Ice and snow from space –

How satellite data help us monitor climate and the cryosphere

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Swiss Polar Day, 12/09/2024

Bachfallenferner
Stubaier Alps, Austria, August 2021

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Stubaier Alps, Austria, September 2023

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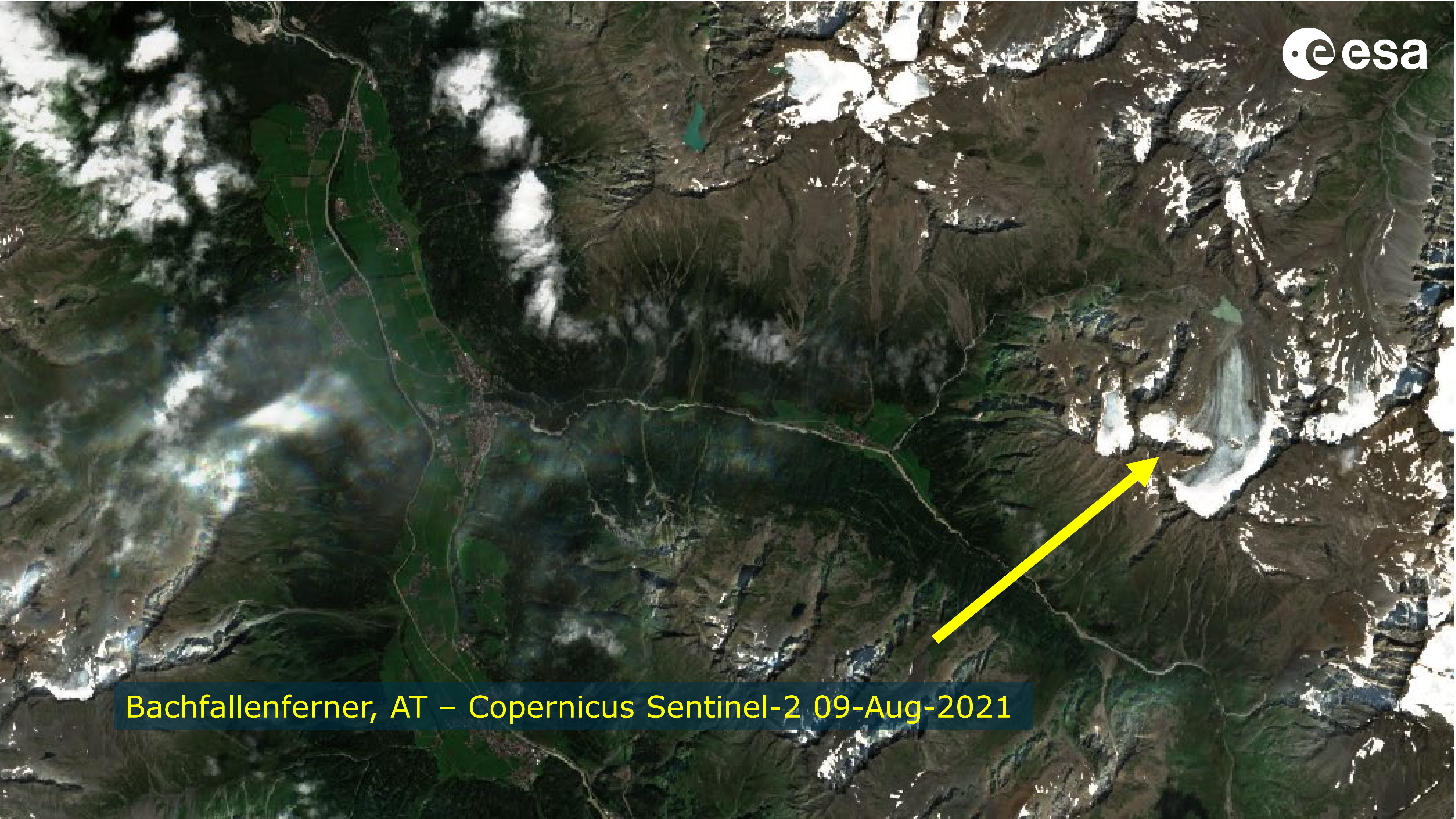
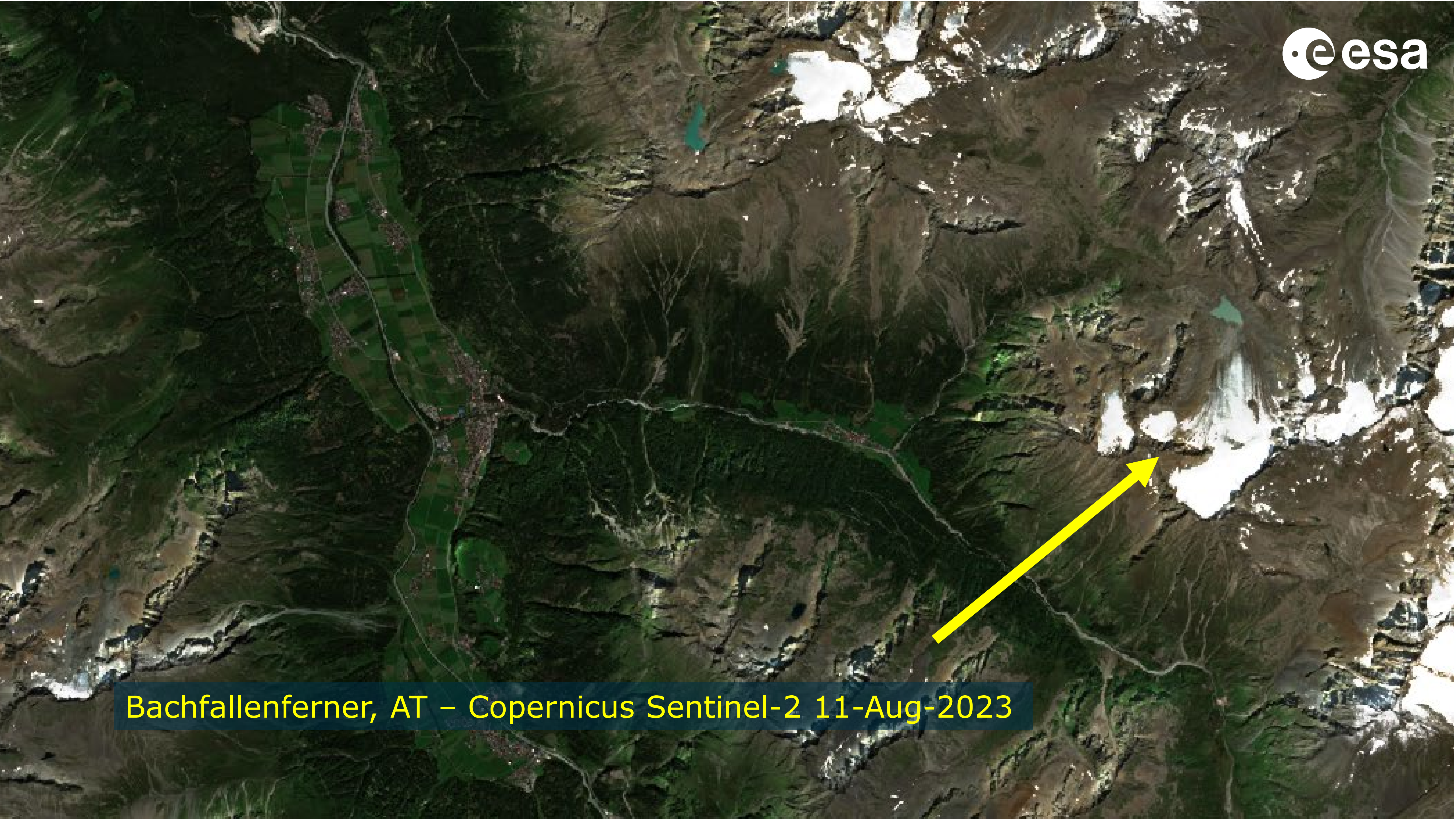
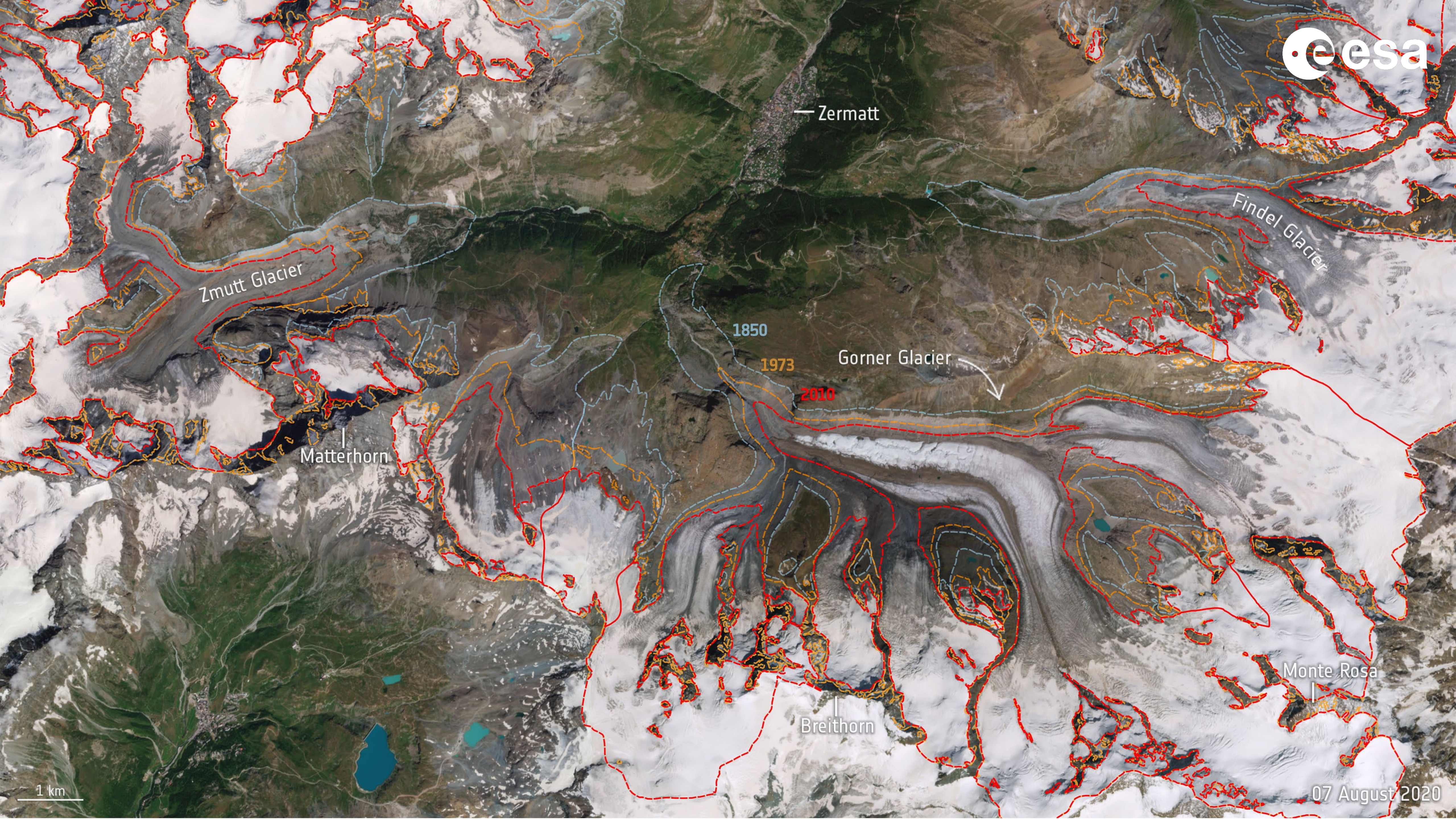


