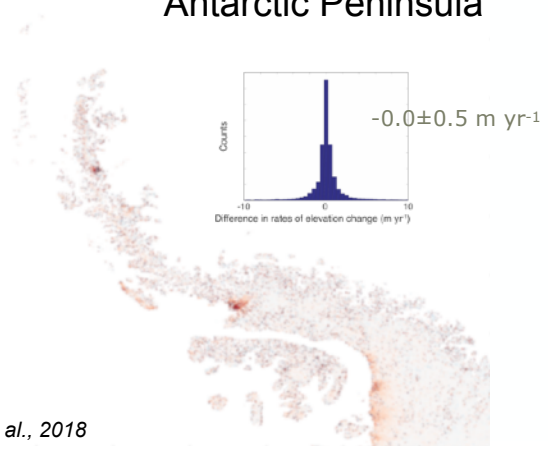
Foresta et al., 2016; Gourmelen et al., 2011

Validation



West Greenland

Antarctic Peninsula



Gourmelen et al., 2018

Table 1
Bias and dispersion of swath mode elevation and derived gridded products, POCA, with respect to Operation IceBridge Airborne Laser Scanner and comparative measurements density between POCA and swath mode.

Region	Swath elevation (m)	POCA elevation (m)	Swath/POCA number of measures (10^3)	Gain in spatial resolution	Swath DEM (m)	Swath dh/dt ($m\,a^{-1}$)	POCA dh/dt ($m\,a^{-1}$)
Petermann	-1.3 ± 1.2	-1.1 ± 0.8	44.9/1.4	5 folds	NA	NA	NA
Jakobshavn	-1.2 ± 2.0	-0.6 ± 1.4	99.9/1.0	10 folds	-1.4 ± 1.8	0.04 ± 1.15	0.17 ± 1.54
Amundsen Sea Sector	-2.0 ± 2.0	-1.1 ± 1.3	199.3/3.3	8 folds	-1.7 ± 2.0	0.04 ± 0.92	0.40 ± 0.95

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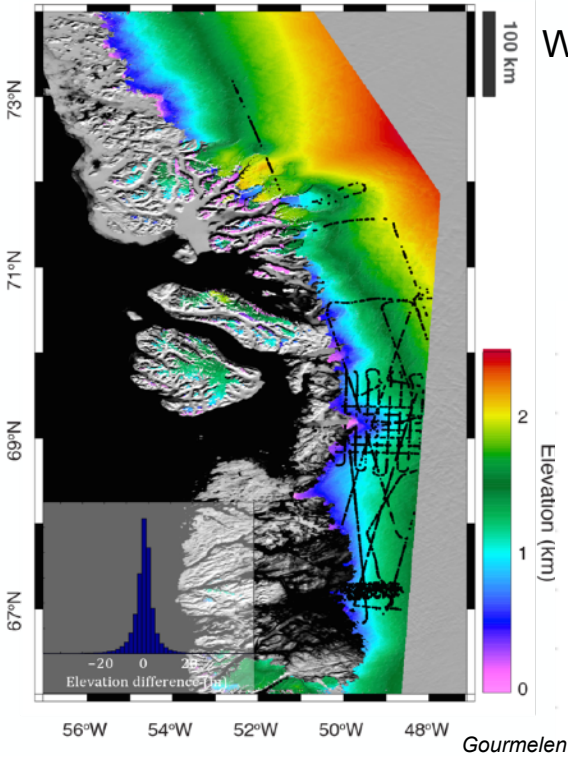

West Greenland

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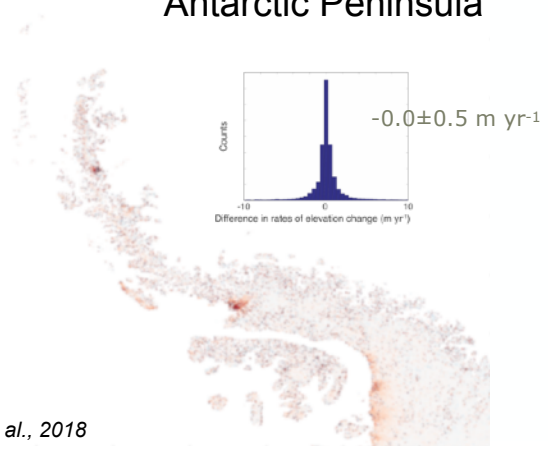
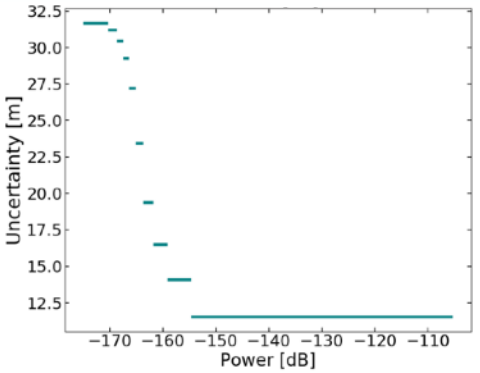
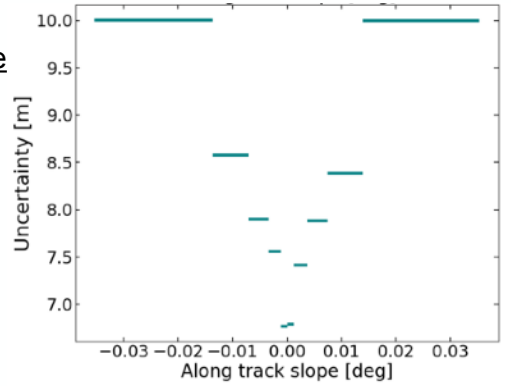


Gourmelen et al., 2018

Backscatter



Along-track slope



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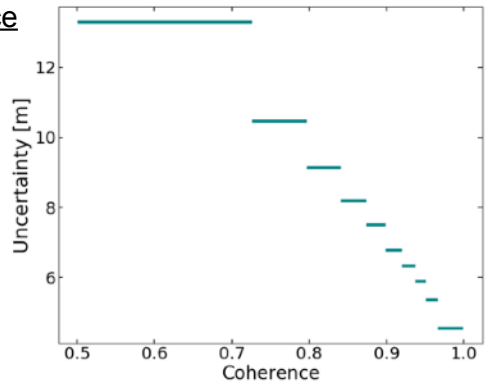
Coherence



Michael et al., 2022

THE UNIVERSITY of EDINBURGH

Applications

Ice sheets

Geophysical Research Letters / Volume 43, Issue 11 / p. 5741-5749
Research Letter | Open Access
Four-decade record of pervasive grounding line retreat along the Bellingshausen margin of West Antarctica
Frazer D. W. Christie, Robert G. Bingham, Noel Gourmelen, Simon F. B. Tett, Atsuhiro Muto

Geophysical Research Letters / Volume 48, Issue 23 / e2021GL094546
Research Letter | Open Access
Helheim Glacier Poised for Dramatic Retreat
Joshua J. Williams, Noel Gourmelen, Peter Nienow, Charlie Bunce, Donald Slater

Geophysical Research Letters / Volume 43, Issue 18 / p. 9729-9738
Research Letter | Open Access
Northeast sector of the Greenland Ice Sheet to undergo the greatest inland expansion of supraglacial lakes during the 21st century
Ádám Ignéczi, Andrew J. Sole, Stephen J. Livingstone, Amber A. Leeson, Xavier Fettweis, Nick Selmes, Noel Gourmelen, Kate Briggs

The Cryosphere, 12, 2461–2479, 2018
https://doi.org/10.5194/tc-12-2461-2018
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The Cryosphere
Glacier change along West Antarctica's Marie Byrd Land Sector and links to inter-decadal atmosphere–ocean variability
Frazer D. W. Christie[1], Robert G. Bingham[1], Noel Gourmelen[1], Eric J. Steig[2], Rosie R. Bisset[1], Hamish D. Pritchard[3], Kate Snow[4], and Simon F. B. Tett[1]

Article | Published: 10 December 2019
Mass balance of the Greenland Ice Sheet from 1992 to 2018
The IMBIE Team
Nature 579, 233–239 (2020) | Cite this article

Geophysical Research Letters / Volume 46, Issue 20 / p. 11253-11260
Research Letter | Open Access
Assessing Uncertainty in the Dynamical Ice Response to Ocean Warming in the Amundsen Sea Embayment, West Antarctica
Isabel J. Nias, Stephen L. Cornford, Tamsin L. Edwards, Noel Gourmelen, Antony J. Payne

Roll Calibration for CryoSat-2: A Comprel Approach
by Albert Garcia-Mondéjar[1,*], Michele Scagliola[2], Noel Gourmelen[3,4] and Mònica Roca[1]
[1] isardSAT S.L., Barcelona Advanced Industry Park, 08242 Barcelona, Spain
[2] Aresys SRL, 20132 Milano, Italy
[3] School of GeoSciences, University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, UK
[4] IPGS UMR 7516, Université de Strasbourg, CNRS, 67000 Strasbourg, France
[5] ESA ESRIN, 00044 Frascati, Italy
* Author to whom correspondence should be addressed.
Remote Sens. 2021, 13(2), 302; https://doi.org/10.3390/rs13020302

Glaciers

Remote Sensing of Environment
Volume 211, 15 June 2018, Pages 441-455
Heterogeneous and rapid ice loss over the Patagonian Ice Fields revealed by CryoSat-2 swath radar altimetry
L. Foresta, N. Gourmelen, F. Weissgerber, P. Nienow, J.J. Williams, A. Shepherd, M.R. Drinkwater, S. Plummer

The Cryosphere, 15, 233–246, 2021
https://doi.org/10.5194/tc-15-233-2021
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The Cryosphere
Review article: Earth's ice imbalance
Thomas Slater[1], Isobel R. Lawrence[1], Inès N. Otosaka[1], Andrew Shepherd[1], Noel Gourmelen[2], Livia Jakob[3], Paul Tepes[2], Lin Gilbert[4], and Peter Nienow[2]

Advances in Space Research
Volume 62, Issue 6, 15 September 2018, Pages 1226-1242
CryoSat-2 swath interferometric altimetry for mapping ice elevation and elevation change
N. Gourmelen, M.J. Escorihuela, A. Shepherd, L. Foresta, A. Muir, A. Garcia-Mondéjar, M. Roca, S.G. Baker, M.R. Drinkwater

Articles
Subglacial controls on dynamic thinning at Trinity-Wykeham Glacier, Prince of Wales Ice Field, Canadian Arctic
William D. Harcourt, Steven J. Palmer, Damien T. Mansell, Anne Le Brocq, Oliver Bartlett, Noel Gourmelen, ...show all

Remote Sensing of Environment
Volume 211, 15 June 2018, Pages 357-375
Accelerating glacier mass loss on Franz Josef Land, Russian Arctic
Whyjay Zheng, Matthew E. Pritchard, Michael J. Willis, Paul Tepes, Noel Gourmelen, Toby J. Benham, Julian A. Dowdeswell

The Cryosphere, 15, 1845–1862, 2021
https://doi.org/10.5194/tc-15-1845-2021
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The Cryosphere
Spatially and temporally resolved ice loss in High Mountain Asia and the Gulf of Alaska observed by CryoSat-2 swath altimetry between 2010 and 2019
Livia Jakob[1], Noel Gourmelen[1,2,3], Martin Ewart[1], and Stephen Plummer[4]

Remote Sensing of Environment
Volume 261, August 2021, 112481
Changes in elevation and mass of Arctic glaciers and ice caps, 2010–2017
P. Tepes, N. Gourmelen, P. Nienow, M. Tsamados, A. Shepherd, F. Weissgerber

Ice shelves

The Cryosphere, 14, 1399–1408, 2020
https://doi.org/10.5194/tc-14-1399-2020
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The Cryosphere
Getz Ice Shelf melt enhanced by freshwater discharge from beneath the West Antarctic Ice Sheet
Wei Wei[1], Donald D. Blankenship[1], Jamin S. Greenbaum[1], Noel Gourmelen[2], Christine F. Dow[3], Thomas G. Richter[1], Chad A. Greene[1], Duncan A. Young[1], SangHoon Lee[3], Tae-Wan Kim[3], Won Sang Lee[3], and Karen M. Assmann[4,5]

Melt at grounding line controls observed and future retreat of Smith, Pope, and Kohler glaciers
David A. Lilien[1,2], Ian Joughin[1], Benjamin Smith[1], and Noel Gourmelen[3]

Open Access | Article
Sub-Annual Calving Front Migration, Area Change and Calving Rates from Swath Mode CryoSat-2 Altimetry, on Filchner-Ronne Ice Shelf, Antarctica
by Jan Wuite, Thomas Nagler, Noel Gourmelen, Maria Jose Escorihuela, Anna E. Hogg and Mark R. Drinkwater

Geophysical Research Letters / Volume 44, Issue 19 / p. 9796-9804
Research Letter | Open Access
Channelized Melting Drives Thinning Under a Rapidly Melting Antarctic Ice Shelf
Noel Gourmelen, Dan N. Goldberg, Kate Snow, Sian F. Henley, Robert G. Bingham, Satoshi Kimura, Anna E. Hogg, Andrew Shepherd, Jeremie Mouginot, Jan T. M. Lenaerts ... See all authors

Geophysical Research Letters / Volume 46, Issue 1 / p. 189-199
Research Letter | Open Access
How Accurately Should We Model Ice Shelf Melt Rates?
D. N. Goldberg, N. Gourmelen, S. Kimura, R. Millan, K. Snow

Sea-ice

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 59, NO. 5, MAY 2021
Multi-peak Retracking of CryoSat-2 SARIn Waveforms Over Arctic Sea Ice
Alessandro Di Bella, Ronald Kwok, *Life Fellow, IEEE*, Thomas W. K. Armitage, Henriette Skourup, *Member, IEEE*, and René Forsberg

Geophysical Research Letters / Volume 43, Issue 23 / p. 12,138-12,145
Research Letter | Free Access
Surface elevation change and mass balance of Icelandic ice caps derived from swath mode CryoSat-2 altimetry
L. Foresta, N. Gourmelen, F. Pálsson, P. Nienow, H. Björnsson, A. Shepherd

Sub-glacial

The Cryosphere, 11, 451–467, 2017
www.the-cryosphere.net/11/451/2017/
doi:10.5194/tc-11-451-2017
© Author(s) 2017. CC Attribution 3.0 License.
The Cryosphere
Connected subglacial lake drainage beneath Thwaites Glacier, West Antarctica
Benjamin E. Smith[1], Noel Gourmelen[2,3], Alexander Huth[4], and I

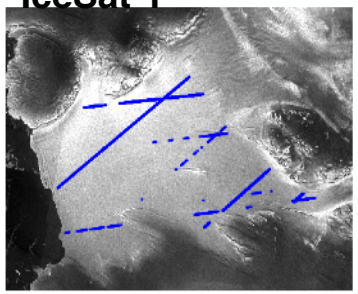
Geophysical Research Letters / Volume 47, Issue 23 / e2020GL089658
Research Letter | Open Access
Repeat Subglacial Lake Drainage and Filling Beneath Thwaites Glacier
G. Malczyk, N. Gourmelen, D. Goldberg, J. Wuite, T. Nagler

Journal of Geophysical Research: Earth Surface / Volume 126, Issue 7 / e2021JF006068
Research Article | Open Access
Accelerating Ice Mass Loss Across Arctic Russia in Response to Atmospheric Warming, Sea Ice Decline, and Atlantification of the Eurasian Arctic Shelf Seas
Paul Tepes, Peter Nienow, Noel Gourmelen

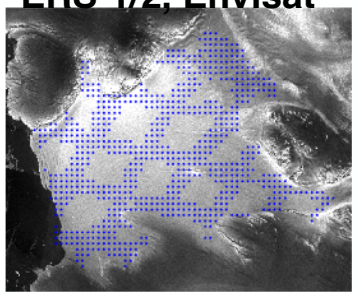
Multisurface Retracker for Swath Processing of Interferometric Radar Altimetry
Publisher: IEEE | Cite This | PDF
Albert Garcia-Mondéjar ; Noel Gourmelen ; Maria José Escorihuela ; Mònica Roca ; ...

