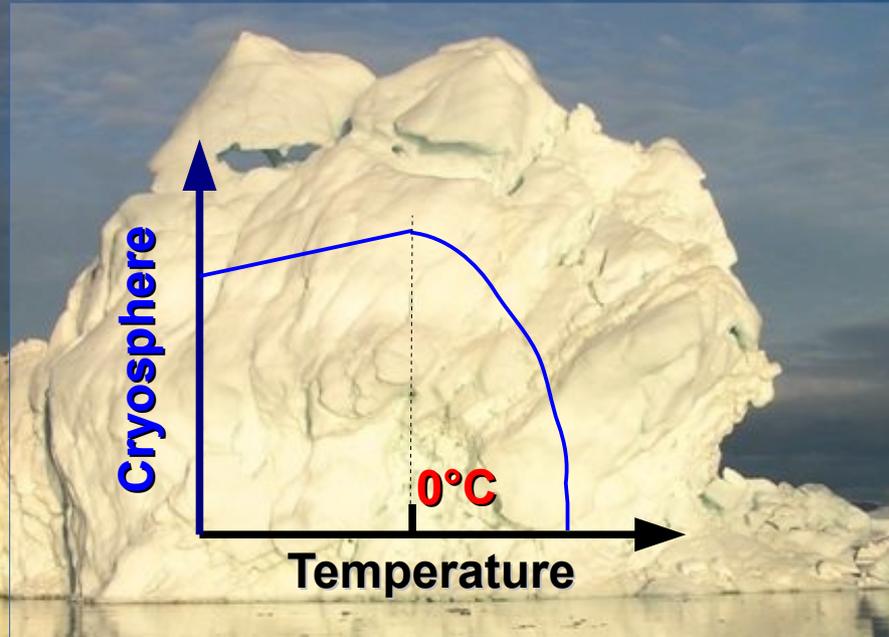


The cryosphere



State of the cryosphere and the tipping point of 0°C



Nature, n°575, 28/11

Tipping point of ice sheets and sea level rise

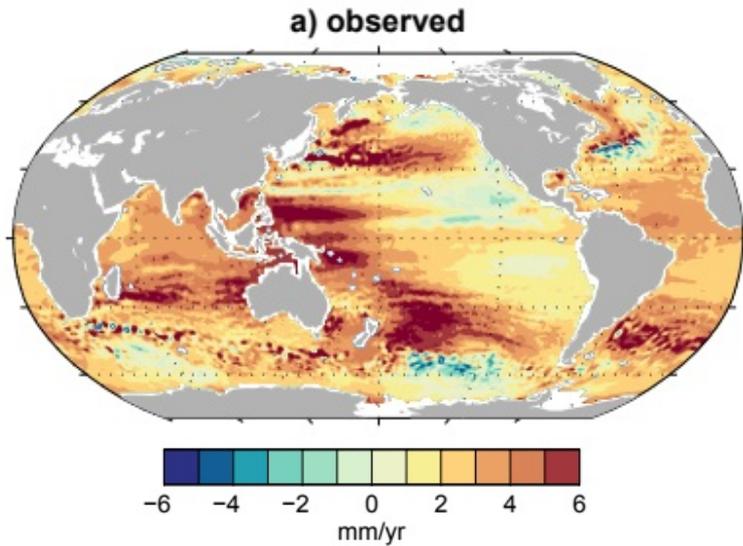
Plan

1. Why studying the cryosphere ?
2. Greenland vs Antarctica
3. Current climate
4. Future projections: Greenland
5. Future projections: Antarctica
6. Sea level rise and conclusion

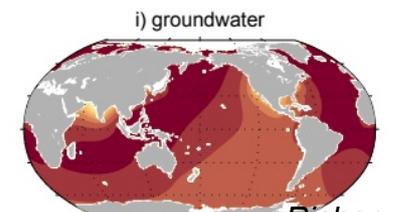
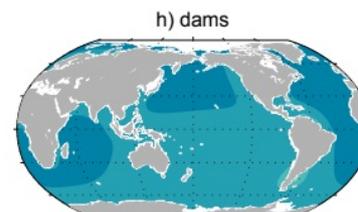
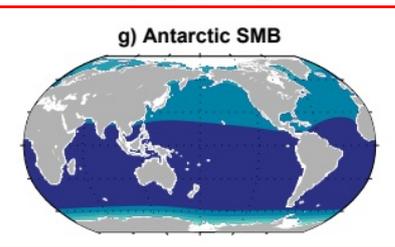
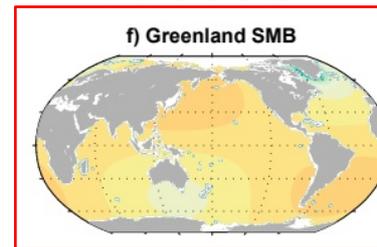
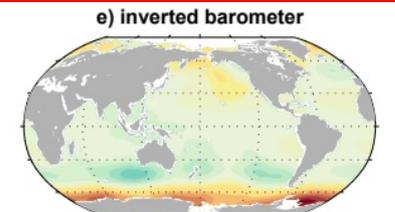
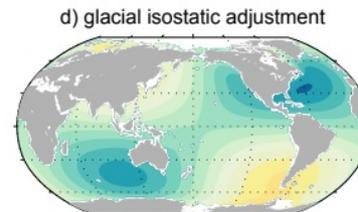
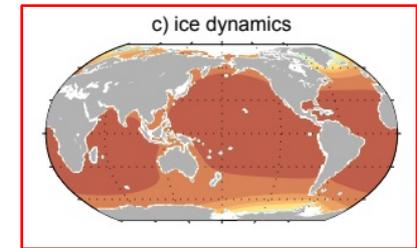
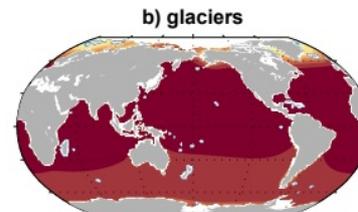
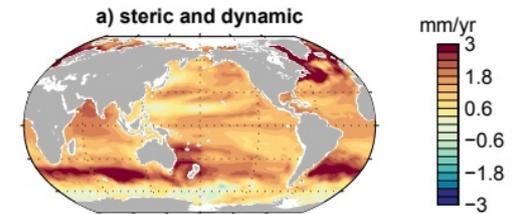
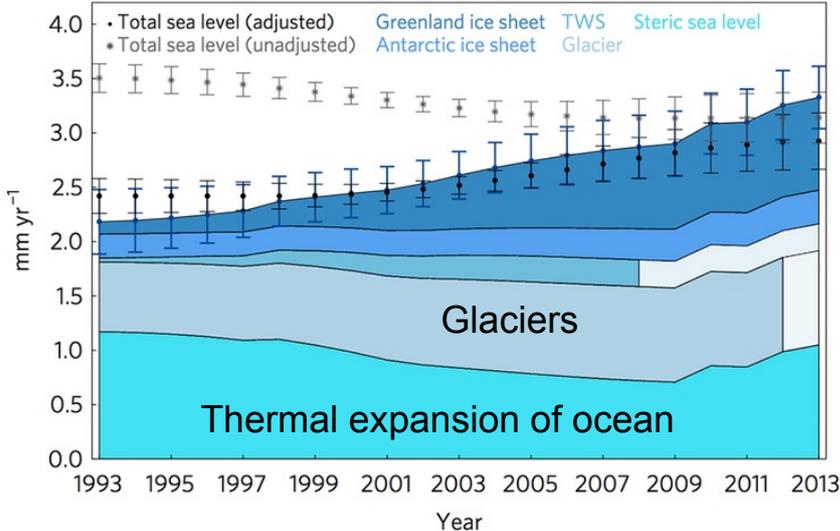
1. Why studying the cryosphere ?

Observed sea level rise: not uniform!

Total sea-level trend over the period 1993-2015



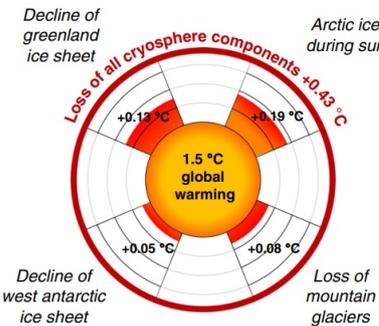
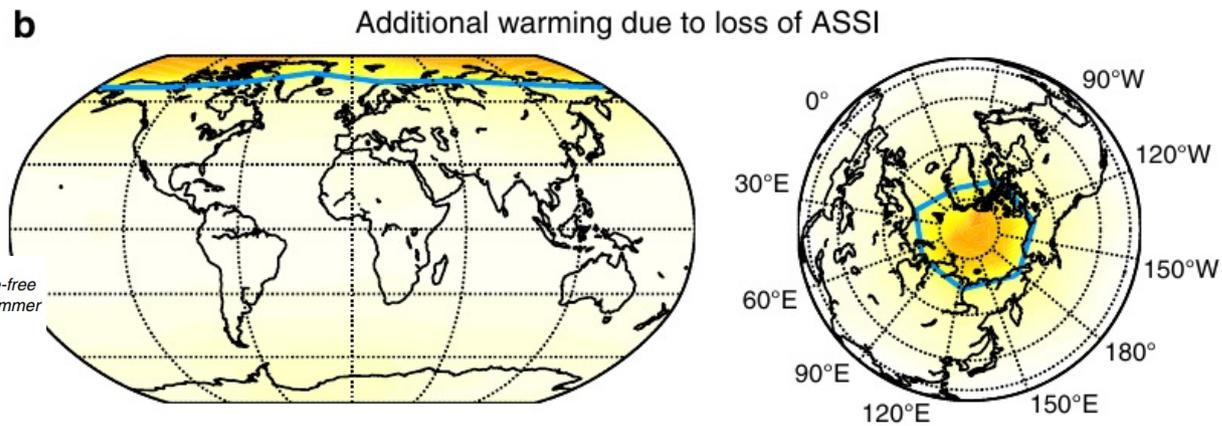
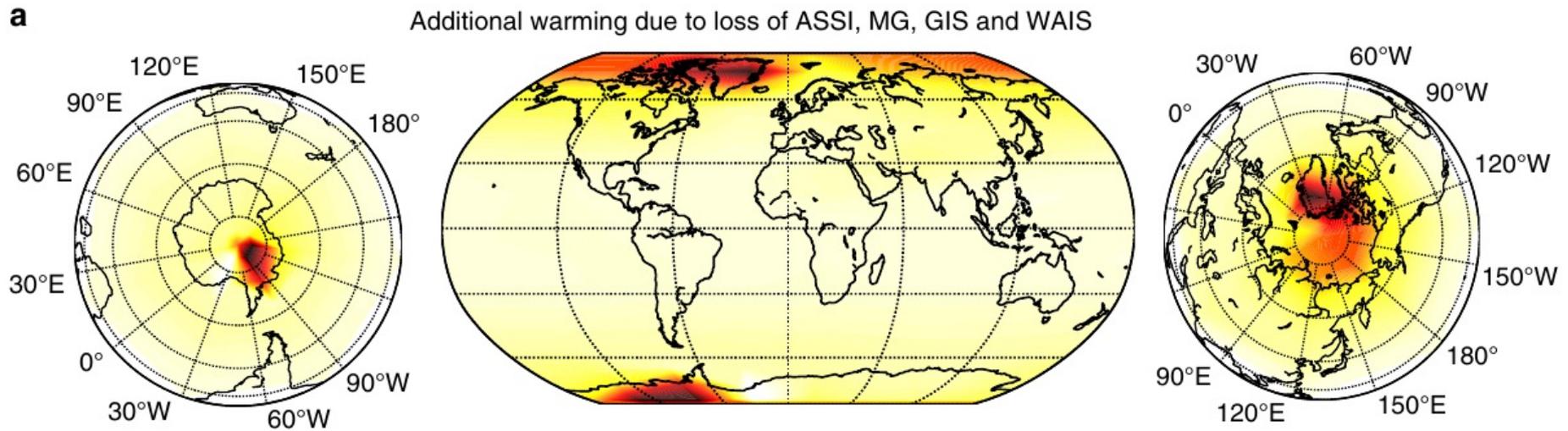
Chen et al. (2017)



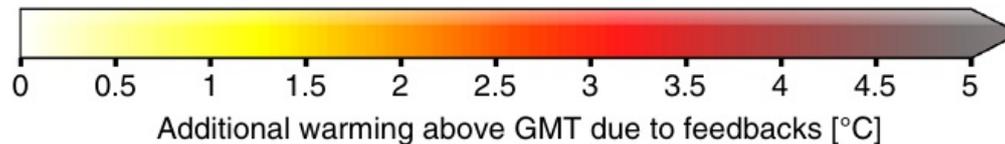
Richer et al. 2020

1. Why studying the cryosphere ?

Loss of cryosphere induces an additional warming !



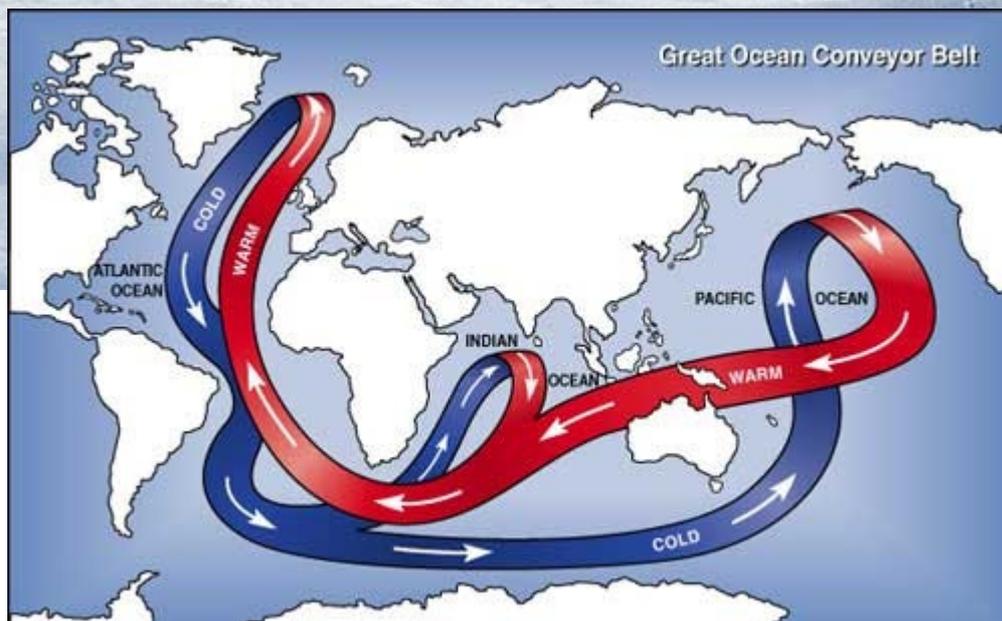
Arctic summer sea ice (**ASSI**)
Mountain glaciers (**MG**)
Greenland Ice Sheet (**GIS**)
West Antarctic Ice Sheet (**WAIS**)



Wunderling et al. (2020)

1. Why studying the cryosphere ?

THE DAY AFTER TOMORROW

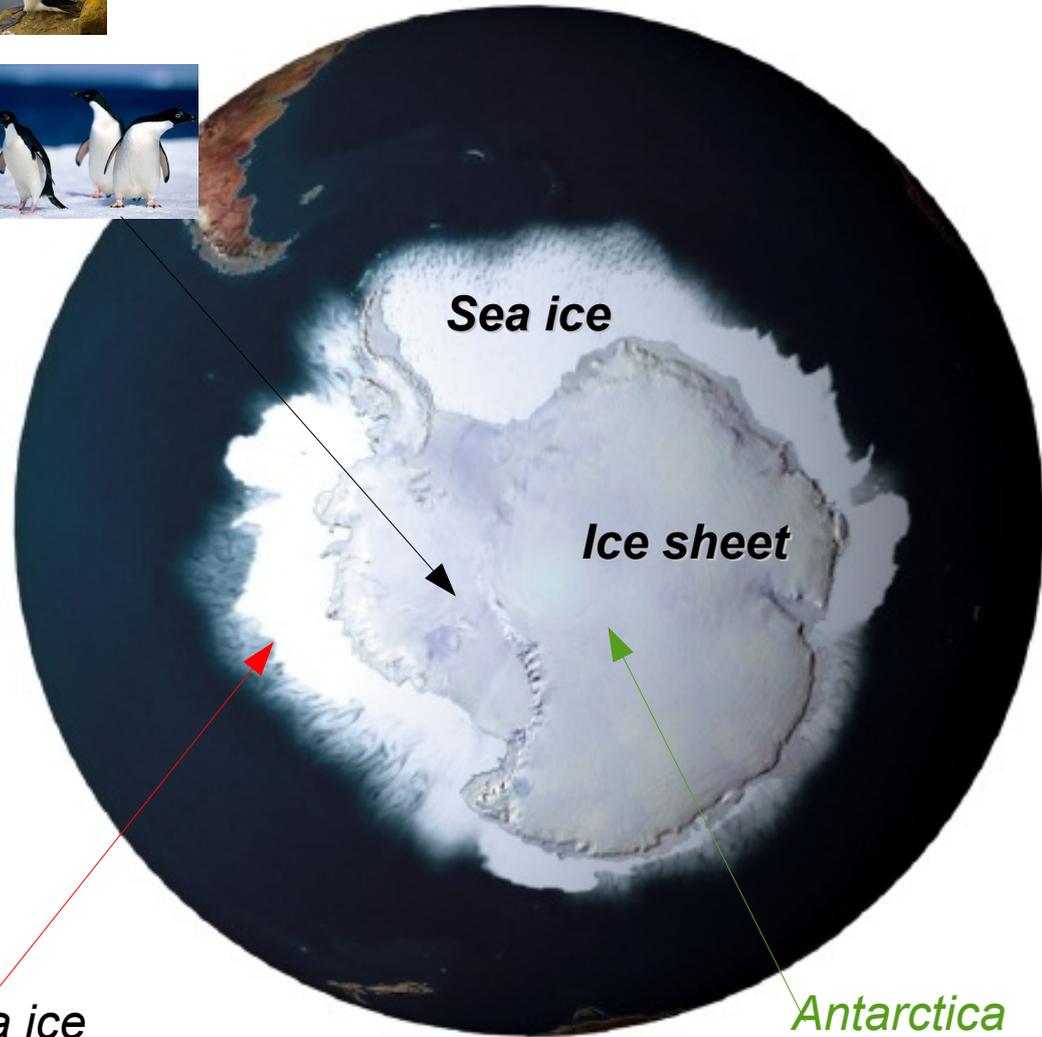
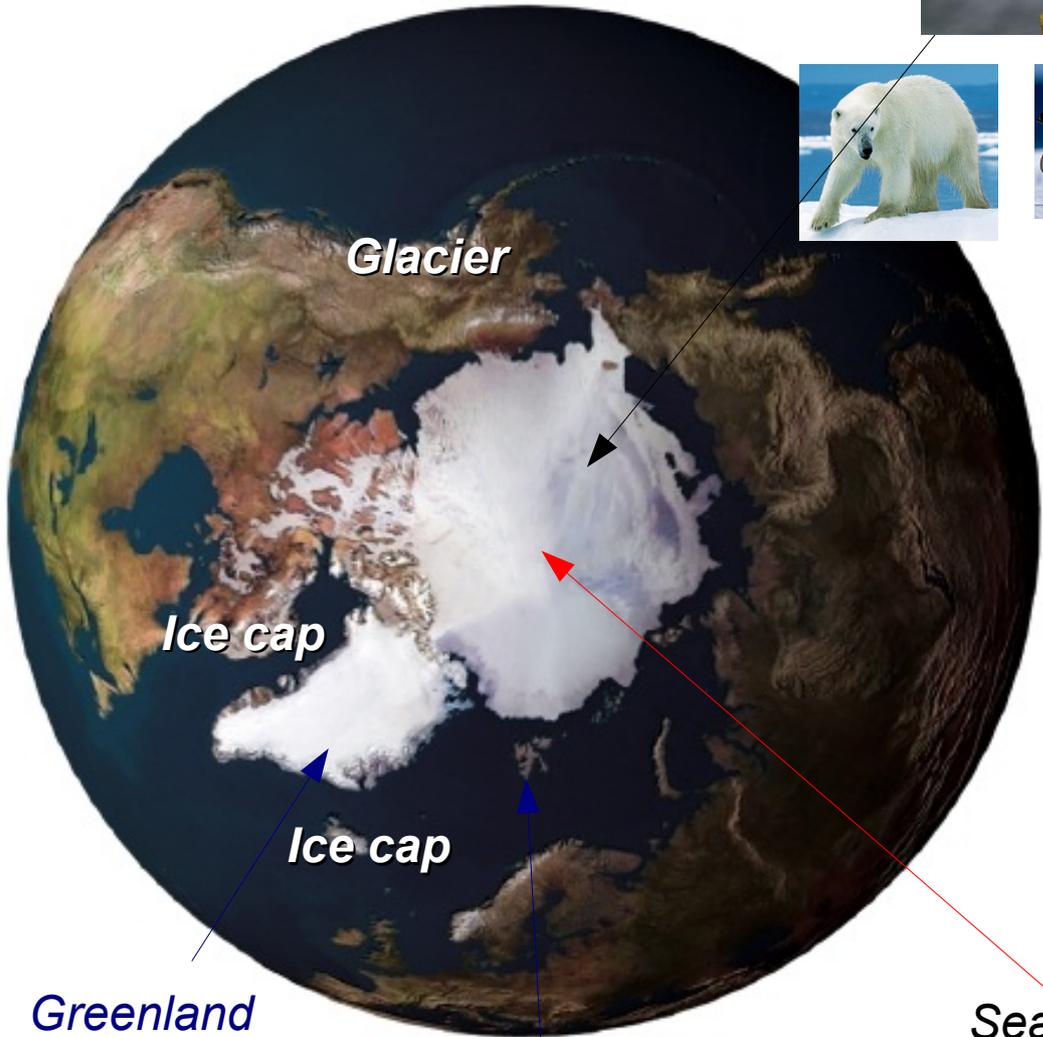
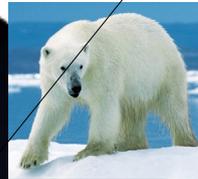


**Collapse of the gulfstream
due to the melt of the
Greenland ice sheet**

2. Greenland vs Antarctica

North Pole - Arctic

South Pole - Antarctica



Greenland
(3 x France)

Svalbard
(1 x Belgium)

Sea ice
(\Leftrightarrow ice sheet)

Antarctica
(20 x France)

© <http://www.cnes.fr>

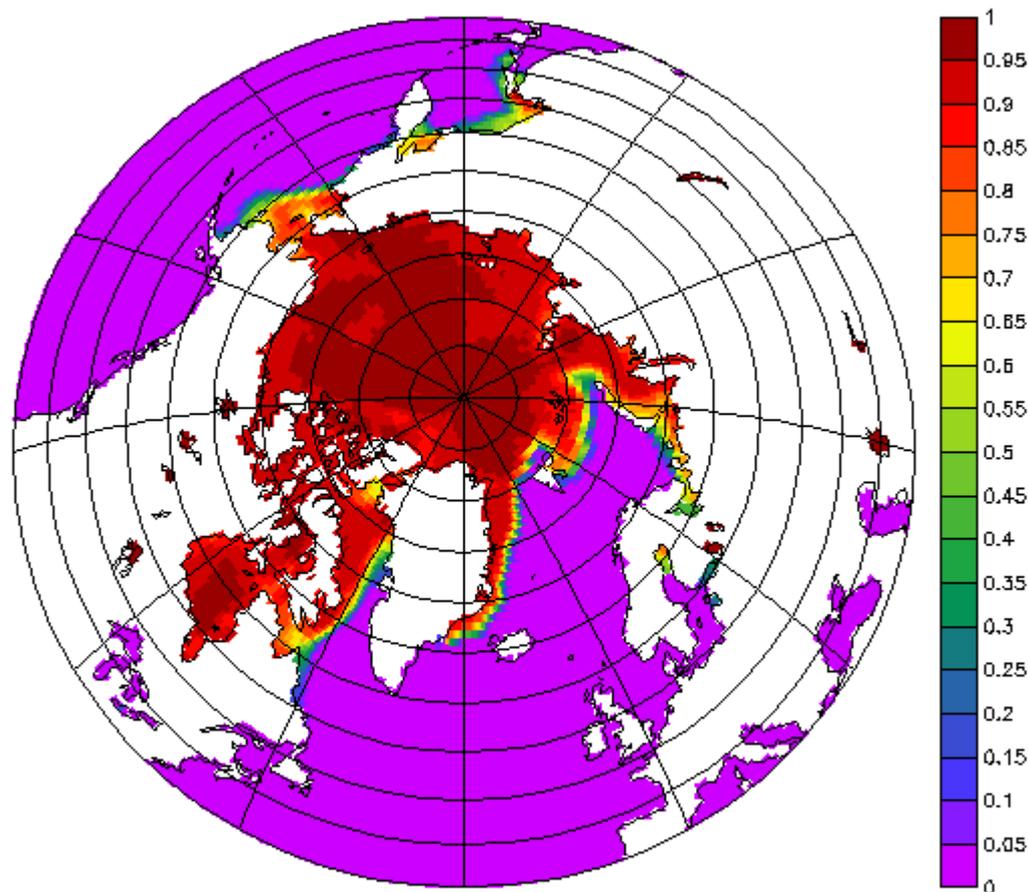
2. Greenland vs Antarctica



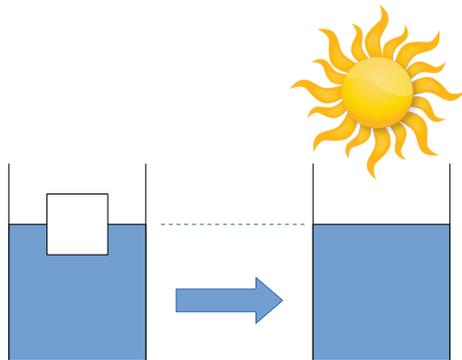
The sea ice variability does not impact on the sea level changes.