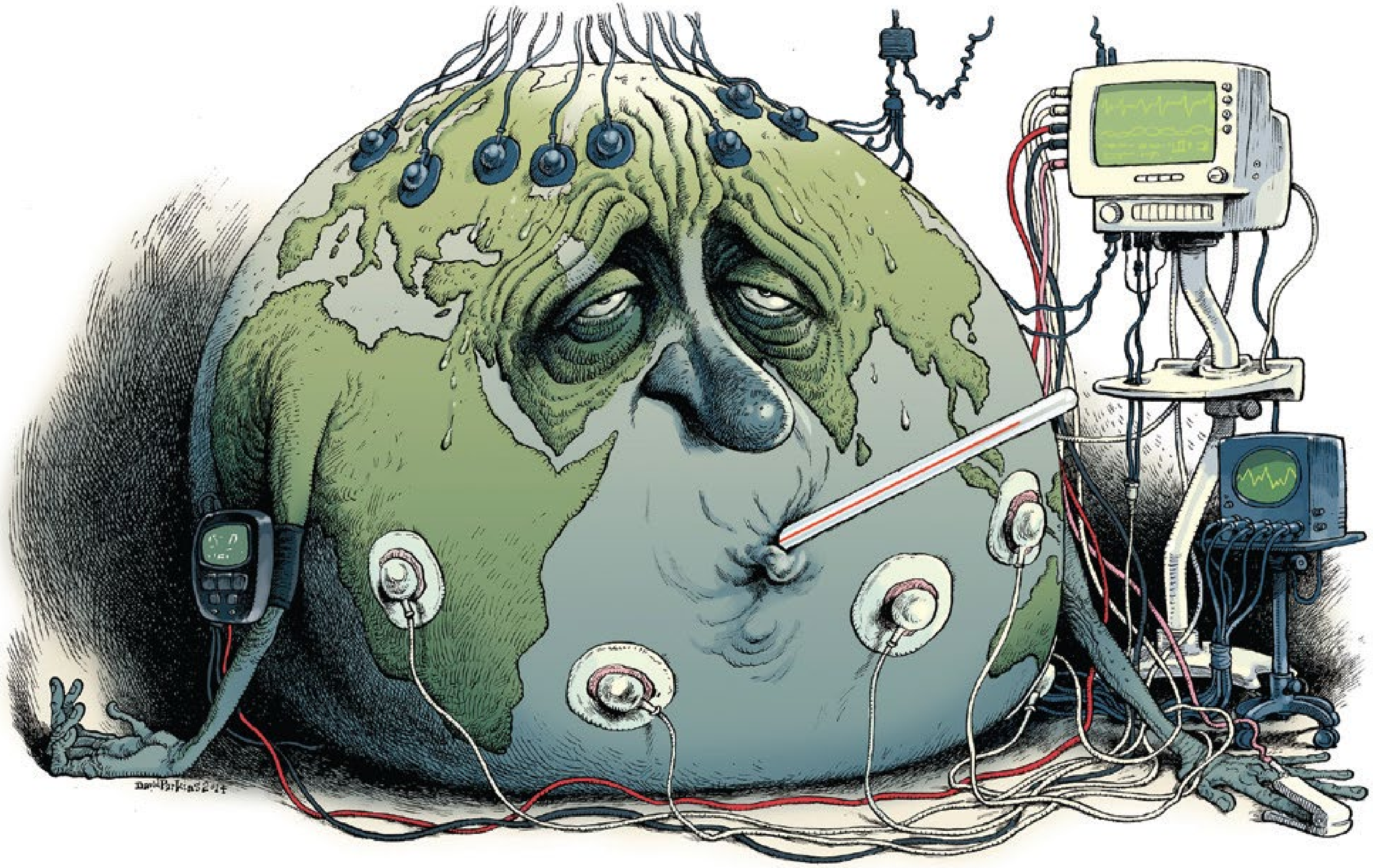
Bachfallenferner, AT – Copernicus Sentinel-2 09-Aug-2021



Bachfallenferner, AT – Copernicus Sentinel-2 11-Aug-2023


esa
Zermatt
Findel Glacier
Zmutt Glacier
1850
1973
2010
Gorner Glacier
Matterhorn
Monte Rosa
Breithorn
1 km
07 August 2020

The importance of observations

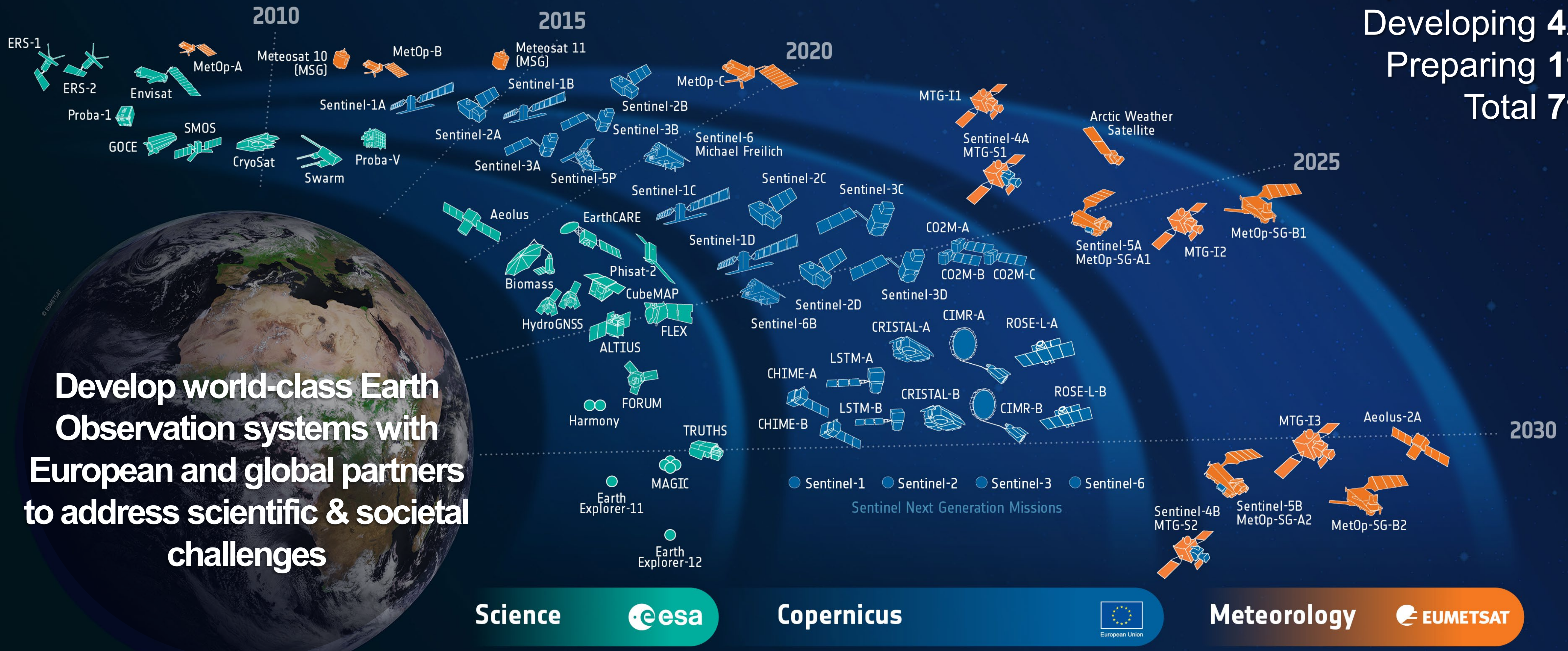


Credit: Victor & Kennel, Nature Climate Change, 2014.

ESA'S Earth Observation Missions

Satellites

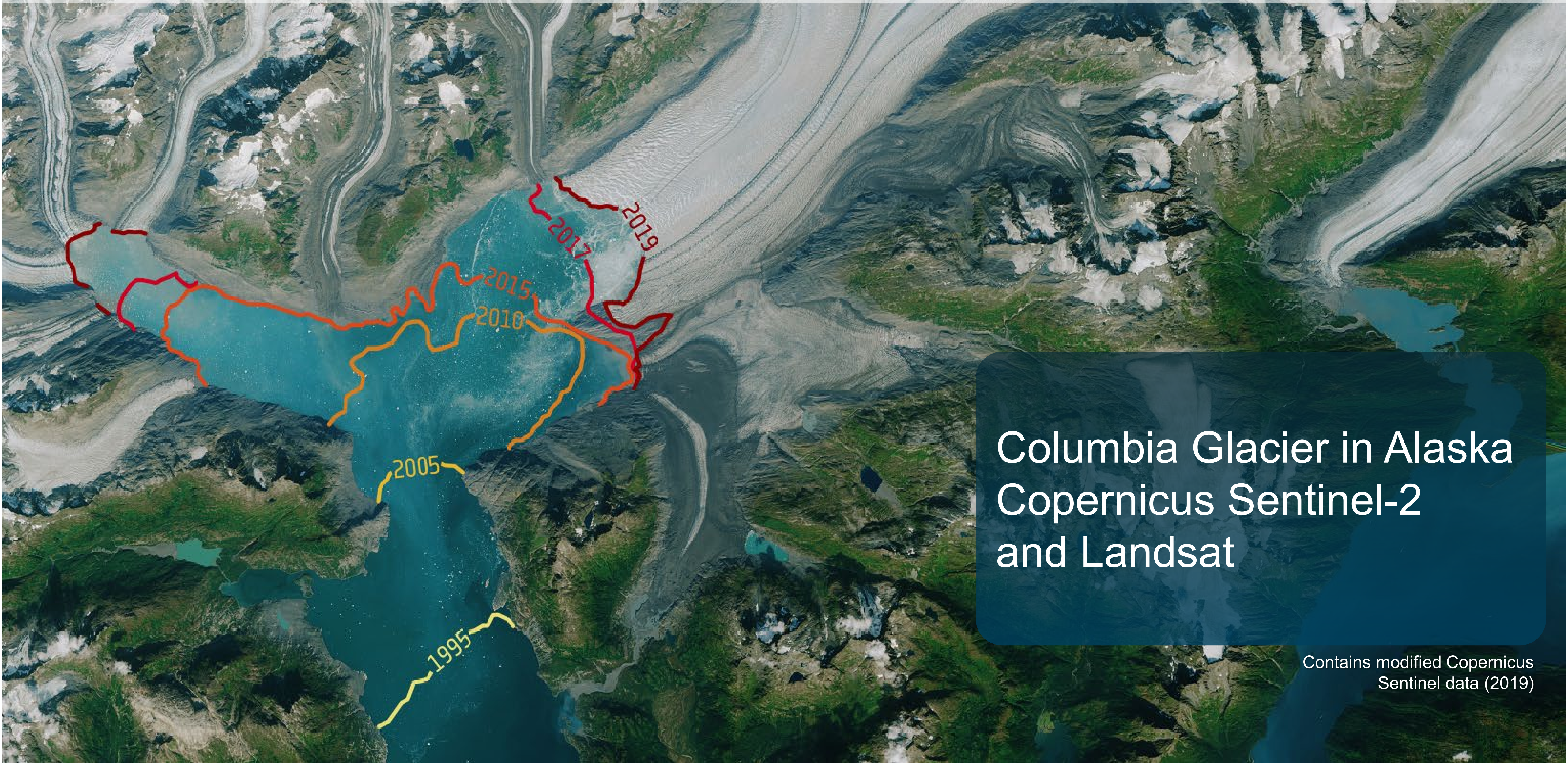
Heritage	**04**
Operational	**14**
Developing	**42**
Preparing	**19**
Total	**79**



Develop world-class Earth Observation systems with European and global partners to address scientific & societal challenges

→ THE EUROPEAN SPACE AGENCY

What types of measurements can we make from space?



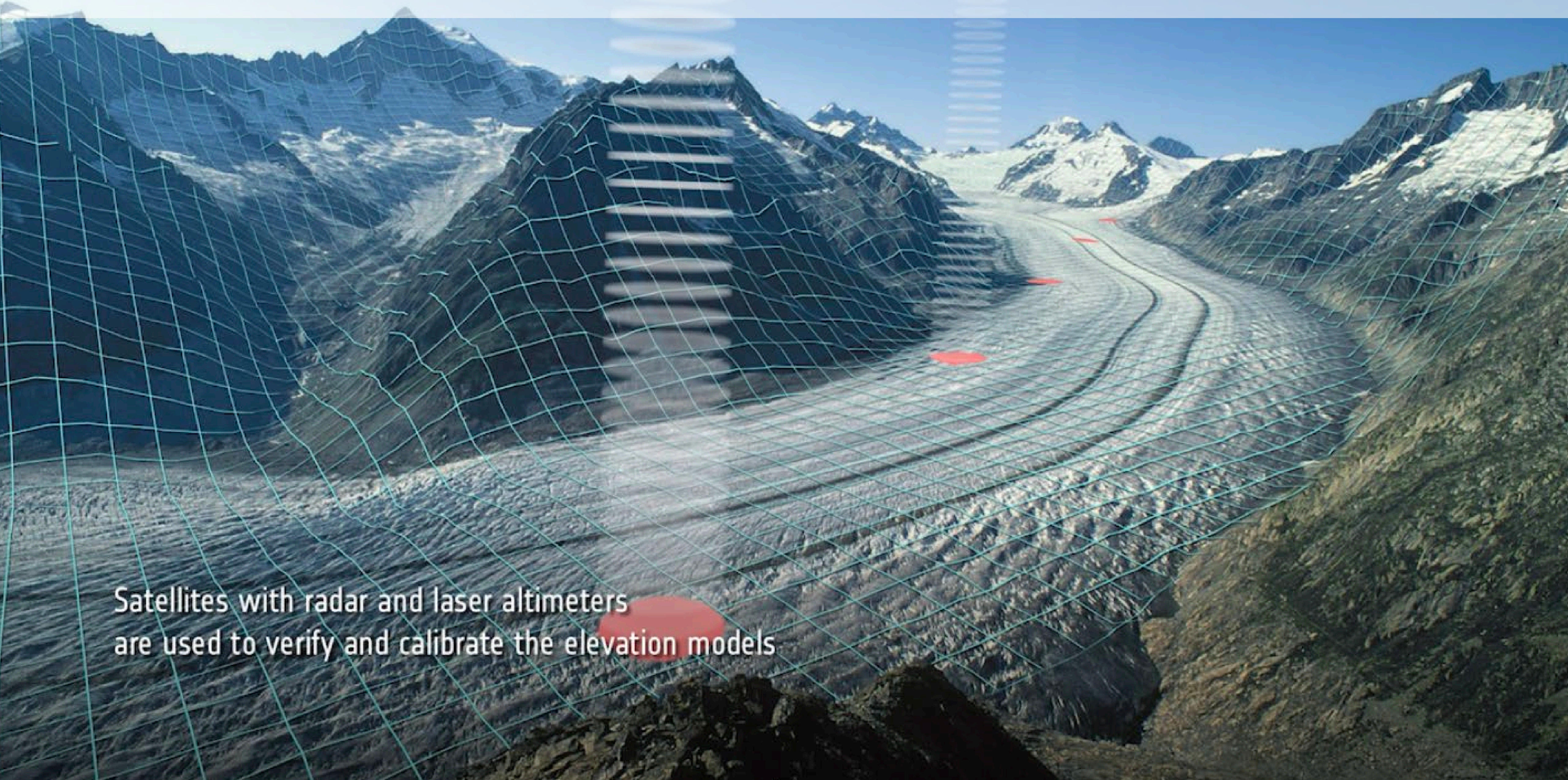
Columbia Glacier in Alaska
Copernicus Sentinel-2
and Landsat

