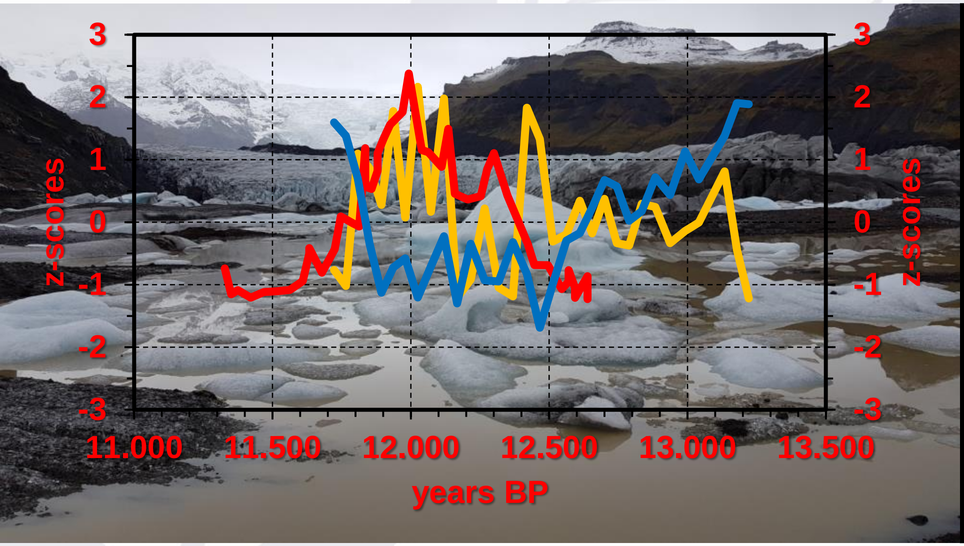
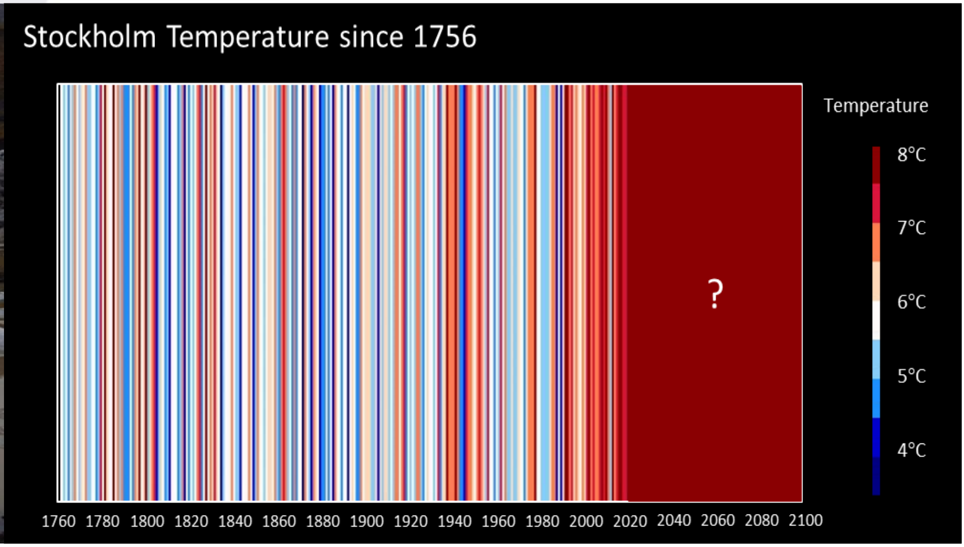
Climate Research School – Climate Science – 2021-03-22

RA5:
Historical to millennial climate variability





Frederik Schenk
Climate Researcher at the Rossby Centre, SMHI
Bolin Centre RA5 co-leader
frederik.schenk@smhi.se

Ditt Schema

26/2. Introduction: Alasdair Skelton

8/3. RA2: Clouds, aerosols, turbulence and climate: Matthew Salter

11/3. RA3: Hydrosphere, Cryosphere and Climate: Fernando Jaramillo

15/3. RA4: Biogeochemical cycles and climate: Volker Brüchert

18/3. RA8: Biodiversity and climate: Sara Cousins

22/3. RA5: Historical to millennial climate variability: Frederik Schenk

25/3. RA7: Landscape processes and climate: Kristoffer Hylander / Zahra Kalantari / Regina Lindborg

8/4. RA6: Orbital to tectonic climate variability: Helen Coxall

12/4. Baltic Sea Centre / Östersjöcentrum: Christoph Humborg

15/4. Environmental Research in the Human Sciences area: Francesca Rosignoli

19/4. Stockholm Resilience Centre: Sarah Cornell / Lan Erlandsson

22/4. RA1: Oceans-atmosphere dynamics and climate: Thorsten Mauritsen

29/4. Exam

RA5 co-leaders

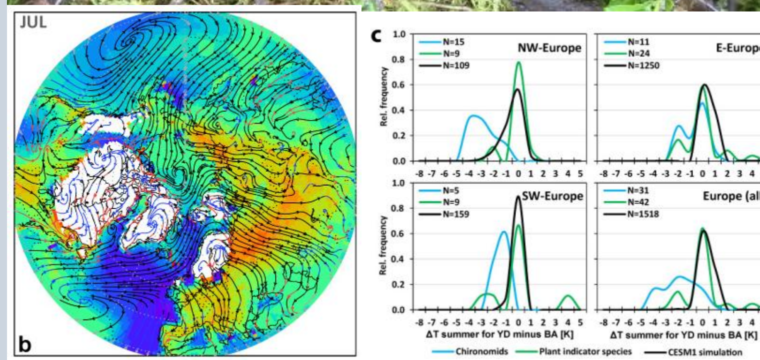
loves peat, sand & dust
± chemical sedimentology

Malin Kylander | Senior Lecturer
Dept. of Geological Sciences (IGV),
Stockholm University

malin.kylander@geo.su.se

Frederik Schenk | Researcher
Rossby Centre, SMHI
& Stockholm University

frederik.schenk@smhi.se



tries to match models & proxies
± paleoclimate modelling

Frederik Schenk

Last updated Aug 19, 2020 Published Aug 04, 2020

PhD, climate researcher

Phone +46 11 495 84 26
Email: firstname.lastname@smhi.se
Skype: frederik.schenk
Research Gate ID: Frederik Schenk
ORCID: 0000-0002-4768-9832

Fields of work

- Global climate modelling and decadal climate predictions
- Large-scale atmospheric circulation and teleconnections
- Natural climate variability, extreme events and future changes
- Abrupt climate change and paleoclimatology
- Focus on northern hemisphere, North Atlantic and Europe

RESEARCH

Climate research at SMHI

The Rossby Centre is SMHI's climate modelling research unit. The Rossby Centre pursues research on climate processes and the behaviour of the climate system.

Climate research at the Rossby Centre

Research group for climate modelling, Rossby Centre

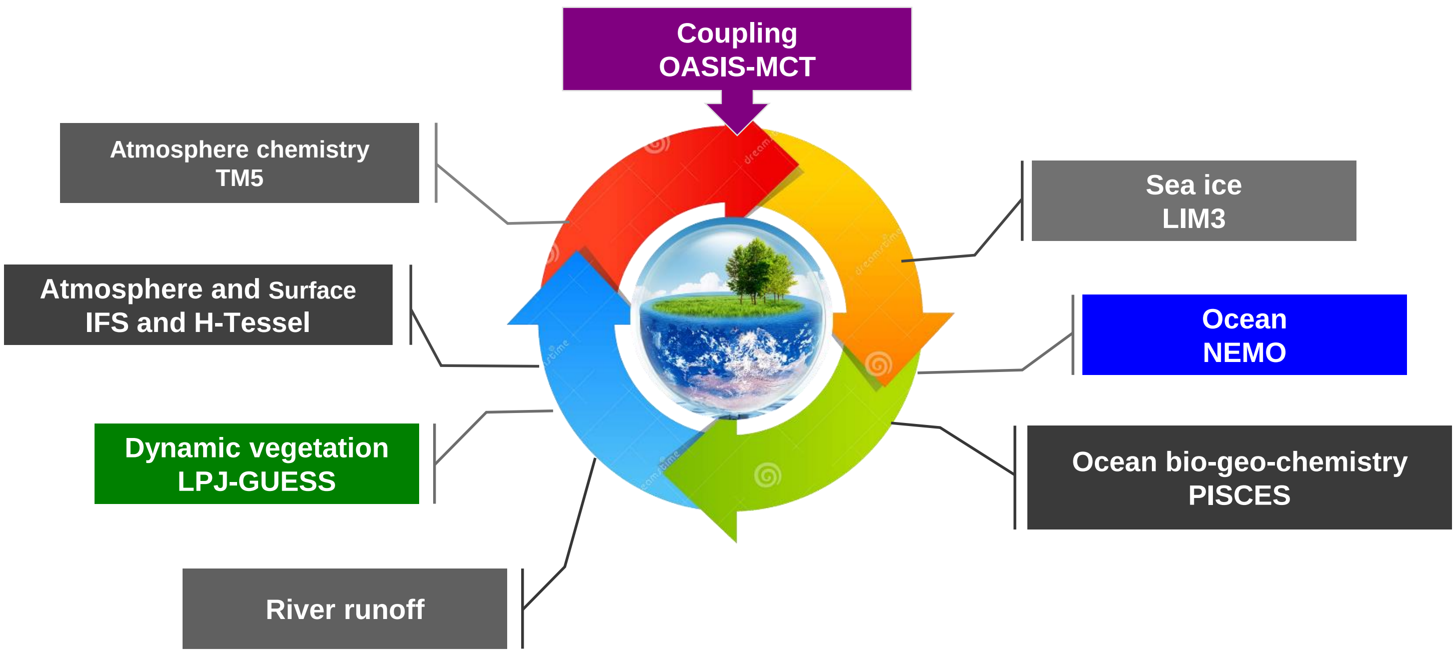
Contact information valid for the Rossby Centre research group.