TIME : 01-JAN-2010 00:00

DATA SET: ERA-Interim

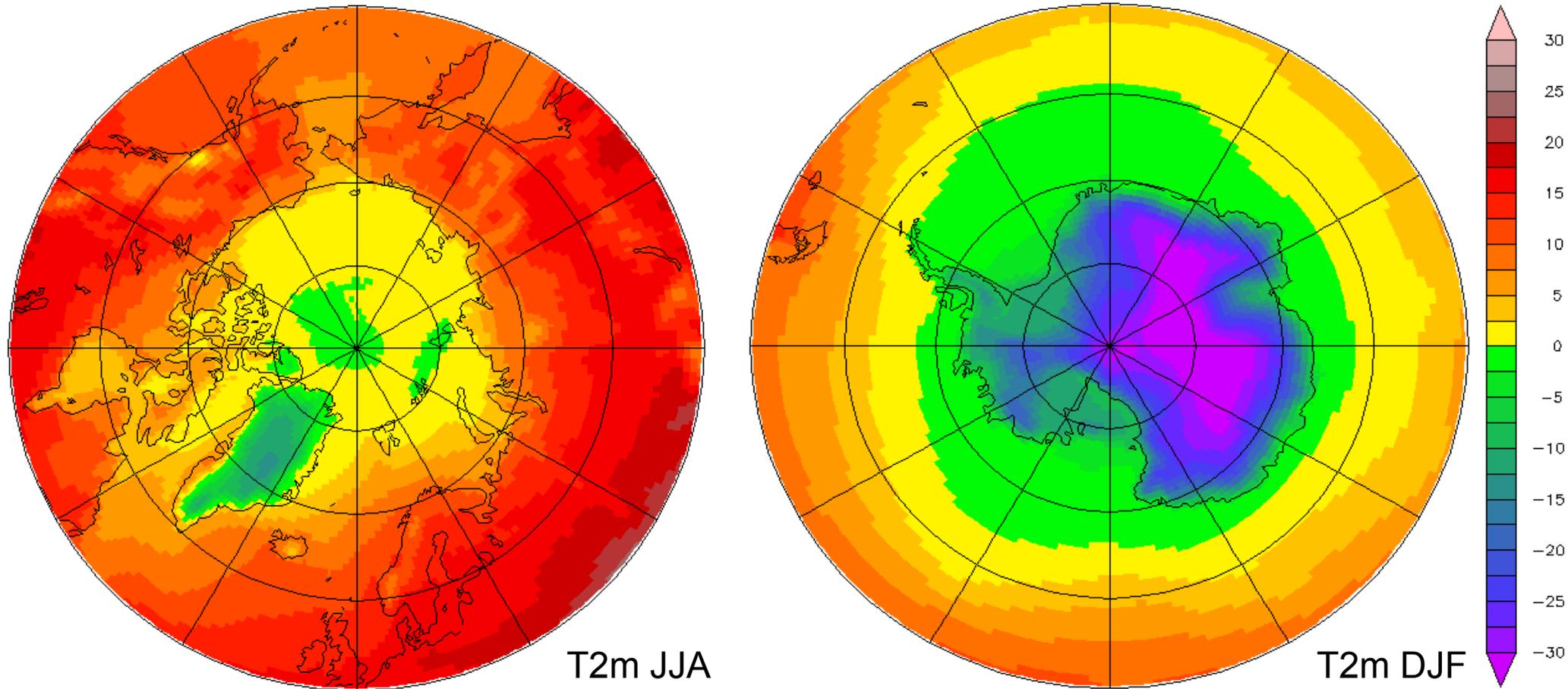


Monthly Sea ice extent (0-1)



2. Greenland vs Antarctica

Warmer climate over Greenland than over Antarctica



T2m JJA

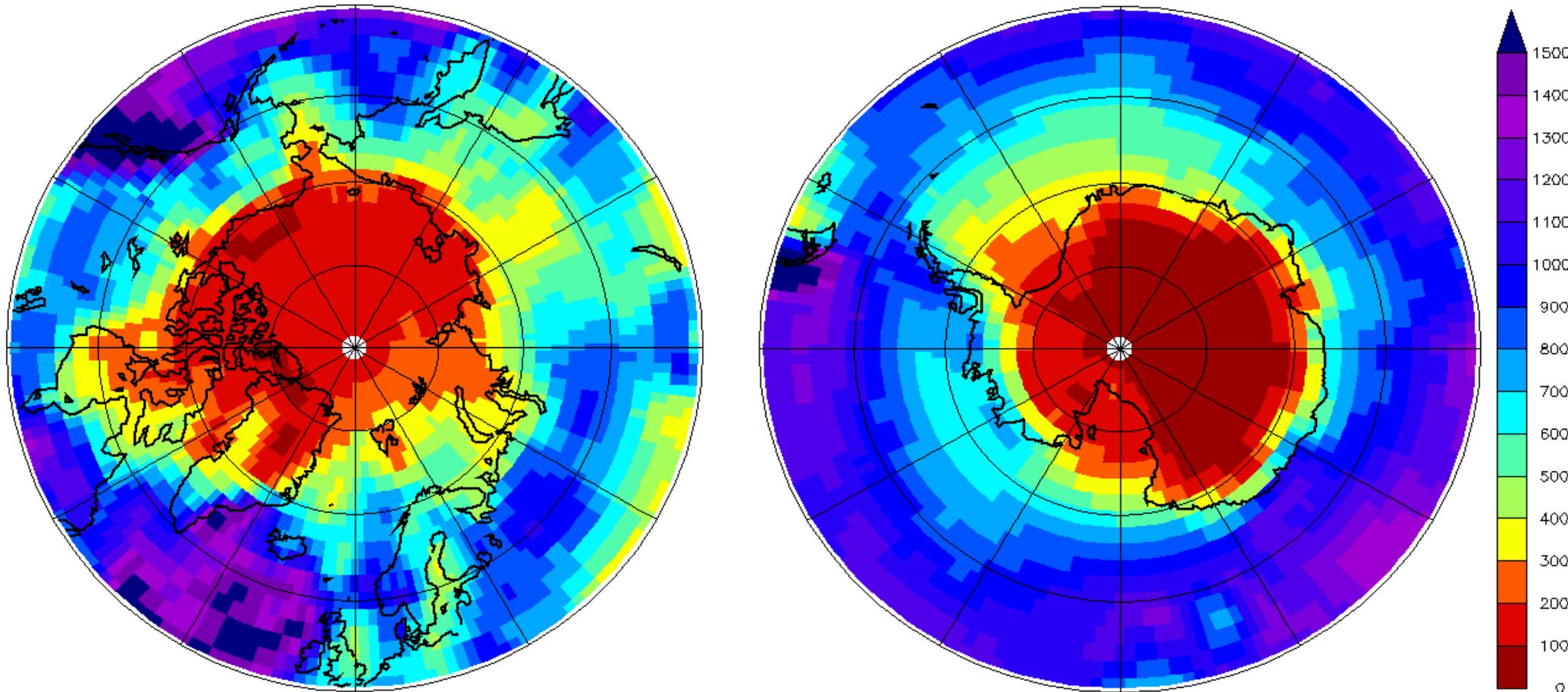
T2m DJF

Data : ERA-Interim (1979-2013)

Mean summer 2m-temperature

2. Greenland vs Antarctica

Wetter climate over Greenland than over Antarctica

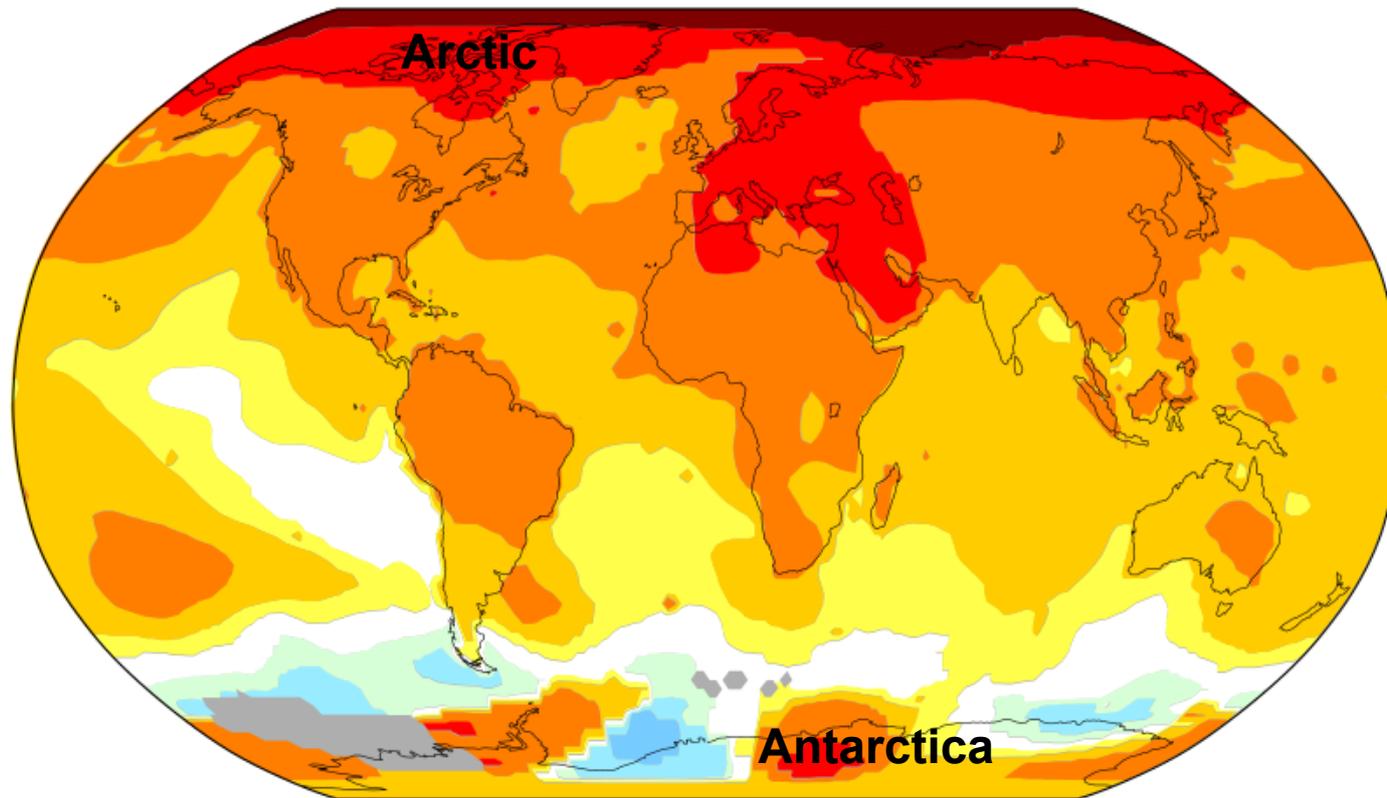


Data : NCEP-NCAR v2 (1979-2013)

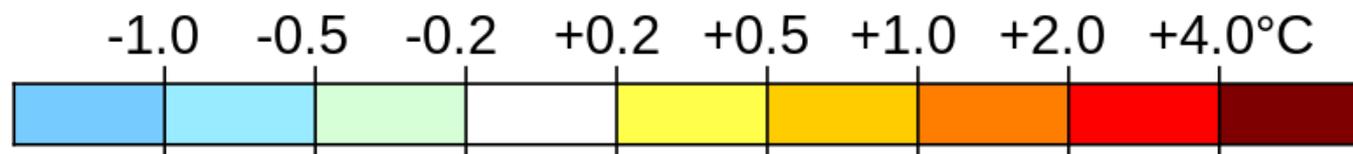
Annual mean precipitation (mm/yr)
(Brussels : ~ 800mm/yr)

2. Greenland vs Antarctica

Arctic is warming 4 x faster than Equator due to the albedo feedback (snow/ice is disappearing), water vapour feedback (clouds) and lapse rate feedback (surface is warming).

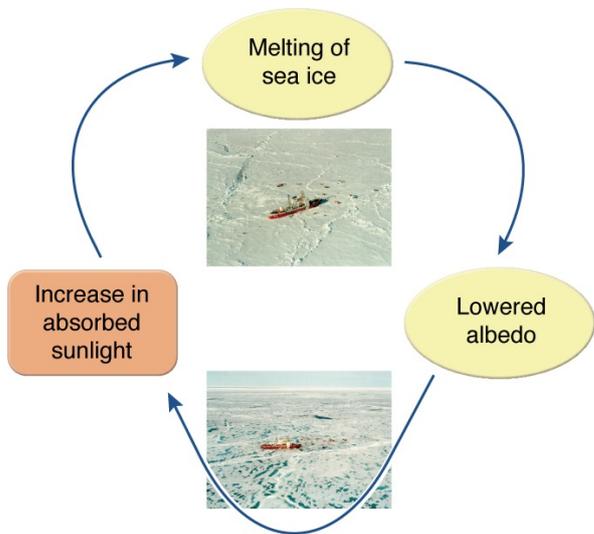


Trend from 1973 to 2023



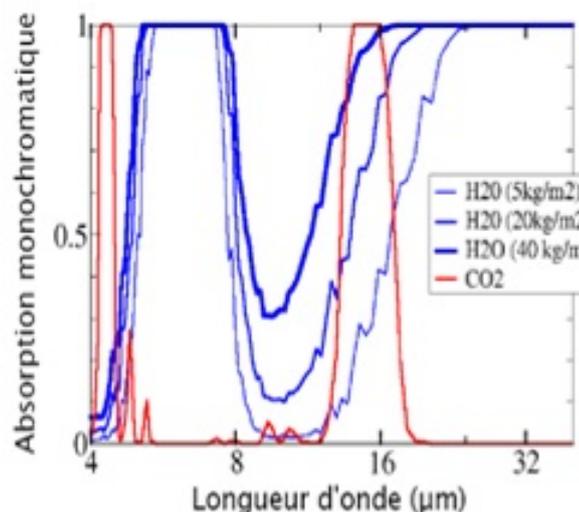
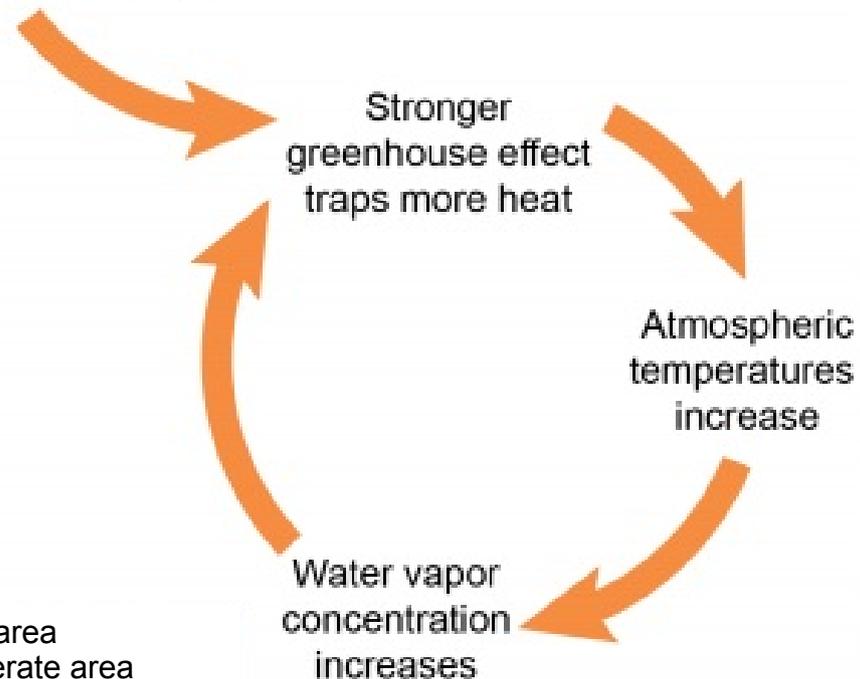
2. Greenland vs Antarctica

Arctic is warming 4 x faster than Equator due to the **albedo feedback, water vapour feedback...**



Water Vapor and the Greenhouse Effect

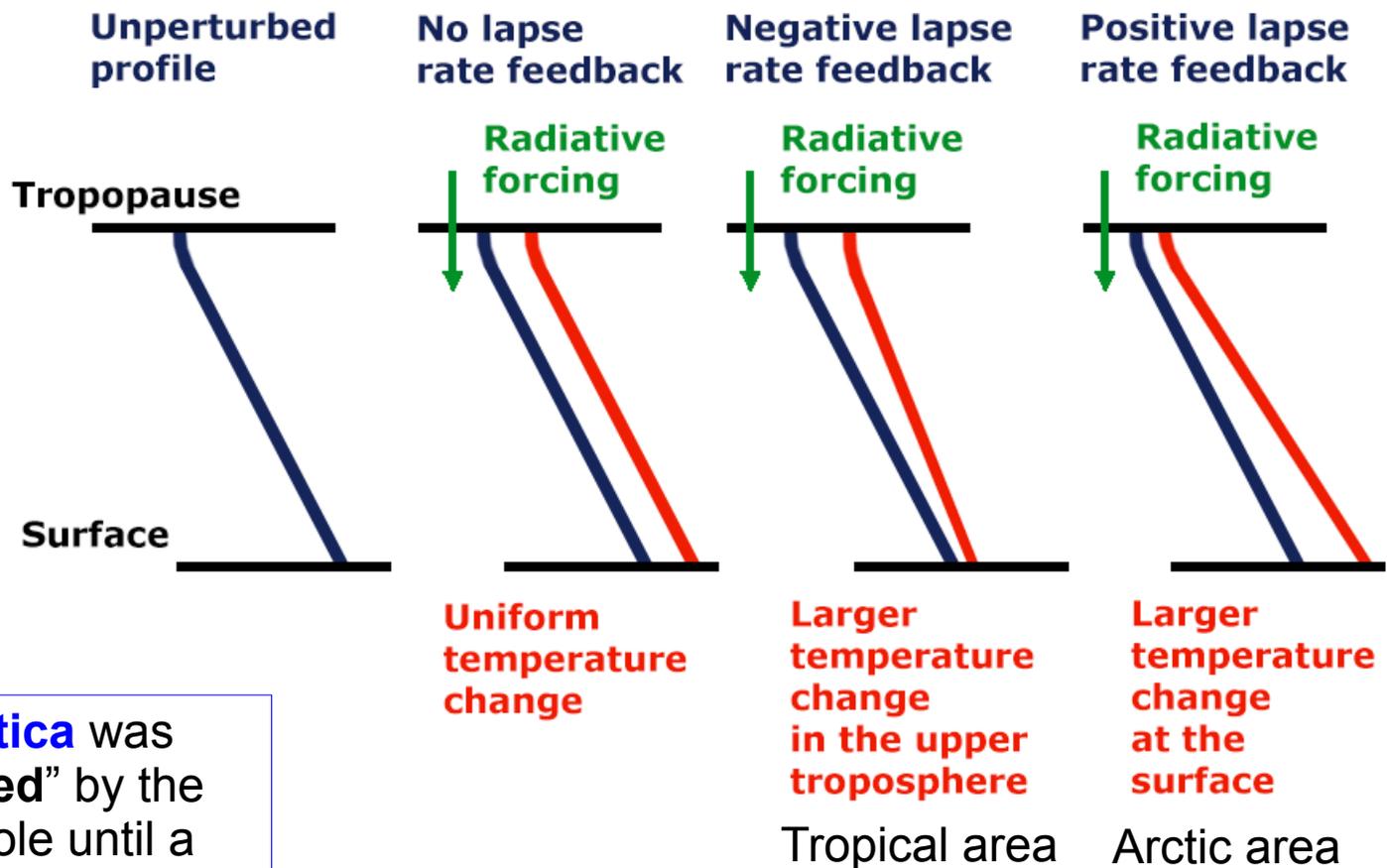
Human input of carbon dioxide and other greenhouse gases



Polar area
Temperate area
Tropical area

2. Greenland vs Antarctica

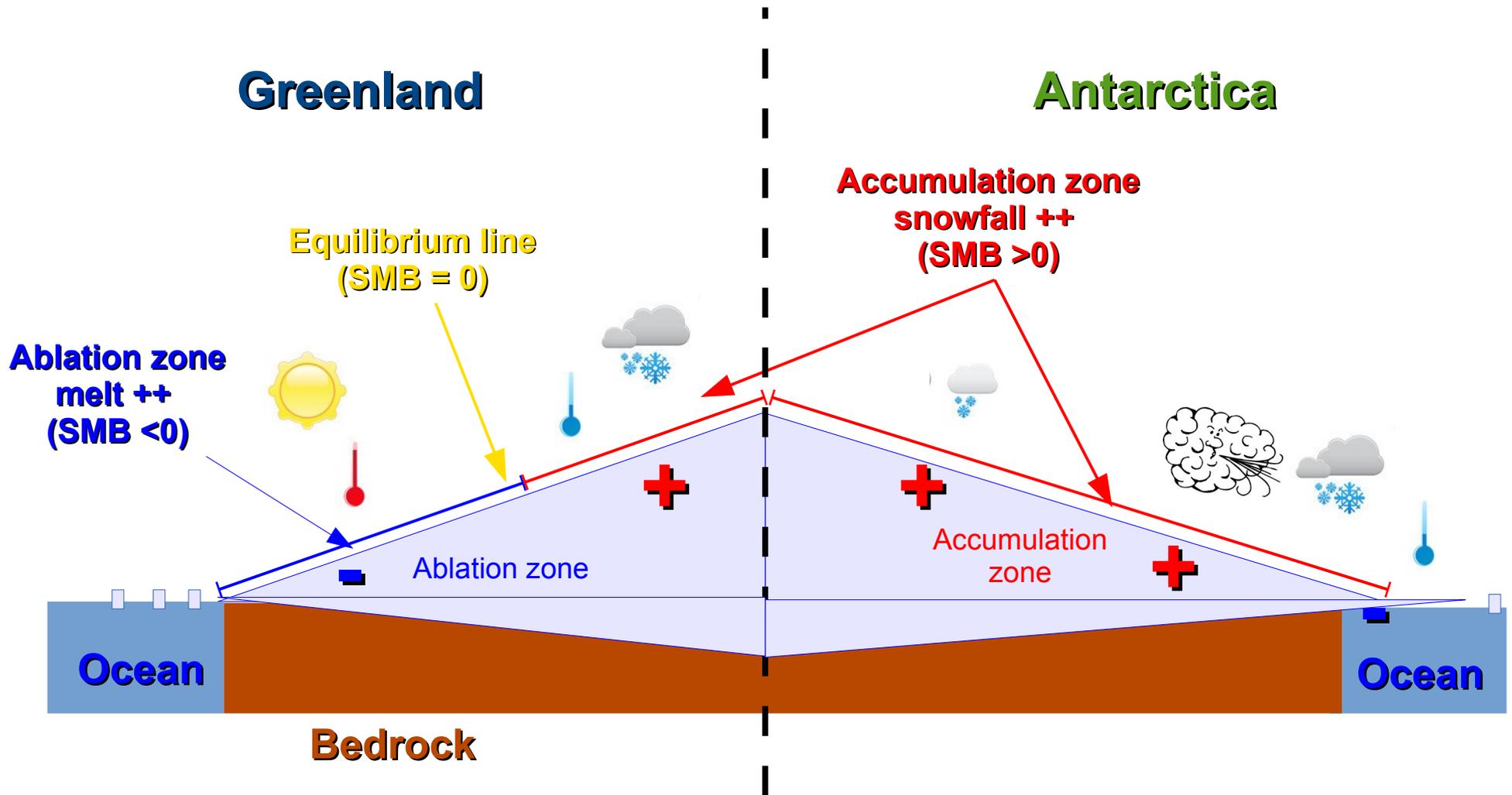
Arctic is warming 4 x faster than Equator due to the 3) lapse rate feedback