Contains modified Copernicus
Sentinel data (2019)

What types of measurements can we make from space?

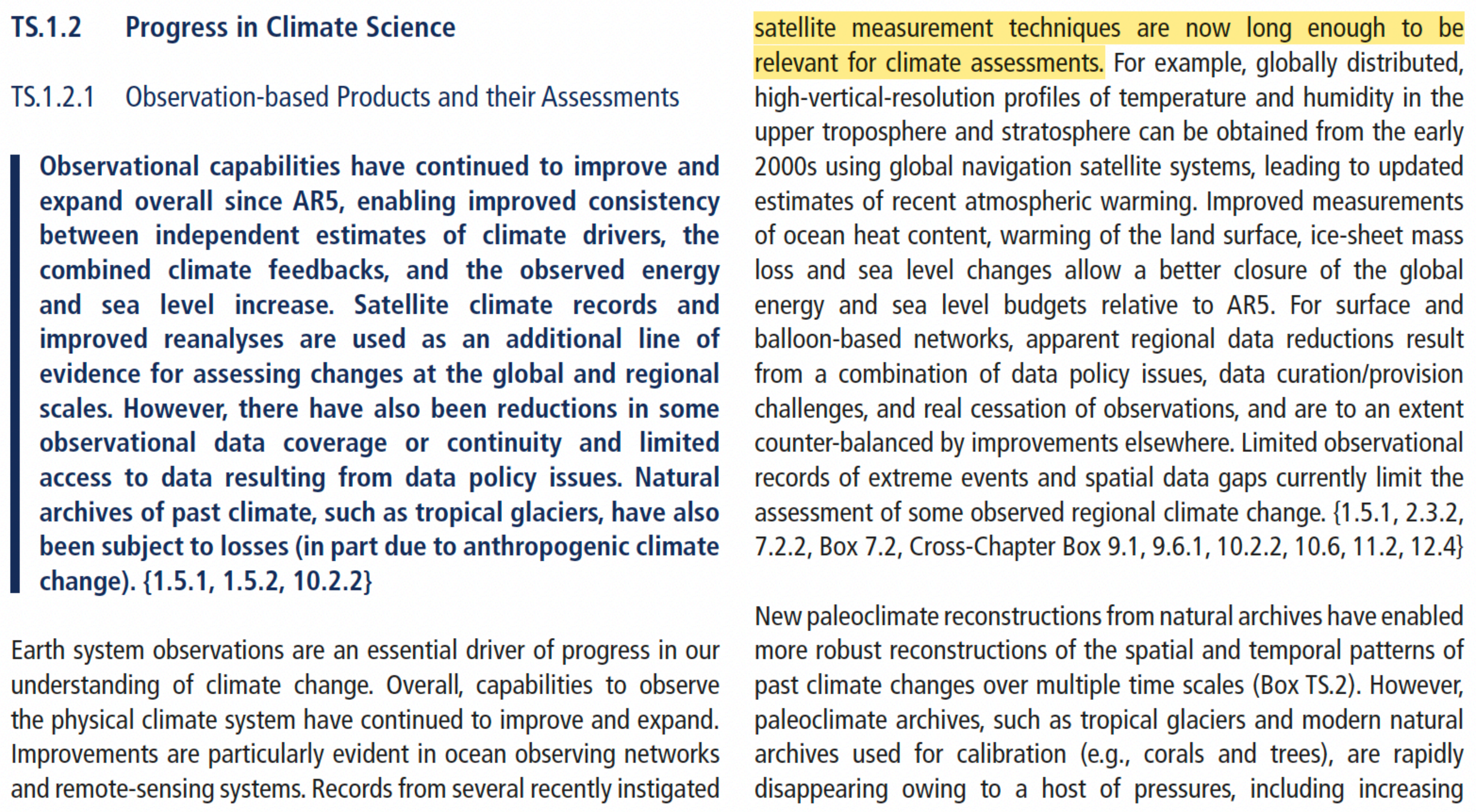
Satellites with stereo cameras looking at different angles map the terrain and ice surface elevation

What types of measurements can we make from space?



Satellites with radar and laser altimeters
are used to verify and calibrate the elevation models

ESA CCI and the IPCC AR6



TS.1.2 Progress in Climate Science

TS.1.2.1 Observation-based Products and their Assessments

Observational capabilities have continued to improve and expand overall since AR5, enabling improved consistency between independent estimates of climate drivers, the combined climate feedbacks, and the observed energy and sea level increase. Satellite climate records and improved reanalyses are used as an additional line of evidence for assessing changes at the global and regional scales. However, there have also been reductions in some observational data coverage or continuity and limited access to data resulting from data policy issues. Natural archives of past climate, such as tropical glaciers, have also been subject to losses (in part due to anthropogenic climate change). {1.5.1, 1.5.2, 10.2.2}

Earth system observations are an essential driver of progress in our understanding of climate change. Overall, capabilities to observe the physical climate system have continued to improve and expand. Improvements are particularly evident in ocean observing networks and remote-sensing systems. Records from several recently instigated satellite measurement techniques are now long enough to be relevant for climate assessments. For example, globally distributed, high-vertical-resolution profiles of temperature and humidity in the upper troposphere and stratosphere can be obtained from the early 2000s using global navigation satellite systems, leading to updated estimates of recent atmospheric warming. Improved measurements of ocean heat content, warming of the land surface, ice-sheet mass loss and sea level changes allow a better closure of the global energy and sea level budgets relative to AR5. For surface and balloon-based networks, apparent regional data reductions result from a combination of data policy issues, data curation/provision challenges, and real cessation of observations, and are to an extent counter-balanced by improvements elsewhere. Limited observational records of extreme events and spatial data gaps currently limit the assessment of some observed regional climate change. {1.5.1, 2.3.2, 7.2.2, Box 7.2, Cross-Chapter Box 9.1, 9.6.1, 10.2.2, 10.6, 11.2, 12.4}

New paleoclimate reconstructions from natural archives have enabled more robust reconstructions of the spatial and temporal patterns of past climate changes over multiple time scales (Box TS.2). However, paleoclimate archives, such as tropical glaciers and modern natural archives used for calibration (e.g., corals and trees), are rapidly disappearing owing to a host of pressures, including increasing

The international community and climate

1992 UNFCCC at Rio Earth Summit
Calls for research and systematic observations of the Earth (Article 5)

Global Climate Observing System founded to identify parameters needed to understand the climate system:
Birth of the *Essential Climate Variables (ECVs)*

2007 COP13 at UN Climate Change Conference in Bali
No adequate long-term monitoring from space to address climate change

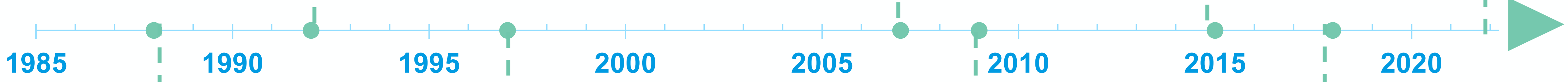
Space agencies work together to establish a common strategy for climate monitoring from space

2015 COP21 led to the Paris Agreement – 1st legally binding and universal agreement on climate is established.

Inter alia, it calls to strengthen scientific knowledge on climate, including research, [and] systematic observation of the climate system (Article 7.7)

Credit: Thomas Pesquet ESA/NASA

2023 ESA CLIMATE-SPACE programme



1988 IPCC established by WMO and UNEP

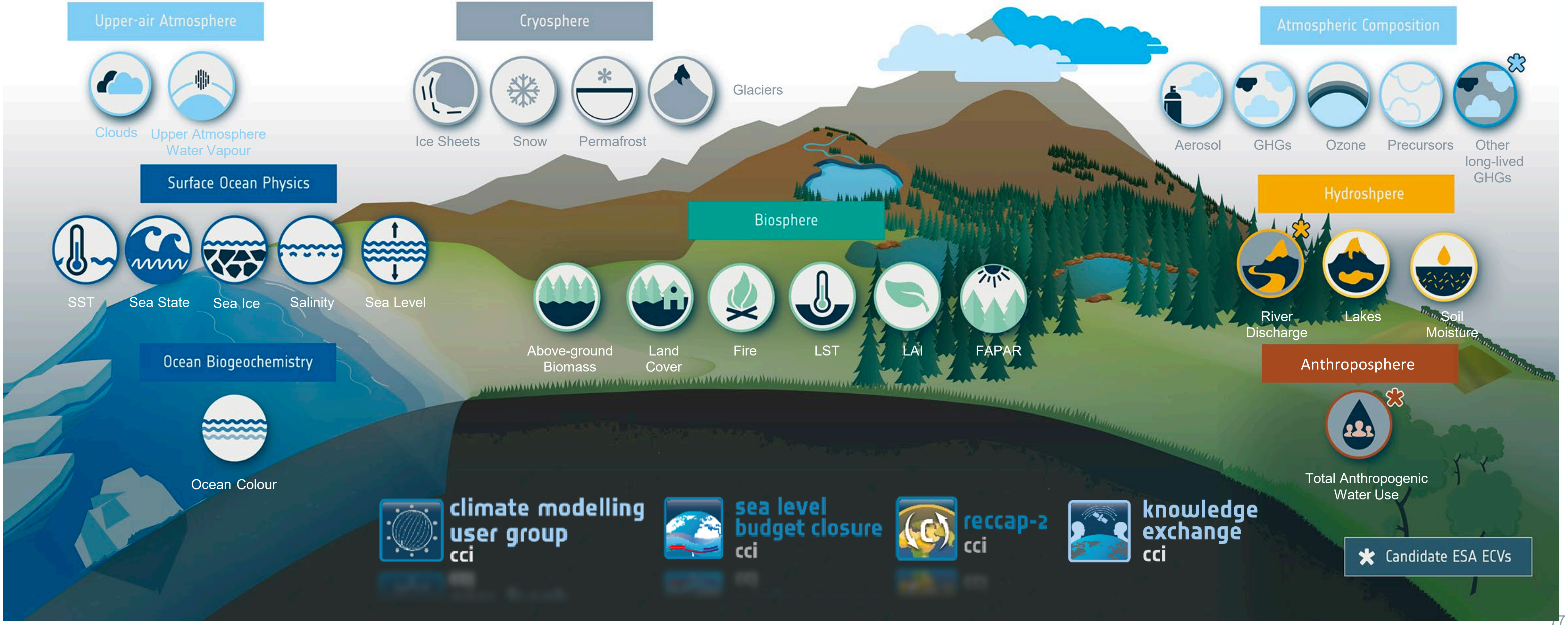
1997 COP3 Kyoto Protocol – 1st GHG emissions reduction treaty

2009 ESA initiates the Climate Change Initiative programme (CCI)

2018 CCI+ extension programme builds on the success of CCI

ESA CLIMATE CHANGE INITIATIVE (CCI)

GCOS defined **55** Essential Climate Variables | **36** benefit from space observations | **27** generated by ESA Climate Change Initiative



