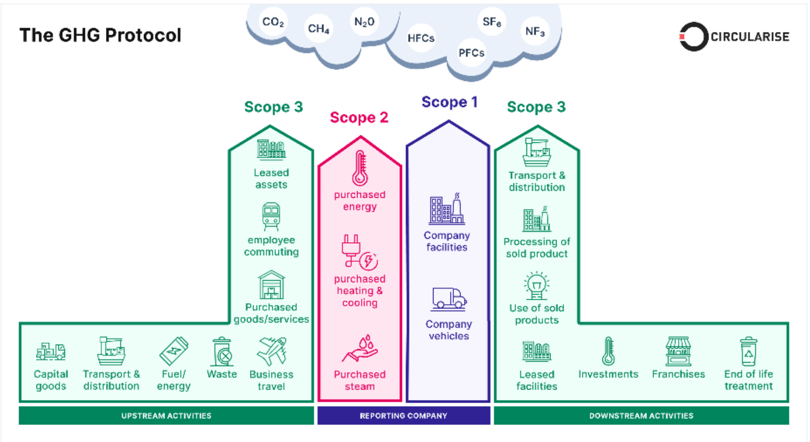
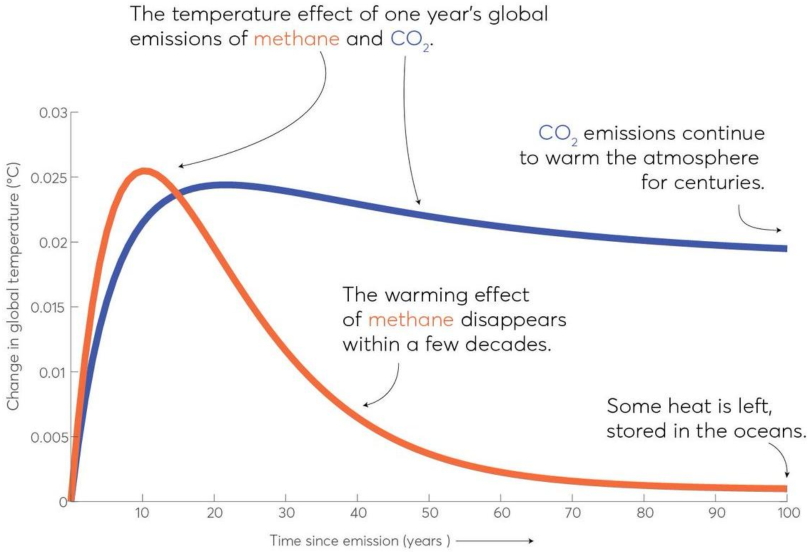
Recap from last lecture



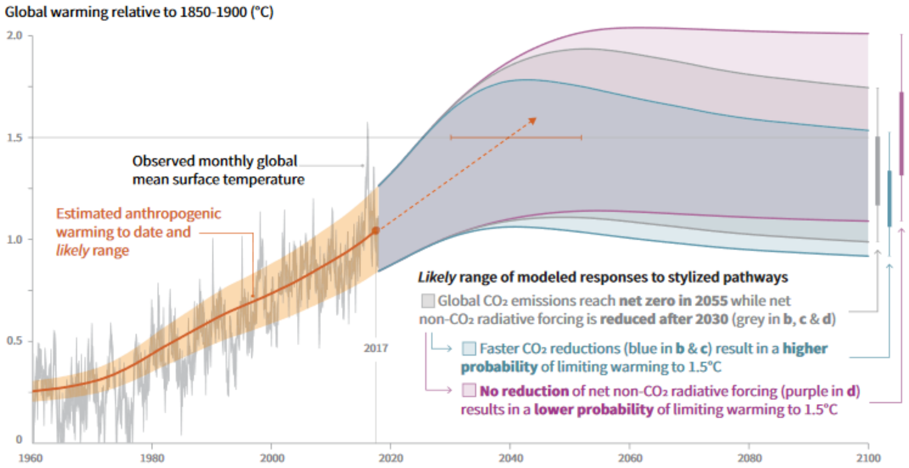
Within the EU certain companies need to report their carbon emissions based on GWP_{100}. That includes emissions from scope 1,2 and 3.



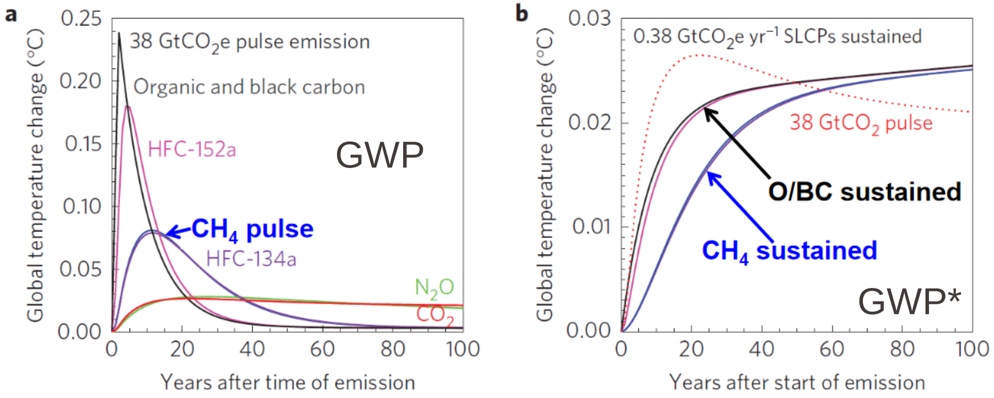
Due to different lifetimes and radiative forcing efficacy, the warming effect of CO_2 and CH_4 is very different in timing and amount. Emission metrics need to account for that. GWP_{100} cannot.

	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.

EPFL

General outline

No.	Date	Topics	Deadlines / tentative
1.	11.09.2025	Introduction to the climate system	Questionnaire (not graded)
2.	18.09.2025	Climate System, Radiation	
3.	25.09.2025	Radiation, Earth's Energy balance, Greenhouse effect	launch of first assignment
4.	02.10.2025	Aerosols & clouds, Radiative Forcing	Launch of poster project
5.	09.10.2025	Feedback mechanisms, Climate Sensitivity	
6.	16.10.2025	Paleoclimate	submission of Poster proposal (graded)
7.	30.10.2025	Climate variability, Introduction to IPCC	
8.	06.11.2025	Current state of climate, IPCC – report, Paris Agreement, Climate scenarios (RCPs, SSPs)	
9.	13.11.2025	Emissions Gap, 1.5 vs 2.0°C vs warmer, Tipping elements, Extreme Events	submission of Poster draft (graded)
10.	20.11.2025	COP 30, Extreme Events Attribution Studies, Carbon budget	
11.	27.11.2025	Climate litigation, Metrics,	submission of assignment (graded)
12.	04.12.2025	Carbon offsets, Polar climate change	
13.	11.12.2025	Mitigation measures	Poster Conference (graded)
14.	18.12.2025	Climate engineering, questions and answers session	fill in Questionnaire in exercises (not graded)

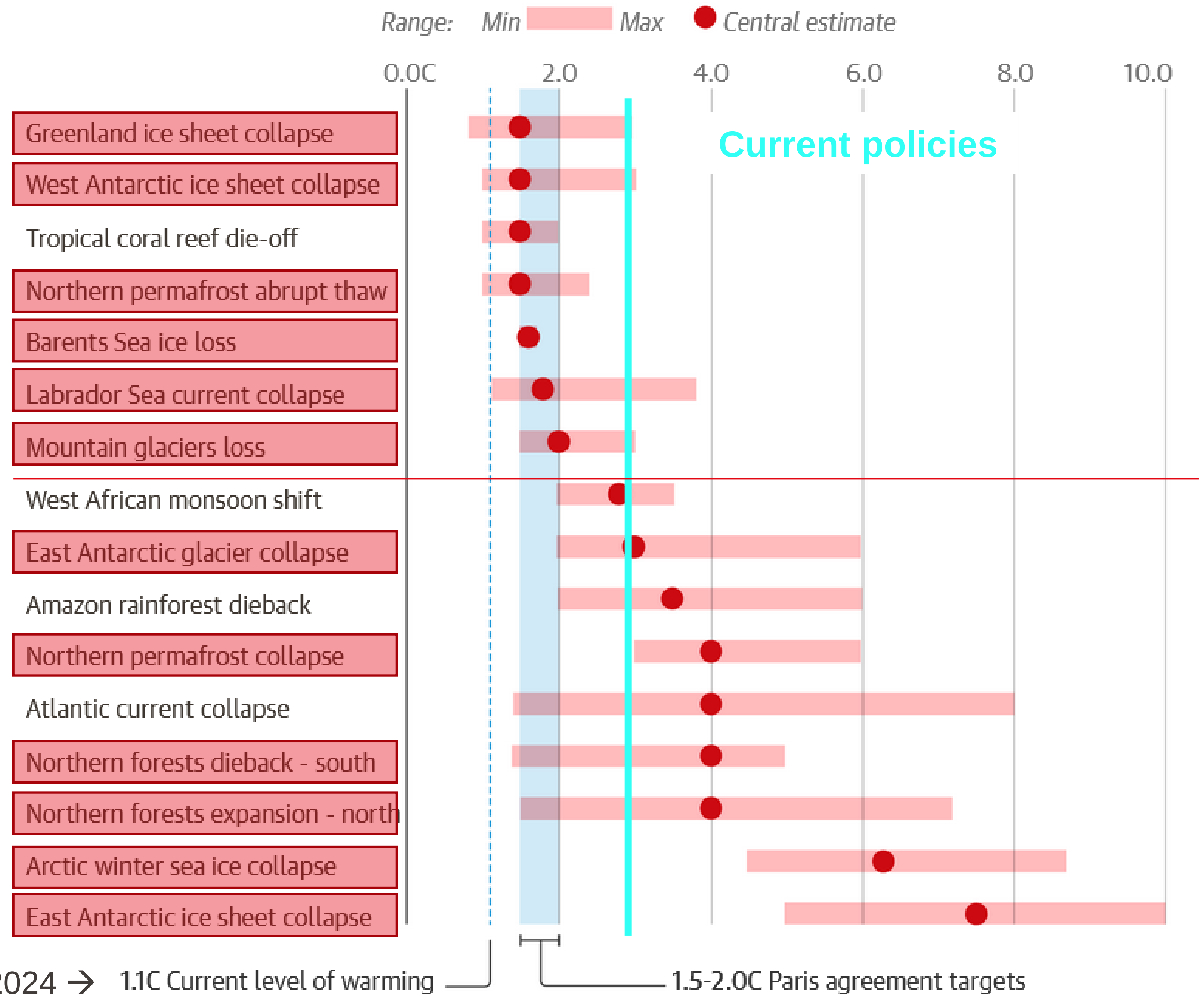
Basics (1–6)

Present and future Climate change (7–12)

Actions (13–14)

Polar climate change

Paris agreement and polar tipping points



1.3 °C in 2024 →

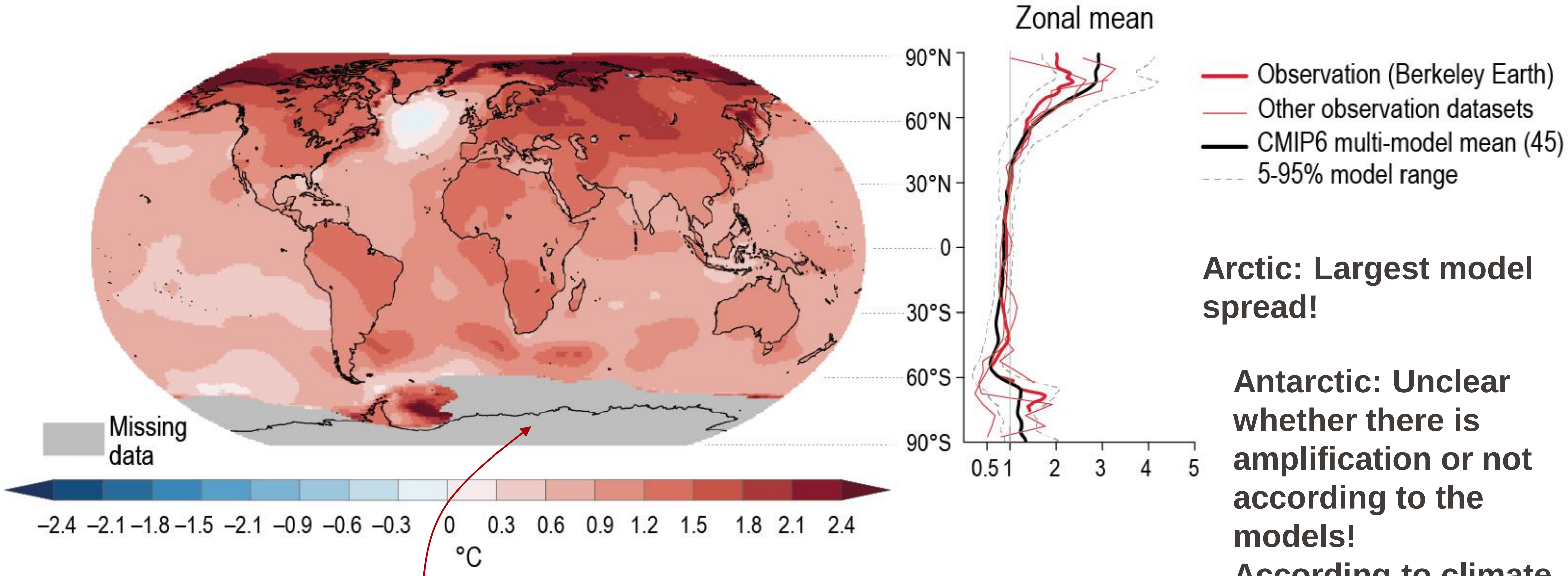
Guardian graphic. Source: Armstrong McKay et al, Science, 2022. Note: Current global heating temperature rise 1.1C Paris agreement targets 1.5-2.0C

- 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



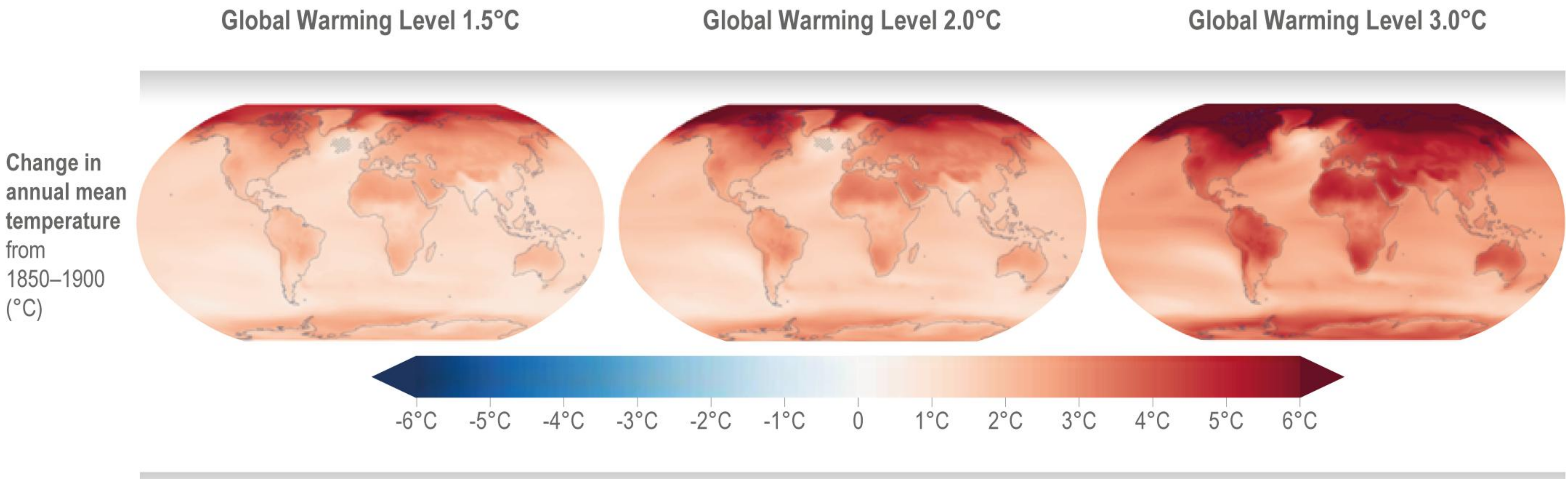
Only 23 weather stations on Antarctica!

Arctic: Largest model spread!

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

- 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

Disappearing landscapes: The Arctic at +2.7°C global warming

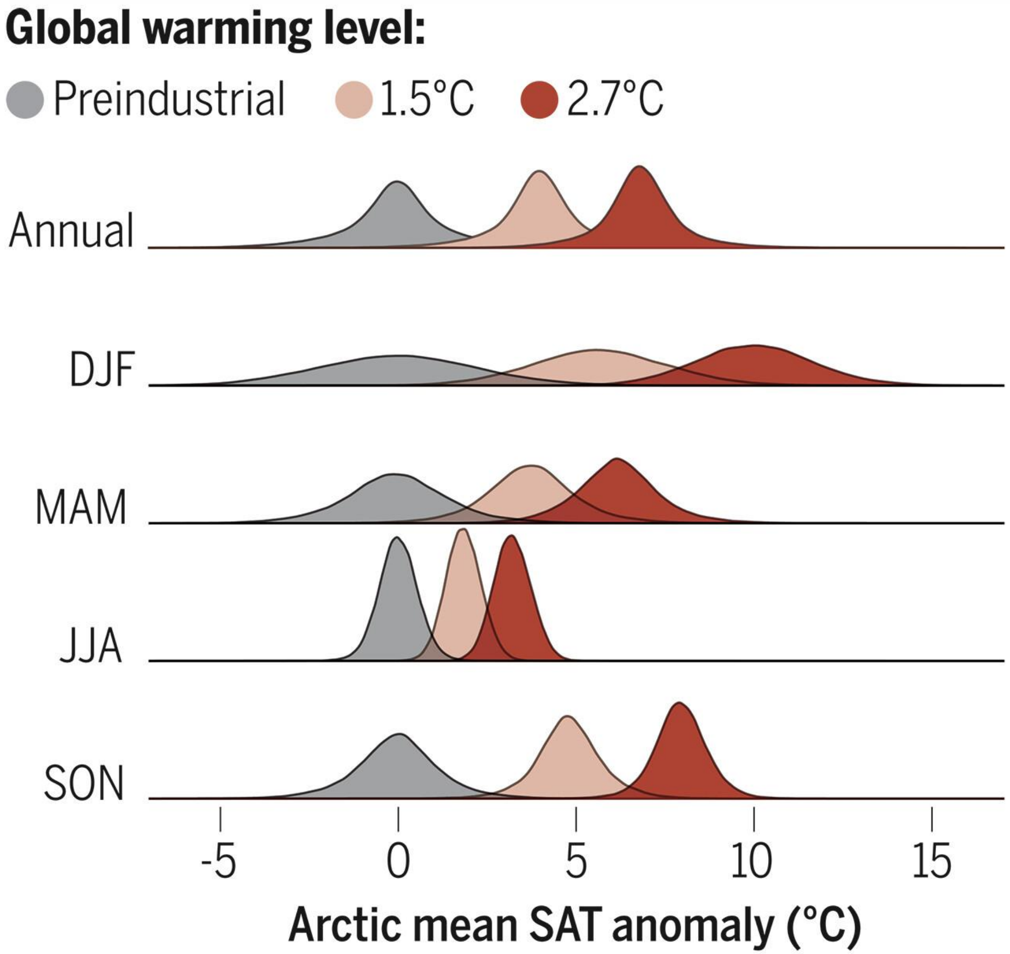
JULIENNE C. STROEVE, DIRK NOTZ, JACKIE DAWSON, EDWARD A. G. SCHUUR, DORTHE DAHL-JENSEN, AND CÉLINE GIESSE Authors Info & Affiliations

SCIENCE • 6 Feb 2025 • Vol 387, Issue 6734 • pp. 616-621 • DOI: 10.1126/science.ads1549

- Under current nationally determined contributions (NDCs) to mitigate greenhouse gas emissions, global warming is projected to reach 2.7°C above preindustrial levels.
- …we show that at such a level of warming, the Arctic would be transformed beyond contemporary recognition:
  - Virtually every day of the year would have air temperatures higher than preindustrial extremes,
  - the Arctic Ocean would be essentially ice free for several months in summer,
  - the area of Greenland that reaches melting temperatures for at least a month would roughly quadruple,
  - and the area of permafrost would be roughly half of what it was in preindustrial times.