Contact the Rossby Centre

SMHI and SU use ± the same model for past vs. future

SMHI

EC-Earth
Earth System Model



Paleoclimate modelling group at Dept. of Physical Geography, Qiong Zhang et al.

PMIP4 PlioMIP2 PRISM4

EC-Earth paleo-modelling by Qiong Zhang et al.

PMIP4/CMIP6 simulations

Last Millennium 850-1850 AD

- Observed variability (multi-decadal and longer time scales)
- Internal variability vs external forcing (volcanic, solar, land use)
- Longer-term perspective for detection and attribution studies

Mid-Holocene 6,000 years ago

- Comparison to paleodata for a warmer climate in NH, with enhanced hydrological cycle (strong African monsoon) & green Sahara experiments

Last Glacial Maximum 21,000 years ago

- Comparison to paleodata for an extreme cold climate
- Attempt to provide empirical constrains on global climate sensitivity

Last Interglacial 127,000 years ago

- Model evaluation for warm period, high sea-level stand
- Impacts of smaller ice-sheets/higher sea-level on climate

Mid-Pliocene warm period ~ 3.2 million years ago

- Evaluation of response of CO_2 level (400 ppmv) analogous to today

RA5 retreat: Key drivers of past climate change – lessons learned and remaining inconsistencies

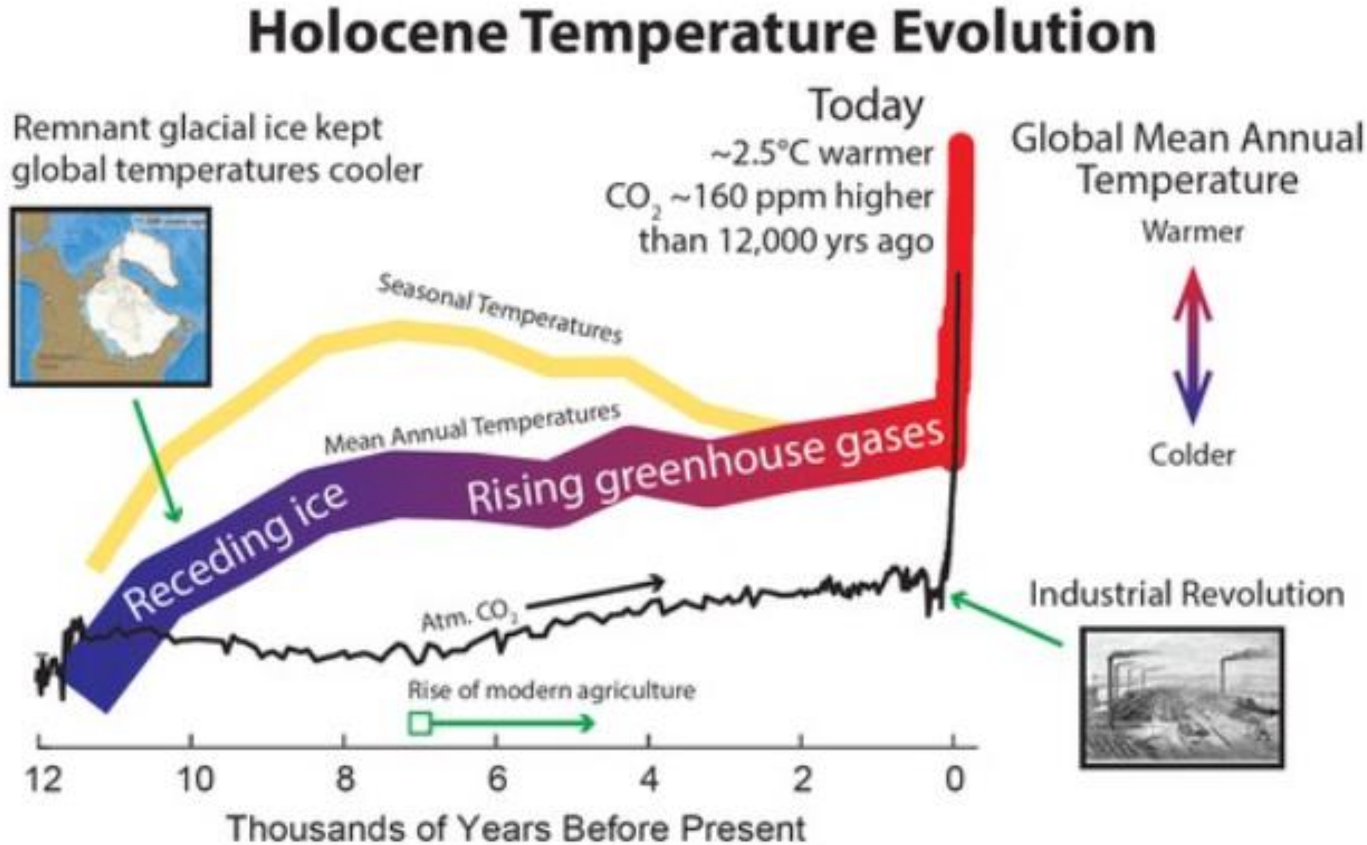
Stockholm, 29 April 2019

SMHI

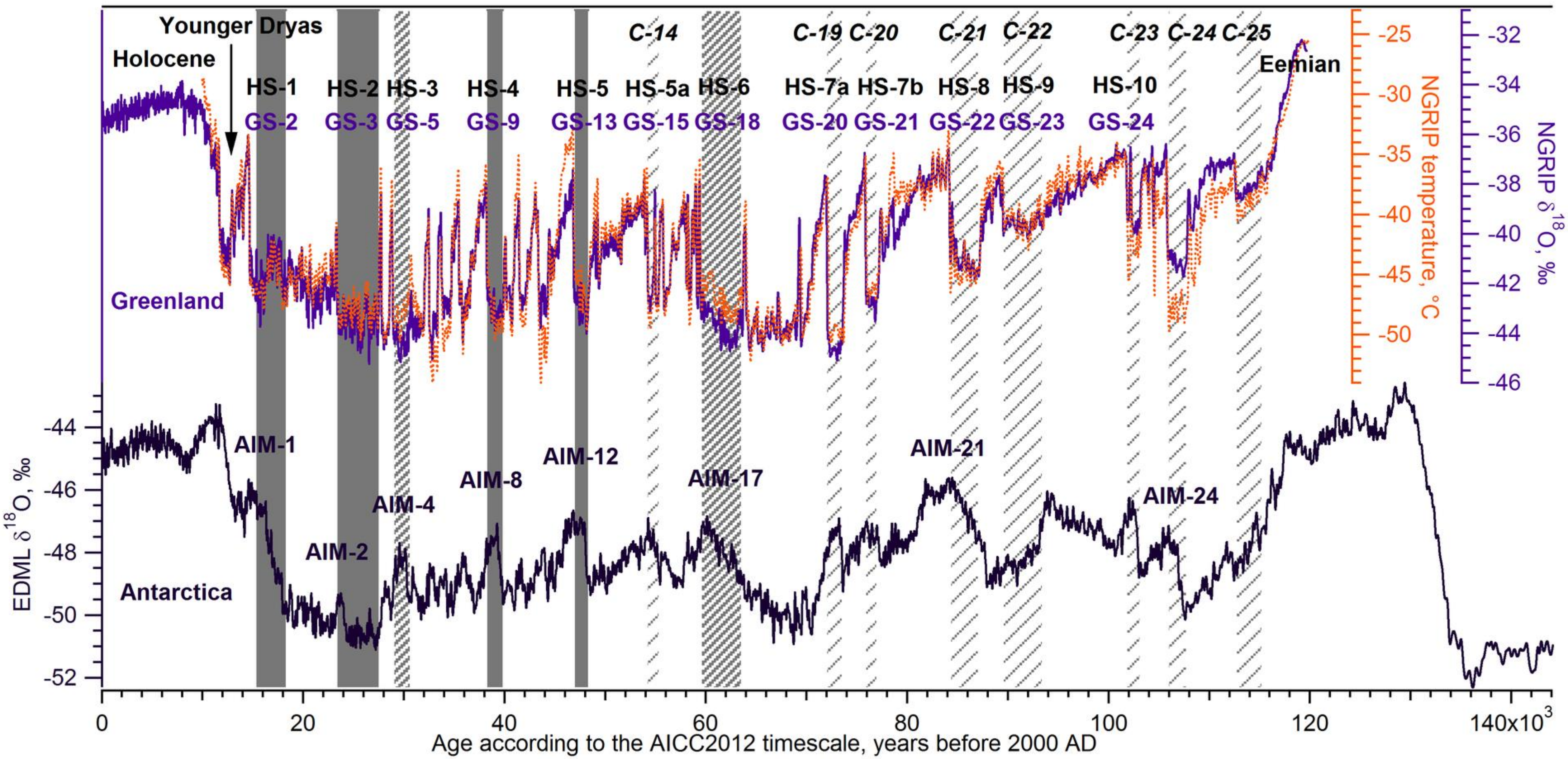
RA5 lecture on the Holocene Conundrum

Bolin Centre Seminar Series | Research Area 5

Time & venue: April 14 at 14h30, Zoom
Title: Global warming, or global cooling, in the last 10000 years? The Holocene temperature conundrum
Speaker: Zhengyu Liu, Professor of Climate Dynamics, Ohio State University



Pleistocene: Heinrich/Greenland Stadials & „bipolar seesaw“



Greenland Stadials (GS) = cold period within an ice age

Greenland Interstadials (GI) = warm period within an ice age

Antarctic Isotope Maximum (AIM) ~ ± in sync with Heinrich Stadials ~ **bipolar seesaw**

