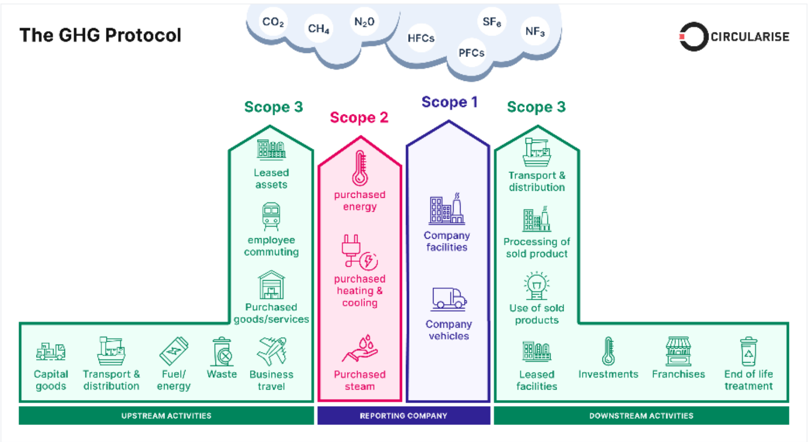
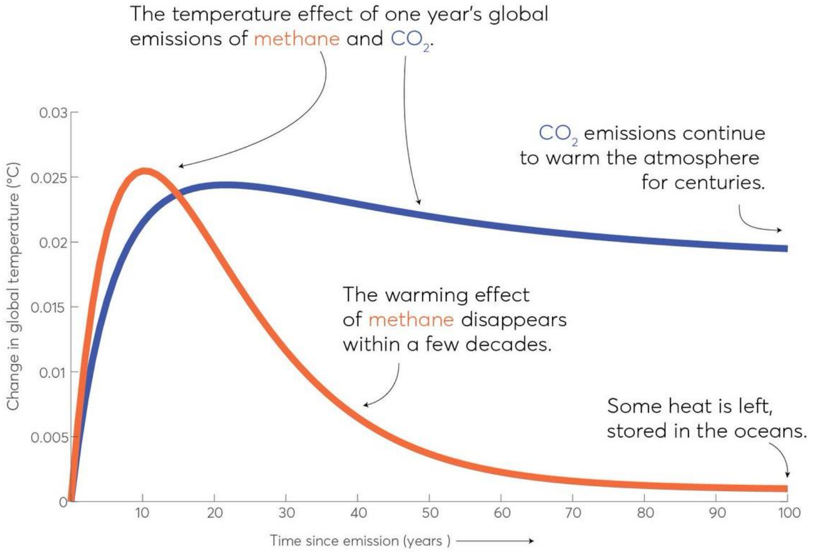
Recap from last lecture



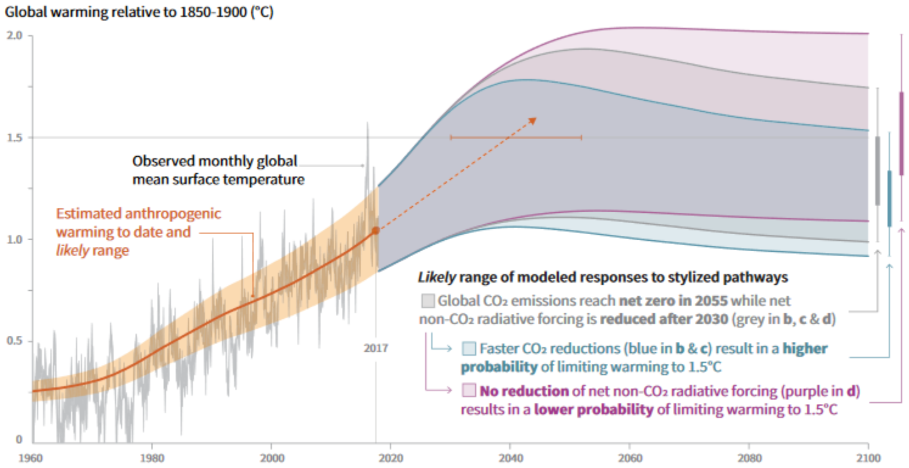
Within the EU certain companies need to report their carbon emissions based on GWP_{100}. That includes emissions from scope 1,2 and 3.



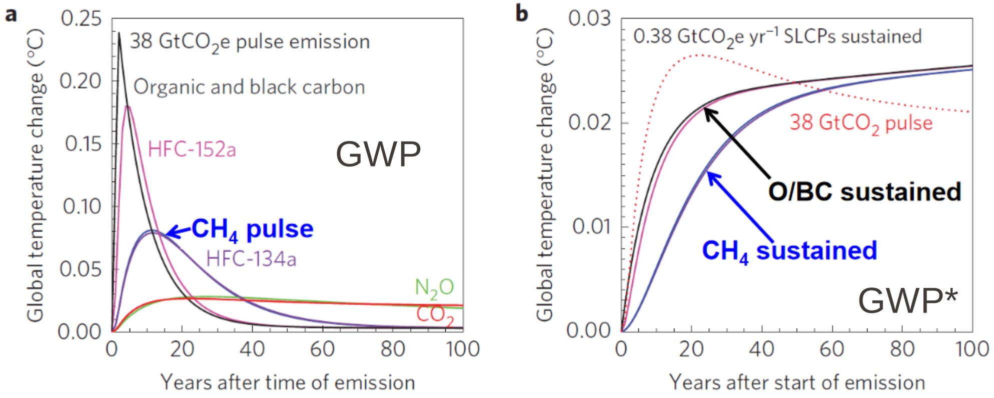
Due to different lifetimes and radiative forcing efficacy, the warming effect of CO_2 and CH_4 is very different in timing and amount. Emission metrics need to account for that. GWP_{100} cannot.

	GWP (100)	GWP (20)
1990, CH_4	21	
1995, CH_4	21	
2001, CH_4	23	
2007, CH_4	25	
2013, CH_4	28	
2021, CH_4 fossil	29.8 ±11	82.5 ± 25.8
2021, CH_4 non-fossil	27.2 ±11	80.8 ± 25.8
2021, N_2O	273 ± 130	273 ± 118

GWP100 or 20 is based on pulsed emissions and the integrated radiative forcing over the time horizon.



The timing and mix of emission reductions matters for temperature outcomes.



GWP* accounts for the fact that it is the change in the rate of emissions that induces the warming/cooling of short lived GHGs.

General outline

Basics

Present and future Climate change

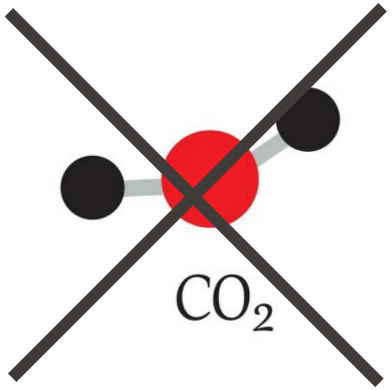
Actions

No.	Date	Topics	Deadlines
1.	12.09.2024	Introduction	fill in Questionnaire in exercises (not graded)
2.	19.09.2024	Climate System, Radiation, Greenhouse effect	
3.	26.09.2024	Earth's energy balance, Radiative transfer,	
4.	03.10.2024	Aerosols & clouds, Radiative Forcing	Launch of poster assignment
5.	10.10.2024	Feedback mechanisms, Climate Sensitivity	
6.	17.10.2024	Emergent Constraints, Paleoclimate	submission of Poster proposal (01.11.2024)
7.	31.10.2024	Climate variability	
8.	07.11.2024	IPCC, present day climate change, Paris Agreement, Emissions Gap, COP	
9.	14.11.2024	Extreme Events, COP29	
10.	21.11.2024	Climate scenarios, Tipping elements, Carbon Budget	submission of Poster draft
11.	28.11.2024	Metrics, carbon offsets	submission of assignment (graded)
12.	05.12.2024	**Carbon offsets, Polar climate change**	
13.	12.12.2024	Mitigation and adaptation, Climate Engineering	**Poster Conference** (graded)
14.	19.12.2024	Recapitulation of key points, questions and answers session	fill in Questionnaire in exercises (not graded)

Offset strategies and sectors

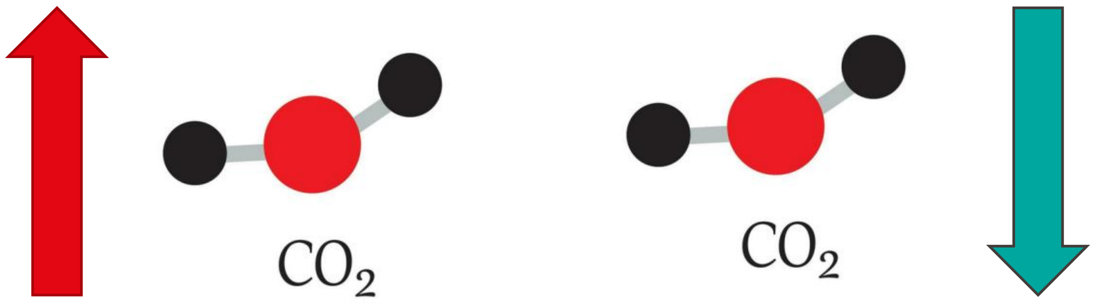
- There are two strategies that work with different sectors.

Avoidance



CO_2 is not released.

Removal



CO_2 is released AND removed.

Because CO_2 is globally distributed, emission and avoidance or removal can happen anywhere across the world.

Avoidance

- These projects **prevent carbon emissions** that would have been released into the atmosphere. It can be divided into 4 categories:
  1. **Renewable Energy**
     e.g., renewable power infrastructures that contribute to the decarbonization of the local energy grid.
  2. **Energy Efficiency and Fuel Switching**
     e.g., energy-saving measures that reduce carbon emissions and replace fossil fuels with sustainable energy sources.
  3. **Household Devices**
     e.g., efficient cookstoves that significantly reduce wood consumption. Or individual biogas digesters that provide sustainable fuel to local communities, prevent deforestation, and avoid GHG emissions.
  4. **Water Management**
     e.g., projects that supply clean water to households in rural communities, remove the need to boil water, and reduce GHG emissions.

Removal

- These projects **reduce carbon emissions** by absorbing them from the atmosphere. It can be divided into 3 categories:

1. **Agriculture**
   e.g., agricultural practices that store carbon in soils while restoring biodiversity and developing new sources of income for smallholders.
2. **Forestry and Land Use**
   e.g., projects that protect and restore existing forest areas threatened by deforestation.
3. **Waste Management**
   e.g., landfill projects designed to capture the methane released by waste disposal, which can turn it into clean fuel.

Isn't it wonderful?

- Strong emitters are regulated in mandatory carbon credit systems.
- The rest of the world can get ahead of time and engage in voluntary carbon reduction.
- We'll be at net-zero in no time!

Too good to be true

- Voluntary carbon offsets have grown into a multi-billion-dollar industry.
- Many companies take advantage of voluntary carbon offsets, and more than a few claim this makes them climate neutral.
- The skyrocketing demand for cheap offsets incentivizes project developers to scale up projects with increasing speed.

- https://ethz.ch/en/news-and-events/eth-news/news/2023/07/blog-voluntary-carbon-offsets-often-fail-to-deliver-what-they-promise.html

Reasons for failure

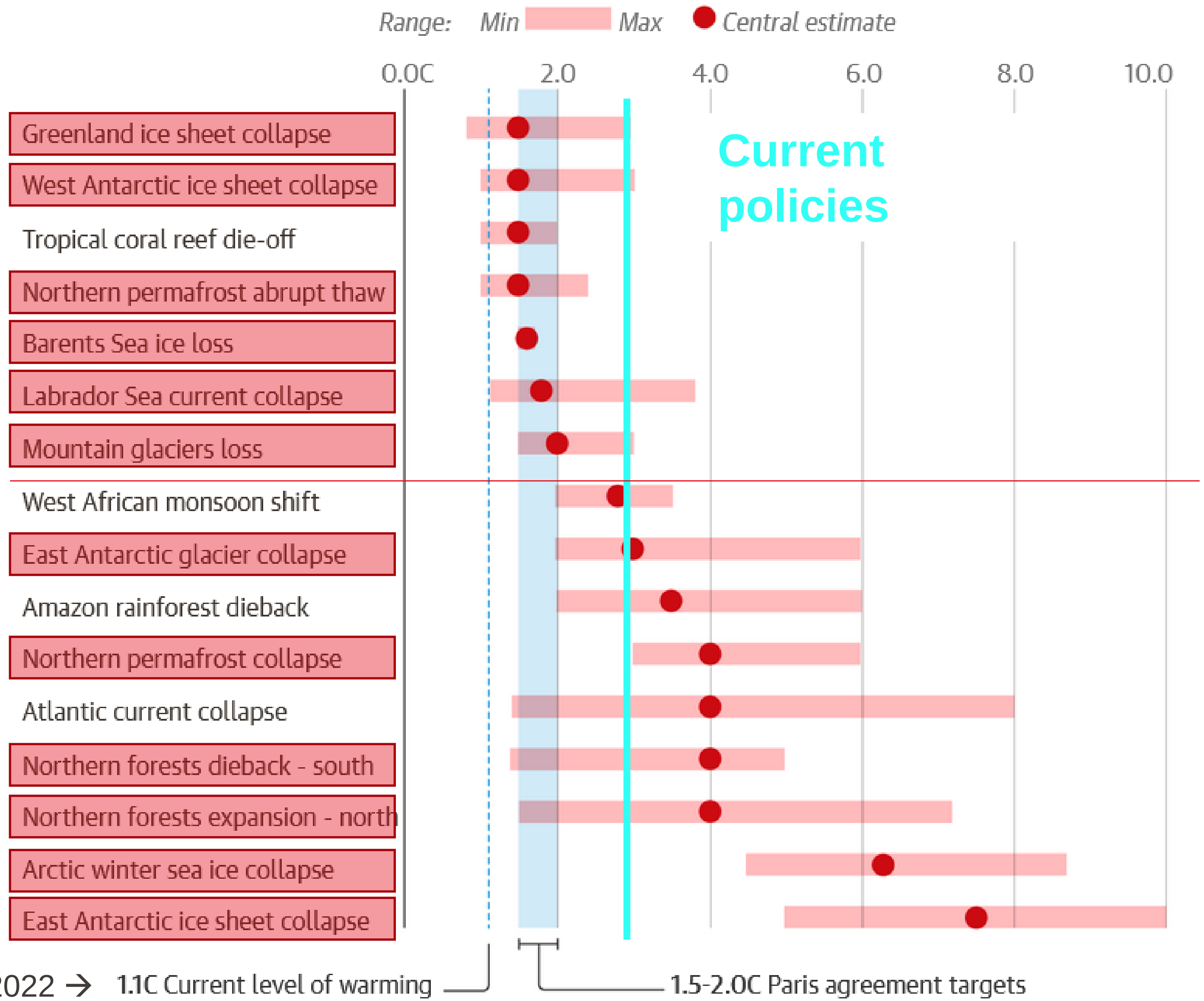
1. **Additionality**
   - The most prominent reason why carbon projects fail is that they are not additional, meaning that the project does not contribute to achieving additional climate benefits - compared to if the project had not existed.
2. **There are significant risks to forests**
   - There are significant risks to forests after a project ends, as any carbon sequestered is likely to be released back into the atmosphere. This risk can manifest in several different ways, from natural disasters to illegal logging - especially in countries with unstable political situations.
3. **Unreliable baseline inflate emissions promises**
   - A common issue seen in many projects is artificially inflating baseline emissions in order to generate more carbon credits for the project, thus taking credit for what the project did not do.
4. **Carbon credits cause community conflicts**
   - In some cases, in order to establish projects that generate carbon credits, landowners (such as governments) may forcefully evict people living on the project area territory.
5. **Emission reductions rely on vague predictions**
   - Credits promising that emission reductions will materialise in future are often referred to as 'ex-ante credits'.

~84% of voluntary projects fail

- https://www.euronews.com/green/2023/01/10/the-five-biggest-reasons-carbon-offsetting-schemes-can-fail, https://www.nature.com/articles/s41467-024-53645-z

Polar climate change

Paris agreement and polar tipping points



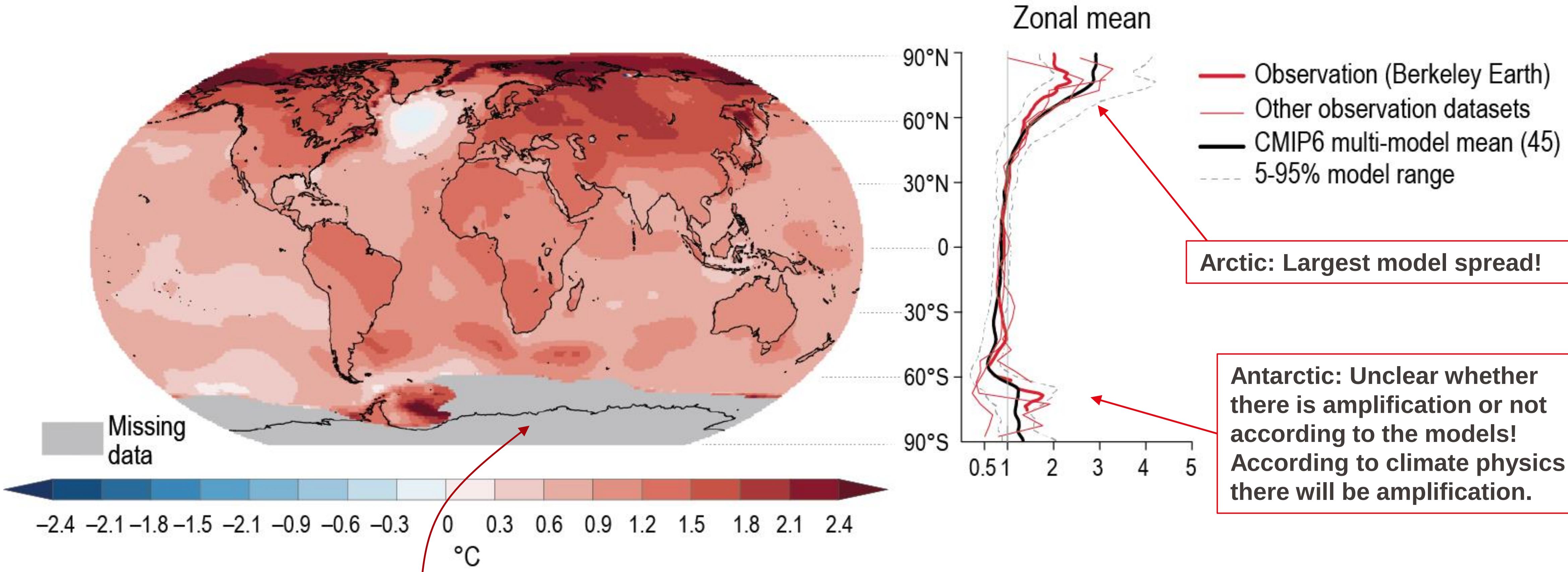
1.15 °C in 2022 →

Guardian graphic. Source: Armstrong McKay et al, Science, 2022. Note: Current global heating temperature rise 1.1C
Paris agreement targets 1.5-2.0C

- 12 out of 16 top tipping points are associated to extreme environments
  (polar and high altitude regions)
- 6 out of 7 tipping points potentially activated within the Paris range are related to polar regions and the cryosphere.

Armstrong McKay et al. (2022)

Accelerated warming in the polar regions



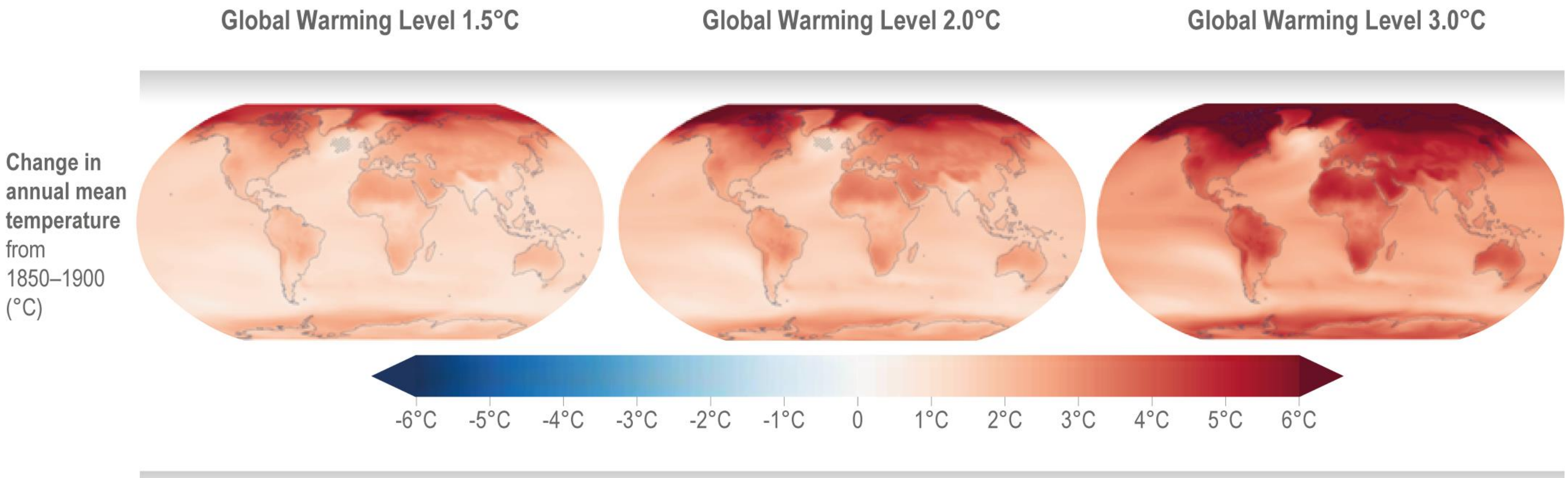
Arctic: Largest model spread!

Antarctic: Unclear whether there is amplification or not according to the models! According to climate physics there will be amplification.

Only 23 weather stations on Antarctica!

- IPCC, AR6

Polar Amplification

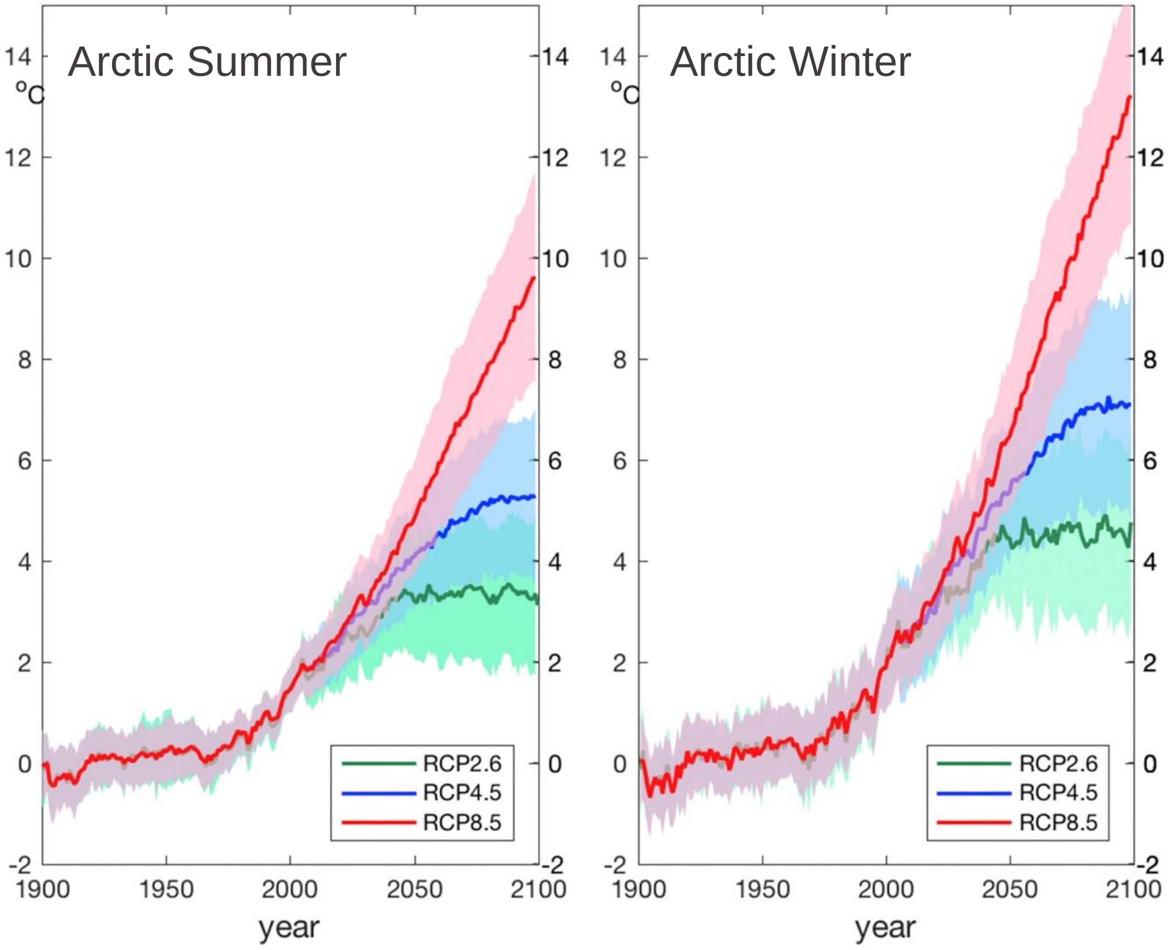


- The polar regions warm faster than the rest of the globe, this is called: Polar Amplification.
- Warming in the Arctic is more accelerated compared to the Antarctic.
- The IPCC states that we do not know when and how fast Antarctica is going to respond to climate forcing. This is a concern (e.g. sea level rise).