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

- Stroeve et al. (2025)

Present day Arctic Amplification

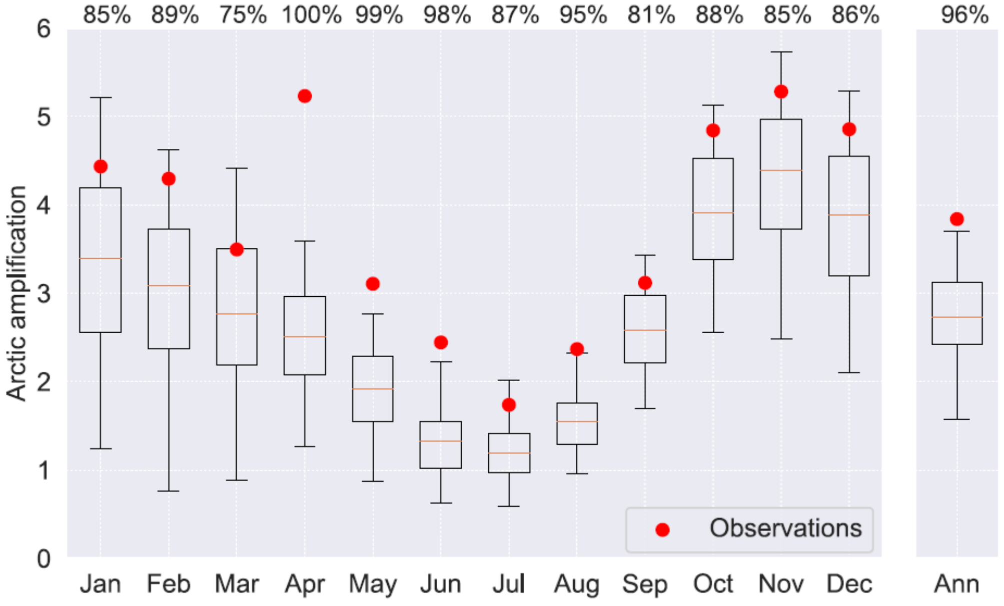
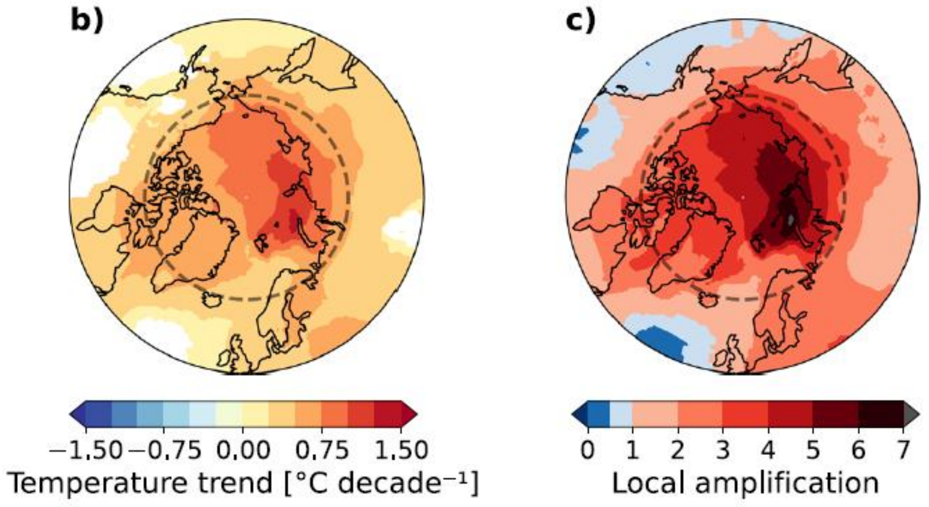
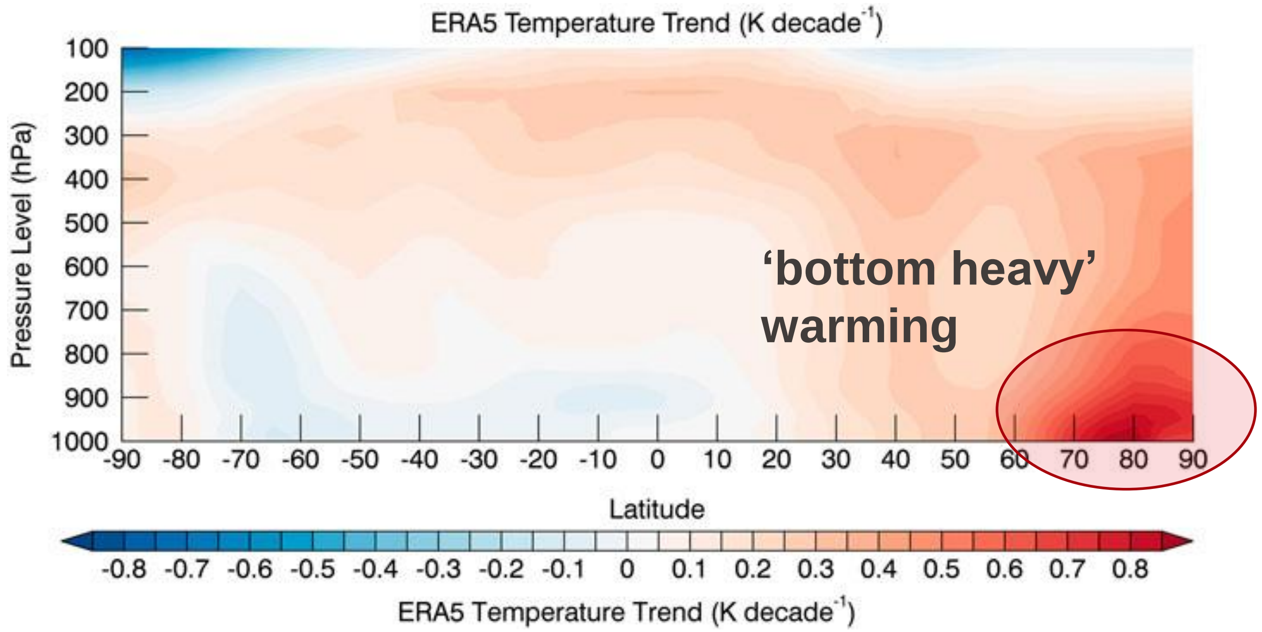


Fig. 5 Seasonality of the 43-year (1979–2021) Arctic amplification ratio.



Rantanen et al. (2022)



Hersbach et al. (2019)

- **Arctic Amplification is largest in winter.**
- **The absolute trends are largest in the central Arctic.**
- **Most of the warming occurs in the lower atmosphere.**

Contributions to Arctic warming

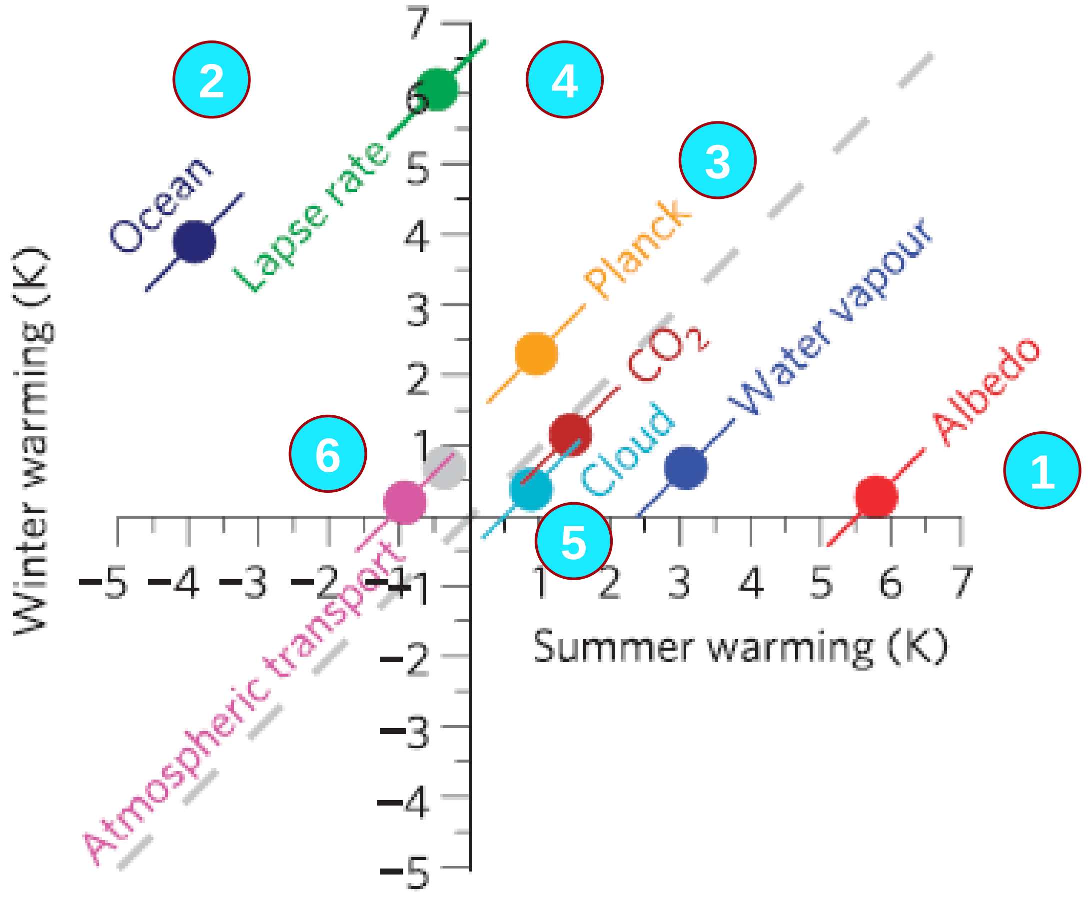
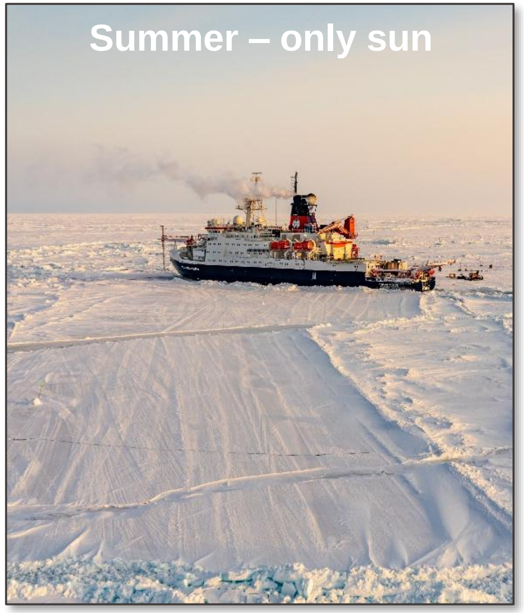


Figure 2 | Warming contributions of individual feedback mechanisms. **b**, Arctic winter versus summer warming. Grey is the residual error of the decomposition.

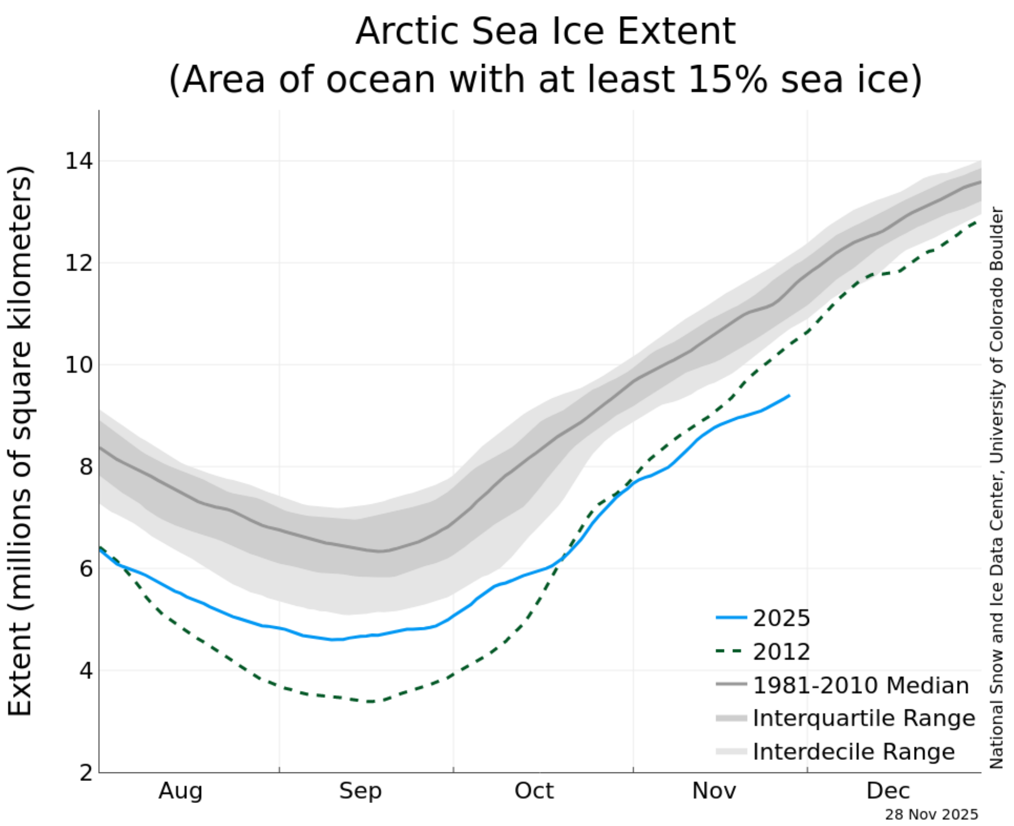


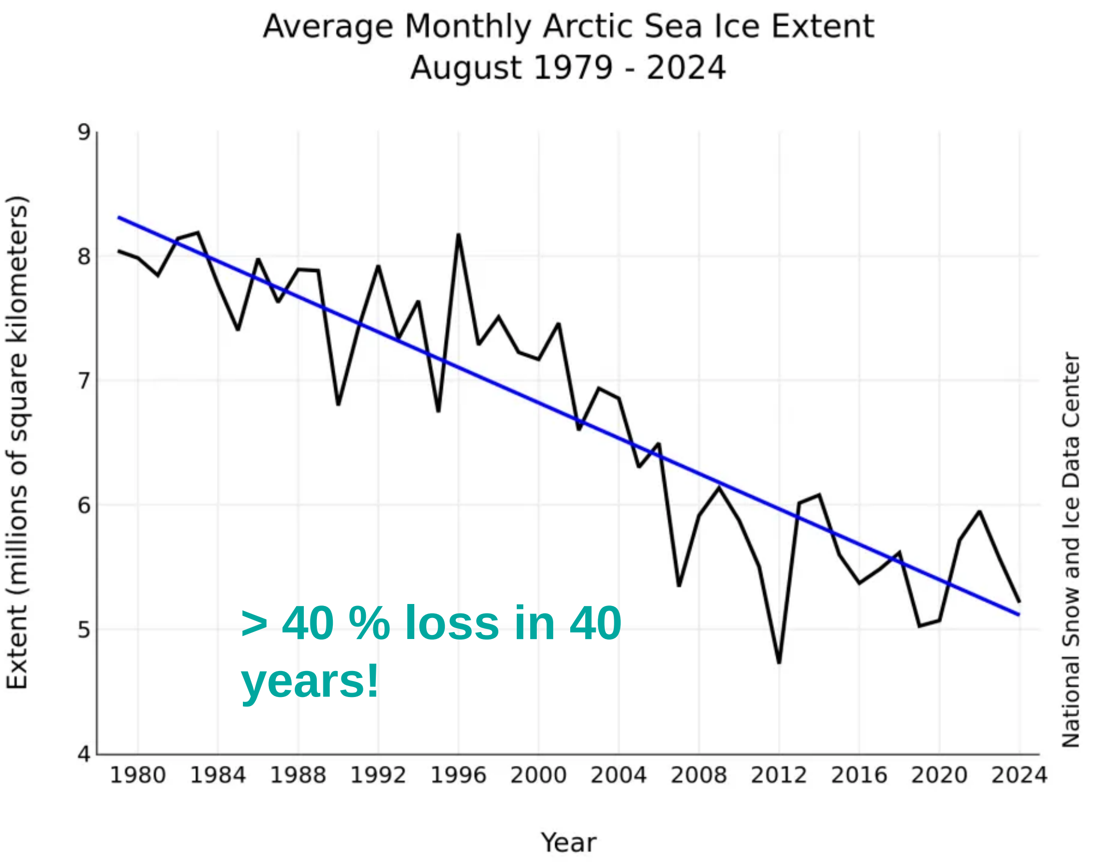
- Need to distinguish winter and summer mechanisms.
- Note the role that CO_2 plays.

- Pithan and Mauritsen, Nat. Geoscience, 2014

1. Albedo effect: Arctic sea ice retreat

1

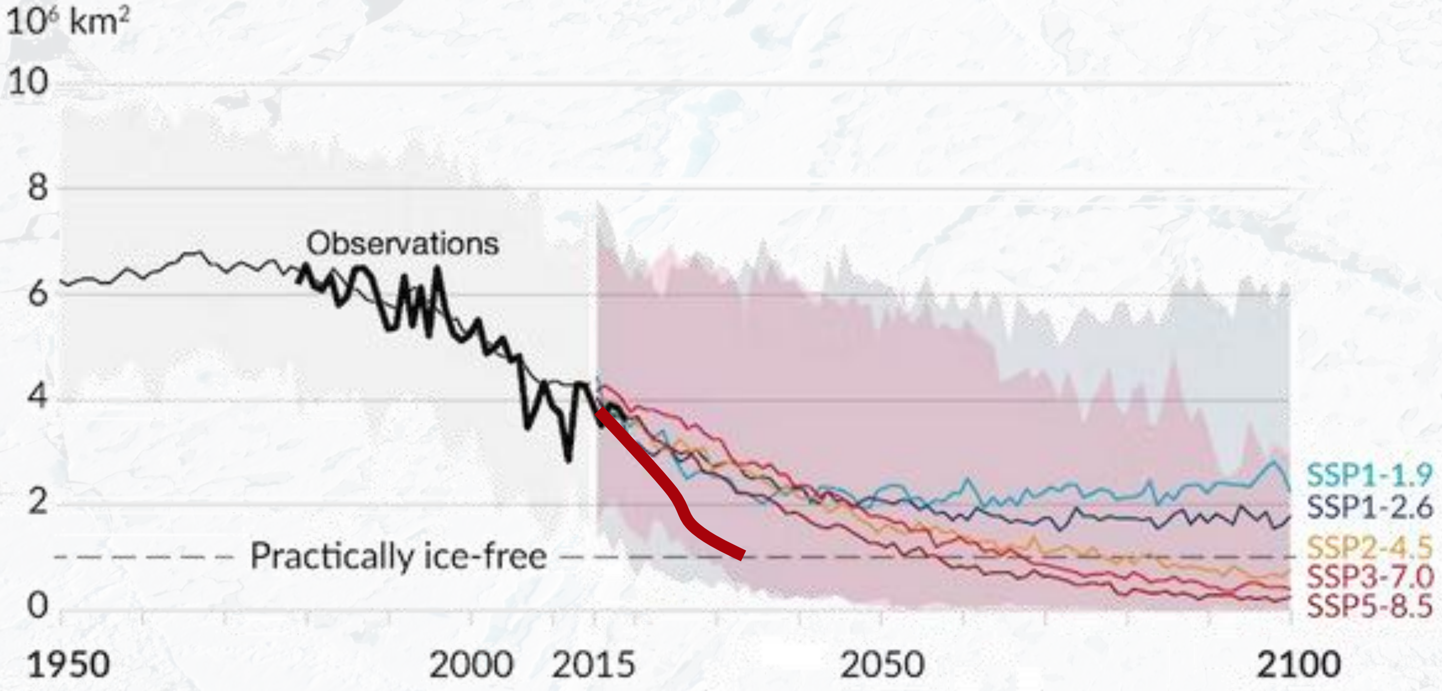




Less sea ice means that less solar radiation is reflected back to space and that the ocean absorbs more heat.

- http://nsidc.org/arcticseaicenews/

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)

North Pole August 2018

Ice-free Arctic

- Definition: sea ice area < 1 Million km^2
- A summer ice-free Arctic would be the first time over 80’000 yrs (or even longer)

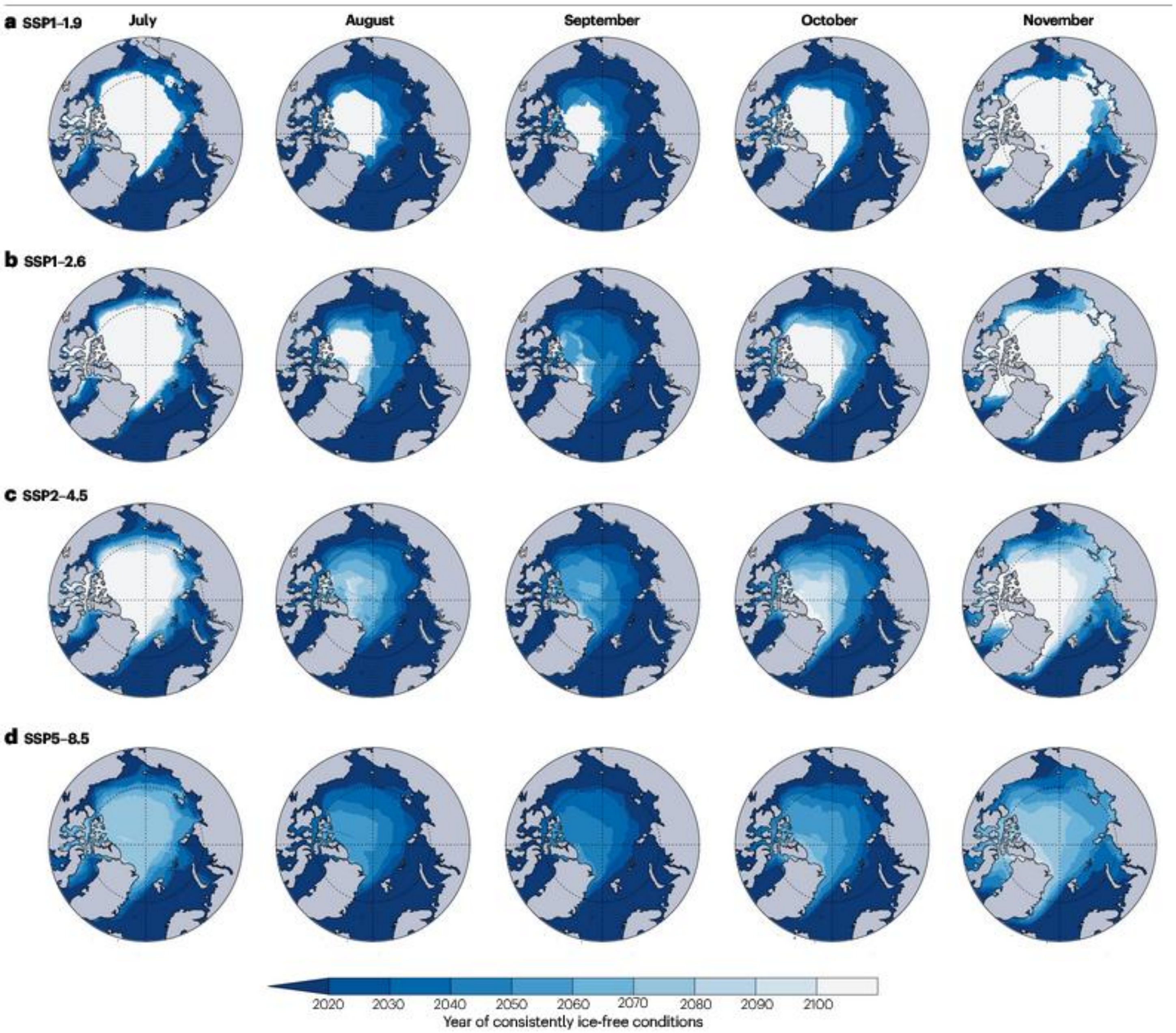


Fig. 5 | Regional ice-free conditions. a, Year sea ice is consistently ice free for July to November for SSP1-1.9, calculated as the first time sea ice concentration (SIC) in each grid is below 15% in a given month in the ensemble mean[81] of the selected CMIP6 models[10]. Bright white areas indicate regions that retain ice cover with more than 15% SIC in 2100, whereas dark blue areas indicate regions that became ice free before 2020 or that never had ice cover. **b**, The same as in part **a**, but for SSP1-2.6. **c**, The same as in part **a**, but for SSP2-4.5. **d**, The same as in part **a**, but for SSP5-8.5. Forcing scenarios have a big impact on the regional sea ice loss, with no ice-covered regions expected to remain between July and November by 2090 under SSP5-8.5, but some ice-covered regions remaining for every month under SSP1-1.9.