Upper-air Atmosphere
- Clouds
- Upper Atmosphere Water Vapour

Surface Ocean Physics
- SST
- Sea State
- Sea Ice
- Salinity
- Sea Level

Ocean Biogeochemistry
- Ocean Colour

Cryosphere
- Ice Sheets
- Snow
- Permafrost
- Glaciers

Biosphere
- Above-ground Biomass
- Land Cover
- Fire
- LST
- LAI
- FAPAR

Atmospheric Composition
- Aerosol
- GHGs
- Ozone
- Precursors
- Other long-lived GHGs *

Hydrosphere
- River Discharge *
- Lakes
- Soil Moisture

Anthroposphere
- Total Anthropogenic Water Use *

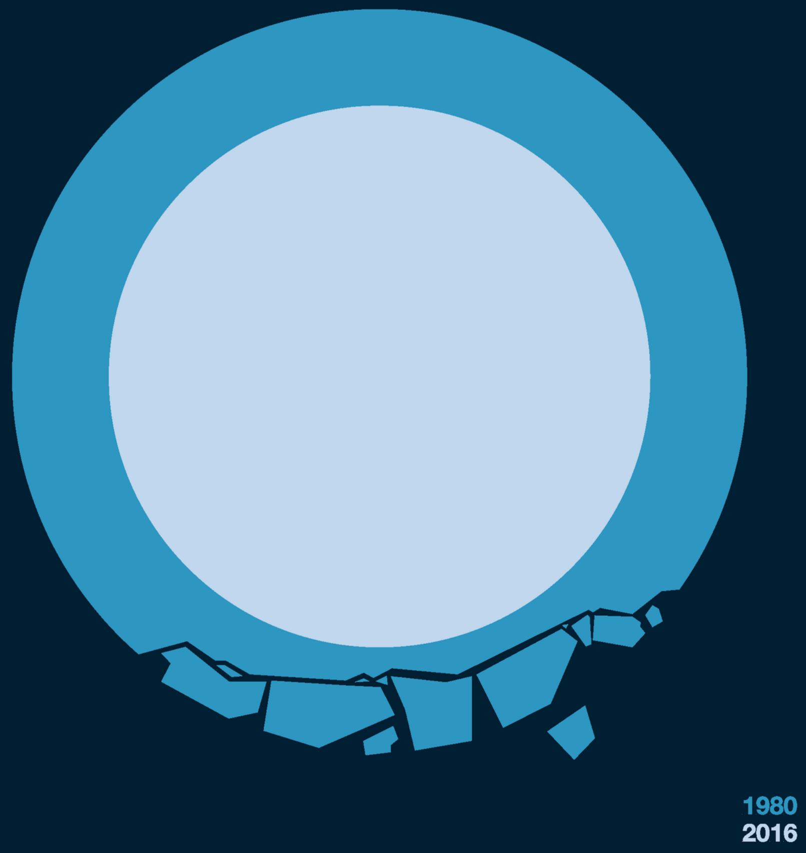
climate modelling user group cci

sea level budget closure cci

reccap-2 cci

knowledge exchange cci

✱ Candidate ESA ECVs

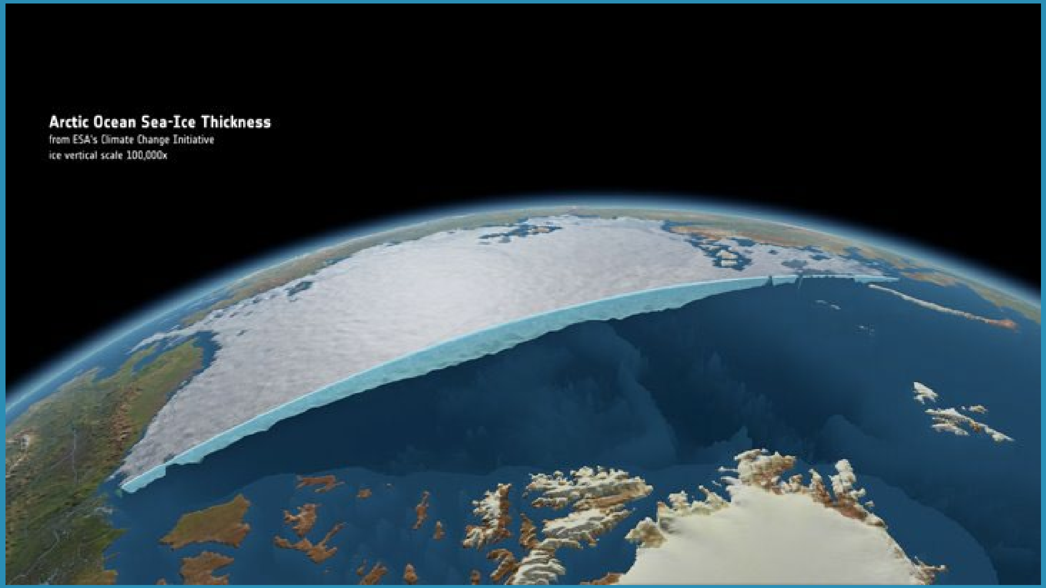


sea ice loss

1980 – 2016

This simple graphic depicting the reduction of Arctic sea ice between 1980 and 2016, highlights the urgency of the Arctic sea ice loss crisis. As our planet's temperature continues to rise due to climate change, the Arctic is losing sea ice.

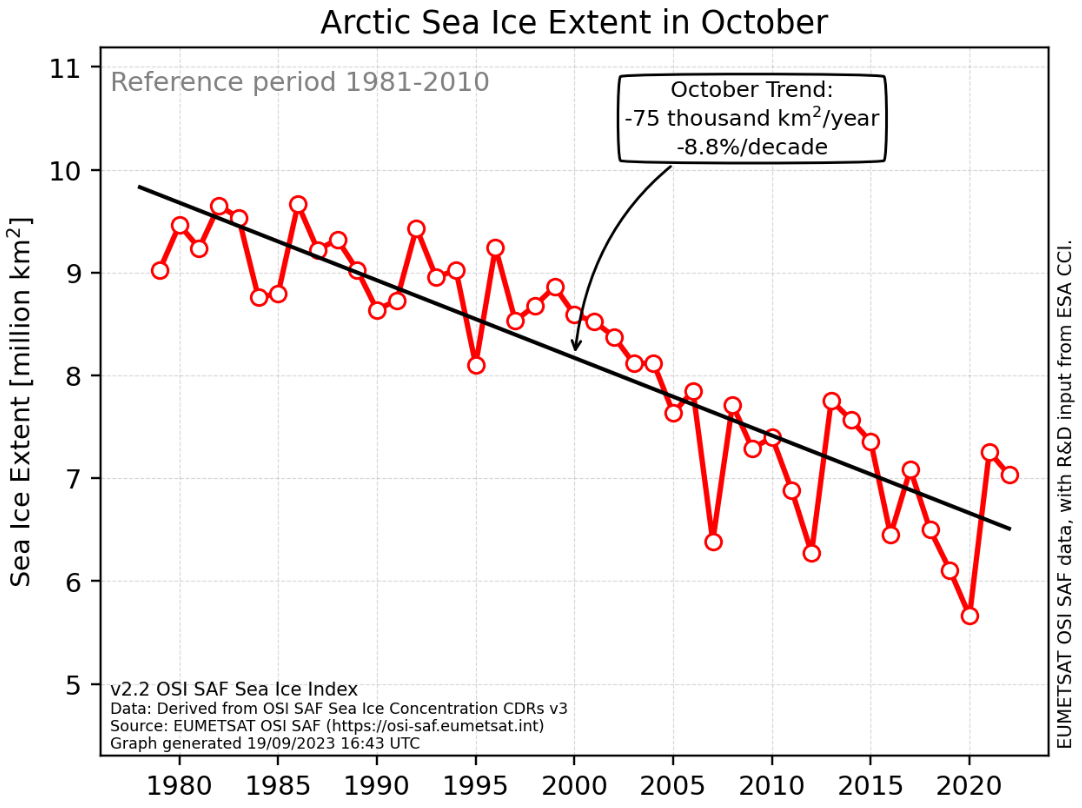
Arctic Ocean Sea-Ice Summer Minimum Extent
from ESA's Climate Change Initiative
(in collaboration with EUMETSAT OSISAF)



Arctic Ocean Sea-Ice Thickness
from ESA's Climate Change Initiative
ice vertical scale 100,000x

Sea Ice Extent – decline in the Arctic

What does a satellite-derived climate data record look like?



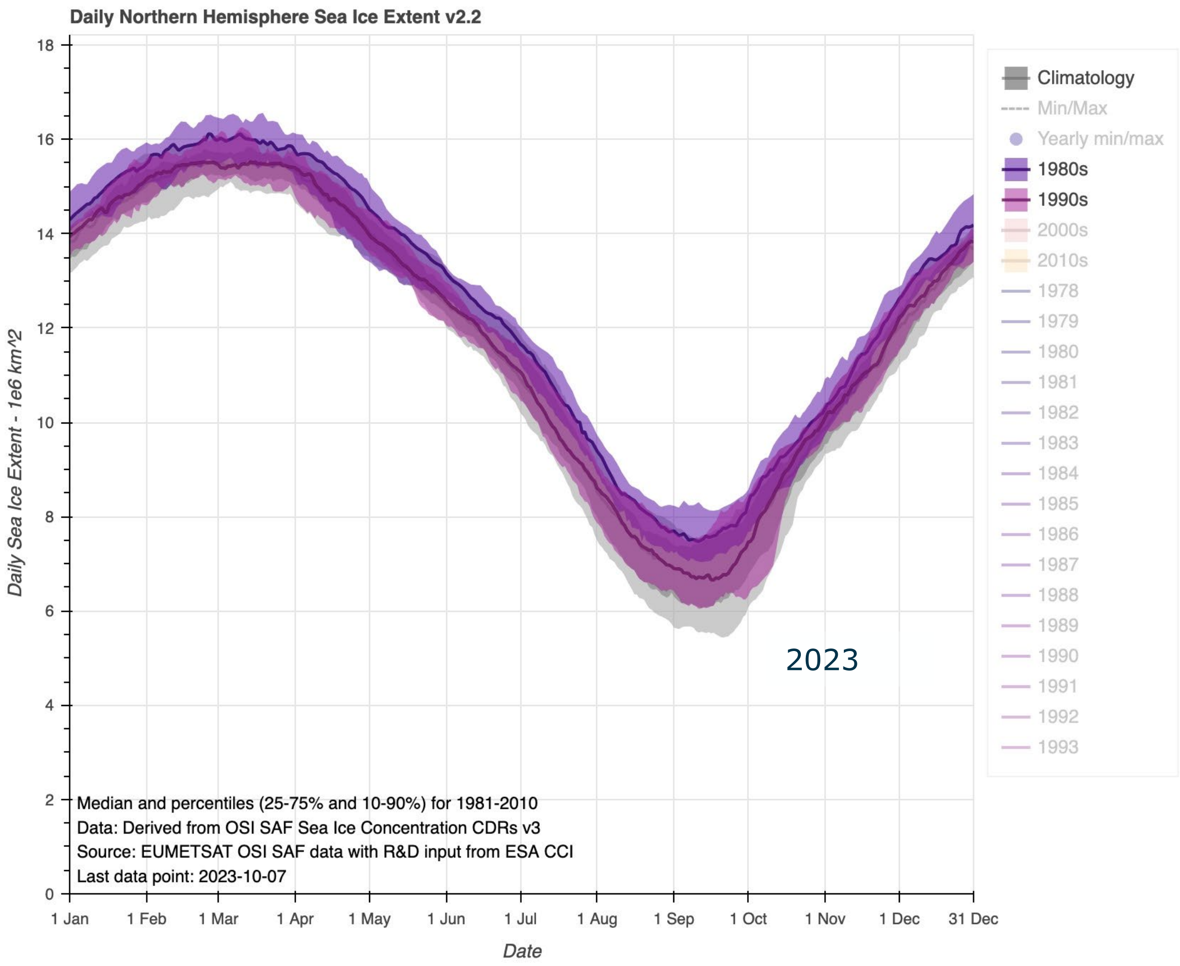
Arctic Sea Ice Extent in October

Reference period 1981-2010

October Trend:
-75 thousand km²/year
-8.8%/decade

v2.2 OSI SAF Sea Ice Index
Data: Derived from OSI SAF Sea Ice Concentration CDRs v3
Source: EUMETSAT OSI SAF (https://osi-saf.eumetsat.int)
Graph generated 19/09/2023 16:43 UTC

EUMETSAT OSI SAF data, with R&D input from ESA CCI.