IPCC, AR6, WG2, Fig. 18.4, https://www.ipcc.ch/report/ar6/wg2/figures/chapter-18/figure-18-004a

Arctic Amplification

Seasonal warming



more warming
in winter
Why?

Overland et al., (2019)

Contributions to Arctic warming

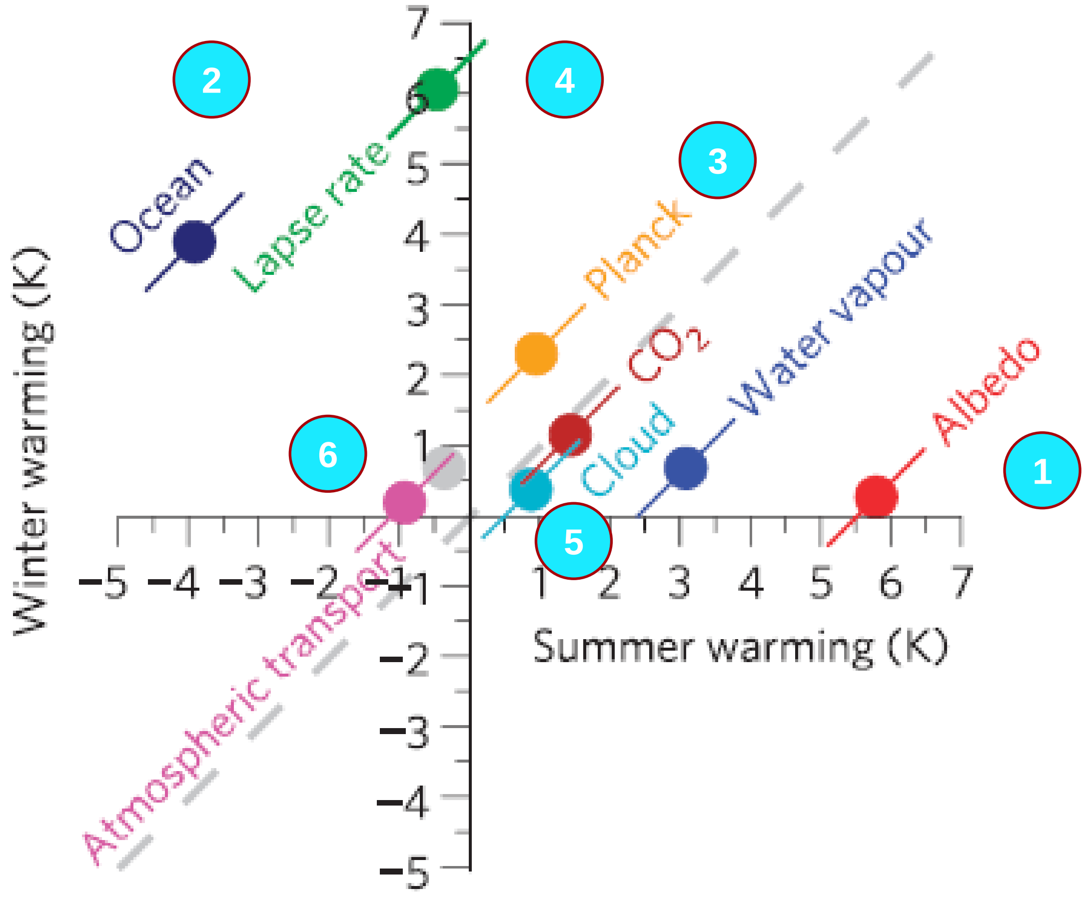
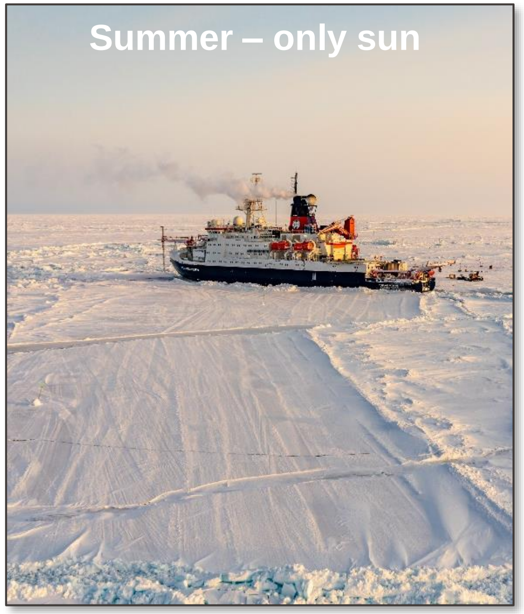


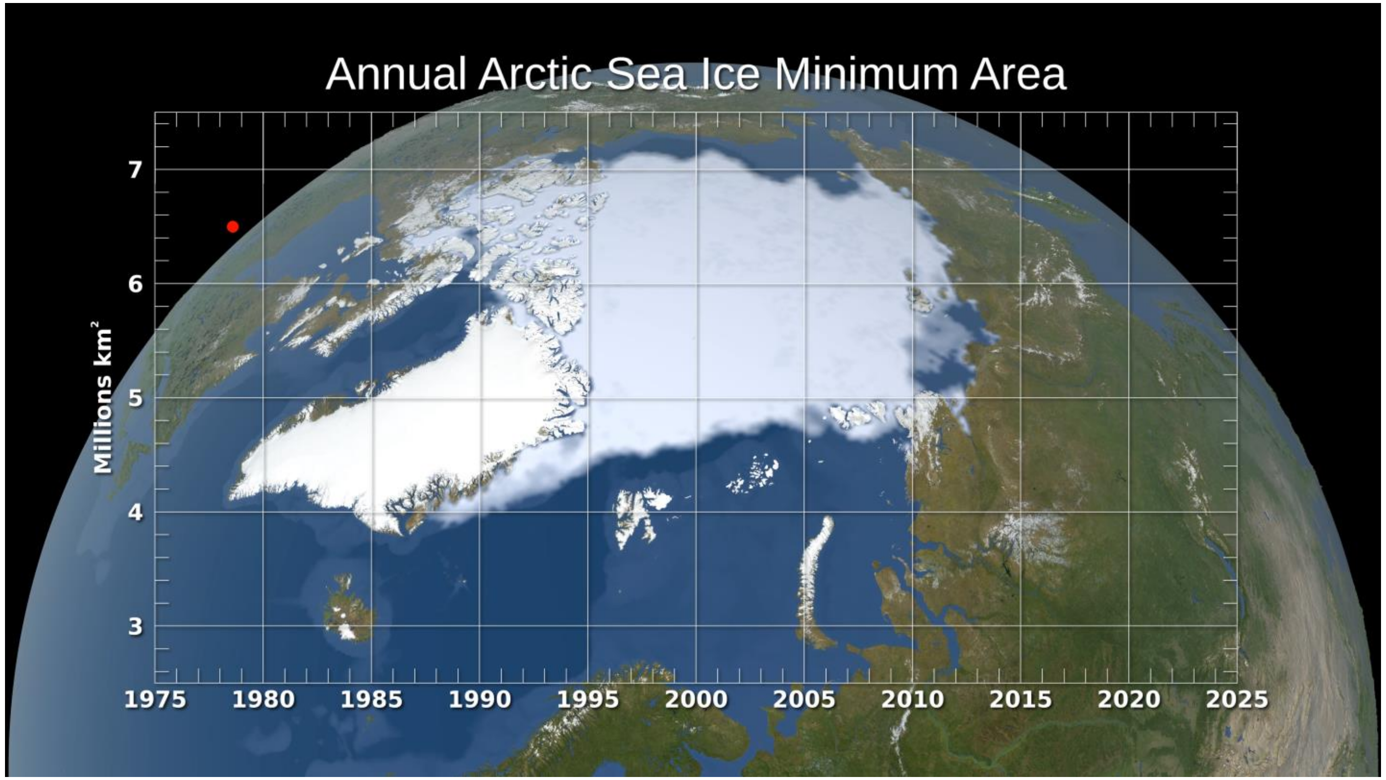
Figure 2 | Warming contributions of individual feedback mechanisms. **b**, Arctic winter versus summer warming. Grey is the residual error of the decomposition.

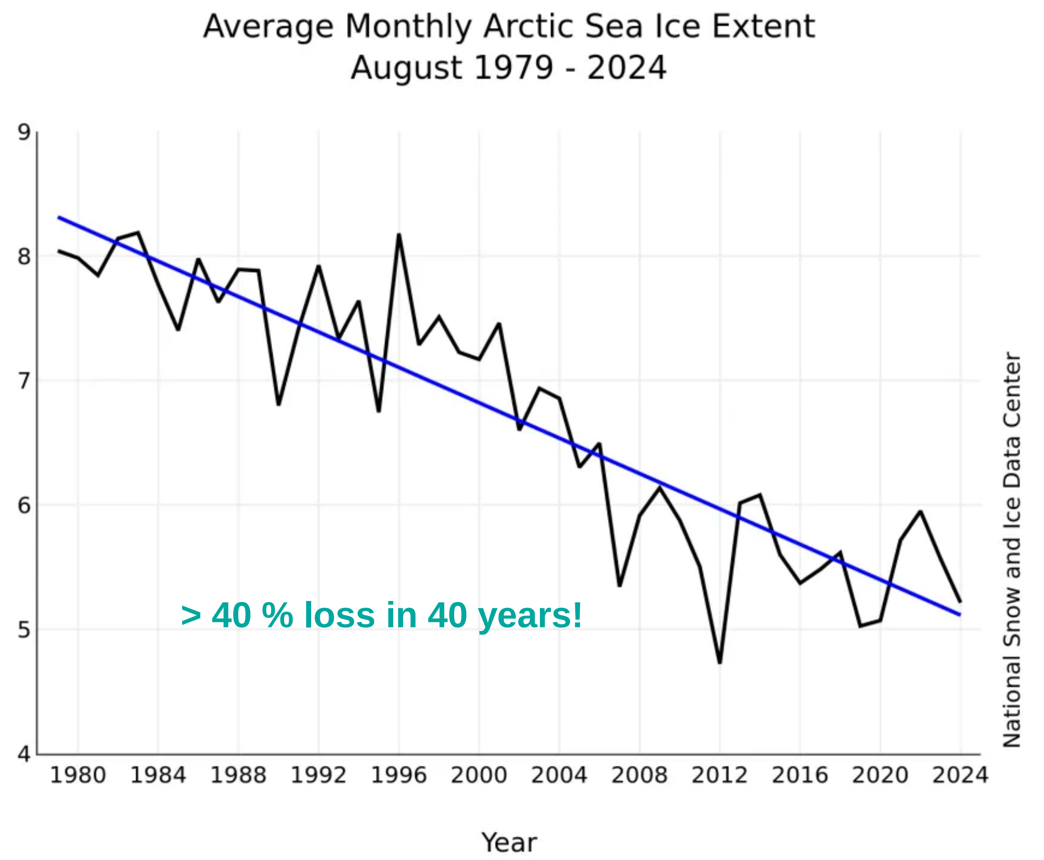


- Need to distinguish winter and summer mechanisms.
- Note the role that CO_2 plays.

- Pithan and Mauritsen, Nat. Geoscience, 2014

1. Albedo effect: Arctic sea ice retreat

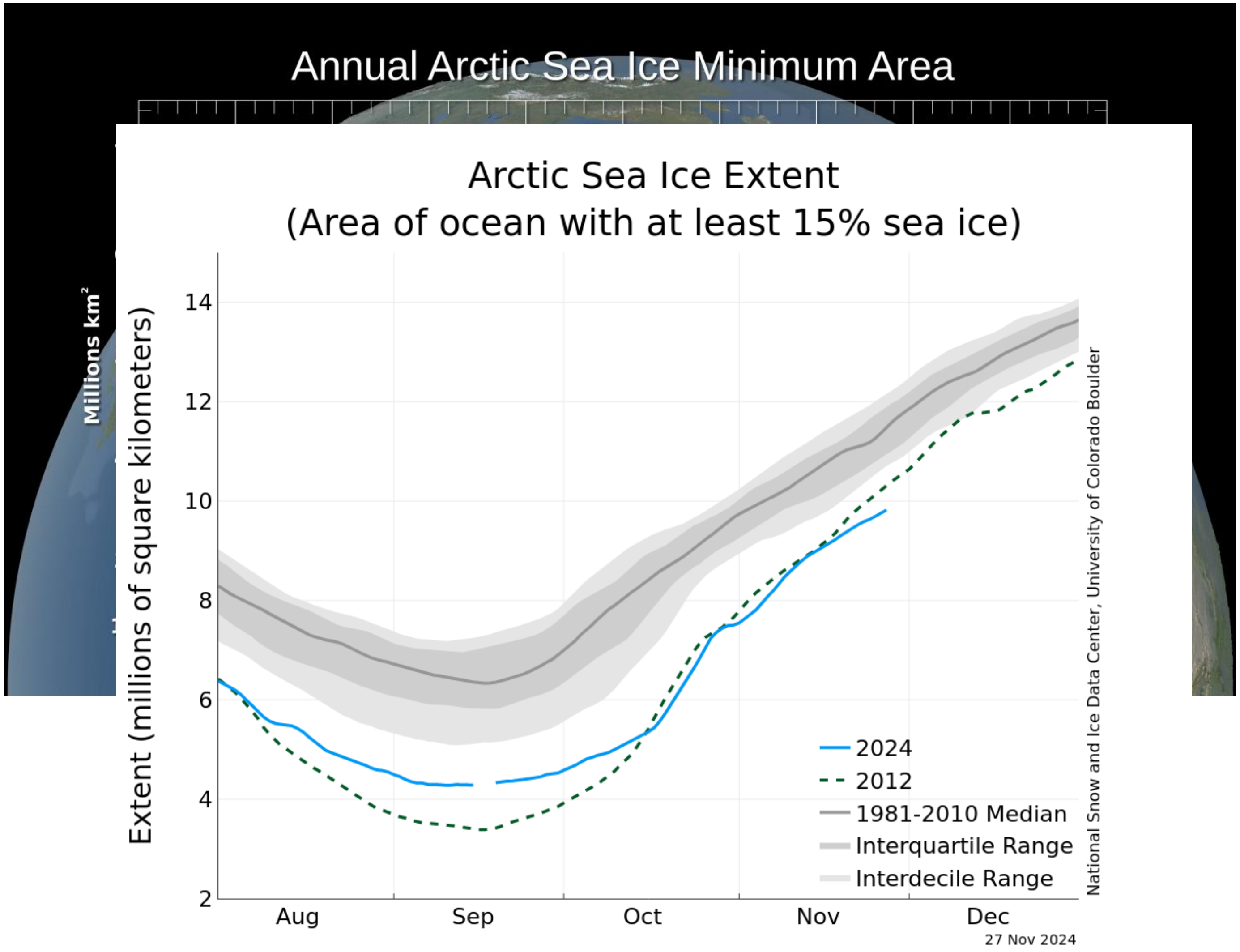


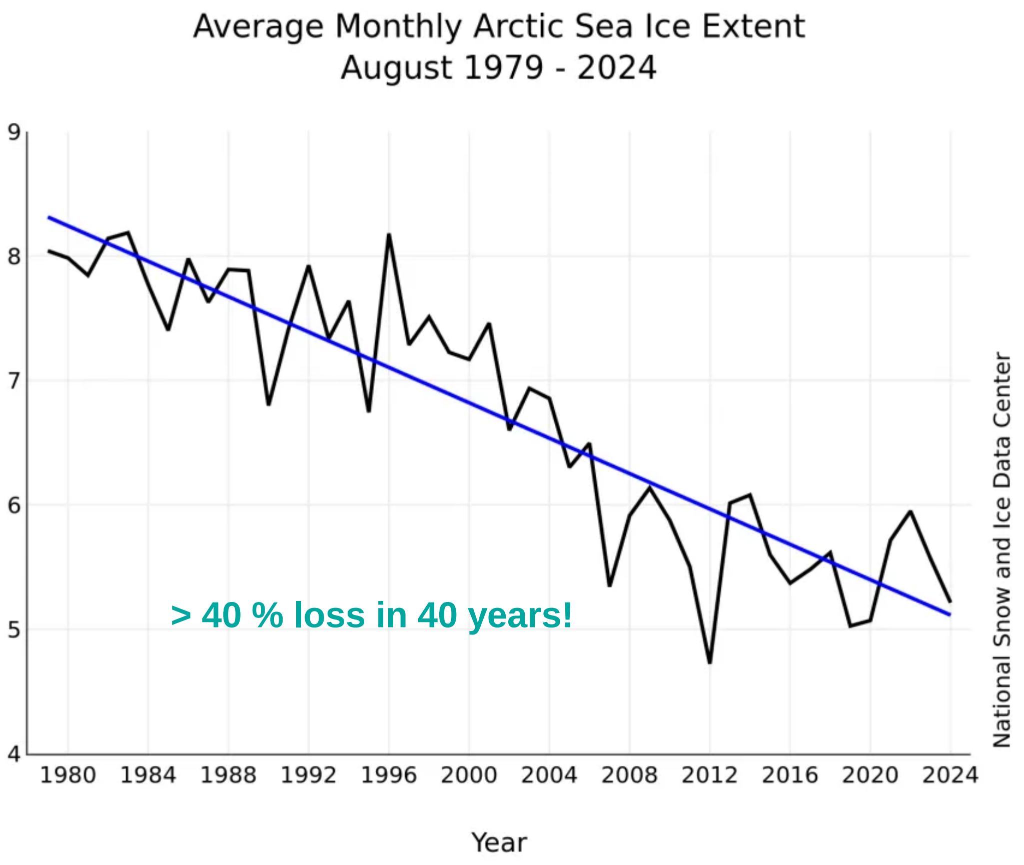


Less sea ice means that less solar radiation is reflected back to space and that the ocean absorbs more heat.

- http://nsidc.org/arcticseaicenews/

1. Albedo effect: Arctic sea ice retreat





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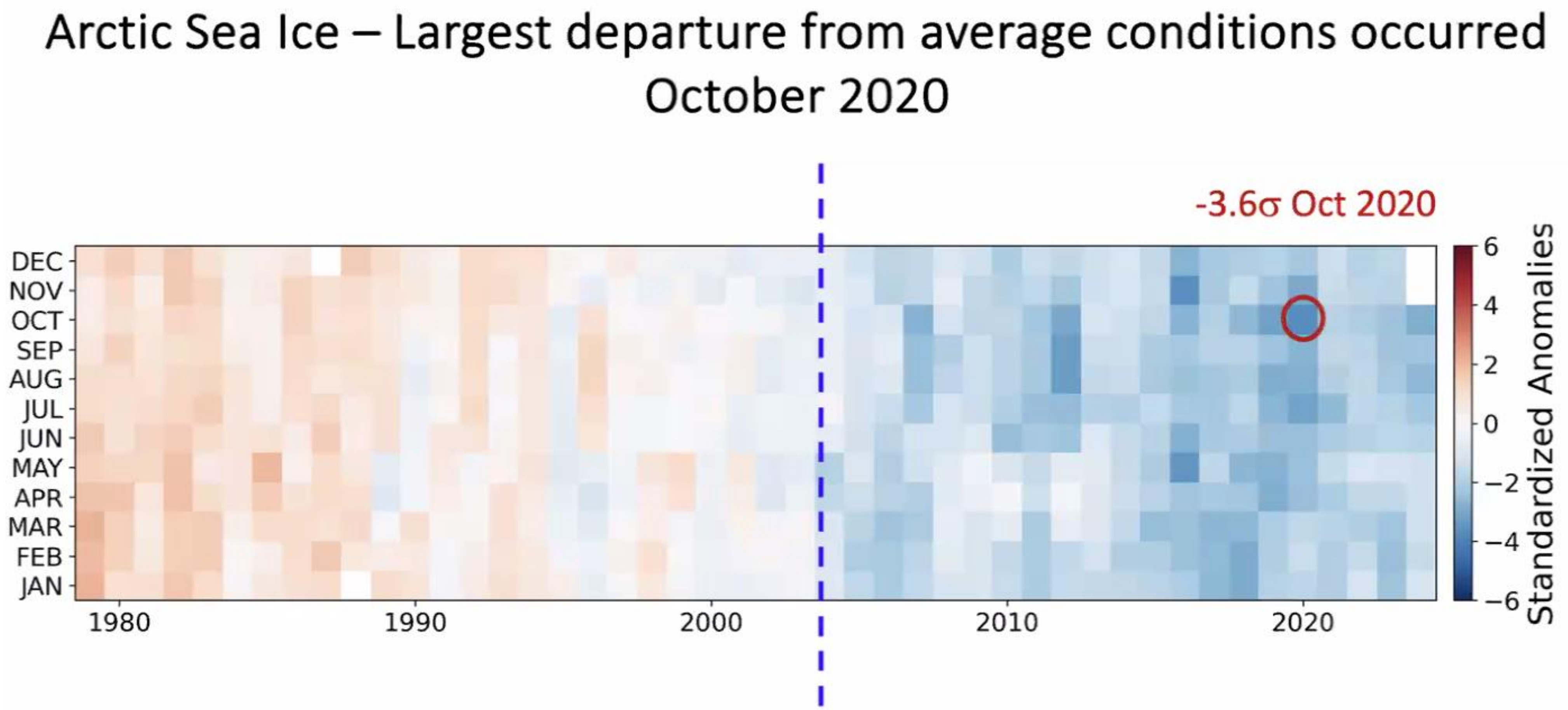
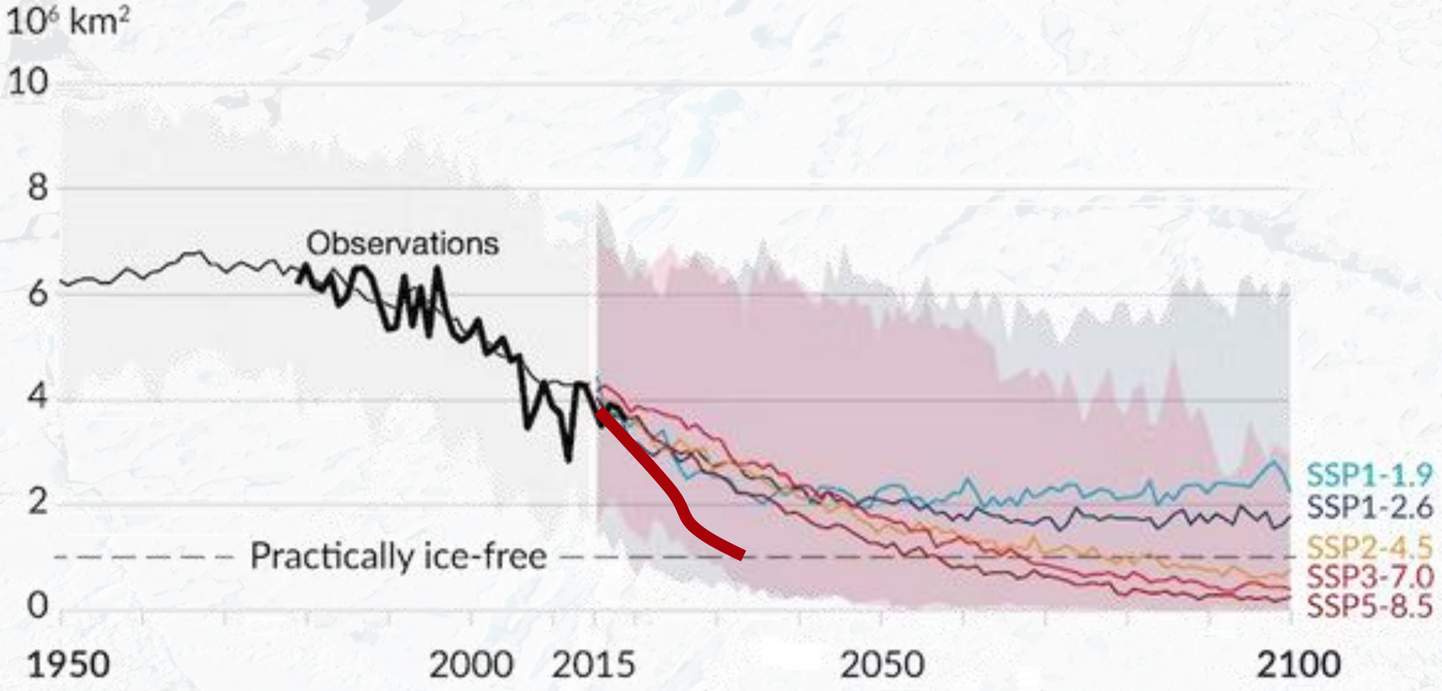
1. Arctic sea ice