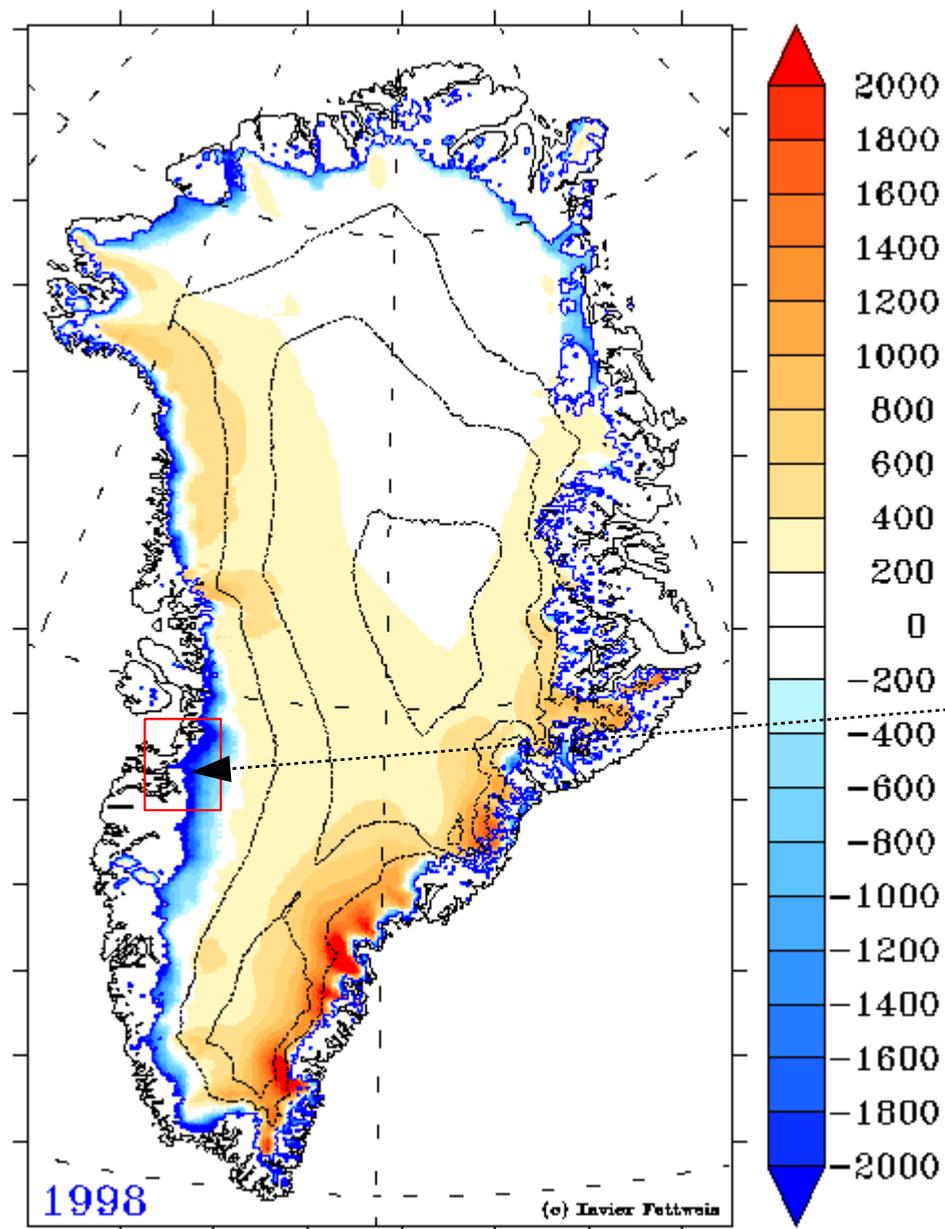
Antarctica was "protected" by the ozone hole until a couple of years + it is a land vs ocean in Arctic

3. Current climate

Surface mass balance (SMB) ~ snowfall – melt (Greenland)
snowfall – snow drift (Antarctica)



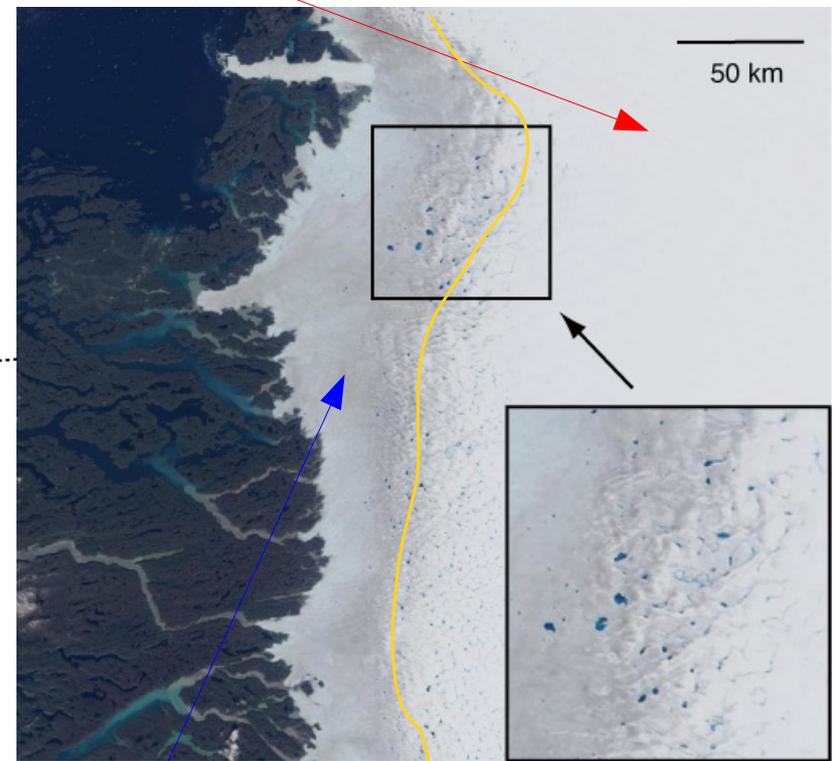
3. Current climate



Data : MAR forced par ERA-Interim

Surface mass balance over Greenland (in mm/yr)

Accumulation zone (albedo ~ 70-80%)



© <http://www.spri.cam.ac.uk/>

Ablation zone (albedo 30-50%)

3. Current climate

Ablation zone over Greenland



Bédière

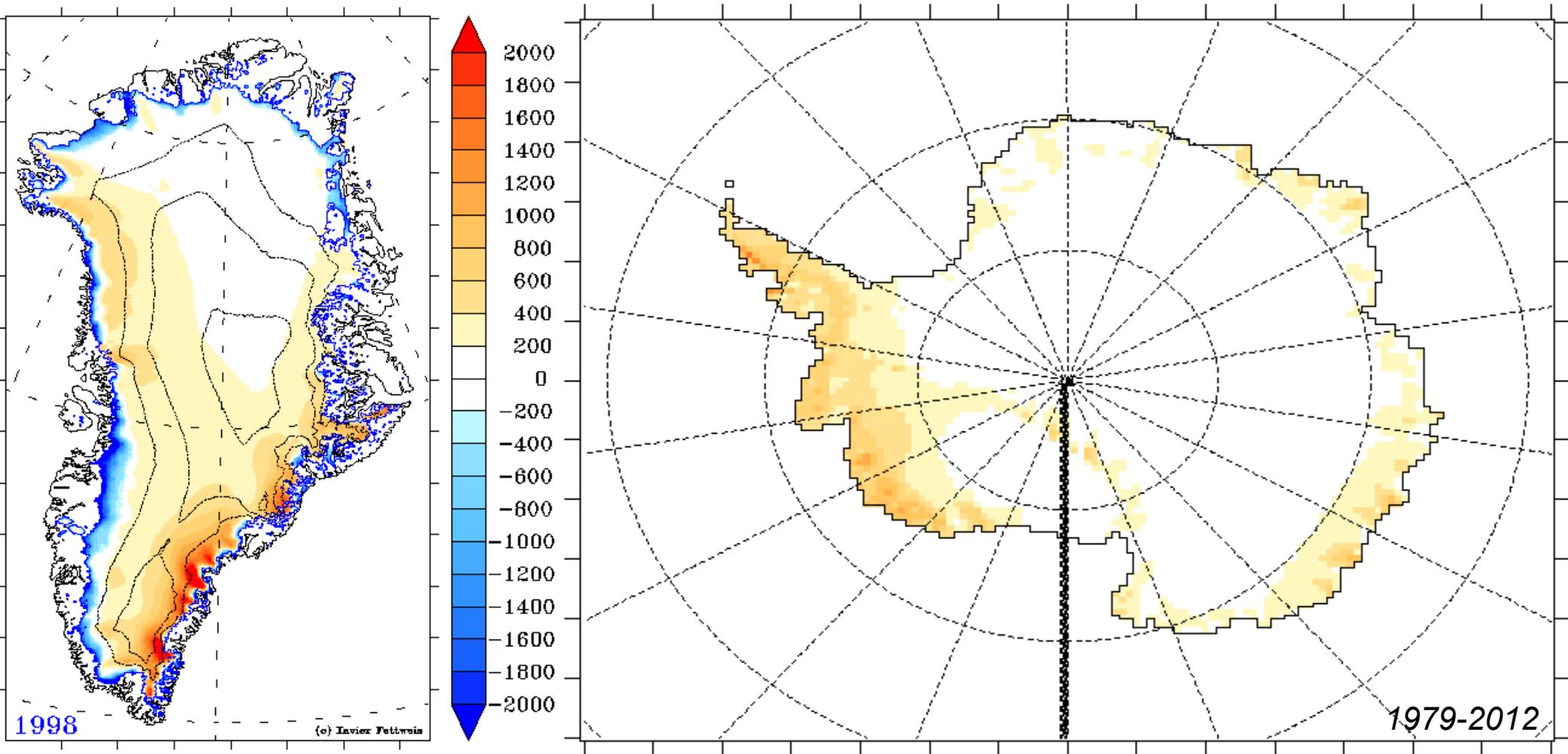
Dirty bare ice



3. Current climate



SMB over Antarctica vs Greenland (in mm/yr)



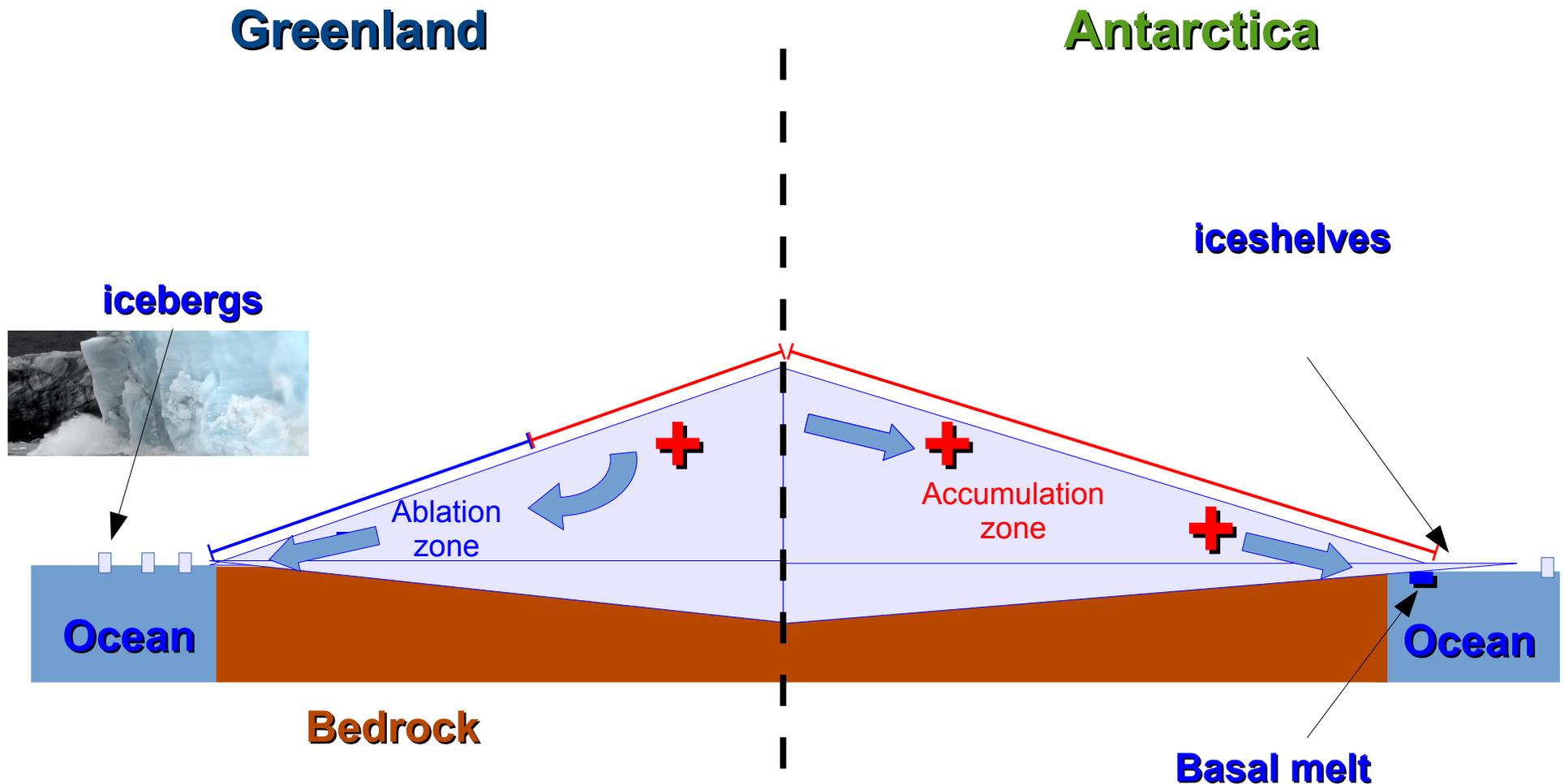
Less accumulation but no ablation zone

Data : MAR forced by ERA-Interim

3. Current climate

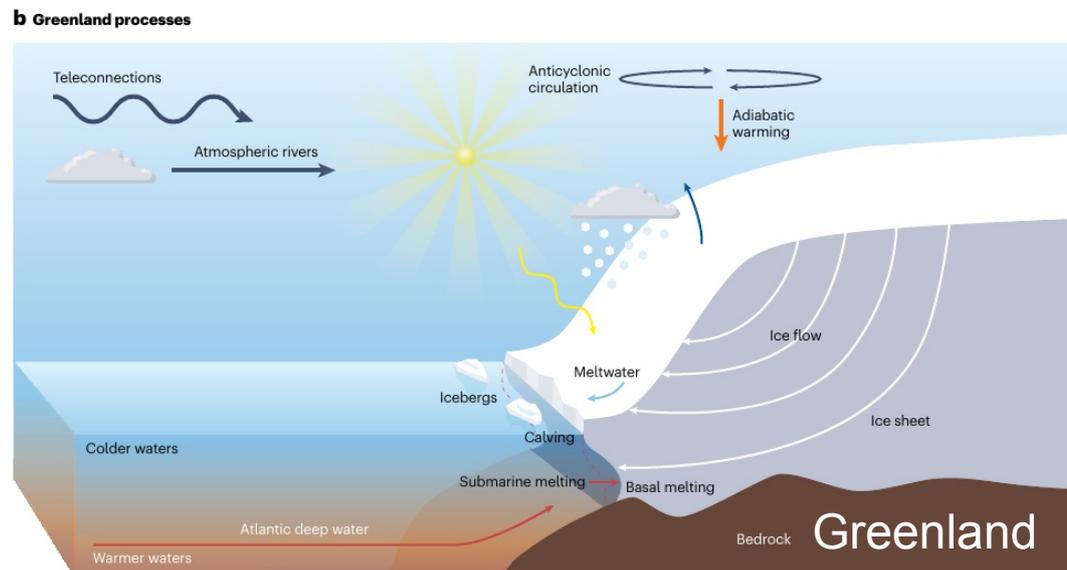
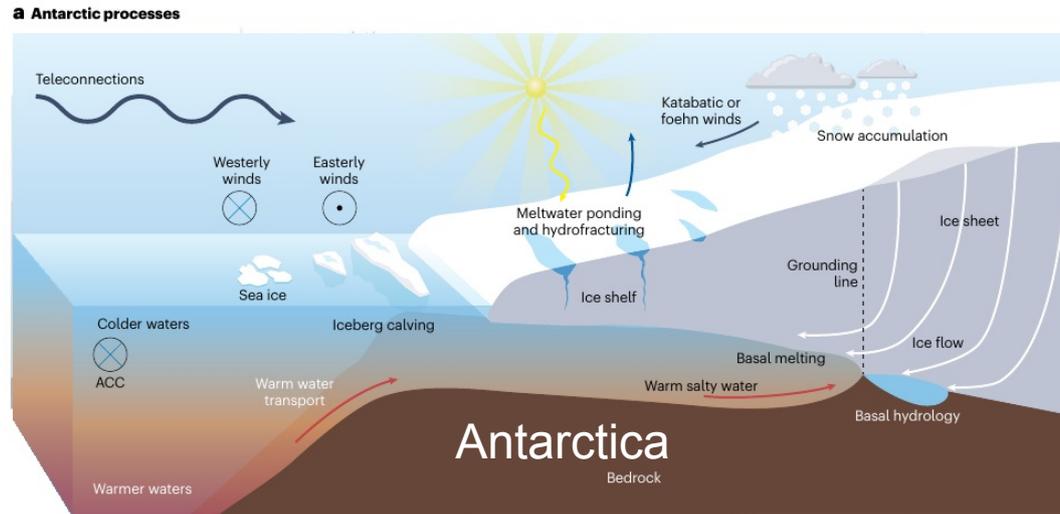
Total mass balance (TMB) ~ SMB – icebergs (Greenland)
SMB – icebergs – basal melting (Antarctica)

Ice sheet is in equilibrium if TMB ~ 0

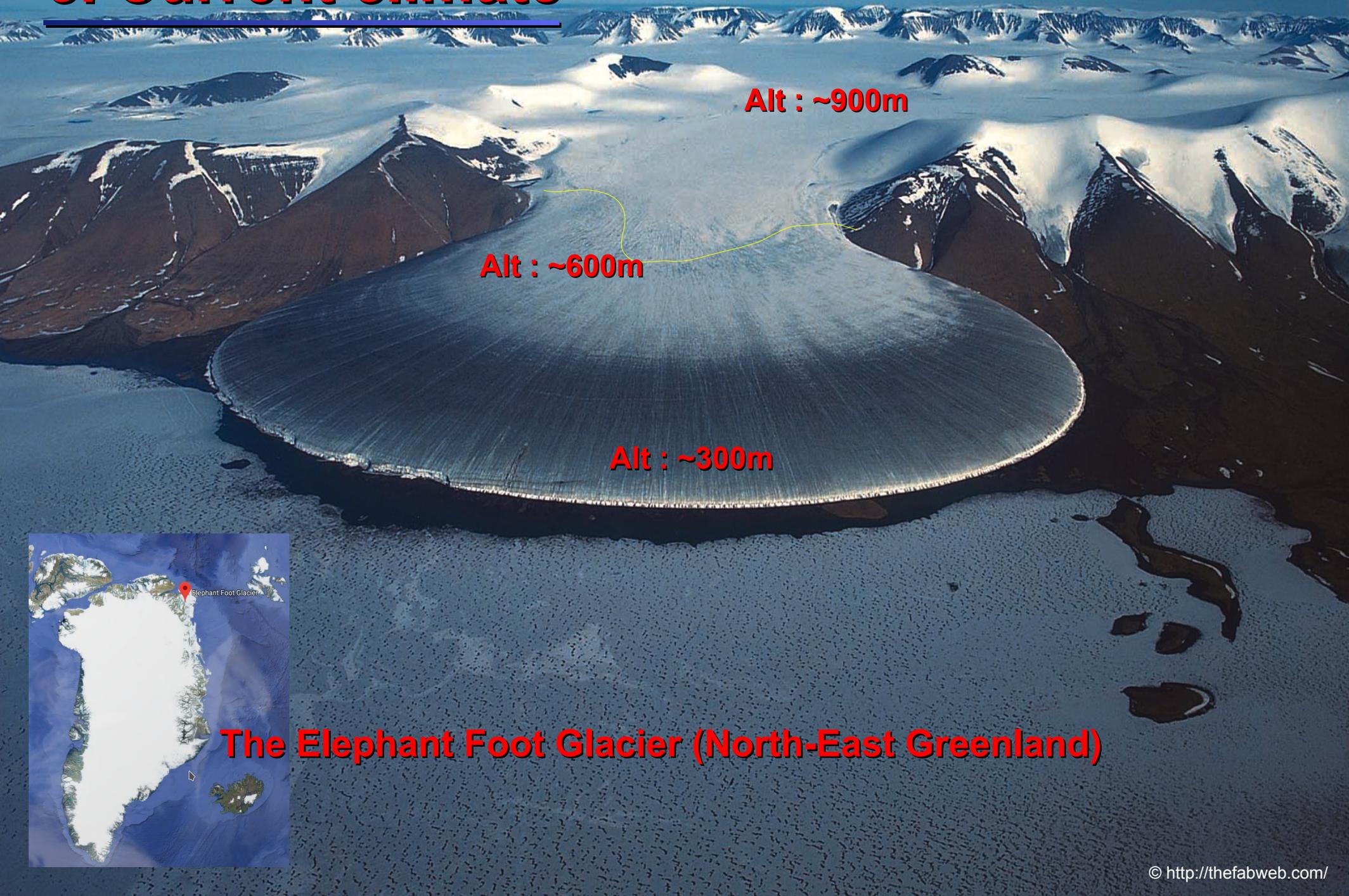


3. Current climate

Total mass balance (TMB) ~ SMB – icebergs (Greenland)
SMB – icebergs – basal melting (Antarctica)