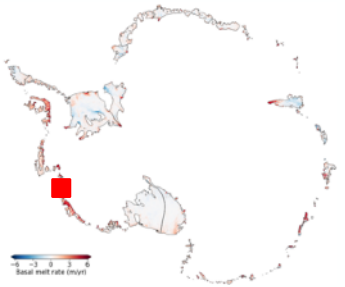
Ice shelf thinning and melting

IceSat-1

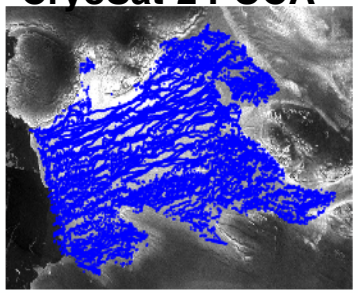


ERS-1/2, Envisat

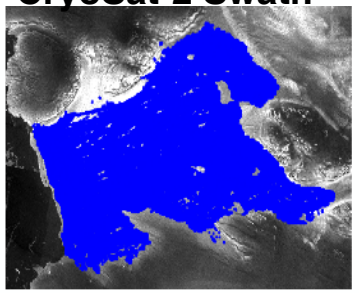




CryoSat-2 POCA

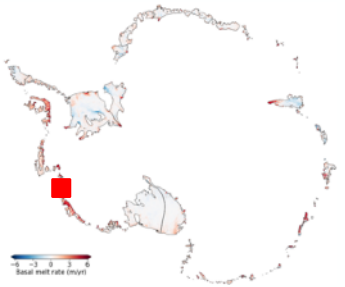


CryoSat-2 Swath

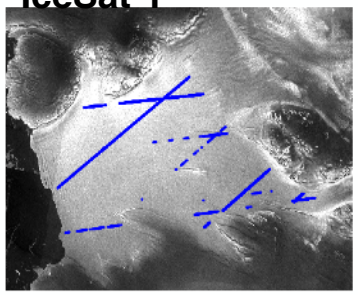


Gourmelen et al., 2018

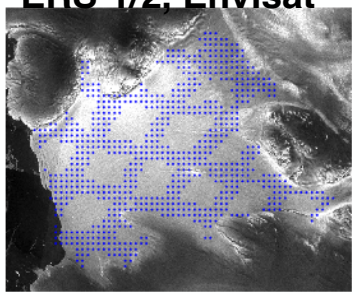
Ice shelf thinning and melting



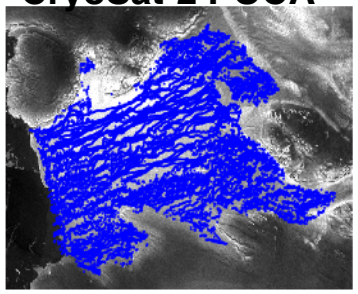
IceSat-1



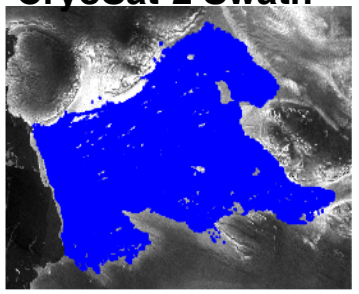
ERS-1/2, Envisat



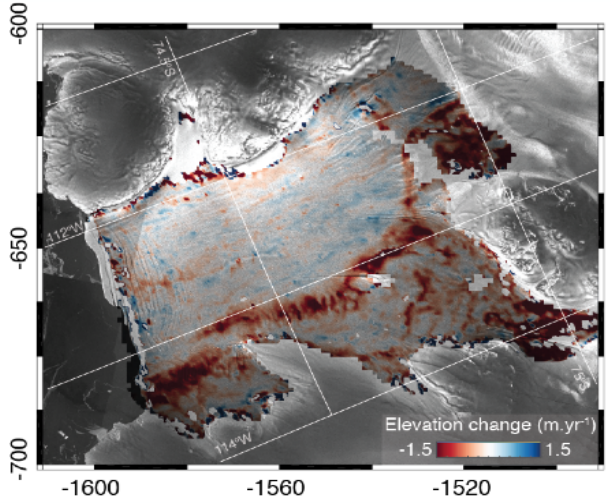
CryoSat-2 POCA



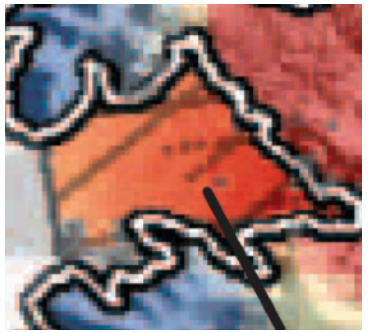
CryoSat-2 Swath



Gourmelen et al., 2018



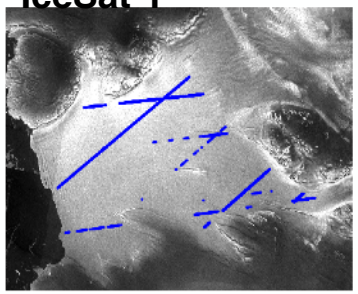
Ice thickness change



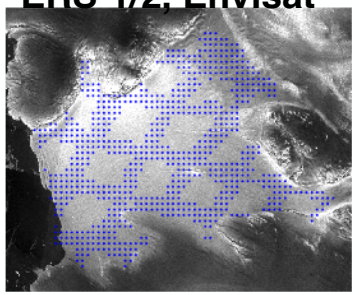
Pritchard et al., 2012

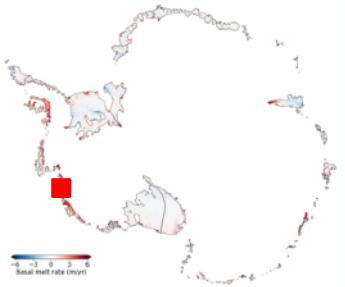
Ice shelf thinning and melting

IceSat-1

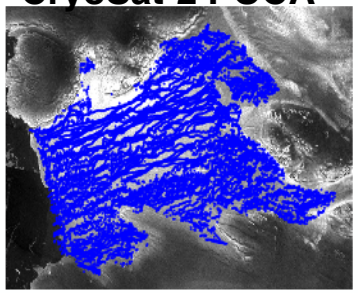


ERS-1/2, Envisat

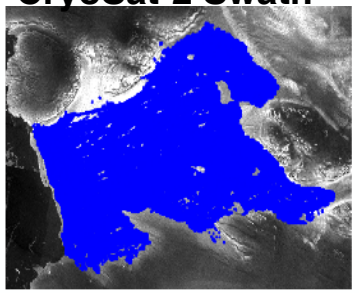




CryoSat-2 POCA



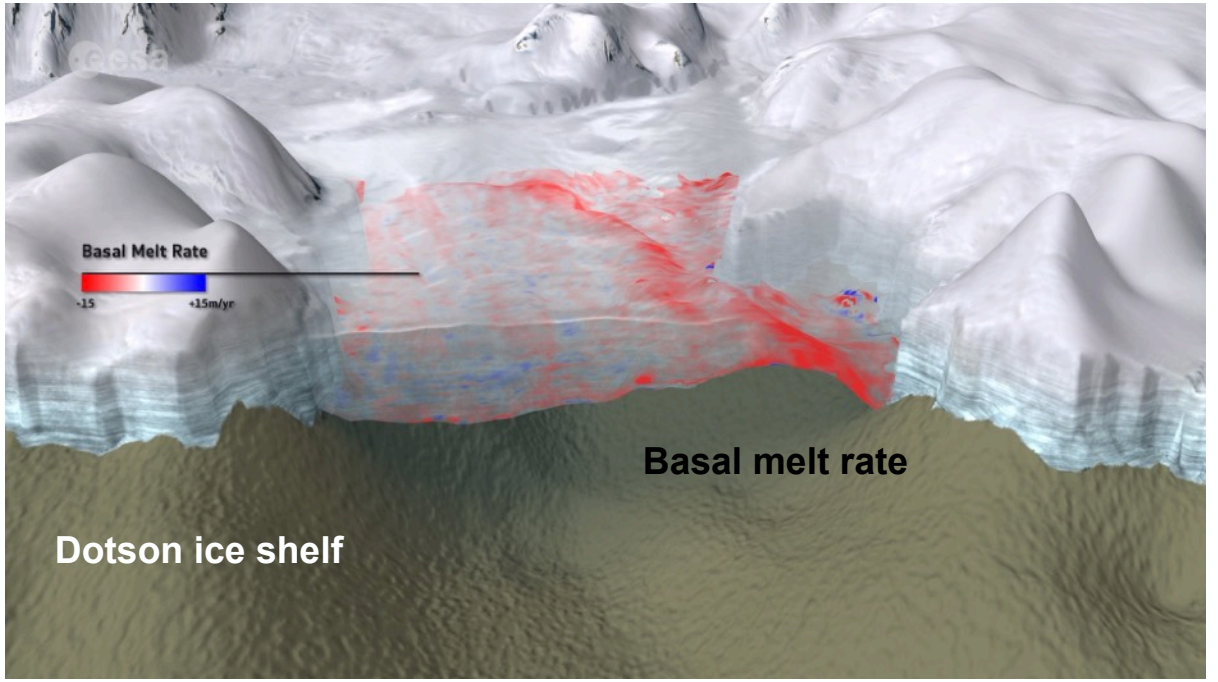
CryoSat-2 Swath

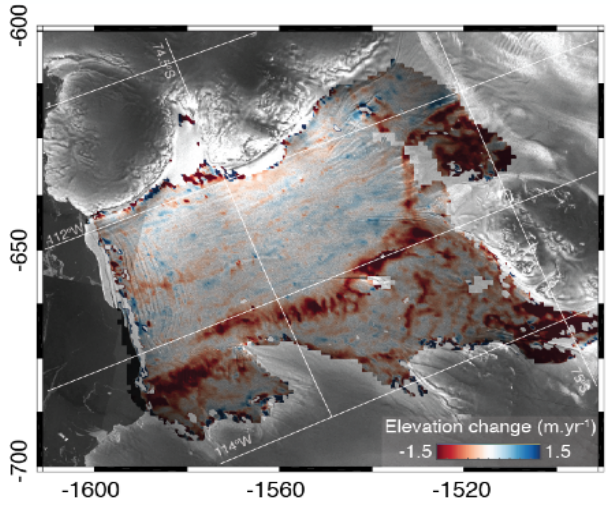


Gourmelen et al., 2018

$$\dot{m} = SMB - \left(\frac{dS}{dt} + S\nabla \cdot \mathbf{u}\right)$$

Basal melt — Surface processes — Divergence — Surface elevation change





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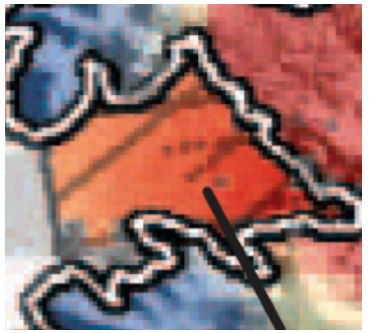
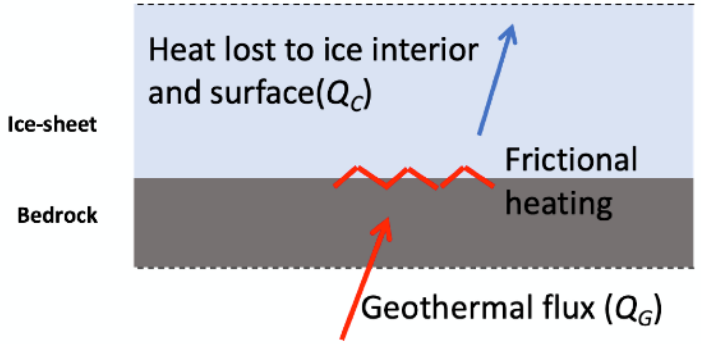
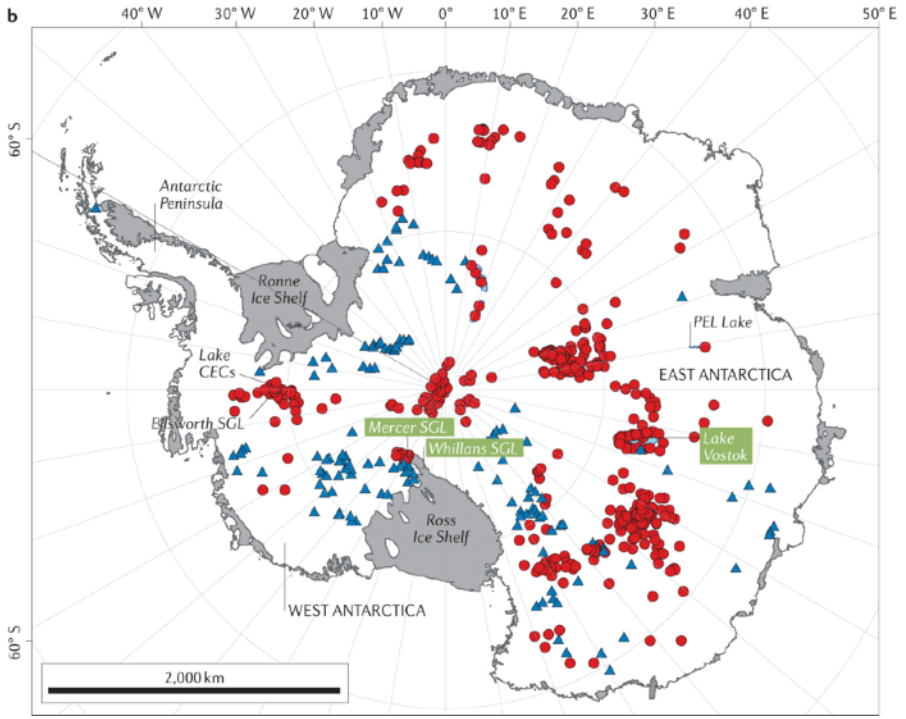


Pritchard et al., 2012

Subglacial hydrology

Subglacial hydrology





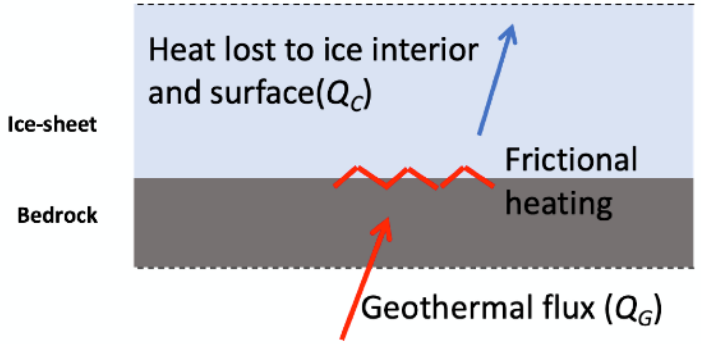
Livingston et al., 2020

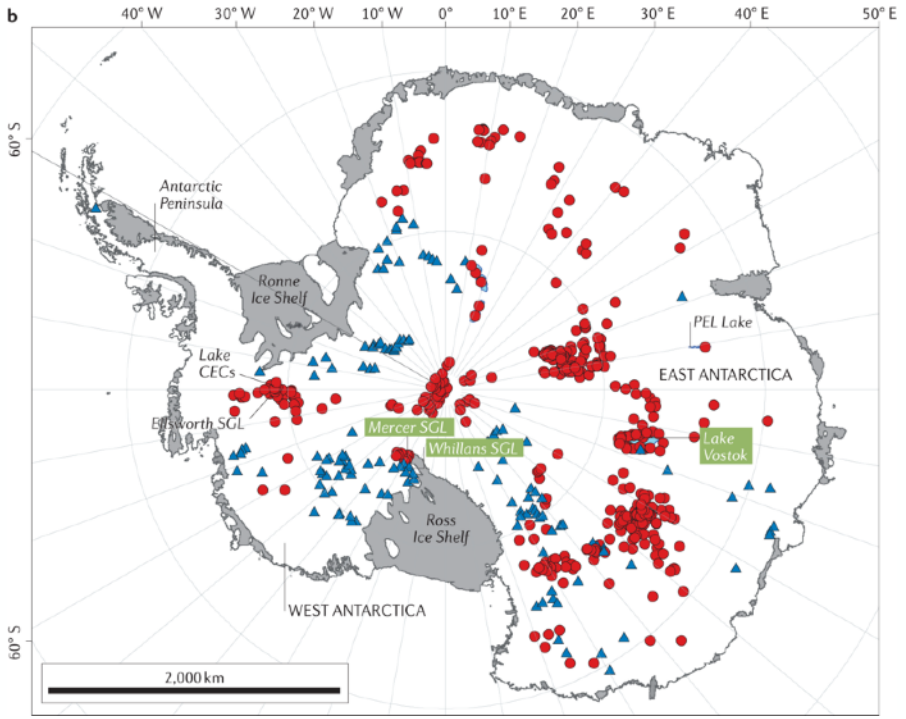
Active lakes

Malczyk et al., 2020

Subglacial hydrology

Subglacial hydrology





Livingston et al., 2020

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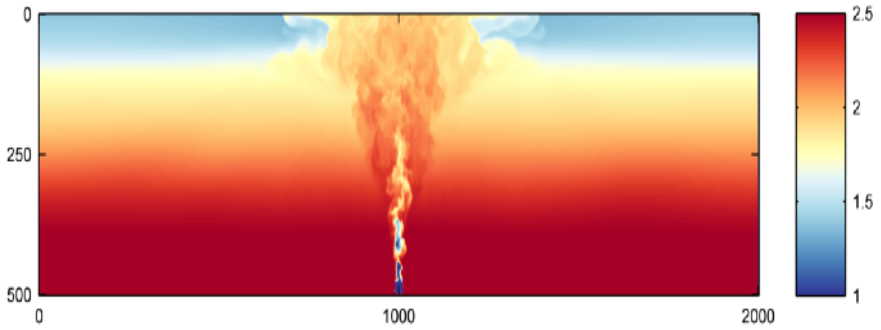
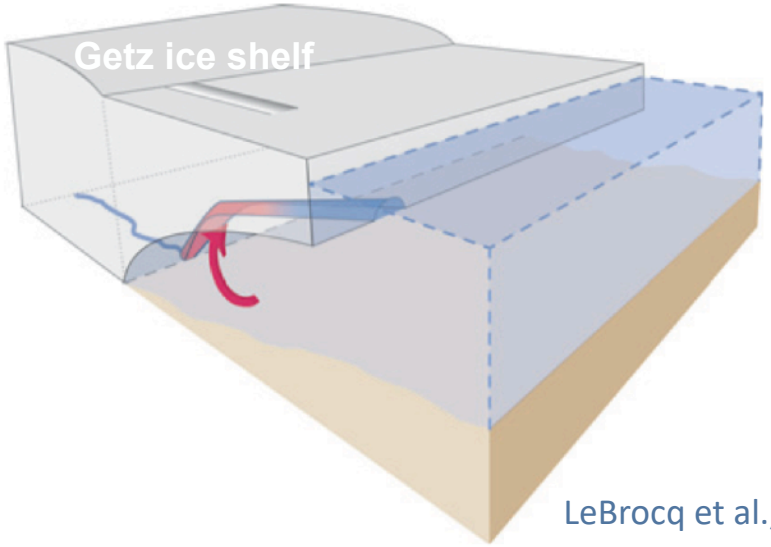
Subglacial hydrology = impact ocean