Arctic Sea Ice Loss



- Ice free September:
  - IPCC: at the end of the 21st century in moderate emission scenarios, mid-century with high emission scenarios
  - New studies: as soon as 2030, highly likely by mid-century (e.g. Kim et al., 2023)

Credit: P. Zieger

Albedo effect: snow cover

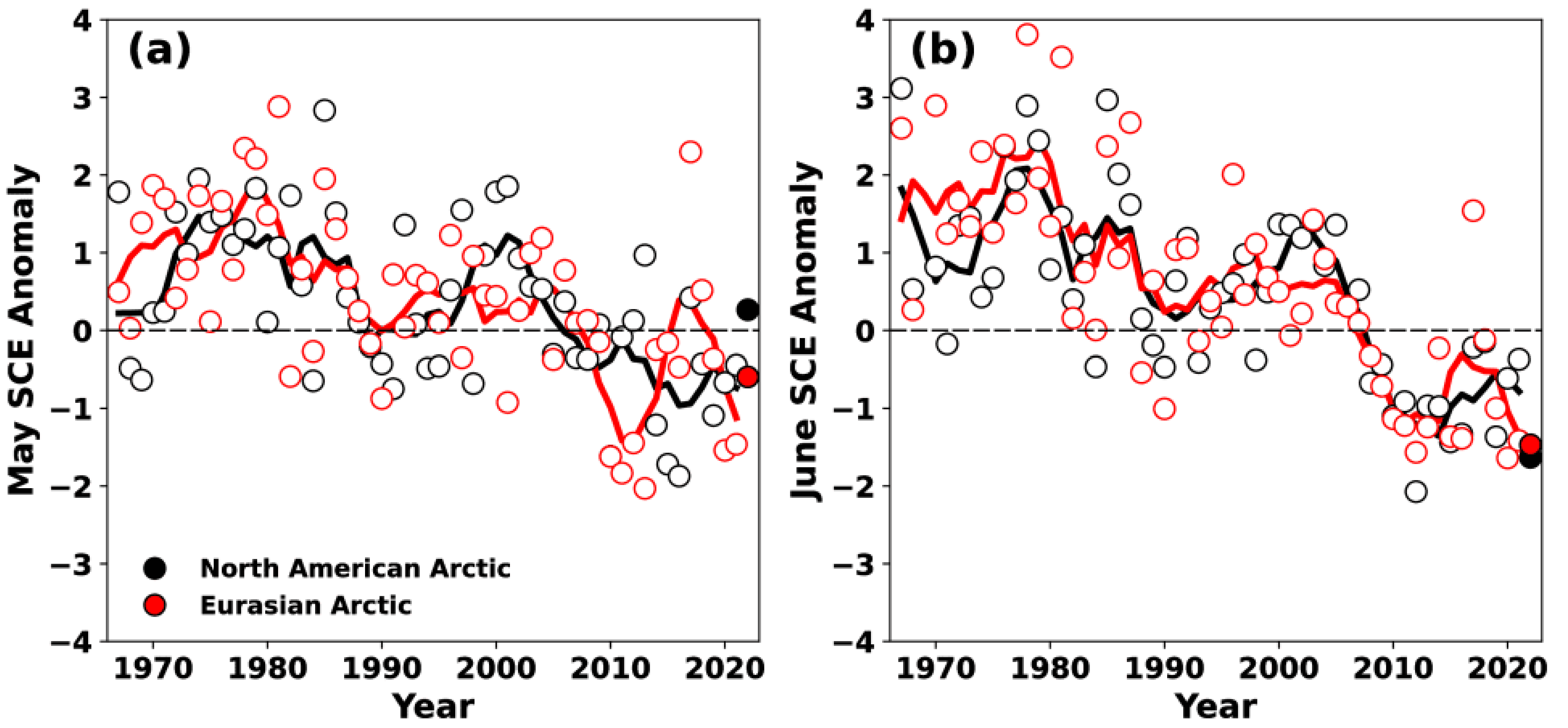


Fig. 1. Standardized monthly snow cover extent anomalies relative to the 1991-2020 climatology for Arctic land areas (>60° N) for **(a)** May, and **(b)** June, from 1967 to 2022. Solid black and red lines depict 5-year running means for North America and Eurasia, respectively. Filled circles are used to highlight 2022 anomalies. Source: NOAA snow chart Climate Data Record (CDR).

- https://arctic.noaa.gov/report-card/report-card-2022/terrestrial-snow-cover/

Albedo effect: snow cover

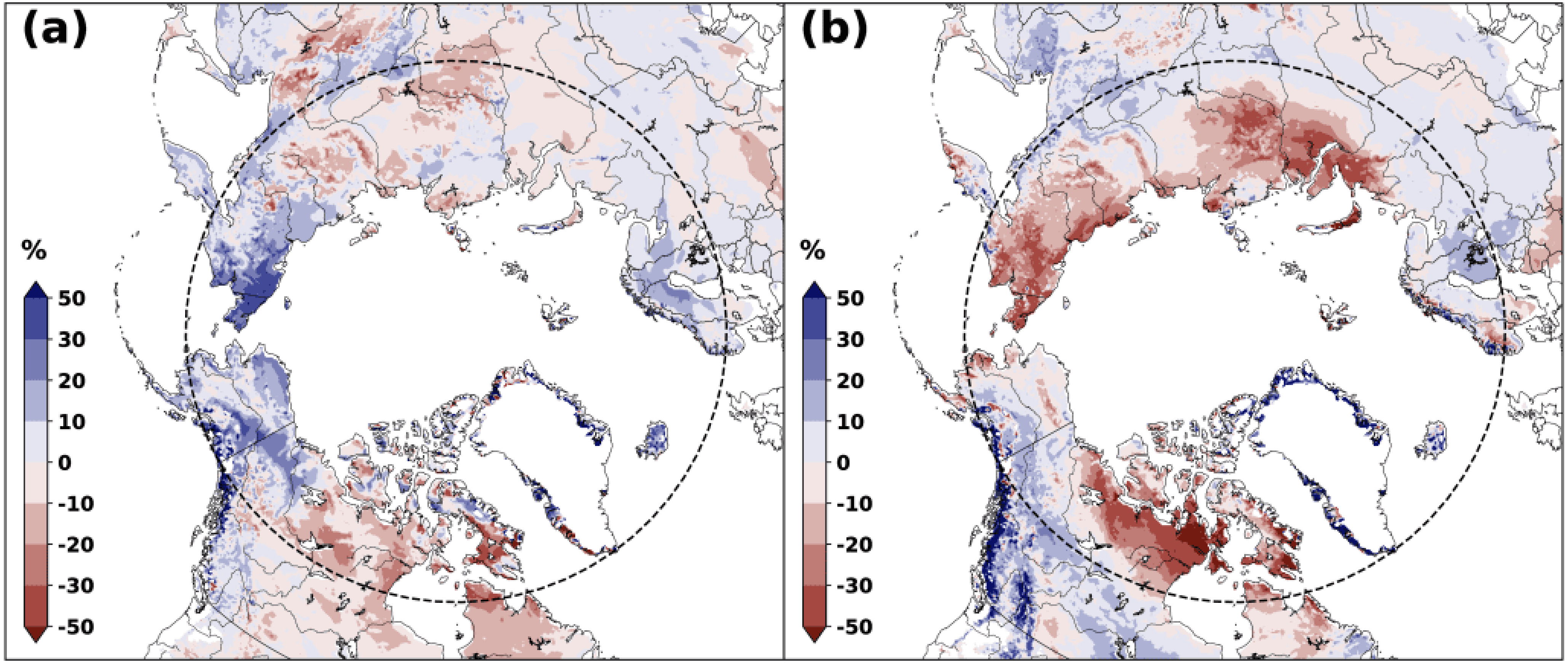
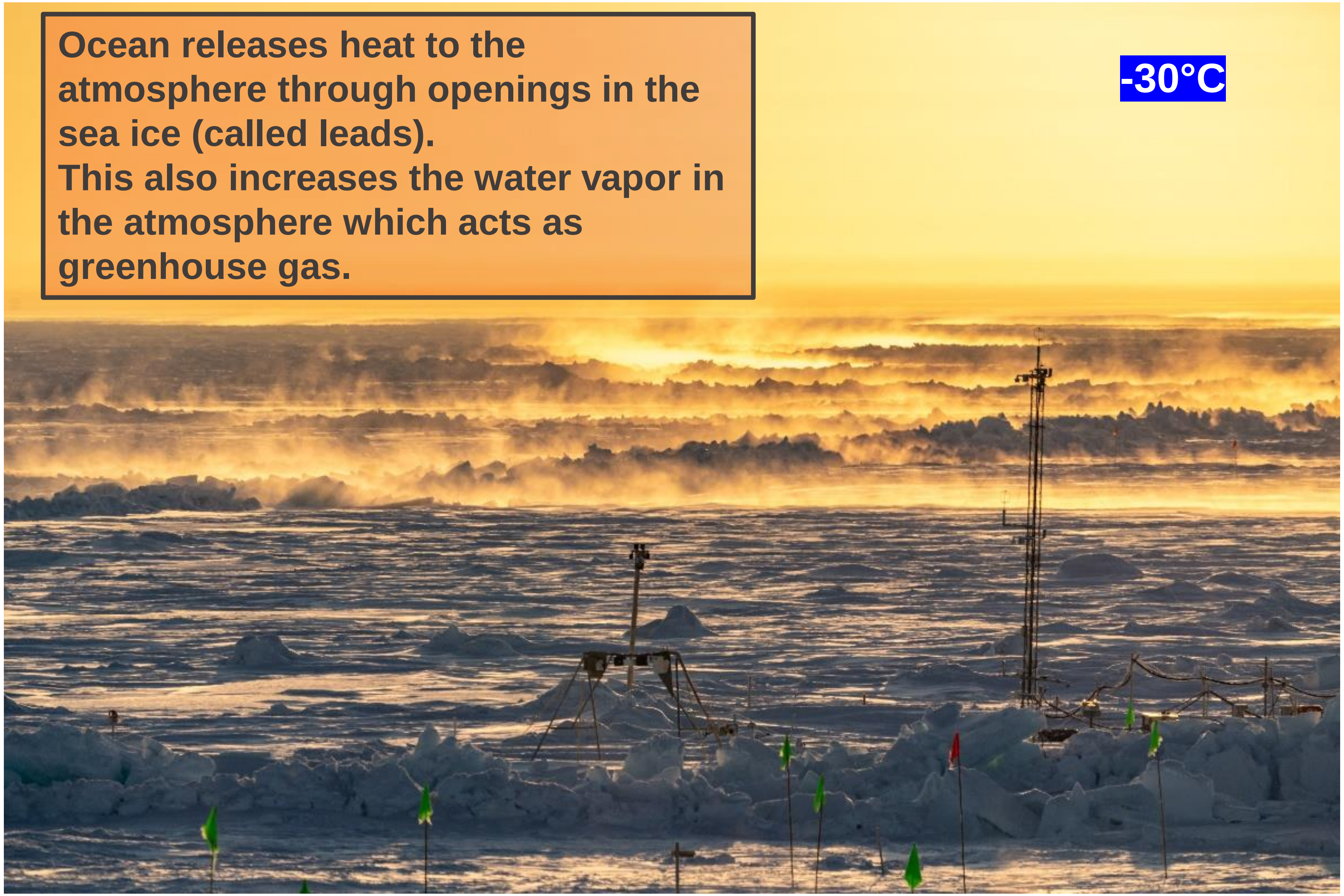


Fig. 2. Snow cover duration anomalies (% difference relative to average number of snow-free days) for the 2021/22 snow year: **(a) snow onset (Aug-Jan); and (b) snow melt (Feb-Jul).** Red (blue) indicates increased (decreased) snow-free days compared to the 1998/99 through 2017/18 mean. The dashed circle marks the latitude 60° N; land north of this defines Arctic land areas considered in this study. Source: NOAA IMS data record.

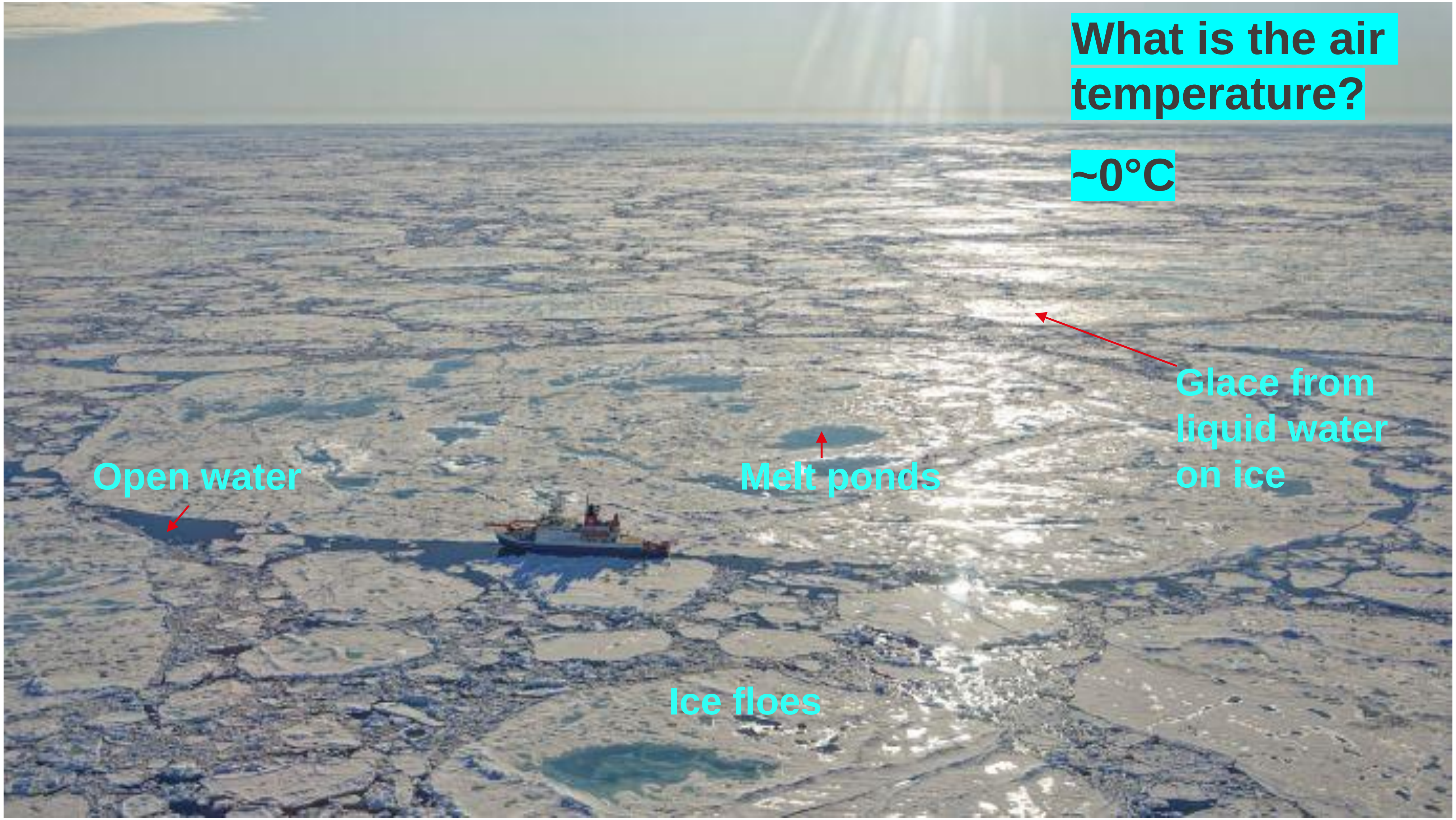
- https://arctic.noaa.gov/report-card/report-card-2022/terrestrial-snow-cover/

2. Ocean effect: winter

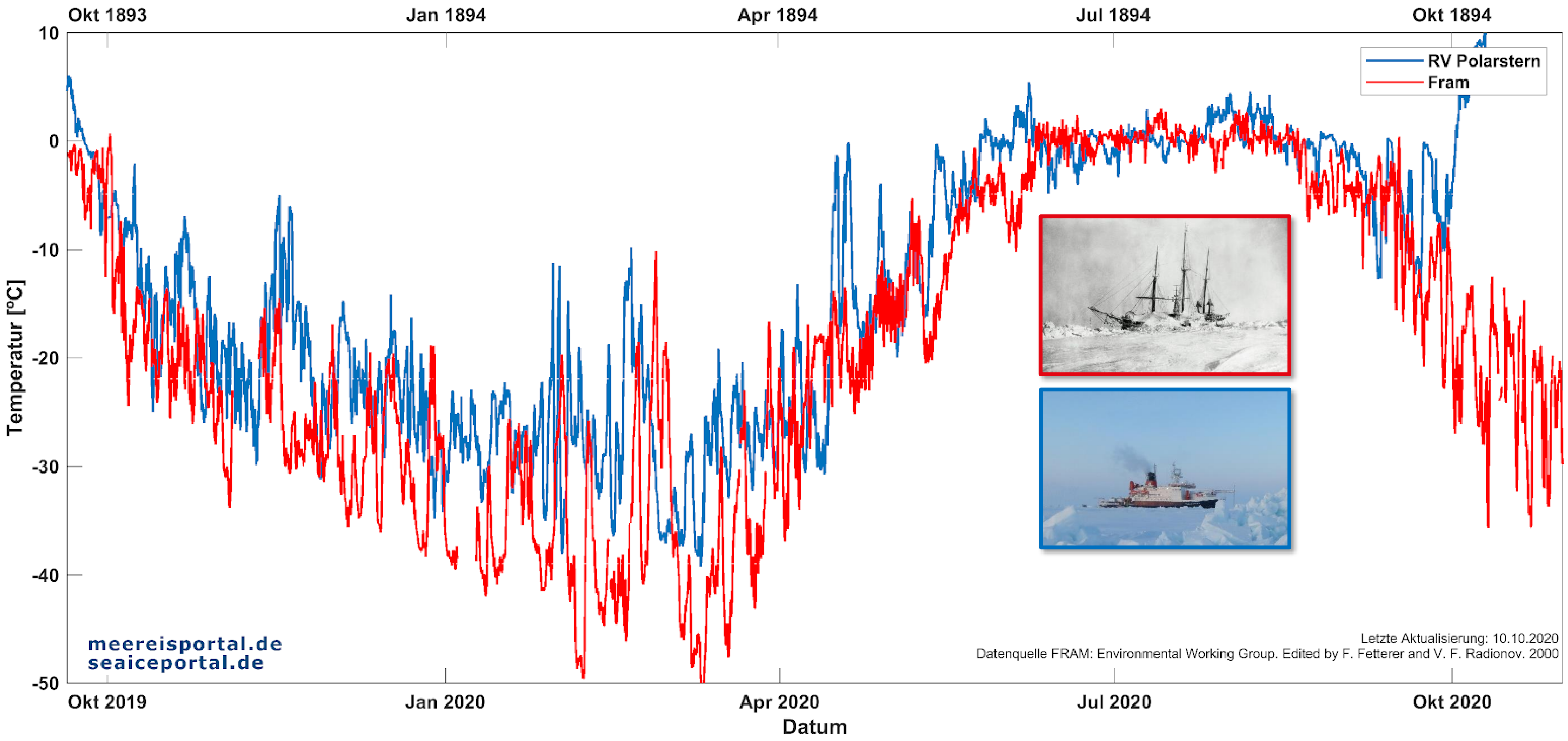


Ocean water -1.6°C

2. Ocean effect: summer



Arctic temperature change: 1893/94 vs 2019/20



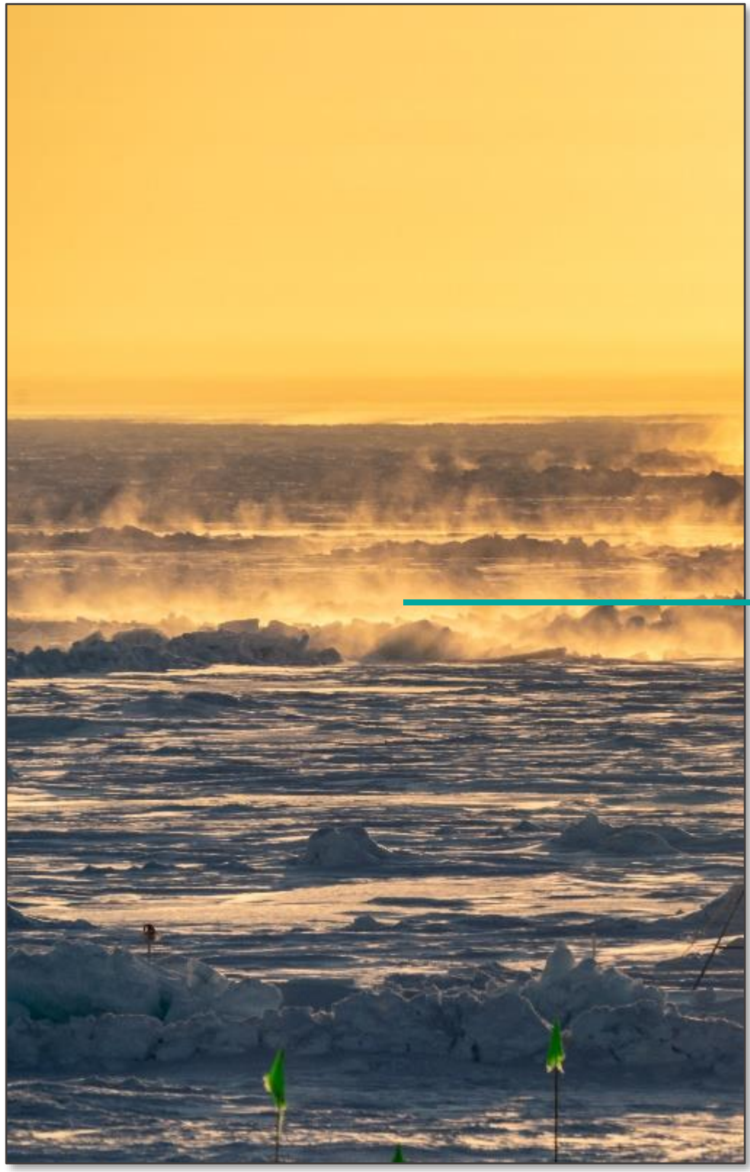
3. Planck effect

- Blackbody radiation
- The different regions of Earth need to compensate for the radiative forcing from GHGs.
- The colder the body the more it must heat:
  - **To equilibrate 1 W m^{-2}**
  - @ 30 °: black body needs to warm by 0.16 °C
  - @ -30 °C: black body needs to warm by 0.31 °C

$$LWR = \varepsilon * \sigma T_e^4$$

LWR longwave radiation
ε = surface emissivity (~1)

4. Lapse rate effect



height

200 m

0 m

-40°C

-10°C

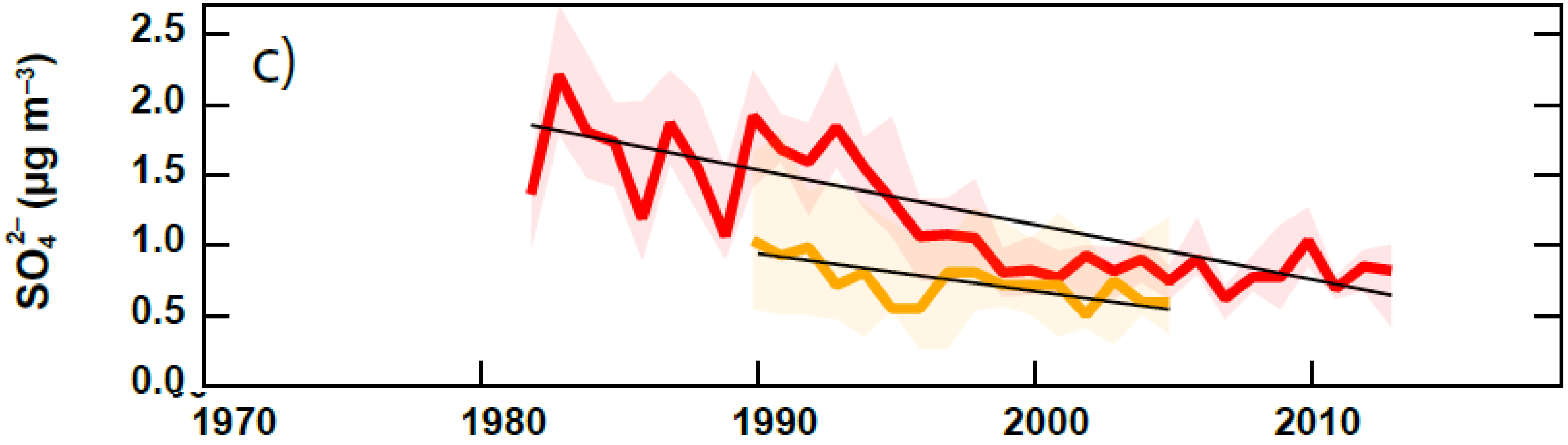
- Temperature increases with height → positive slope
- The lapse rate is defined as the slope

Cold air does not rise
→ Atmosphere is highly stratified
→ Heat is stuck at the surface
→ Surface experiences amplified warming

The lower Arctic atmosphere is unable to transport heat upwards because of positive lapse rates (also called temperature inversions).