3. Current climate



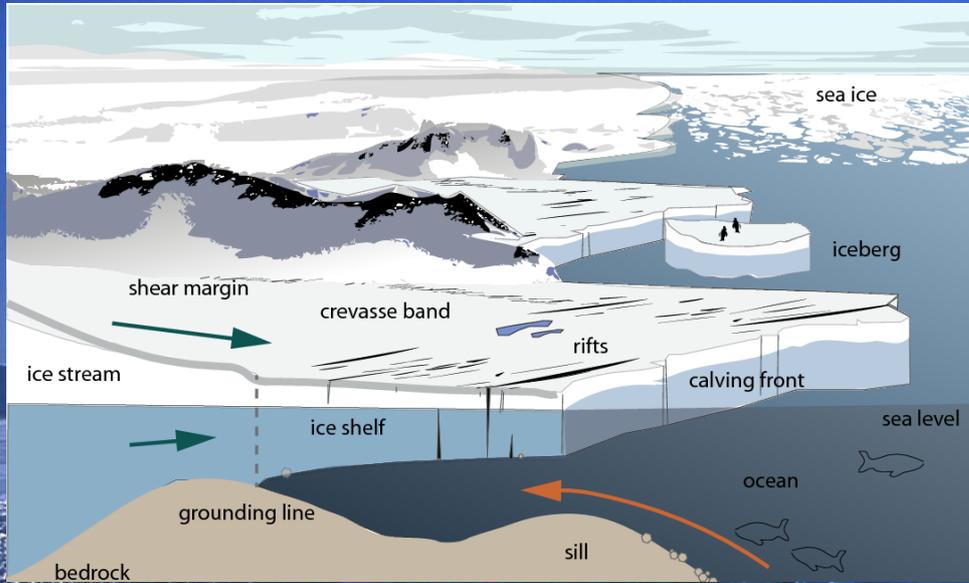
Alt : ~900m

Alt : ~600m

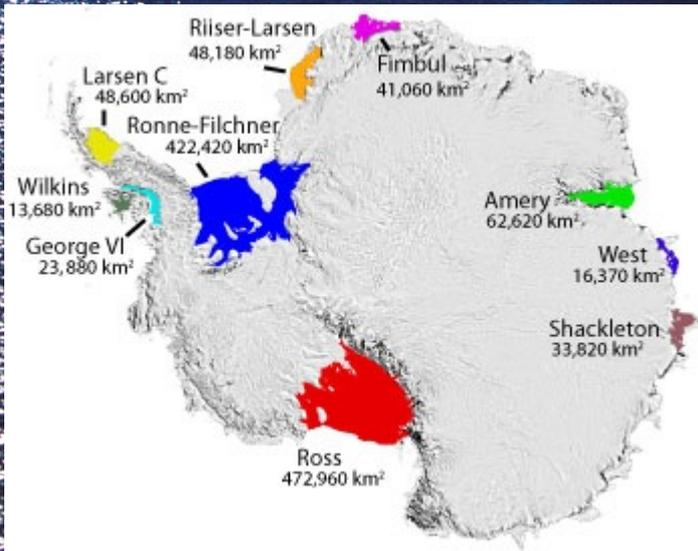
Alt : ~300m

The Elephant Foot Glacier (North-East Greenland)

3. Current climate



Ice-shelf over Antarctica

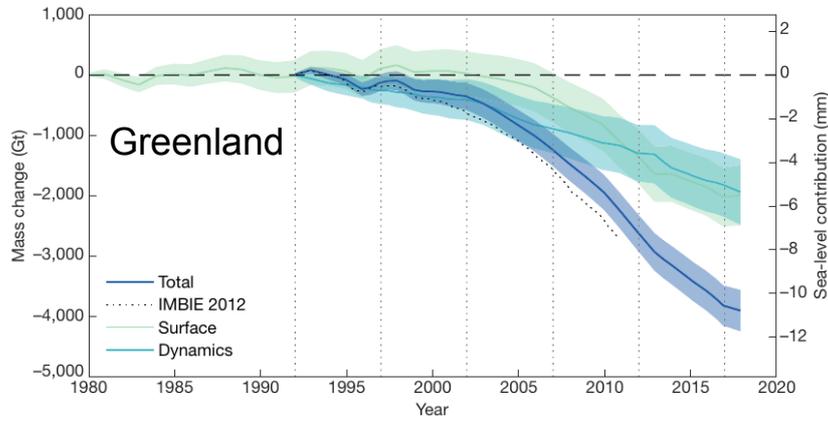


© <http://fr.cdn.v5.futura-sciences.com/>

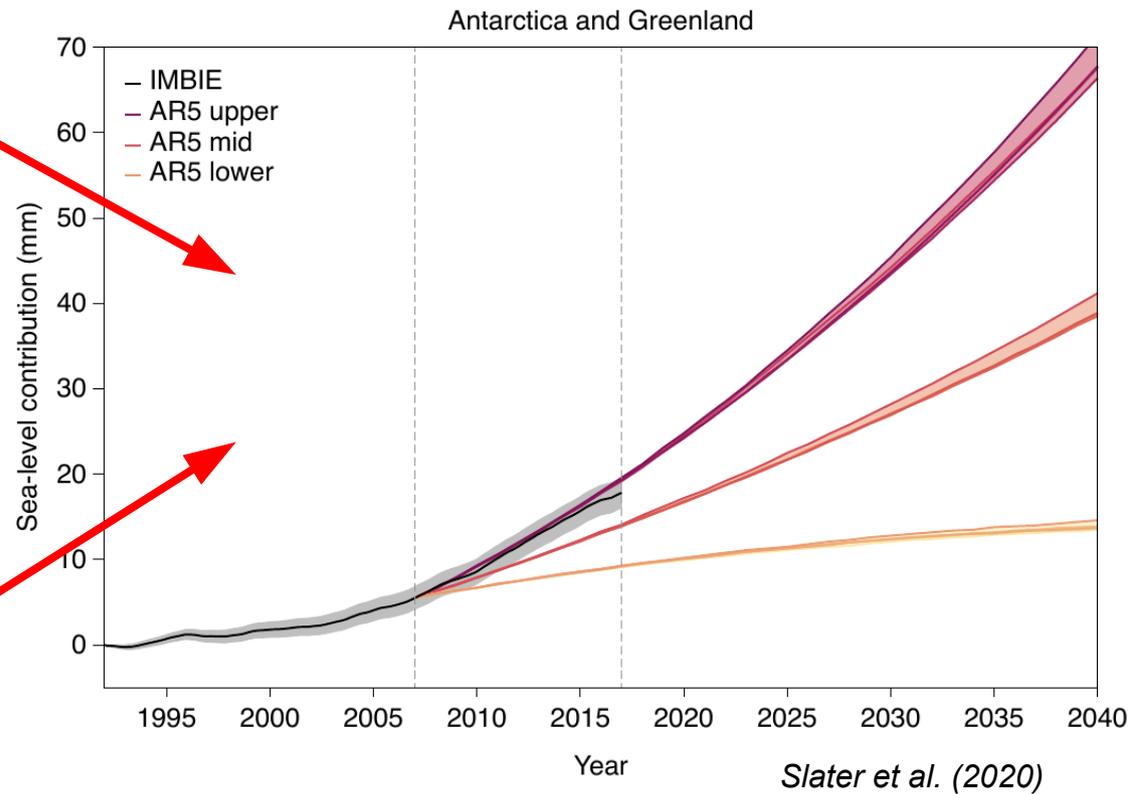
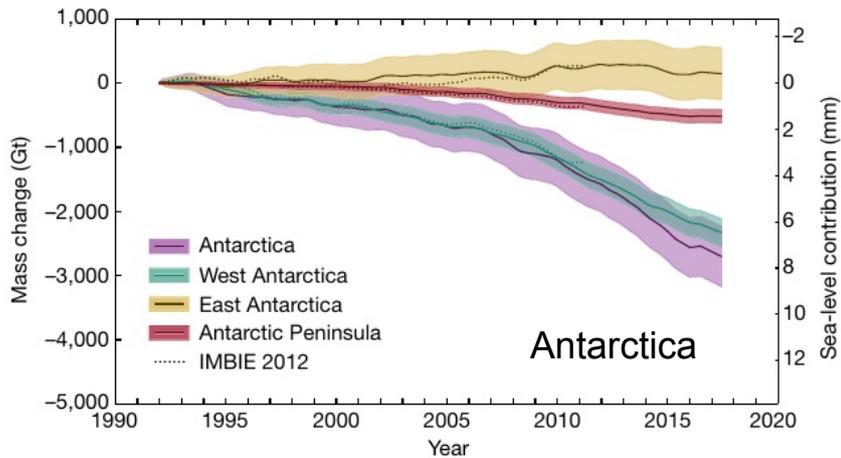
© <http://upload.wikimedia.org//>

3. Current climate

Current contribution of both Greenland and Antarctica



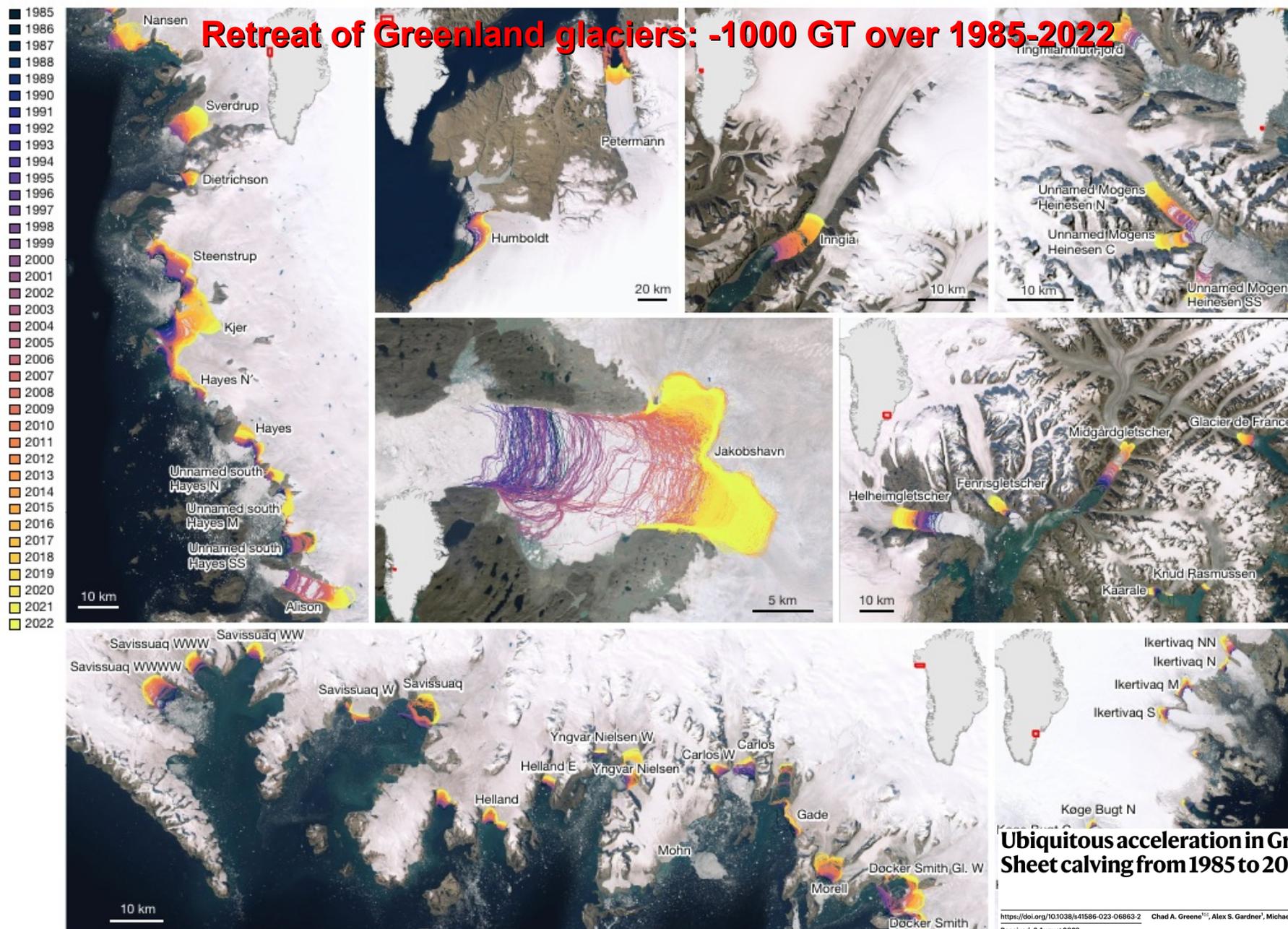
IMBIE2 et al. (2019)



Slater et al. (2020)

Mass loss from the end of the 1990s!

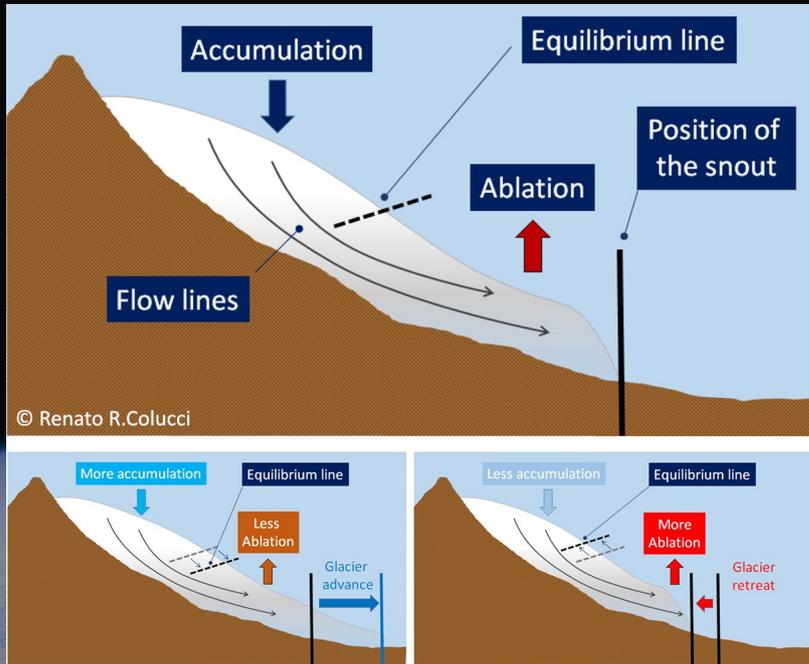
3. Current climate



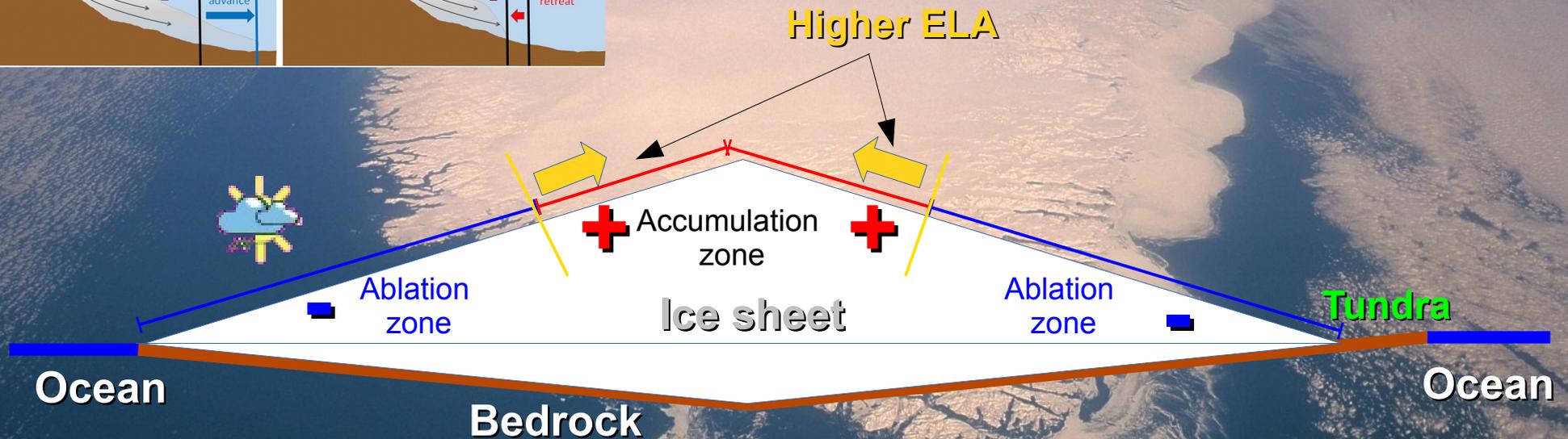
Ubiquitous acceleration in Greenland Ice Sheet calving from 1985 to 2022

<https://doi.org/10.1038/s41586-023-06863-2> Chad A. Greene^{1,2}, Alex S. Gardner¹, Michael Wood³ & Joshua K. Cuzzone¹
Received: 3 August 2023

4. Future projections: Greenland



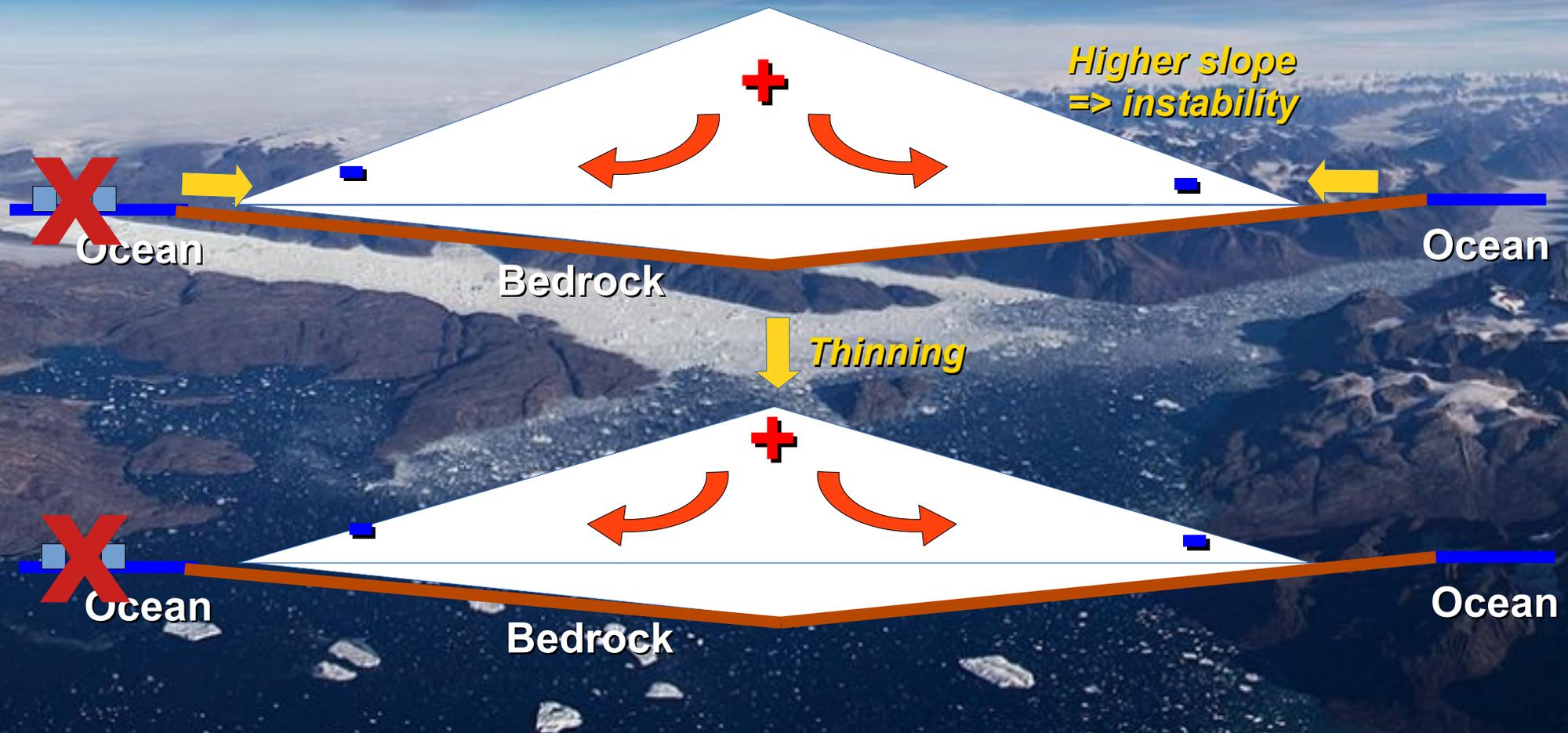
In a warmer climate: snowfall + 5% by +1°C
melt + 25% by +1°C



4. Future projections: Greenland

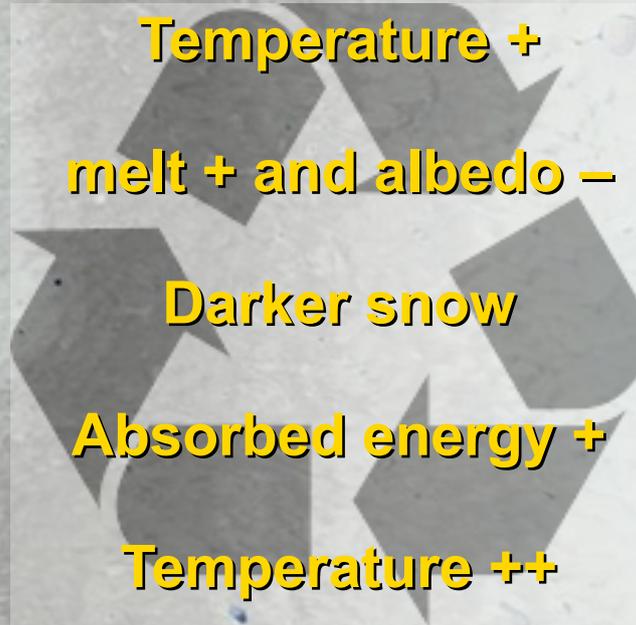
With the ice dynamics

Retreat of the ice sheet and thinning



4. Future projections: Greenland

1. Melt acceleration due to the melt-albedo positive feedback



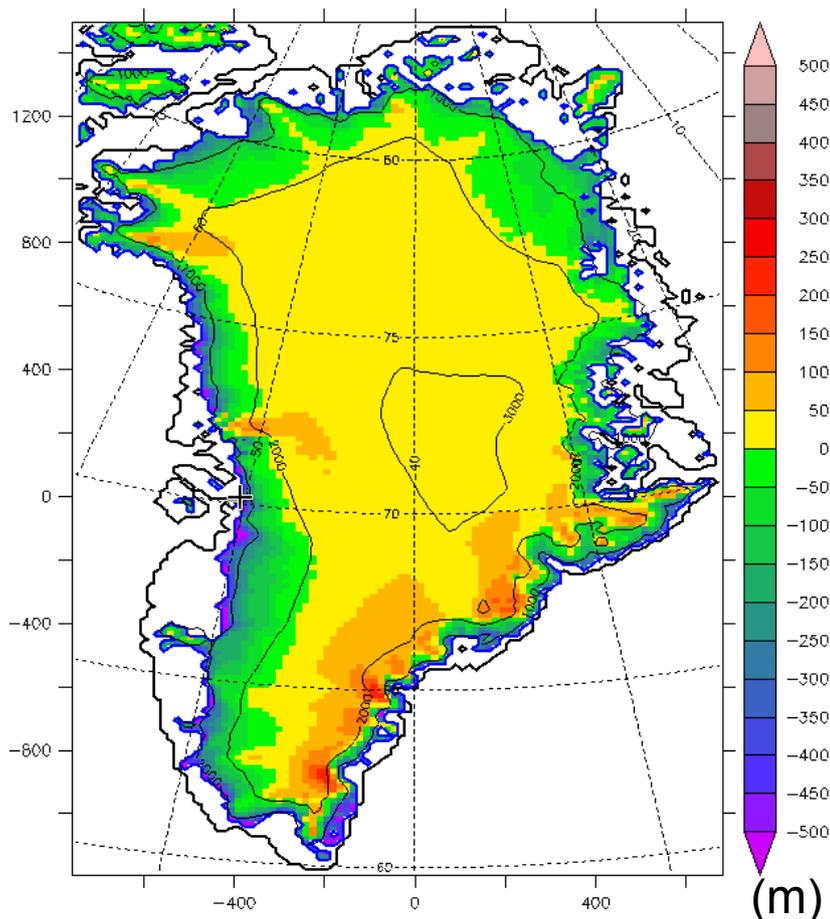
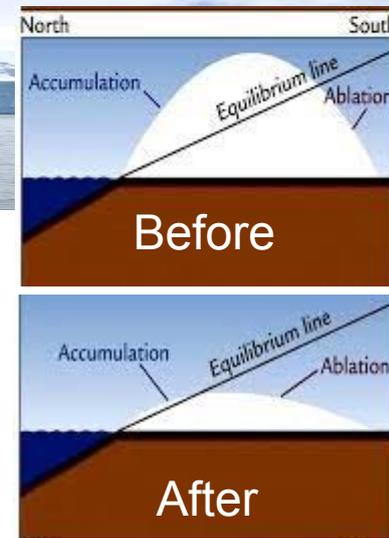
Accumulation zone
(albedo 70-80%)