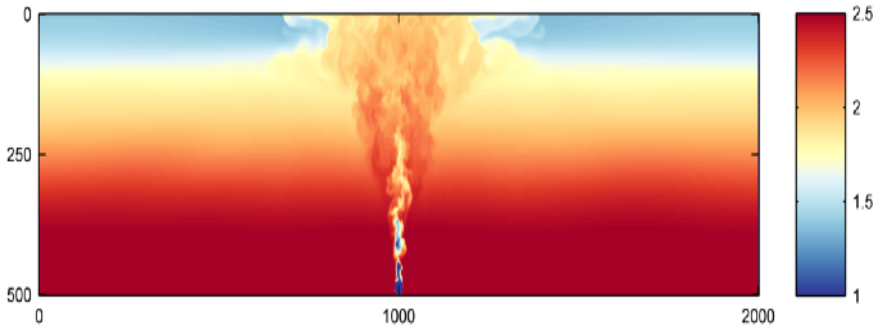


Slater et al., 2015

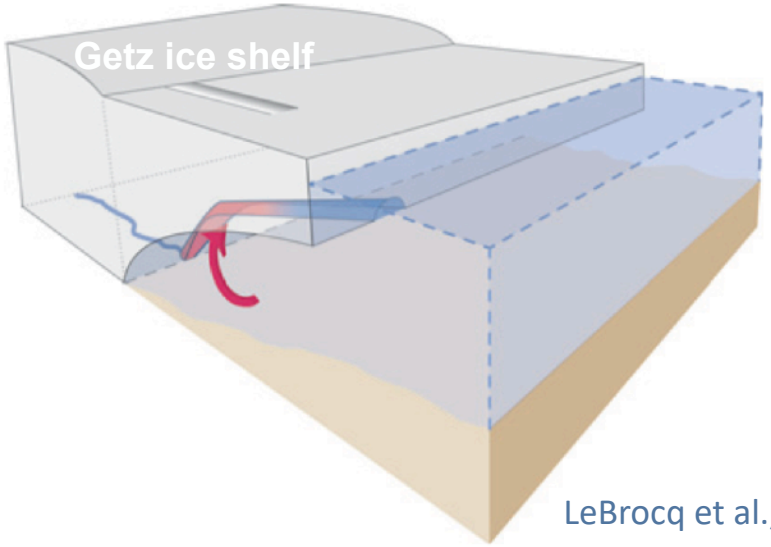


LeBrocq et al., 2013

Subglacial hydrology = impact ocean



Slater et al., 2015



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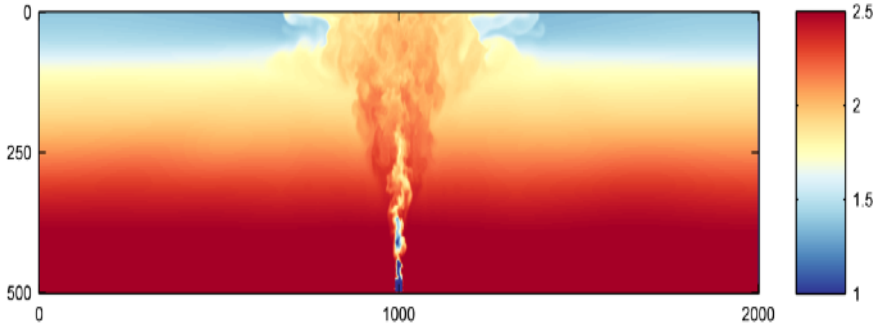
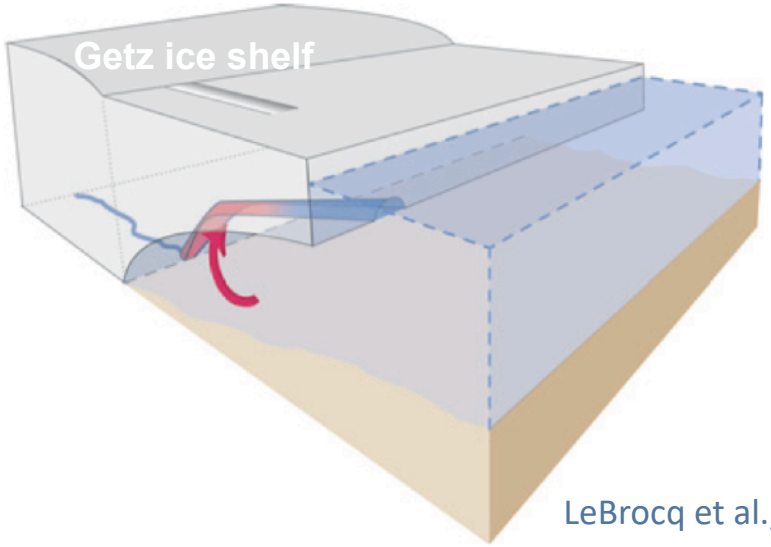


Slater et al., 2015



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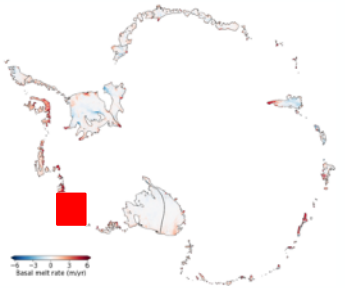

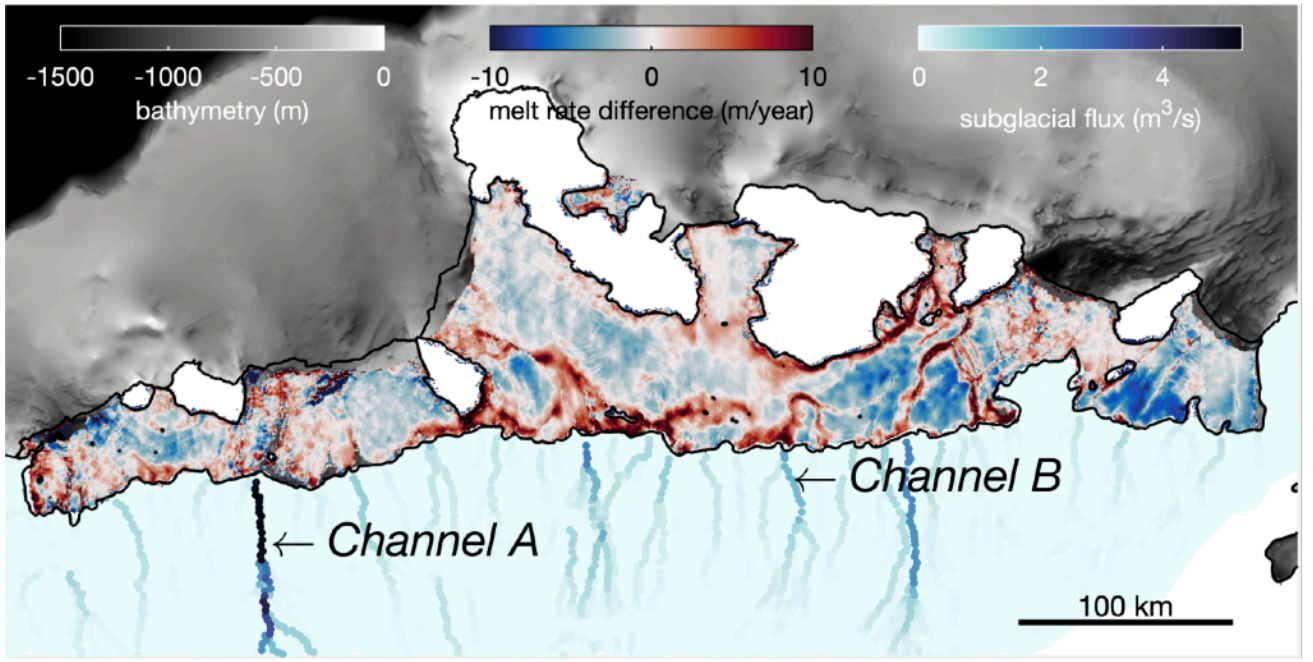

Wei et al., 2020

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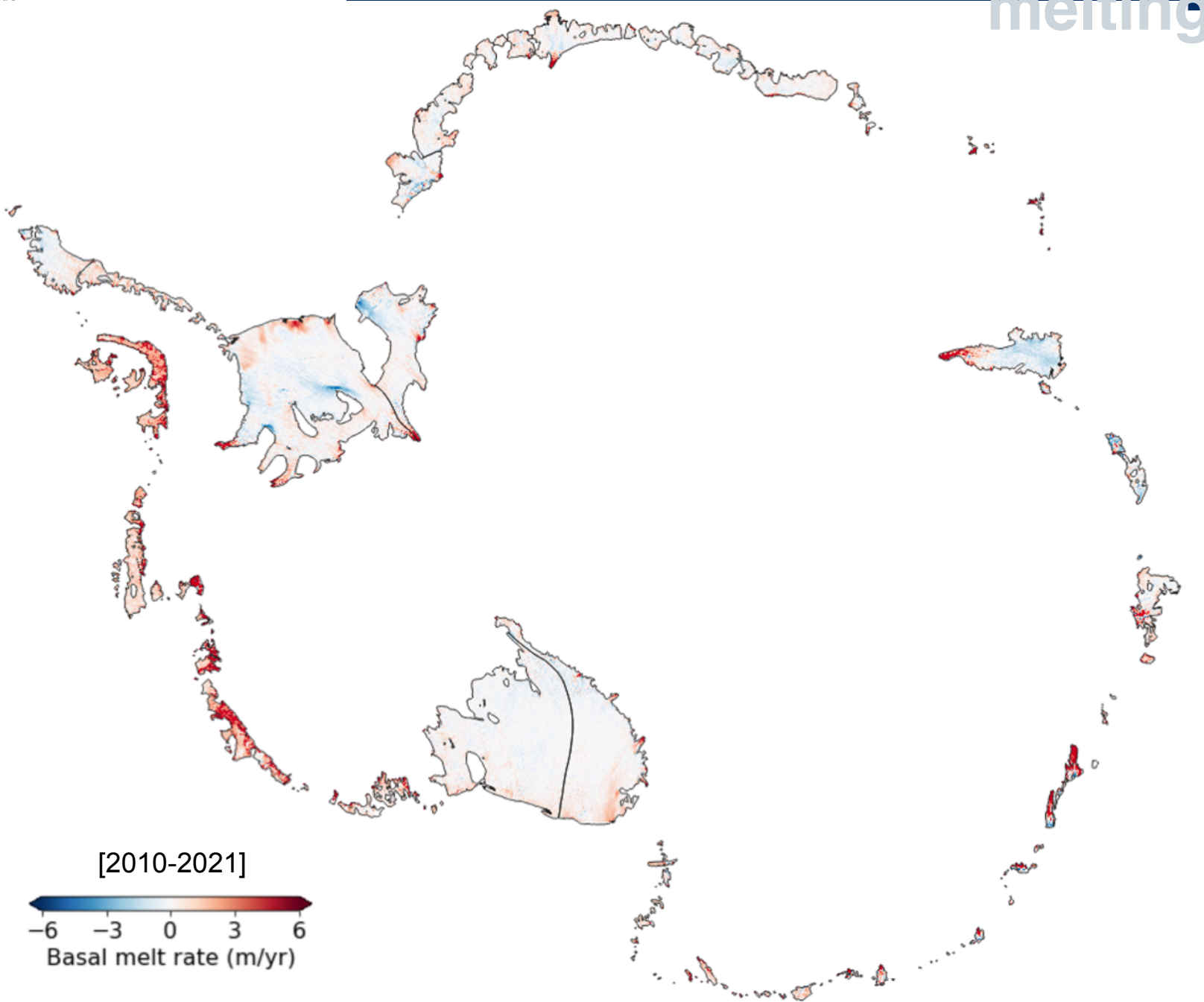
Ice shelf thinning and melting



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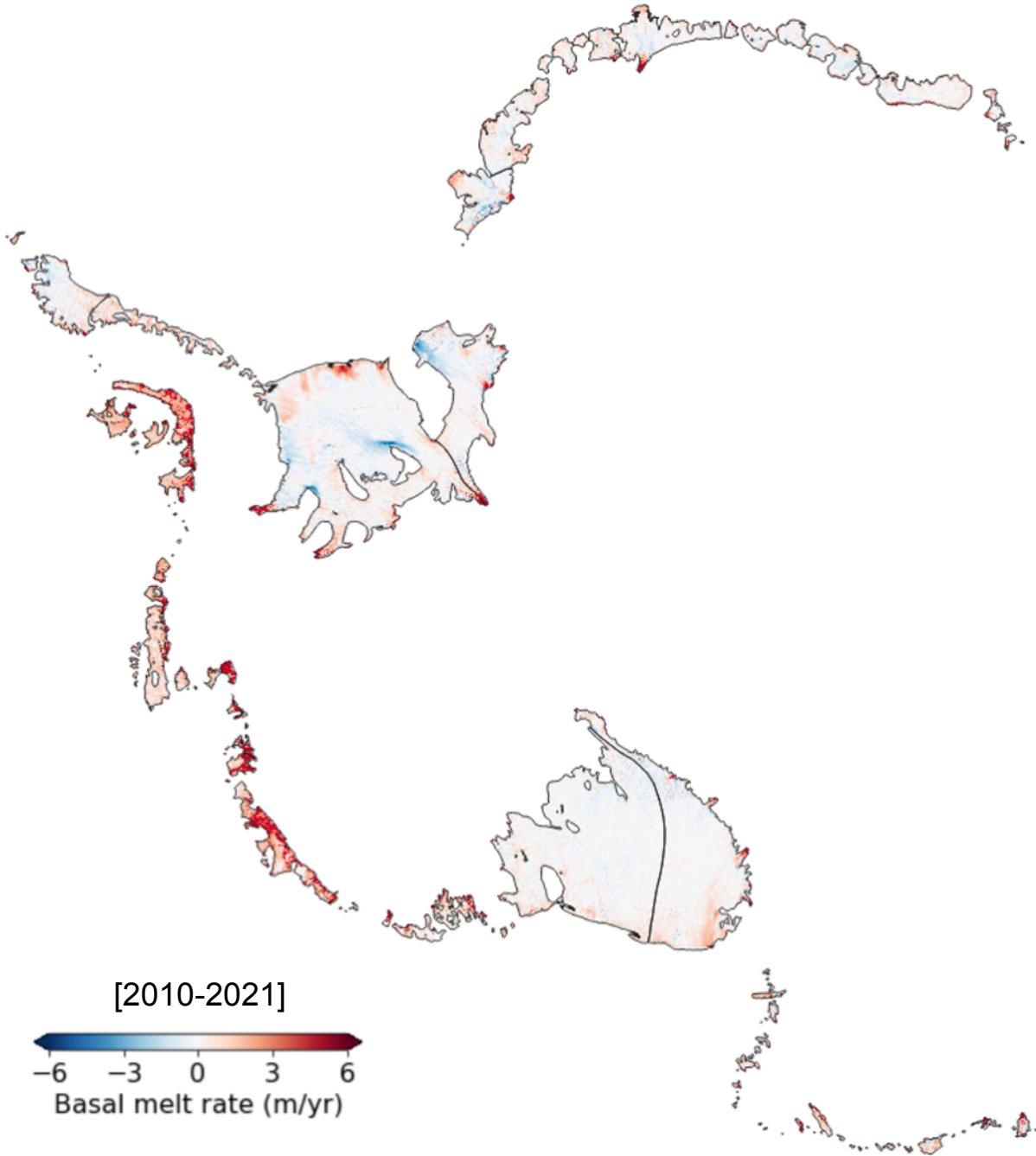
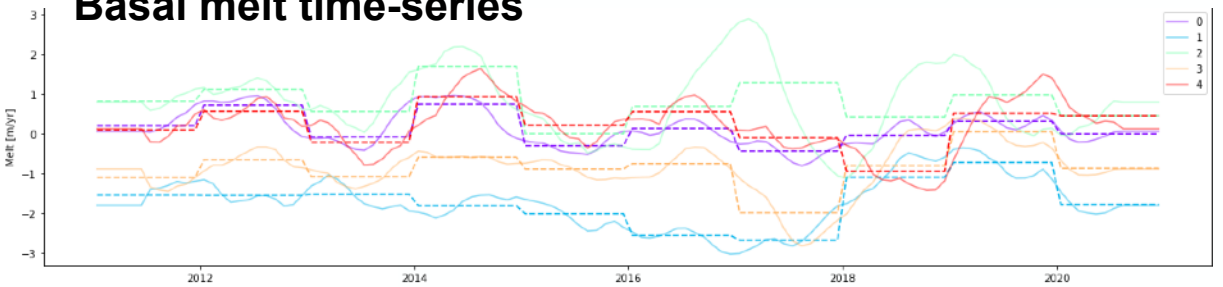


Basal melt time-series



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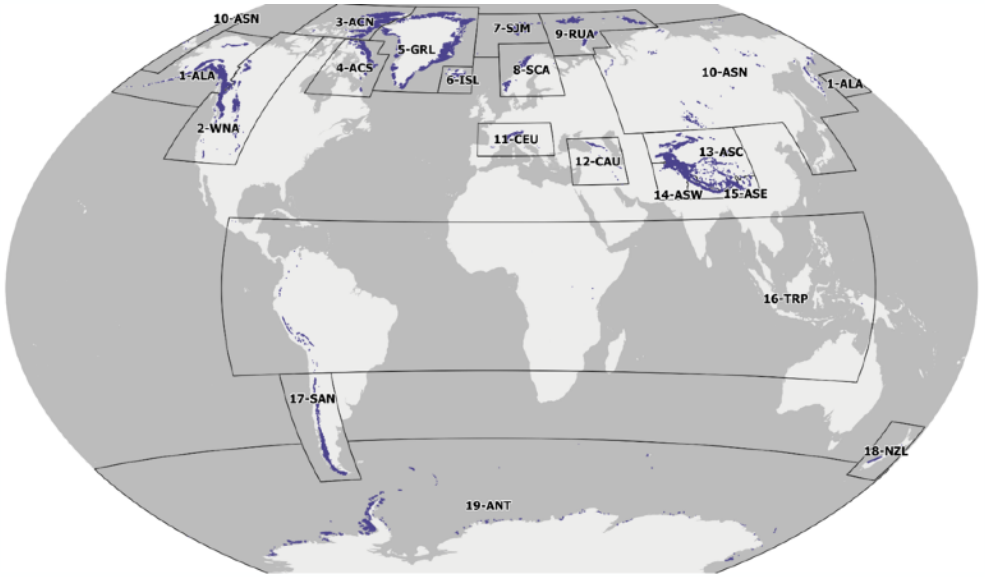
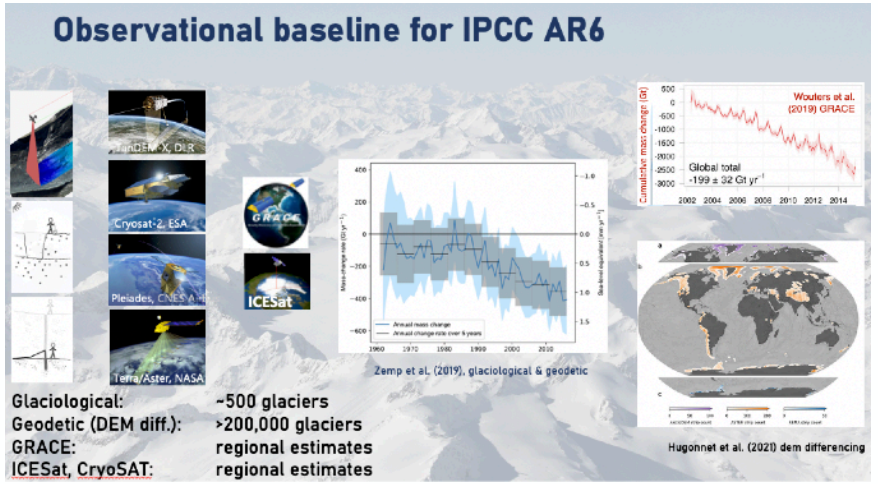
Key questions of international glacier monitoring



Randolph Glacier Inventory 6.0



Glaciers

(distinct from Greenland and Antarctic ice sheets)