Outline

Part 1: Historical timescales

- long weather records, historical documents, dendroclimatology…
- e.g. recent extreme events in the context of long-term variability

Part 2: Millennial timescales

- transient orbital forcing, rapid shifts & climate instabilities (deglaciation)
- climate & ecosystem reconstructions, ice sheets, tephra chronology…

Part 3: Atmosphere-Ocean coupling: European extremes across Δtime

- comparison of climate model simulations and climate proxies

Part 4: Summary & reflection

Part 1
Historical timescales

- last ~500 to 1000 years
- (in-)direct observations partly available & classical proxies
- (multi-)decadal to centennial variability
- weak Δexternal forcing → natural & internal variability
- solar activity (sunspots) & volcanic eruptions

Klimatförandring – historical timescale (observations)

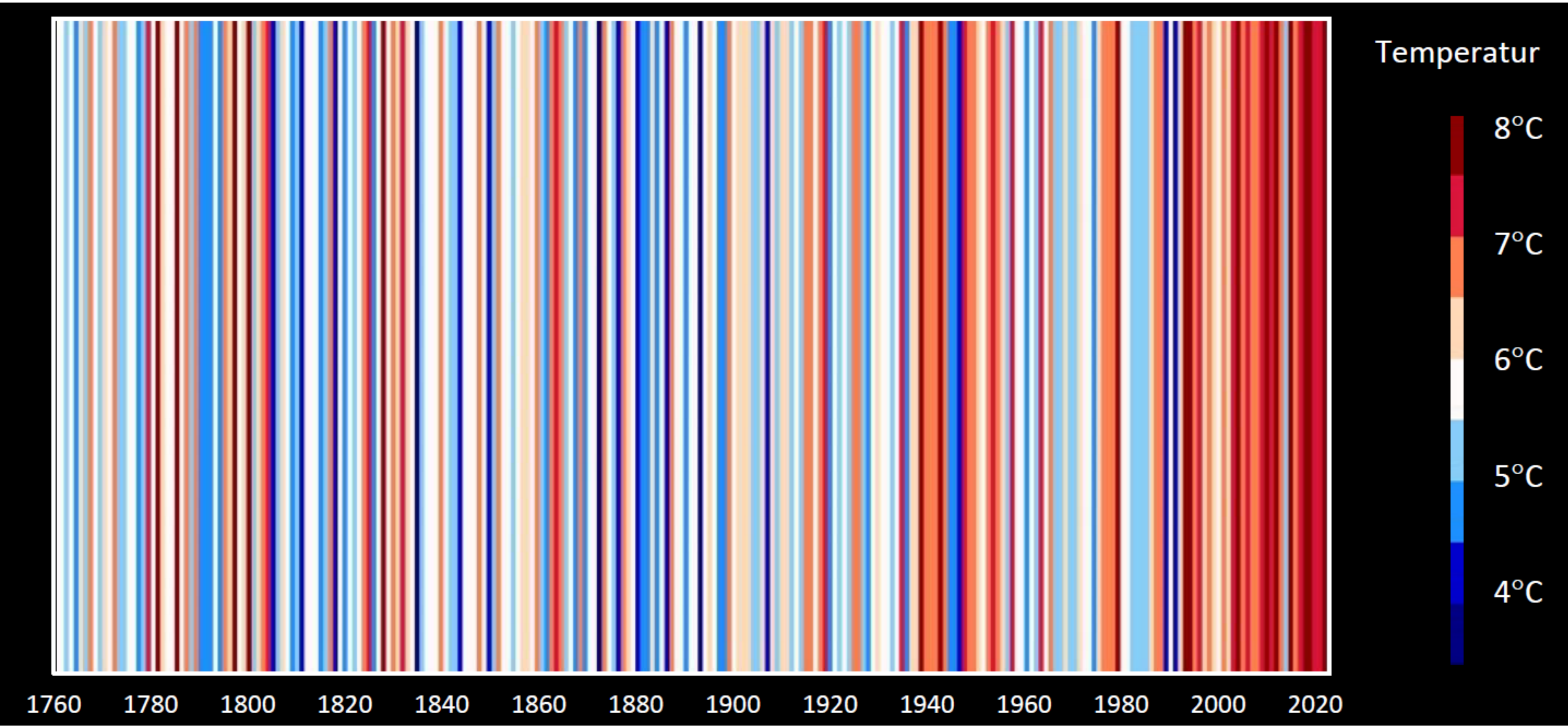
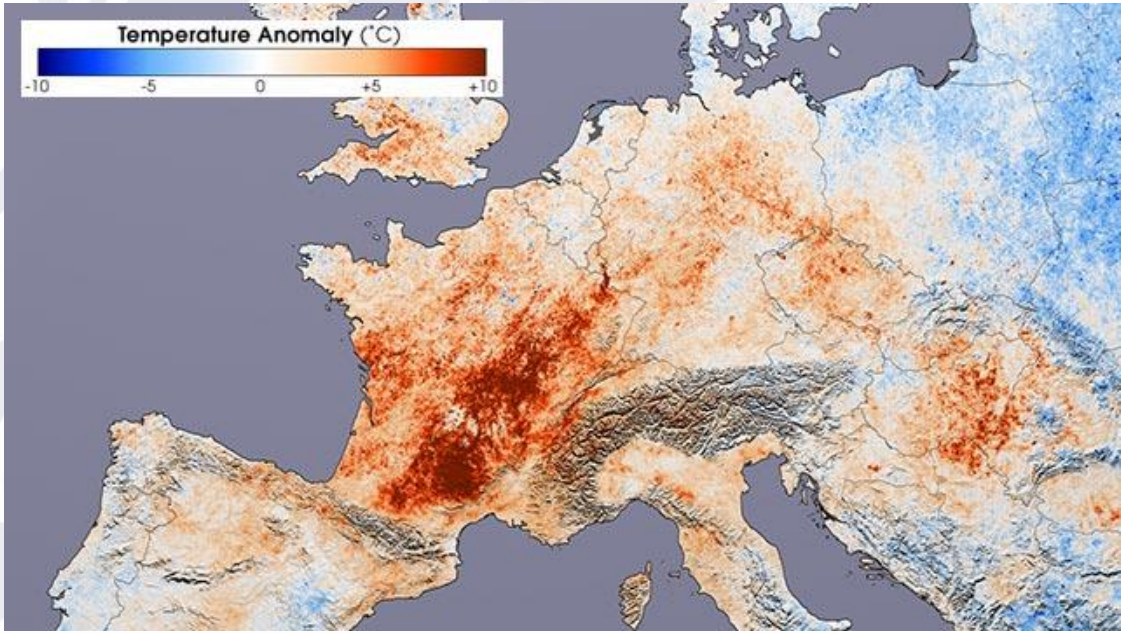


Bild: Nina Kirchner, Data: Anders Moberg, https://bolin.su.se/data/

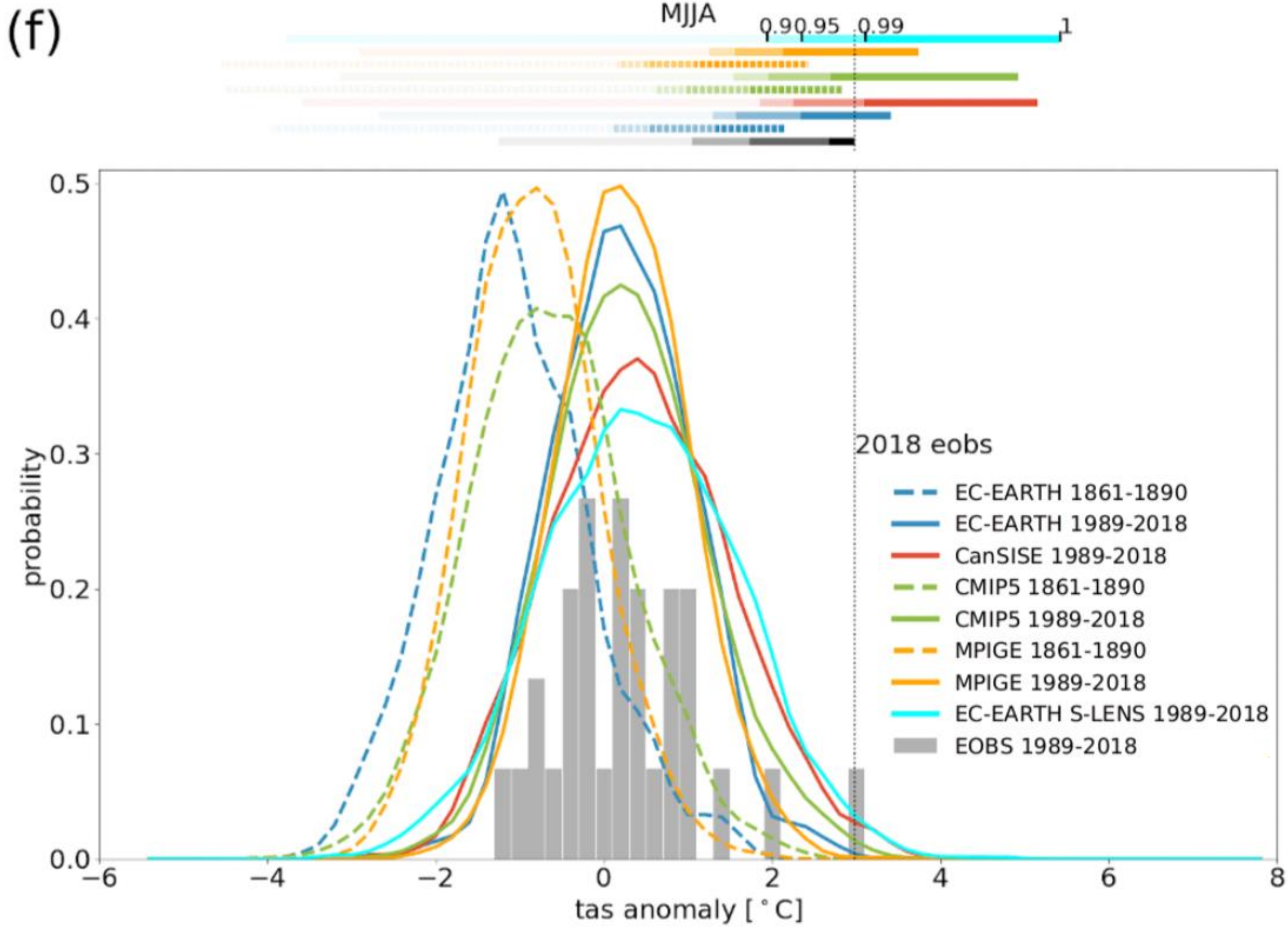
2019/20 was the warmest winter on record since 1756 in Stockholm

- average winter (DJF) temperature: +2.6°C
- this is 5.6 degrees warmer than the 250 year average
- around 1 degree warmer than the second warmest winter (1790, 2008)

How unusual was the European heatwave of 2018?