Tundra

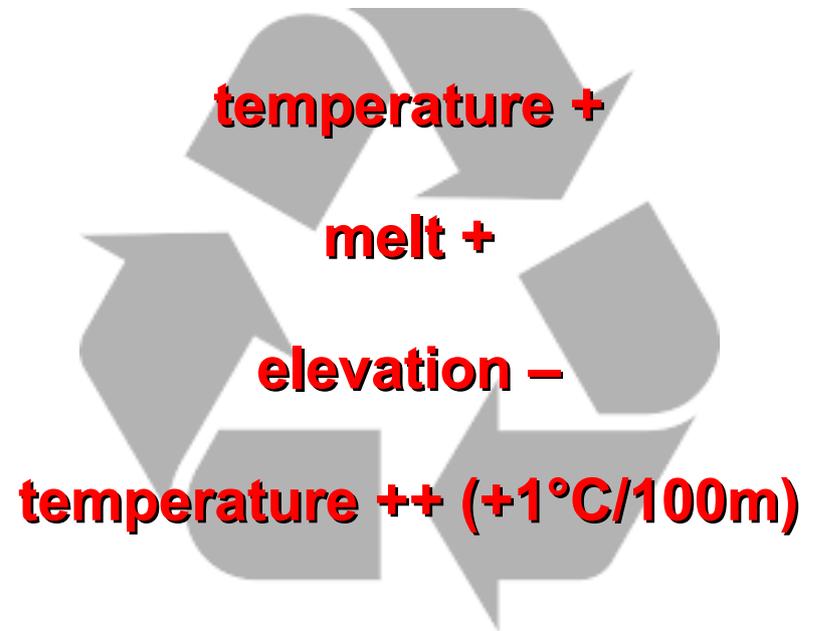
Ablation zone
(albedo 30-50%)

4. Future projections: Greenland

2. Melt acceleration due to the melt-elevation positive feedback



Cumulated height change over 2000-2100



By coupling MAR with an ice sheet model, this increase the melt by 10 % in 2100 (Le Clech't et al., 2019)

4. Future projections: Greenland

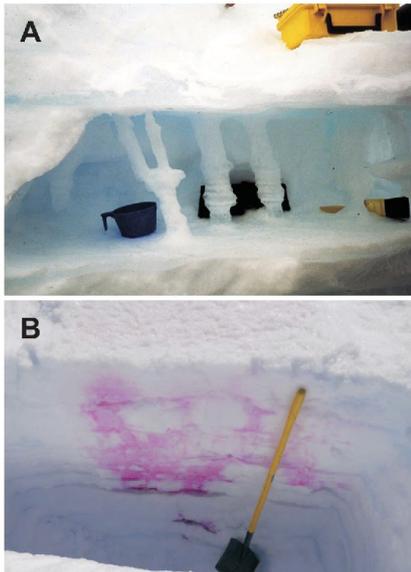
3. Melt acceleration due to the decrease of the melt water retention capacity

LETTER

doi:10.1038/nature11566

Greenland ice-sheet contribution to sea-level rise buffered by meltwater storage in firn

J. Harper¹, N. Humphrey², W. T. Pfeffer³, J. Brown¹ & X. Fettweis⁴



LETTER

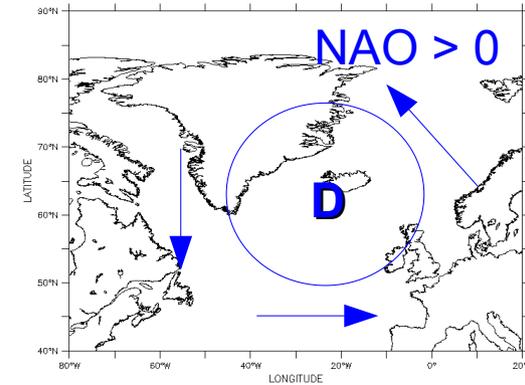
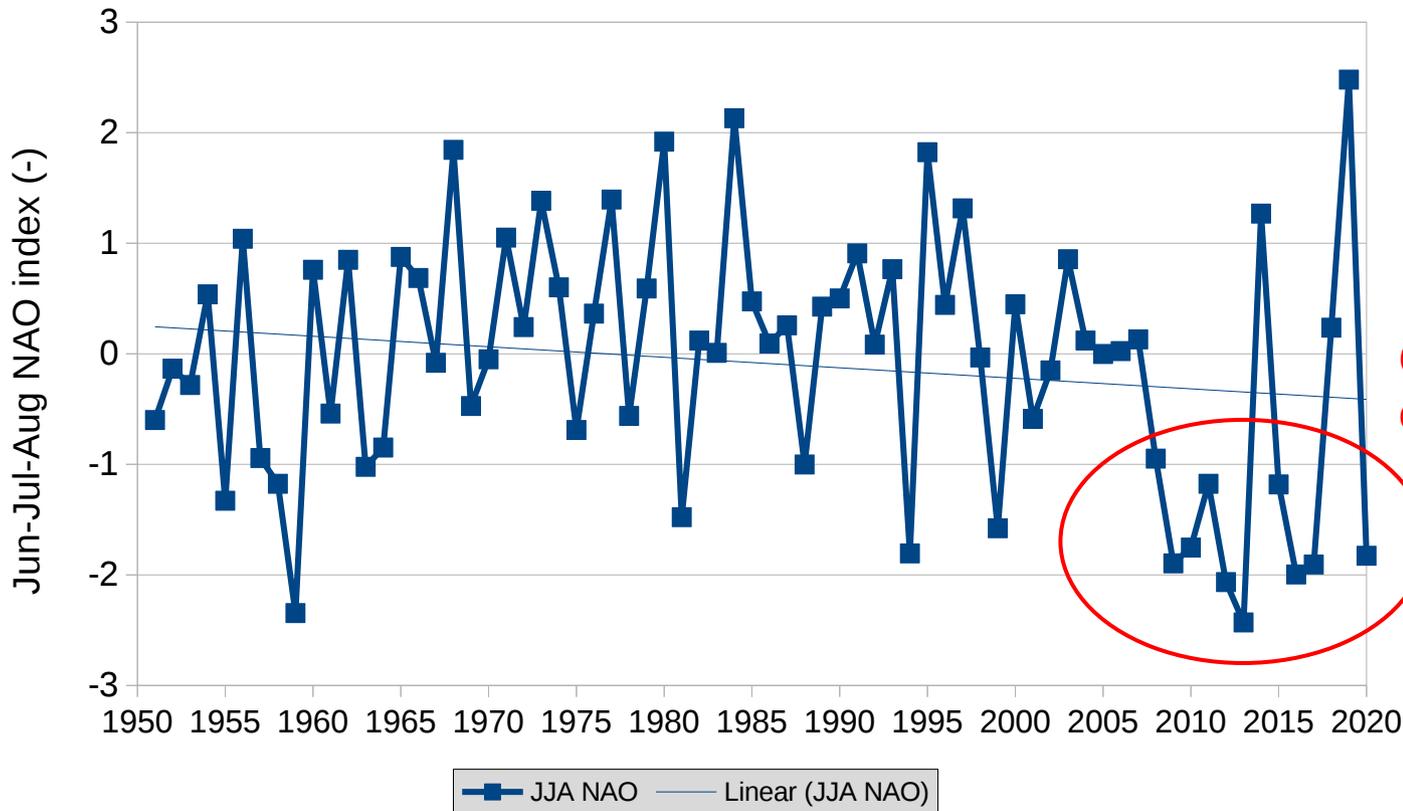
<https://doi.org/10.1038/s41586-019-1550-3>

Rapid expansion of Greenland's low-permeability ice slabs

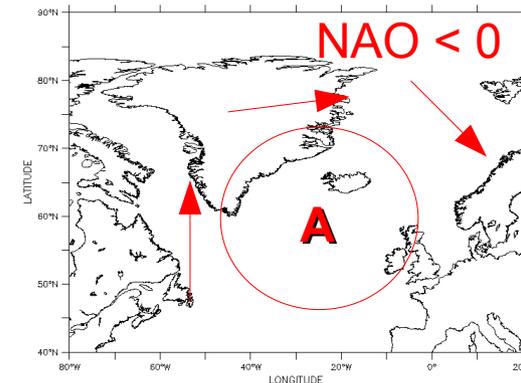
M. MacFerrin^{1*}, H. Machguth^{2,3}, D. van As⁴, C. Charalampidis⁵, C. M. Stevens⁶, A. Heilig^{7,8,9}, B. Vandecrux^{4,10}, P. L. Langen¹¹, R. Mottram¹¹, X. Fettweis¹², M. R. van den Broeke¹³, W. T. Pfeffer¹⁴, M. S. Moussavi^{1,15} & W. Abdalati¹

4. Future projections: Greenland

4. Potential melt acceleration due to changes in atmospheric circulation (1/3)



Climate changes ??



NAO index: normalised pressure difference between the Azores High and the Icelandic Low

4. Future projections: Greenland

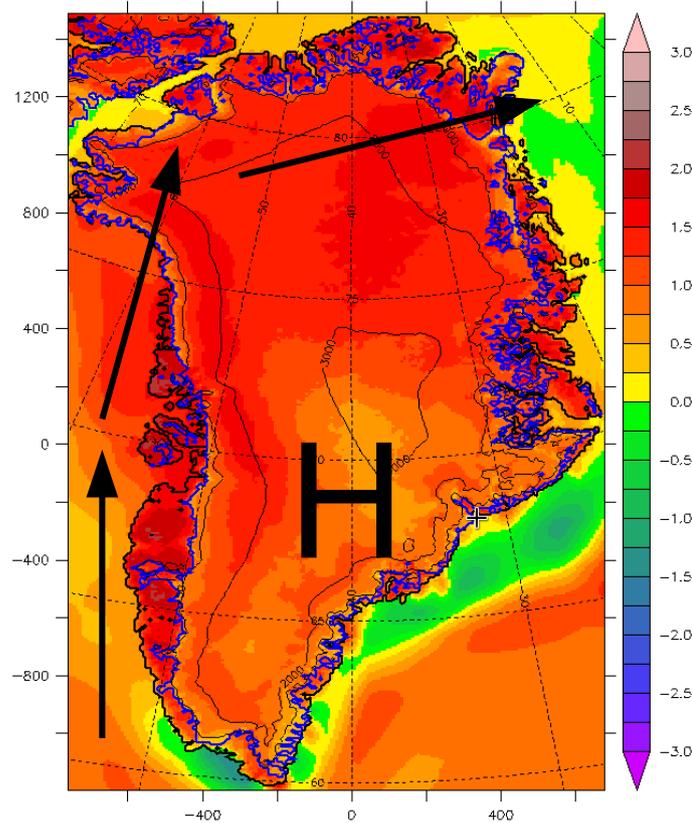
4. Potential melt acceleration due to changes in atmospheric circulation (2/3)

RESEARCH ARTICLE

International Journal of Climatology

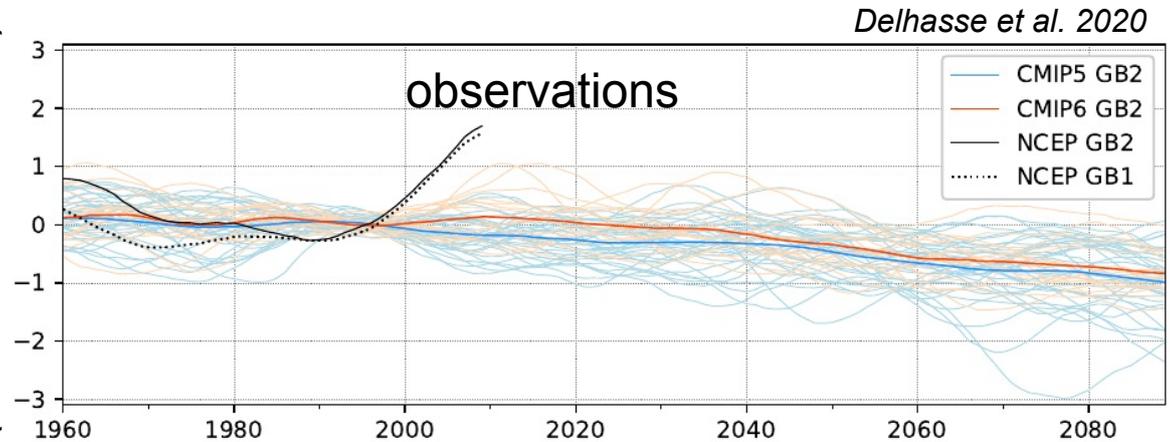
Brief communication: CMIP6 does not suggest any atmospheric blocking increase in summer over Greenland by 2100

Alison Delhasse¹ | Edward Hanna² | Christoph Kittel¹ | Xavier Fettweis¹



JJA 2m temperature anomaly in the 2000s (°C)

Greenland Blocking index (derived from NAO)



Delhasse et al. 2020

Who is right ?

Are these changes due to global warming or climate variability ?

4. Future projections: Greenland

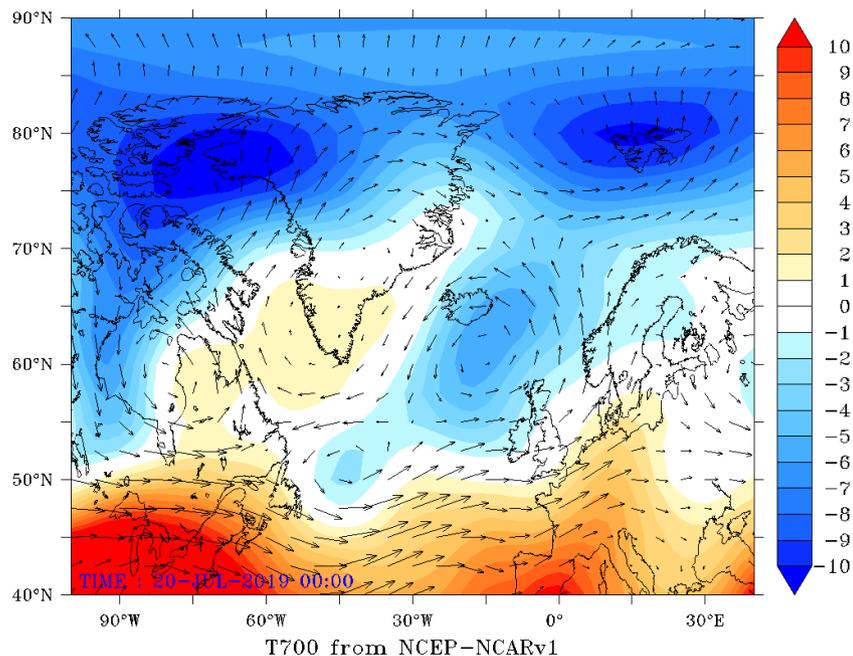
4. Potential melt acceleration due to changes in atmospheric circulation (3/3)

Brief communication: Impact of the recent atmospheric circulation change in summer on the future surface mass balance of the Greenland ice sheet

Alison Delhasse¹, Xavier Fettweis¹, Christoph Kittel¹, Charles Amory¹, and Cécile Agosta^{1,2}

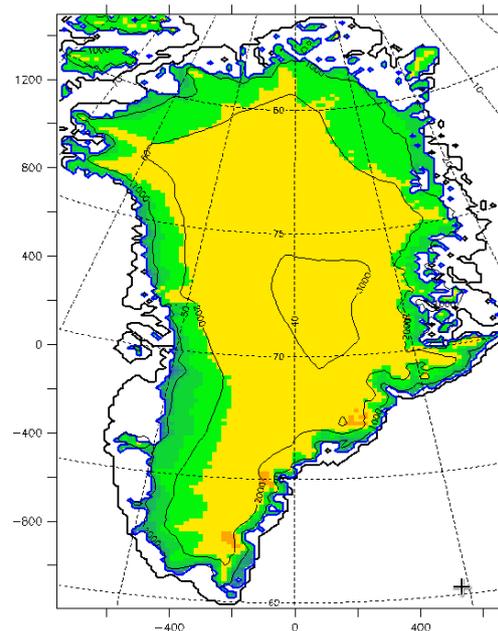
If the current change in general circulation persists in future, the melt of the GrIS should be multiplied by 2!

July 2019:
40°C in Belgium and
record of melt afterwards

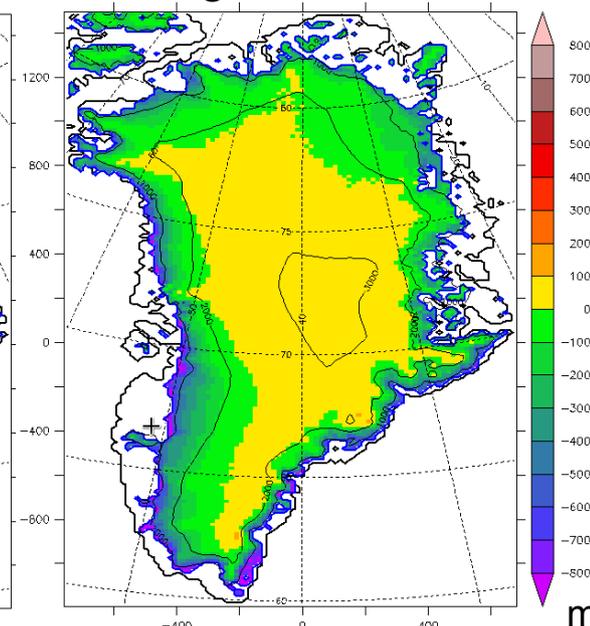


Surface height changes en 2100:

normal circulation



changed circulation



4. Future projections: Greenland

5. Potential melt acceleration due to changes in clouds (1/2)

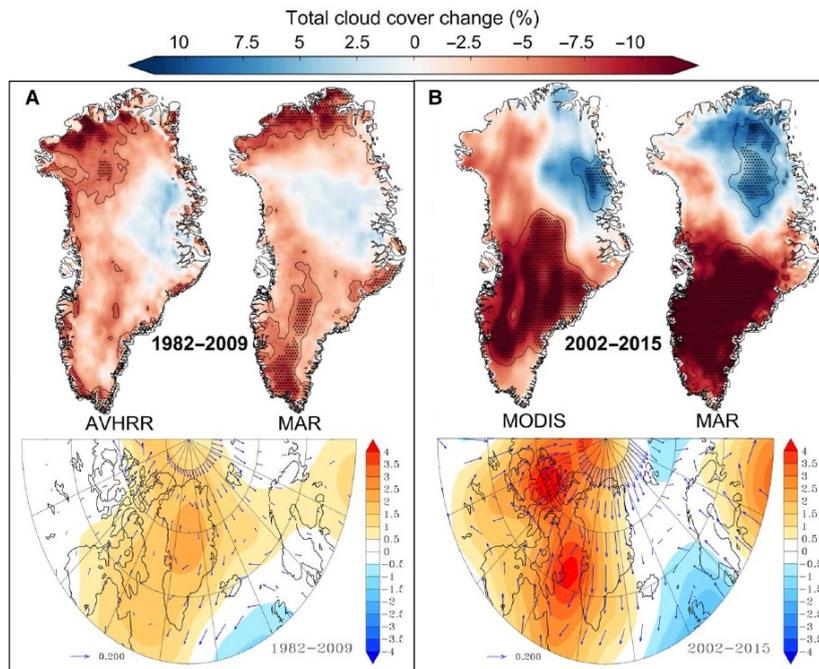
nature
climate change

LETTERS

<https://doi.org/10.1038/s41558-019-0507-8>

Cloud microphysics and circulation anomalies control differences in future Greenland melt

Stefan Hofer^{1,2*}, Andrew J. Tedstone¹, Xavier Fettweis^{1,2} and Jonathan L. Bamber¹



SCIENCE ADVANCES | RESEARCH ARTICLE

METEOROLOGY

Decreasing cloud cover drives the recent mass loss on the Greenland Ice Sheet

Stefan Hofer,^{1*} Andrew J. Tedstone,¹ Xavier Fettweis,² Jonathan L. Bamber¹

The Greenland Ice Sheet (GrIS) has been losing mass at an accelerating rate since the mid-1990s. This has been due to both increased ice discharge into the ocean and melting at the surface, with the latter being the dominant contribution. This change in state has been attributed to rising temperatures and a decrease in surface albedo. We show, using satellite data and climate model output, that the abrupt reduction in surface mass balance since about 1995 can be attributed largely to a coincident trend of decreasing summer cloud cover enhancing the melt-albedo feedback. Satellite observations show that, from 1995 to 2009, summer cloud cover decreased by $0.9 \pm 0.3\%$ per year. Model output indicates that the GrIS summer melt increases by 27 ± 13 gigatons (Gt) per percent reduction in summer cloud cover, principally because of the impact of increased shortwave radiation over the low albedo ablation zone. The observed reduction in cloud cover is strongly correlated with a state shift in the North Atlantic Oscillation promoting anticyclonic conditions in summer and suggests that the enhanced surface mass loss from the GrIS is driven by synoptic-scale changes in Arctic-wide atmospheric circulation.