- Jahn et al. 2024

Albedo effect: snow cover

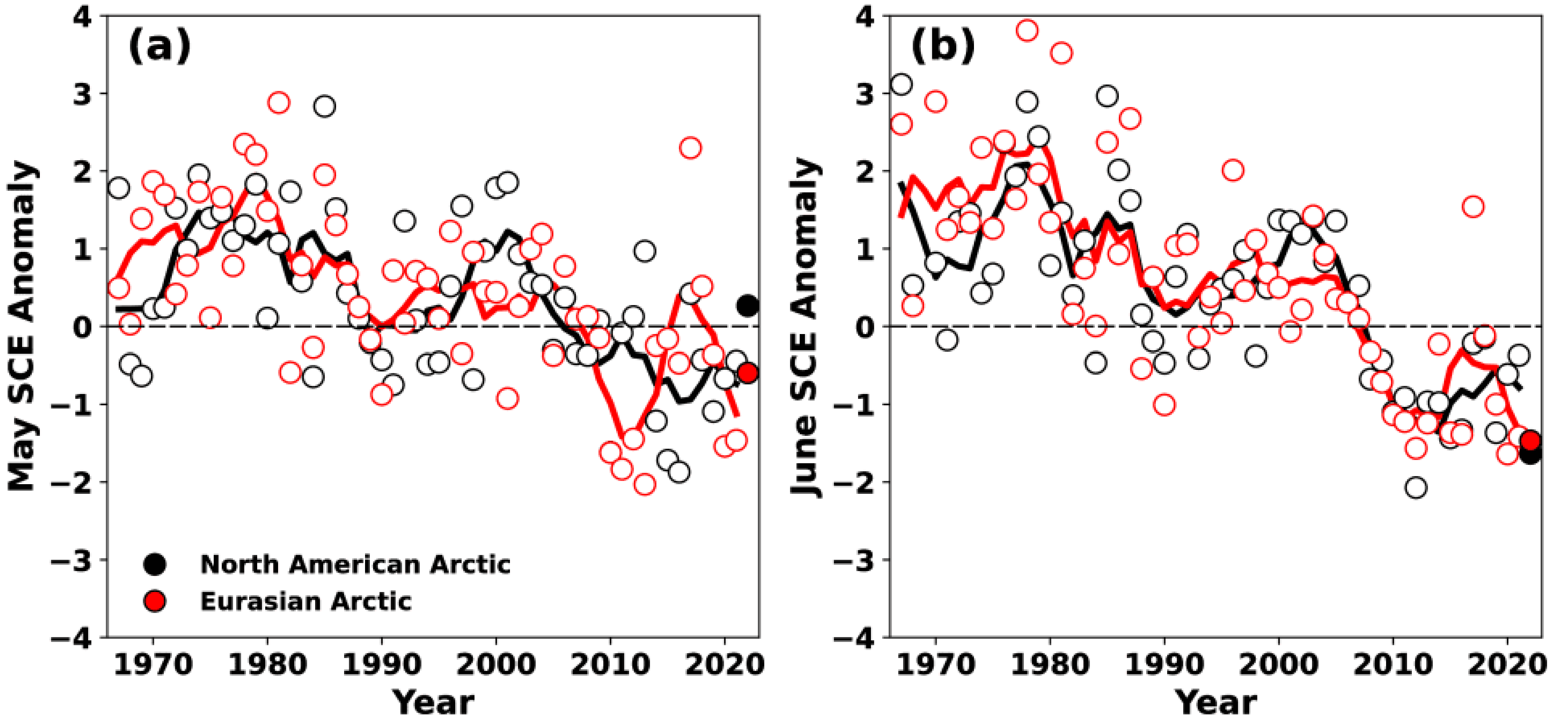


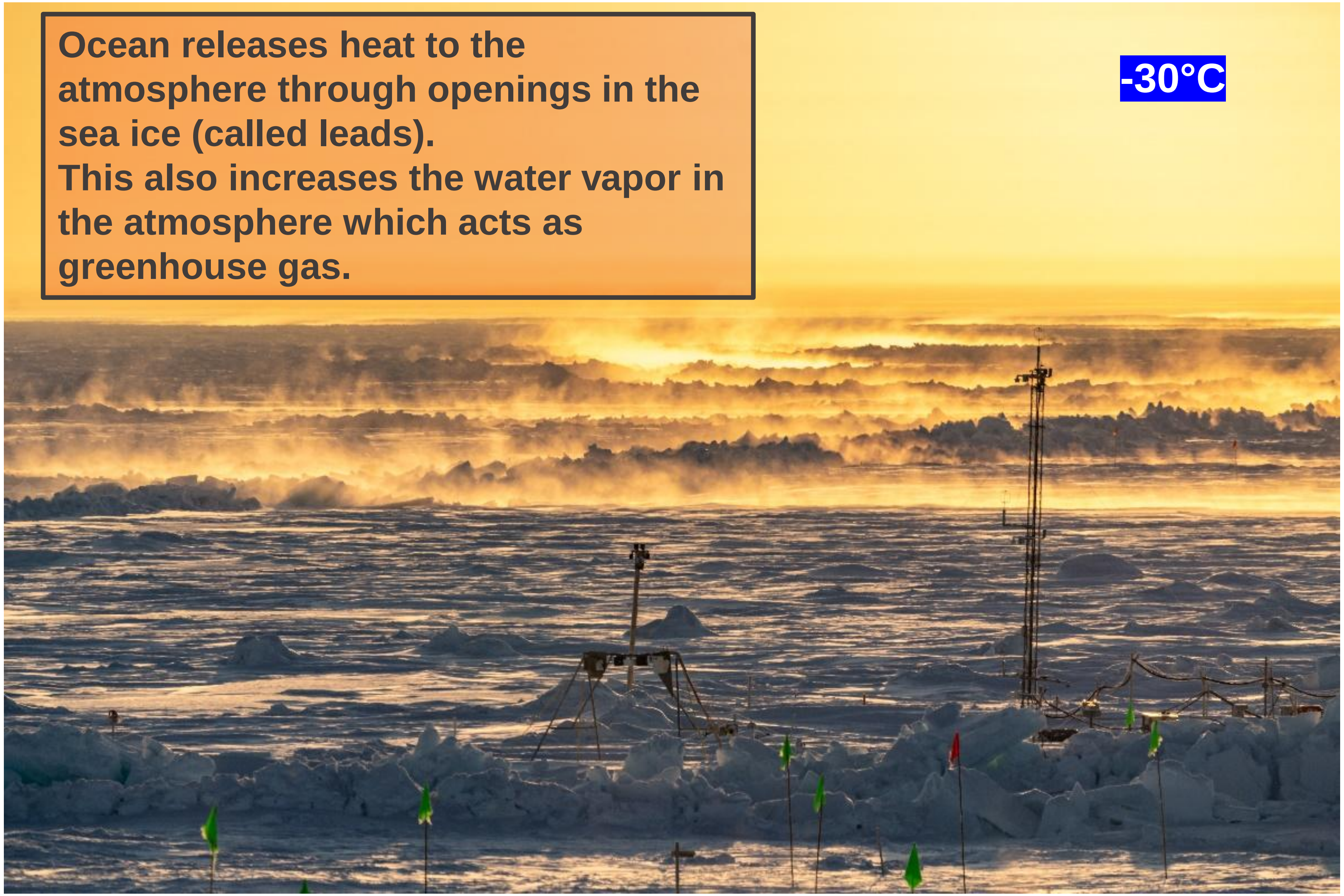
Fig. 1. Standardized monthly snow cover extent anomalies relative to the 1991-2020 climatology for Arctic land areas (>60° N) for **(a)** May, and **(b)** June, from 1967 to 2022. Solid black and red lines depict 5-year running means for North America and Eurasia, respectively. Filled circles are used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

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

2. Ocean effect: winter

2

Ocean releases heat to the atmosphere through openings in the sea ice (called leads).
This also increases the water vapor in the atmosphere which acts as greenhouse gas.



Ocean water -1.6°C

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

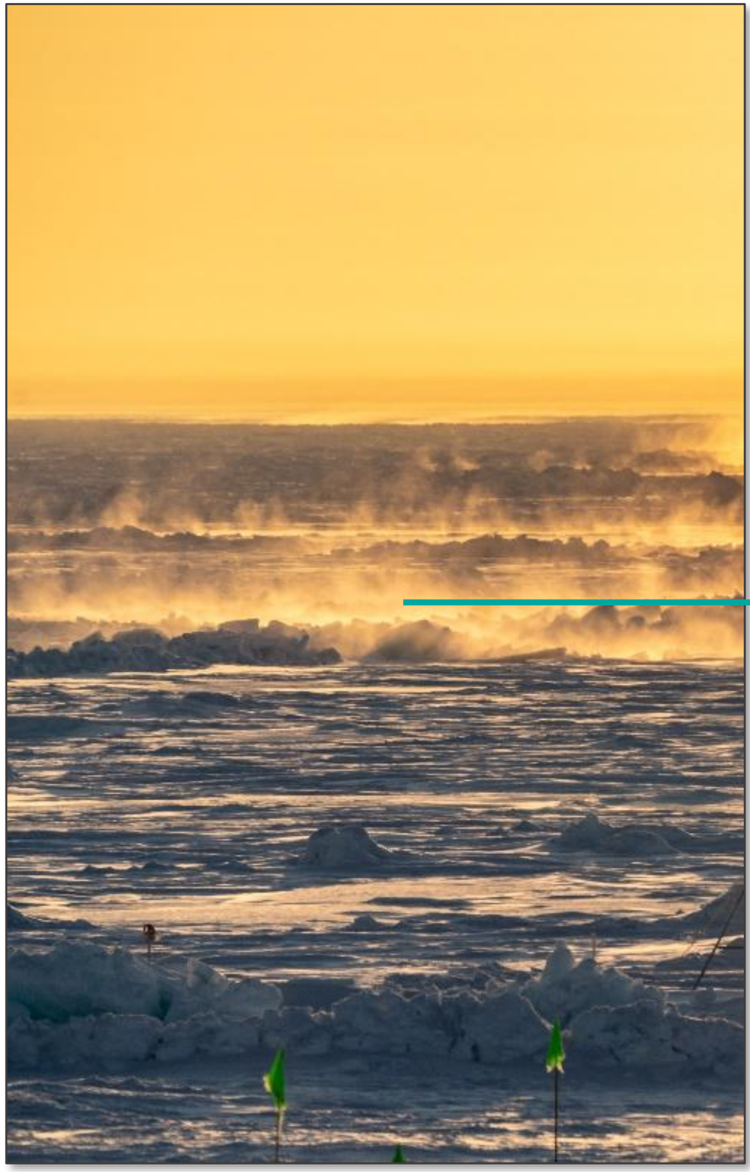
Field work in the central Arctic, 2020

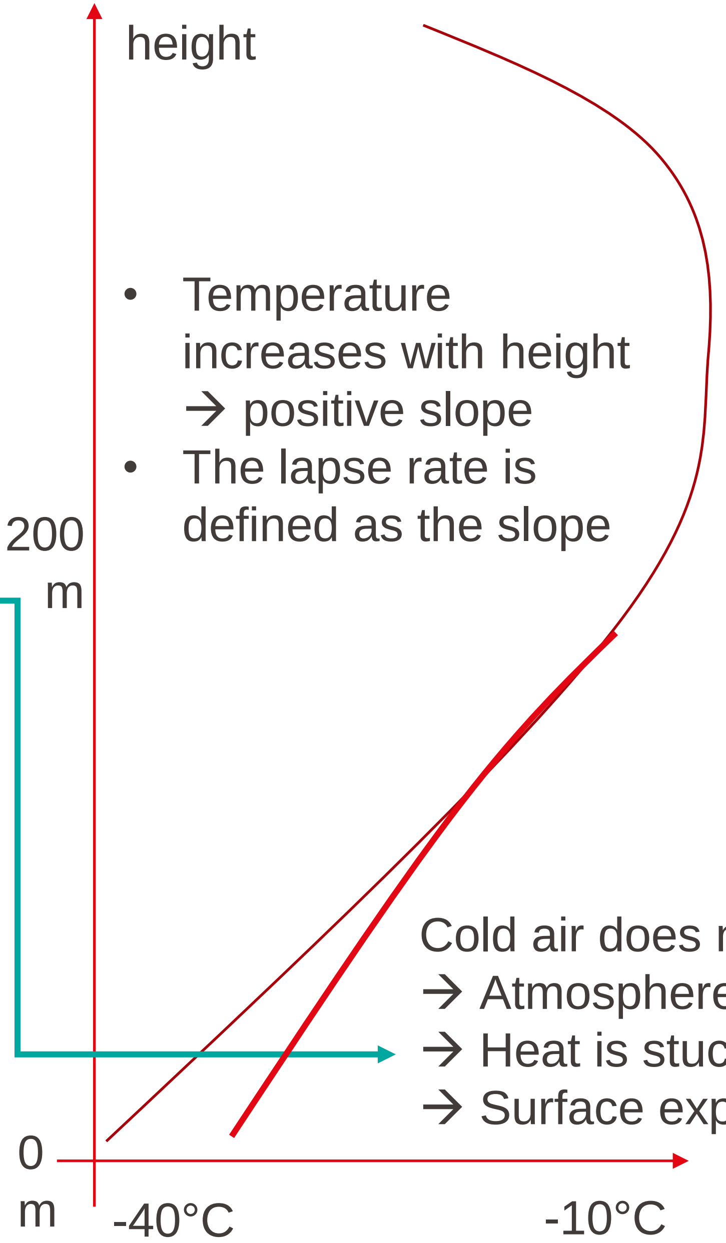
$$LWR = \varepsilon * \sigma T_e^4$$

LWR longwave radiation
ε = surface emissivity (~1)

4. Lapse rate effect

4





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

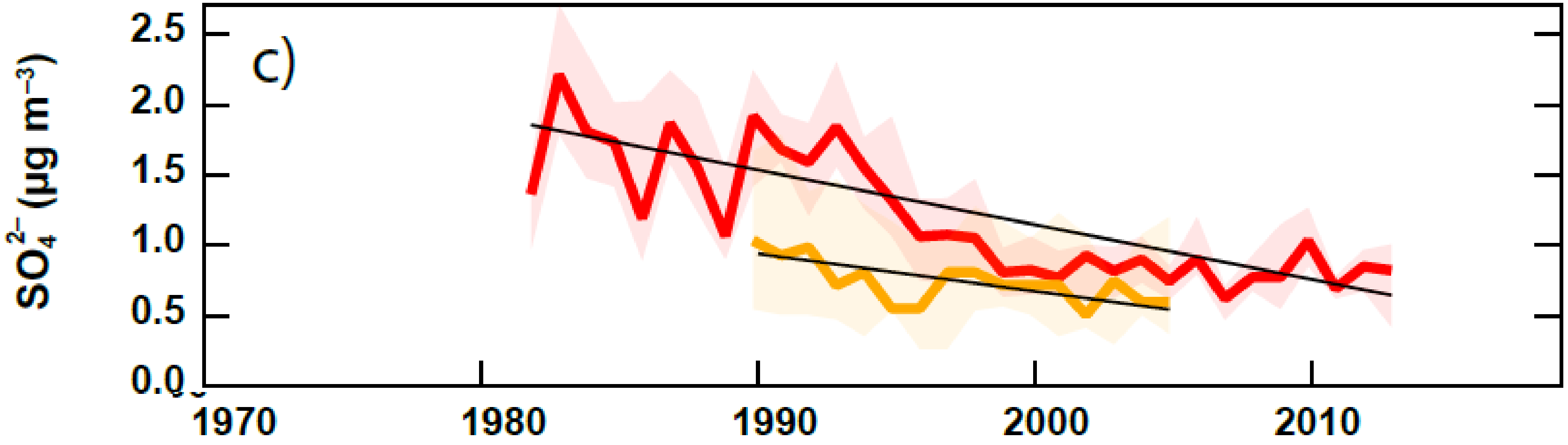
Cold air does not rise
→ Atmosphere is highly stratified
→ Heat is stuck at the surface
→ Surface experiences amplified warming

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

5. Aerosol effect

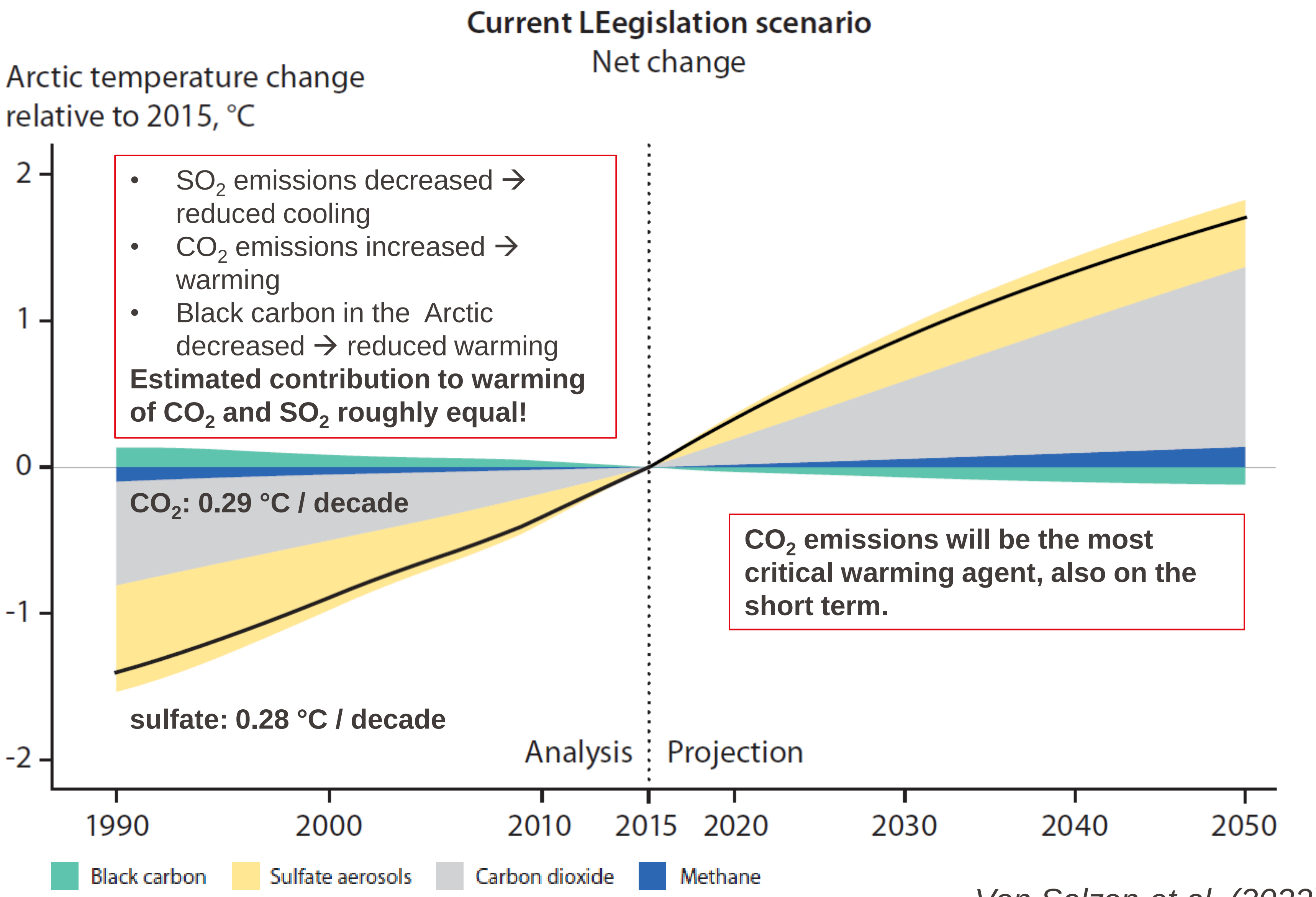
5

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



Schmale et al. (2022)

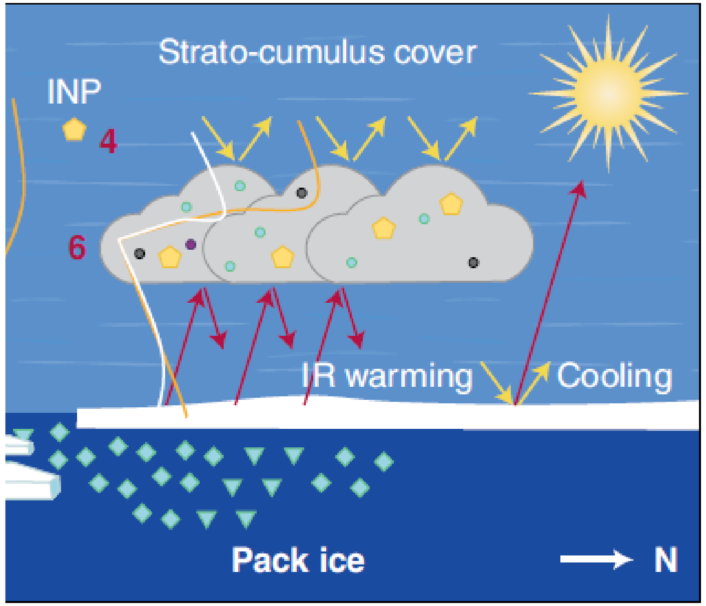
5. Aerosol effect

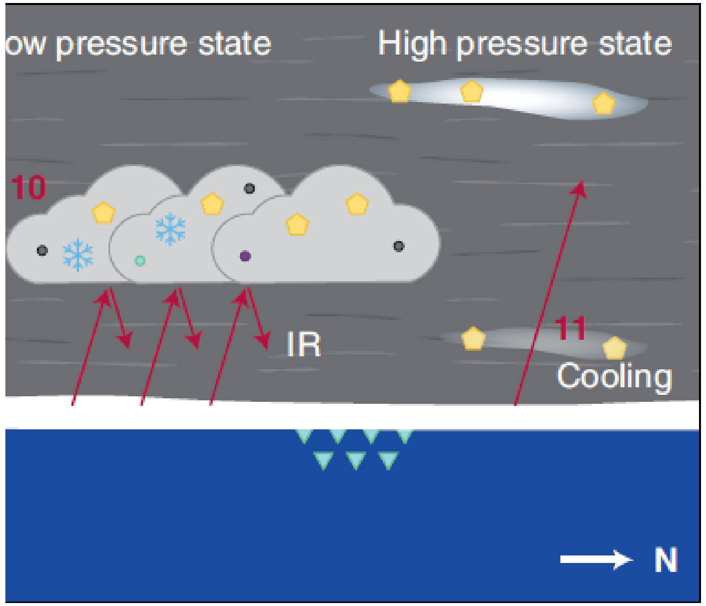


Von Salzen et al. (2022)

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.