>215,000

~700,000 km^2

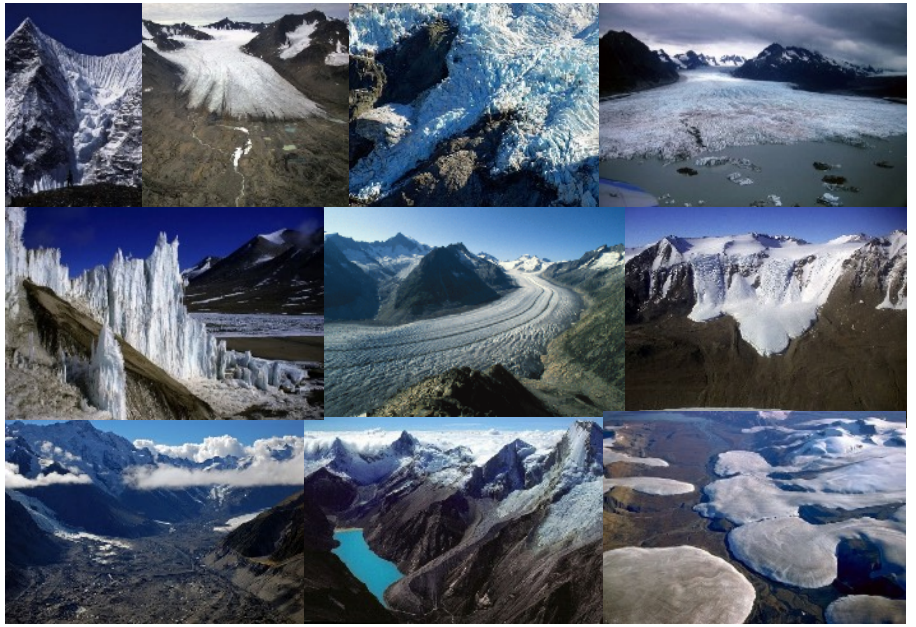
RGI Consortium (2017)

~160,000 km^3

< 0.5 m potential SLE

Farinotti et al. (2019)

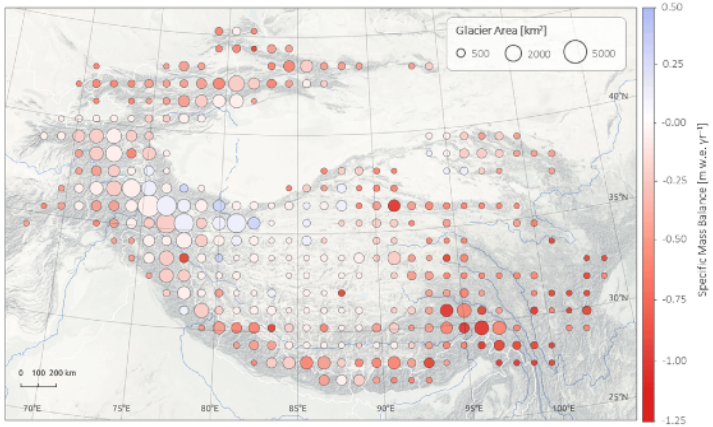
~25 % of current SLR



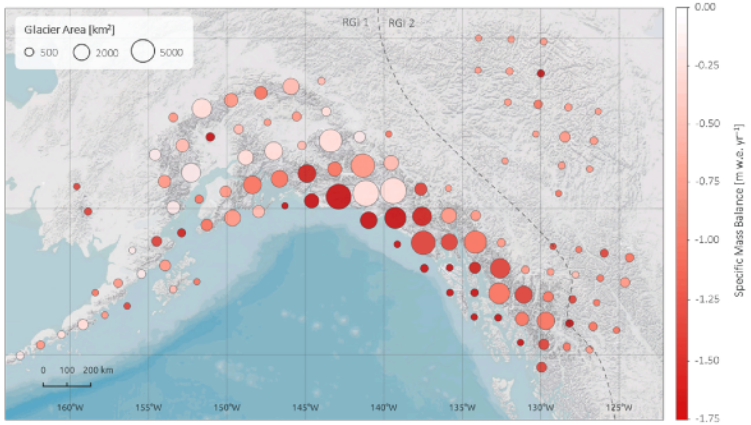
Photos from www.swisseduc.ch/glaciers/

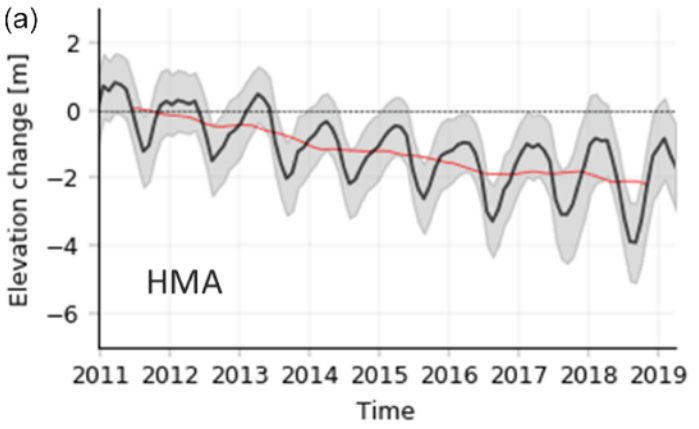
Mountain glacier change

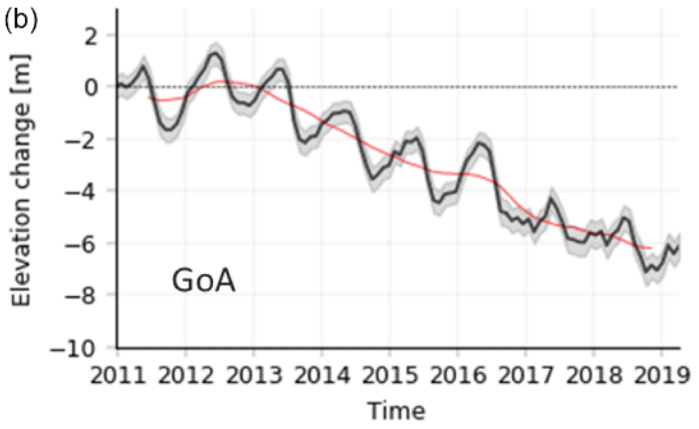
High Mountain Asia



Gulf of Alaska

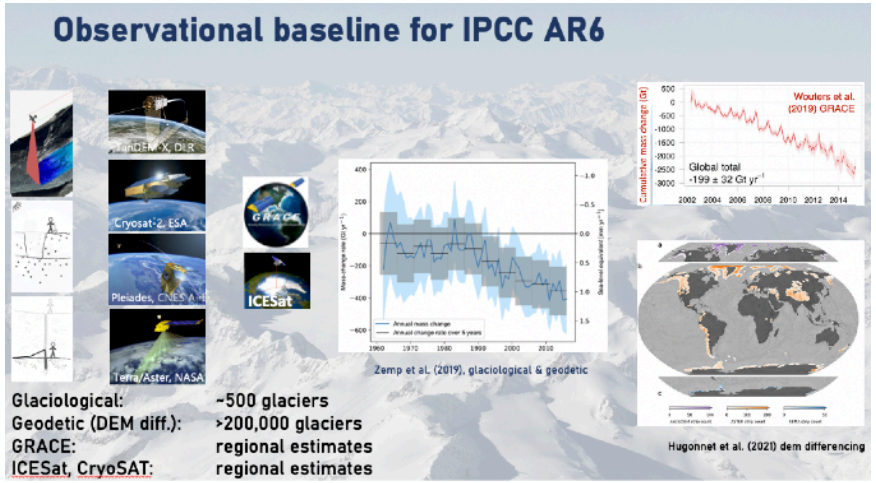






Jakob et al., 2021

Glacier mass balance – reconciliation & monitoring



Towards next IPCC report

RAGMAC & GLAMBIE: Glacier Mass Balance Intercomparison Exercise

Community effort to reconcile measurements of glacier mass balance

IACS

Building on existing activities and network of RAGMAC (Regional Assessments of Glacier Mass Change)

2-year project supported by ESA

glambie

https://glambie.org

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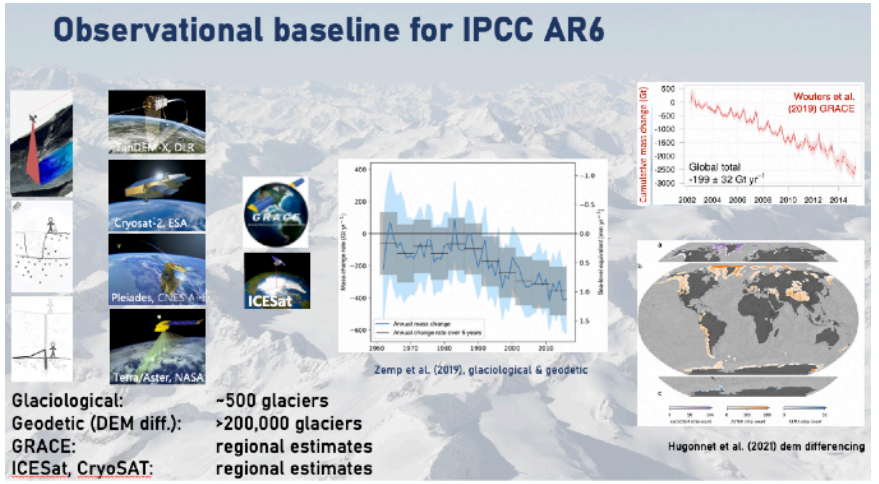

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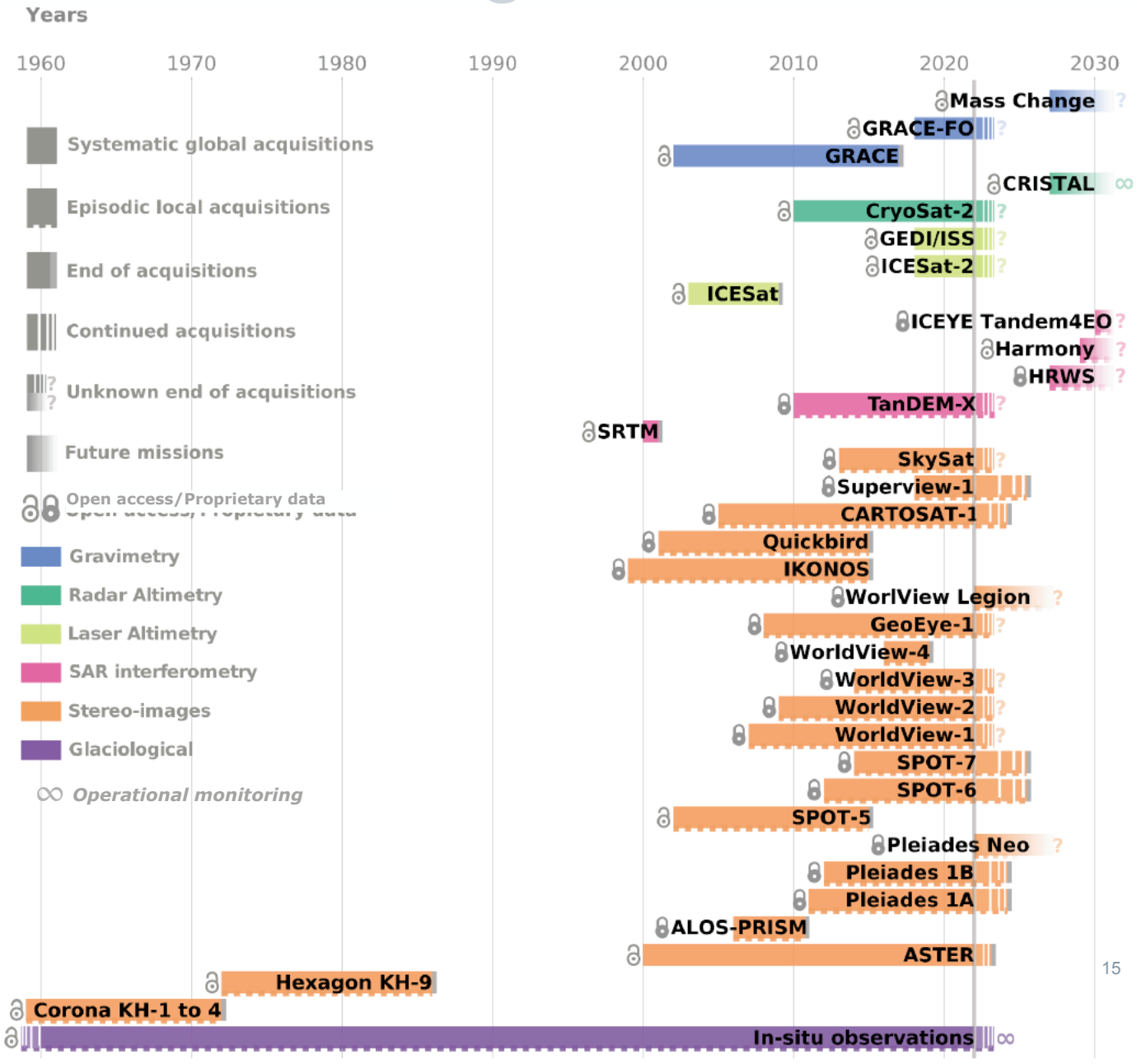

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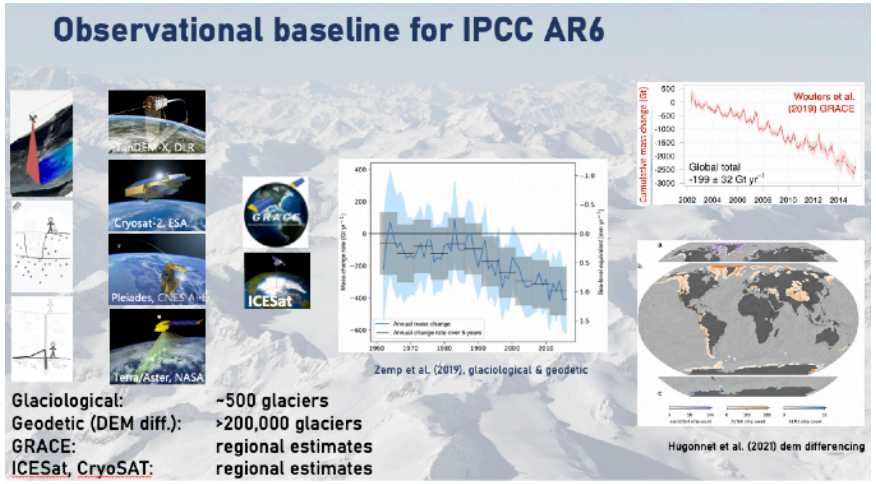

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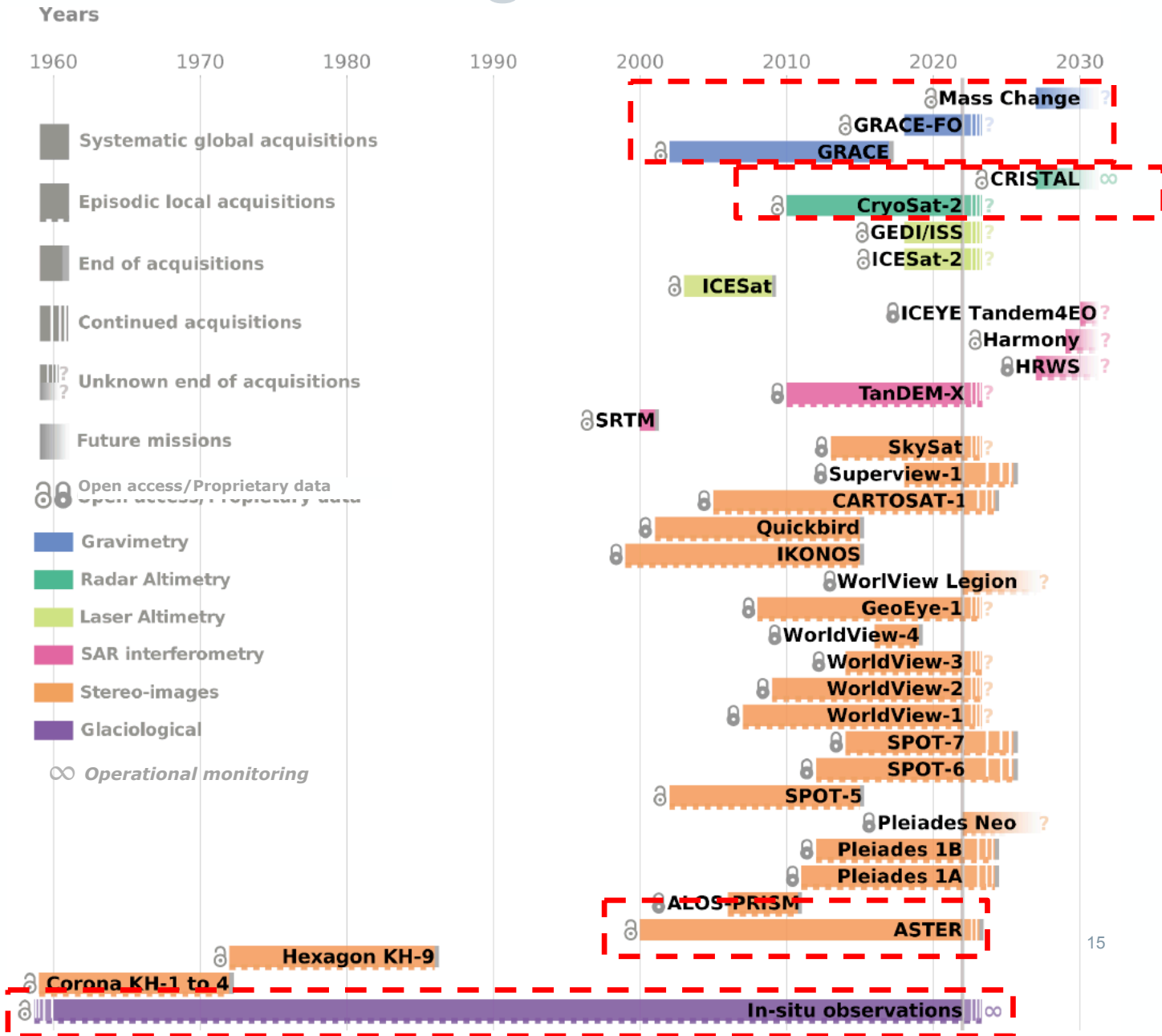
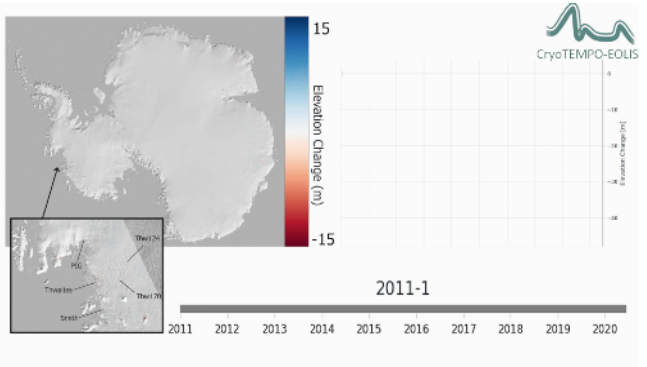