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4. Future projections: Greenland

5. Potential melt acceleration due to changes in clouds (2/2)

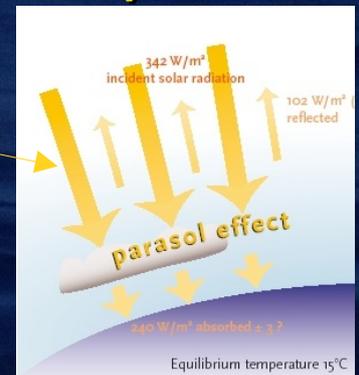
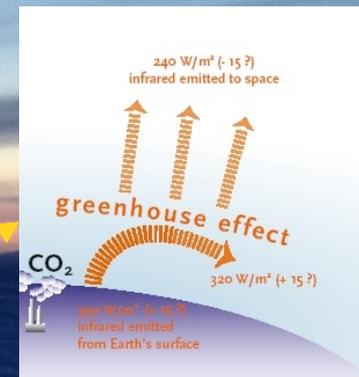
In the **accumulation zone**, melt is driven by infrared radiation

In the **ablation zone**, melt is driven by solar radiation

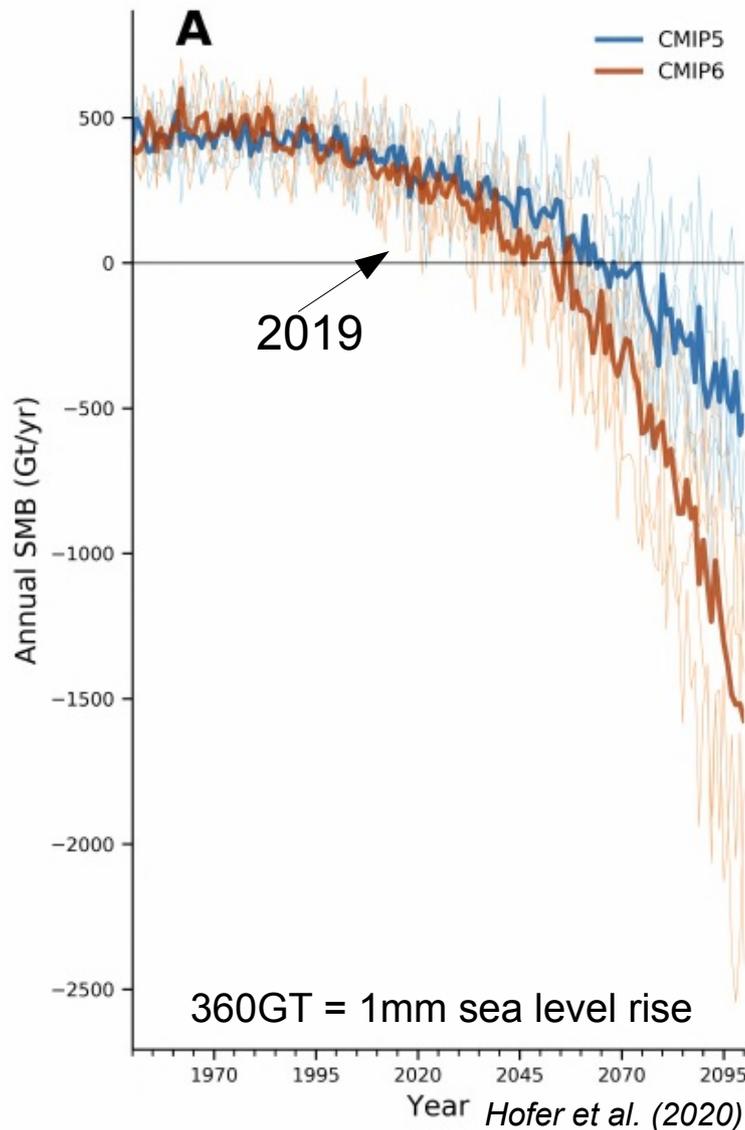
Role of clouds

- warming in the accumulation zone (greenhouse effect)
- cooling in the ablation zone (parasol effect)

+ liquid clouds (grey) vs solid clouds (white)



4. Future projections: Greenland



ARTICLE

<https://doi.org/10.1038/s41467-020-20011-8>

OPEN

Check for updates

Greater Greenland Ice Sheet contribution to global sea level rise in CMIP6

Stefan Hofer^{1,2}, Charlotte Lang², Charles Amory², Christoph Kittel², Alison Delhasse², Andrew Tedstone³ & Xavier Fettweis²

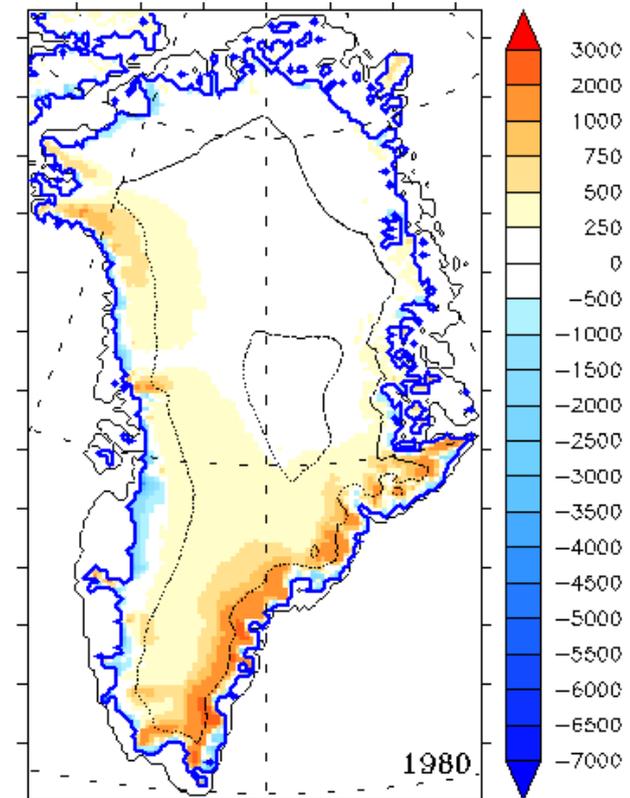
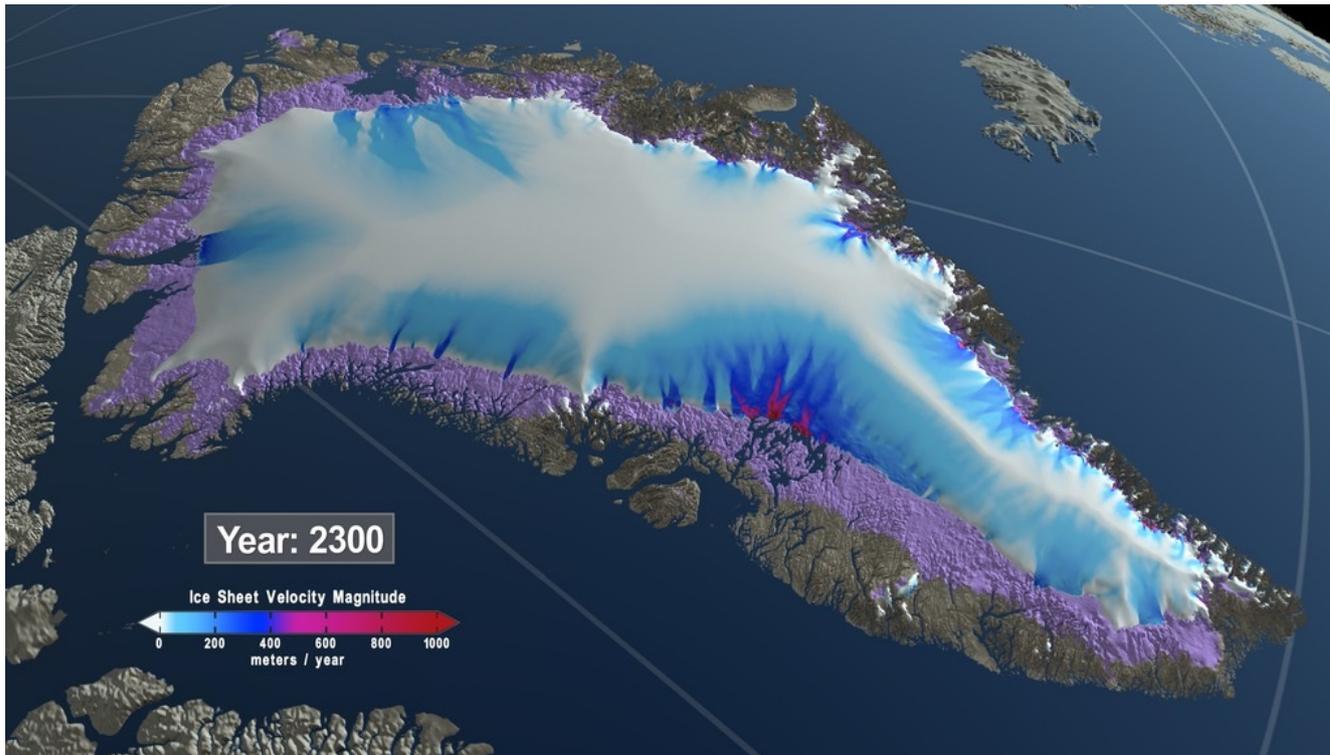
Future projections of the Greenland ice sheet **surface mass balance** using MAR-ULiège

AR5 (IPCC, 2013): SLR = ~ 11 +/- 3 cm

AR6 (IPCC, 2021): SLR ~ 15 +/- 6 cm

max SLR ~ 25 cm

4. Future projections: Greenland



After the retreat, a new stable state could be reached without iceberg discharges.

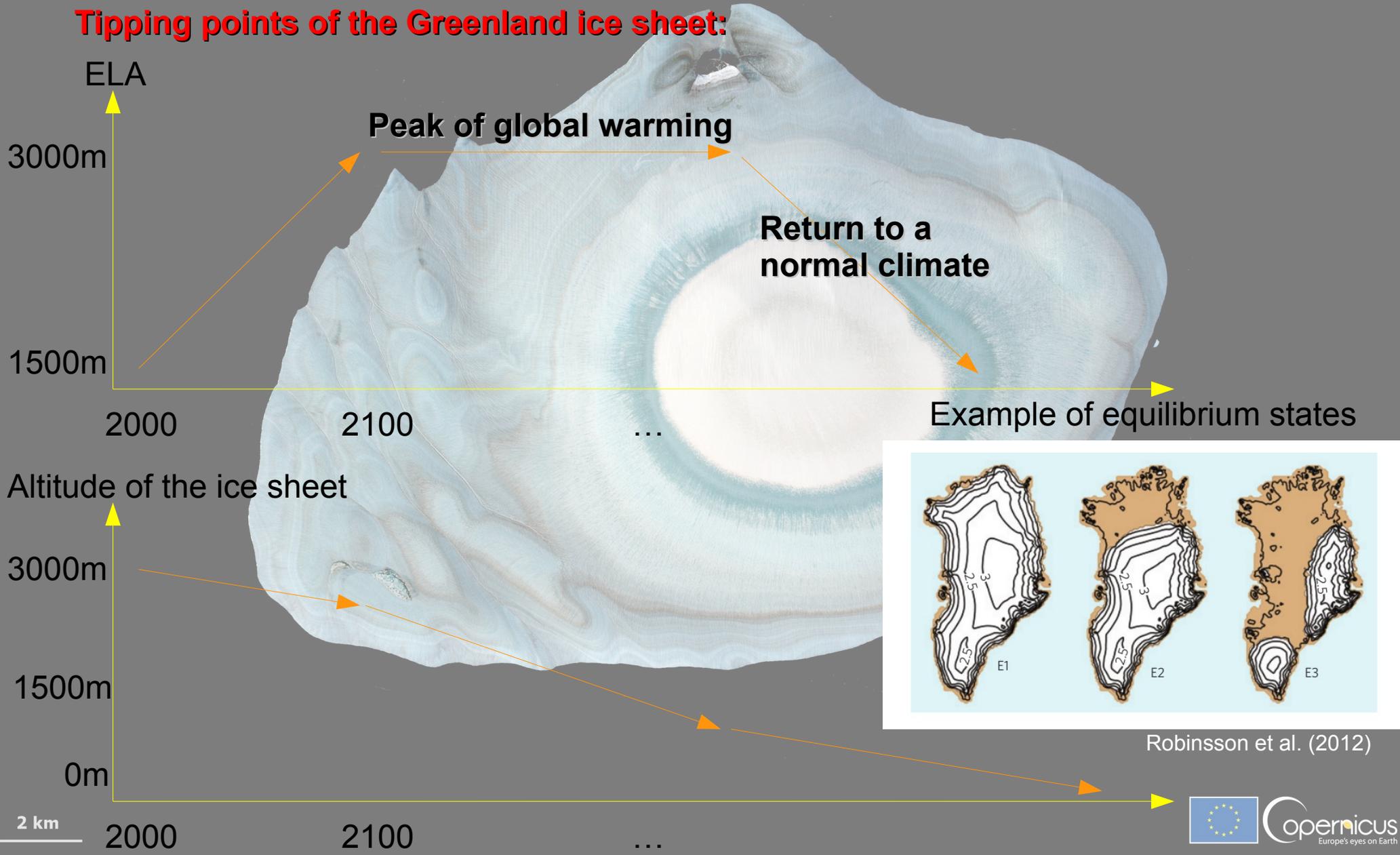
The tipping point will be then mainly driven by SMB and ELA:

SMB < 0 is expected for the end of this century

- but such anomaly should persist during several centuries to reach a tipping point.
- but no surprise as there is non-chaotic change!

4. Future projections: Greenland

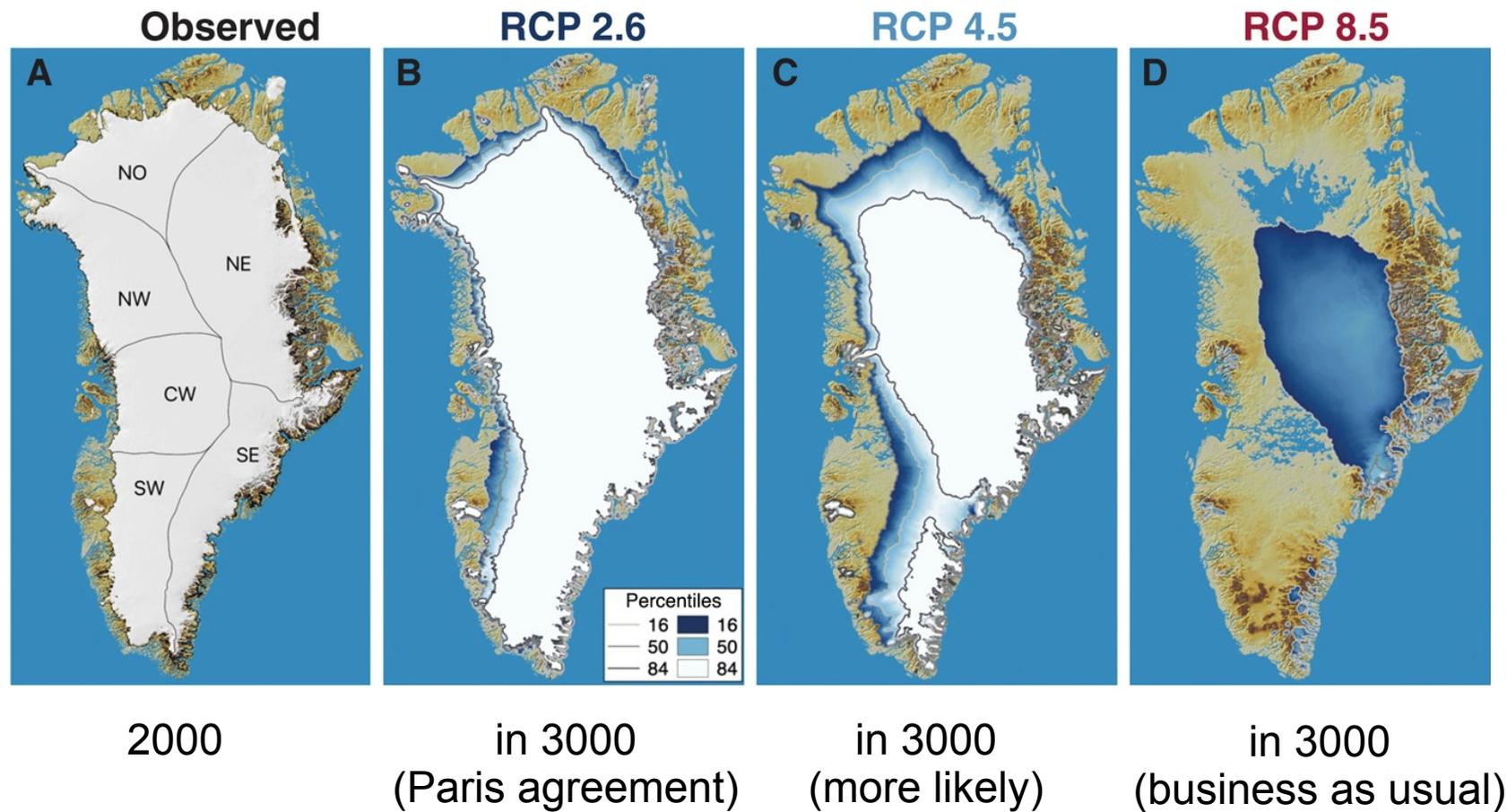
Tipping points of the Greenland ice sheet:



Credit: European Union, Copernicus Sentinel-2 imagery - Processed by @DEFIS_EU.

4. Future projections: Greenland

Example of reached tipping points...



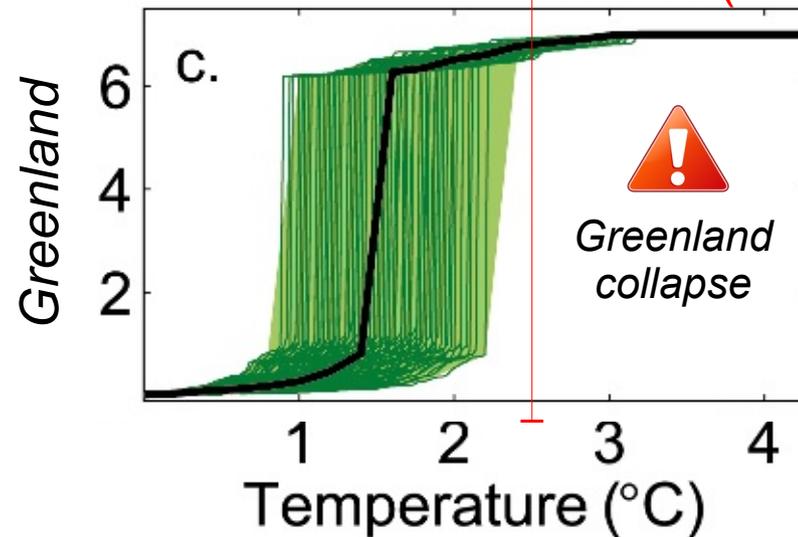
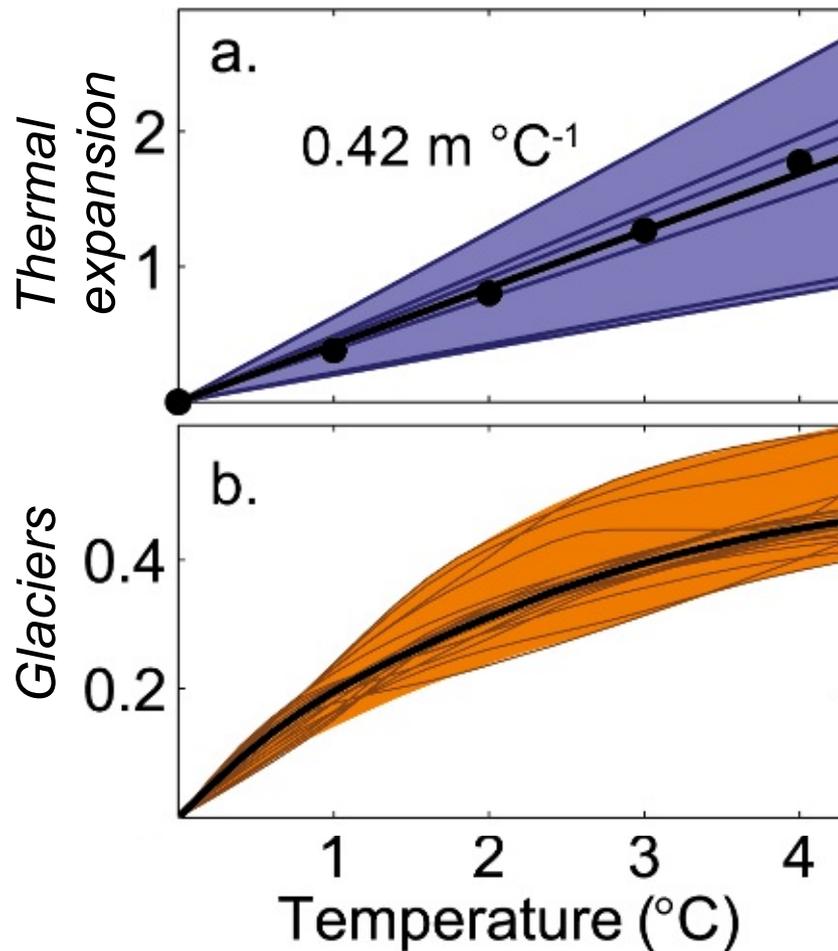
Ref: Aschwanden et al. (2019)

4. Future projections: Greenland

Sea level rise after a temperature anomaly of $X^{\circ}\text{C}$ during 1000 years

➔ Likely irreversibility if $\Delta T > 2\text{-}3^{\circ}\text{C}$

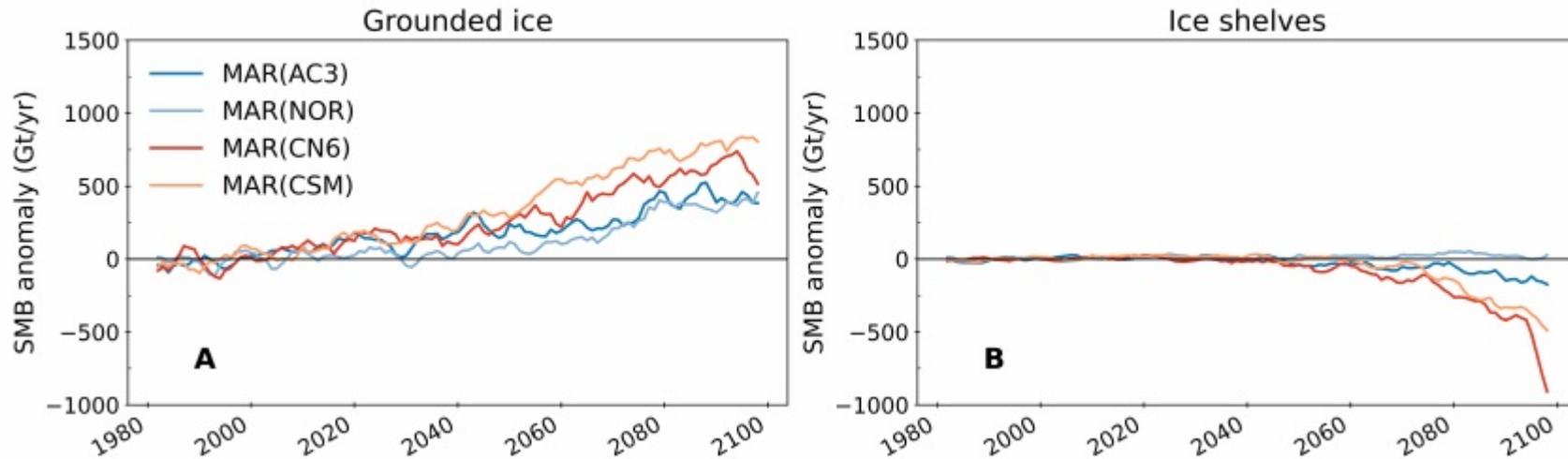
More recent studies (AR6, 2021)



4. Future projections: Antarctica

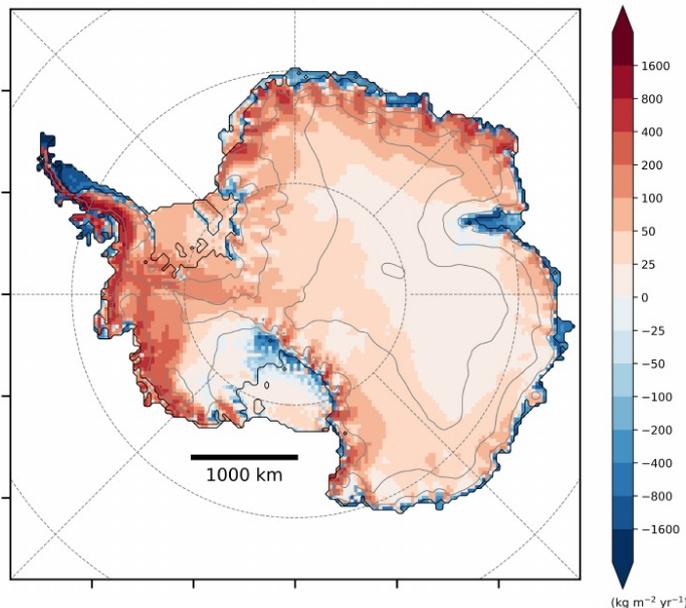


The SMB is projected to increase except over the ice shelves...



Kittel et al. (2021)

C. SMB MAR(CESM2) future - present



Except in some areas (Peninsula and ice shelves), SMB should remain positive and even a lot of more positive!

=> Antarctic = sea level drop ??