Daily Northern Hemisphere Sea Ice Extent v2.2

Median and percentiles (25-75% and 10-90%) for 1981-2010
Data: Derived from OSI SAF Sea Ice Concentration CDRs v3
Source: EUMETSAT OSI SAF data with R&D input from ESA CCI
Last data point: 2023-10-07

2023

40+ years consistent Sea Ice Concentration time series

Sea ice freeboard and snow depth from CryoSat-2

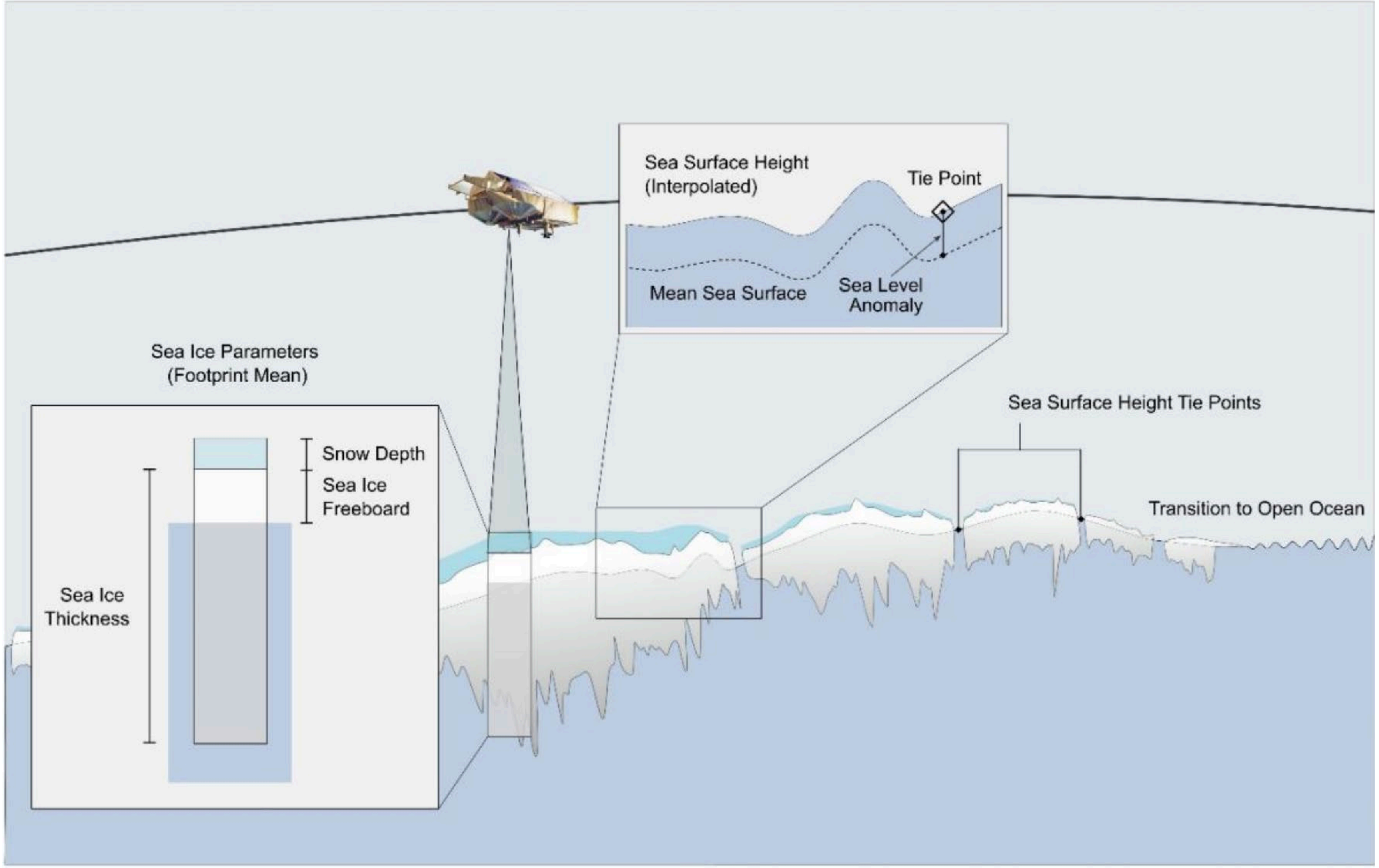
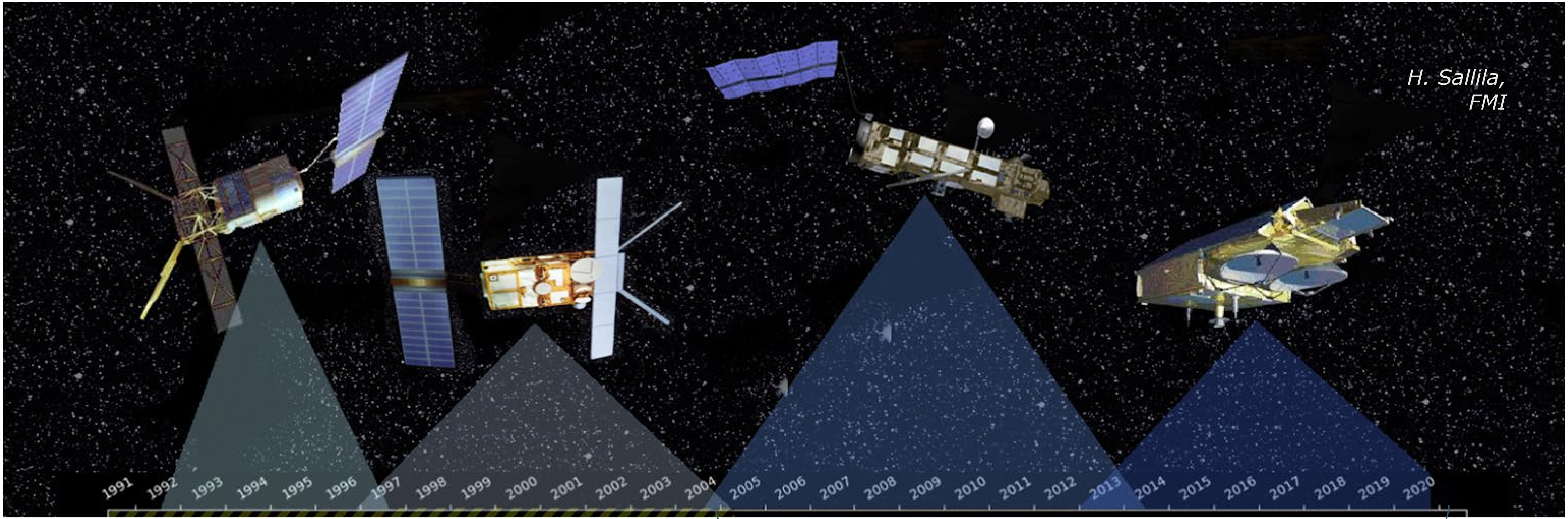


Figure 1 from ESA Cryo-TEMPO Algorithm Theoretical Basis Document (2022)

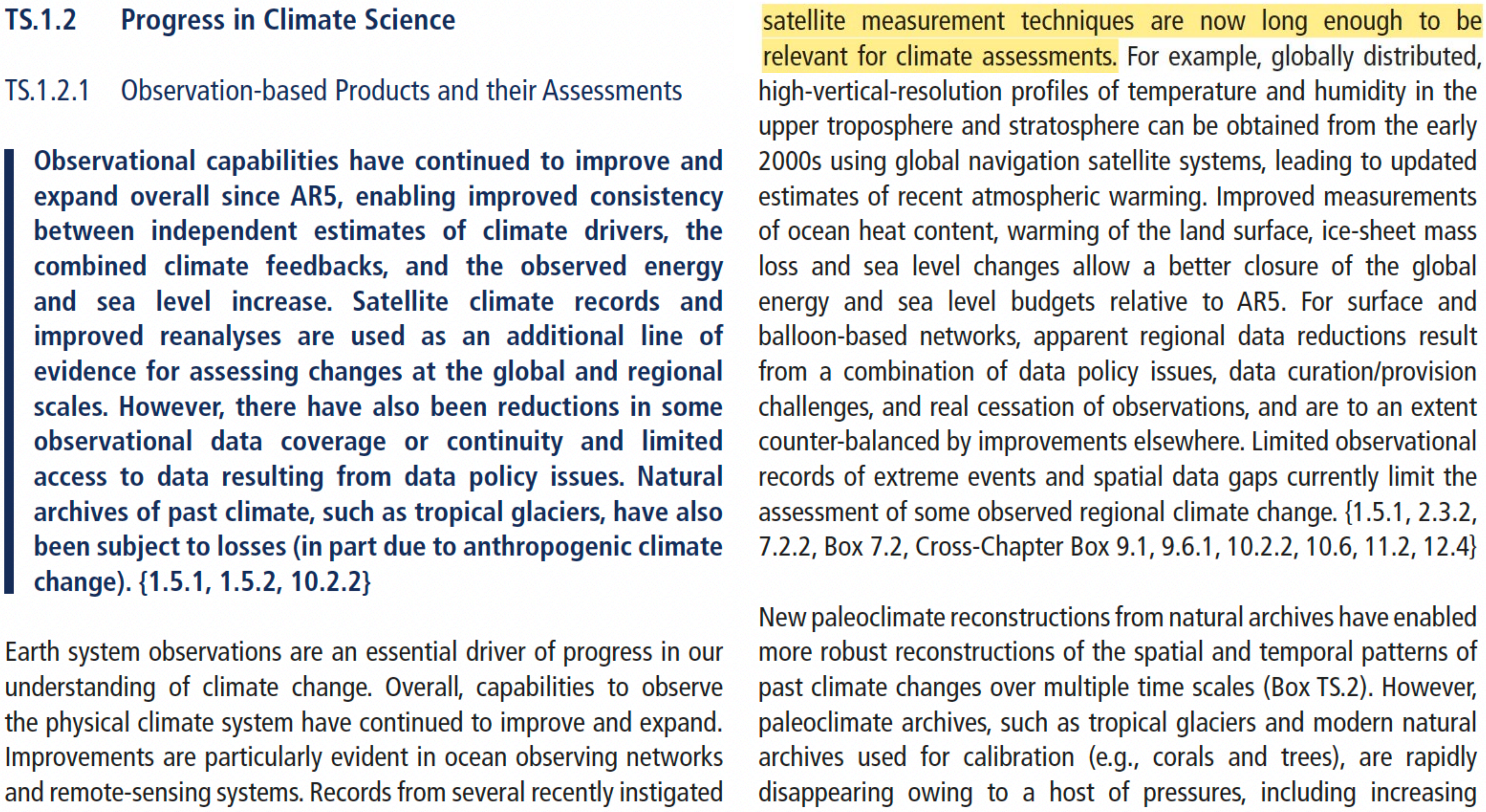
Satellite sea ice thickness since 1992 for climate assessments



ERS-1 & 2
(work in progress in CCI+)

Envisat + CryoSat2
(already in CCI, improved in CCI+)