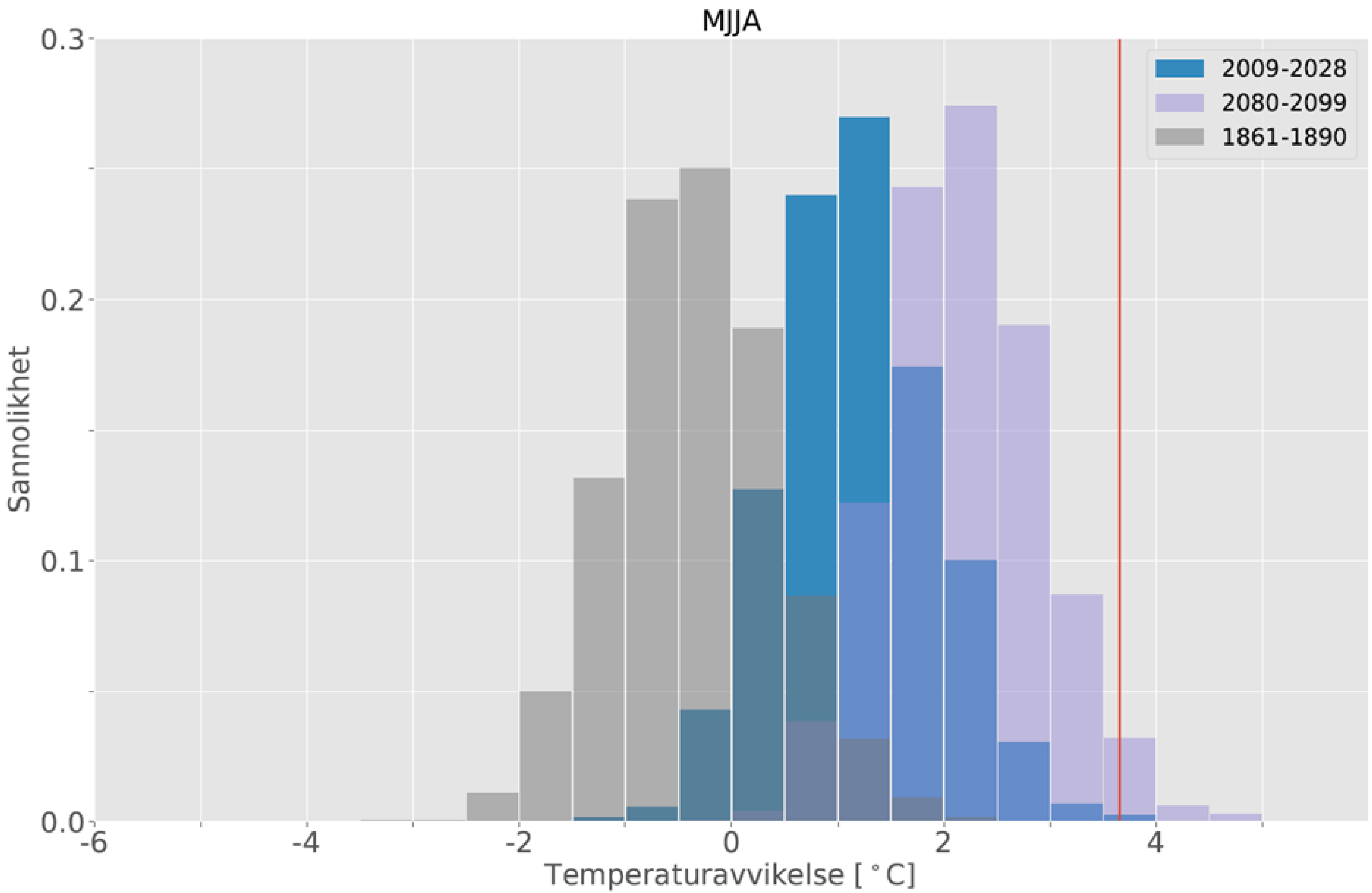


How unusual was 2018 (MJJA, S-Sweden)? Models vs. EOBS



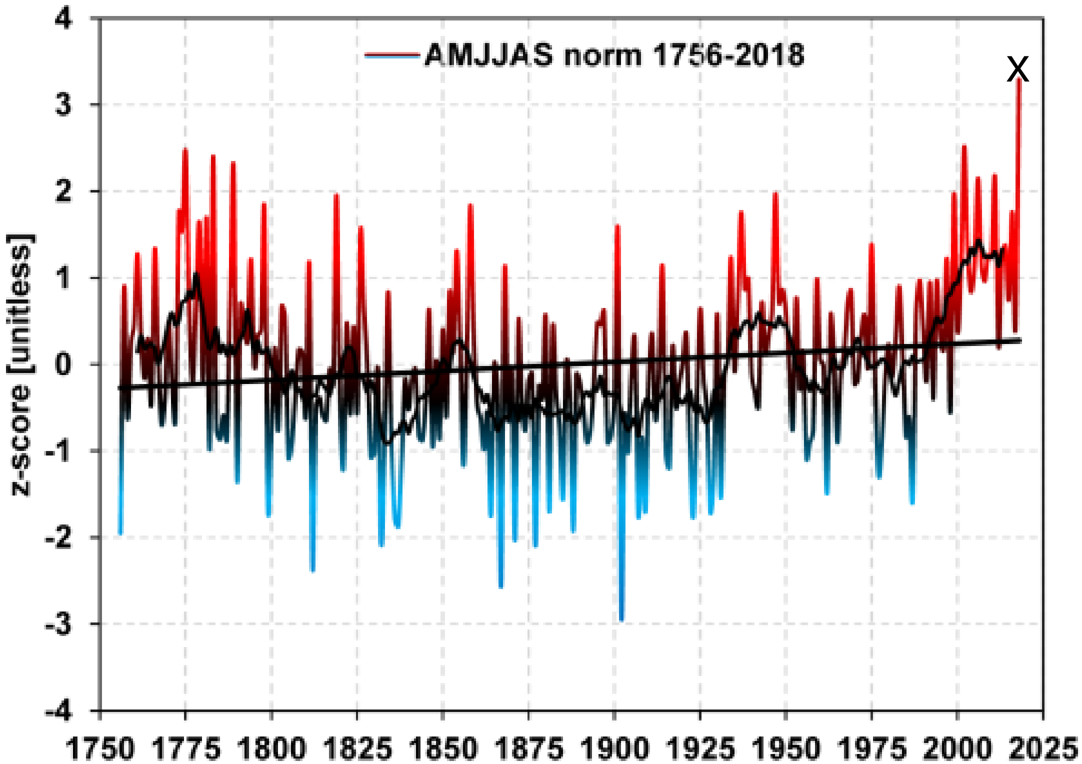
Wilcke et al. (2020): The extremely warm summer of 2018 in Sweden – set in a historical context. Earth Syst. Dynam., 11, 1107–1121

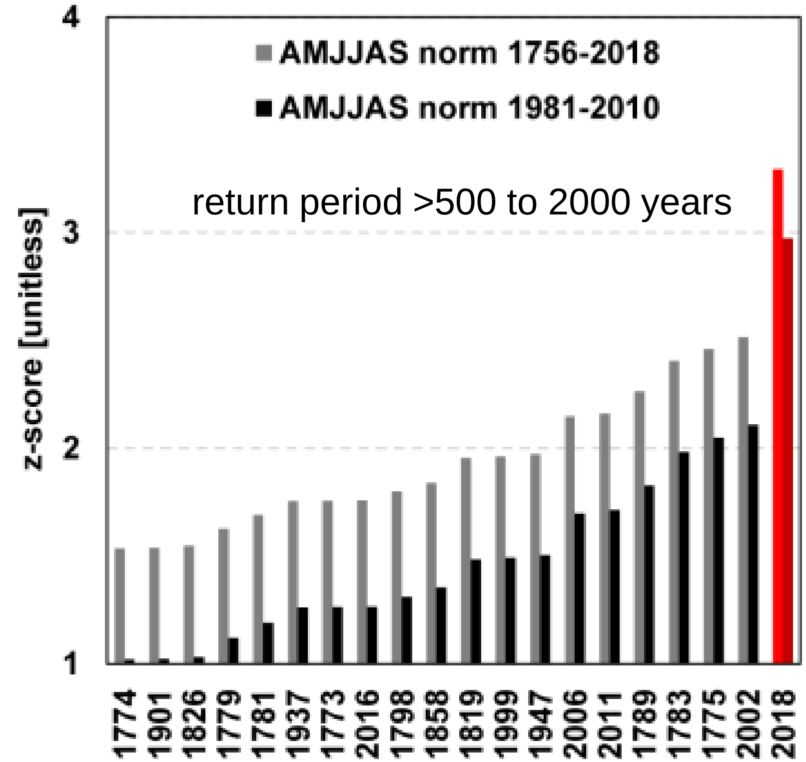
Sweden (south of 63°N) in simulations vs. 2018 observation