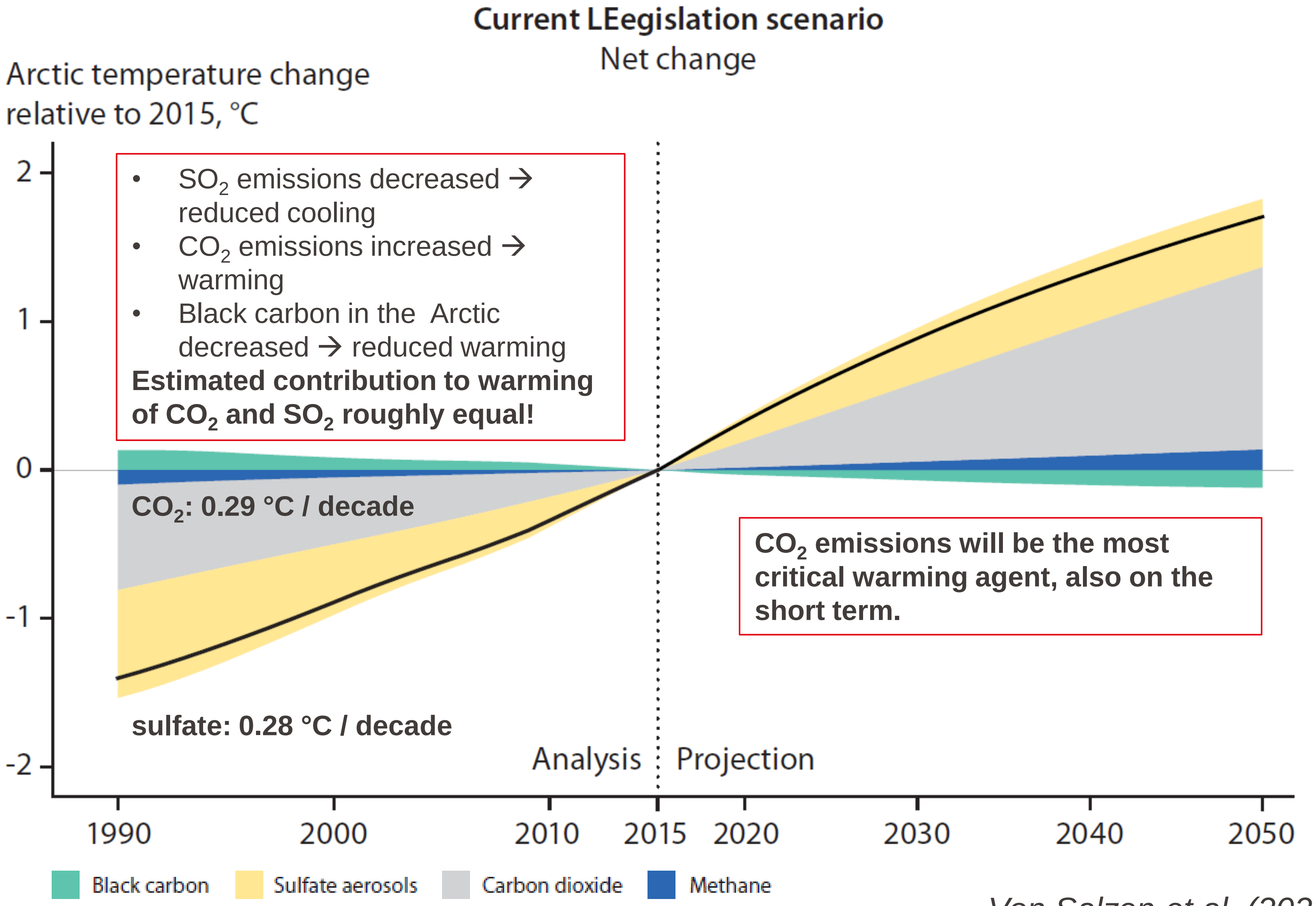
5. Aerosol effect

- Anthropogenic emissions have decreased in the past decades because of cleaner air policies.
- There are less aerosols in the Arctic.



Schmale et al. (2022)

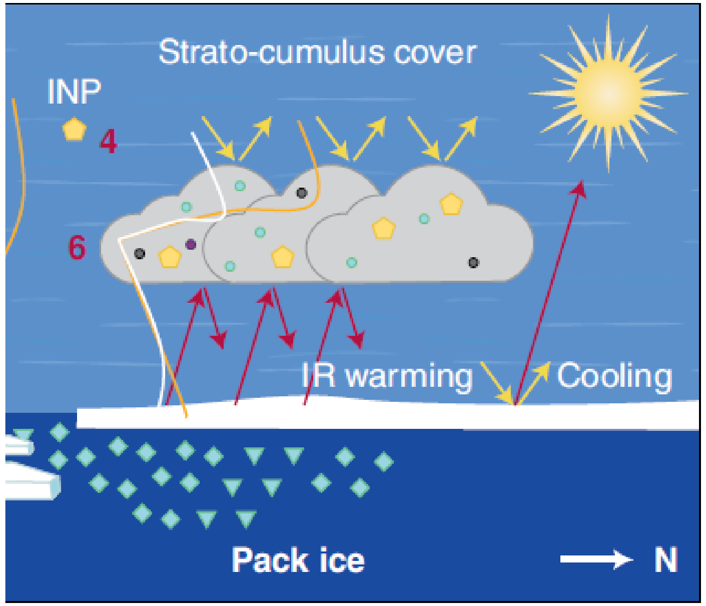
5. Aerosol effect

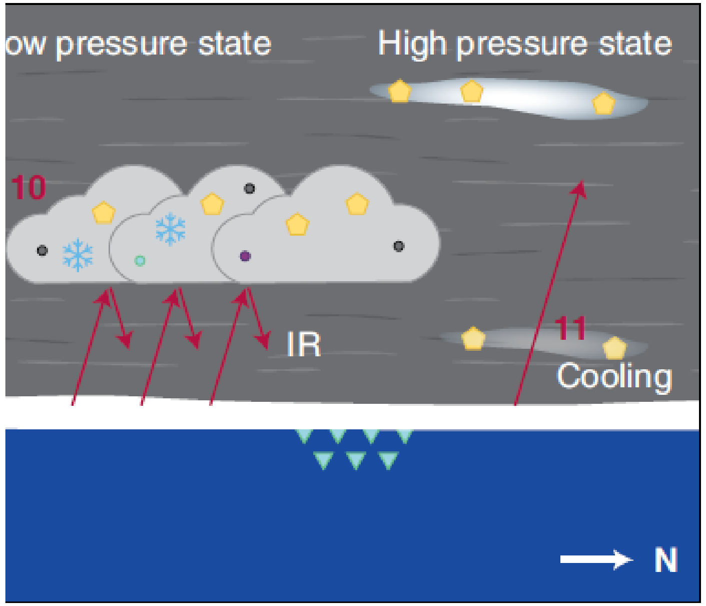


Von Salzen et al. (2022)

5. Cloud effect

- The typical low level clouds in the Arctic act as a blanket. They absorb longwave radiation and re-emit it to the surface.
- The surface warms.
- This effect is opposite to the global cooling effect of low clouds.
- The reason is that the shortwave radiation does not play much of a role. The sea ice under the cloud reflects the solar radiation as much as the cloud, so there is no surface warming and it does not matter whether there is a cloud or not from the shortwave perspective.

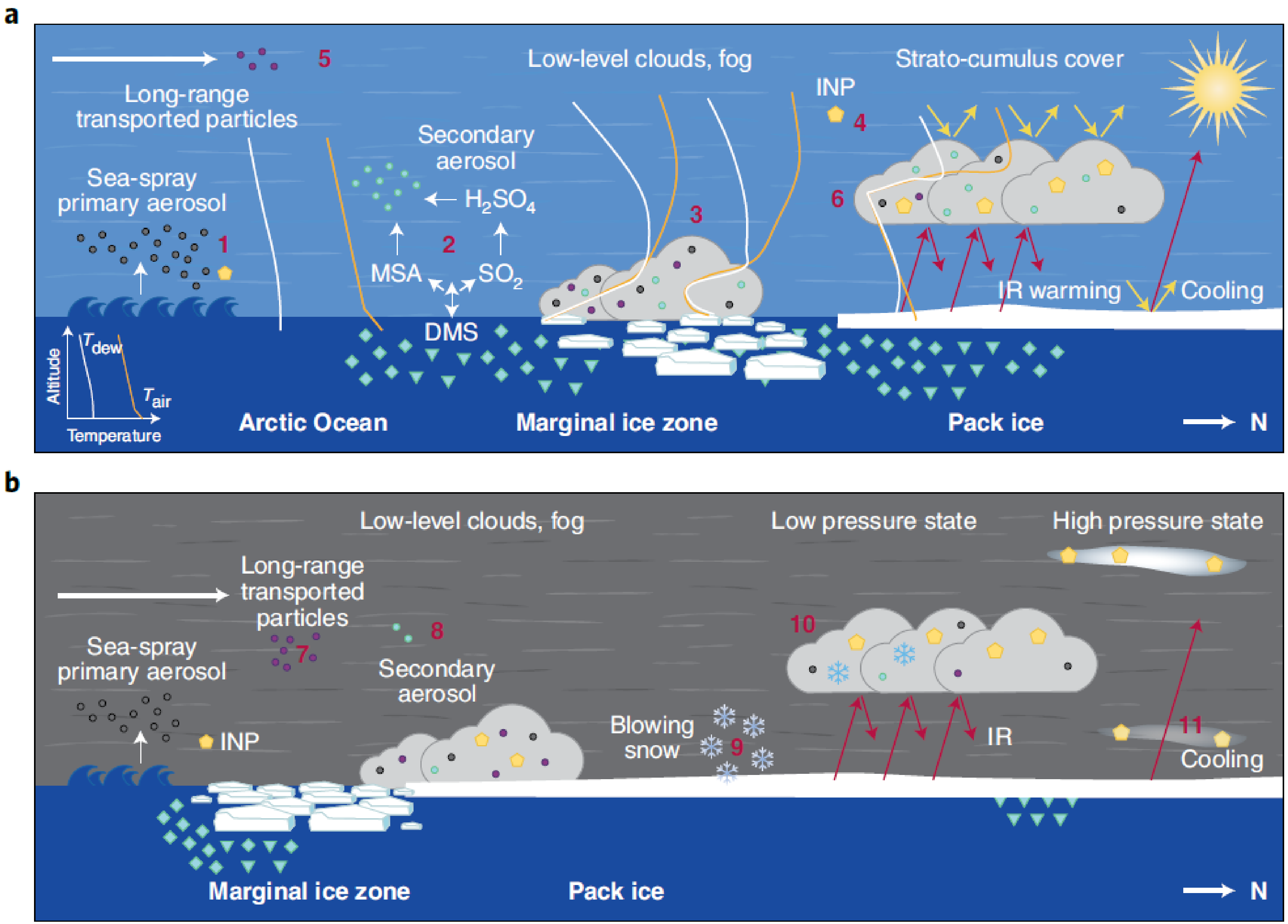




5. More aerosol and cloud effects

EERL

This is what my group typically works on.



- Schmale et al. (2021)

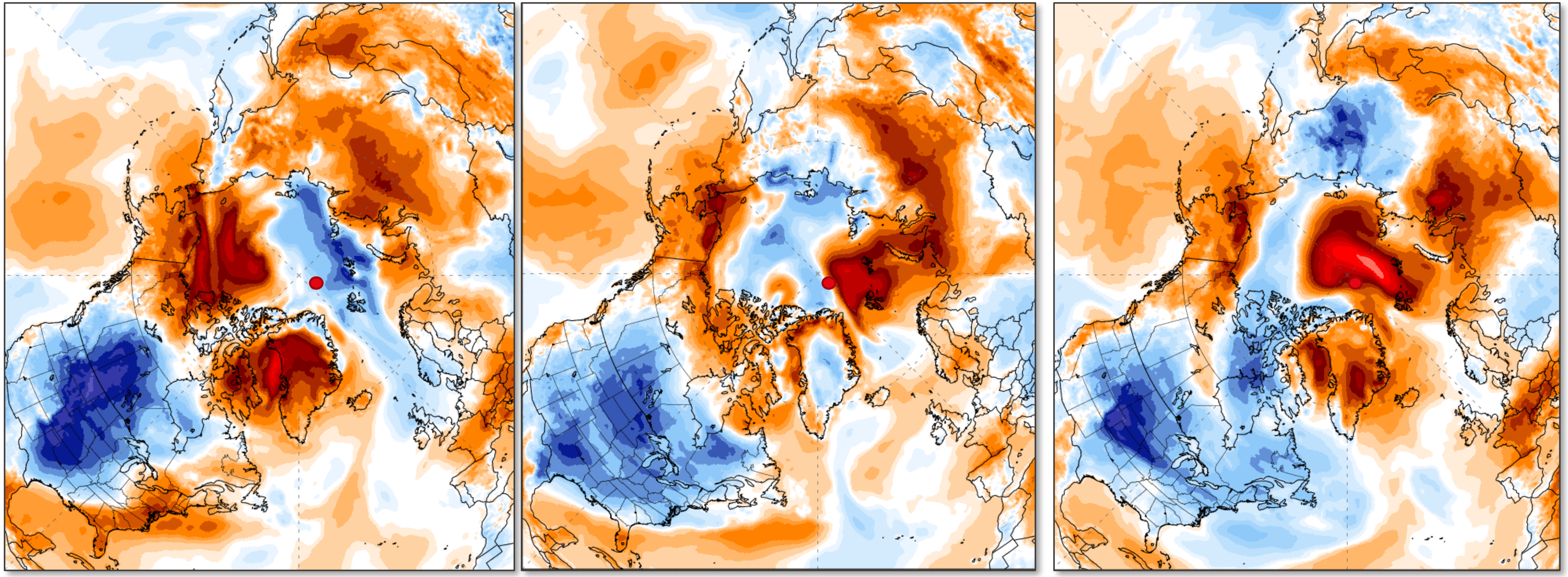
Studying reasons for Arctic Amplification

Credit: Oden Crew

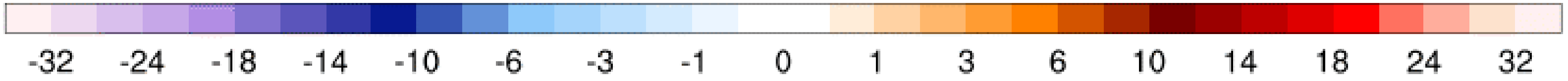
EPFL

6. Atmospheric Transport of heat and moisture

Moist and warm air mass transport from lower latitudes to the Arctic is becoming more frequent and intense.
This has strong impacts on the sea ice melt.

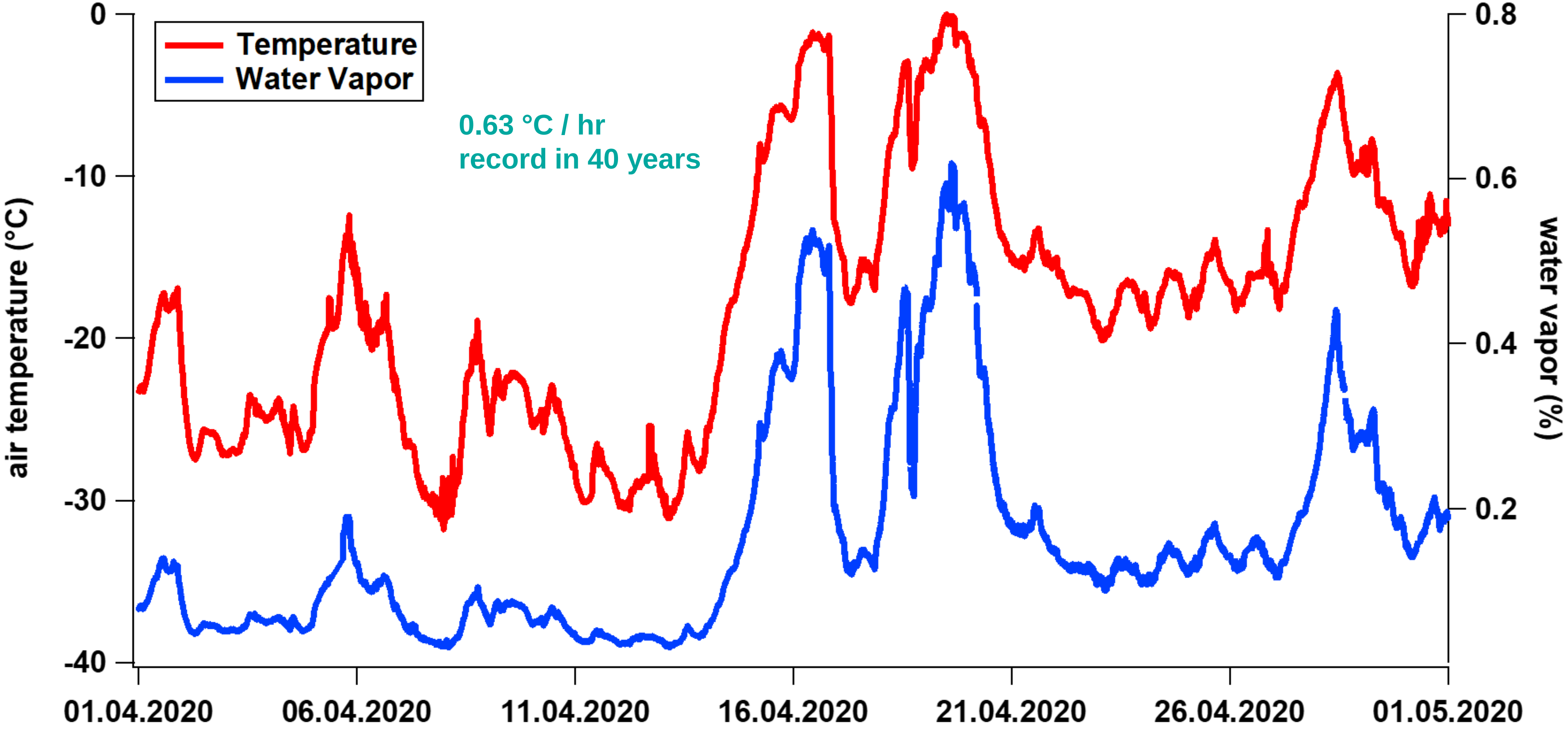


13 April 2020 | 15 April 2020 | 17 April 2020



2 m temperature anomaly (°C)

Warm air mass intrusion



- Dada et al. Nat. Commun., 2022

Warm and moist air mass approaching

Sea ice breaks up with the strong winds

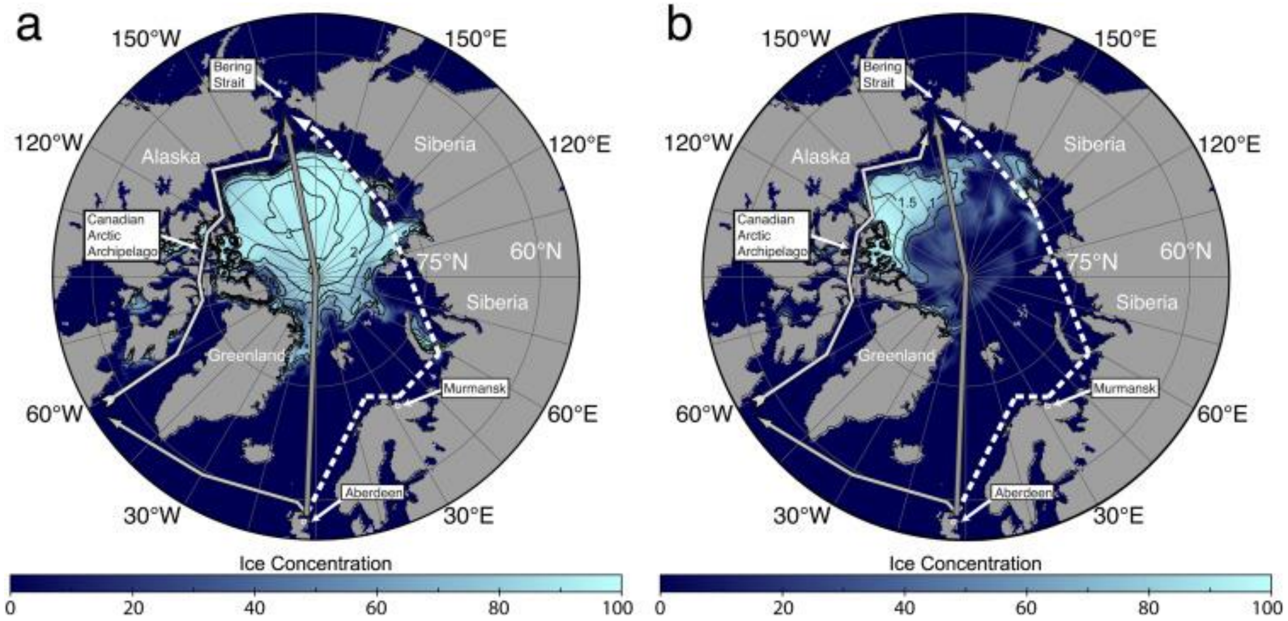
Glare at the surface because of melt (called meltspiegel)

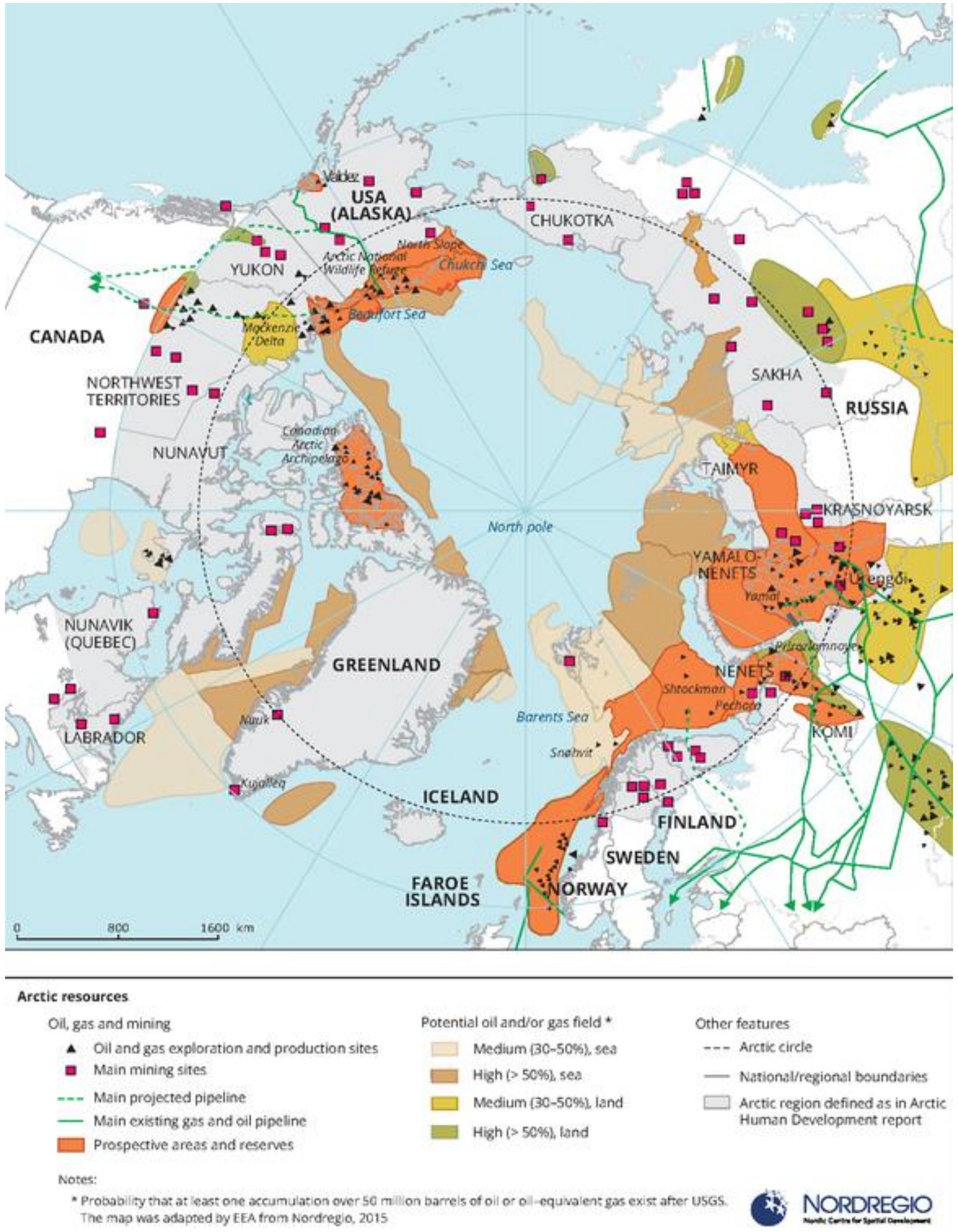
Drifting one year in Arctic sea ice

Implications: shipping and resources

Summer: 2010-2019

Summer: 2030-2039





- 13 % of world's oil, and
- 30 % of world's gas resources may be found in the Arctic

- Aksenov et al. (2017), Gautier et al. (2009)

Why do we care about the Arctic?