Diverging future surface mass balance between the Antarctic ice shelves and grounded ice sheet

Christoph Kittel¹, Charles Amory^{1,2}, Cécile Agosta³, Nicolas C. Jourdain², Stefan Hofer⁴, Alison Delhasse¹, Sébastien Doutreloup¹, Pierre-Vincent Huot⁵, Charlotte Lang^{1,6}, Thierry Fichefet⁵, and Xavier Fettweis¹

¹Laboratory of Climatology, Department of Geography, SPHERES research unit, University of Liège, Liège, Belgium

²Institut des Géosciences de l'Environnement (IGE), Univ. Grenoble Alpes/CNRS/IRD/G-INP, Grenoble, France

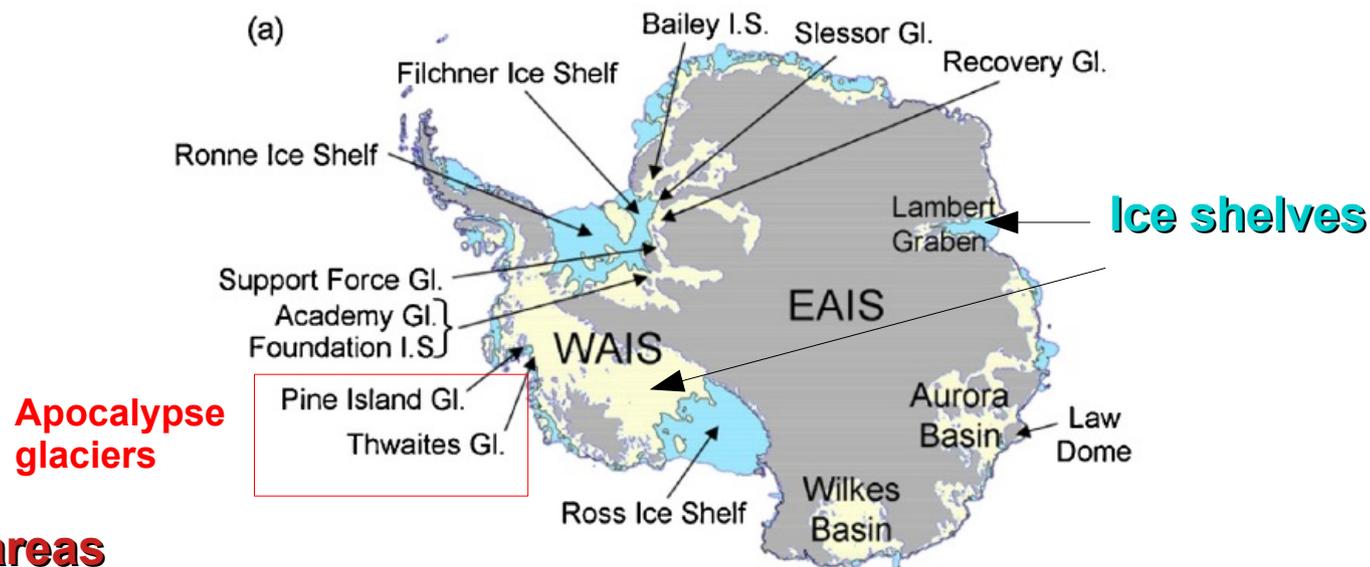
³Laboratoire des Sciences du Climat et de l'Environnement, LSCE-IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, Gif-sur-Yvette, France

⁴Department of Geosciences, University of Oslo, Oslo, Norway

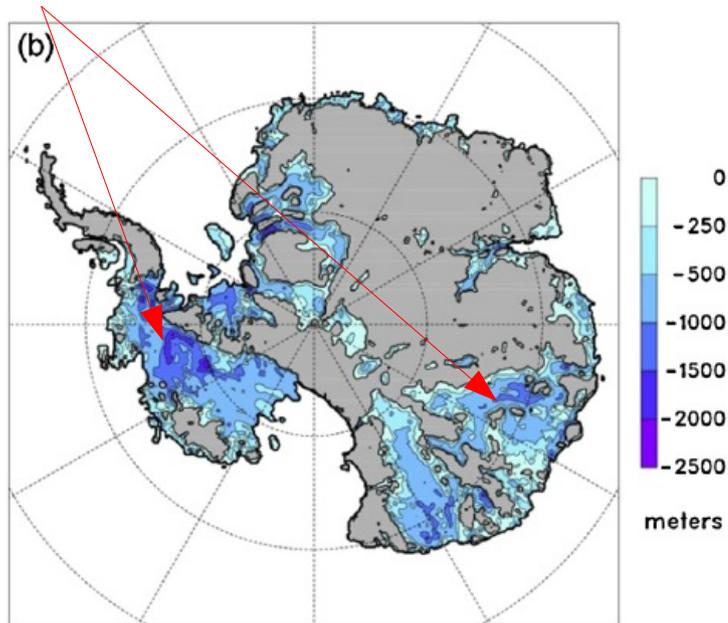
⁵Earth and Climate, Earth and Life Institute, Catholic University of Louvain, Louvain-la-Neuve, Belgium

⁶National Centre for Atmospheric Science, University of Reading, Reading, United Kingdom

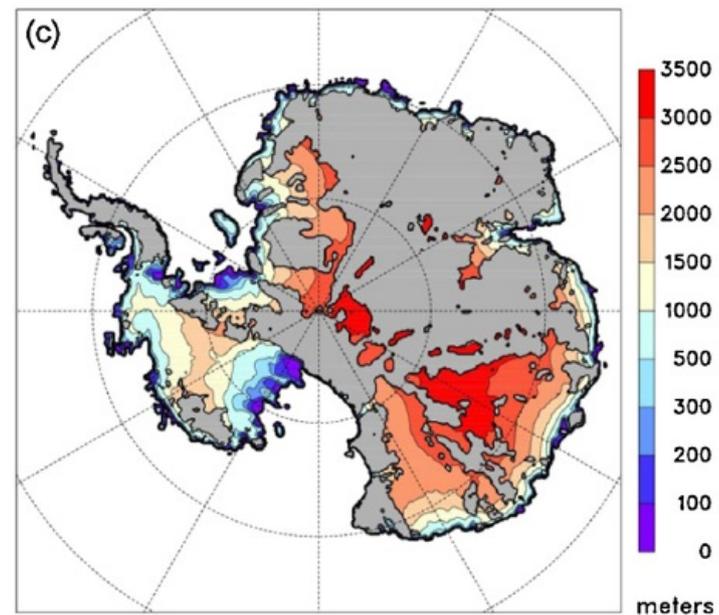
4. Future projections: Antarctica



Critical areas

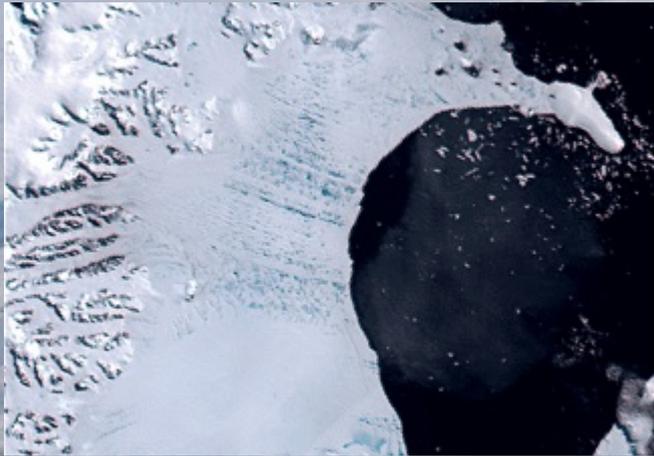


Topography below sea level



Pollard et al. (2015)

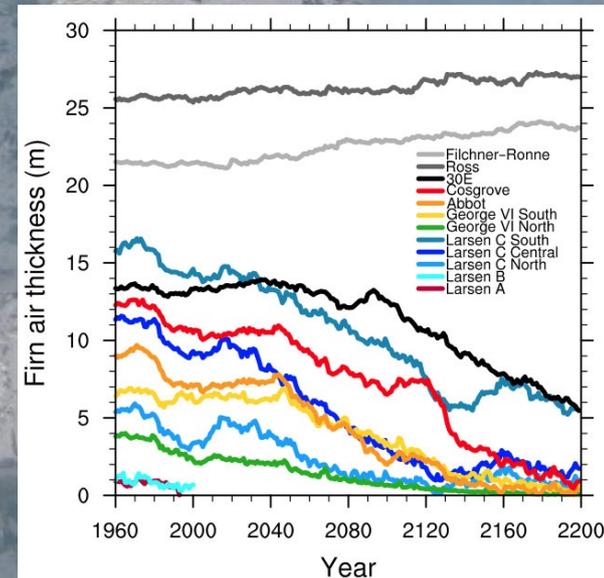
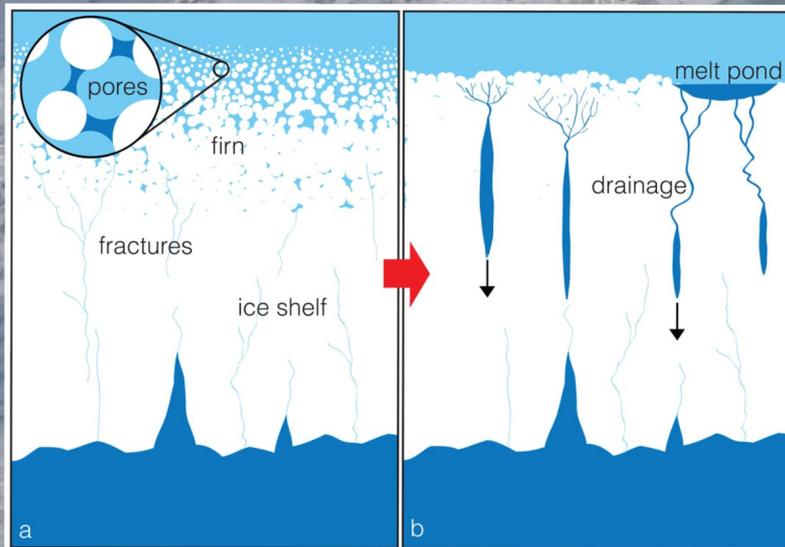
4. Future projections: Antarctica



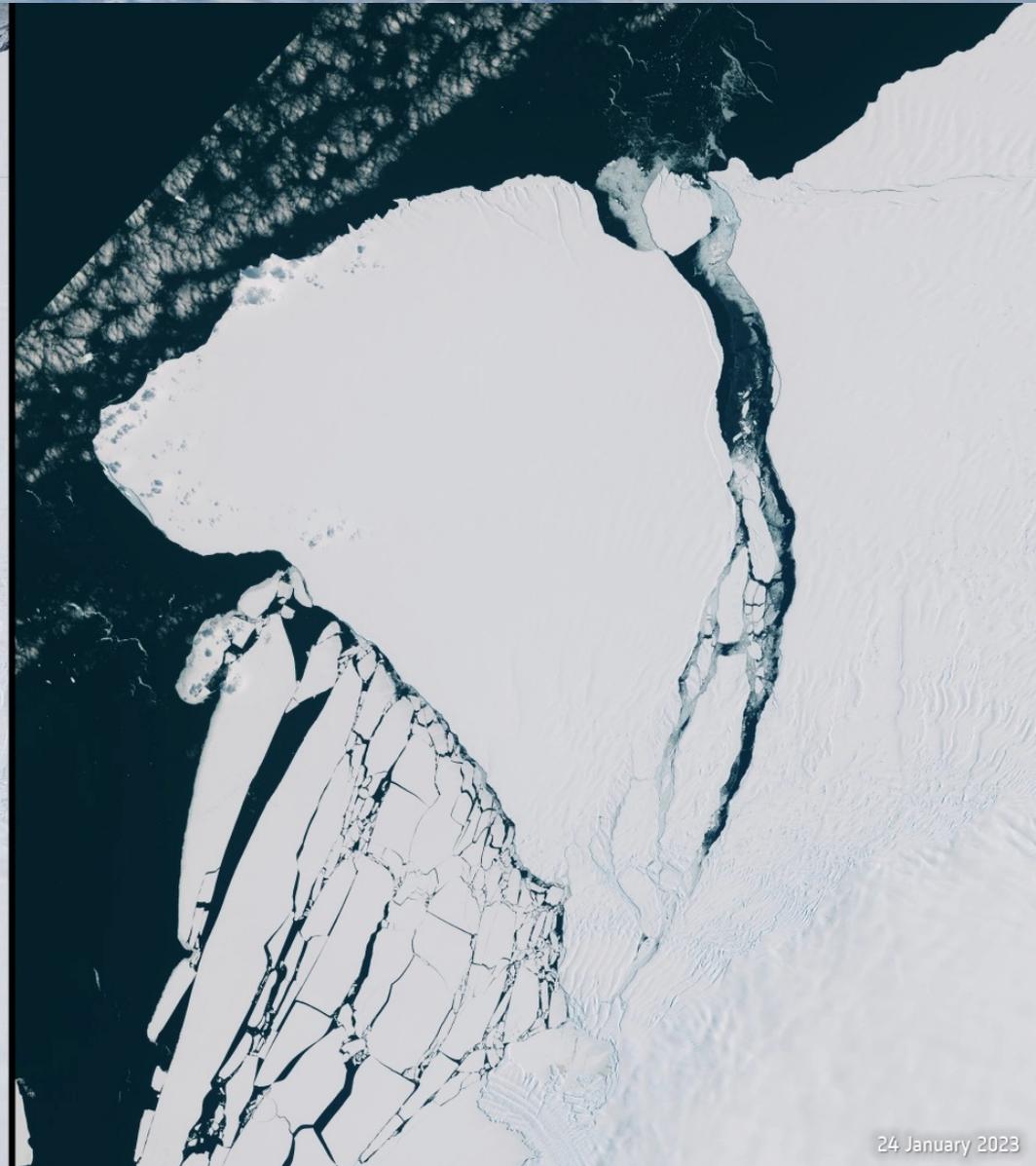
Larsen B collapse (31 Jan - 7 Mar 2002) (Source: P. Kuipers Munneke)

A collapse of most of small ice shelves before 2100 is very likely!

=> no contribution to the sea level!
=> but decrease of the buttressing
=> increase of ice dynamics



4. Future projections: Antarctica

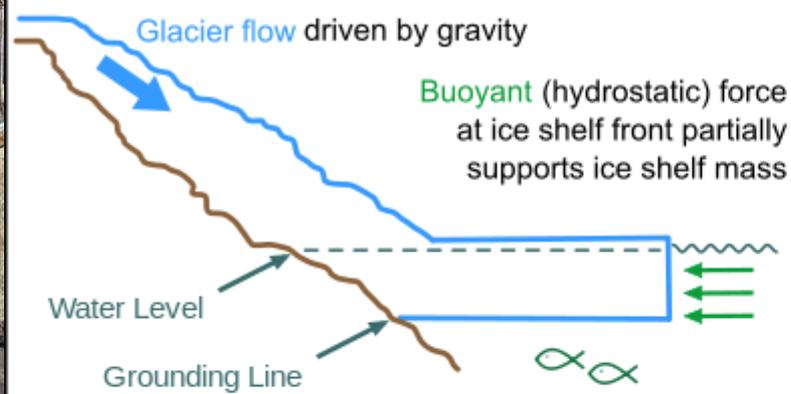


Brunt ice shelf (24 Jan 2023)

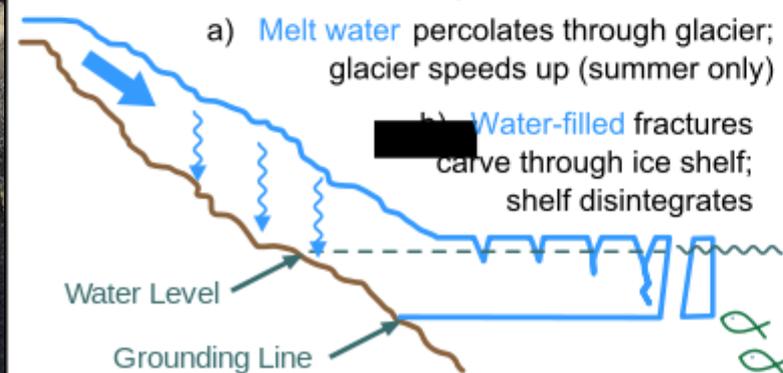
4. Future projections: Antarctica

Glacier acceleration due to an ice shelf collapse

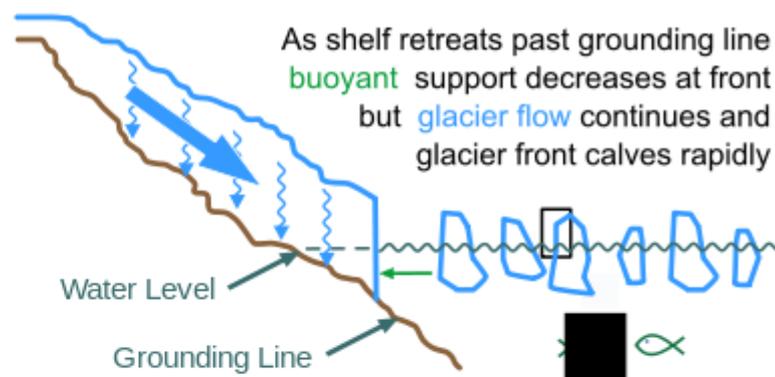
1. Stable glacier and ice shelf



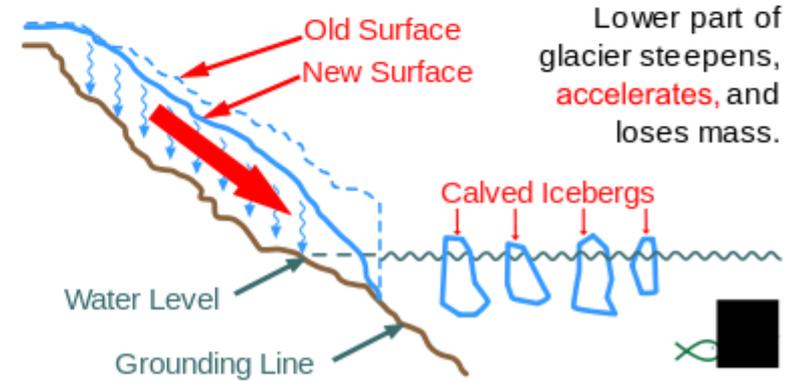
2. Two effects of warmer temperatures



3. Unstable glacier front after ice shelf collapse



4. Glacier acceleration

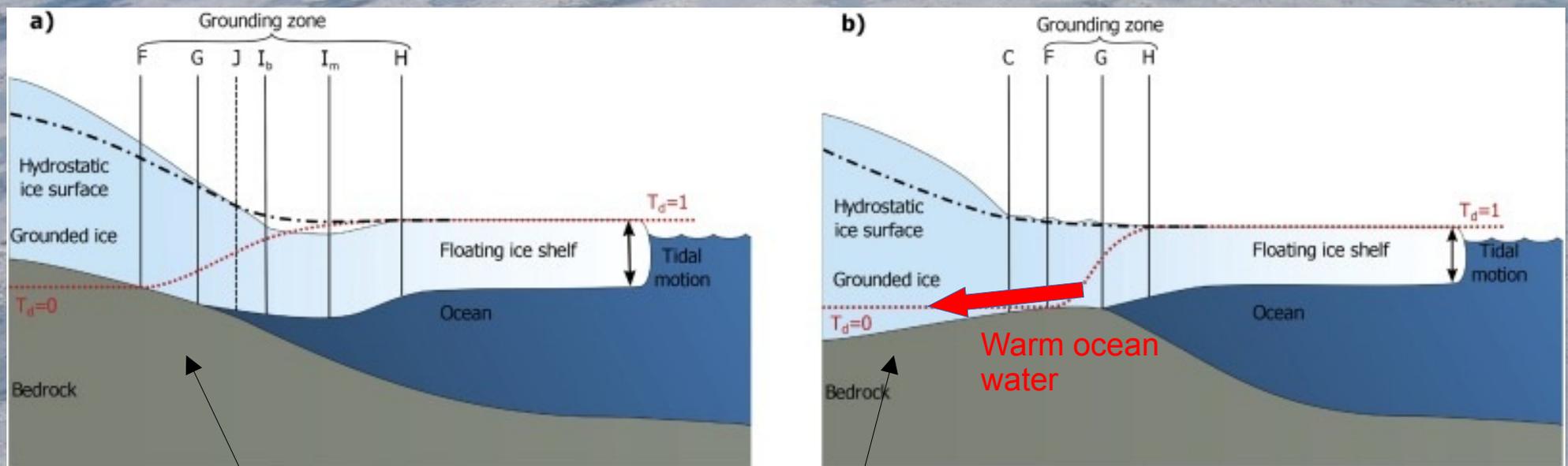


Ice shelf = buttress of a cathedral (Arc-Boutant in French)

Source: <http://www.antarcticglaciers.org/>

4. Future projections: Antarctica

Problem with unstable grounding lines

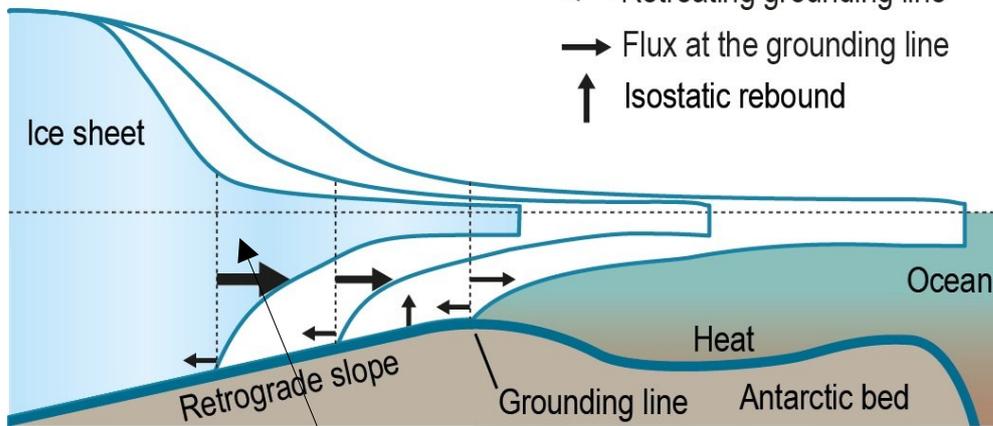


Hanna et al. (2013)

4. Future projections: Antarctica

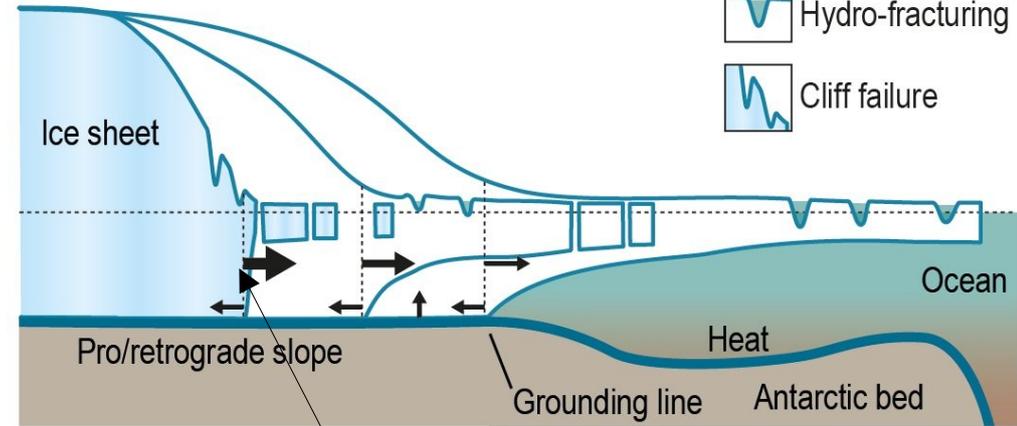
2 positive feedbacks... (Pattyn, 2018)