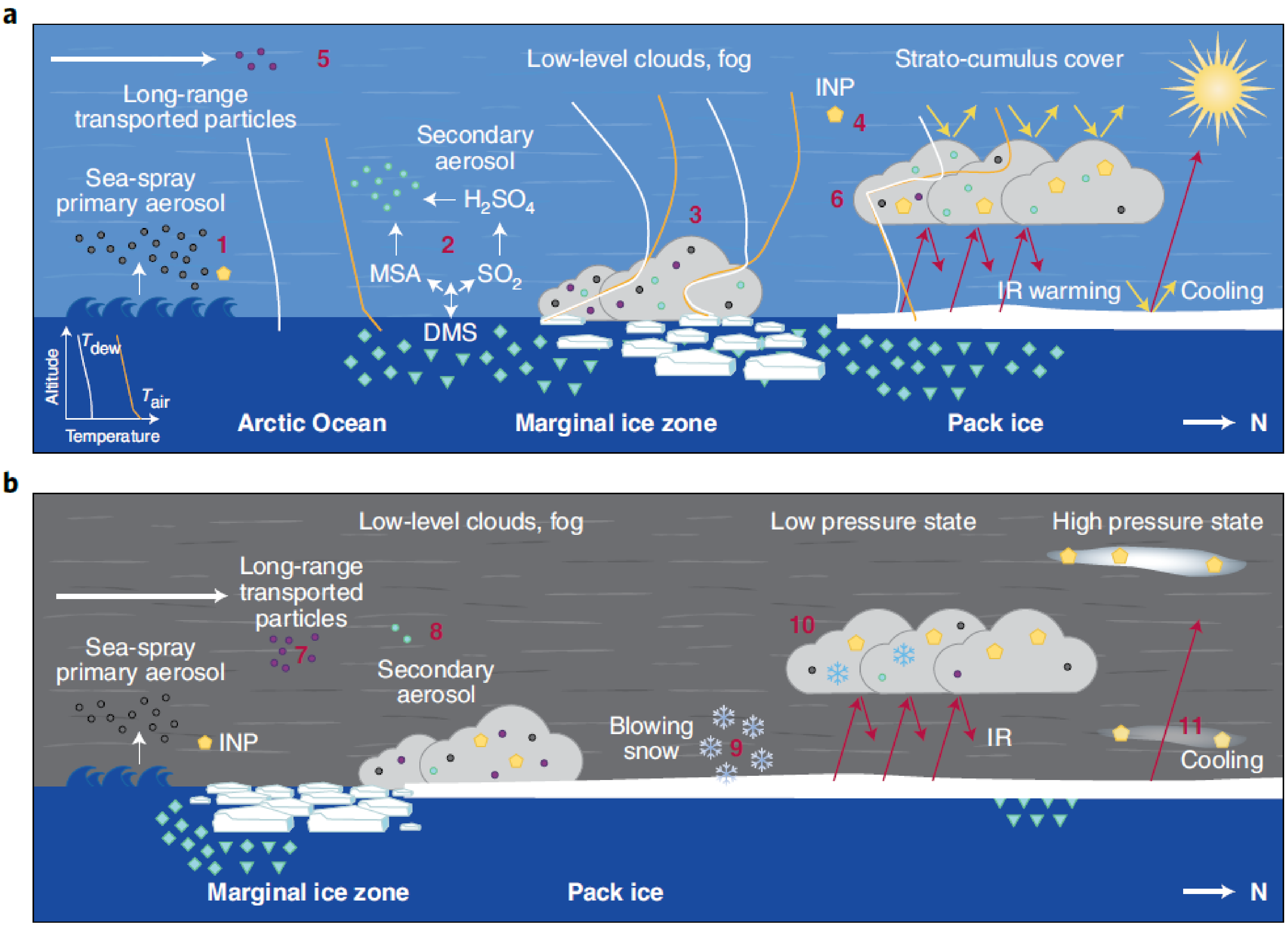


EPFL

5. More aerosol and cloud effects

EERL

This is what my group typically works on.



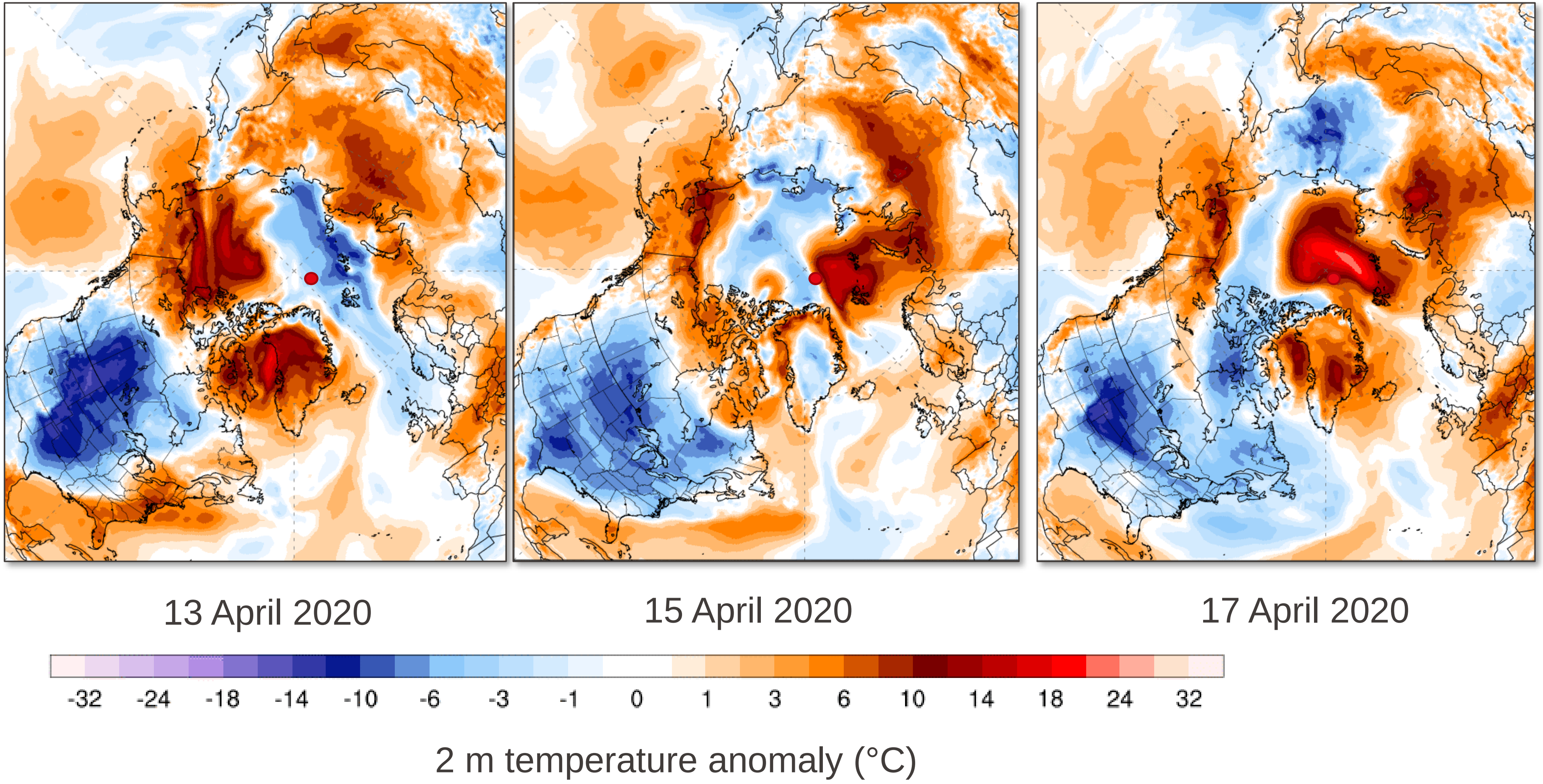
- Schmale et al. (2021)

Studying reasons for Arctic Amplification

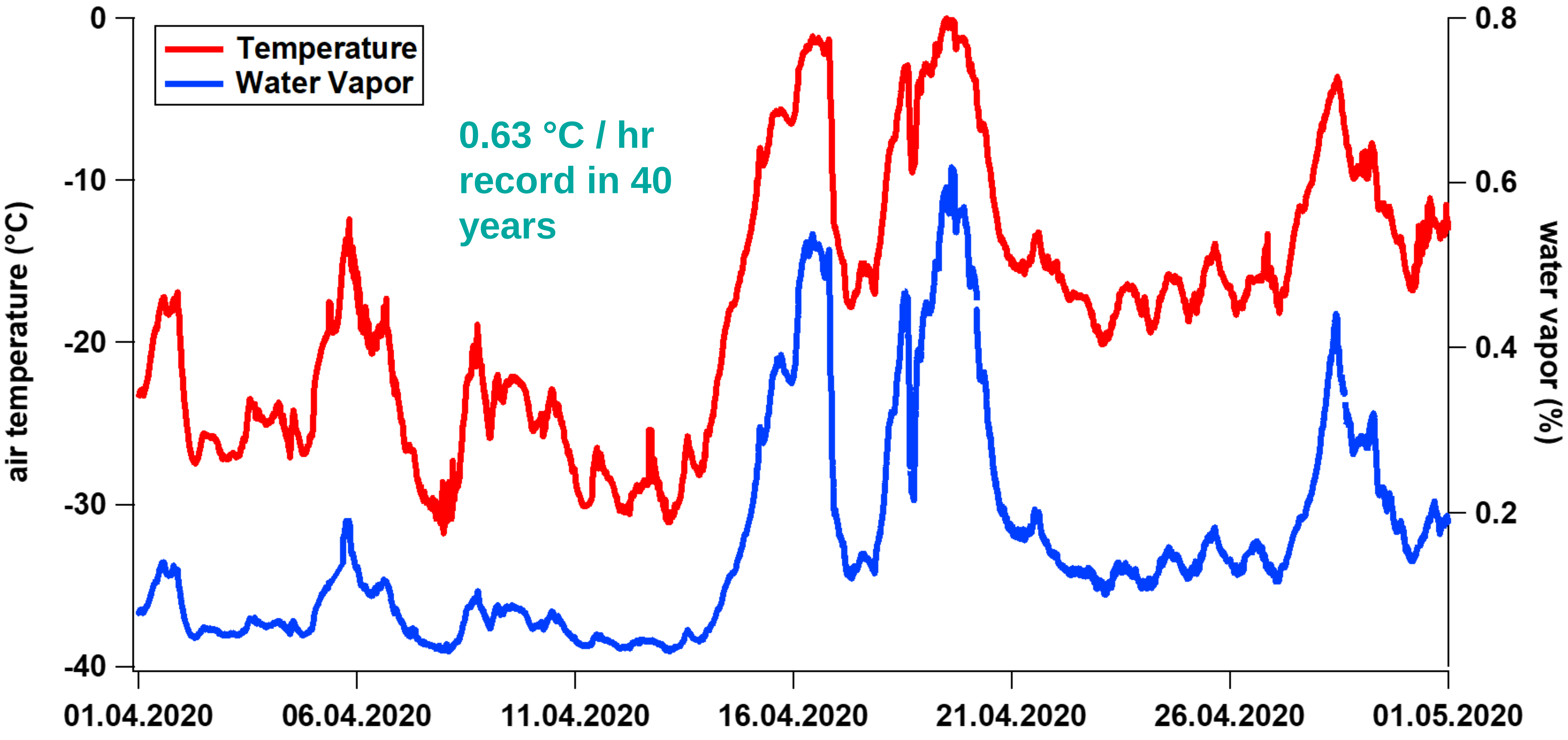
Credit: Oden Crew

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.



Warm air mass intrusion



- Dada et al. Nat. Commun., 2022

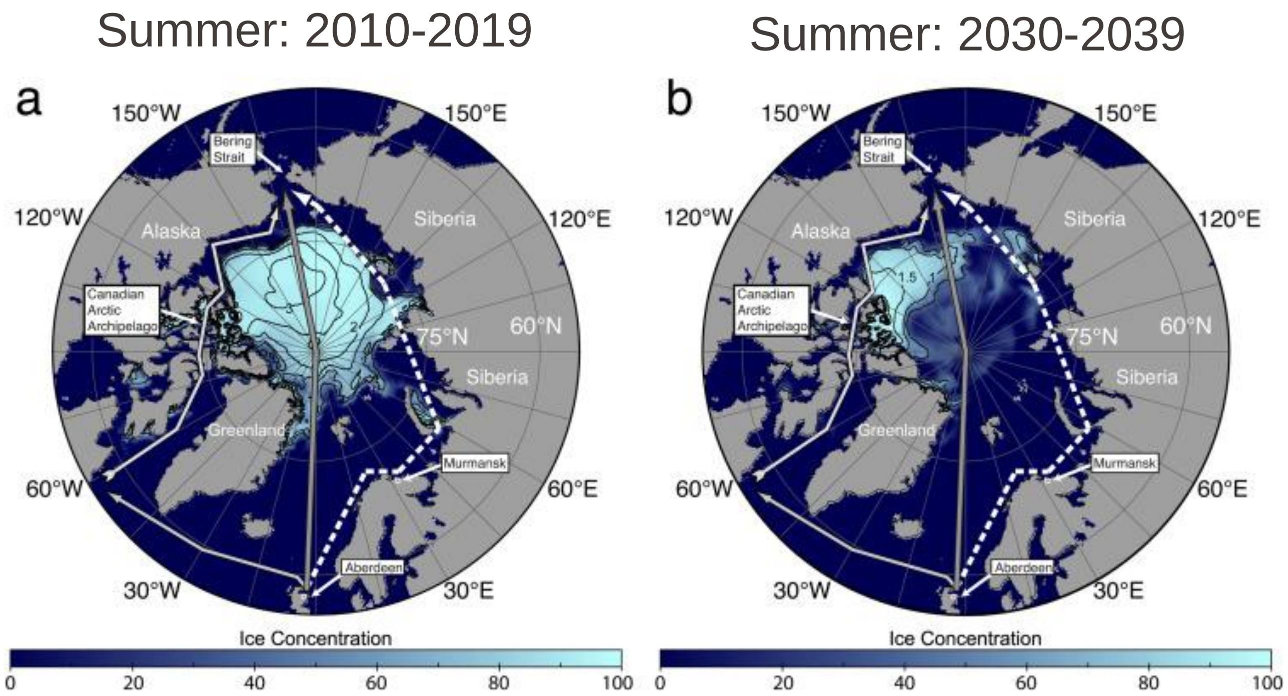
Warm and moist air mass approaching

Sea ice breaks up with the strong winds

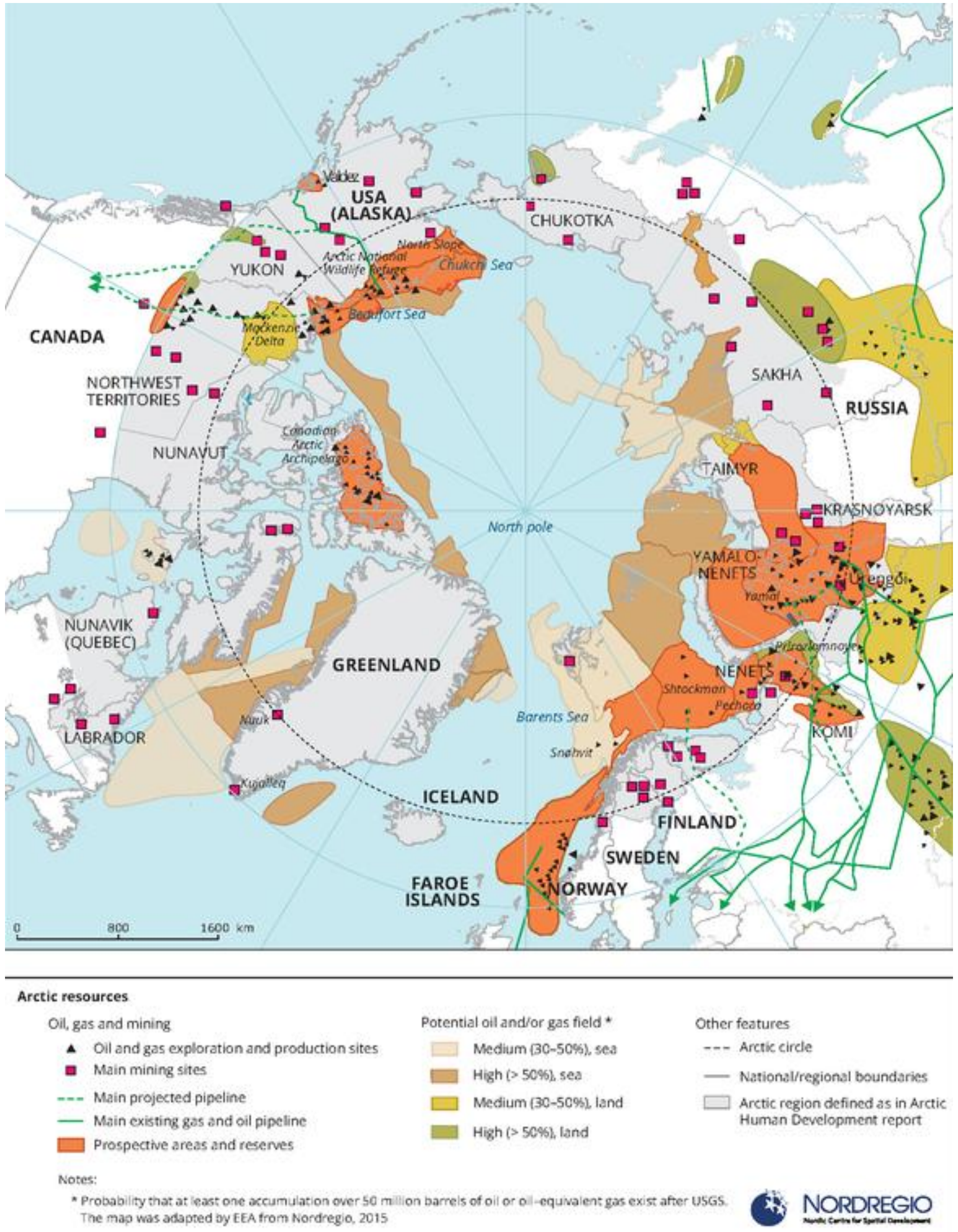
Glare at the surface because of melt (called meltspiegel)

Drifting one year in Arctic sea ice

Implications: shipping and resources



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



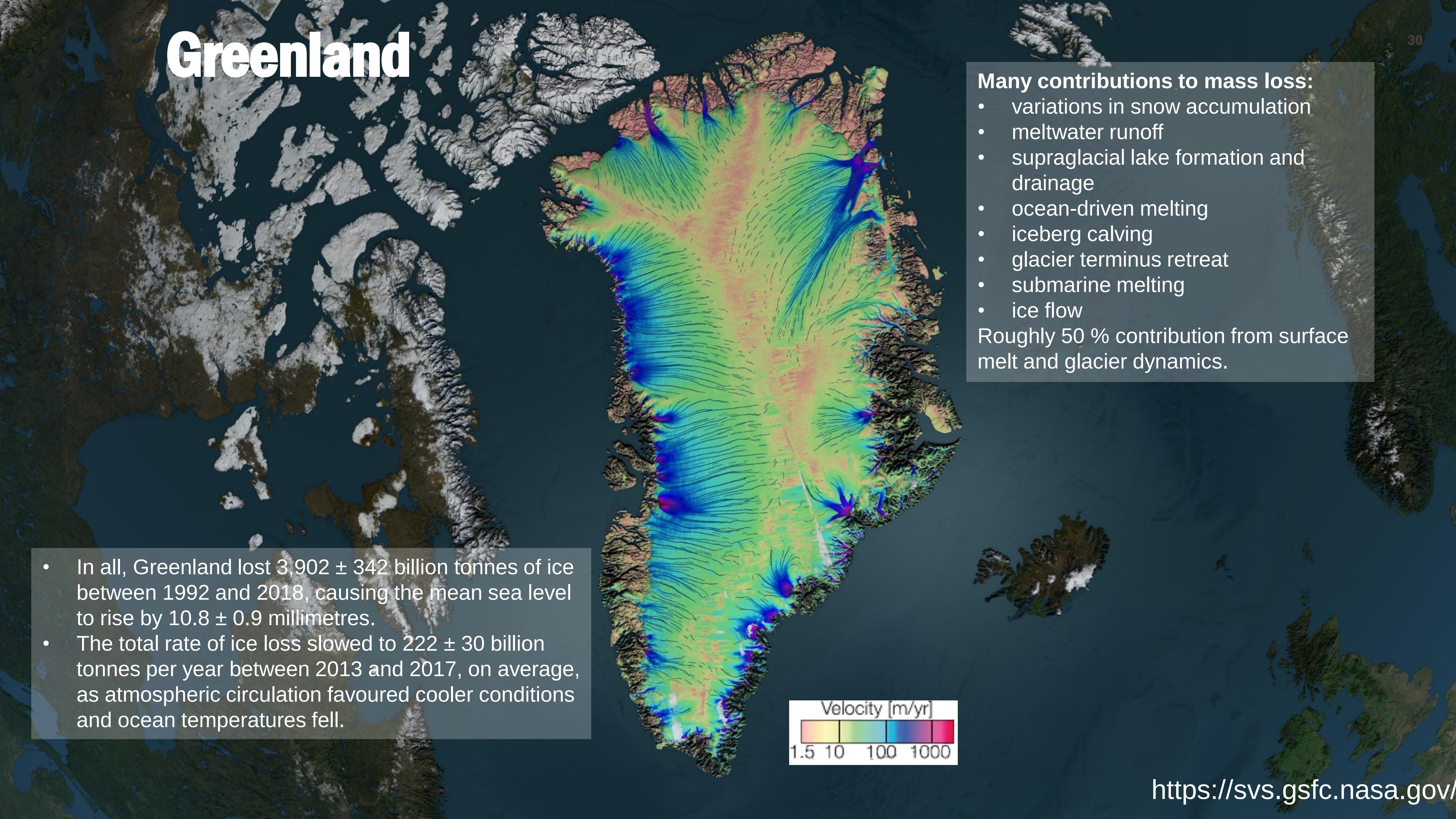
- Aksenov et al. (2017), Gautier et al. (2009)

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.