RCP4.5 with 100 ensemble members with MPI model ECHAM6 (anomalies wrt 1961-1990). *Figure: Renate Wilcke @ SMHI with data from MPI (Daniela Matei and Evangelos Tyrlis) and observations from the SMHI database MORA. From Erik Kjellström.* → 2018 would be still a rare event until ~2080 (models)

April-September 2018 was persistently warm (all-time record)





Chen et al. (2020)

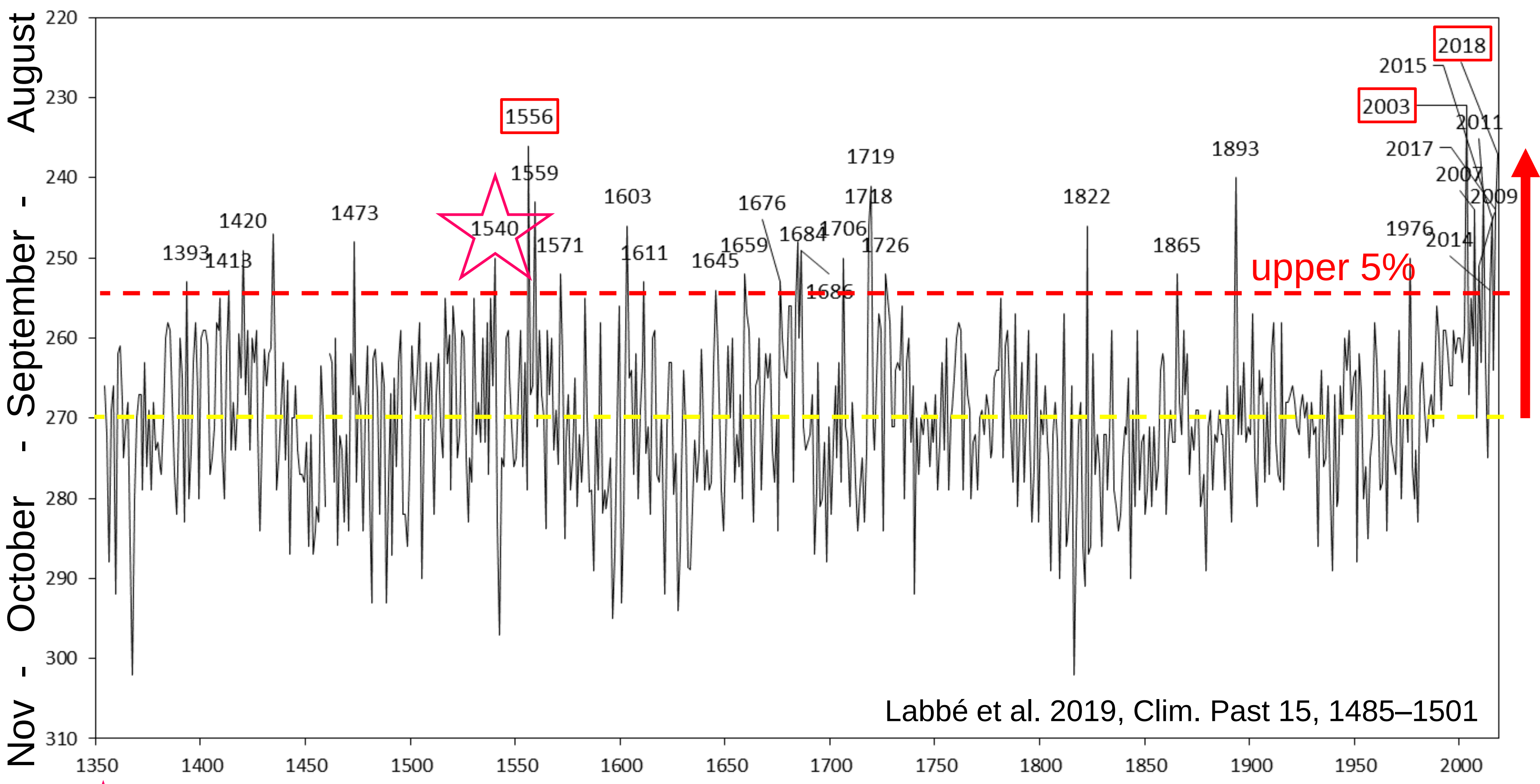
A treasure to conduct statistical analysis

- long datasets → allow for more robust extreme value statistics
- extreme events, e.g. return value of 2018 compound event

Stockholm Historical Weather Observations 1756-2018 (Moberg et al. 2002; 2003)

- homogenized & corrected for urban heat island effect. Data: Anders Moberg/Bolin Centre Database)

Grape Harvest Day (GHP) in Beaune, France (1354 – 2018)
→ highly correlated with spring-summer temperatures



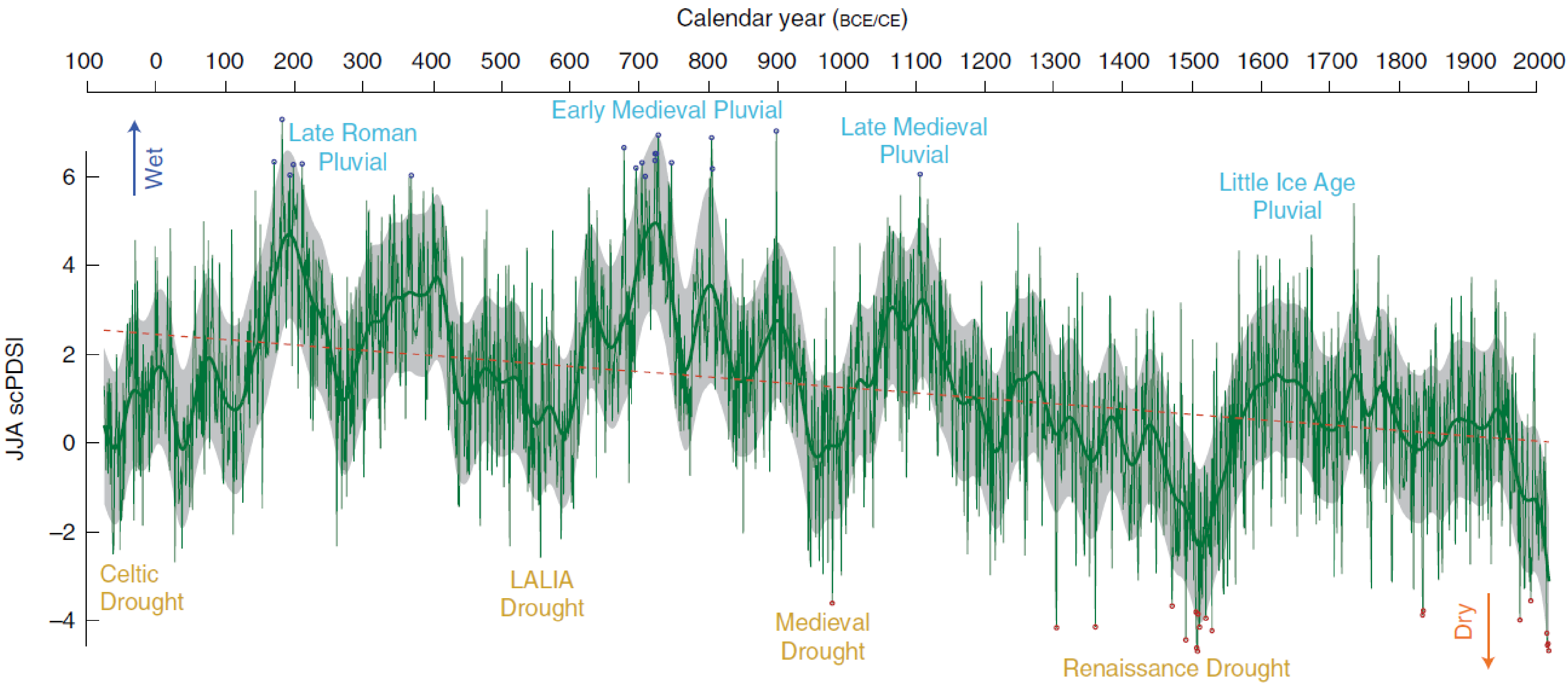
possibly the worst historical European megadrought and heatwave, *„grape became raisins“*

→ biological thresholds – e.g. too dry to grow, temperature signal is lost…

→ past extremes might be underestimated

Central European drought severity: 2015-2018 worst in 2110 years

SMHI



Use a new method to reconstruct hydroclimate variability from oaks (*Quercus* spp.)