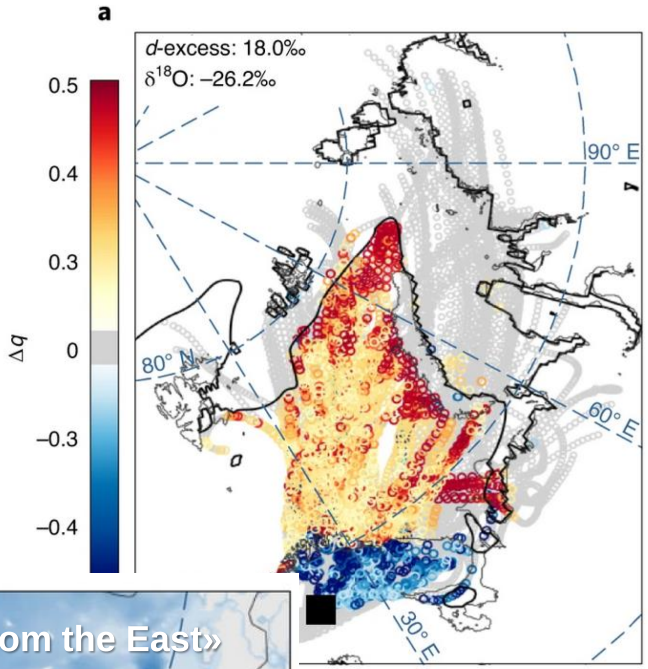
- Snow chaos in Europe
- Sea Level rise
- Release of carbon to the atmosphere
- Fires

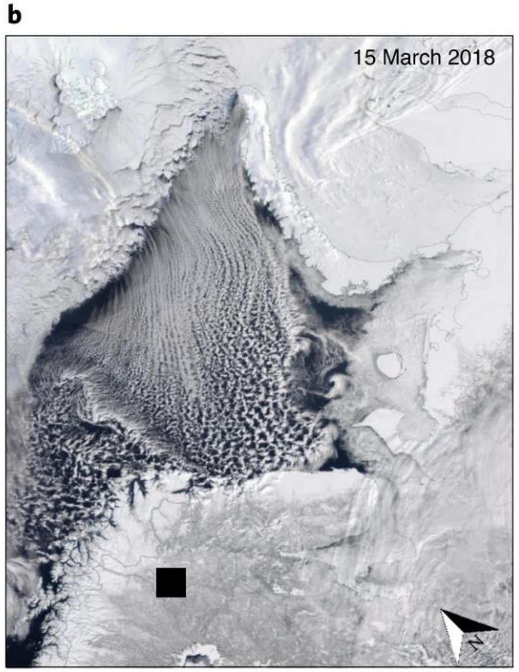
A snow blower clears a road in the village of Goeschenen in the canton of Uri during heavy snowfall. Keystone / Urs Flueeler, https://www.swissinfo.ch/

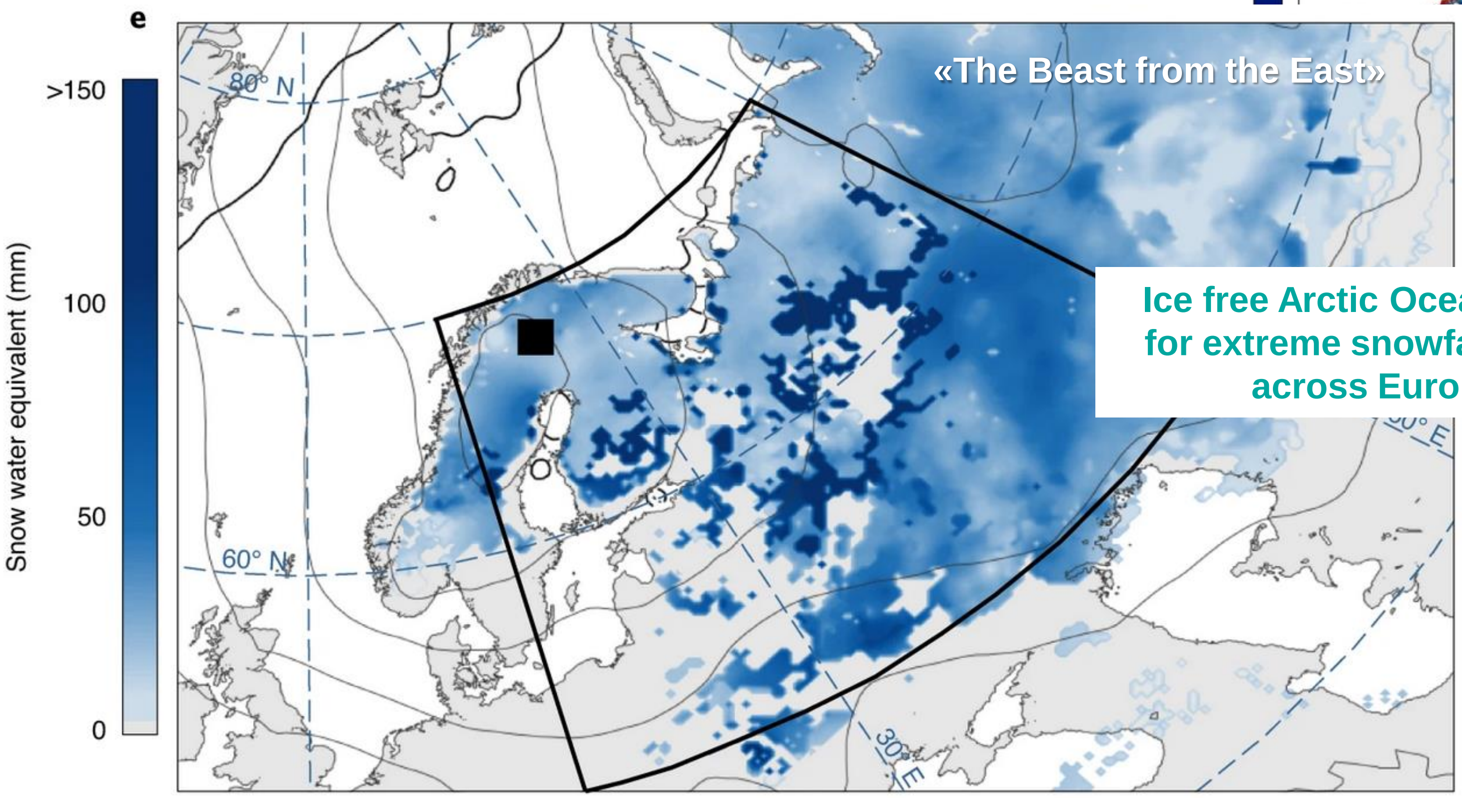
Teleconnections

a. Back-trajectories from Pallas (square) between 19–27 February 2018 and associated mean vapour *d*-excess and $\delta^{18}O$. Colours depict hourly specific humidity changes (Δq), where a positive (negative) Δq indicates a moisture increase (decrease) due to evaporation (precipitation). Grey circles indicate either no net moisture change or a change above the ABL. **b**. cloud scene, **c**. evaporation

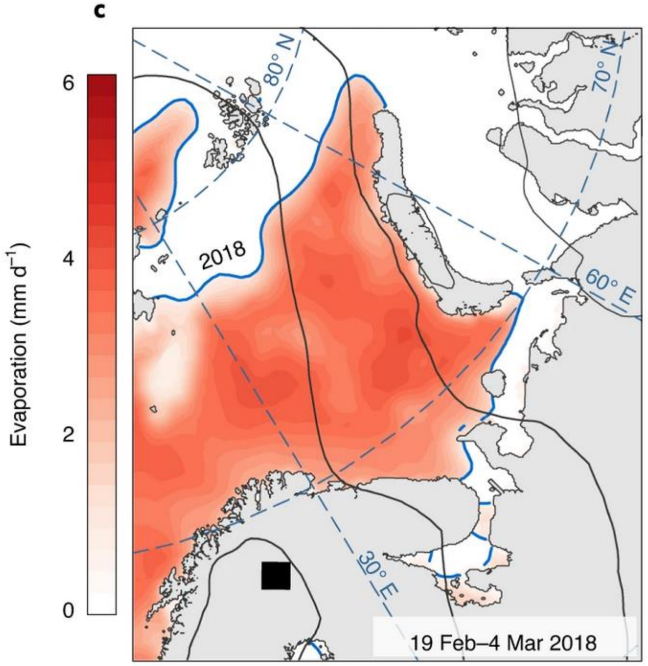
e, Northern Europe (15–60° E to 50–70° N) snow mass increase during 19 Feb – 4 Mar 2018







Ice free Arctic Ocean allows for extreme snowfall events across Europe.



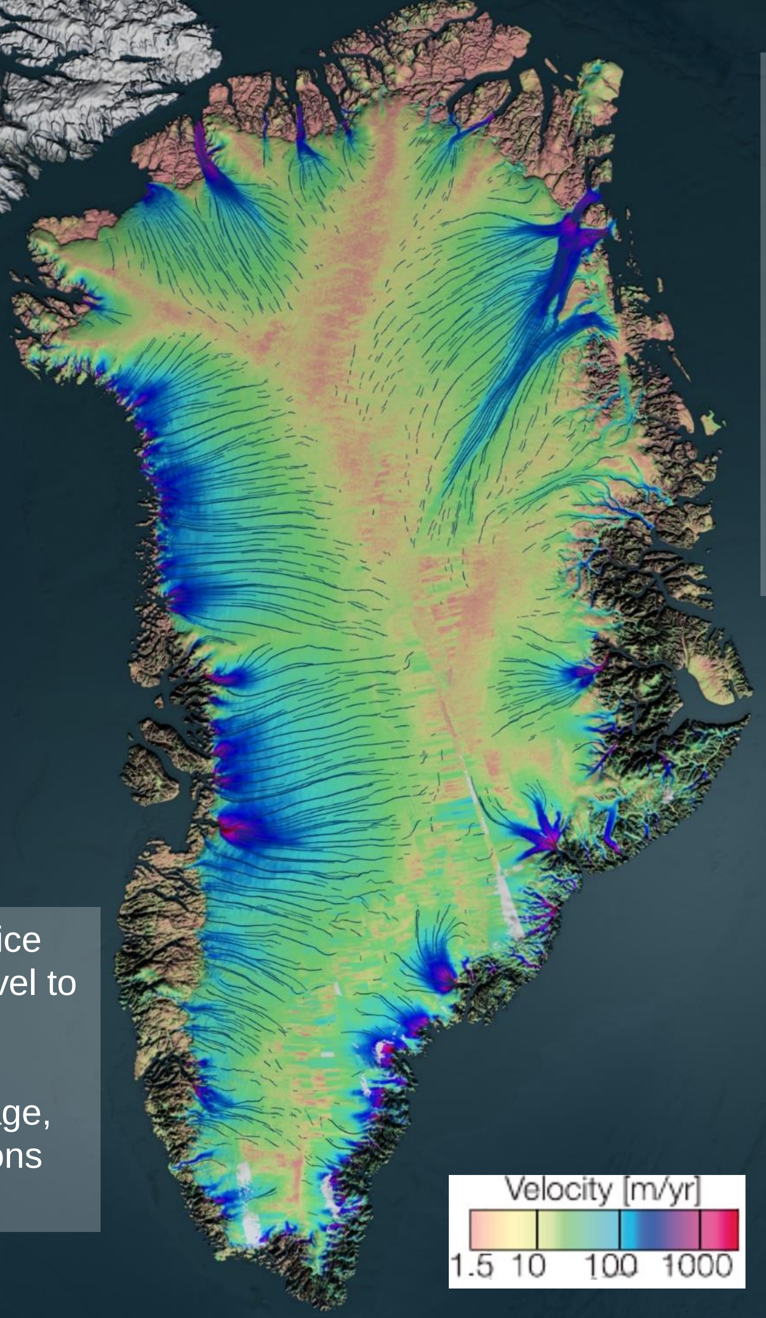
Bailey et al. Nat. Geoscience, 2021, https://www.nature.com/articles/s41561-021-00719-y

Greenland

Many contributions to mass loss:

- variations in snow accumulation
- meltwater runoff
- supraglacial lake formation and drainage
- ocean-driven melting
- iceberg calving
- glacier terminus retreat
- submarine melting
- ice flow

Roughly 50 % contribution from surface melt and glacier dynamics.

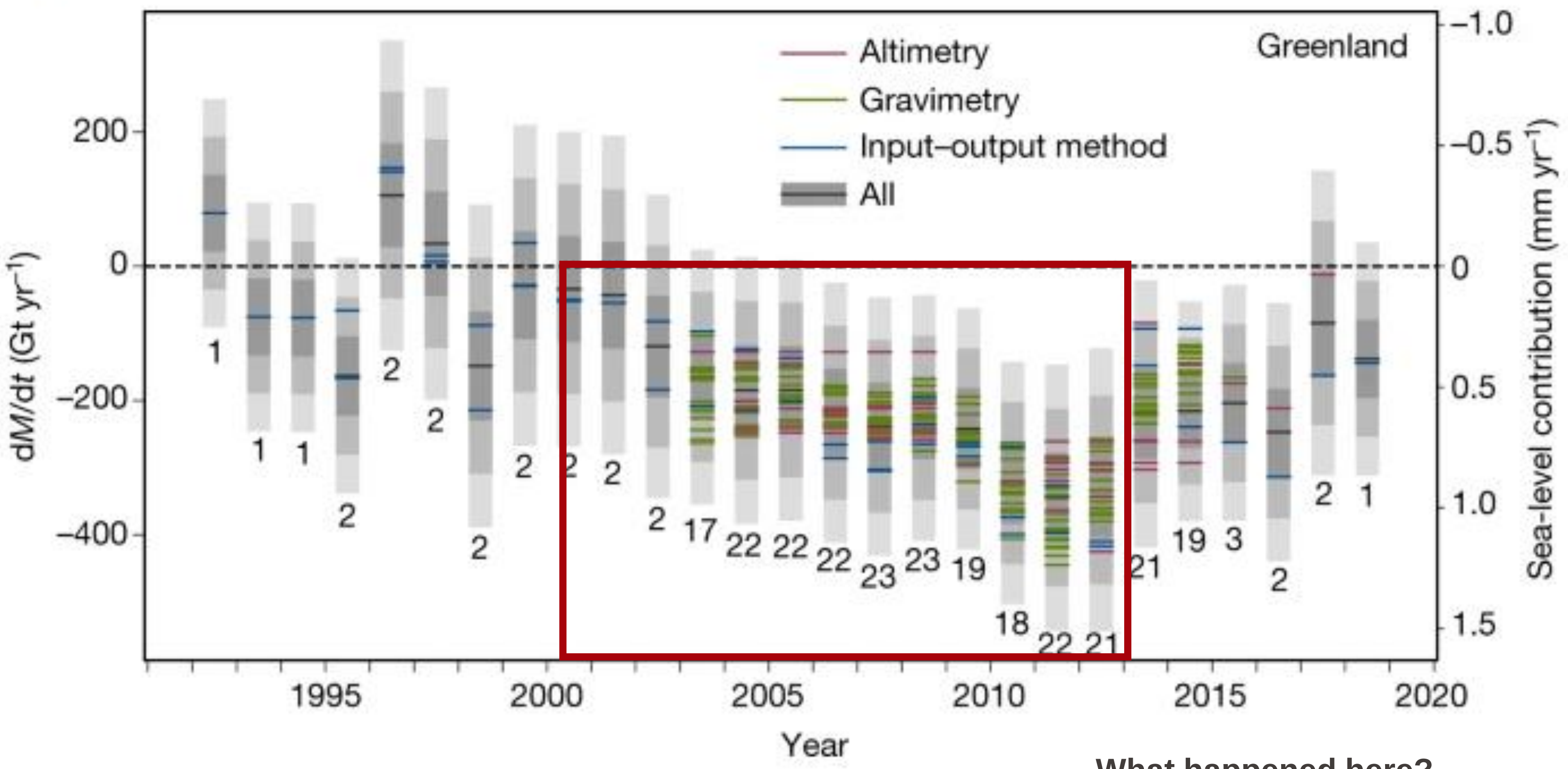


- In all, Greenland lost 3,902 ± 342 billion tonnes of ice between 1992 and 2018, causing the mean sea level to rise by 10.8 ± 0.9 millimetres.
- The total rate of ice loss slowed to 222 ± 30 billion tonnes per year between 2013 and 2017, on average, as atmospheric circulation favoured cooler conditions and ocean temperatures fell.

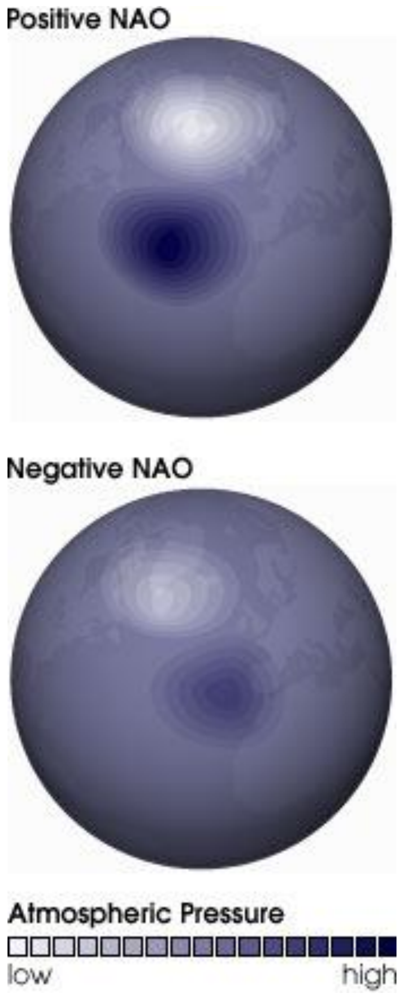
https://svs.gsfc.nasa.gov/3962

Greenland

Fig. 2: Greenland Ice Sheet mass balance.



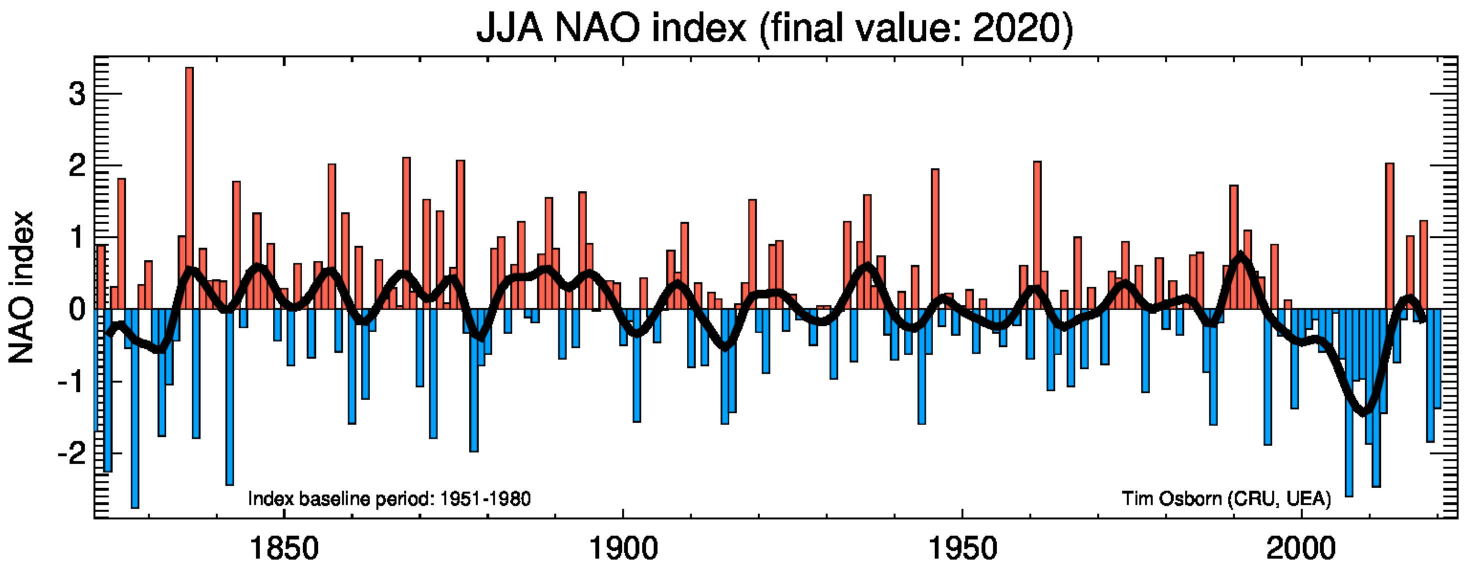
What happened here?



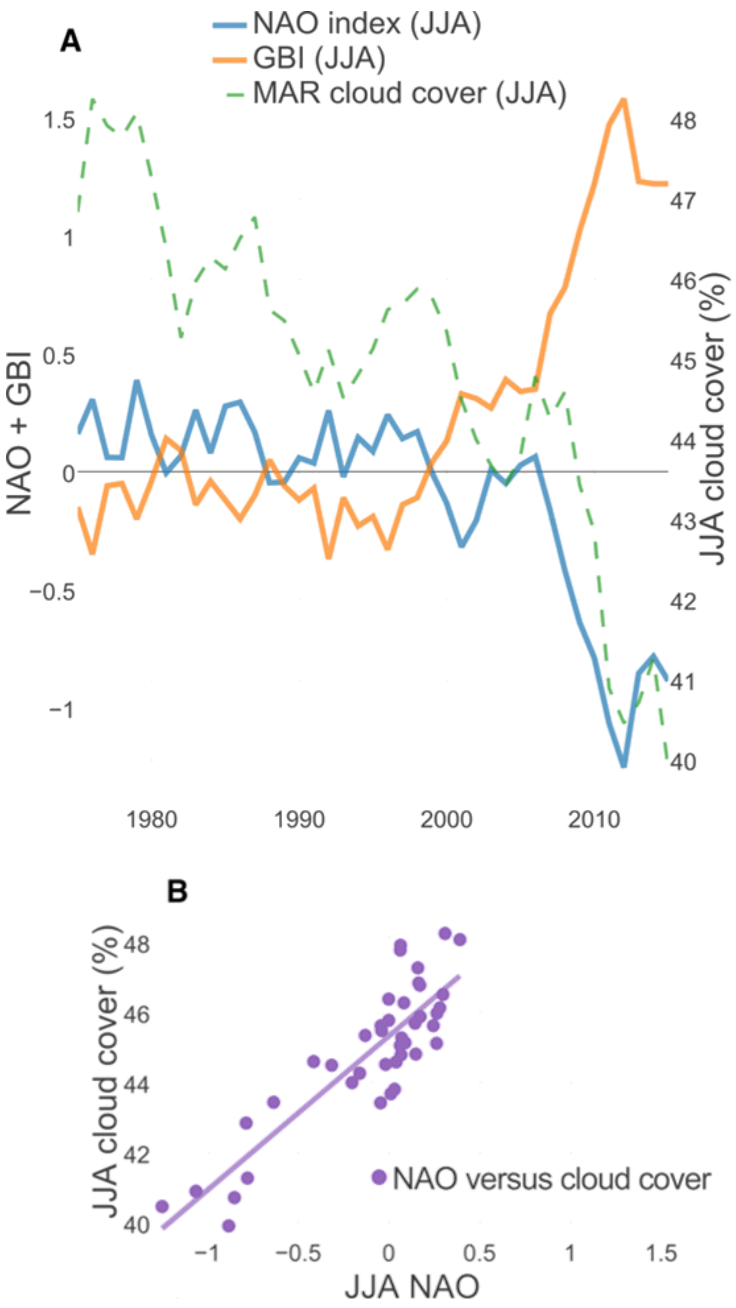
Oscillation between pressures states of the Icelandic Low and Azores High. Their state influences the location and strength of the jet stream.

- IMBIE Team, Nature, 2019, https://www.nature.com/articles/s41586-019-1855-2

Greenland



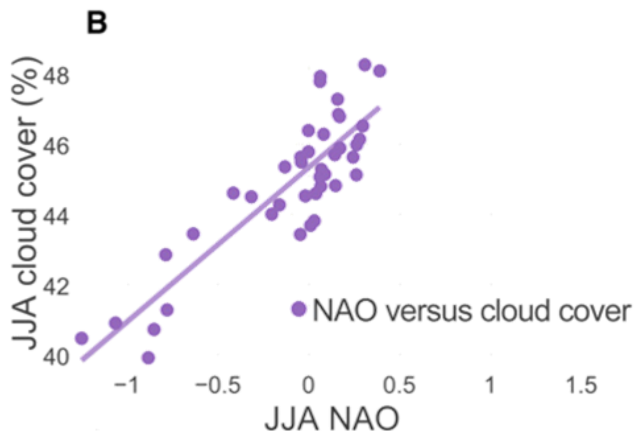
https://crudata.uea.ac.uk/cru/data/nao/viz.htm



- Hofer et al., Sci. Advances, 2017, https://advances.sciencemag.org/content/3/6/e1700584

NAO: North Atlantic Oscillation
GBI: Greenland Blocking Index

What is the mechanism that has led to more melt?