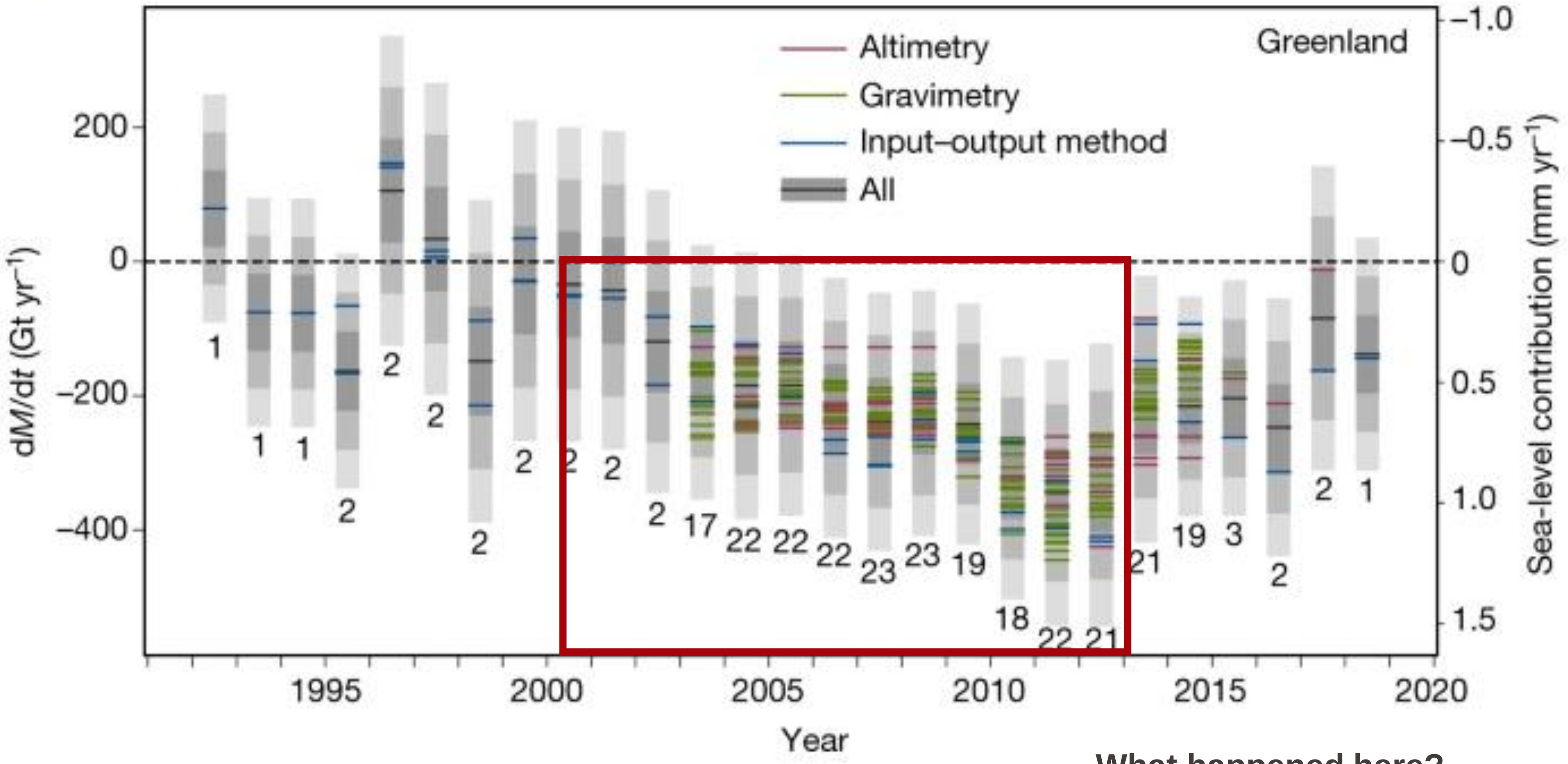


- In all, Greenland lost 3,902 ± 342 billion tonnes of ice between 1992 and 2018, causing the mean sea level to rise by 10.8 ± 0.9 millimetres.
- The total rate of ice loss slowed to 222 ± 30 billion tonnes per year between 2013 and 2017, on average, as atmospheric circulation favoured cooler conditions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

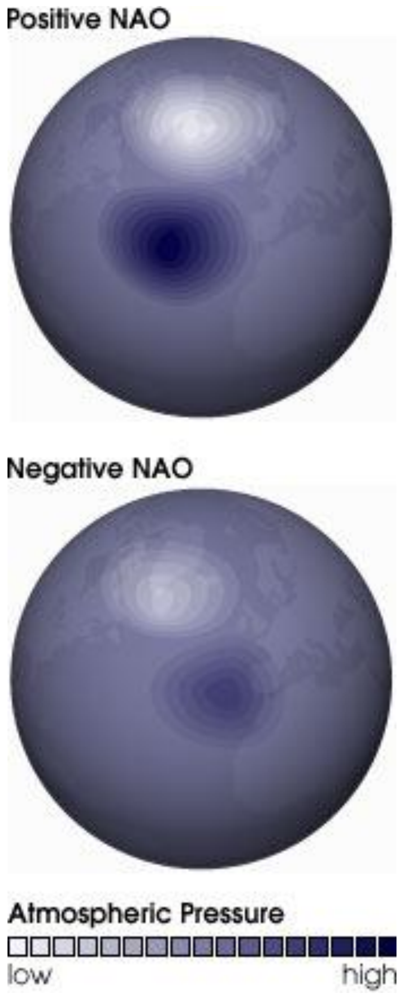
https://svs.gsfc.nasa.gov/

Greenland

Fig. 2: Greenland Ice Sheet mass balance.



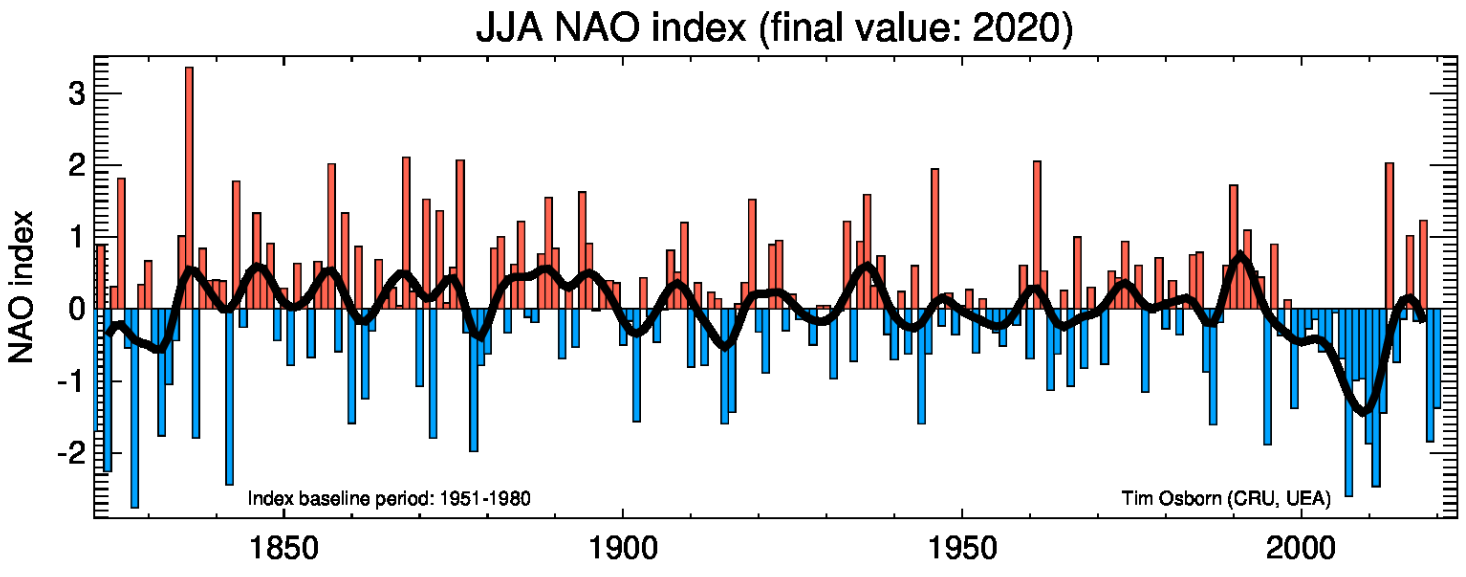
What happened here?



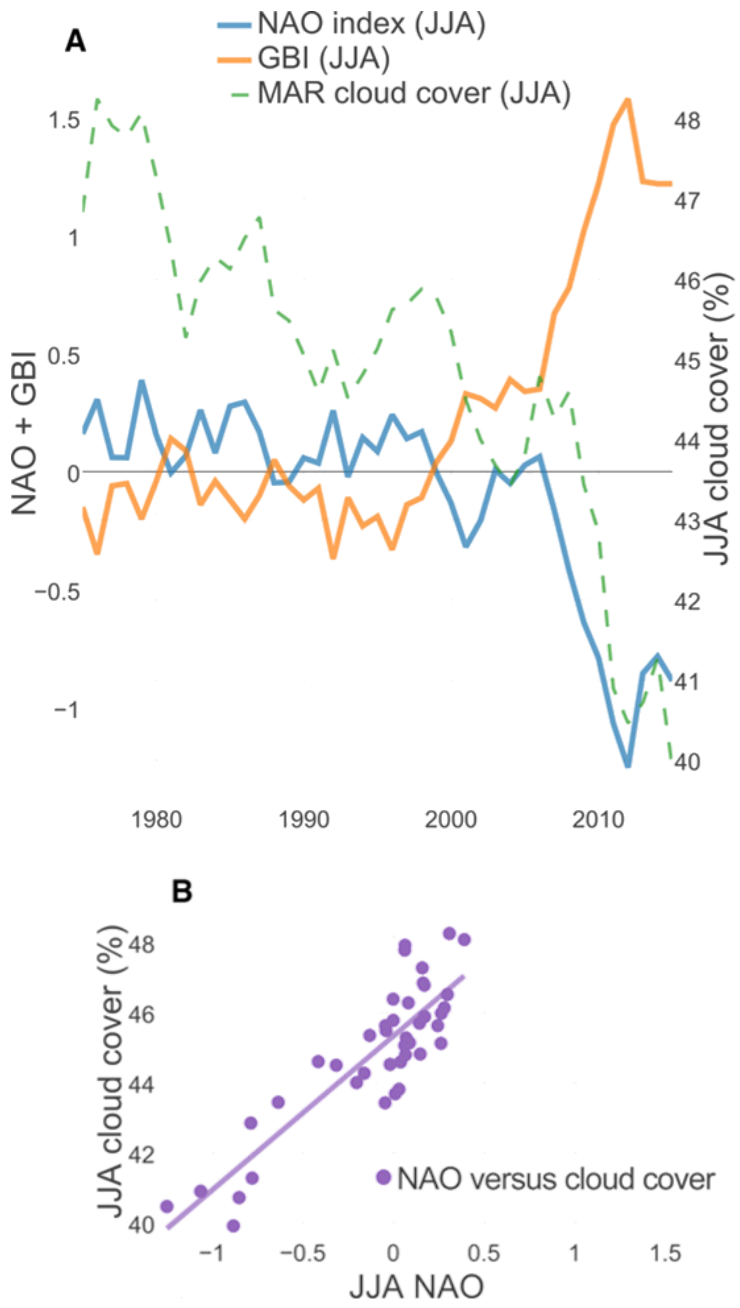
Oscillation between pressures states of the Icelandic Low and Azores High. Their state influences the location and strength of the jet stream.

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

Greenland



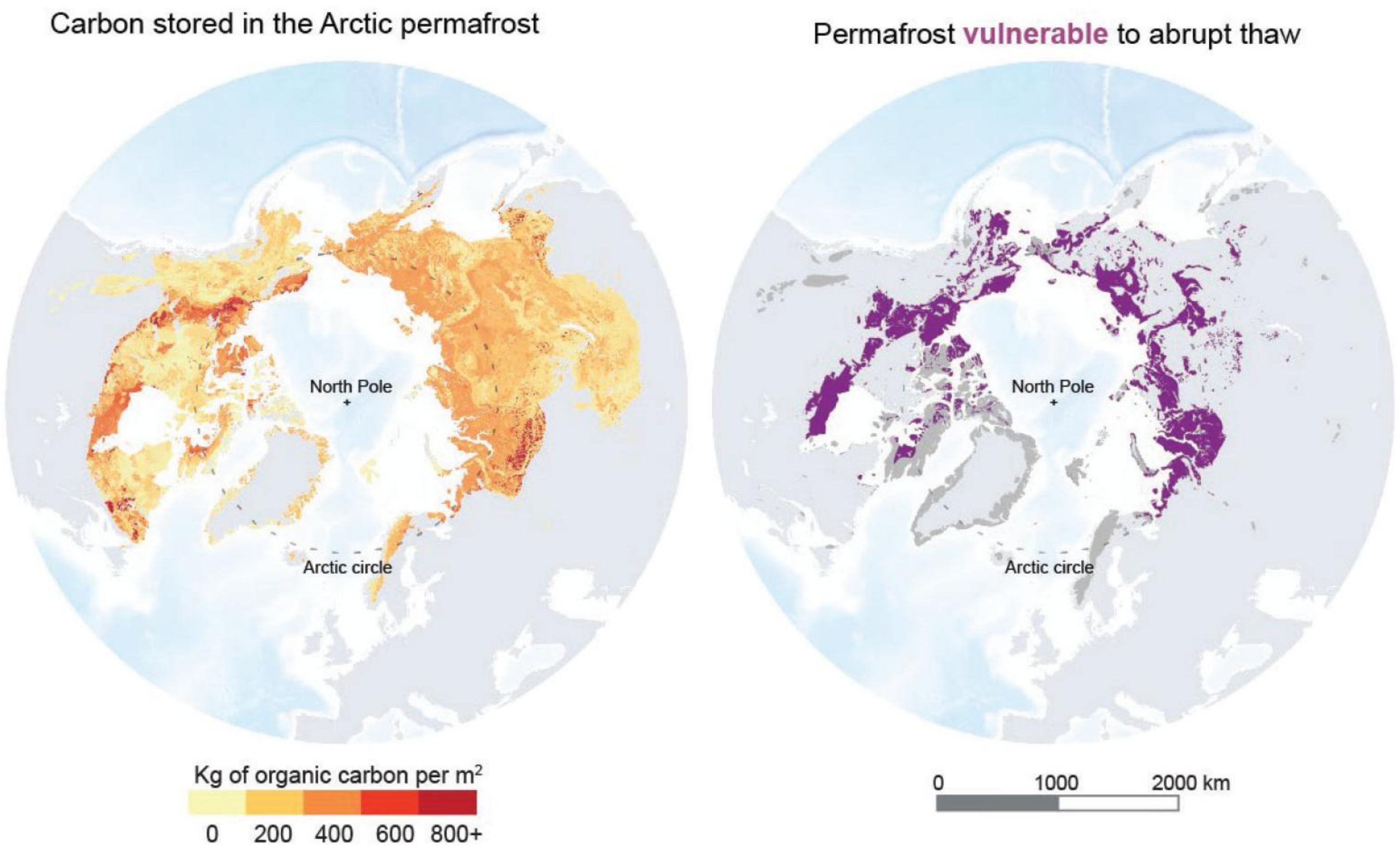
https://crudata.uea.ac.uk/cru/data/nao/viz.htm



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

NAO: North Atlantic Oscillation
GBI: Greenland Blocking Index

Arctic permafrost carbon



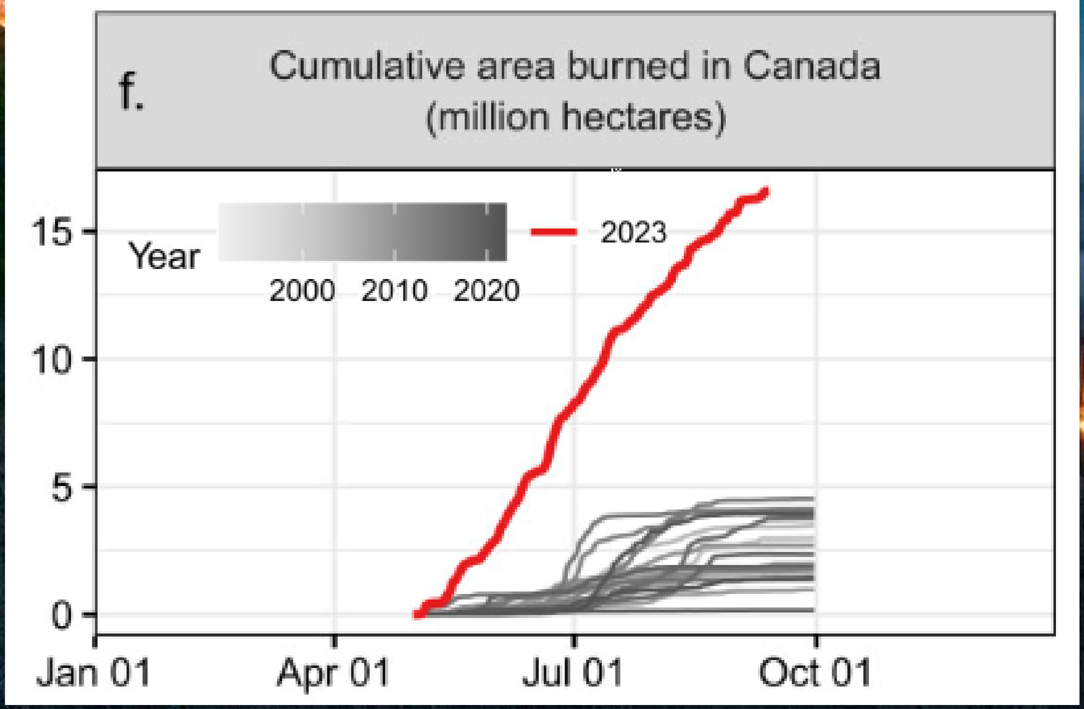
- Arctic permafrost stores 2 x the atmospheric carbon budget.
- Projections from models of permafrost ecosystems suggest that future permafrost thaw will lead to some additional warming – enough to be important, but not enough to lead to a 'runaway warming' situation, where permafrost thaw leads to a 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

EPFL

More and more intense forest fires in the boreal belt

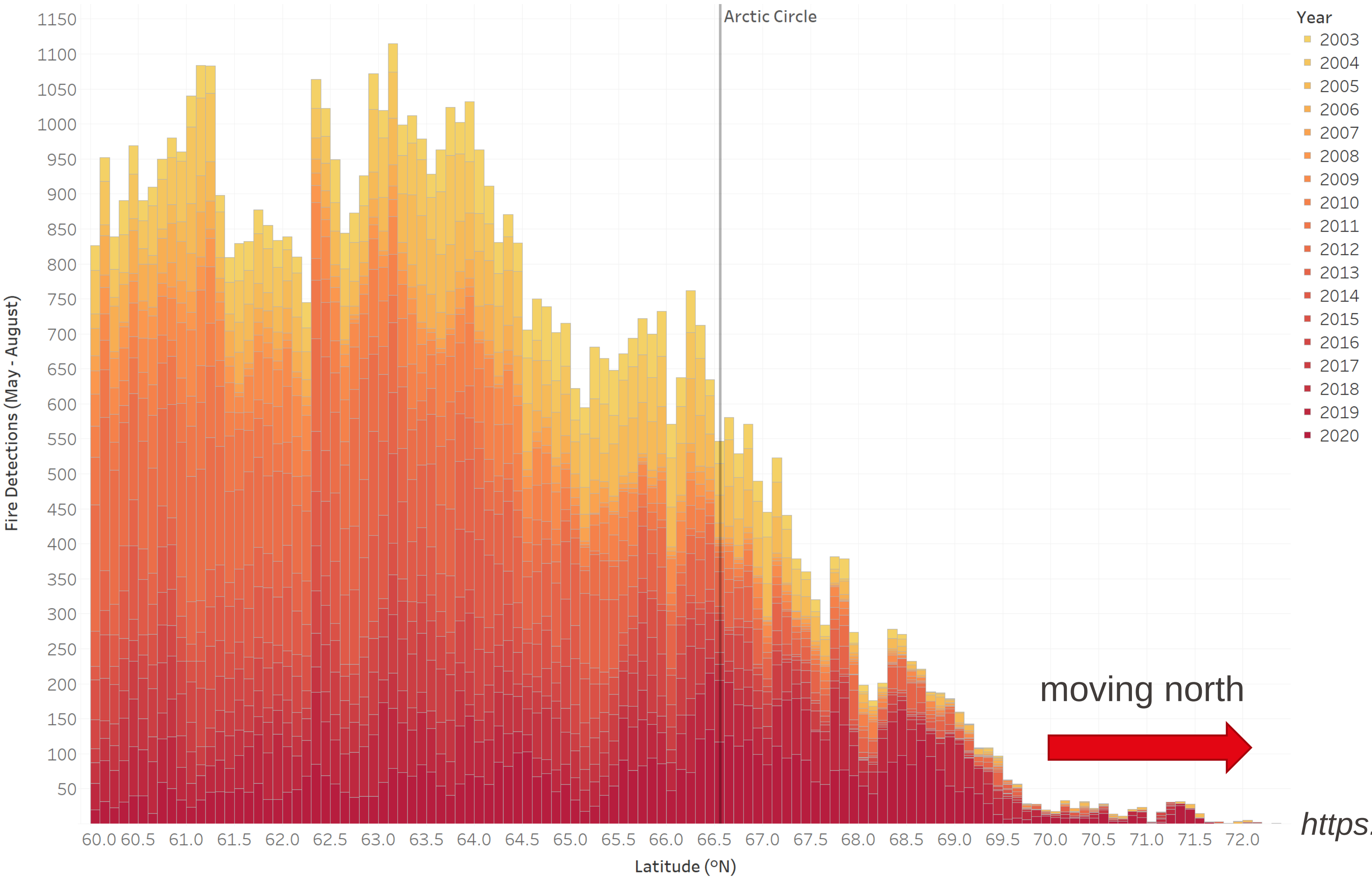
Not a tipping point, but important and not projected



- 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

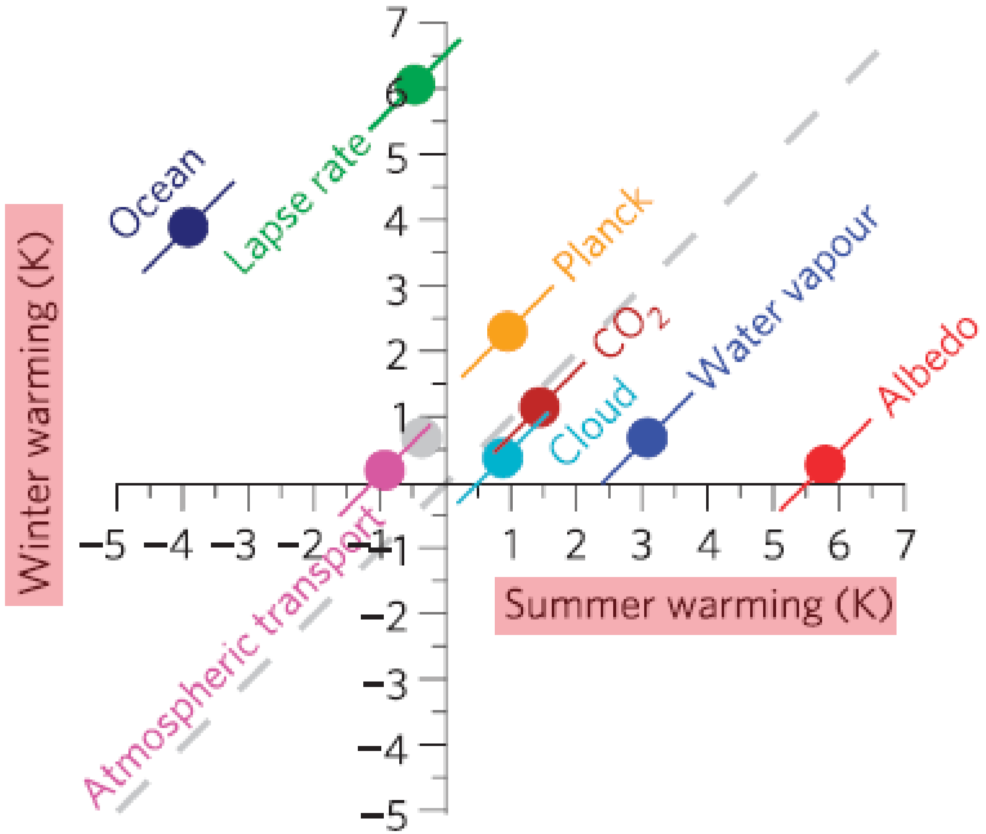
Arctic Fires



https://twitter.com/DrTELS

Contributors to amplification

Arctic

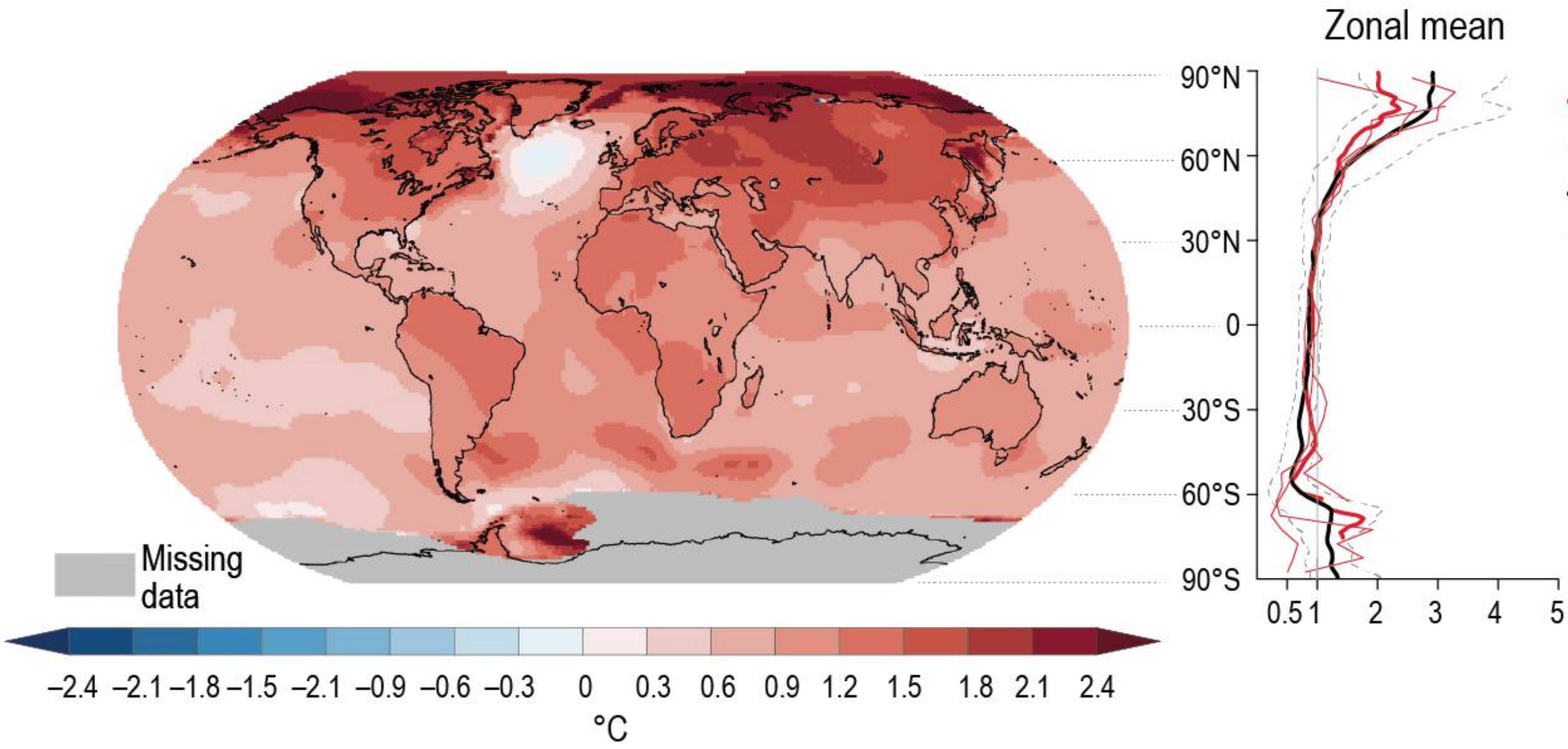


Antarctica

?