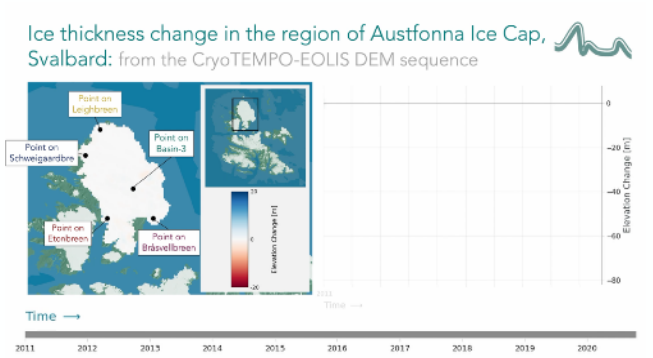
Operational land ice products

CryoTEMPO-EOLIS:

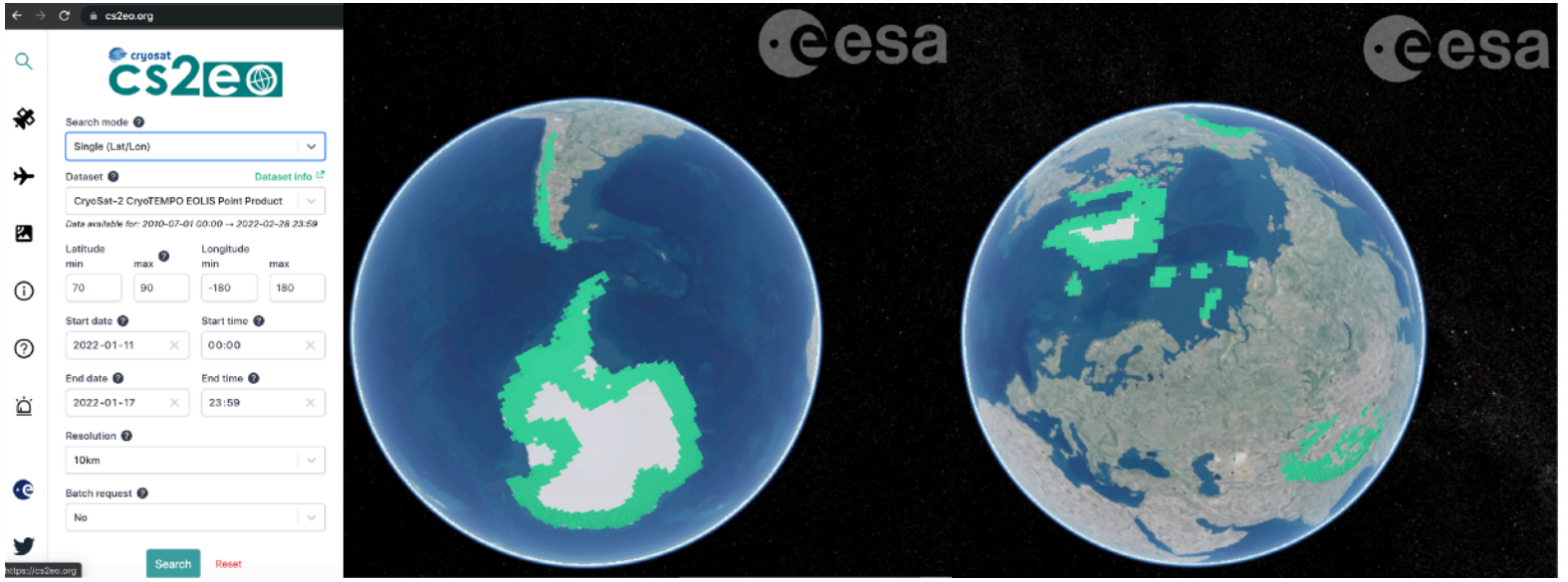
https://cryotempo-eolis.org/

- Swath point-cloud
- Monthly gridded products
- Uncertainty
- Over ice sheets and glaciers (SARIn)





cs2eo.org



>>> Posters SC42022_009 [Michael et al.,] and ODS2022_006 [Horton et al.,] Tuesday and Thursday

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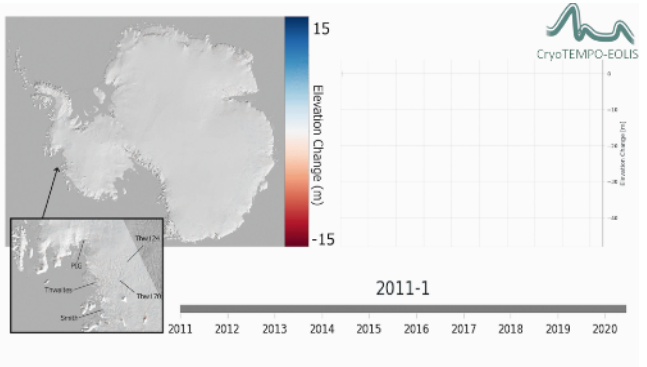

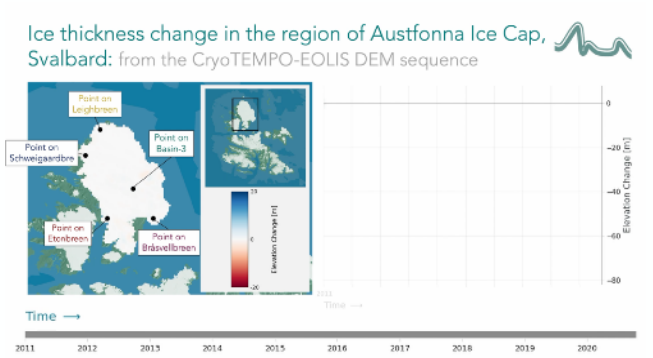

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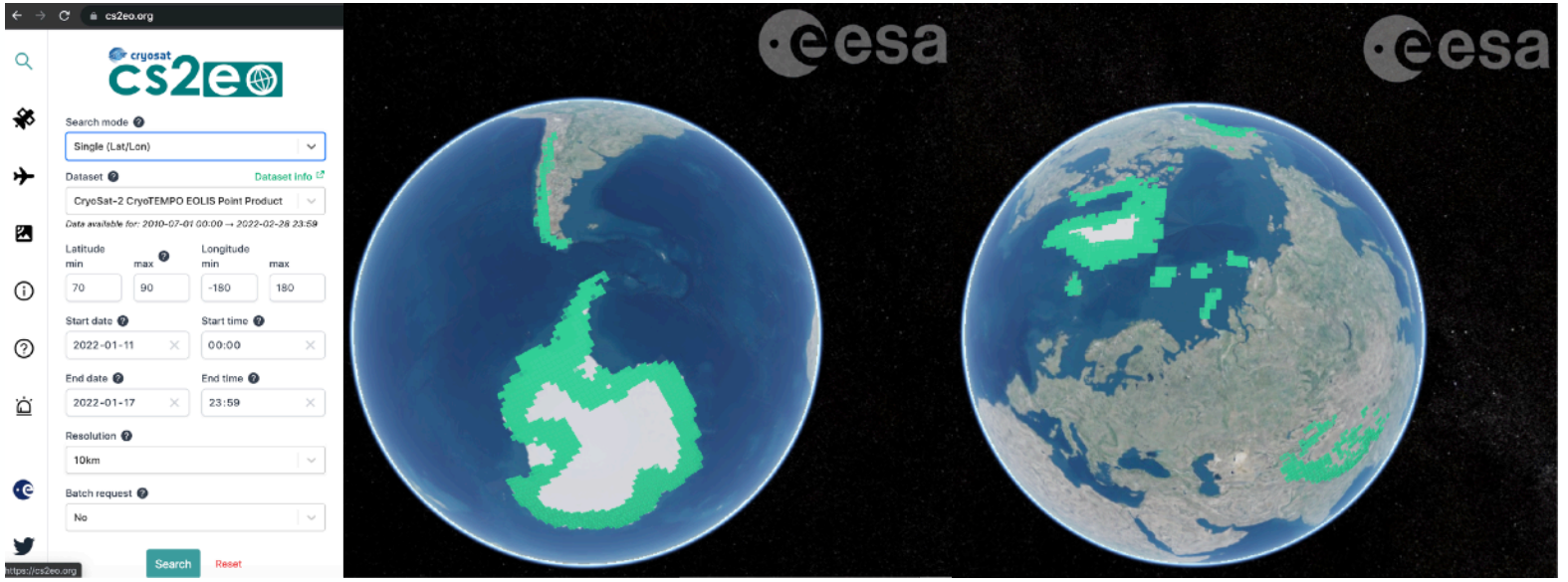

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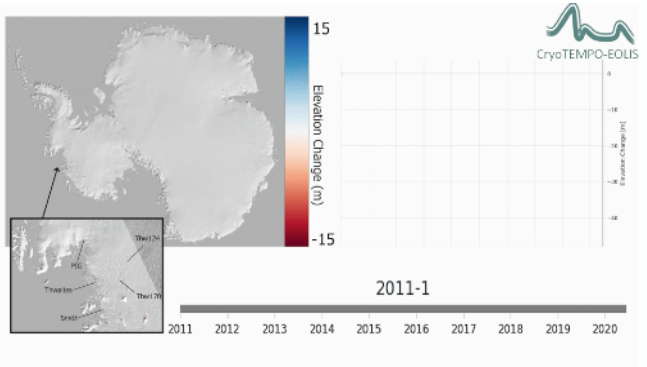

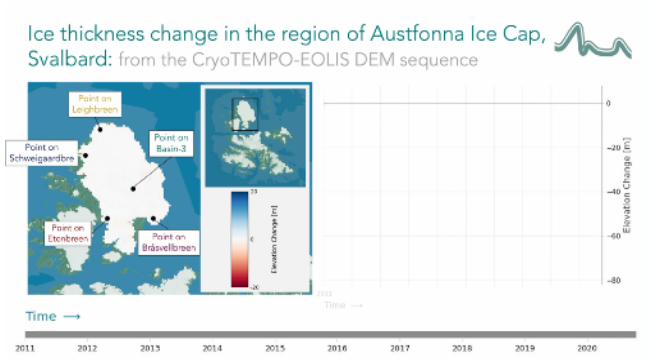

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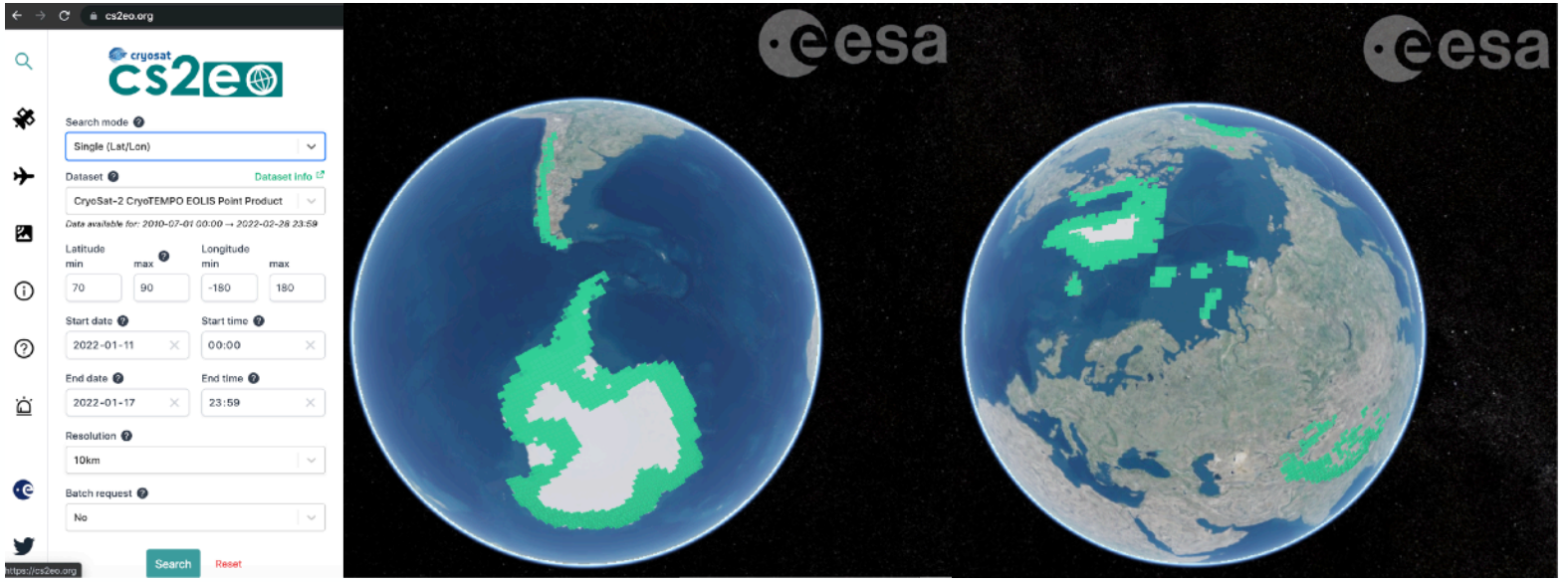

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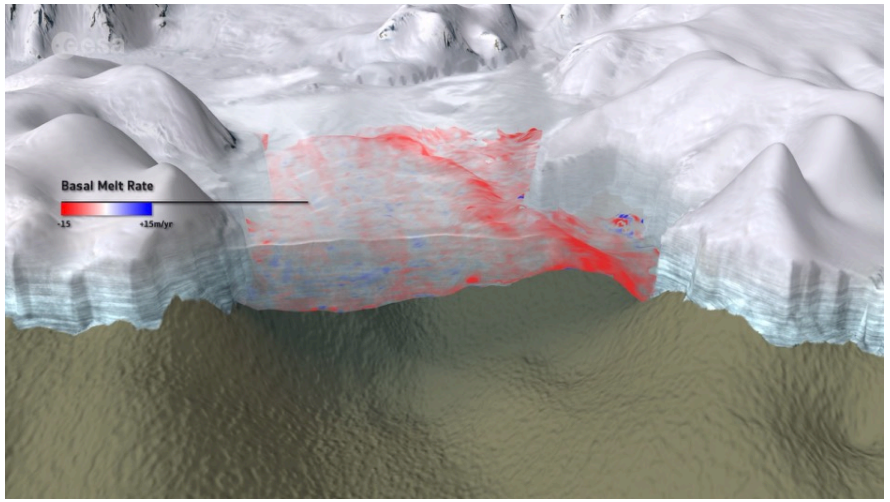
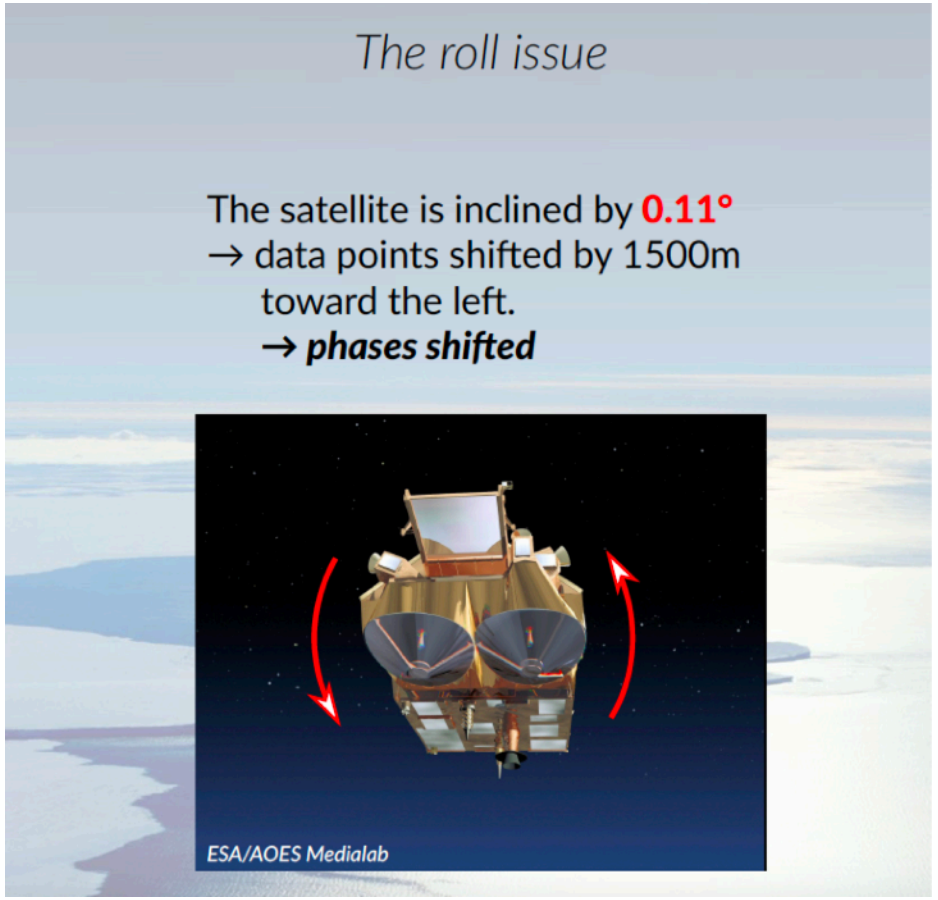
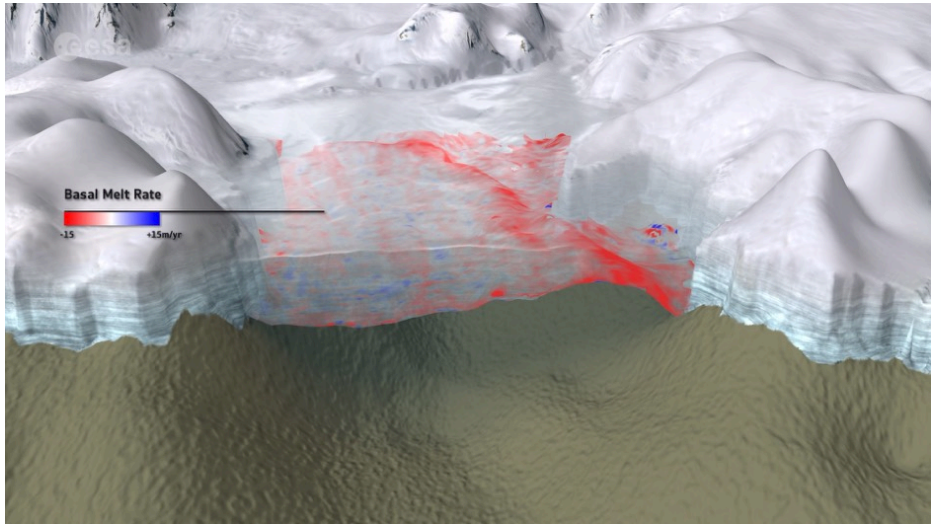
Limitations & opportunities - “Flat” terrain