ESA CCI and the IPCC AR6



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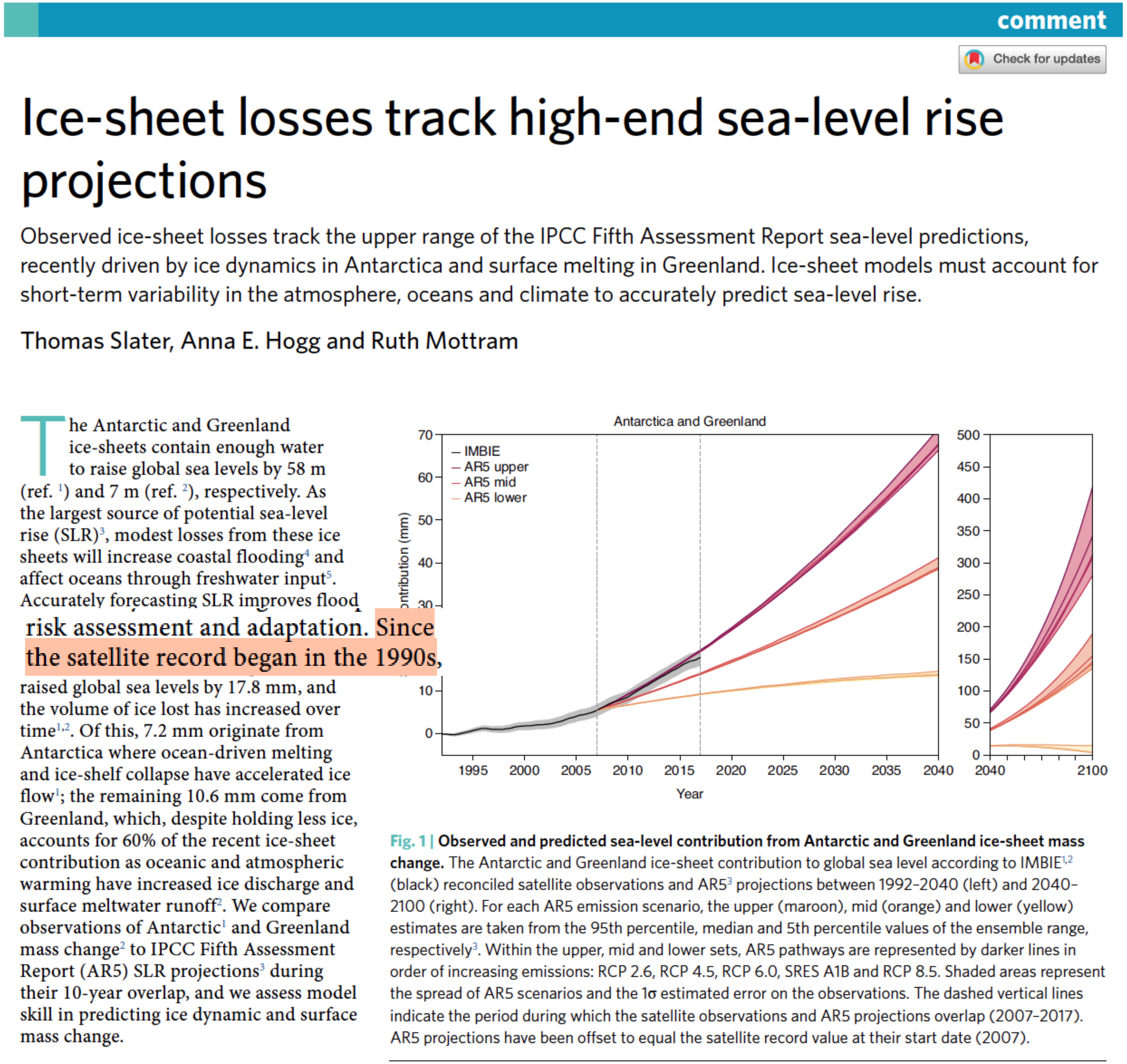


Ice-sheet losses track high-end sea-level rise projections

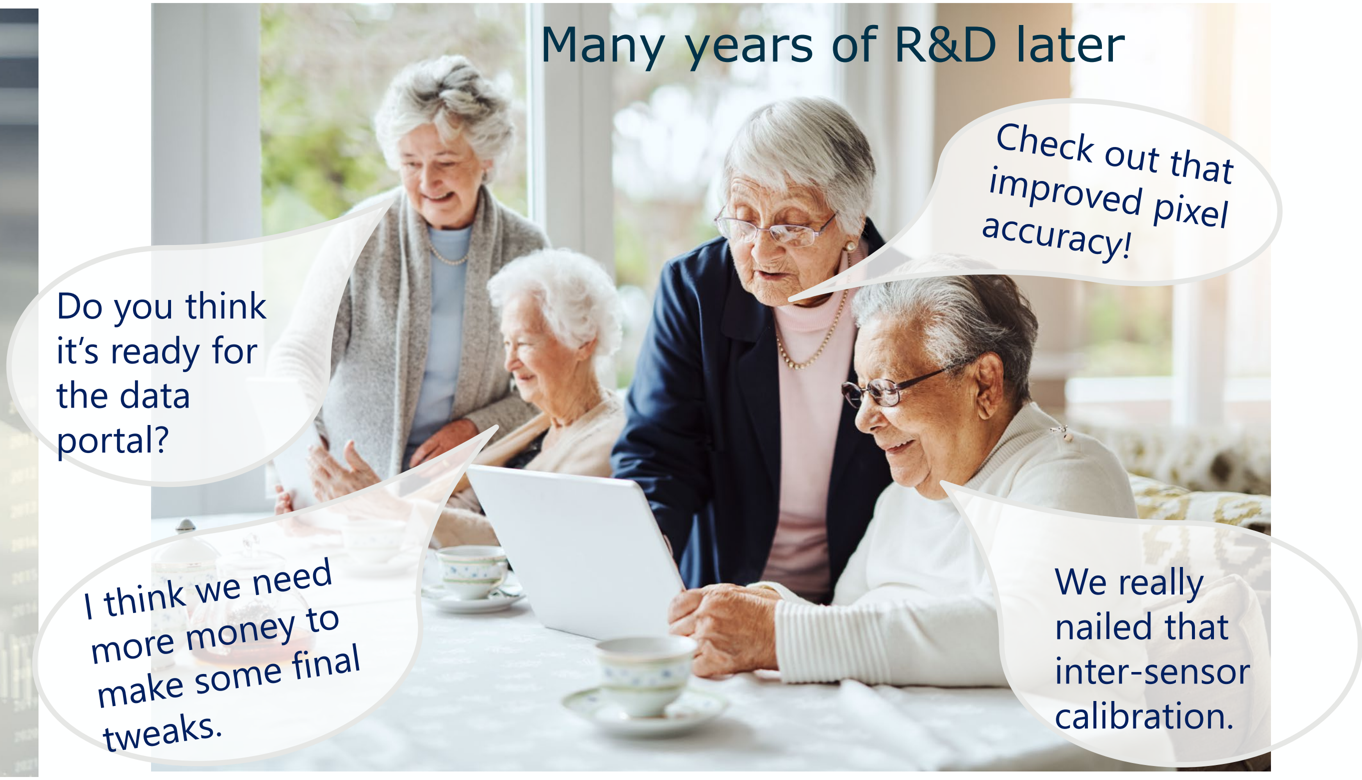
Observed ice-sheet losses track the upper range of the IPCC Fifth Assessment Report sea-level predictions, recently driven by ice dynamics in Antarctica and surface melting in Greenland. Ice-sheet models must account for short-term variability in the atmosphere, oceans and climate to accurately predict sea-level rise.

Thomas Slater, Anna E. Hogg and Ruth Mottram

The Antarctic and Greenland ice-sheets contain enough water to raise global sea levels by 58 m (ref. [1]) and 7 m (ref. [2]), respectively. As the largest source of potential sea-level rise (SLR)[3], modest losses from these ice sheets will increase coastal flooding[4] and affect oceans through freshwater input[5]. Accurately forecasting SLR improves flood risk assessment and adaptation. Since the satellite record began in the 1990s, raised global sea levels by 17.8 mm, and the volume of ice lost has increased over time[1,2]. Of this, 7.2 mm originate from Antarctica where ocean-driven melting and ice-shelf collapse have accelerated ice flow[1]; the remaining 10.6 mm come from Greenland, which, despite holding less ice, accounts for 60% of the recent ice-sheet contribution as oceanic and atmospheric warming have increased ice discharge and surface meltwater runoff[2]. We compare observations of Antarctic[1] and Greenland mass change[2] to IPCC Fifth Assessment Report (AR5) SLR projections[3] during their 10-year overlap, and we assess model skill in predicting ice dynamic and surface mass change.

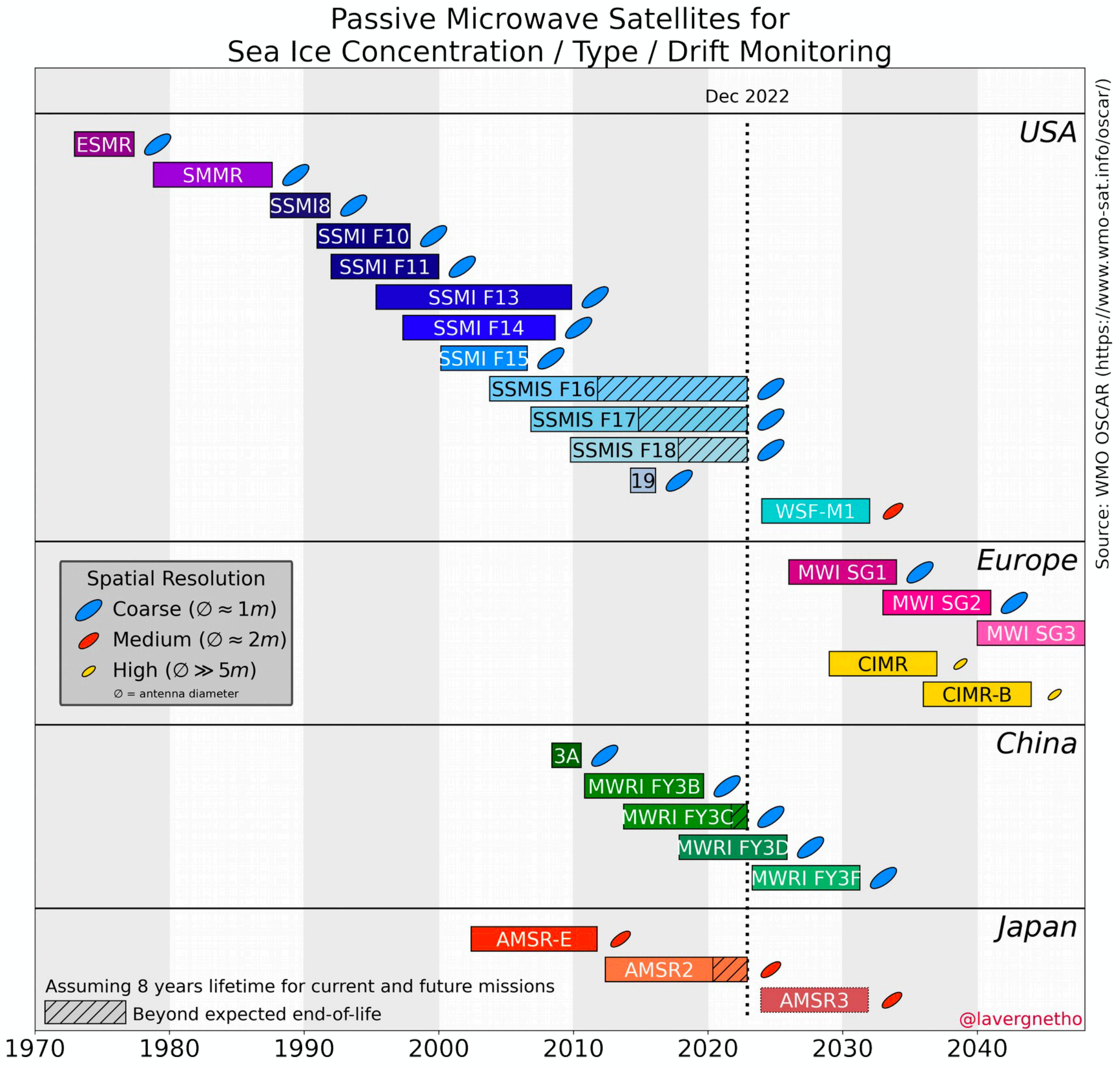
Fig. 1 | Observed and predicted sea-level contribution from Antarctic and Greenland ice-sheet mass change. The Antarctic and Greenland ice-sheet contribution to global sea level according to IMBIE[1,2] (black) reconciled satellite observations and AR5[3] projections between 1992–2040 (left) and 2040–2100 (right). For each AR5 emission scenario, the upper (maroon), mid (orange) and lower (yellow) estimates are taken from the 95th percentile, median and 5th percentile values of the ensemble range, respectively[3]. Within the upper, mid and lower sets, AR5 pathways are represented by darker lines in order of increasing emissions: RCP 2.6, RCP 4.5, RCP 6.0, SRES A1B and RCP 8.5. Shaded areas represent the spread of AR5 scenarios and the 1σ estimated error on the observations. The dashed vertical lines indicate the period during which the satellite observations and AR5 projections overlap (2007–2017). AR5 projections have been offset to equal the satellite record value at their start date (2007).

What most people think happens when we talk about open satellite data.



What actually happens in order to make satellite data openly available.