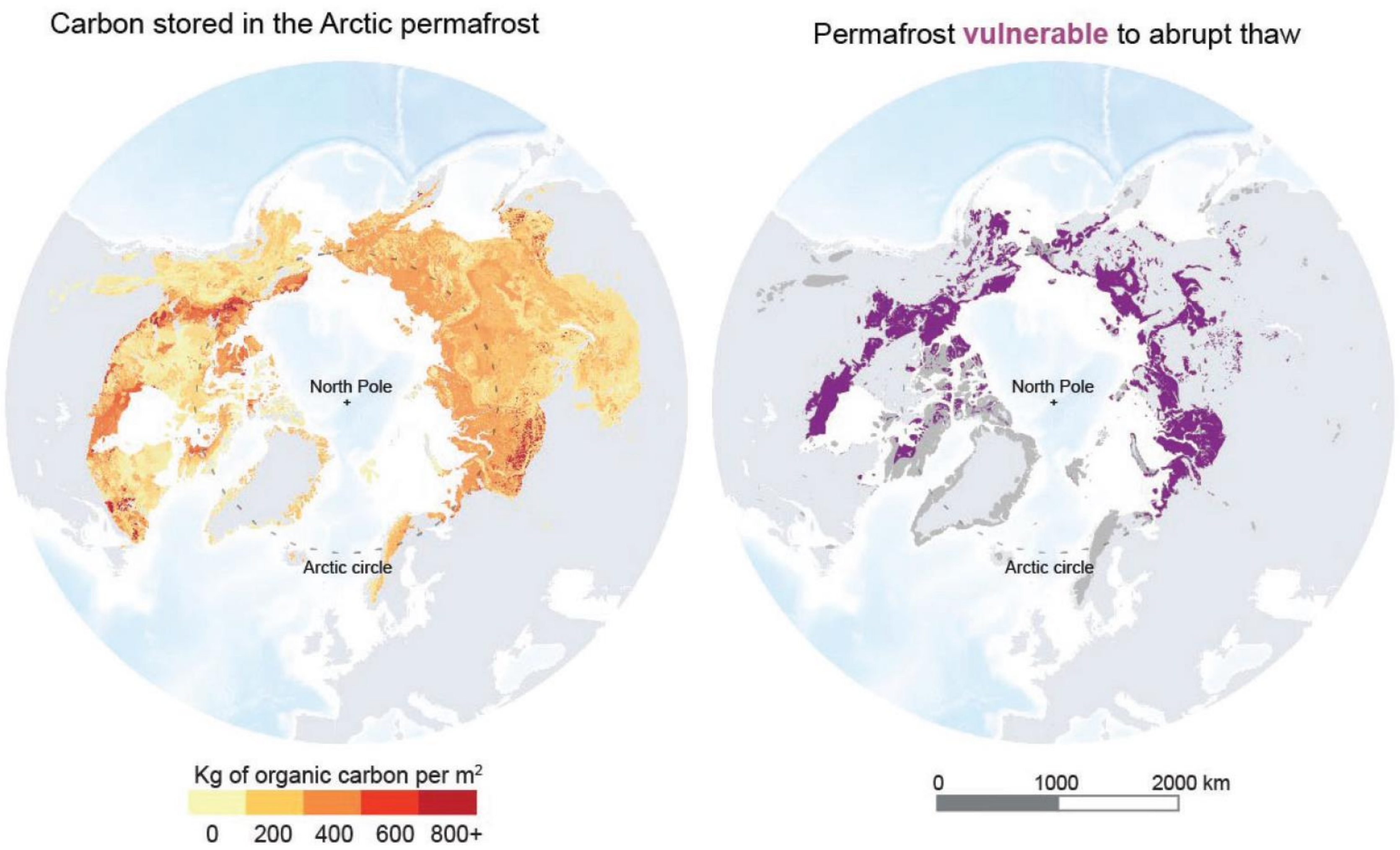


A. A negative NAO index means more clouds, so more longwave radiation heating.

B. A negative NAO index means less clouds, so there is less precipitation and therefore more melt.

C. A negative NAO index means less clouds and therefore more shortwave radiation on the ice sheet that leads to melting.

Arctic permafrost carbon

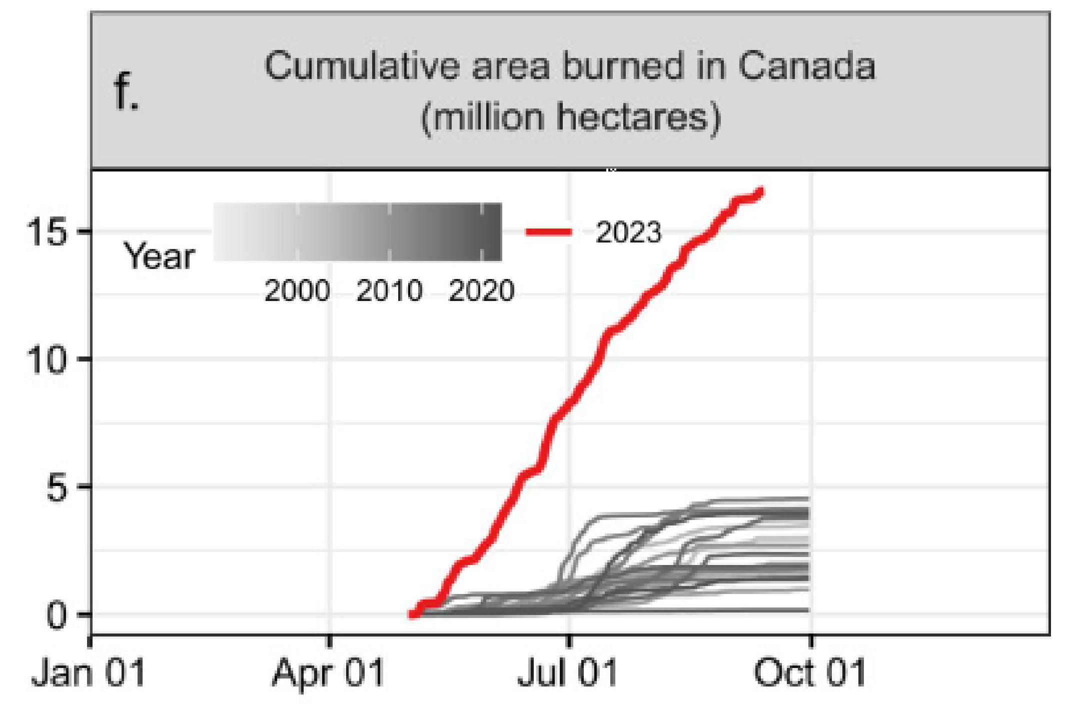


- Arctic permafrost stores 2 x the atmospheric carbon budget.
- Projections from models of permafrost ecosystems suggest that future permafrost thaw will lead to some additional warming – enough to be important, but not enough to lead to a ‘runaway warming’ situation, where permafrost thaw leads to a dramatic, self-reinforcing acceleration of global warming.
- CO_2 and **CH_4** will be released, equivalent to 14–175 Gt of carbon dioxide released per 1°C of global warming. (2020 human CO_2 emissions budget ~34 Gt)

- IPCC AR6, FAQ 5.2

More and more intense forest fires in the boreal belt

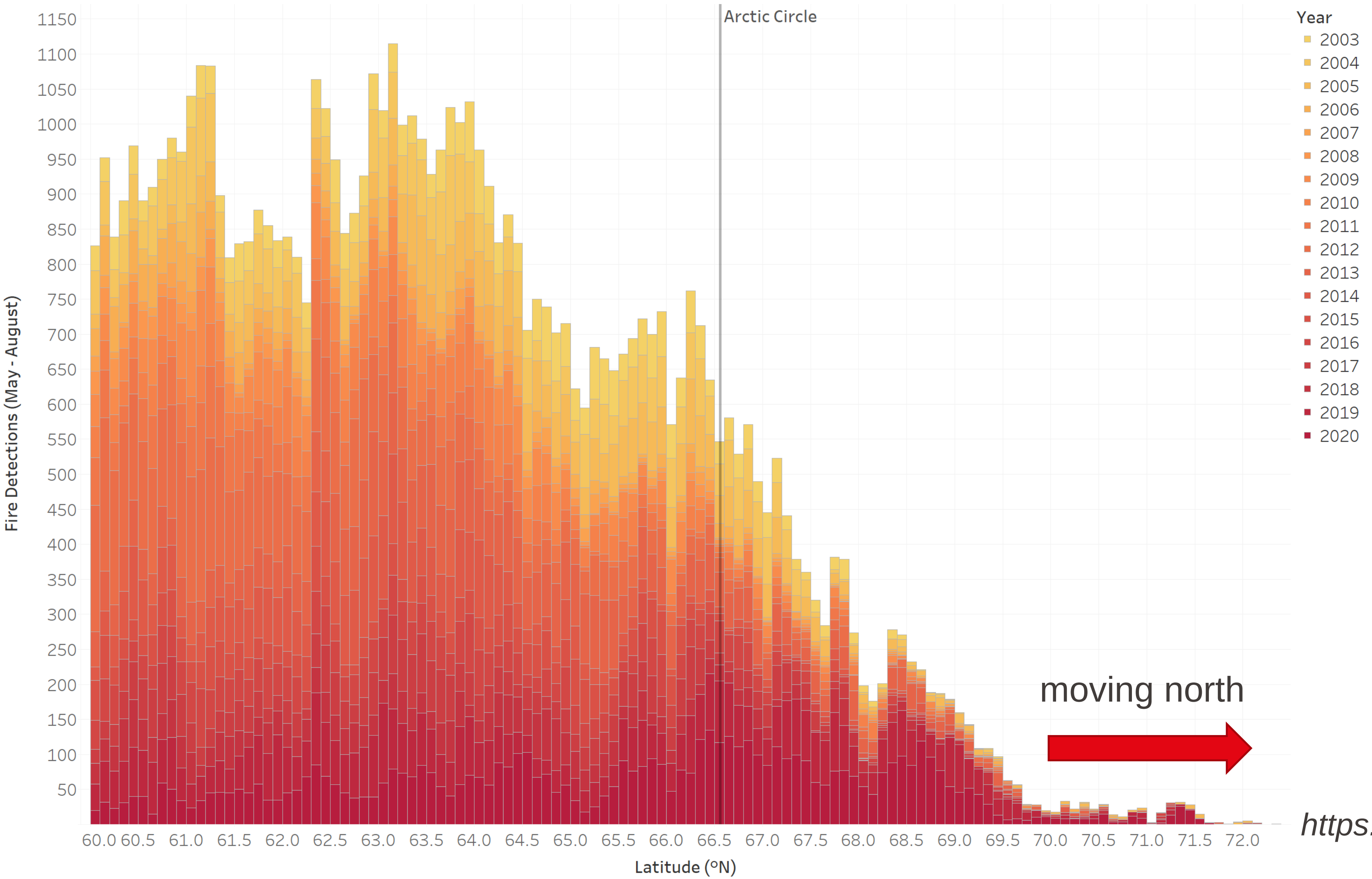
Not a tipping point, but importnat and not projected



- 17 Million hectares burned
  (area CH: 4.1 Million hectares)
- 390 Mtons of C emitted
  (CH: 10 Mt y^{-1})
- Note:
  - Also permafrost thaw contributes to carbon release.
  - Both fires and thaw are difficult to quantify.

Ripple et al. 2023

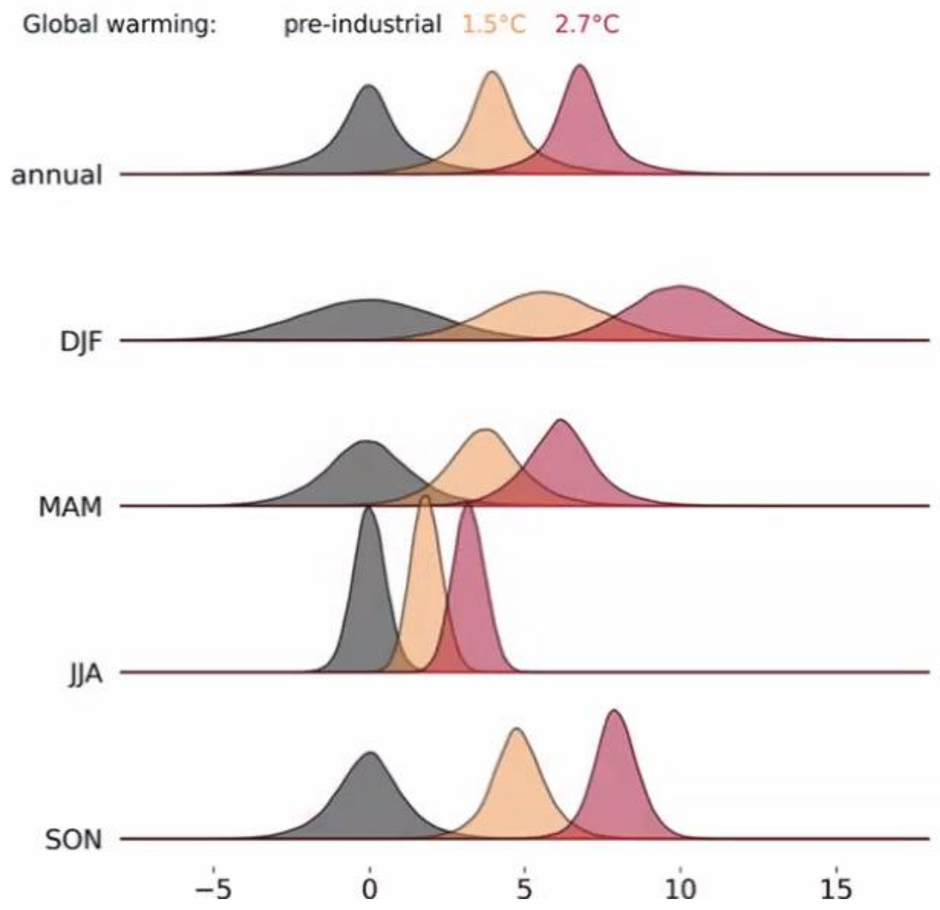
Arctic Fires



https://twitter.com/DrTELS

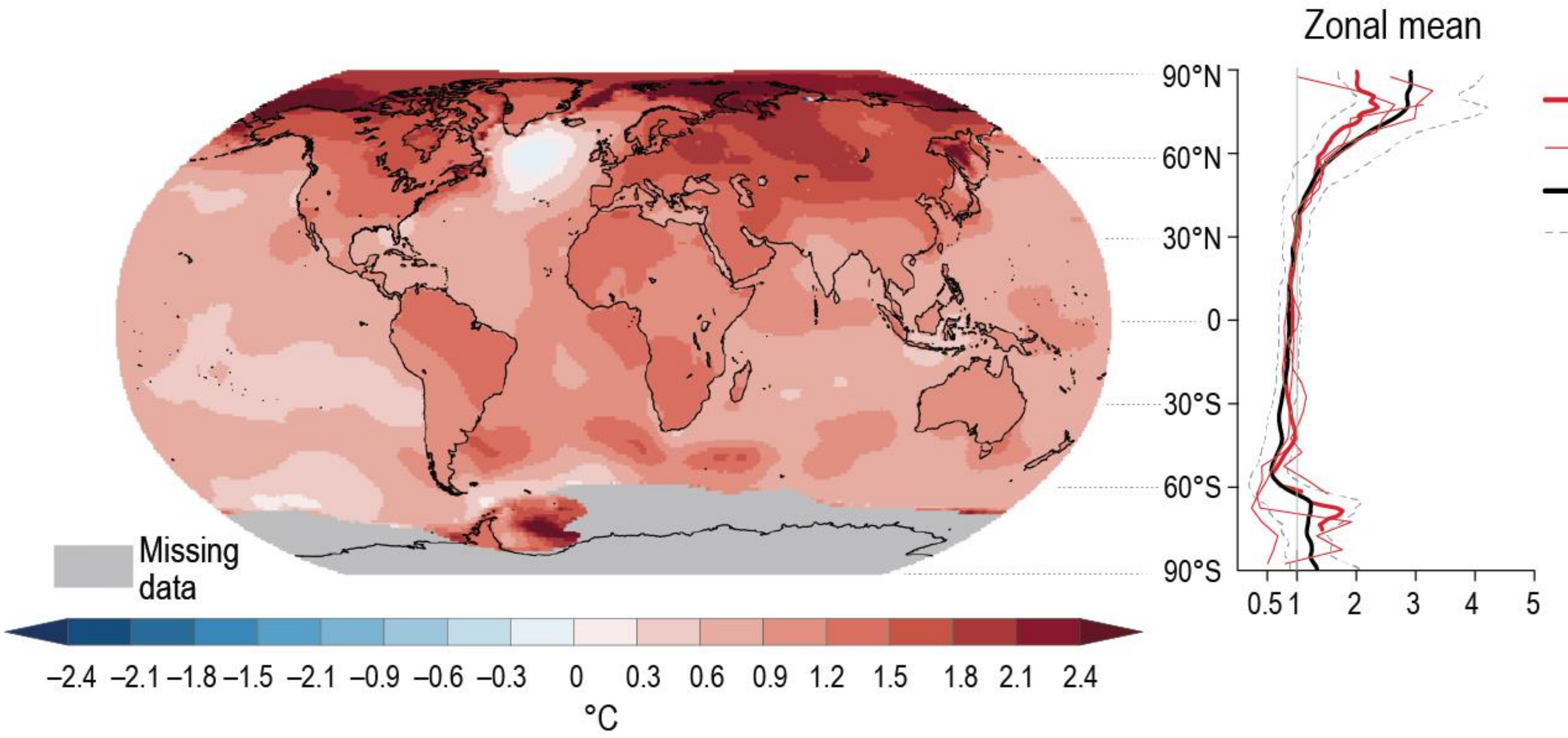
Arctic Future warming

What Does the Future Hold? - Arctic



- In a 1.5°C warmer world, Arctic air temperatures exceed levels considered "extremely warm" under pre-industrial conditions on more than 80% of all days.
- If the world reaches 2.7°C, every day of the year will have Arctic temperatures exceeding the temperature extremes under pre-industrial conditions, with expected average warming in winter exceeding 10°C

Difference between the Arctic and Antarctic

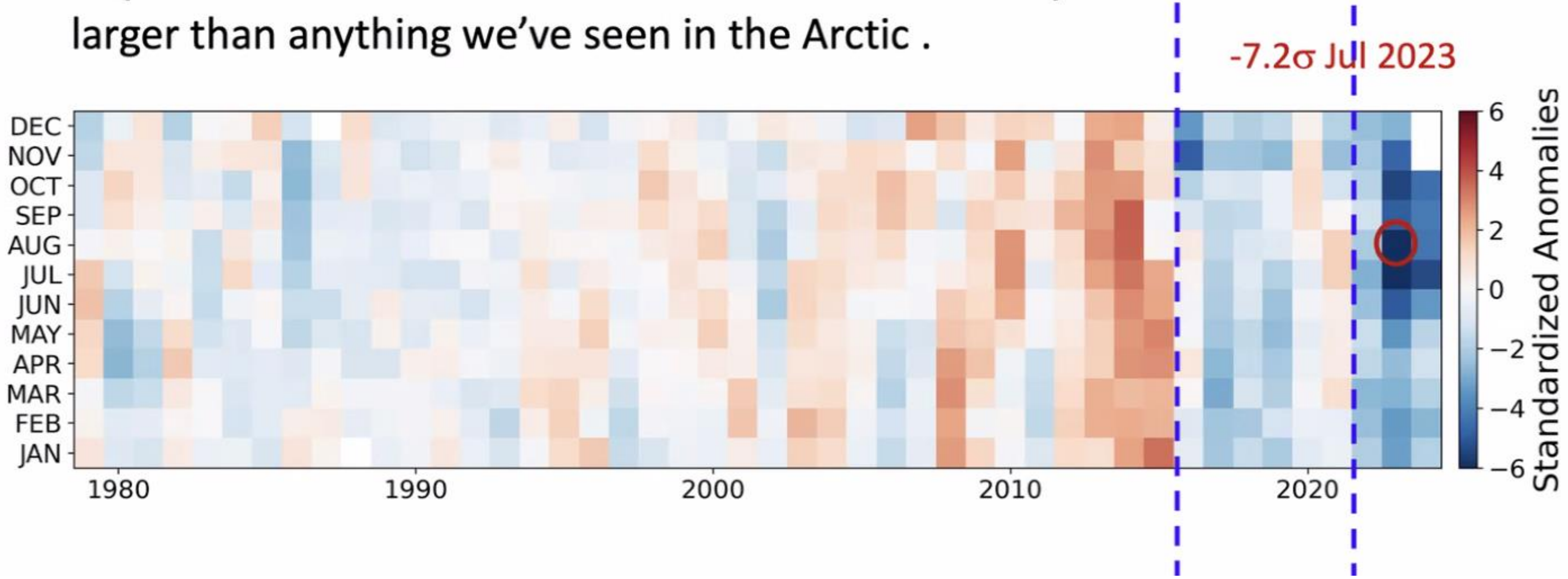


- Difference between the Arctic and Antarctic:
  - The Southern Ocean takes up a lot of excessive warming (bigger buffer).
  - Due to circulation patterns there is less poleward heat transport to the Antarctic, whereas this mechanism is very important in the Arctic.

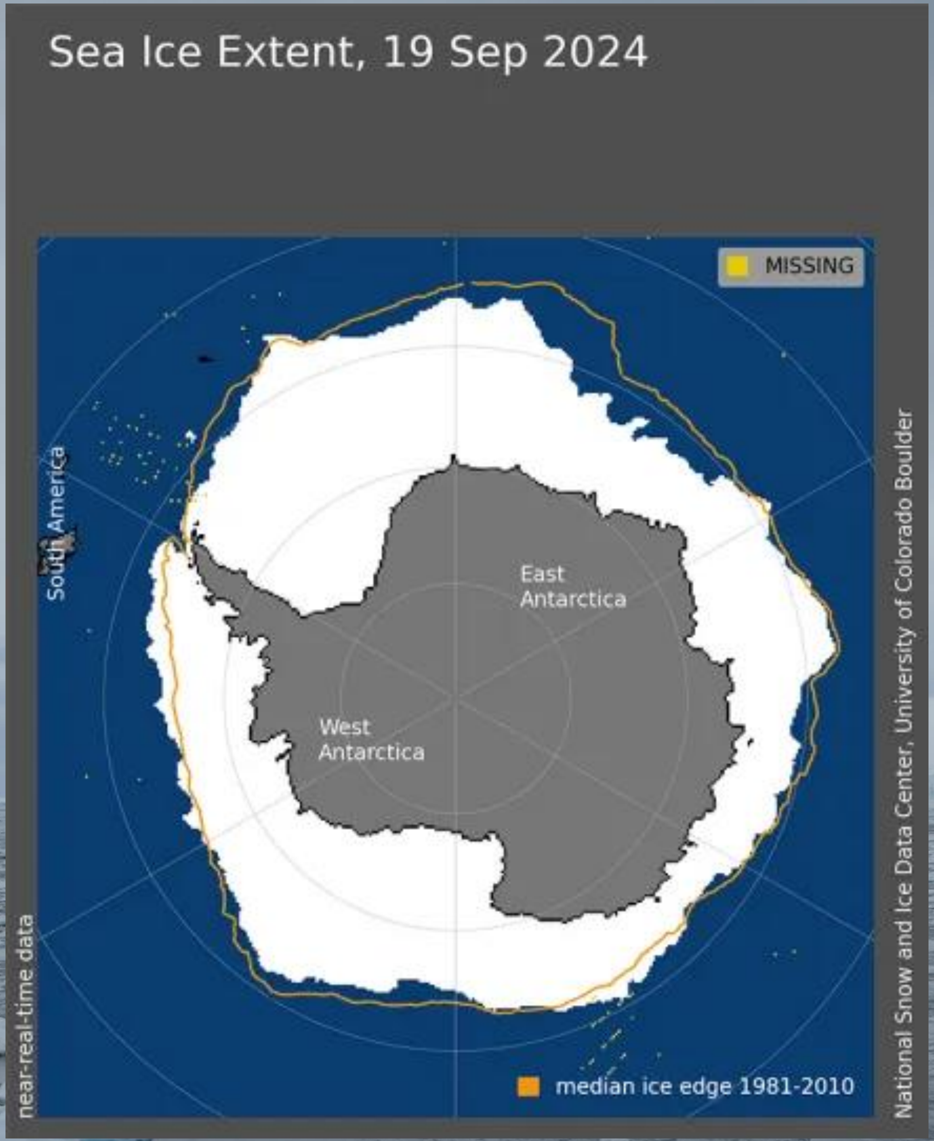
Antarctic sea ice state

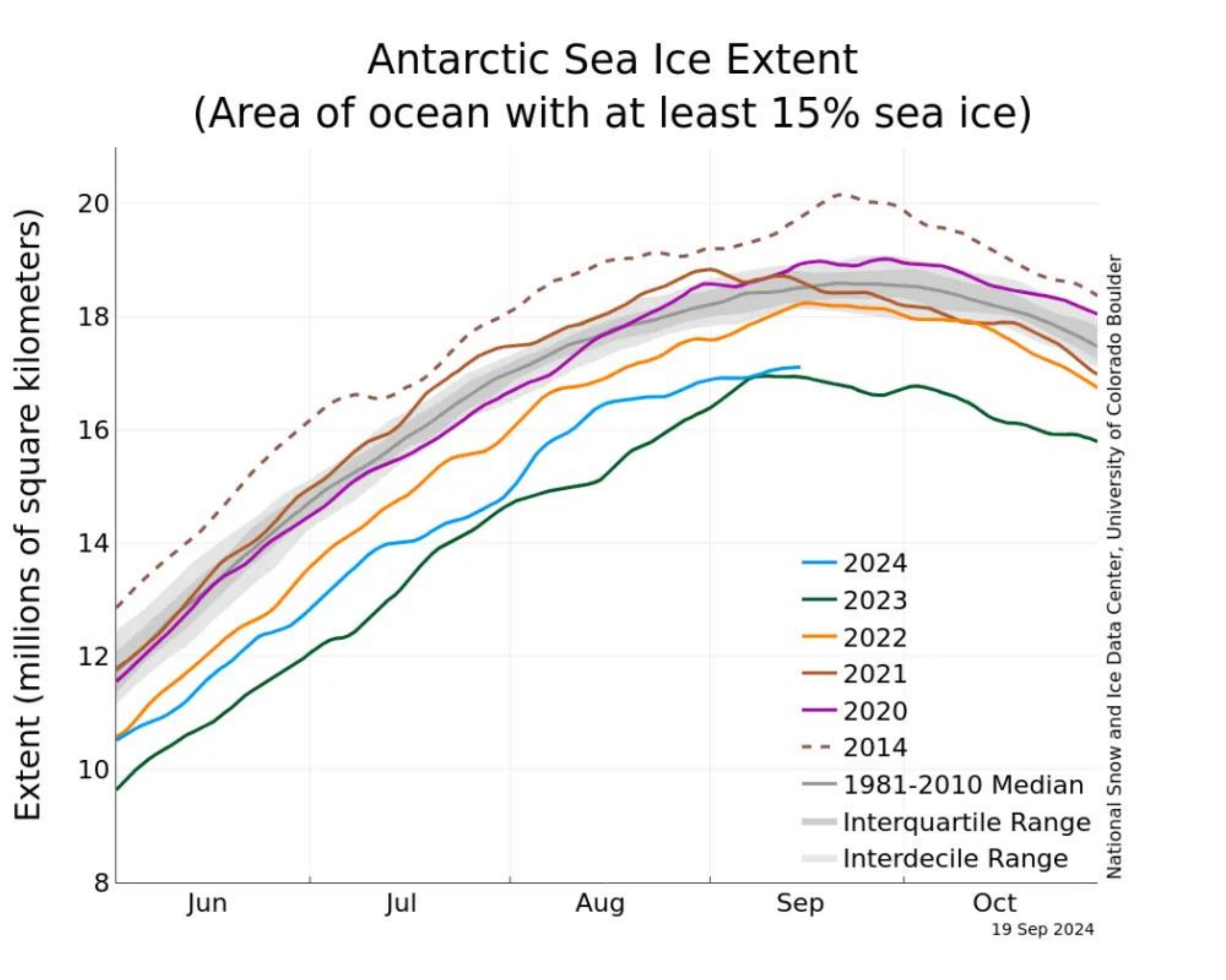
Antarctic Sea Ice – New Climate State?