- Pithan and Mauritsen (2014)

Difference between the Arctic and Antarctic

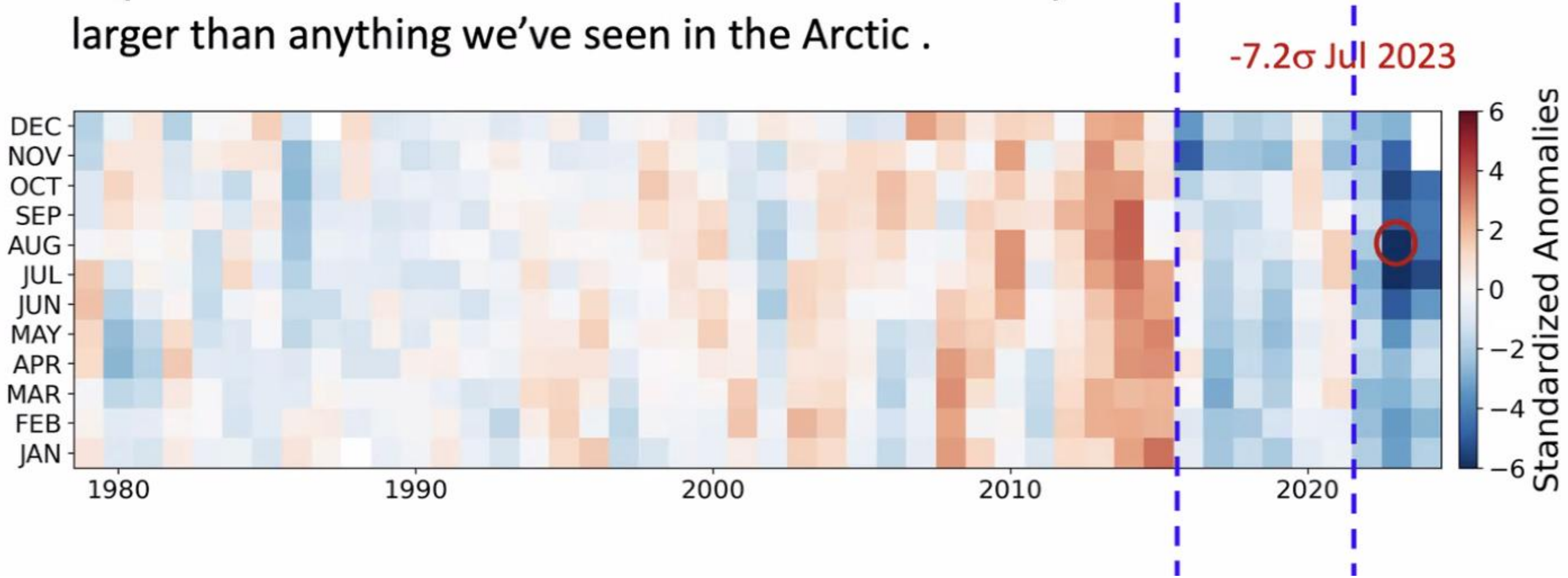


- Difference between the Arctic and Antarctic:
  - The Southern Ocean takes up a lot of excessive warming (bigger buffer).
  - Due to circulation patterns there is less poleward heat transport to the Antarctic, whereas this mechanism is very important in the Arctic.

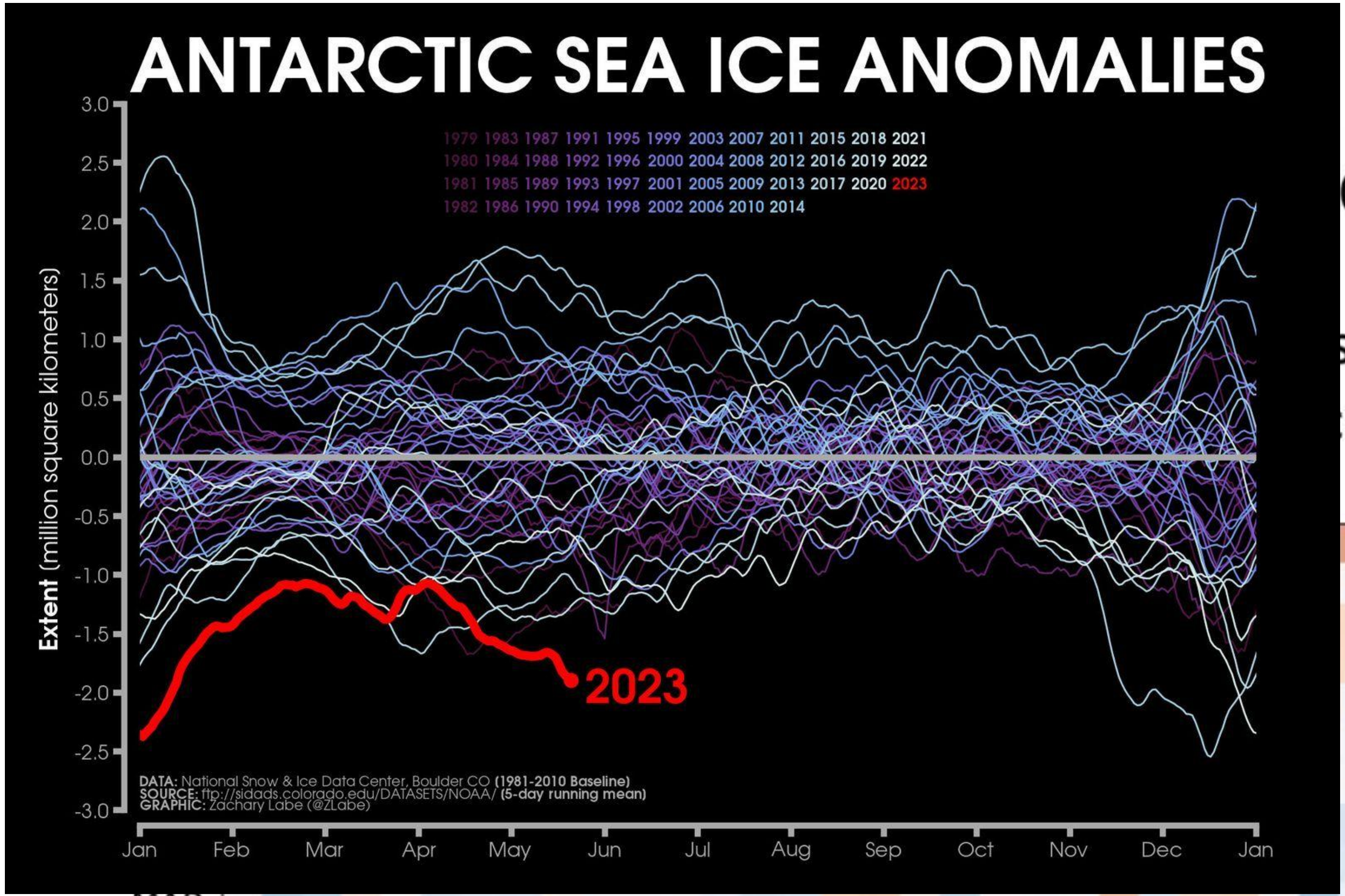
Antarctic sea ice state

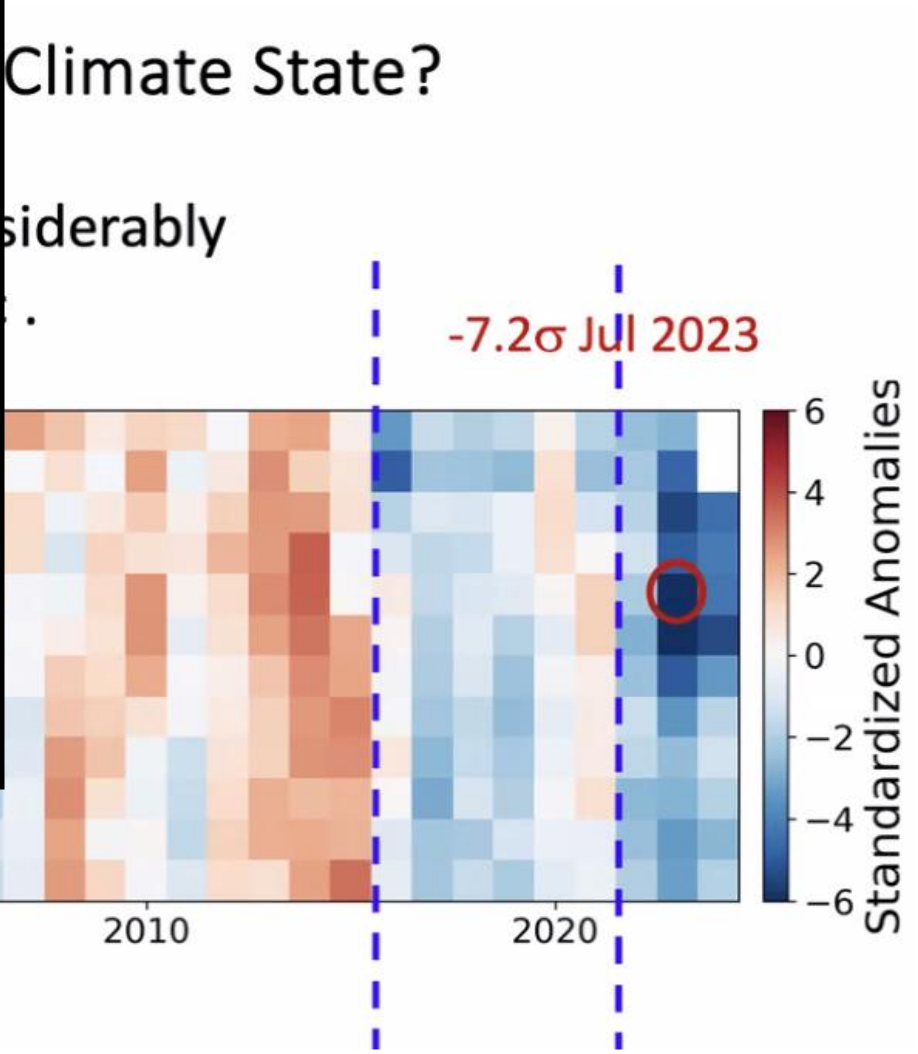
Antarctic Sea Ice – New Climate State?