(a) Marine Ice Sheet Instability (MISI)
Retrograde slope



*No more
buttressing
effect*

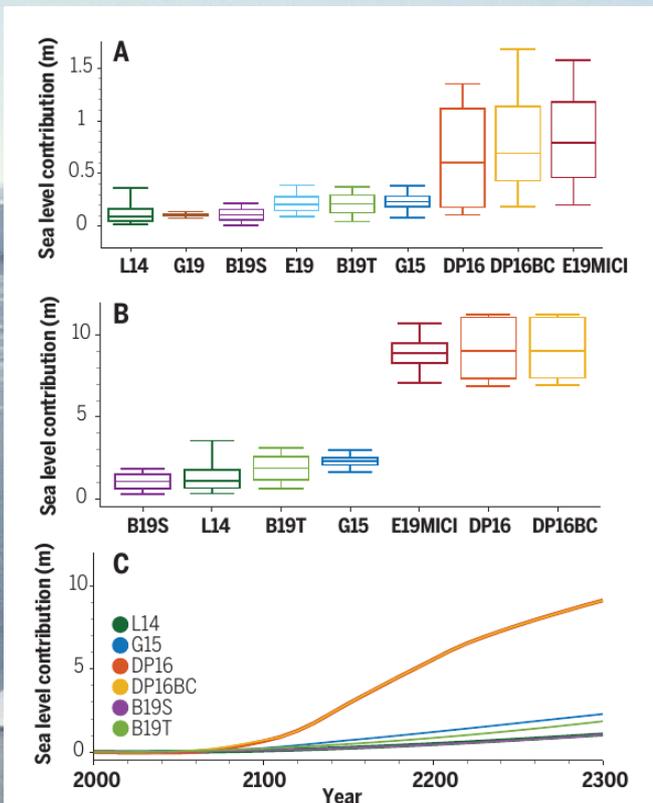
(b) Marine Ice Cliff Instability (MICI)
Pro/retrograde slopes



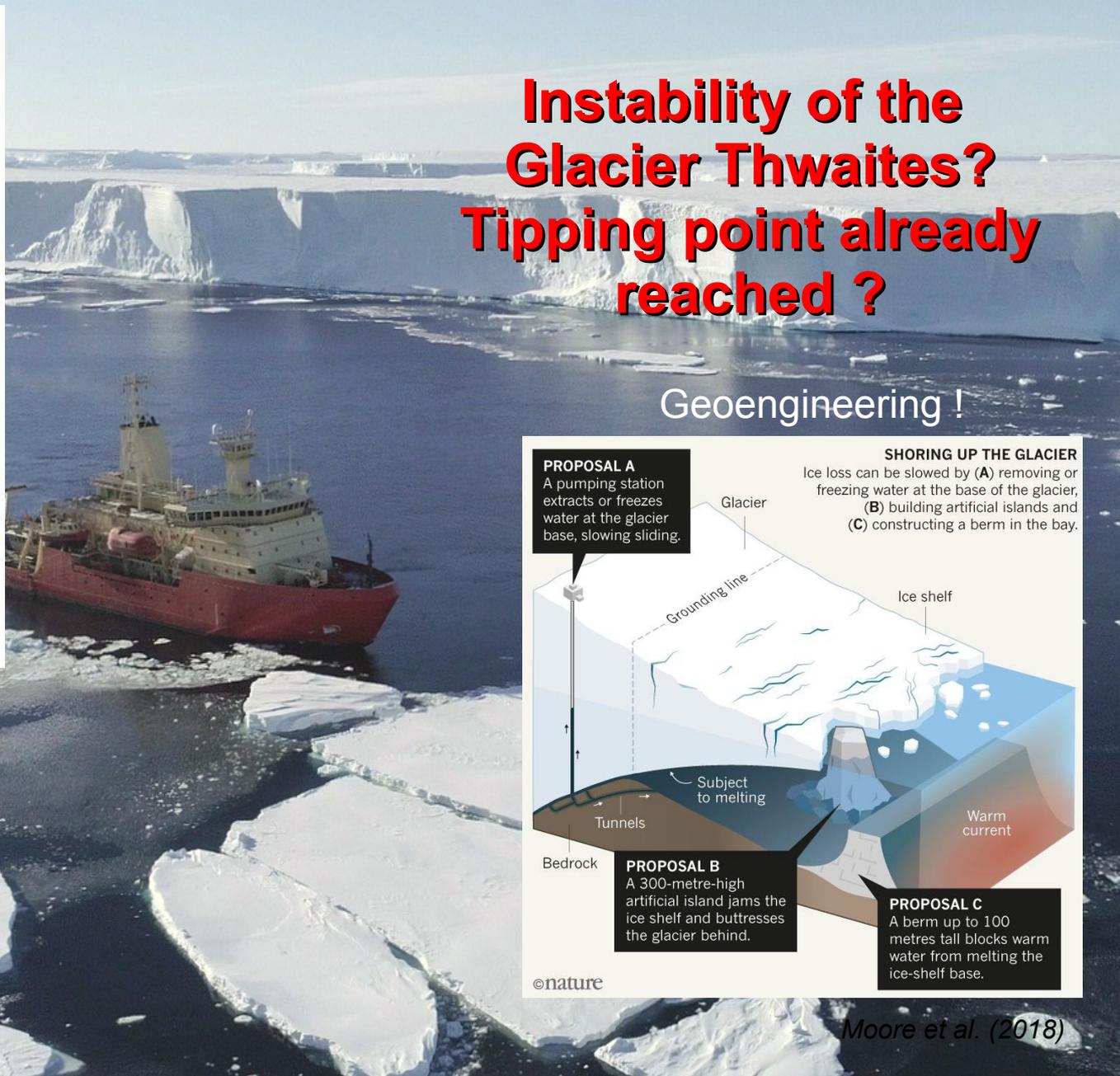
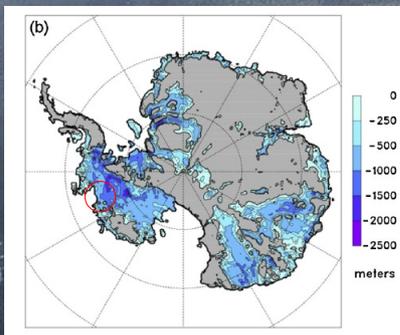
~ 800m

Ice discharge generally increases with increasing ice thickness at the grounding line

4. Future projections: Antarctica

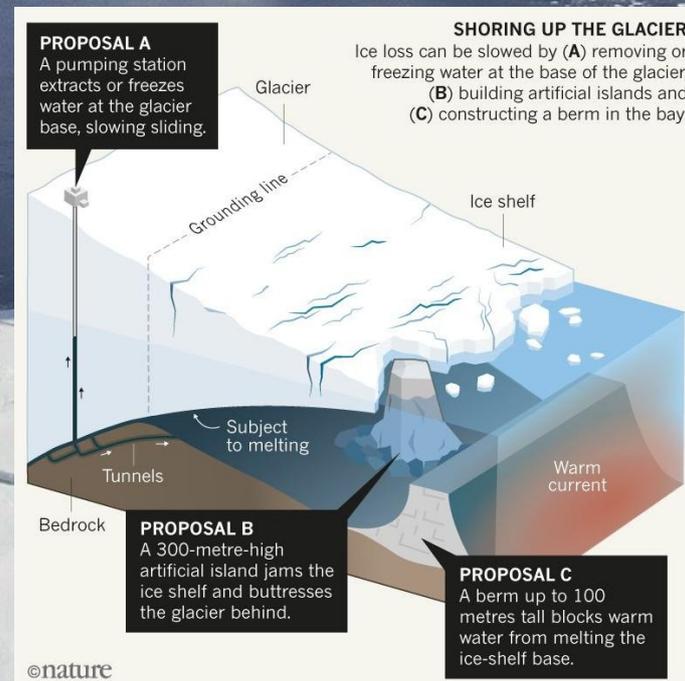


Sea level rise (Pattyn et al., 2020)



Instability of the Glacier Thwaites? Tipping point already reached ?

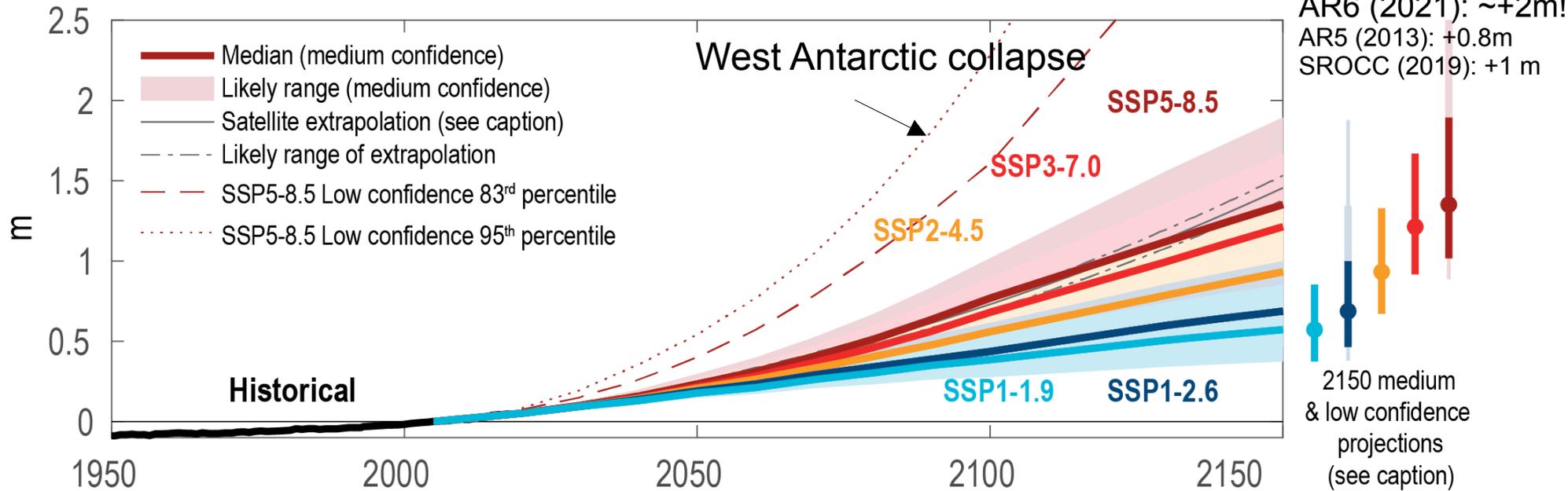
Geoengineering !



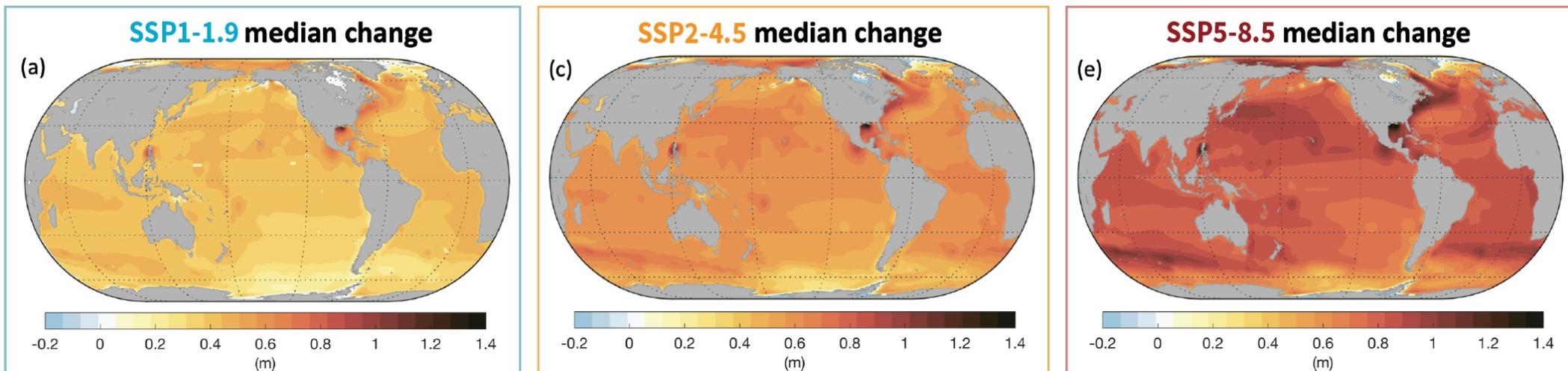
Moore et al. (2018)

5. Sea level rise

Projected global mean sea level rise under different SSP scenarios



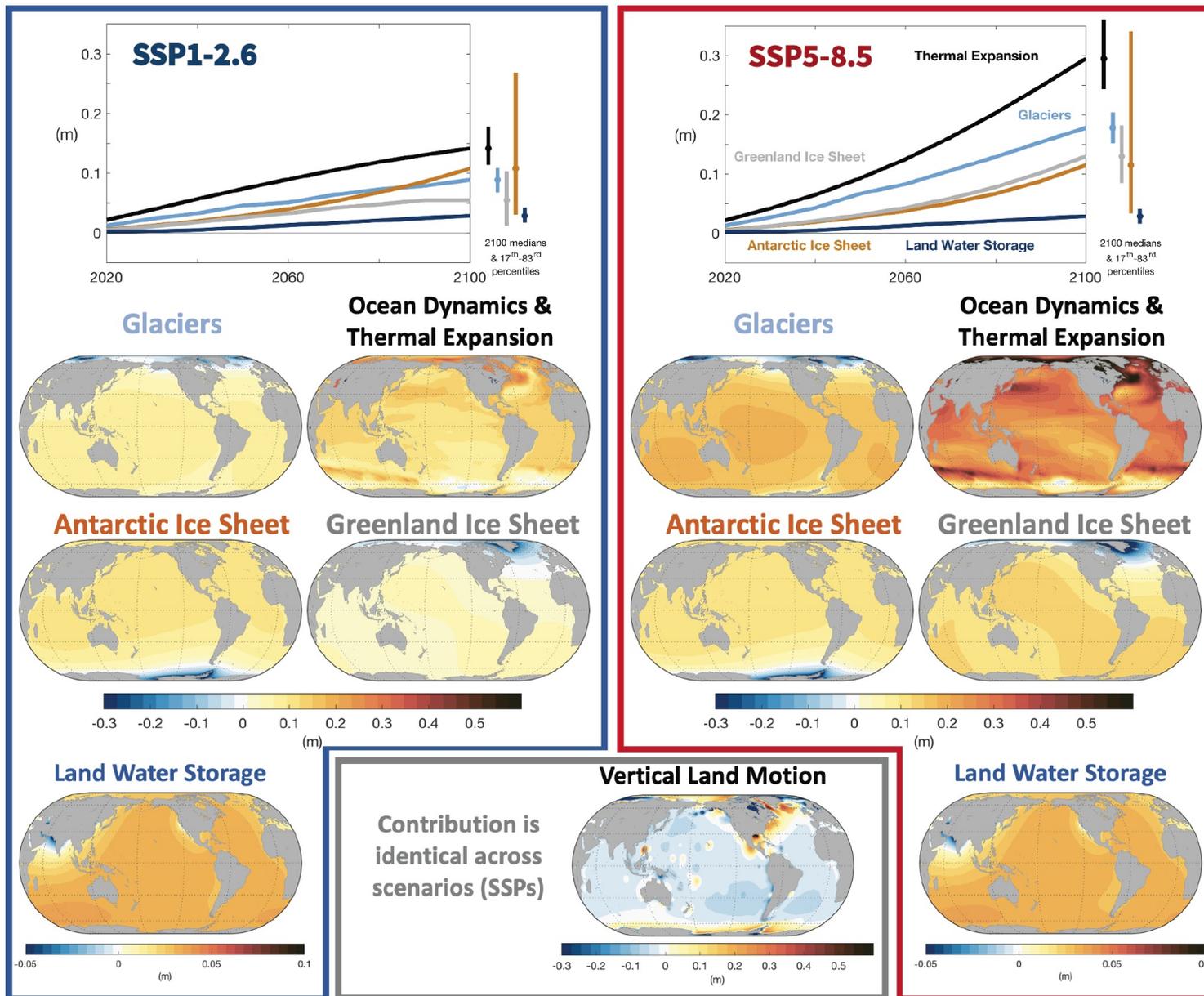
Regional sea level change at 2100 for different scenarios (with respect to 1995-2014)



© IPCC 2021 (AR6, Figs 9.27 and 9.28)

5. Sea level rise

Projected Sea Level Change Contributions under **SSP1-2.6** and **SSP5-8.5**

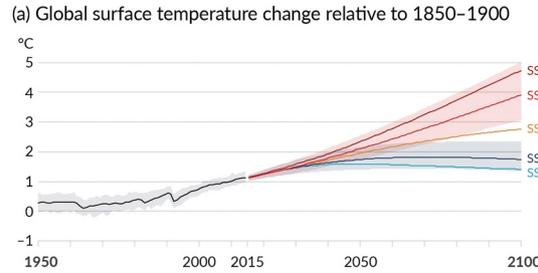
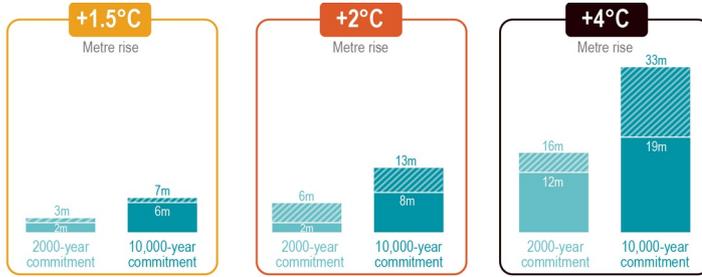


5. Sea level rise

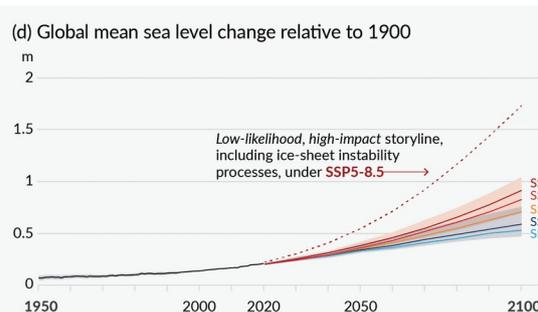
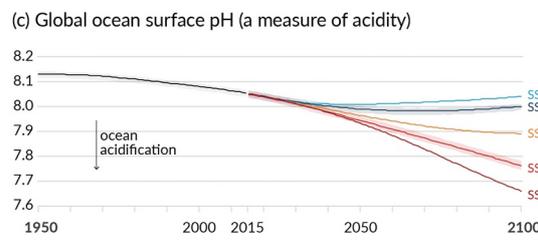
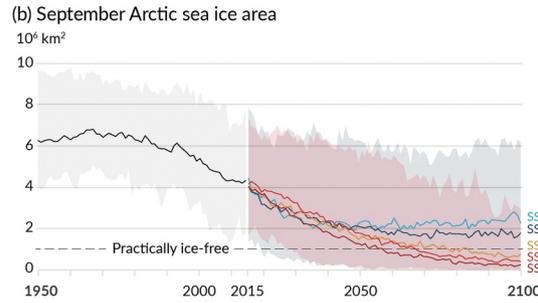
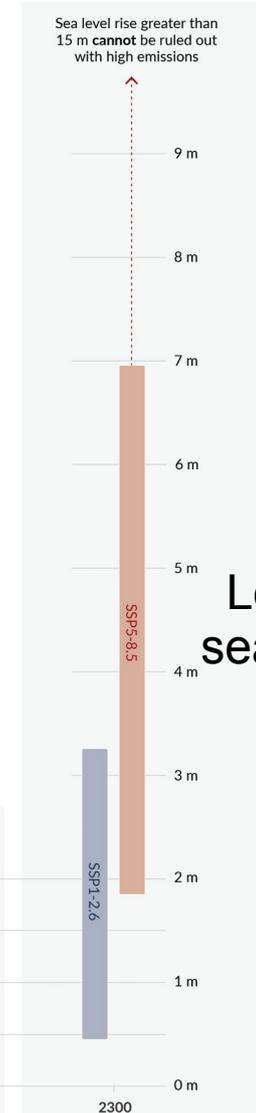
Human activities affect all the major climate system components, with some responding over decades and others over centuries

Today, sea level has already increased by 20 cm and will increase an additional 30 cm to 1 m or more by 2100, depending on future emissions.

Sea level reacts very slowly to global warming so, once started, the rise continues for thousands of years.



(e) Global mean sea level change in 2300 relative to 1900



Long term sea level rise in 2300

Committed (long term) sea level rise

ARTICLES <https://doi.org/10.1038/s41558-022-01441-2> nature climate change

OPEN Greenland ice sheet climate disequilibrium and committed sea-level rise

Jason E. Box¹, Alun Hubbard^{2,3}, David B. Bahr⁴, William T. Colgan¹, Xavier Fettweis⁵, Kenneth D. Mankoff¹, Adrien Wehrlé⁶, Brice Noël⁷, Michiel R. van den Broeke⁷, Bert Wouters^{7,8}, Anders A. Björk⁹ and Robert S. Fausto¹

Ice loss from the Greenland ice sheet is one of the largest sources of contemporary sea-level rise (SLR). While process-based models place timescales on Greenland's deglaciation, their confidence is obscured by model shortcomings including imprecise atmospheric and oceanic couplings. Here, we present a complementary approach resolving ice sheet disequilibrium with climate constrained by satellite-derived bare-ice extent, tidewater sector ice flow discharge and surface mass balance data. We find that Greenland ice imbalance with the recent (2000-2019) climate commits at least 274 ± 68 mm SLR from $59 \pm 15 \times 10^3$ km² ice retreat, equivalent to $3.3 \pm 0.9\%$ volume loss, regardless of twenty-first-century climate pathways. This is a result of increasing mass turnover from precipitation, ice flow discharge and meltwater run-off. The high-melt year of 2012 applied in perpetuity yields an ice loss commitment of 782 ± 135 mm SLR, serving as an ominous prognosis for Greenland's trajectory through a twenty-first century of warming.

Greenland ice sheet: **+27cm** with the current state

(AR6, Fig SPM8)

5. Conclusions

Marine ice sheet instability amplifies and skews uncertainty in projections of future sea-level rise

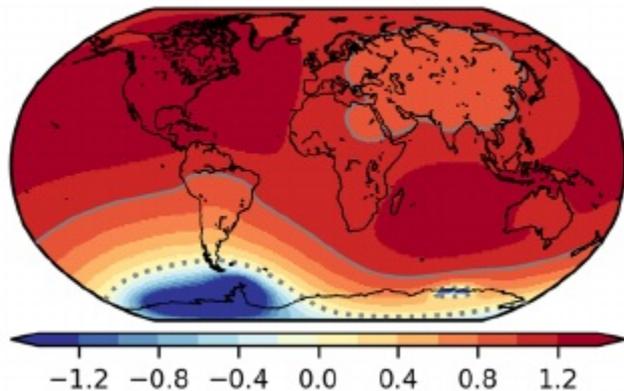
Alexander A. Robel^{a,1}, H el ene Seroussi^b, and Gerard H. Roe^c

^aSchool of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA 30318; ^bJet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109; and ^cEarth and Space Sciences Department, University of Washington, Seattle, WA 98195

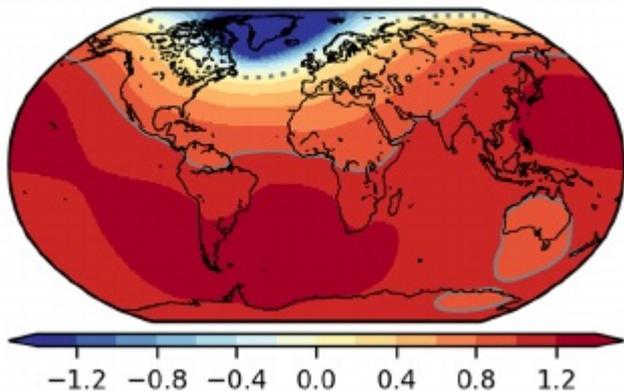
Edited by Isabel J. Nias, Goddard Space Flight Center, Greenbelt, MD, and accepted by Editorial Board Member Jean Jouzel June 11, 2019 (received for review March 20, 2019)

Sea-level rise may accelerate significantly if marine ice sheets The amount and structure of uncertainty in projections of the

(b) Antarctica - dyn



(g) Greenland - SMB



Parlmer et al. (2020)

Greenland

- Changes dominated by the surface melt.
- Tipping point can be reached if the global warming exceeds 3°C

Antarctica

- Snowfall increase should dampen the sea level rise.
- Potential instability of marine ice sheets ?

Sea level rise is not uniform

Arctic is currently melting at a higher rate than projected

But large unknowns remain for Antarctica!