- Departures from 1981-2010 in 2023 are considerably larger than anything we've seen in the Arctic .



Current Antarctic sea ice shrinkage

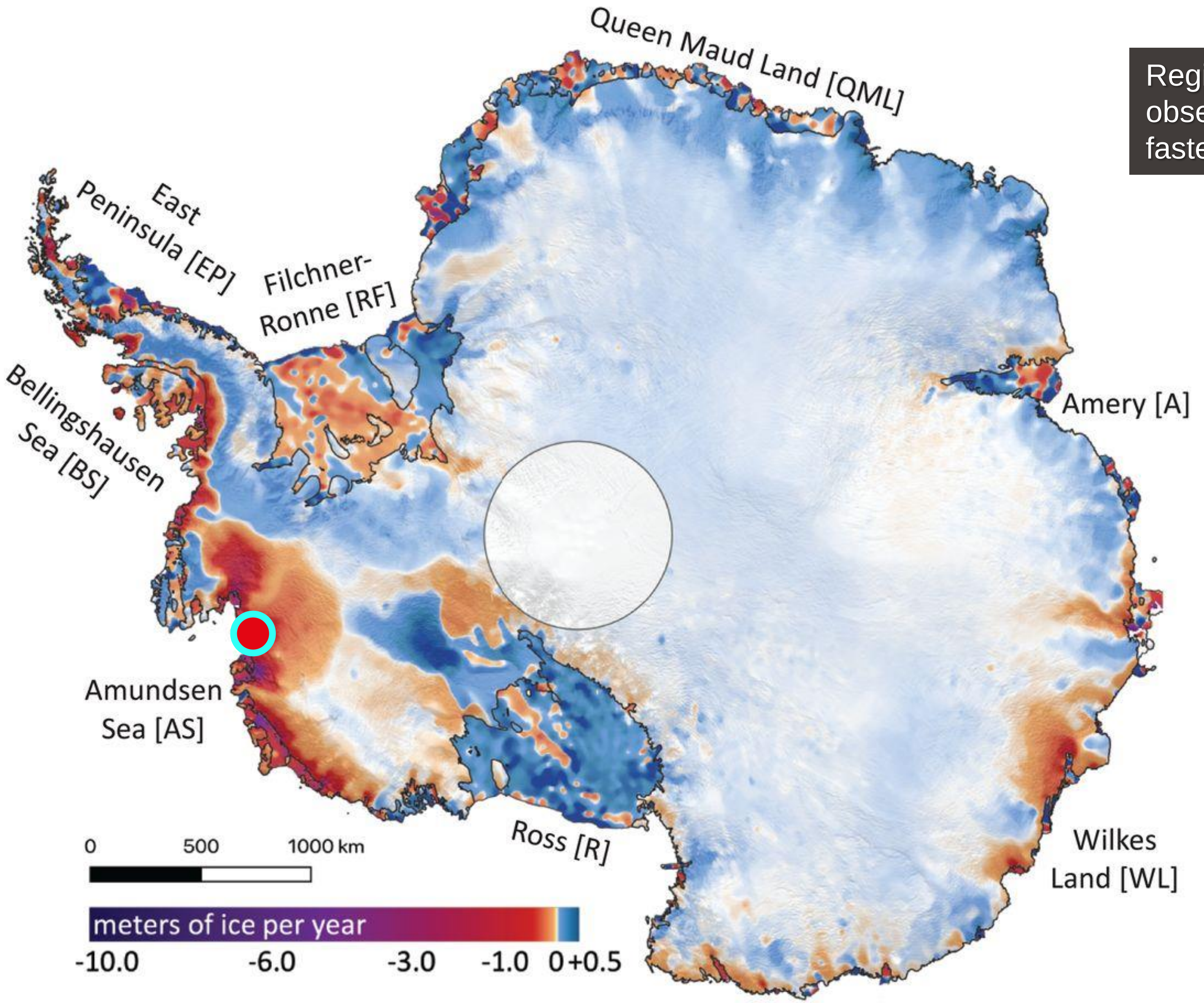




Credit: J. Schmale

NSDIC.org

Land ice melt in Antarctica

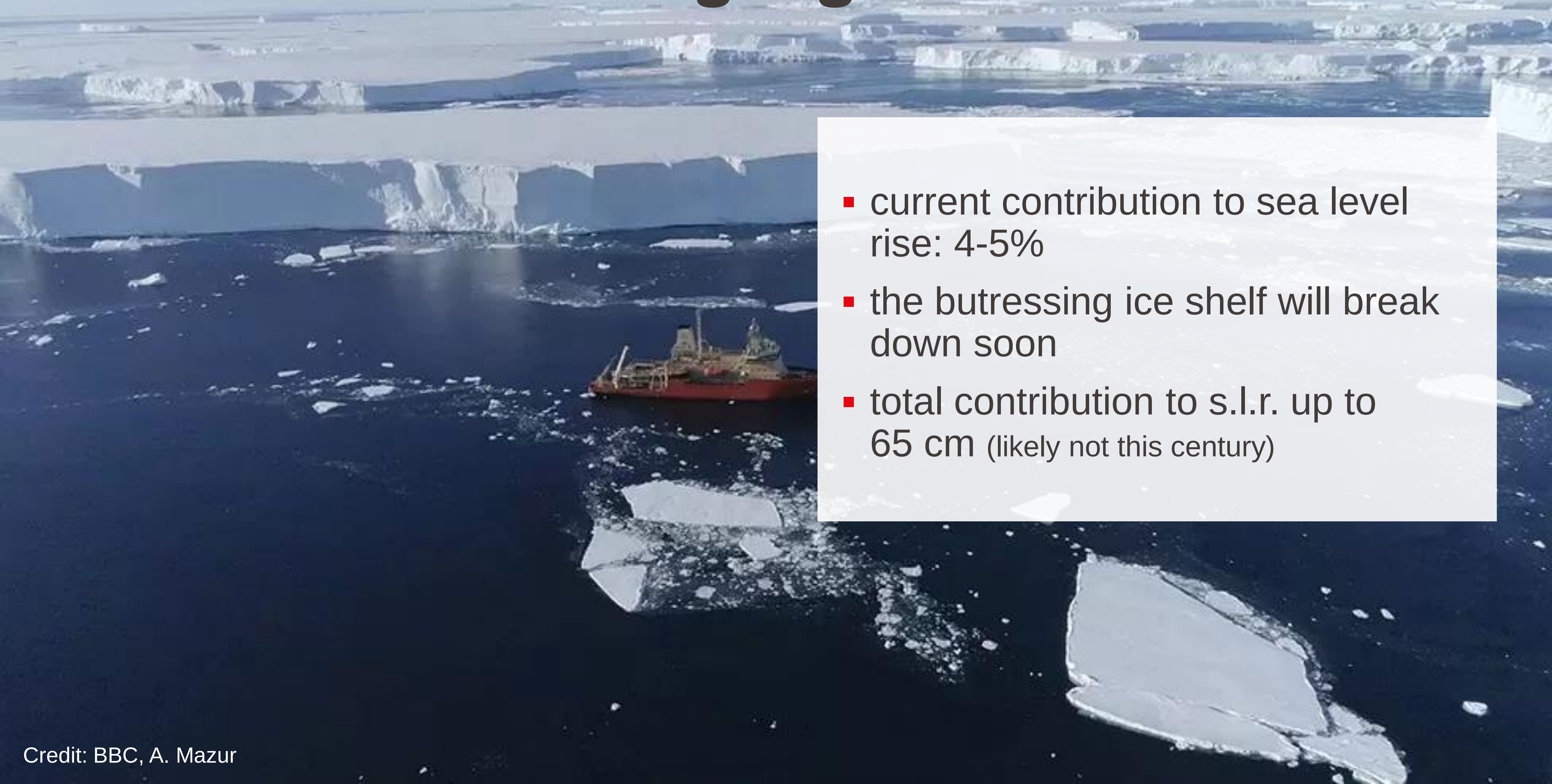


Regional warming observed to be 2x faster than modeled

Bottom melt (warm ocean)

Smith et al. (2020), Casado et al. (2023)

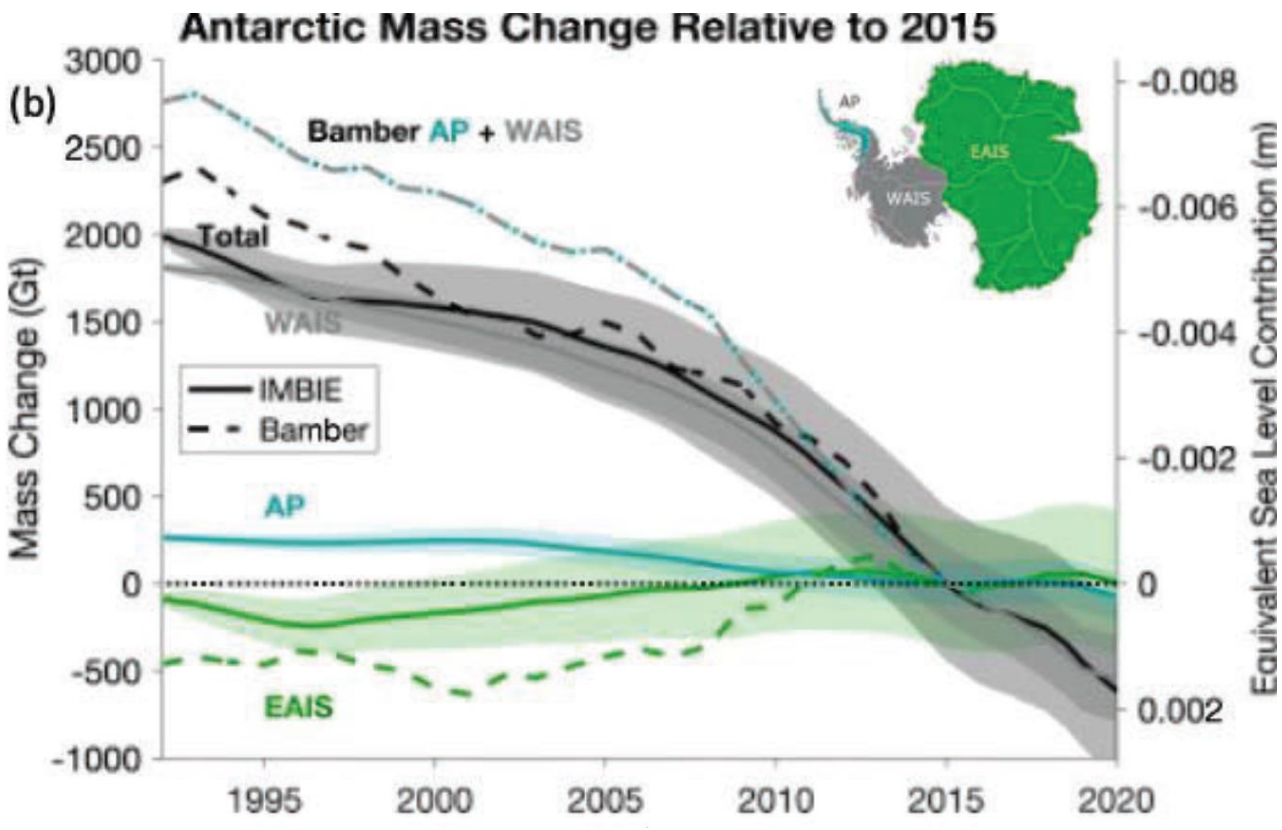
Thwaites Glacier: largest glacier on Earth



- current contribution to sea level rise: 4-5%
- the butressing ice shelf will break down soon
- total contribution to s.l.r. up to 65 cm (likely not this century)

Credit: BBC, A. Mazur

Antarctic melt



- Thinning due to warm ocean water melt. The ice shelves do not hold the inland ice anymore, and it starts flowing faster into the ocean.
- Antarctica loses most of its mass from the West Antarctic Ice Sheet (WAIS) due to ice shelf melting and glacier dynamics.

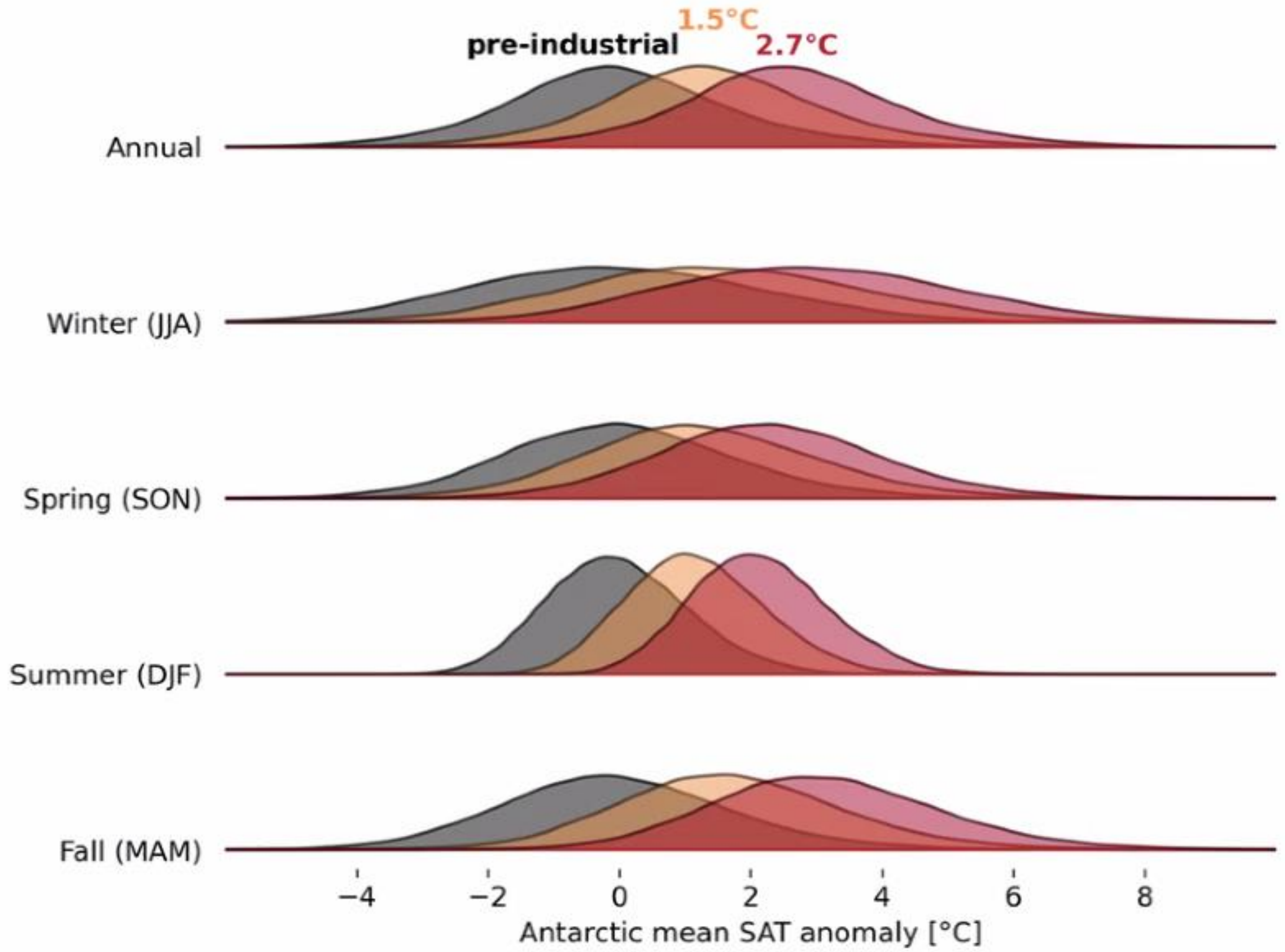
AP: Antarctic Peninsula
WAIS: West Antarctic Ice Sheet
EAIS: East Antarctic Ice Sheet
IMBIE, Bamber are two different references

- IPCC AR6, Fig. 9.16

If you want to learn more about Antarctica:
https://www.asoc.org/learn/antarctic-ice-and-rising-sea-levels/

Future of Antarctica

What Does the Future Hold? - Antarctic

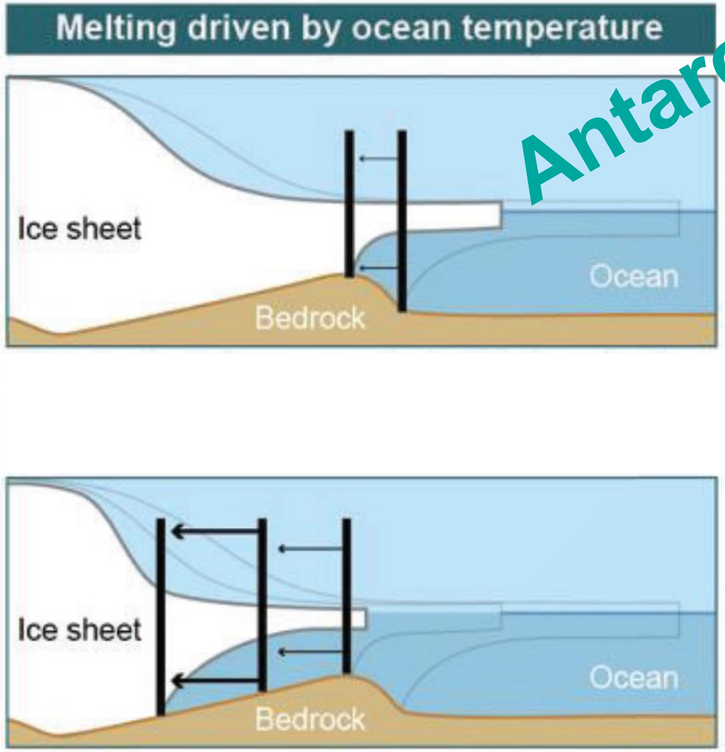


- In the Antarctic future temperature changes at 1.5 and 2.7ºC overlap with present day conditions.

J. Stroeve

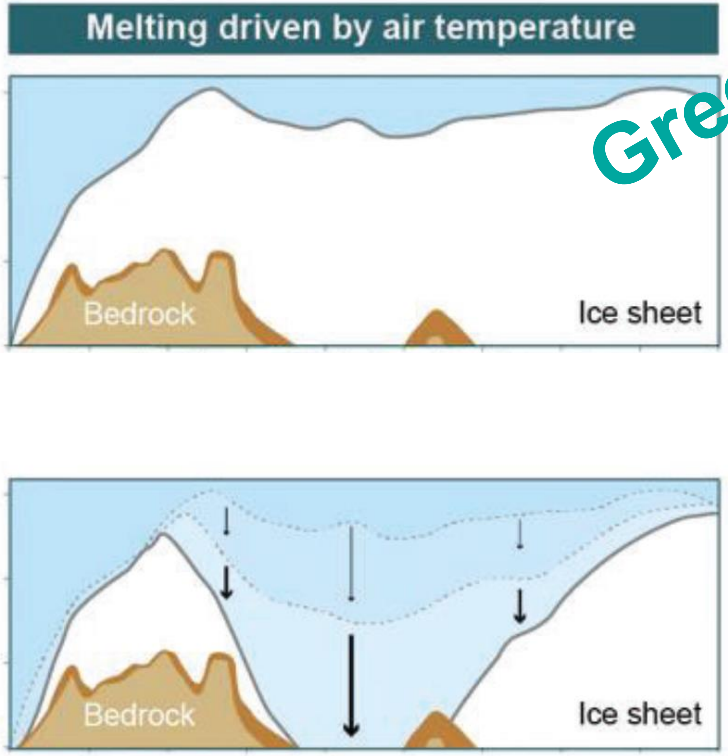
Different drivers of melt for Greenland and Antarctica

Antarctica



The ice shelf (on the ocean) keeps the ice sheet from flowing into the ocean. If the ice shelf becomes thinner and smaller, the ice sheet can flow faster.

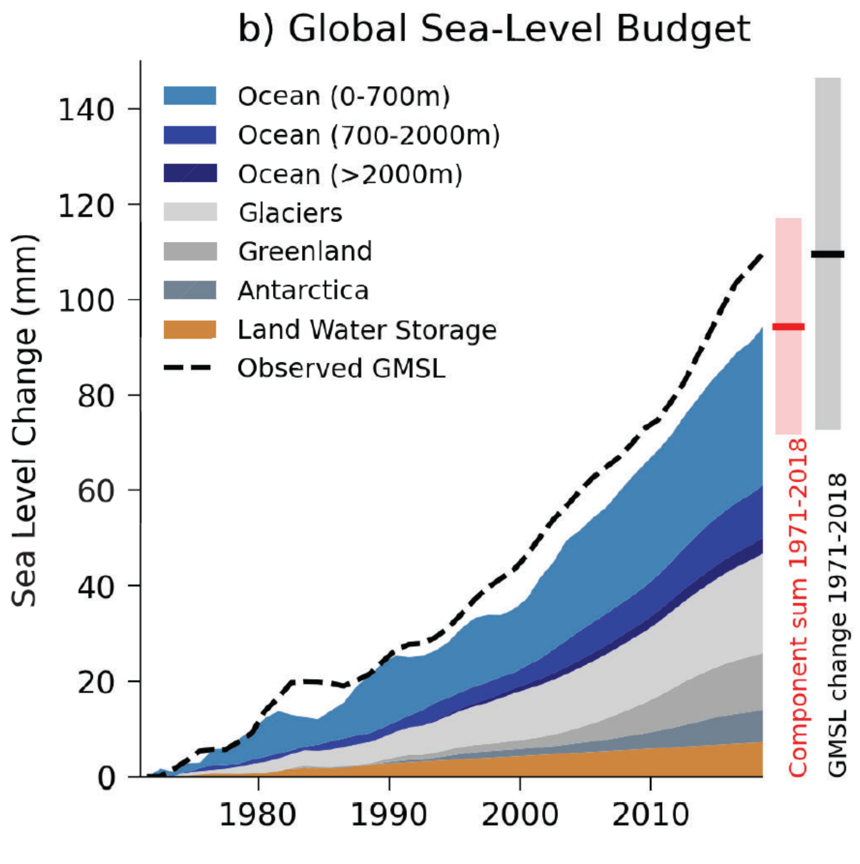
Greenland



Elevated heights are colder and melting is slow. As soon as a threshold altitude is surpassed where the surrounding temperature is > 0°C, melting becomes fast.