- stable carbon (^{13}C) and oxygen (^{18}O) isotopes from tree rings
- traditional method: tree ring width and late wood density
- skill with JJA Palmer Drought Severity Index from 1901–2018 is r=0.73 (p<0.001)

Büntgen et al. 2021: Recent European drought extremes beyond Common Era background variability. *Nature Geosci.*

Part 2
Deglacial & millennial timescales

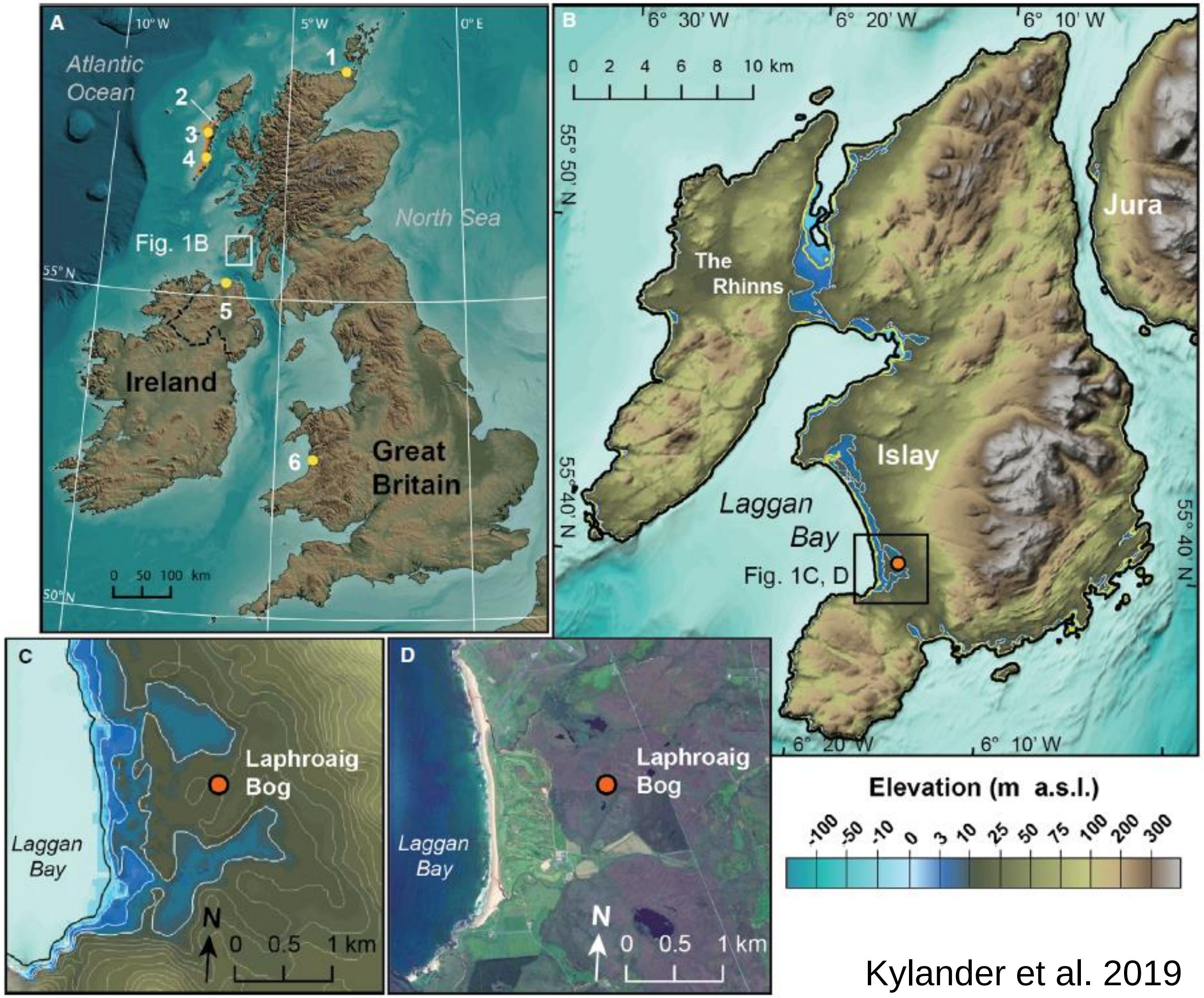
- up to ~50,000 years ago
- multi-proxies, terrestial, marine, ice cores, speleothemes
- instabilities of ice sheets and ocean currents
- millennial variability and abrupt climate shifts
- orbital forcing and greenhouse gases

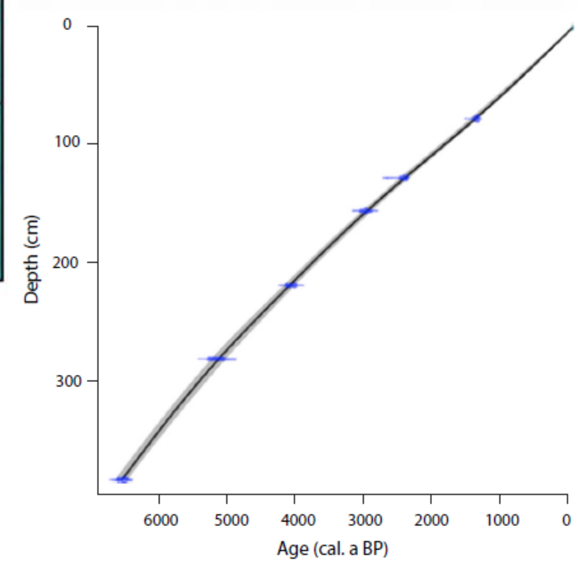
Climate Research School – Climate Science – 2021-03-22

It's in your glass: A history of sea-level and storminess from the Laphroaig bog, Islay (SW-Scotland)

Kylander et al. 2019. It's in your glass: a history of sea level and storminess from the Laphroaig bog, Islay (southwestern Scotland). Boreas 49, 152–167.

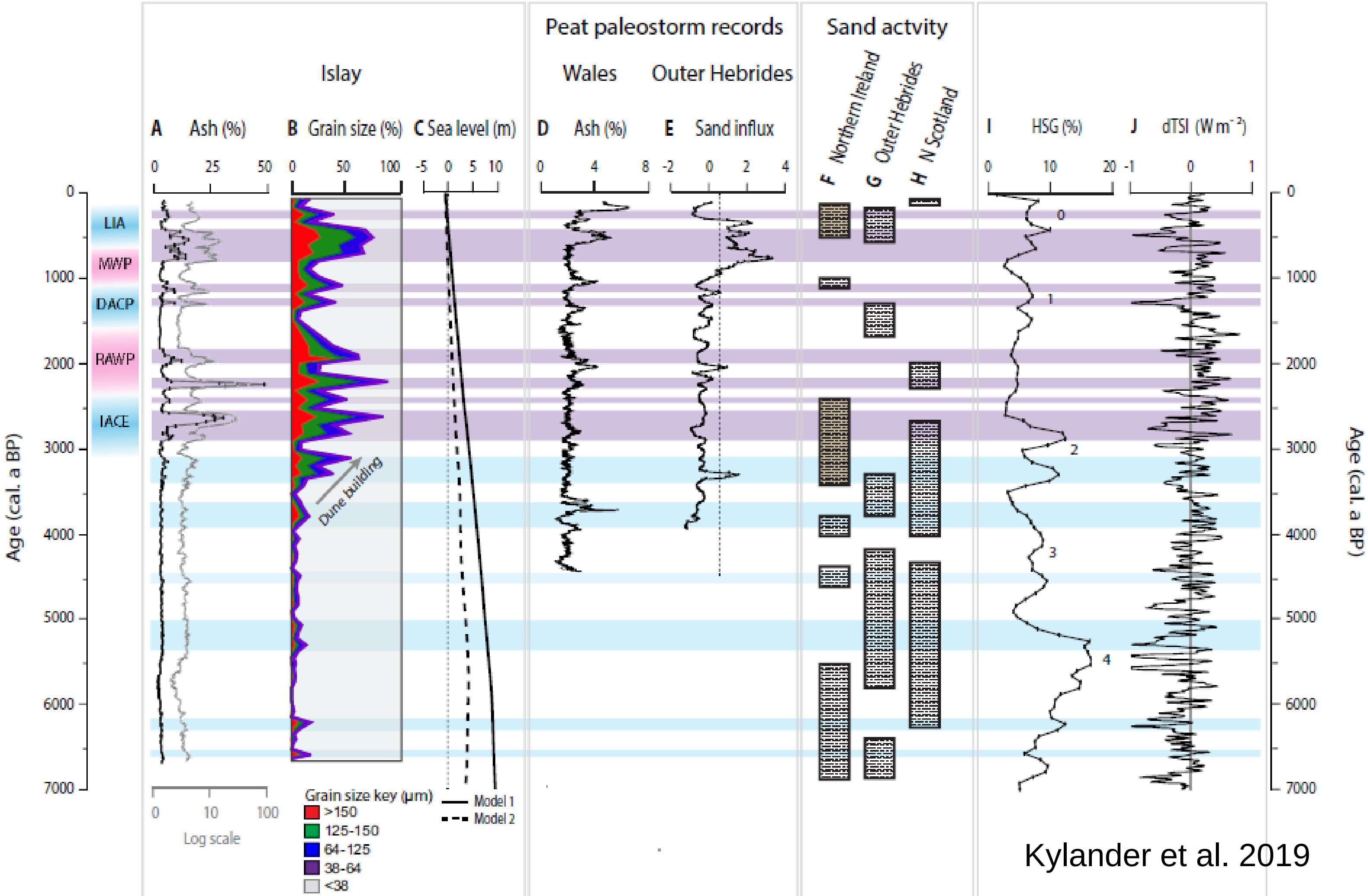
Does storminess change in response to external forcing?