Basal melt rate



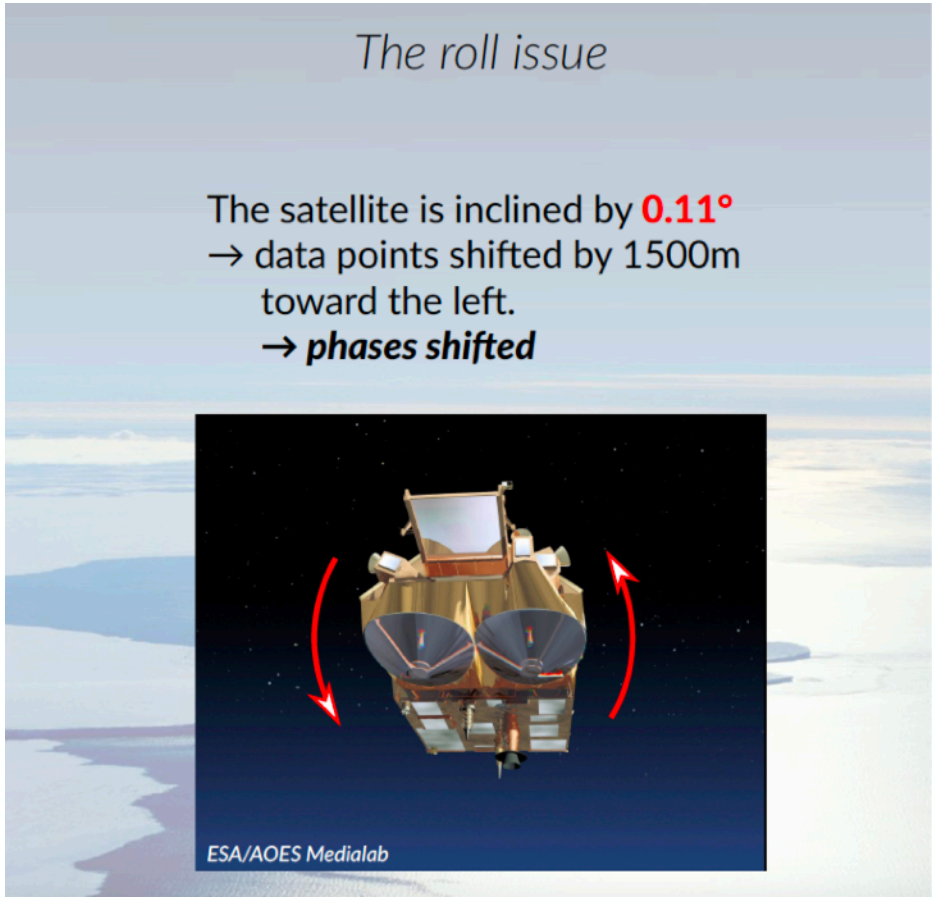
Limitations & opportunities - Mispointing

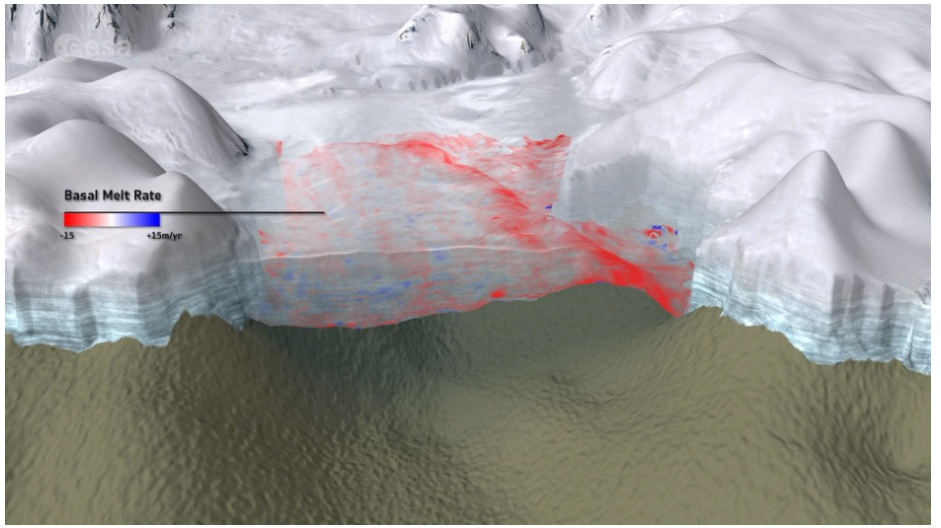




Limitations & opportunities - Mispointing

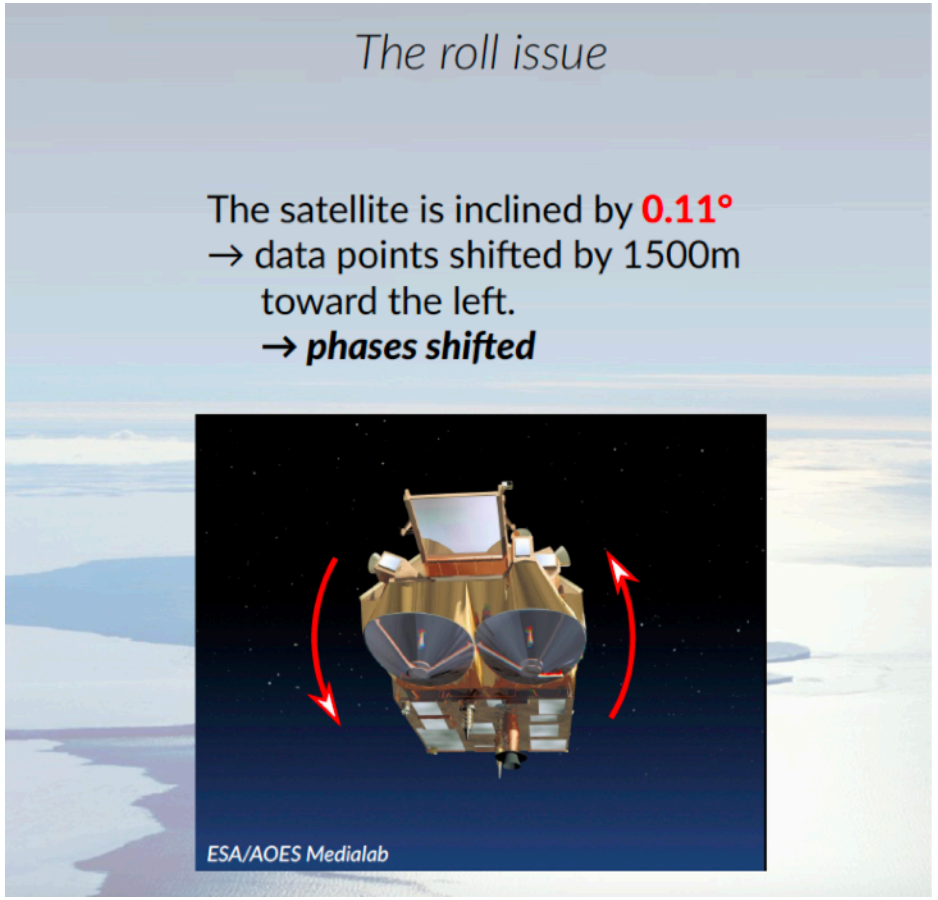
- **Benefit:** allows to potentially map ”flat” surfaces e.g. ice-shelves, sea-ice, icebergs, inland water, ocean

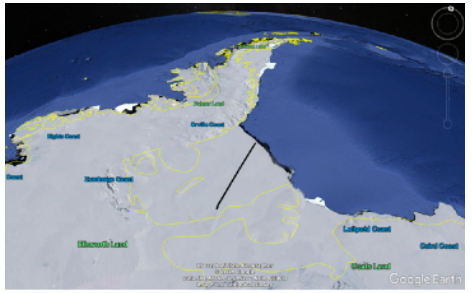


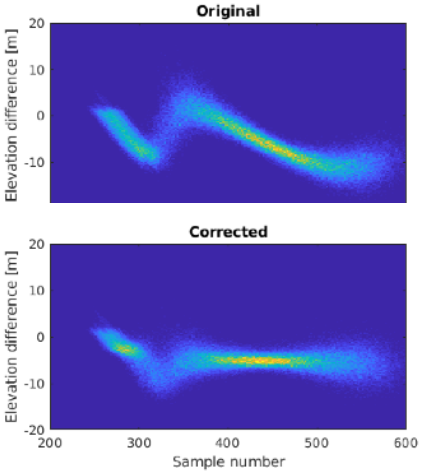


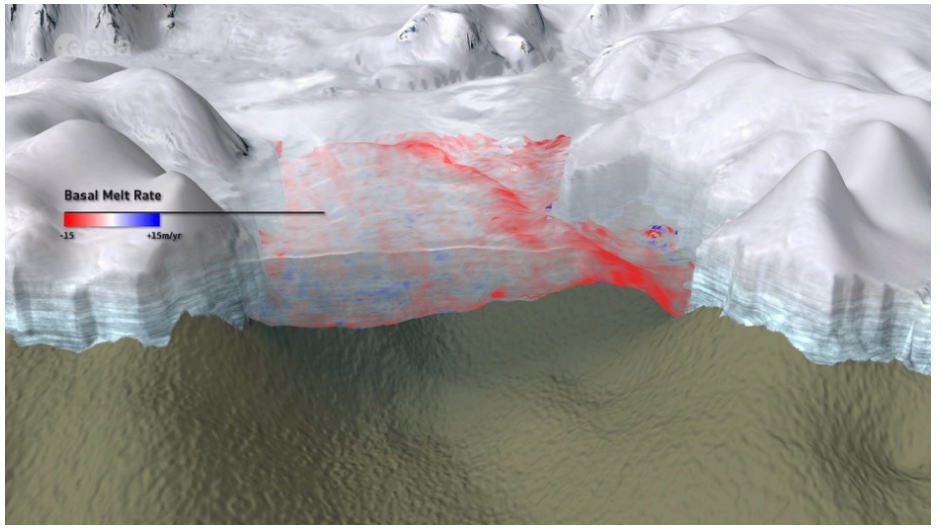
Limitations & opportunities - Mispointing

- **Benefit:** allows to potentially map ”flat” surfaces e.g. ice-shelves, sea-ice, icebergs, inland water, ocean
- **But,** simple optic no longer applicable to convert phase into angle of arrival





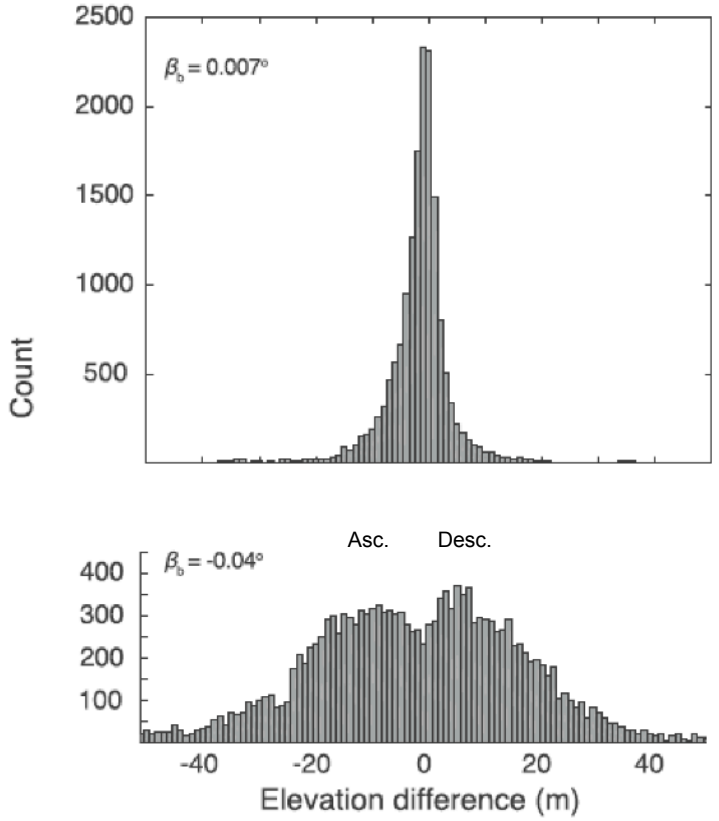




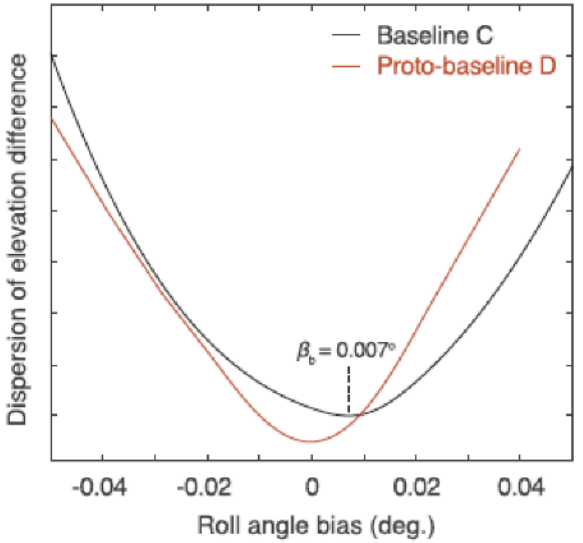
Recchia et al., 2017

Limitations & opportunities - Satellite attitude - roll

CryoSat versus ice Bridge



Swath-base roll calibration



Gourmelen et al., 2018

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Limitations & opportunities - Satellite attitude - roll

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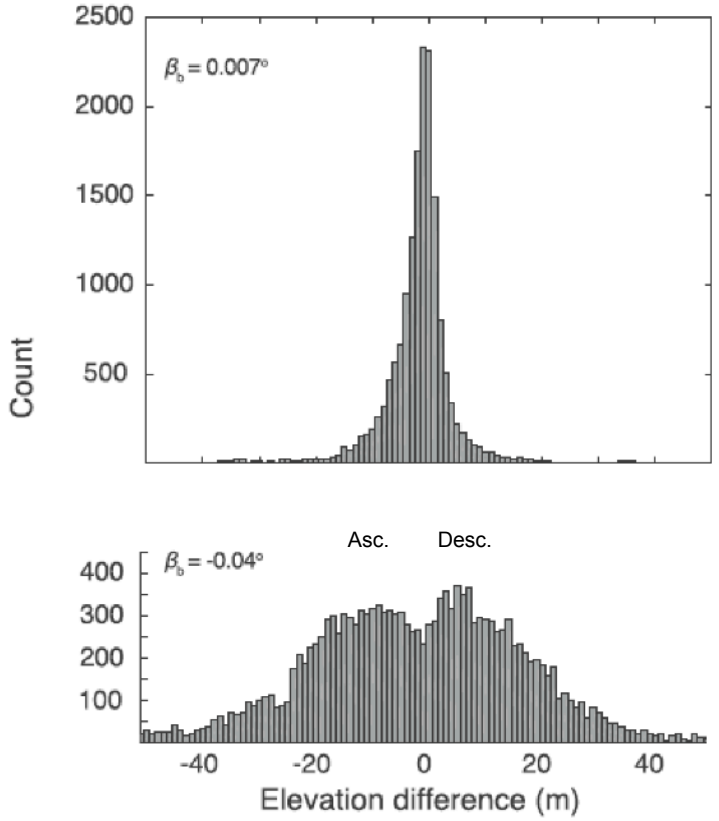

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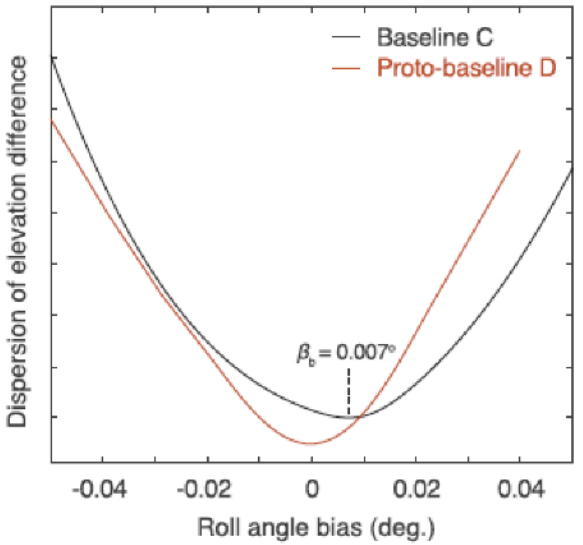

Gourmelen et al., 2018

A revised calibration of the interferometric mode of the CryoSat-2 radar altimeter improves ice height and height change measurements in western Greenland

Laurence Gray[1], David Burgess[2], Luke Copland[1], Thorben Dunse[3], Kirsty Langley[4], and Geir Moholdt[5]

[1]Department of Geography, Environment and Geomatics, University of Ottawa, Ottawa, ON K1N 6N5, Canada
[2]Geological Survey of Canada, Natural Resources Canada, Ottawa, ON K1A 0E8, Canada
[3]Department of Geosciences, University of Oslo, 0316 Oslo, Norway
[4]Asiaq, Greenland Survey, 3900 Nuuk, Greenland
[5]Norwegian Polar Institute, 9296 Tromso, Norway

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Volume 62, Issue 6, 15 September 2018, Pages 1226-1242

CryoSat-2 swath interferometric altimetry for mapping ice elevation and elevation change

N. Gourmelen [a, b], M.J. Escorihuela [c], A. Shepherd [d], L. Foresta [a], A. Muir [e], A. Garcia-Mondéjar [c], M. Roca [c], S.G. Baker [e], M.R. Drinkwater [f]