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

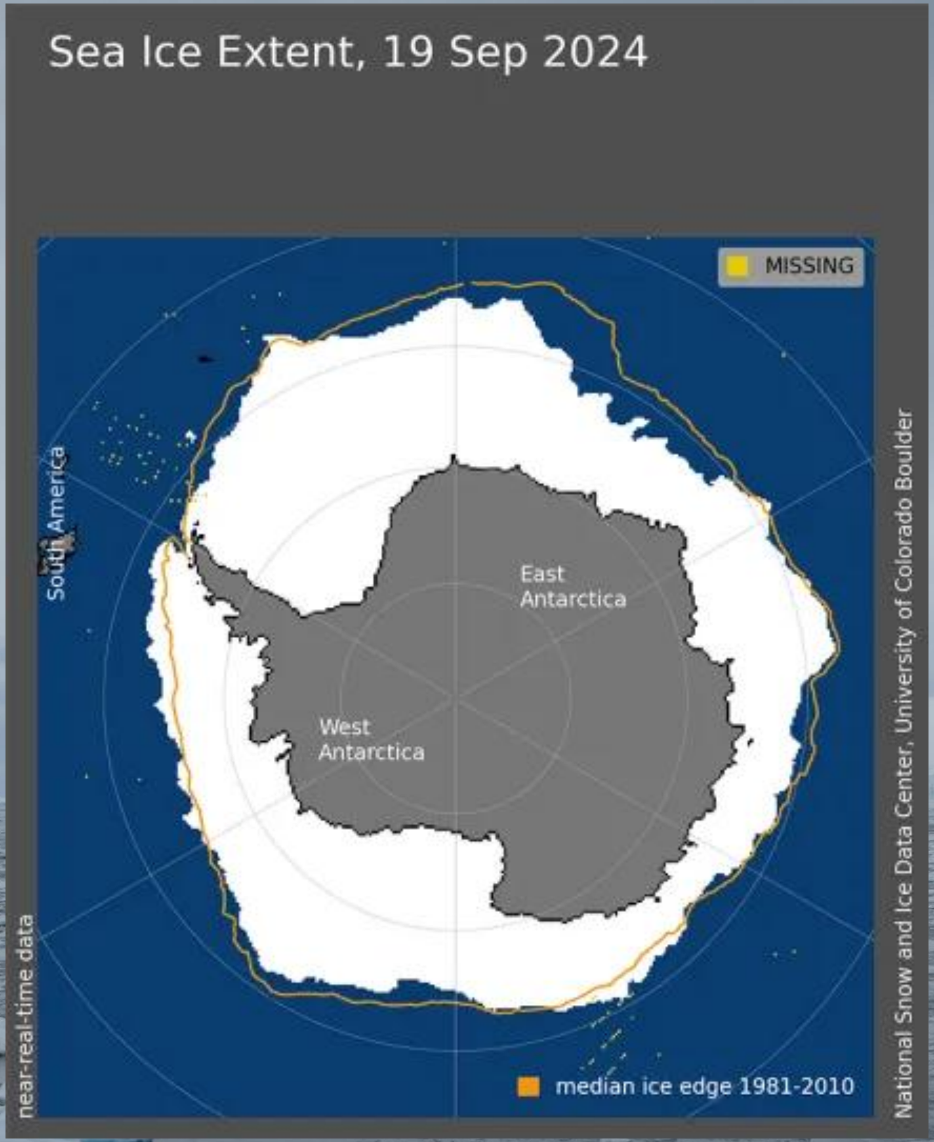


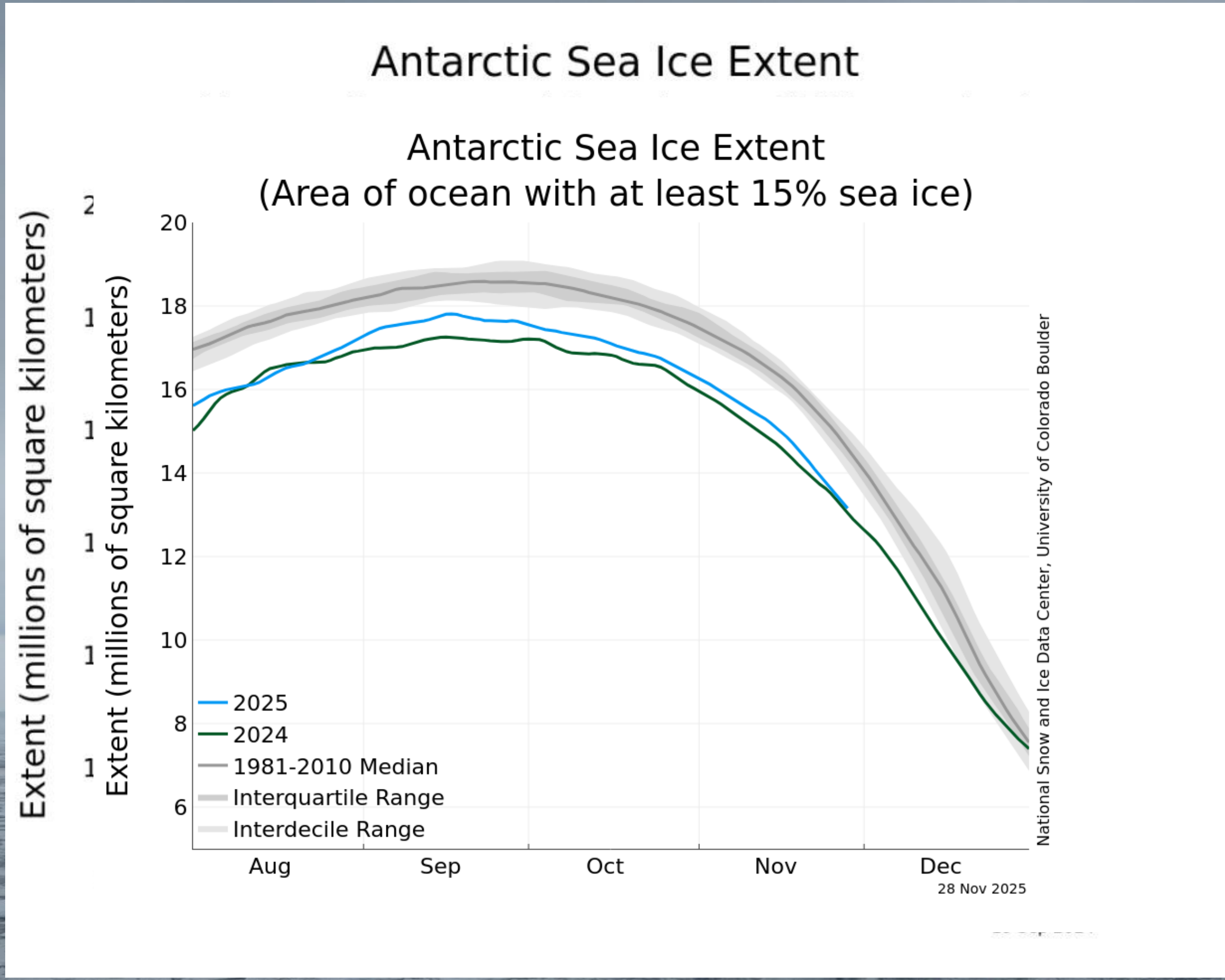
Antarctic sea ice state





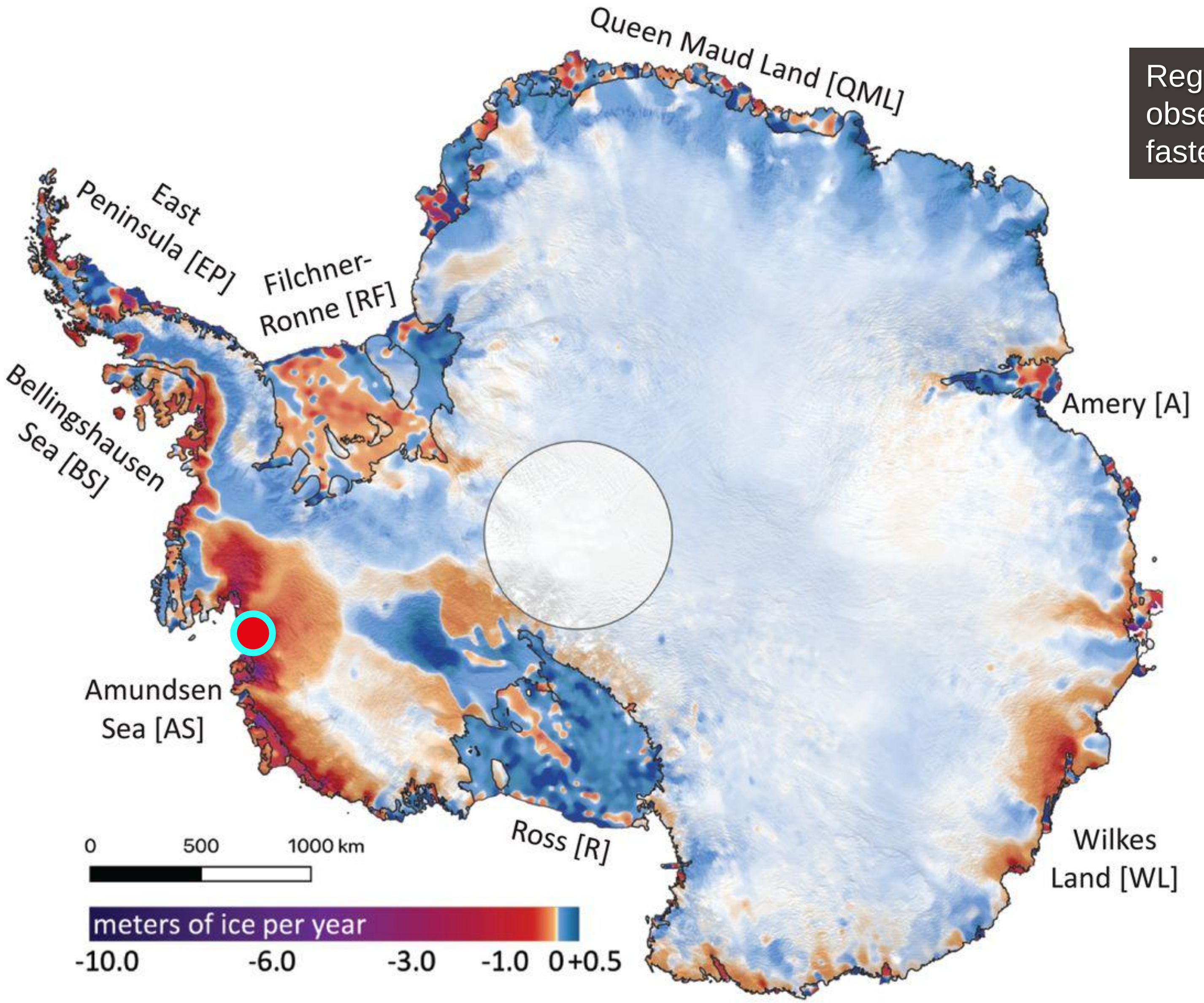
Current Antarctic sea ice shrinkage





NSDIC.org

Land ice melt in Antarctica



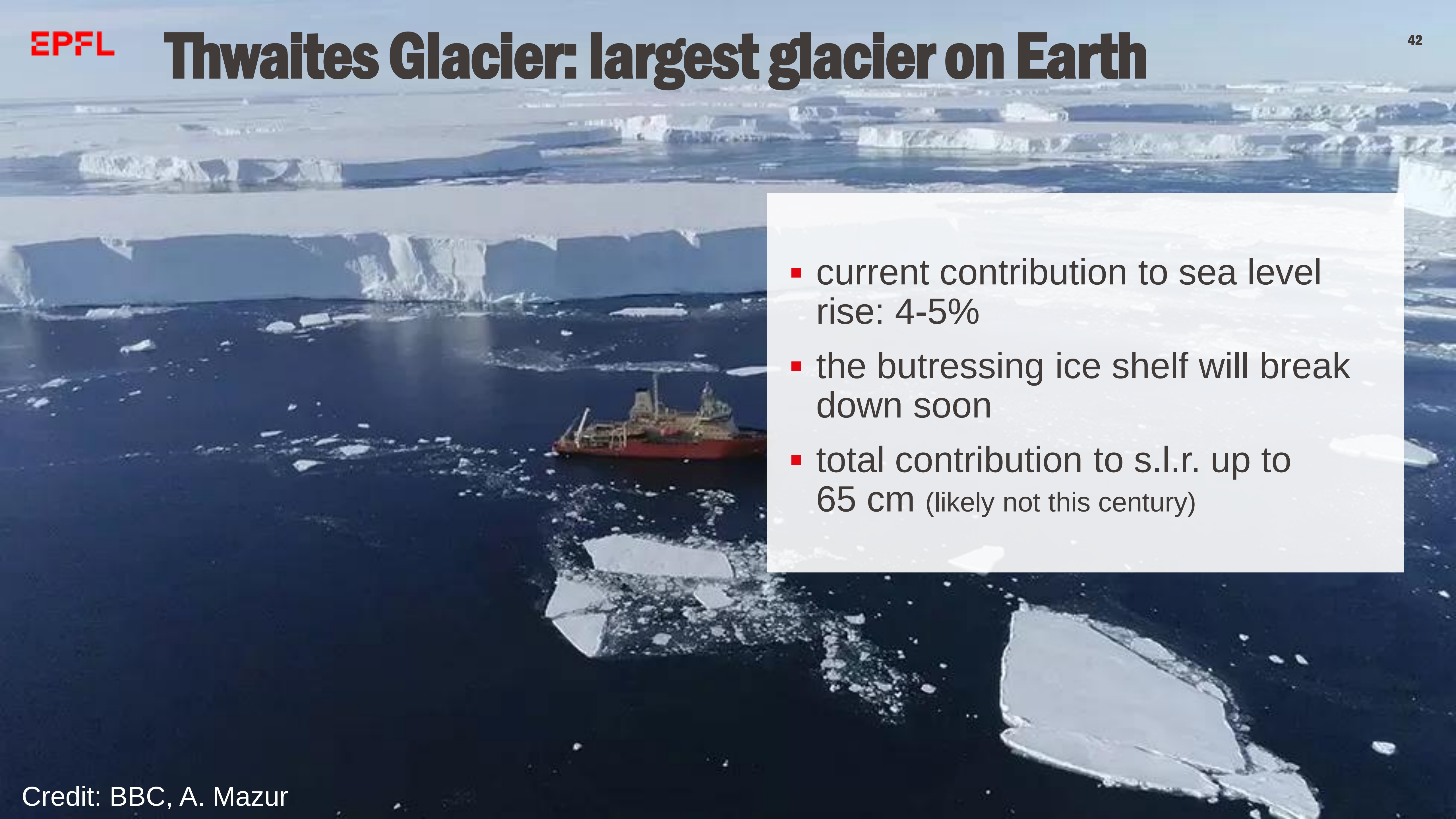
Regional warming observed to be 2x faster than modeled

Bottom melt (warm ocean)

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

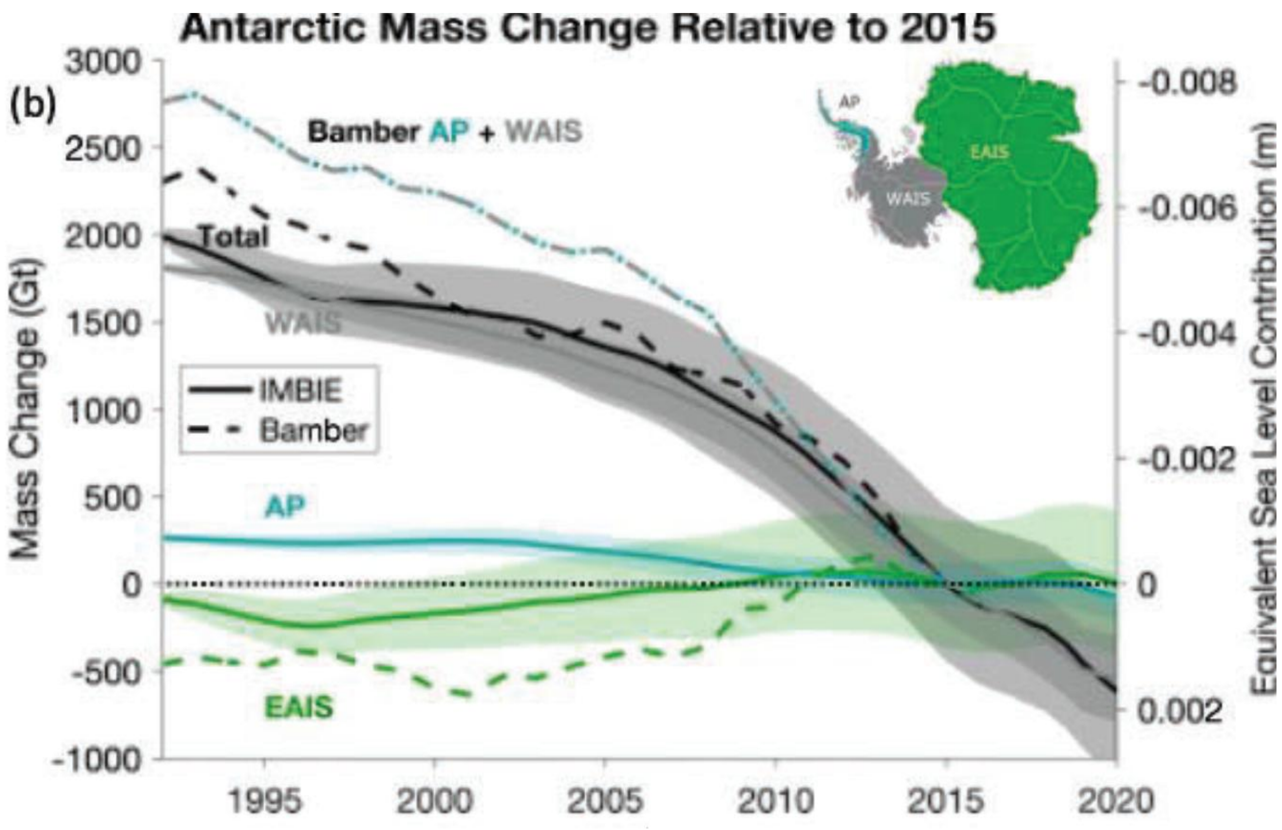
Thwaites Glacier: largest glacier on Earth

- 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.

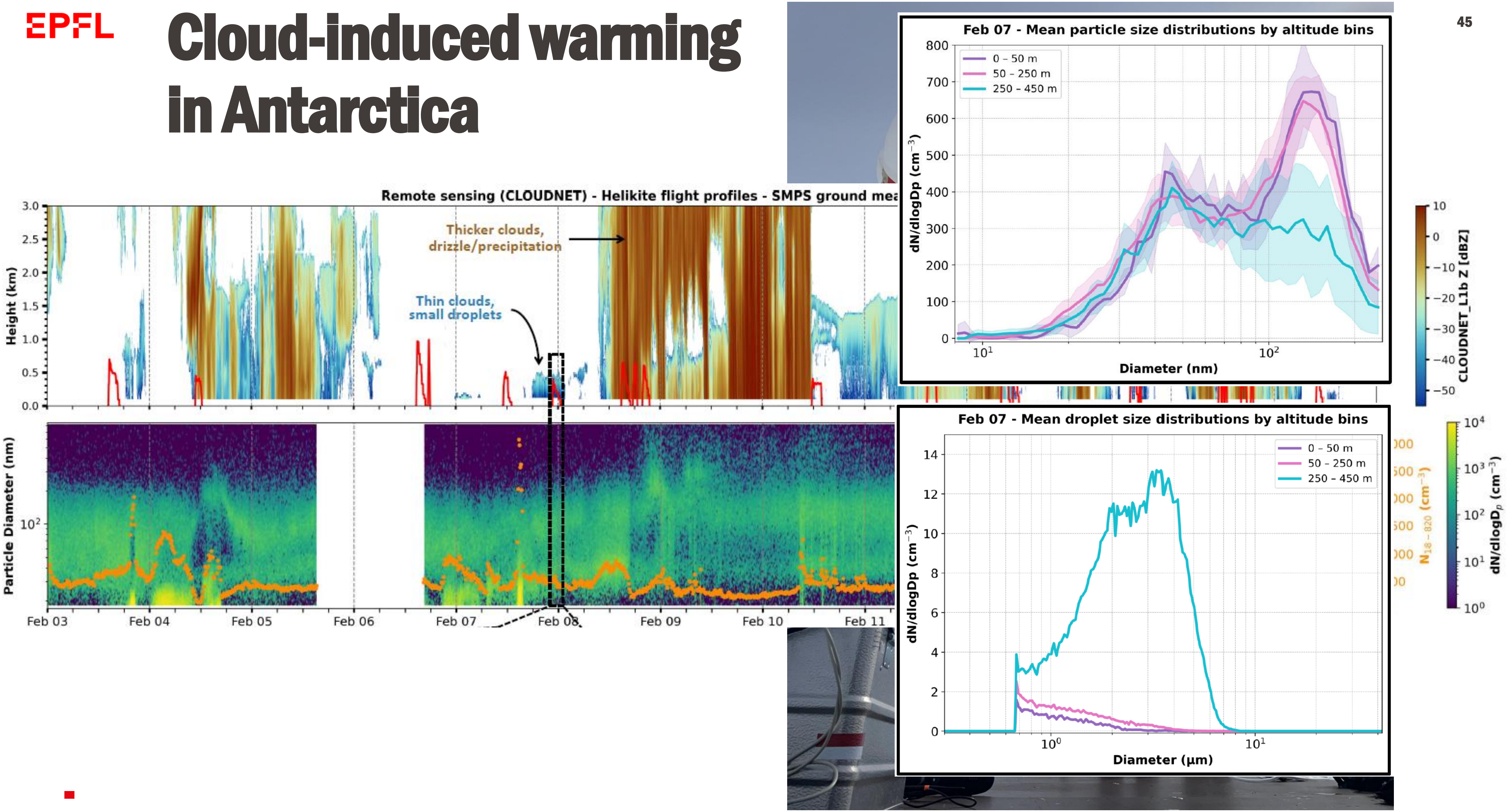
AP: Antarctic Peninsula
WAIS: West Antarctic Ice Sheet
EAIS: East Antarctic Ice Sheet
IMBIE, Bamber are two different references

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

- IPCC AR6, Fig. 9.16

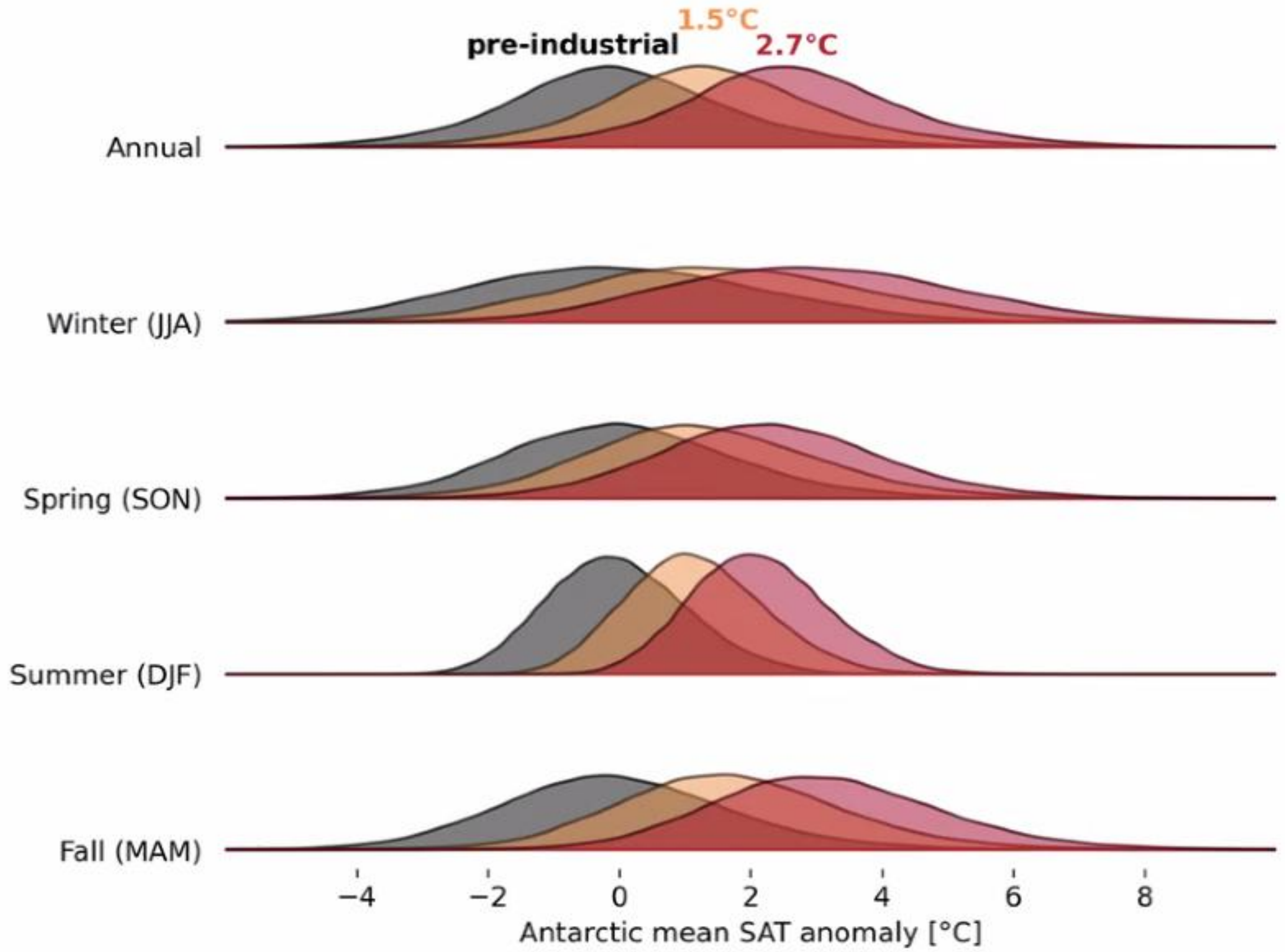
Cloud-induced warming in Antarctica

Cloud-induced warming in Antarctica



Future of Antarctica

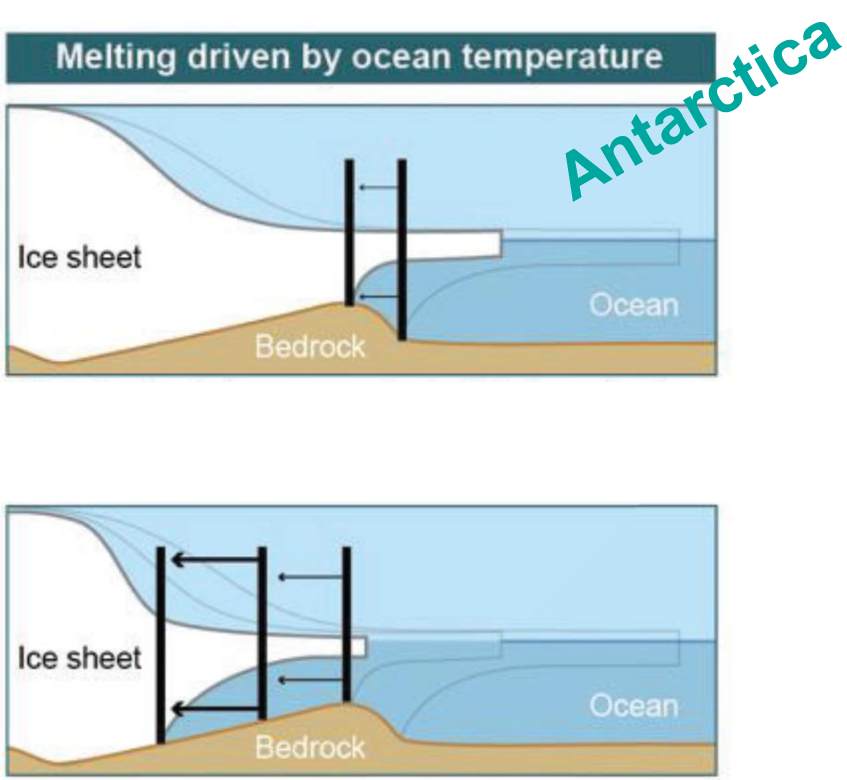
What Does the Future Hold? - Antarctic



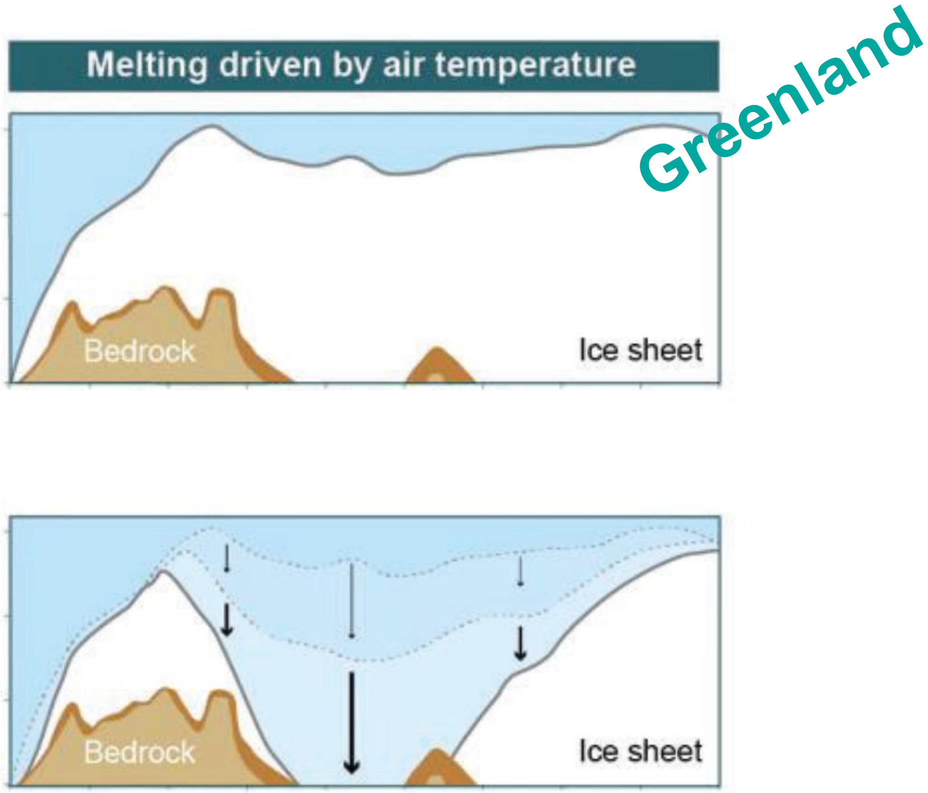
- In the Antarctic future temperature changes at 1.5 and 2.7ºC overlap with present day conditions.

J. Stroeve

Different drivers of melt for Greenland and Antarctica



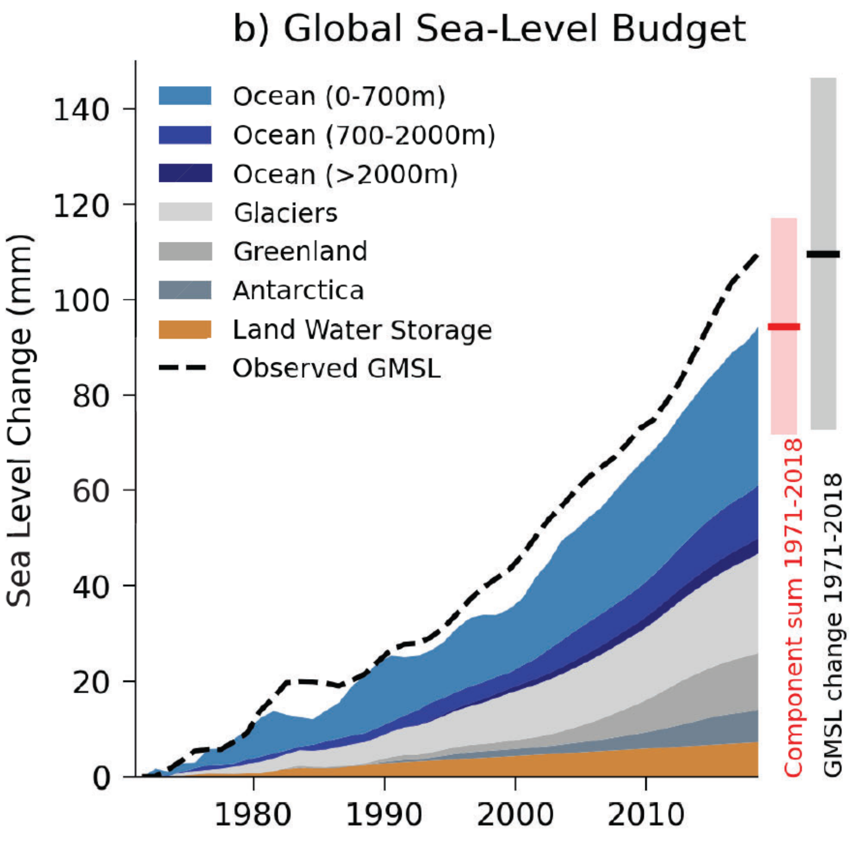
The ice shelf (on the ocean) keeps the ice sheet from flowing into the ocean. If the ice shelf becomes thinner and smaller, the ice sheet can flow faster.