Kylander et al. 2019

Increased storminess during low solar activity (+ sea-ice)

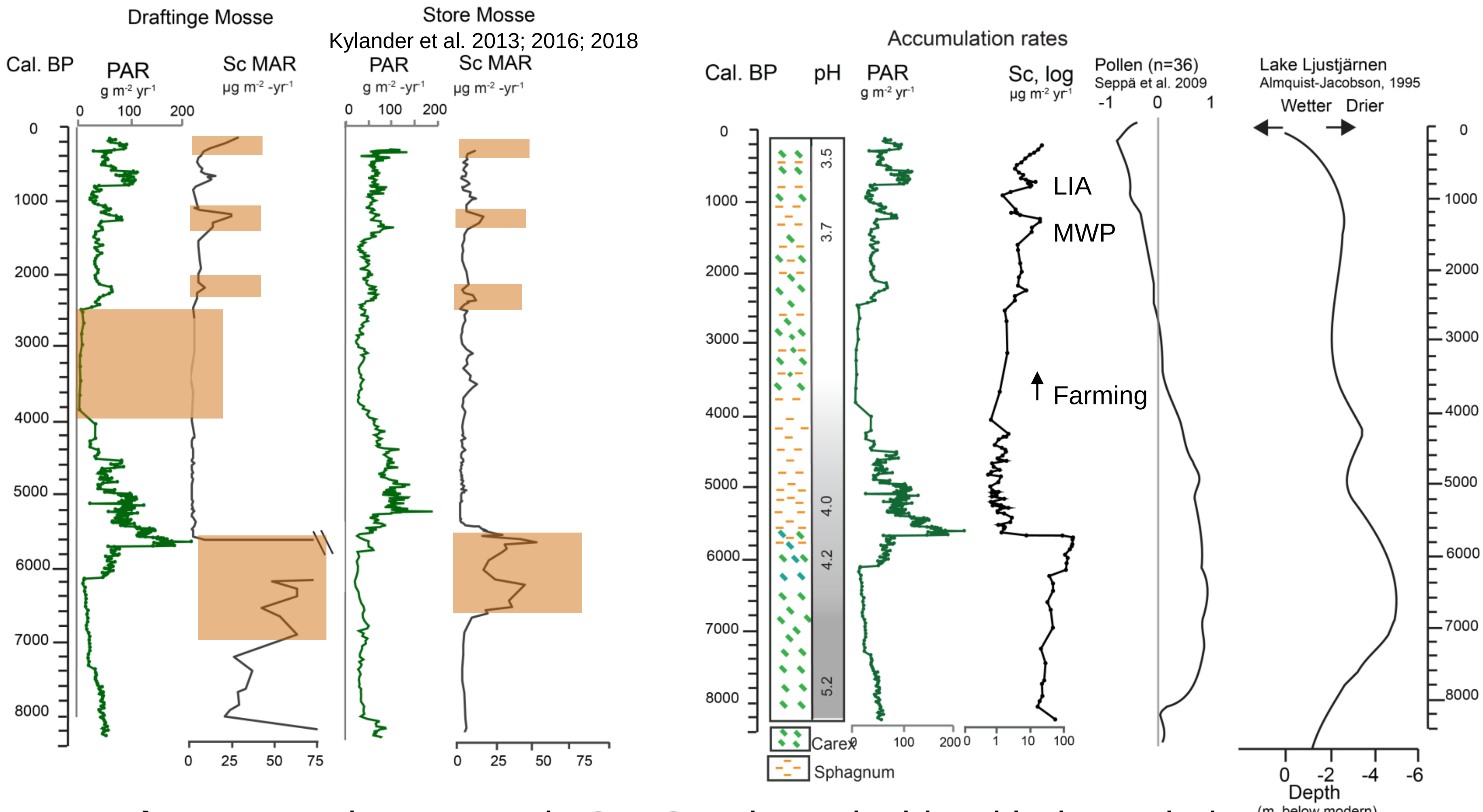


Kylander et al. 2019

→ sand grains are blown into peat = storminess archive (+ sea-level)

→ climate models underestimate response, NE-shift in the future

Paleodust deposition in peat bogs in Sweden (Jenny Sjöström)



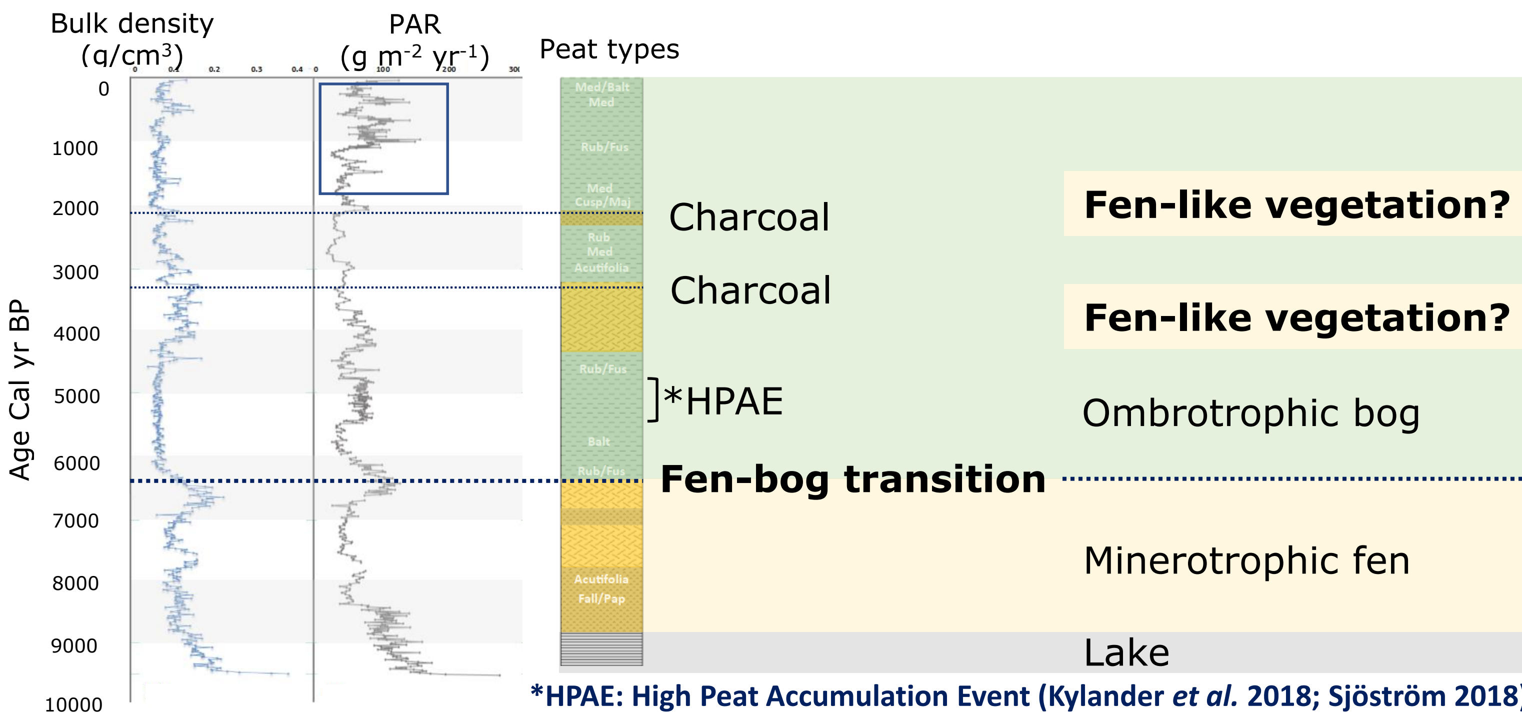
→ common dust events in SW-Sweden coincide with dry periods

→ mid-Holocene: warm/dry, late Holocene cool/wet but with dry events

→ dust/aerosols among the biggest uncertainties in climate models

Macrofossil analysis to study boreal peatlands (Eleonor Rydberg)

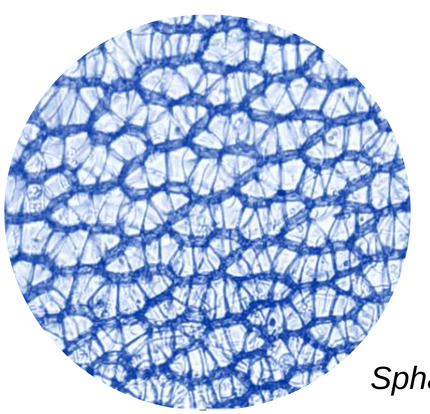
SMHI



***HPAE: High Peat Accumulation Event (Kylander *et al.* 2018; Sjöström 2018)**

Bulk density, peat accumulation rates (PAR) and early interpretations for Store Mosse A (S-Sweden)

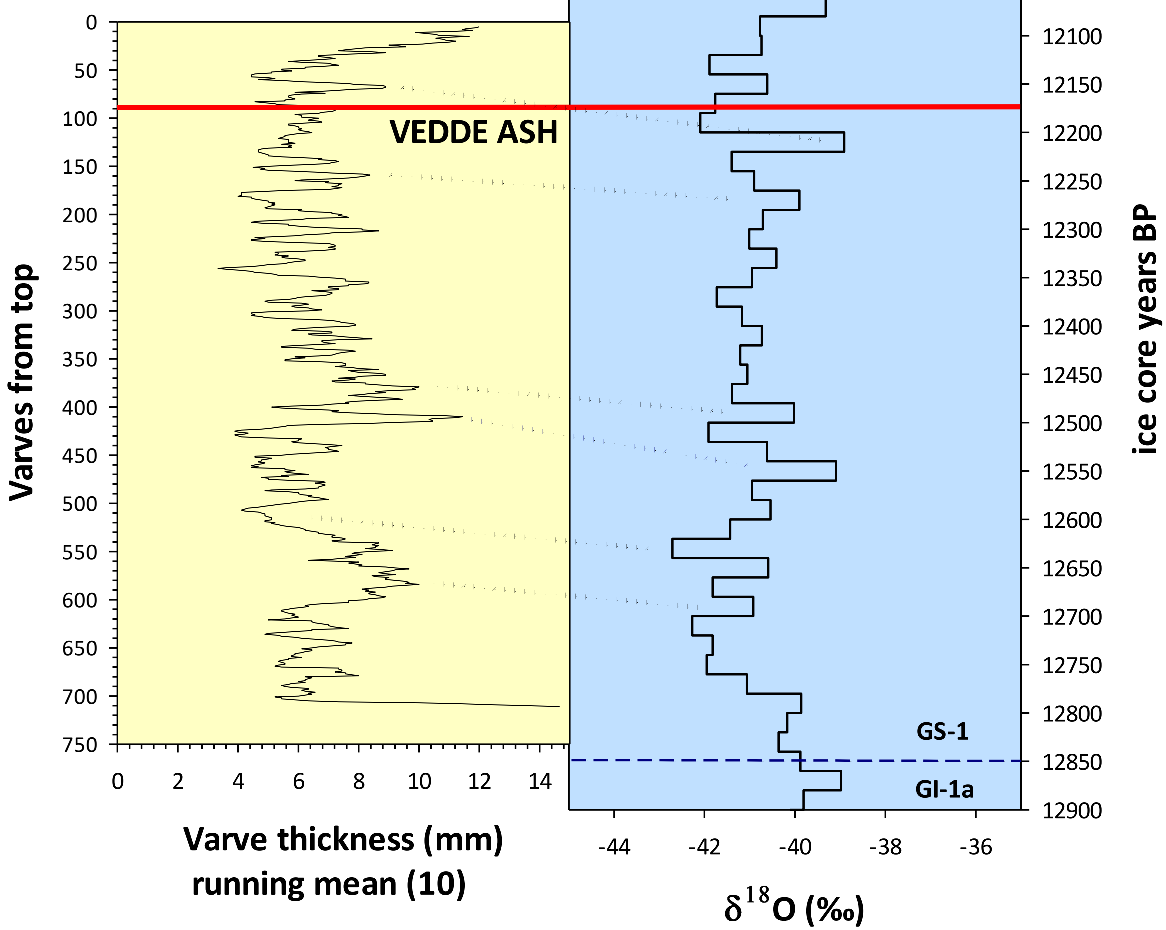
- → boreal peatlands store soil carbon
- → C_{stored} depends on type: lake → fen → bog
- → macrofossils help to define Δtype
- → Δclimate ← Δecosystem → Δcarbon storage