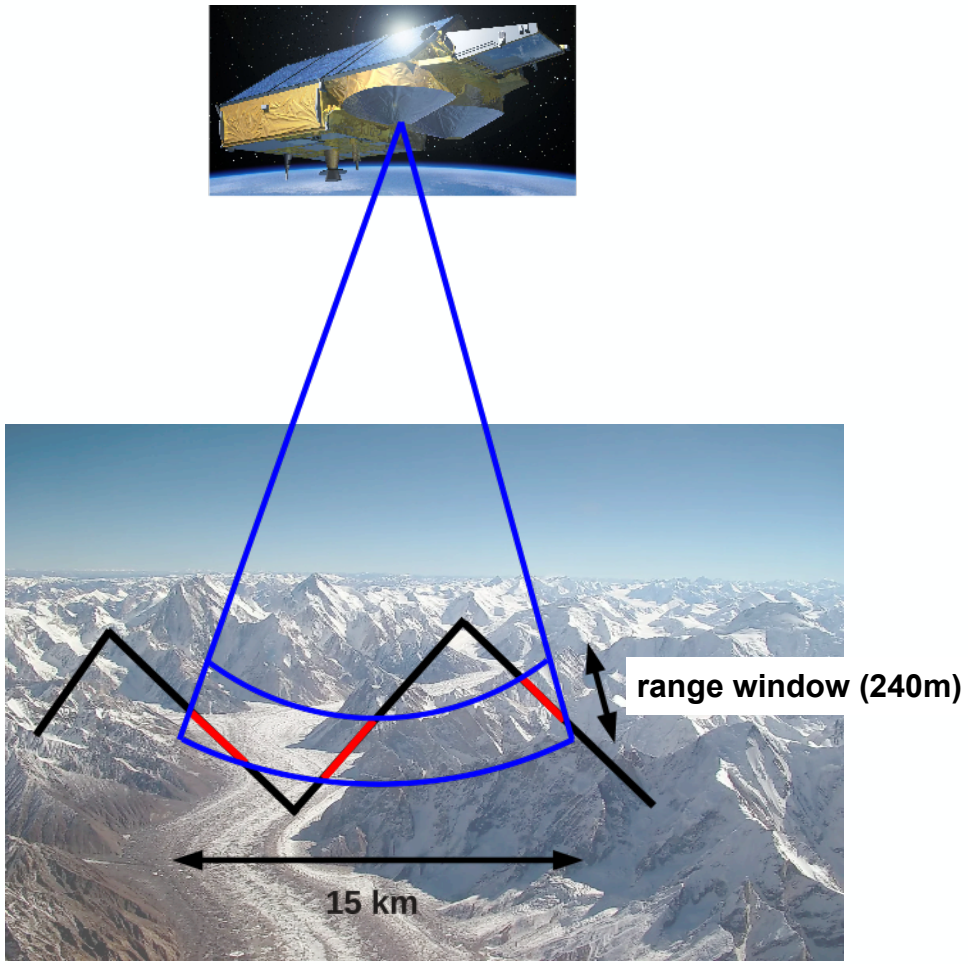
Roll Calibration for CryoSat-2: A Comprehensive Approach

by Albert Garcia-Mondéjar [1,*], Michele Scagliola [2], Noel Gourmelen [3,4], Jerome Bouffard [5] and Mònica Roca [1]

[1] isardSAT S.L., Barcelona Advanced Industry Park, 08042 Barcelona, Spain
[2] Aresys SRL, 20132 Milano, Italy
[3] School of GeoSciences, University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, UK
[4] IPGS UMR 7516, Université de Strasbourg, CNRS, 67000 Strasbourg, France
[5] ESA ESRIN, 00044 Frascati, Italy
[*] Author to whom correspondence should be addressed.

Remote Sens. **2021**, *13*(2), 302; https://doi.org/10.3390/rs13020302

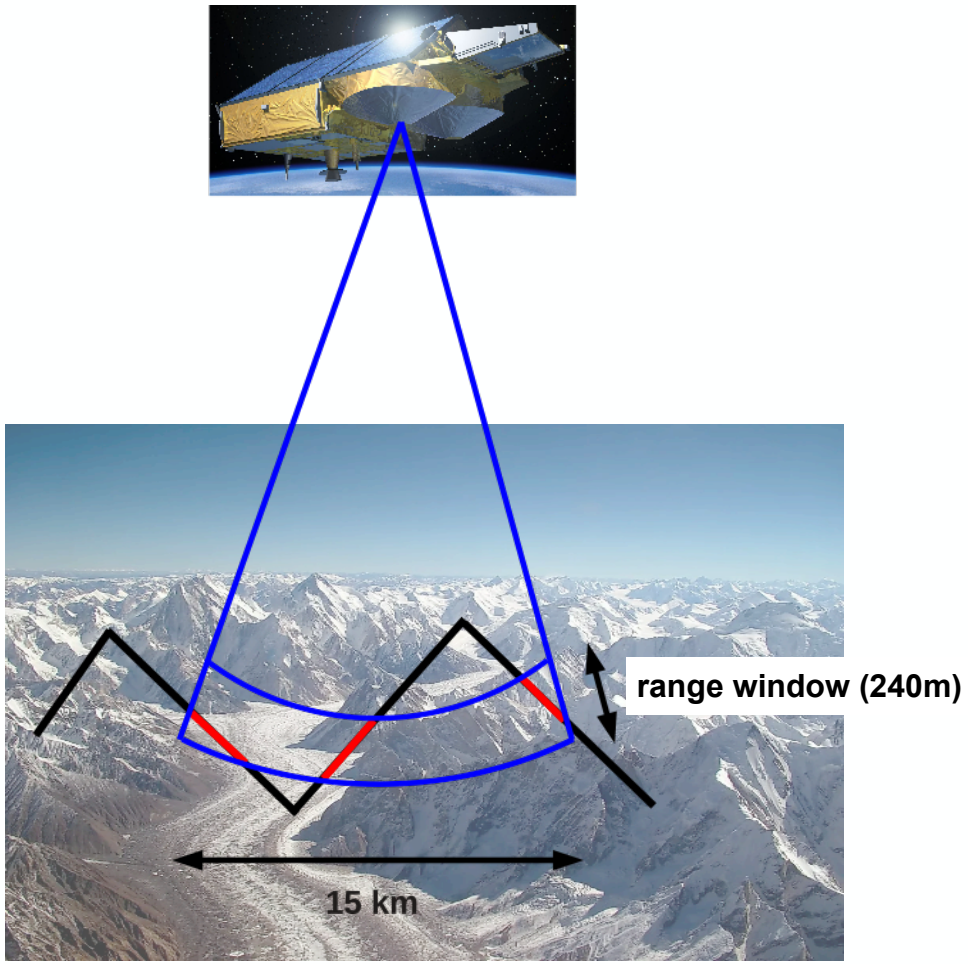
Limitations & opportunities – Onboard tracking



Dehecq et al., 2013

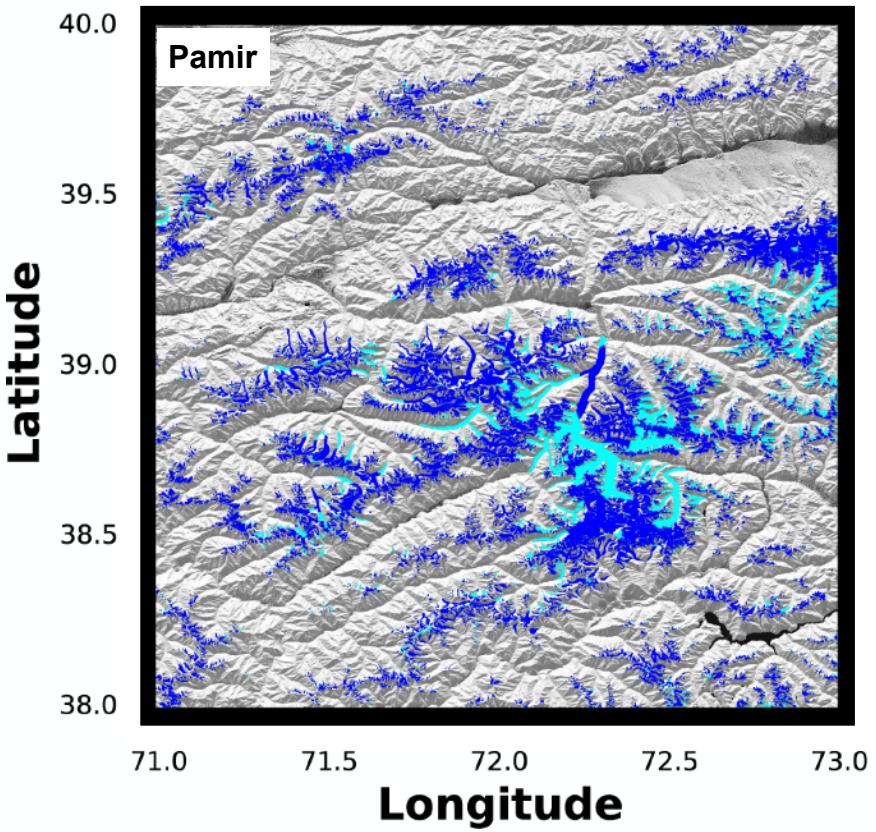
+ tracked range obtained at cycle N applied to tracking cycle N+1

Limitations & opportunities – Onboard tracking



+ **tracked range obtained at cycle N applied to tracking cycle N+1**

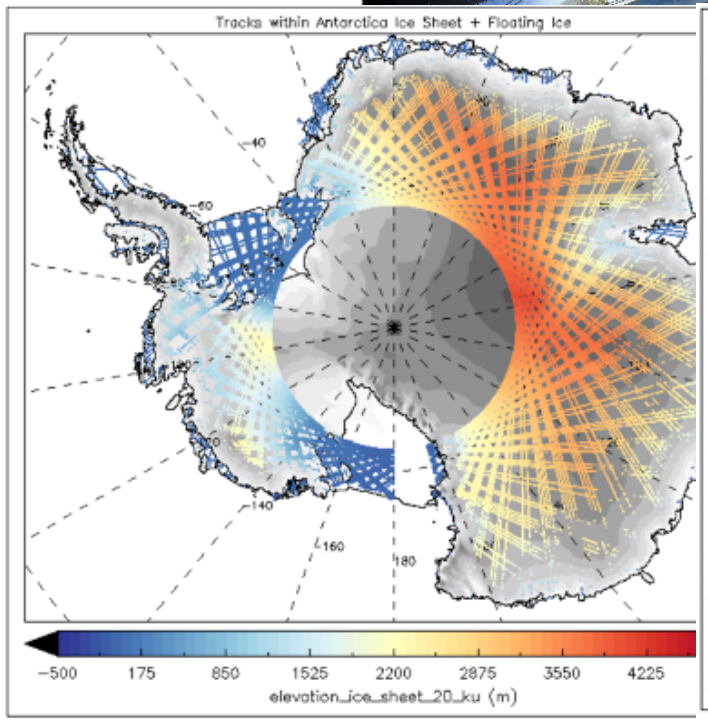
~ 60% of successful glacier acquisition

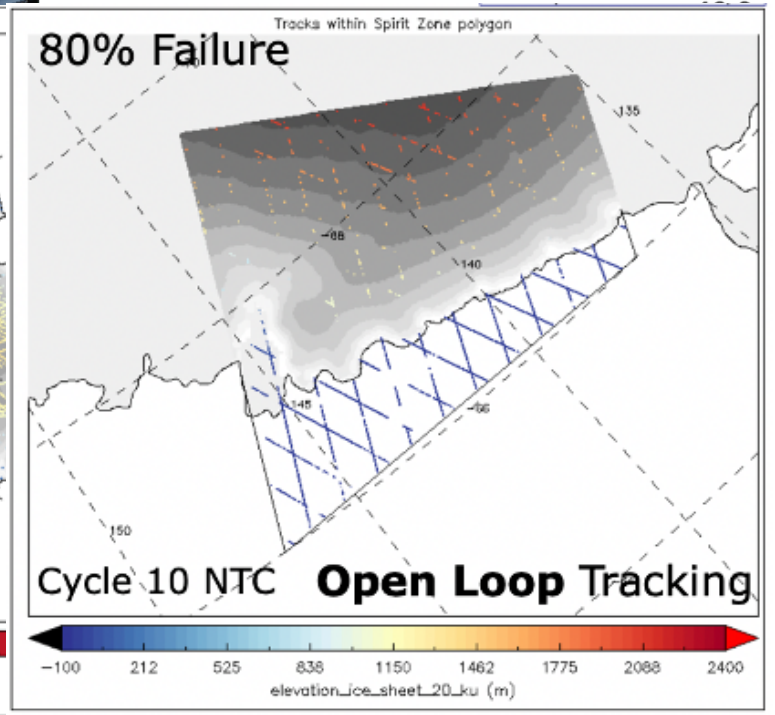


Dehecq et al., 2013

Range window does not intersect glacier
Range window intersects glacier

Limitations & opportunities – Onboard tracking





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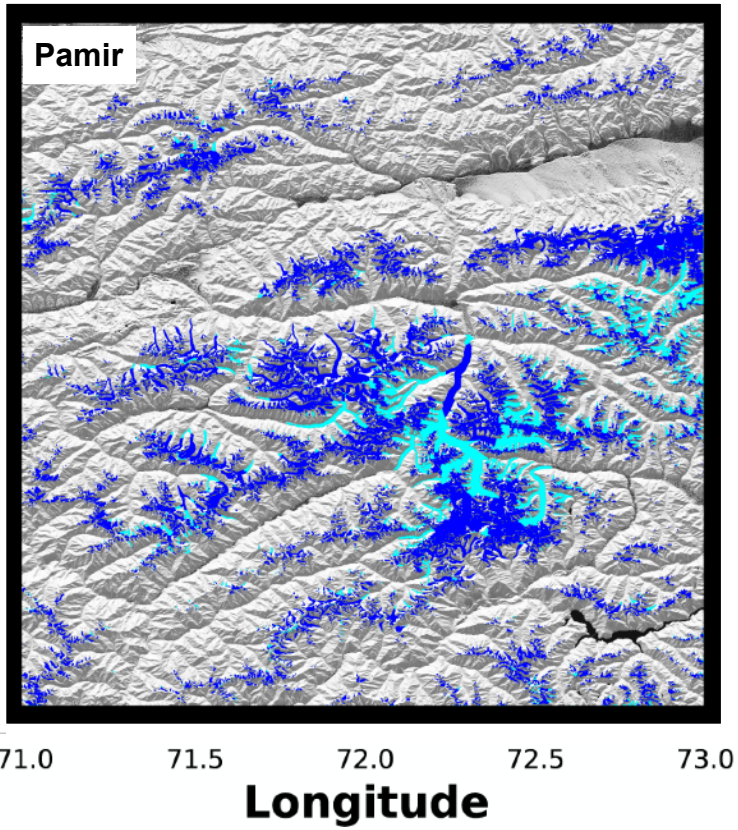

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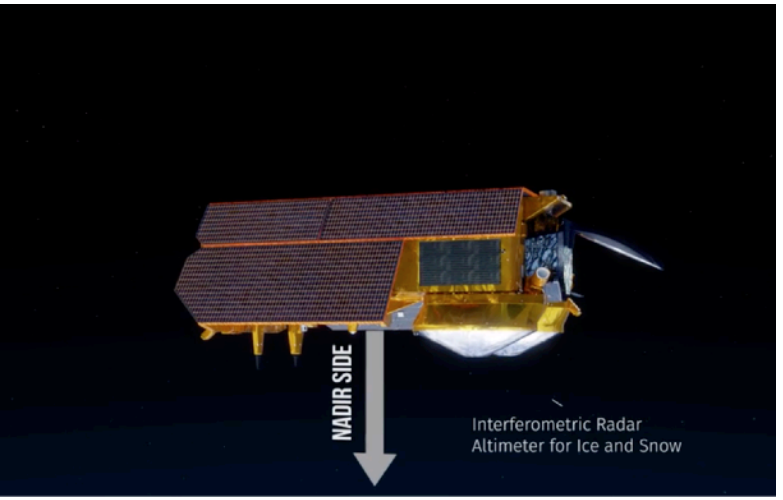
Looking forward - CRISTAL



"The primary high level objectives of the mission are:
1. Monitor critical climate signals: **ice sheet, ice cap melting** and sea level [...] **High spatial resolution** surface elevation [...] and **regular repeat observations** for regions where major changes in surface elevation occur [...] such as, [...], **mountain glaciers**, [...]."

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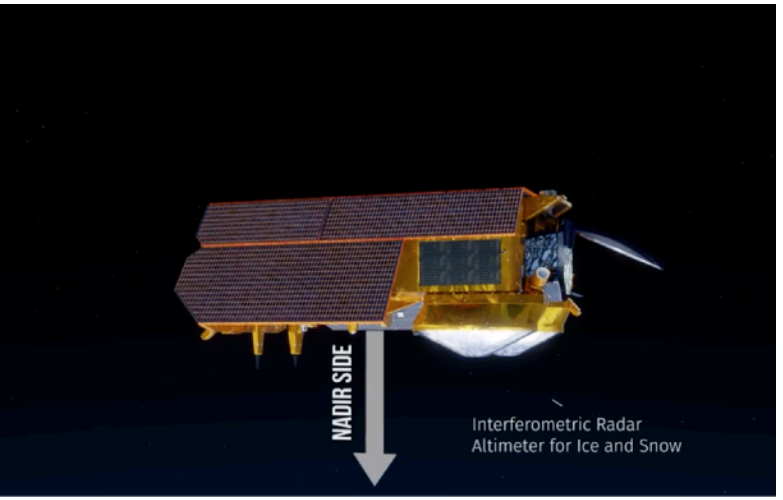

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Interferometric radar altimeters can monitor land ice change globally, at high spatial and temporal resolution

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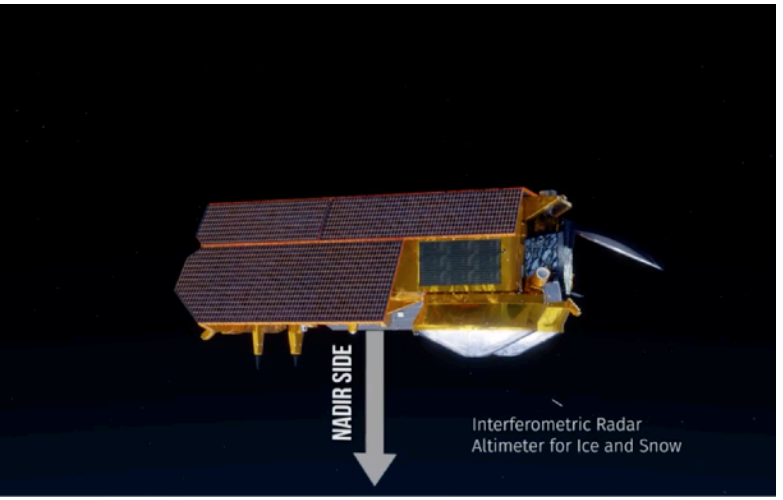