Passive microwave sensors for sea ice monitoring



Passive Microwave Satellites for Sea Ice Concentration / Type / Drift Monitoring

Source: WMO OSCAR (https://www.wmo-sat.info/oscar/)

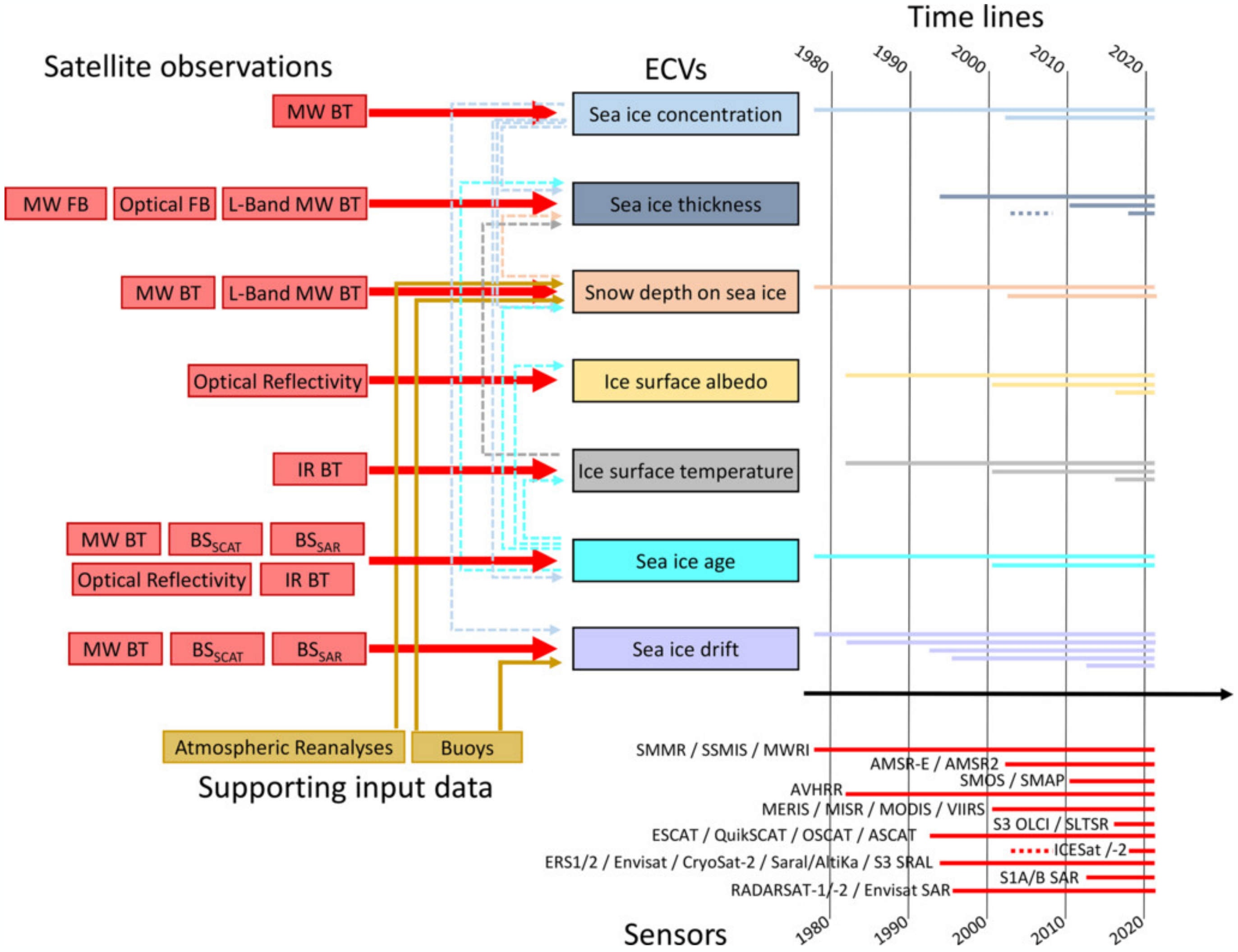
Why do we need clever algorithms to monitor ice over long time periods?

Figure 1 from ESA CCI+ Sea Ice Concentration PUG document: Timeline of the Passive Microwave satellite missions relevant for sea-ice concentration/extent/area monitoring with an indication of their spatial resolution capabilities. The horizontal bars represent satellite missions, which are coloured by sensor family.

The ESA CCI+ Sea Ice Concentration High Resolution CDR uses the SSM/I (F10 onwards) and all SSMIS.

Multi-mission data products: an example for the Sea Ice ECV

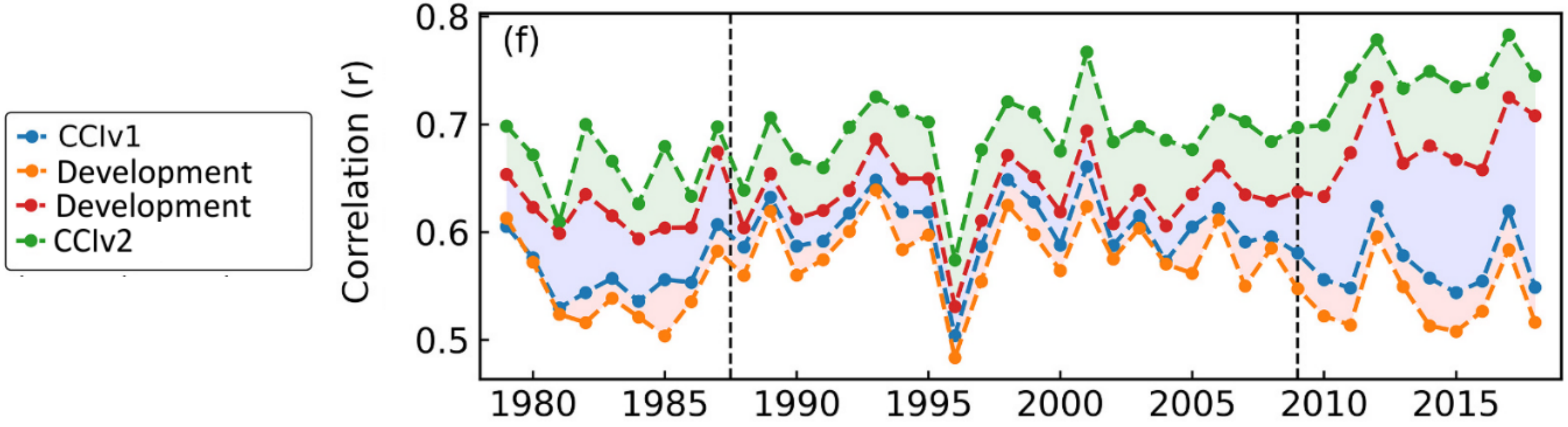
Lavergne, Kern et al (2022) A New Structure for the Sea Ice Essential Climate Variables of the Global Climate Observing System



Legend for type of satellite observation:
MW = microwave, FB = freeboard,
BT = brightness temperature,
BS = backscatter, IR = infrared,
SCAT = scatterometer,
SAR = synthetic aperture radar.

Algorithm improvements: an example from CCI+ Snow

C. Mortimer, et al (2022) Benchmarking algorithm changes to the CCI+ Snow project’s snow water equivalent product



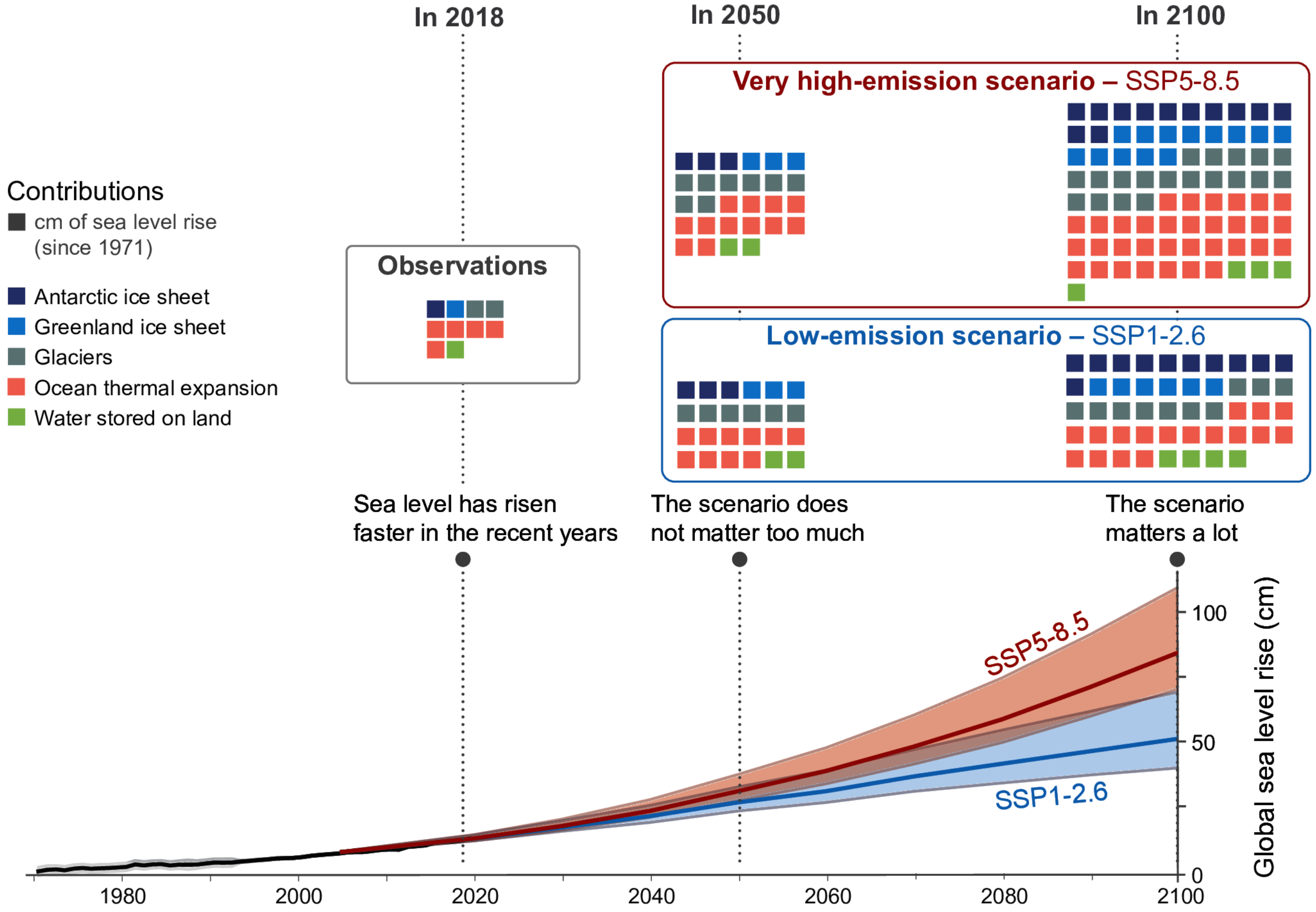
Correlation by year against reference snow course measurements. Shading indicates change in metric for each modification. Vertical dashed lines delineate transition between different satellite passive microwave sensors.

- Improvement from version 1 to version 2 meant that now the timing of peak snow mass has been shifted by two weeks

Why do we need these measurements?

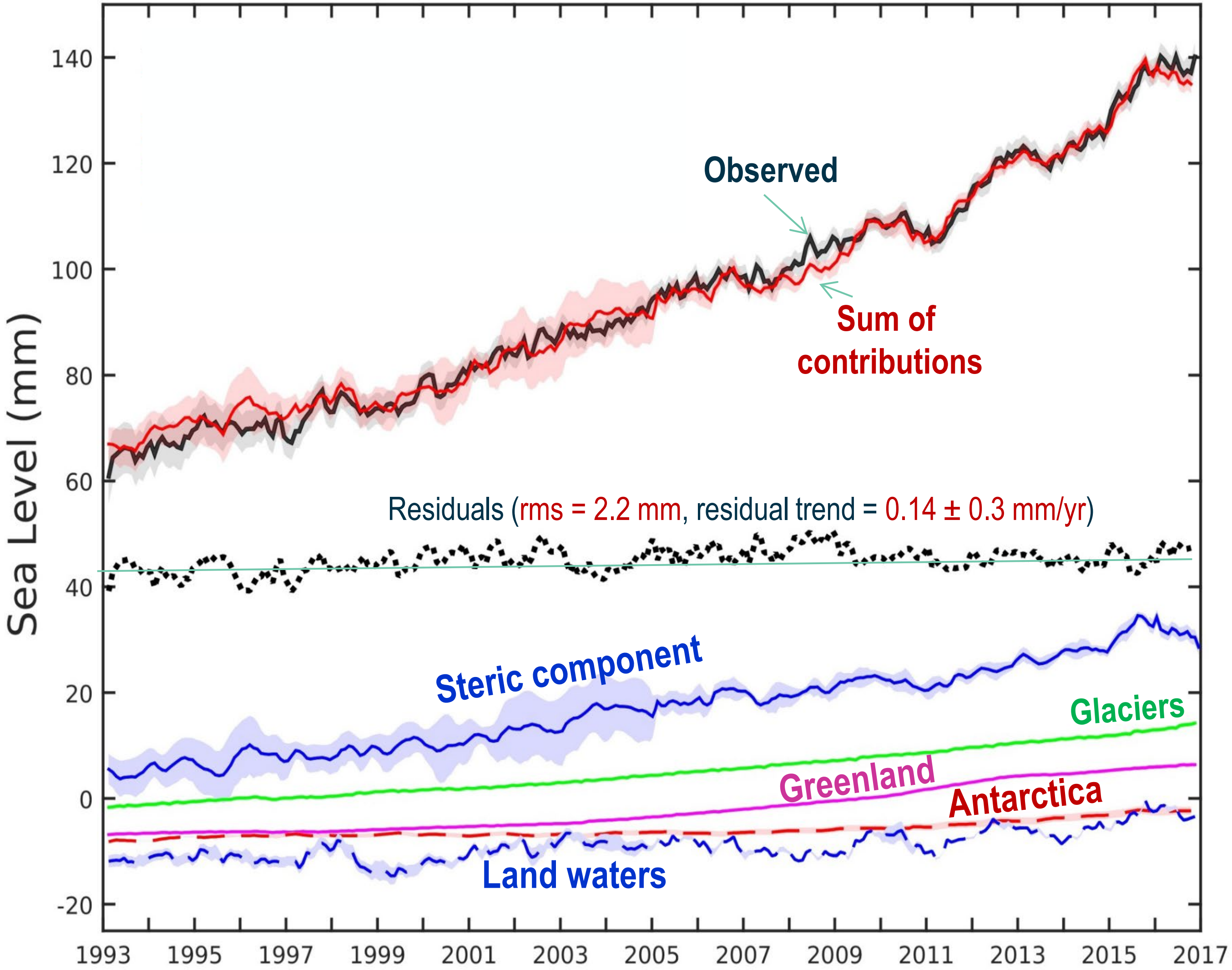
FAQ 9.2: **How much will sea level rise in the next few decades?**

Emissions scenarios influence little sea level rise of the coming decades but has a huge effect on sea level at the end of the century.