- IPCC AR6, FAQ 9.1

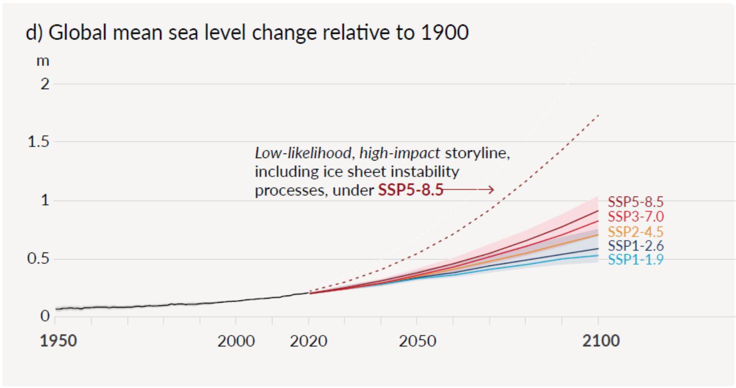
Sea level rise

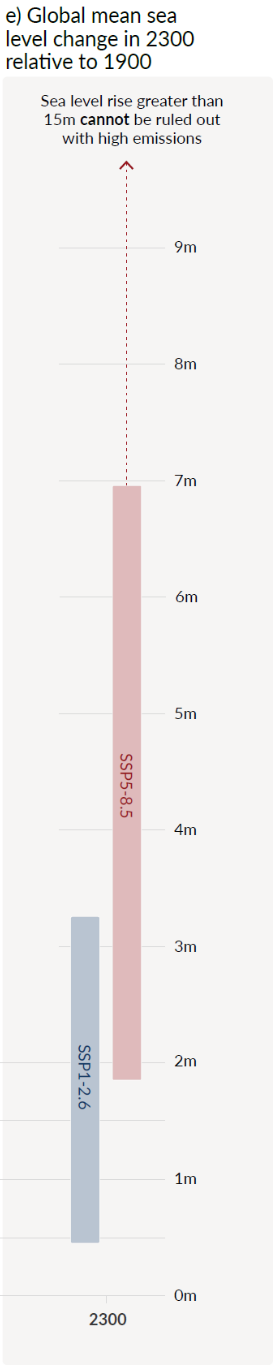


- **Thermal expansion: 50 %**
- **Glaciers: 22 %**
- **Ice sheets: 20 %**

Marine Ice Cliff Instability (MICI)

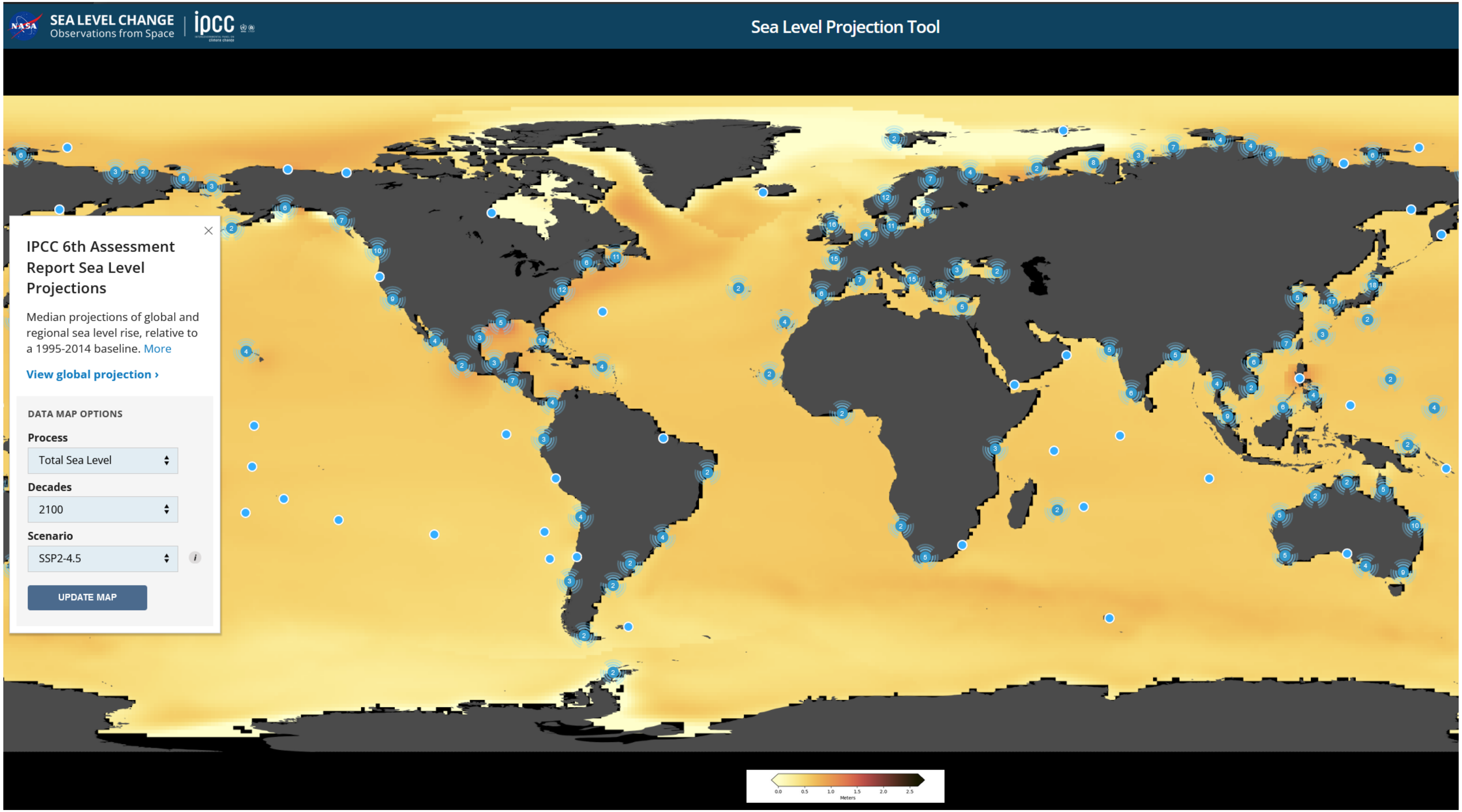
Sea level rise is nurtured by slow processes such as ice sheet melting and will hence continue well after temperatures have stabilized in the atmosphere.





- IPCC AR6, SPM.5, Fig. 1 CrossCh9.1

What does sea level rise mean concretely?

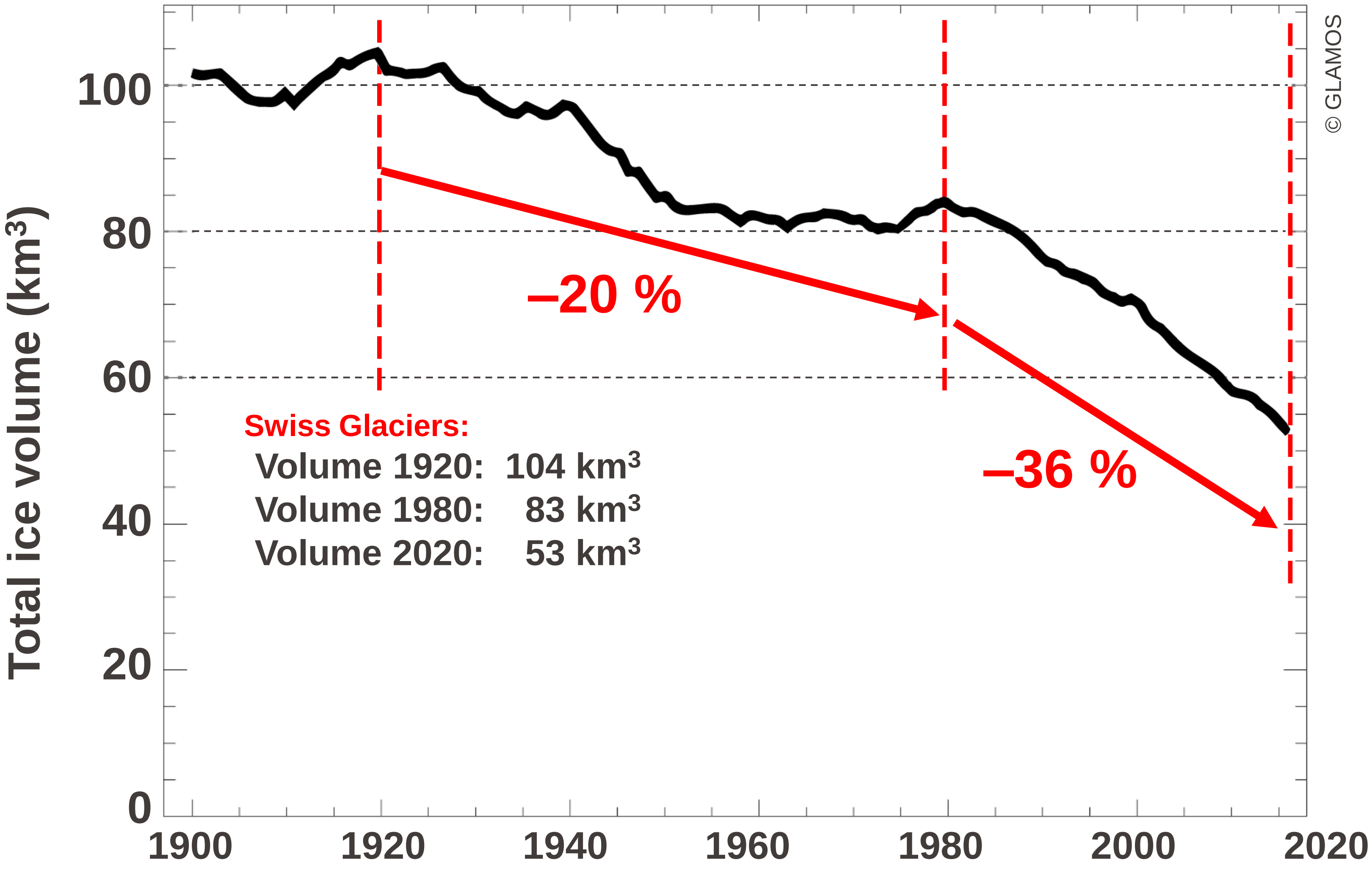


https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool

Glacier melt in Switzerland

Ice volume evolution of all glaciers in Switzerland

EPFL

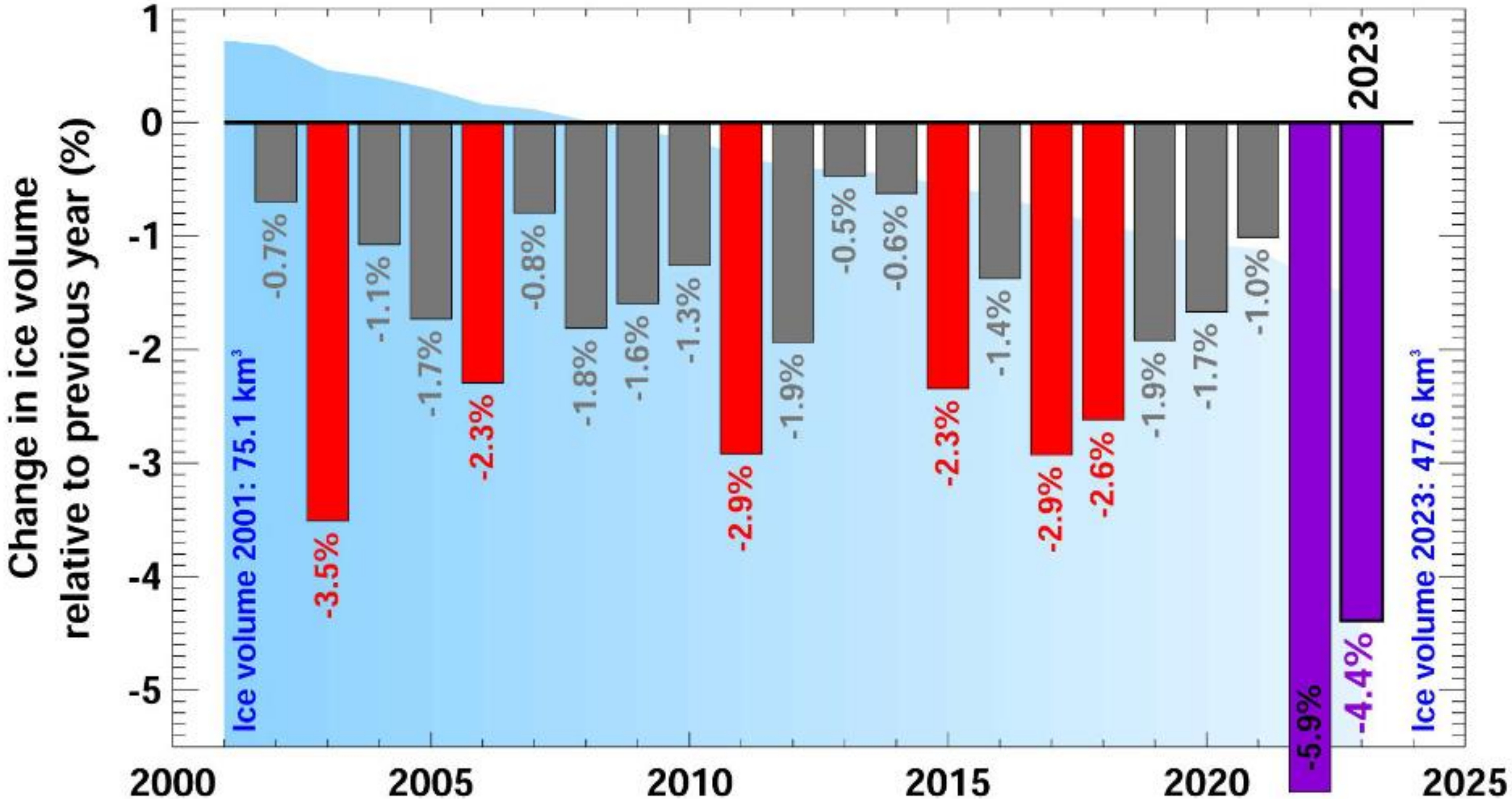


GLAMOS
Glacier Monitoring Switzerland

Volume change of the **past five years** (2015-2020): **–10%**

Volume change in **2020: –1.9%**

Record melt in 2022 and 2023

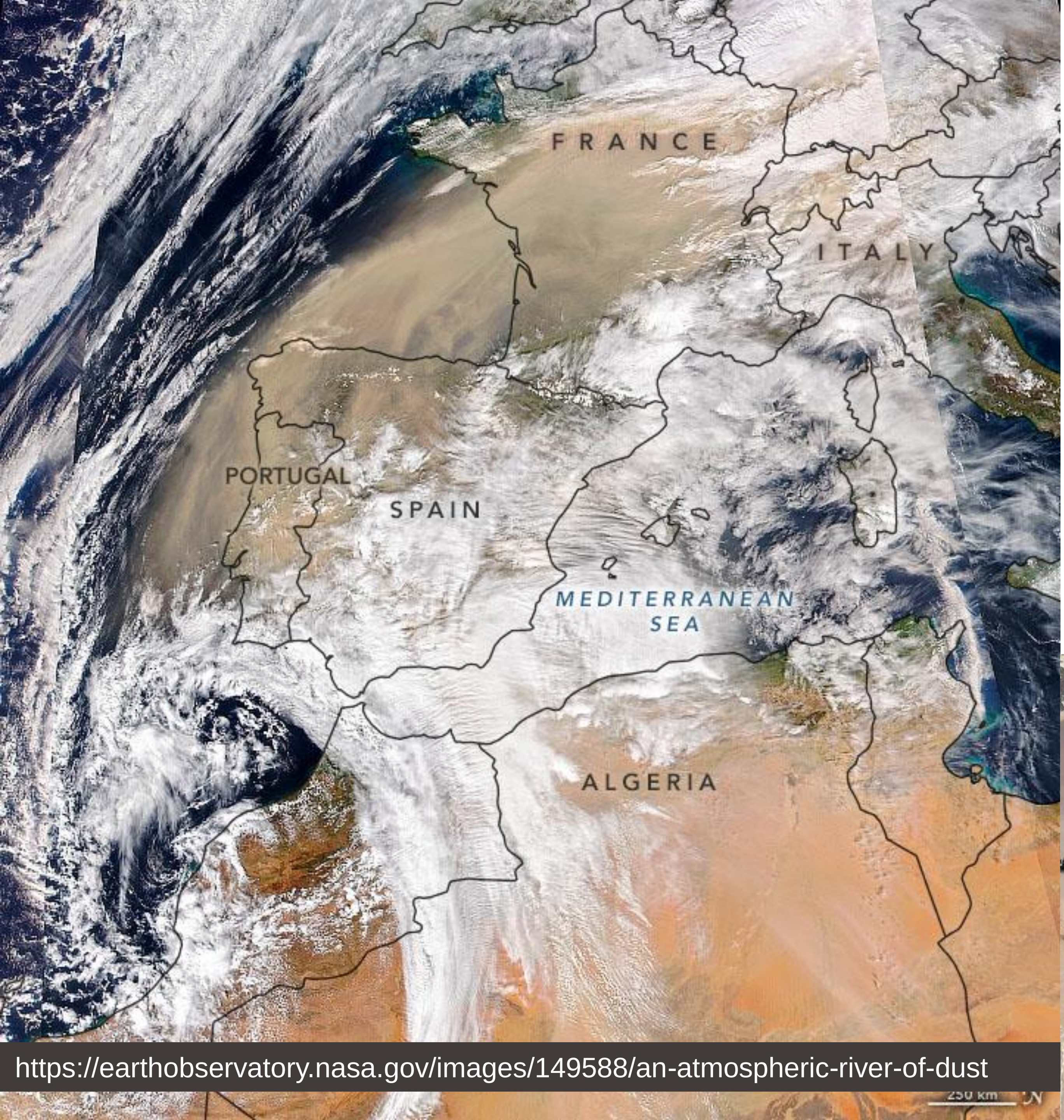


Why was 2022 so extreme?

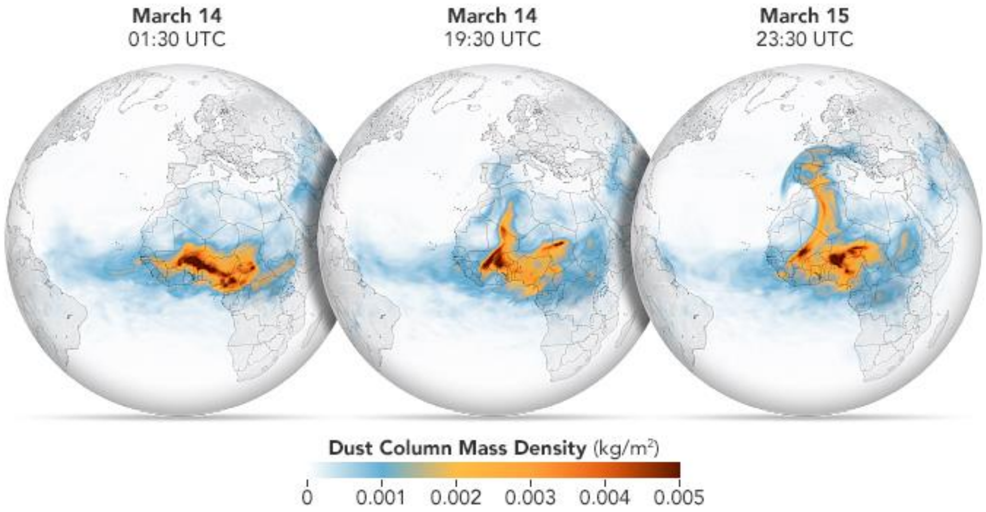
- Dry winter with little snowfall.
- Strong Saharan dust events reduced the snow albedo and led to early melt.
- Strong heat waves between May and September.

- https://wmo.int/sites/default/files/2023-11/WMO%20Provisional%20State%20of%20the%20Global%20Climate%202023.pdf

Transport of Saharan dust to the Alps



https://earthobservatory.nasa.gov/images/149588/an-atmospheric-river-of-dust



What does «Paris» mean for Alpine glaciers?

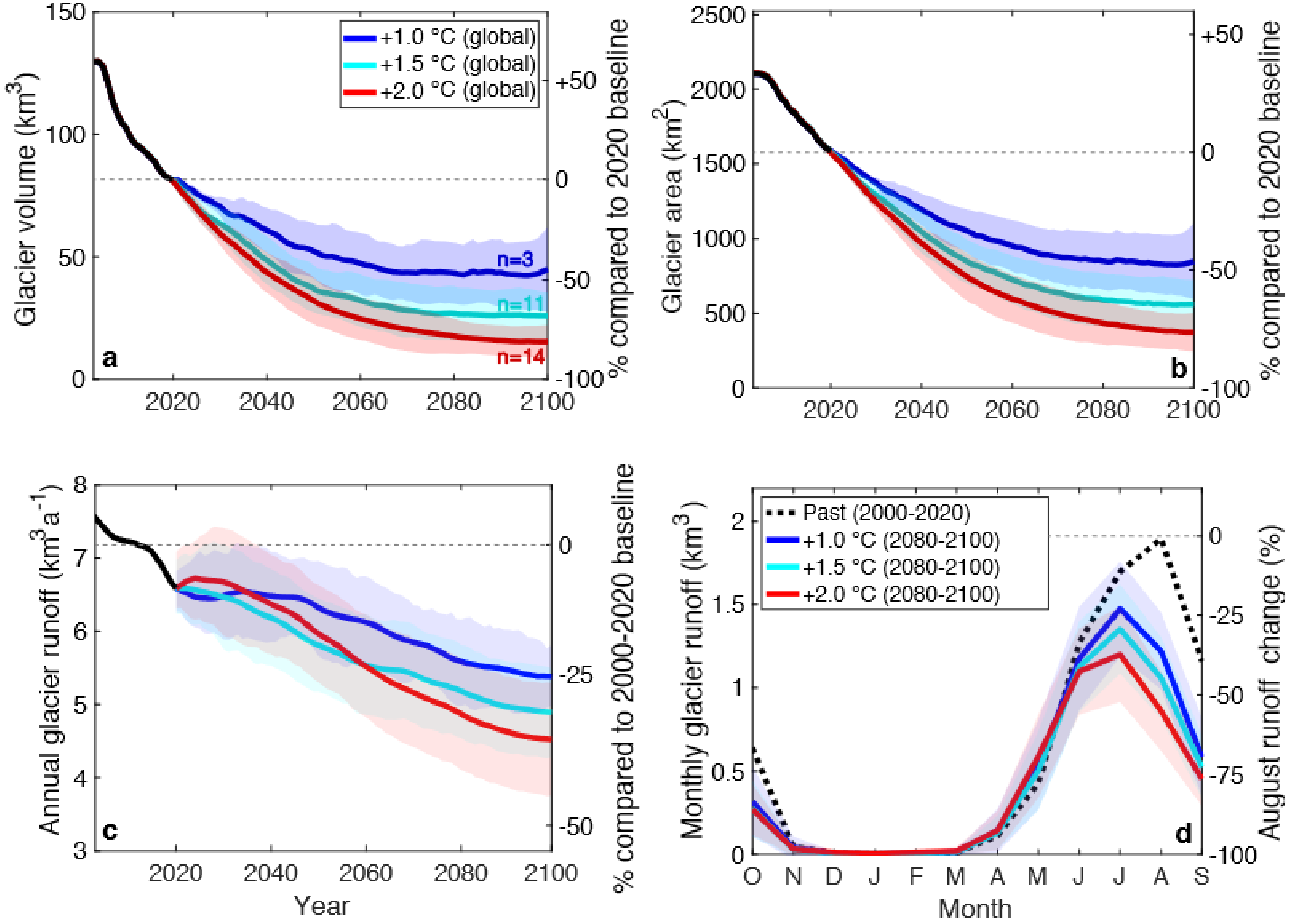


Figure 2.Modelled evolution of total glacier (a) volume, (b) area, (c) annual glacier runoff, and (d) monthly glacier runoff of the European Alps. Time series are smoothed with a 20-year running mean. In all panels, the thick line represents the mean and the transparent band corresponds to one standard deviation of the results obtained by forcing GloGEM flow with the selected GCM members. The numbers or GCM members is given (`n`).

What does this mean for water resource management?

- Compagno et al., The Cryosphere, 2021; https://tc.copernicus.org/articles/15/2593/2021/