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

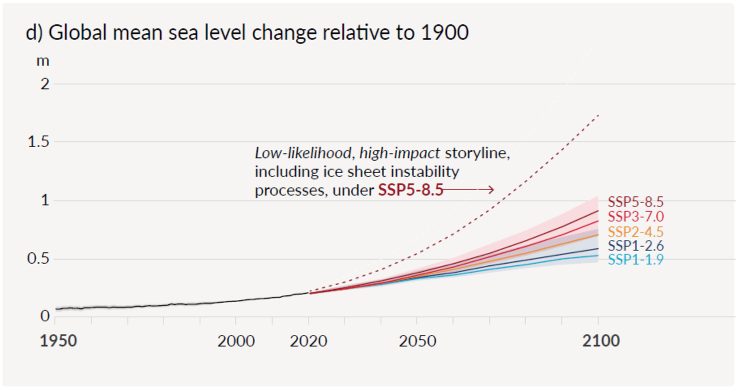
Sea level rise

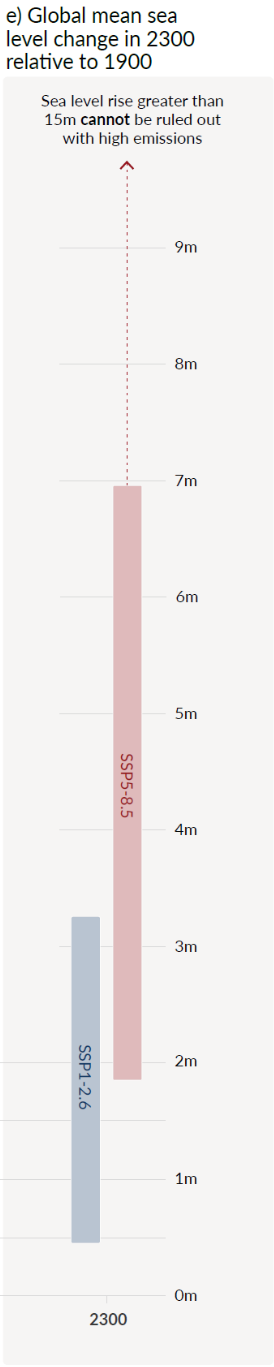


- **Thermal expansion: 50 %**
- **Glaciers: 22 %**
- **Ice sheets: 20 %**

Marine Ice Cliff Instability (MICI)

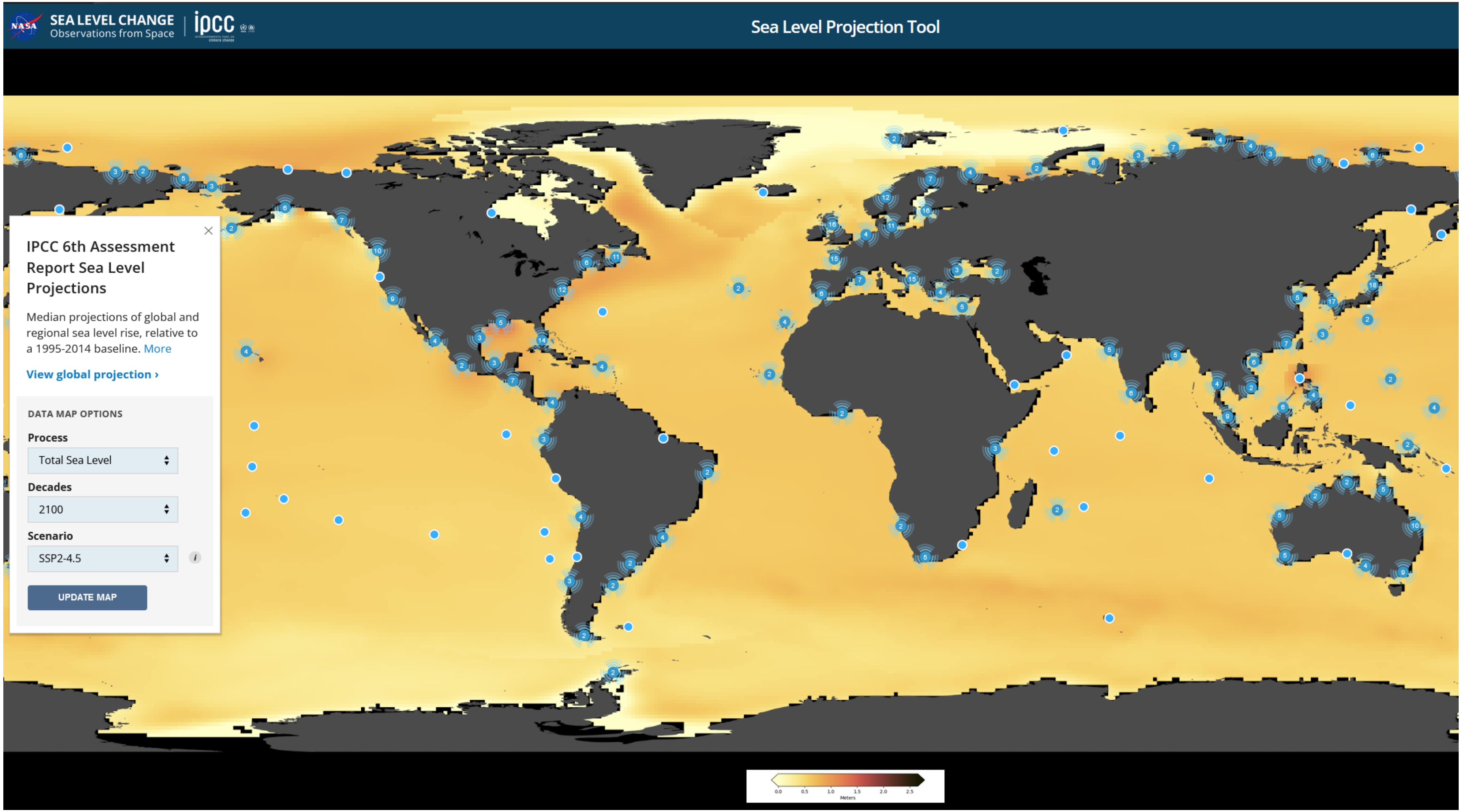
Sea level rise is nurtured by slow processes such as ice sheet melting and will hence continue well after temperatures have stabilized in the atmosphere.





- 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

Extra

Albedo effect: snow cover

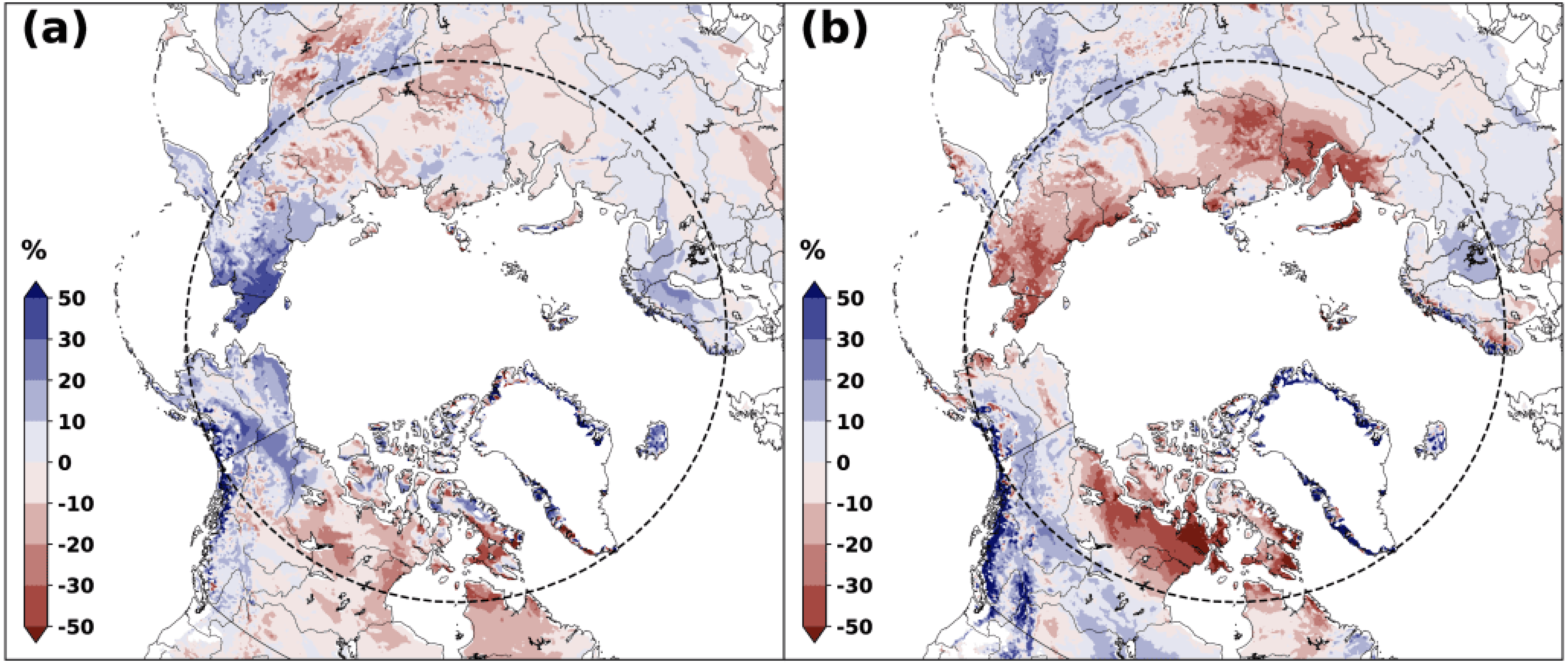
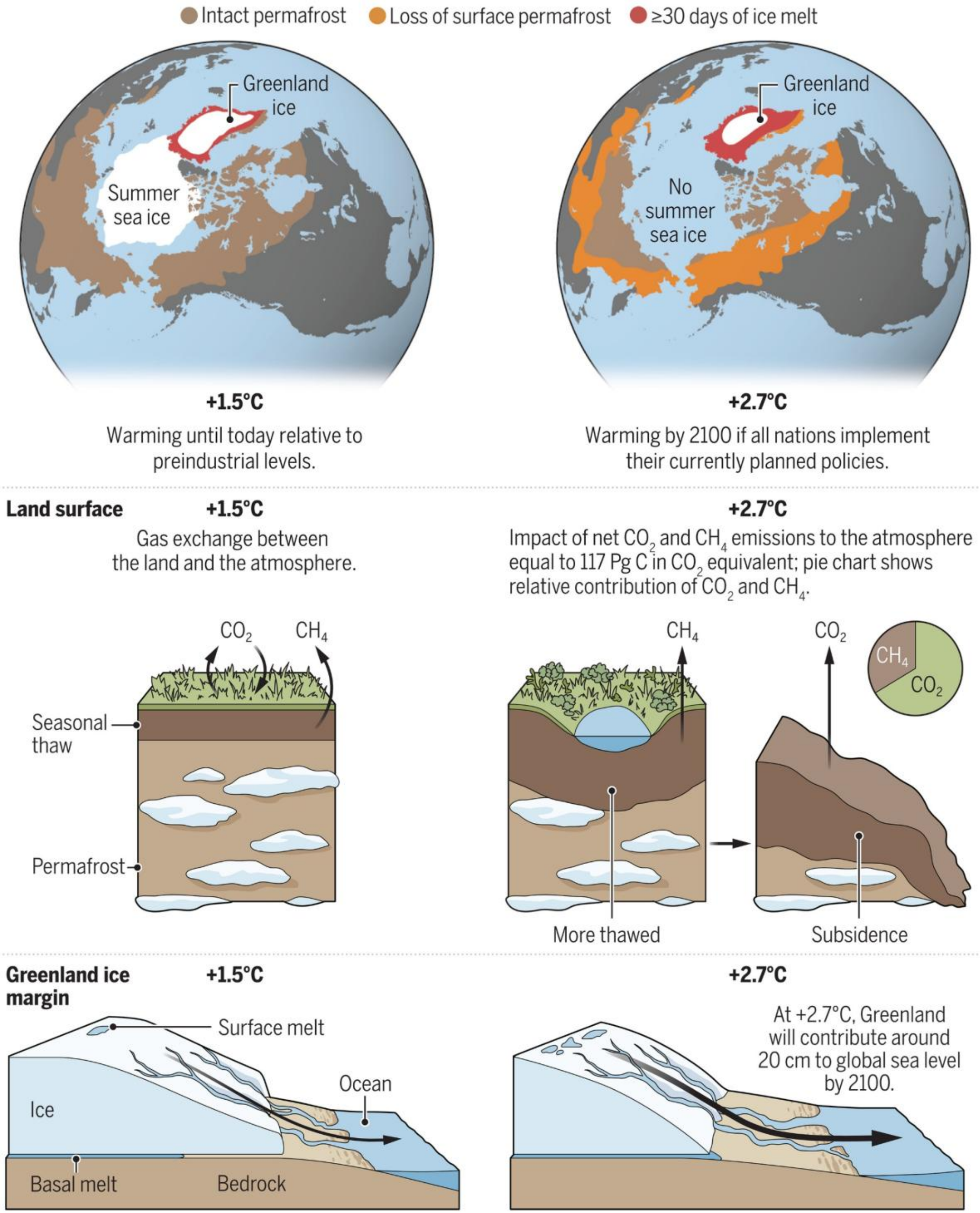


Fig. 2. Snow cover duration anomalies (% difference relative to average number of snow-free days) for the 2021/22 snow year: **(a) snow onset (Aug-Jan); and (b) snow melt (Feb-Jul).** Red (blue) indicates increased (decreased) snow-free days compared to the 1998/99 through 2017/18 mean. The dashed circle 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/

What the future holds



Shown are the changes in September sea-ice area, changes in the Greenland melt area exceeding 30 days, and changes in areas overlaid by at least 3 m of permafrost (top). Additional greenhouse gas emissions from permafrost degradation (middle) are shown at 2.7°C (units of Pg C in CO_2 equivalent, with pie chart illustrating proportional impact of methane and carbon dioxide) together with expected sea level rise contribution from Greenland (bottom).

Stroeve et al. (2025)

Why do we care about the Arctic?

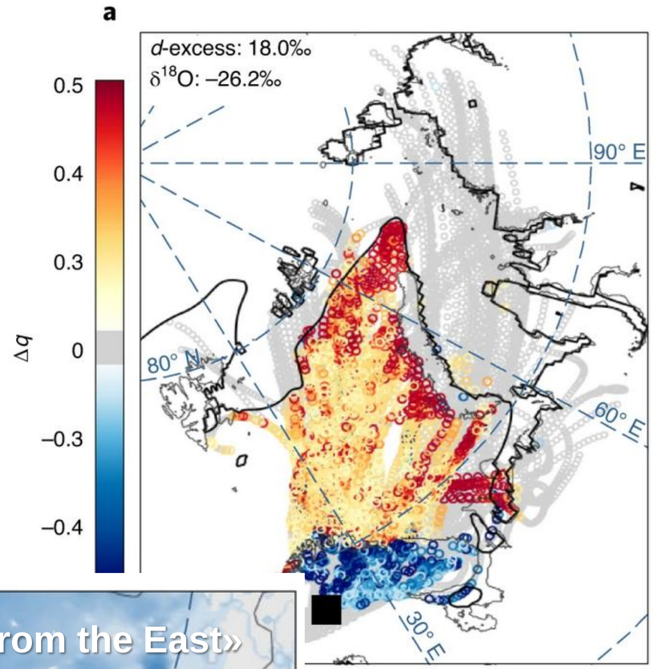
- Snow chaos in Europe
- Sea Level rise
- Release of carbon to the atmosphere
- Fires

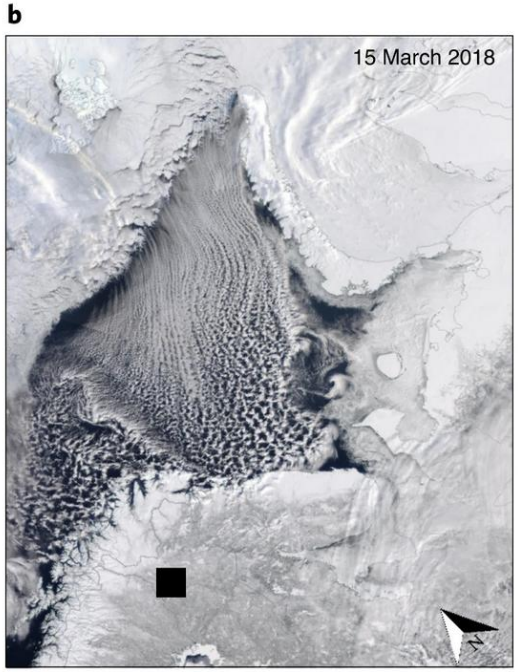
A snow blower clears a road in the village of Goeschenen in the canton of Uri during heavy snowfall. Keystone / Urs Flueeler, https://www.swissinfo.ch/

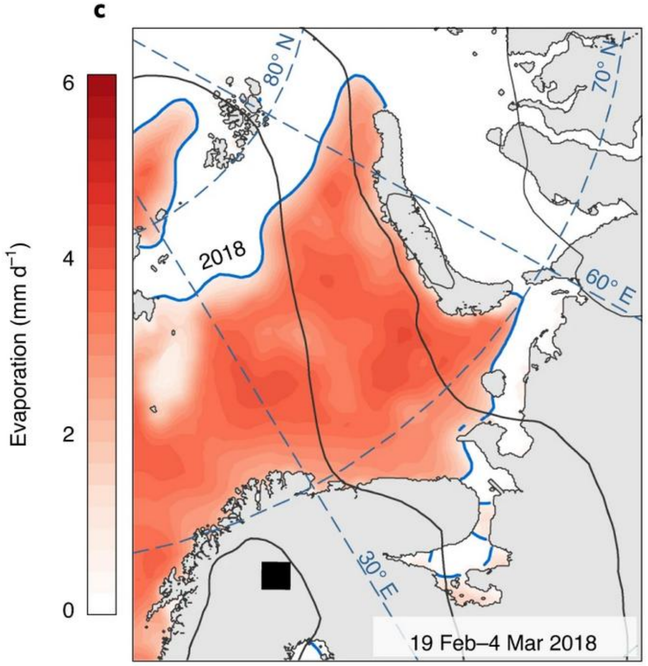
Teleconnections

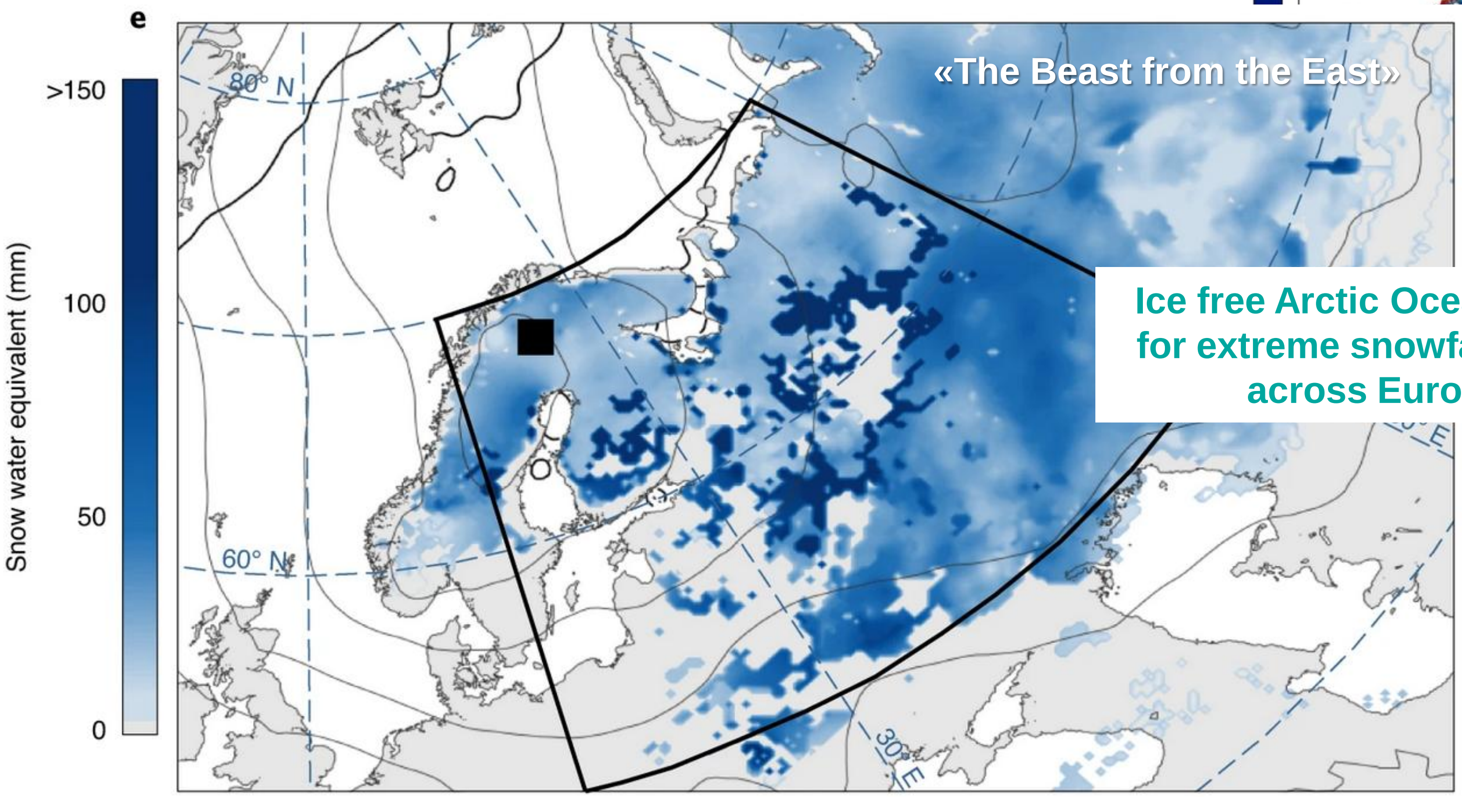
a. Back-trajectories from Pallas (square) between 19–27 February 2018 and associated mean vapour *d*-excess and $\delta^{18}O$. Colours depict hourly specific humidity changes (Δq), where a positive (negative) Δq indicates a moisture increase (decrease) due to evaporation (precipitation). Grey circles 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