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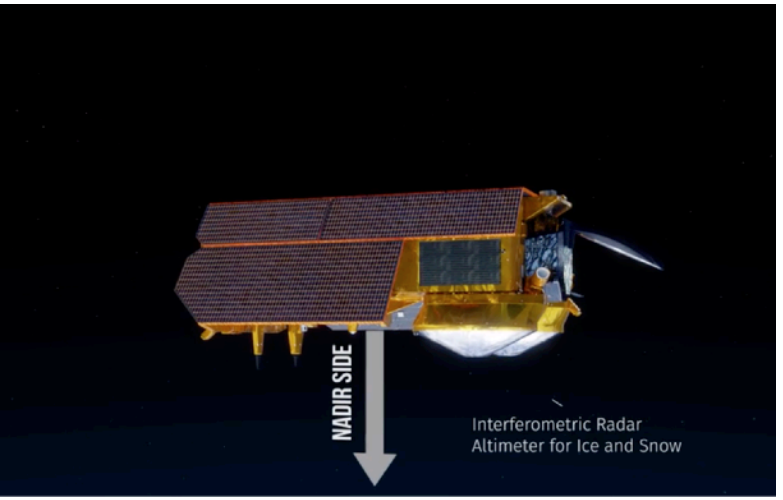

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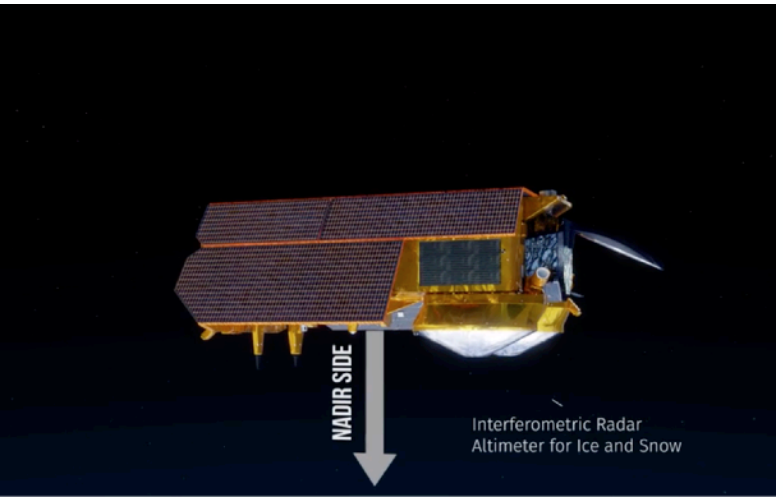

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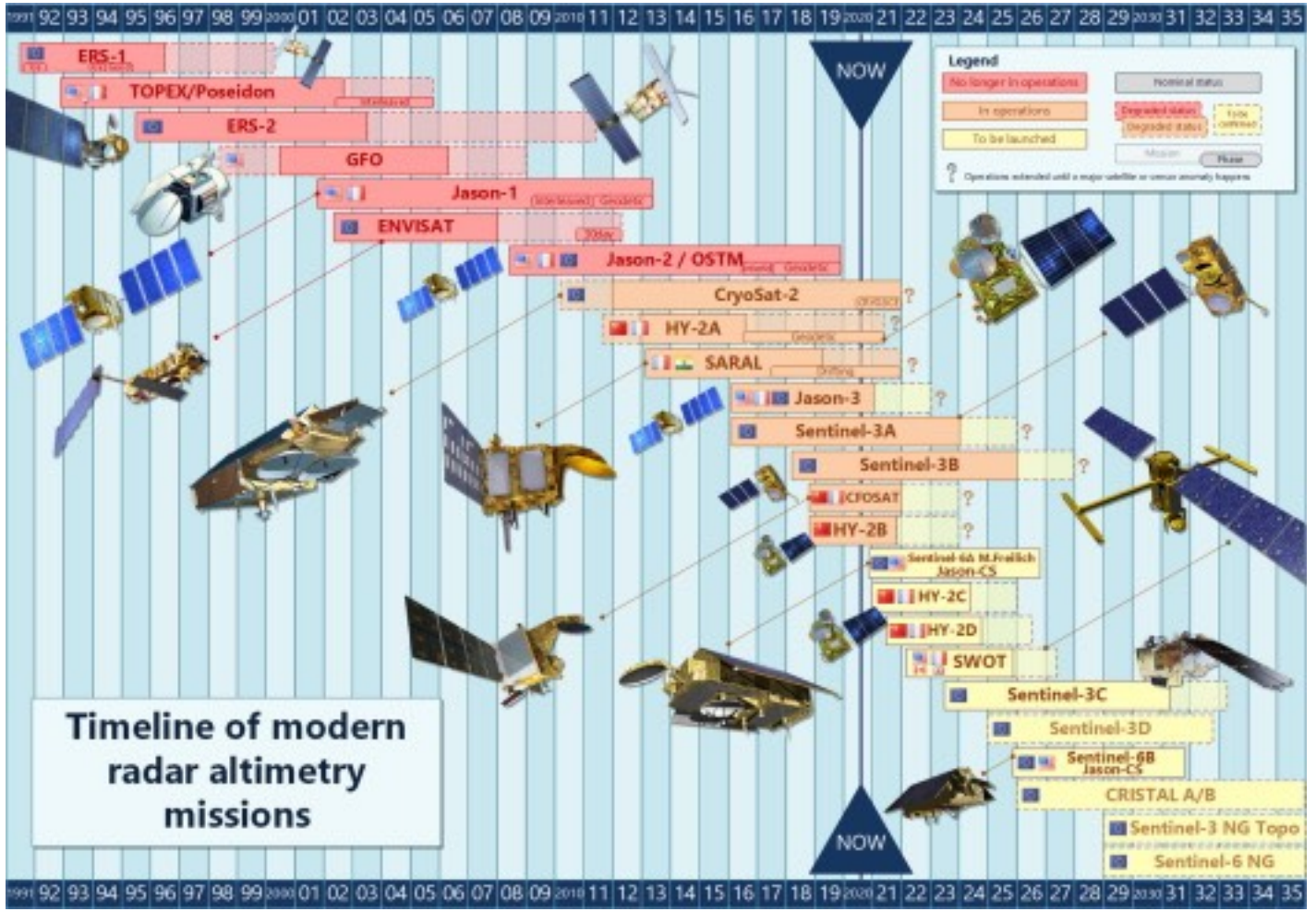
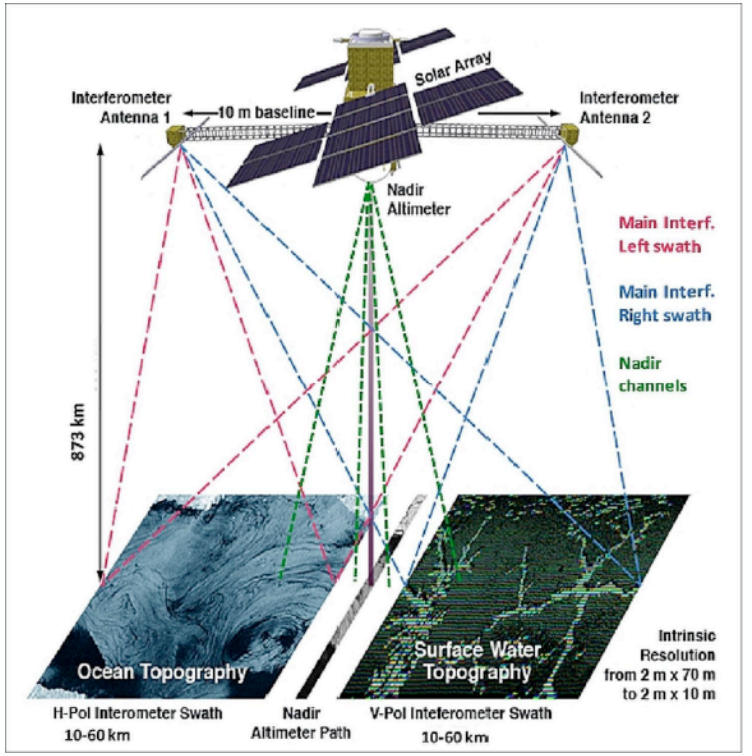
- Fine-tuning of CRISTAL for optimal performances e.g. attitude control (roll), delay-doppler, large across track angle

Looking forward - SWOT



Abdalla et al., 2021

Surface Water and Ocean Topography



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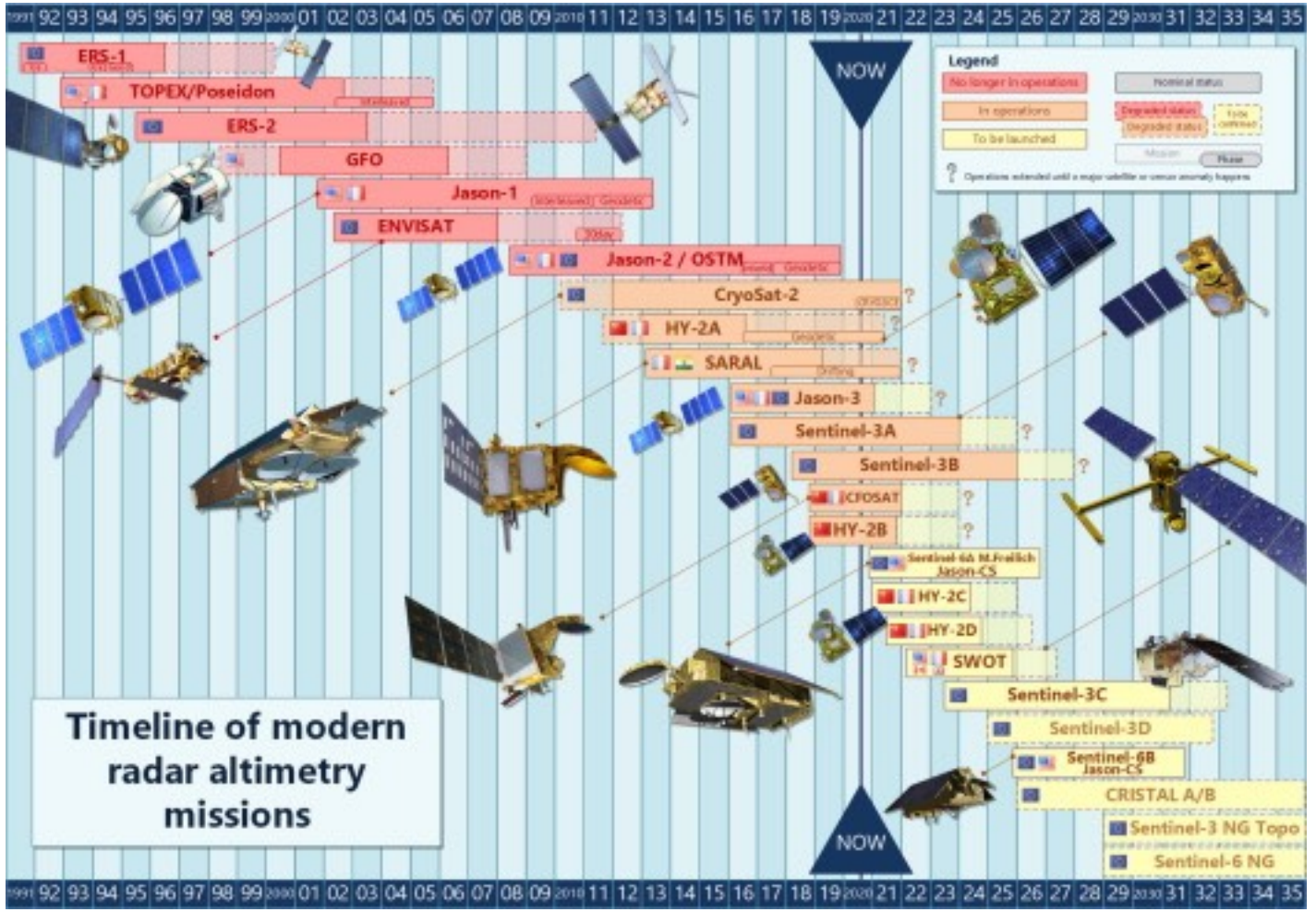

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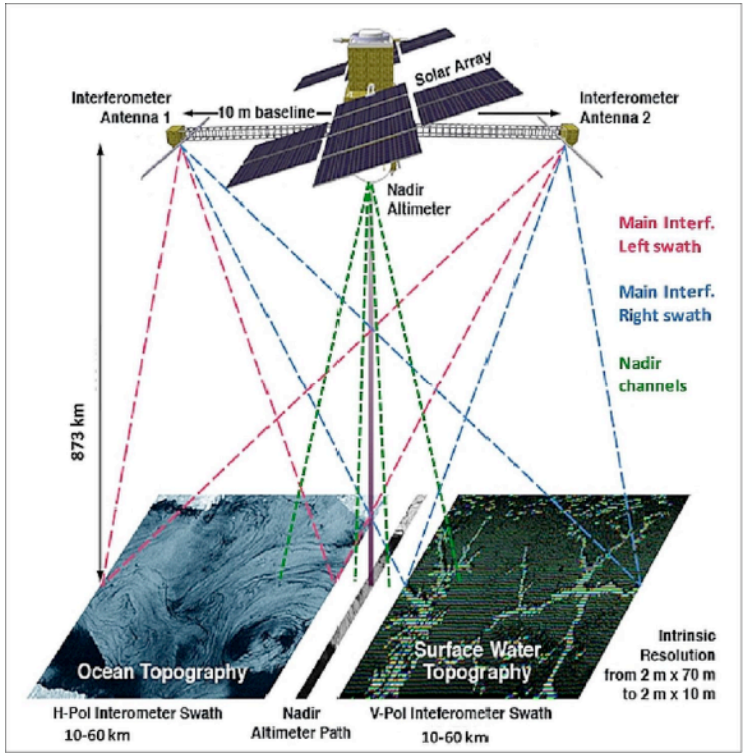

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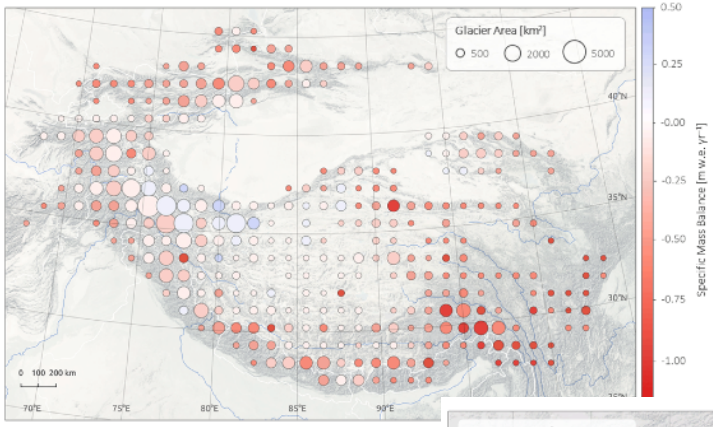
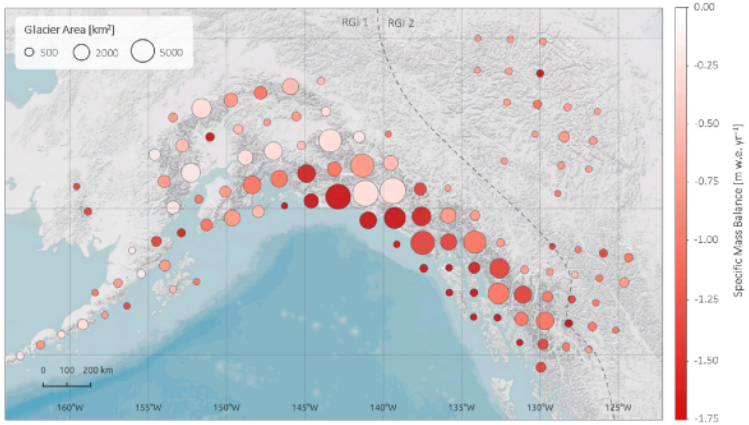
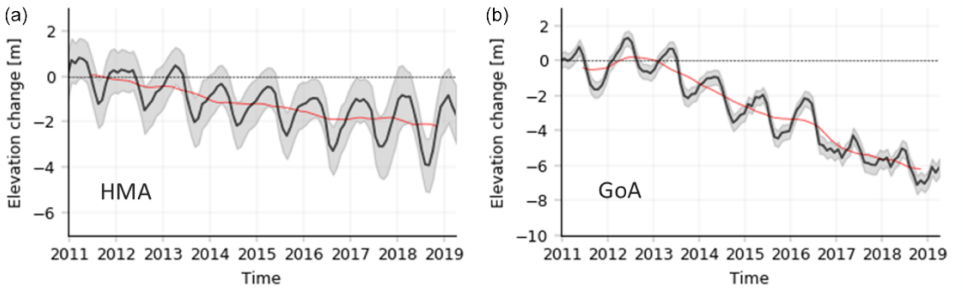
Mountain glacier change





Jakob et al., 2021



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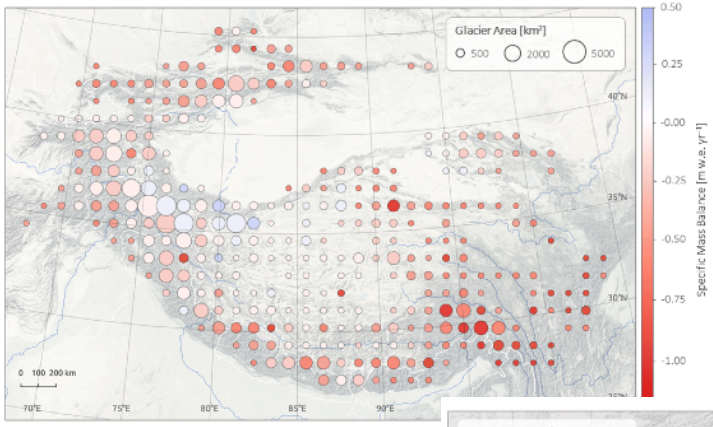

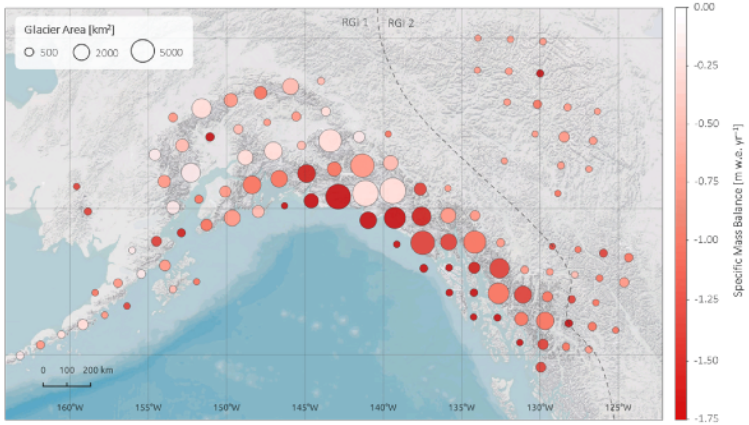

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