FAQ 9.2 Figure 1 in IPCC, 2021: Chapter 9. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, doi: 10.1017/9781009157896.011* .

How trustworthy are these space-derived CDRs?

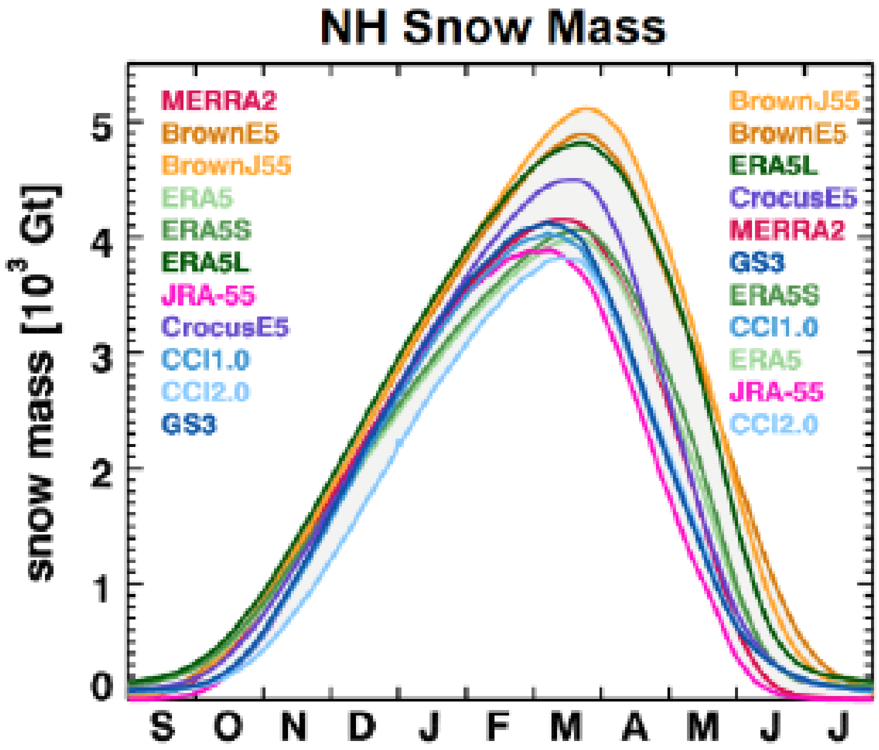


Is observed sea level change explained by the sum of its components?

By investigate the **closure of the global mean sea level budget** we are also able to assess the quality, consistency and uncertainty of our satellite-derived climate data records.

ESA Sea Level Budget Closure CCI / M. Horwath

How trustworthy are these space-derived CDRs?



Climatological snow mass (1981-2010) aggregated over Northern Hemisphere from different SnowPEx+ datasets.

Why do we need to intercompare differently derived CDRs?

By benchmarking various climate data records, we can assess and justify which product is best to use for certain applications.

ESA SnowPEx+ / C. Mortimer, L. Mudryk, C. Derksen, K. Luojus and others

Why is a reliable satellite system in orbit important?

An example from the Greenland Ice Sheet

Mass flow rate ice discharge (MFID):

$$\mathrm{MFID} = \rho_{\mathrm{ice}} \times \mathrm{IV} \times \mathrm{H} \times \mathrm{w}$$

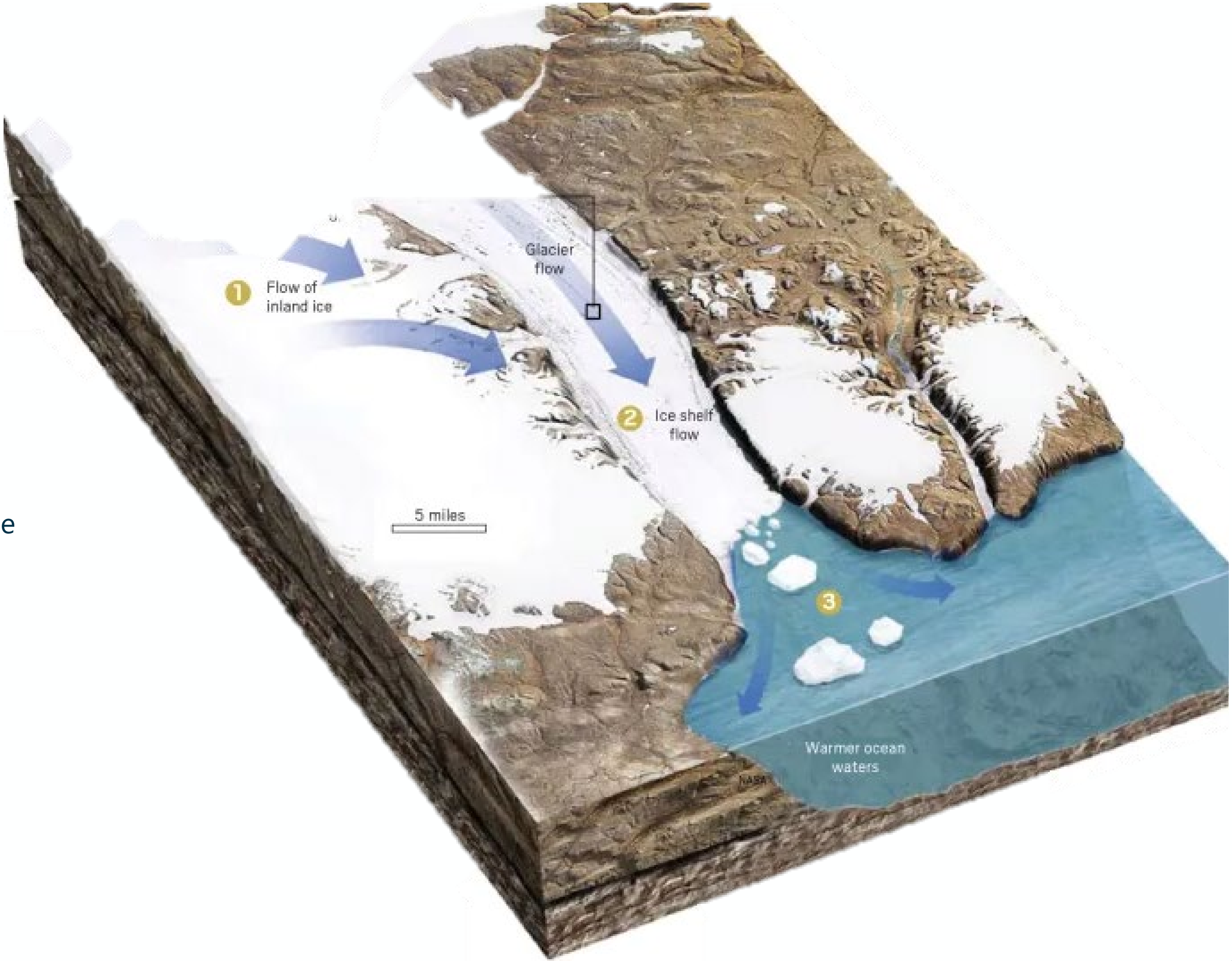
Density of ice

Ice velocity

Ice thickness

Width of the gate

$$\mathrm{H} = \mathrm{DEM} + \mathrm{SEC} - \mathrm{Bed}$$



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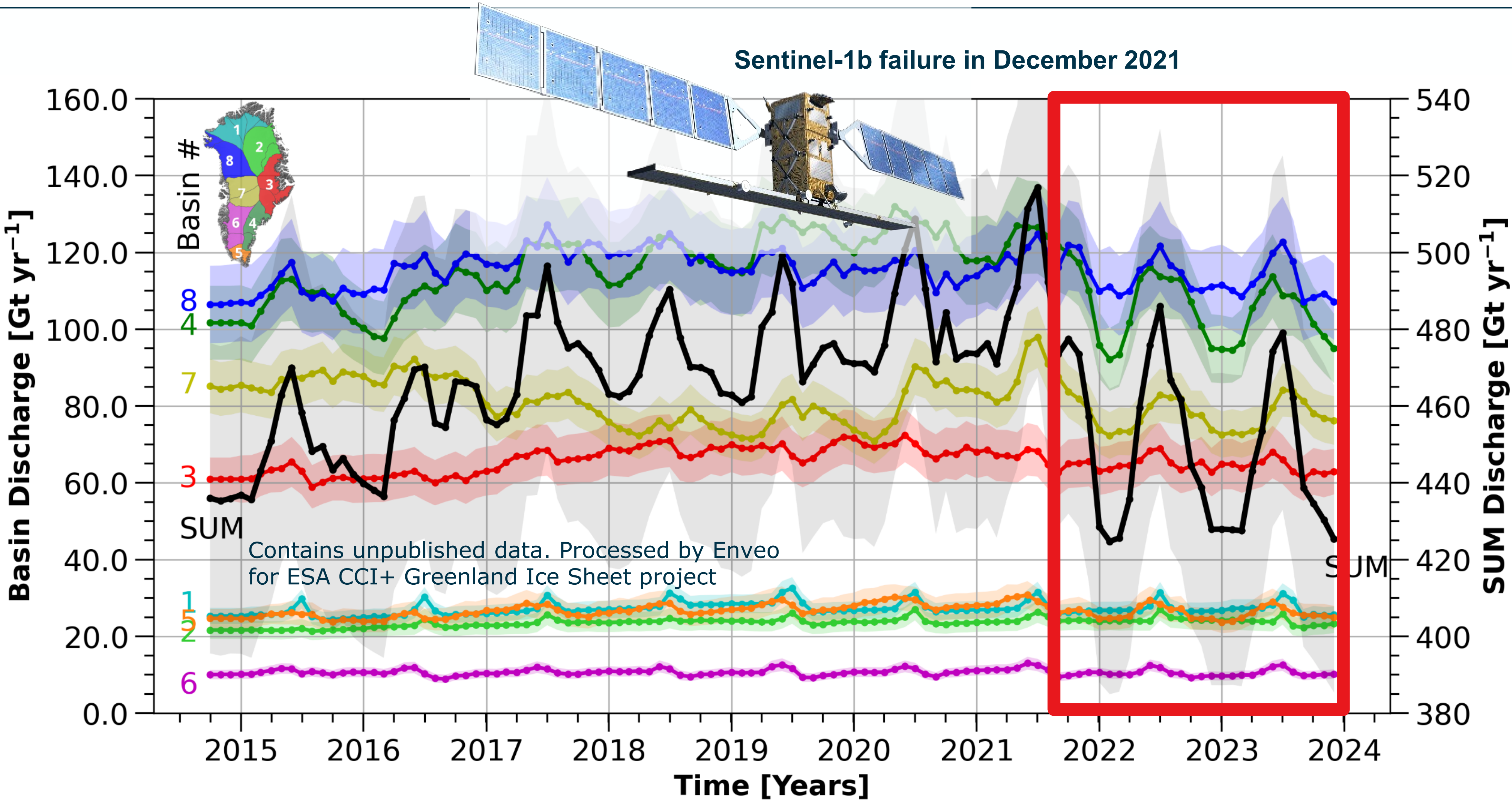

Contains unpublished data. Processed by Enveo for ESA CCI+ Greenland Ice Sheet project

If you remember one thing, then let it be this:

Satellite-derived climate data records provide crucial evidence of global climate change

- We need a sustainable satellite infrastructure in orbit.
- We need to continue R&D on homogenising historic satellite data with data from new sensors.
- Both are essential to making sure we better understand the state of our climate system.