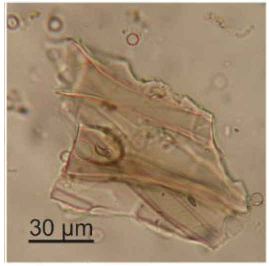
Leaves from a *Sphagnum* capitulum under microscope (photo: Ryberg)

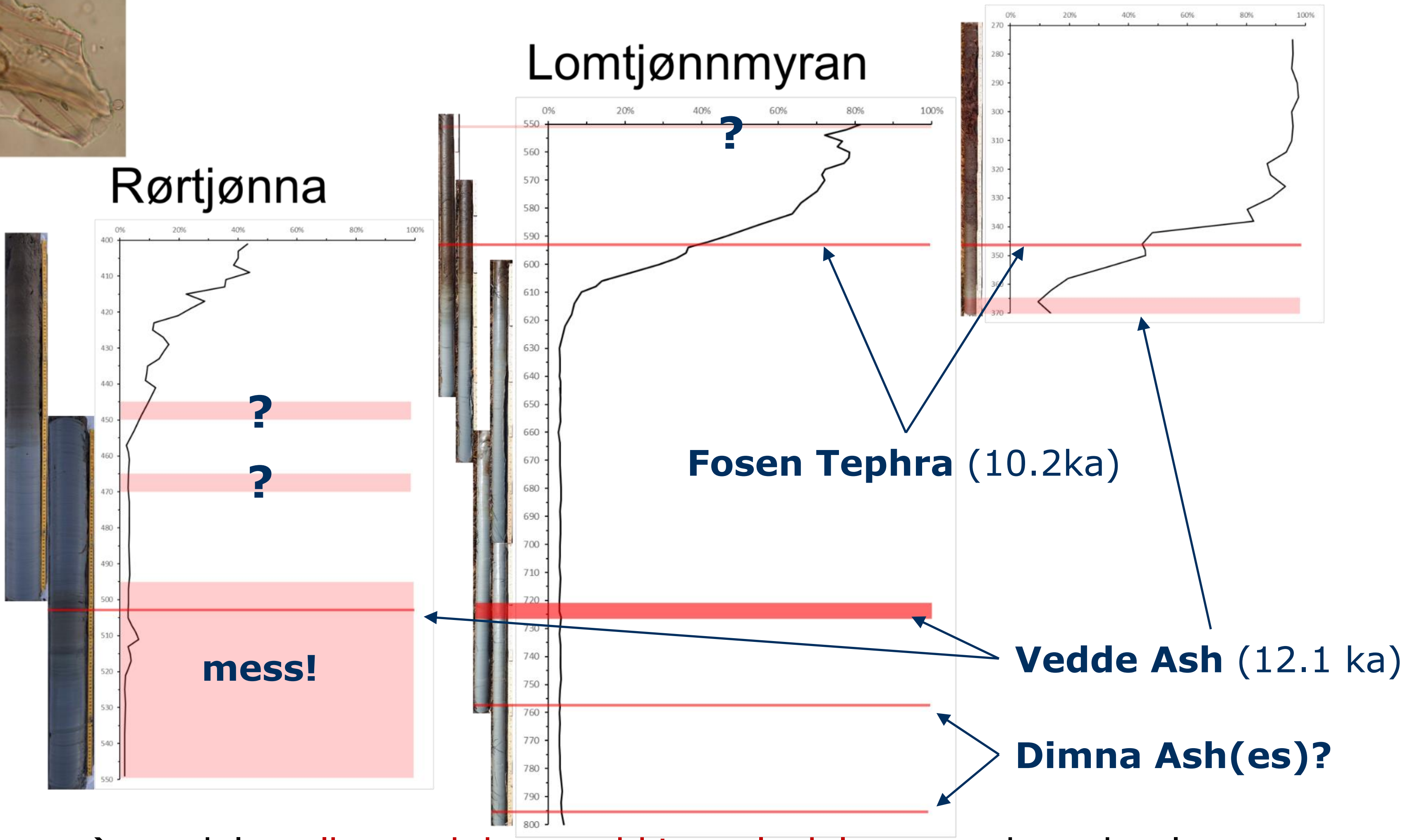
Sphagnum cells under microscope (photo: Ryberg)

#tephratastic research – tephra/dating (Stefan Wastegård et al.)



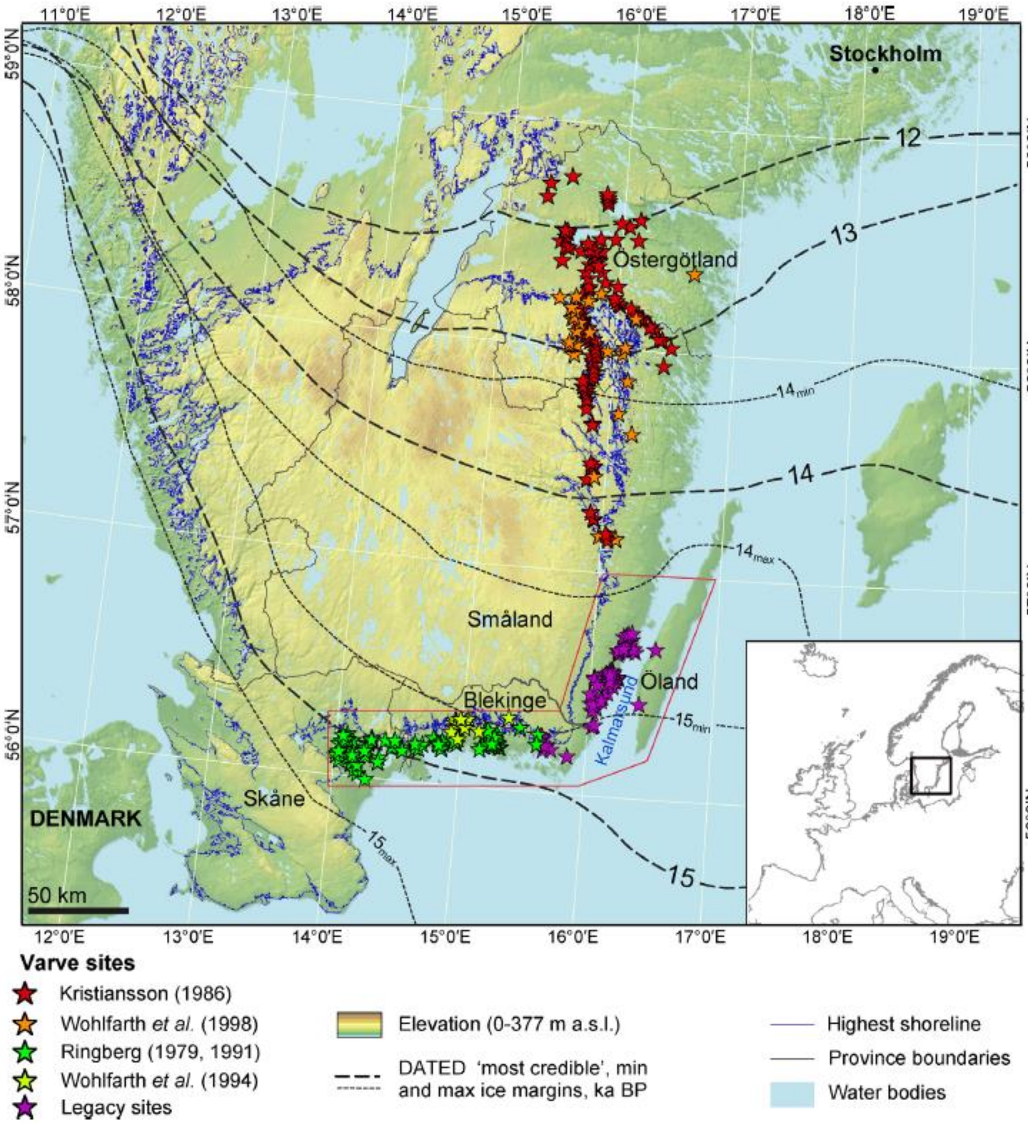
New tephra from Scandinavia for dating (Simon Larsson)

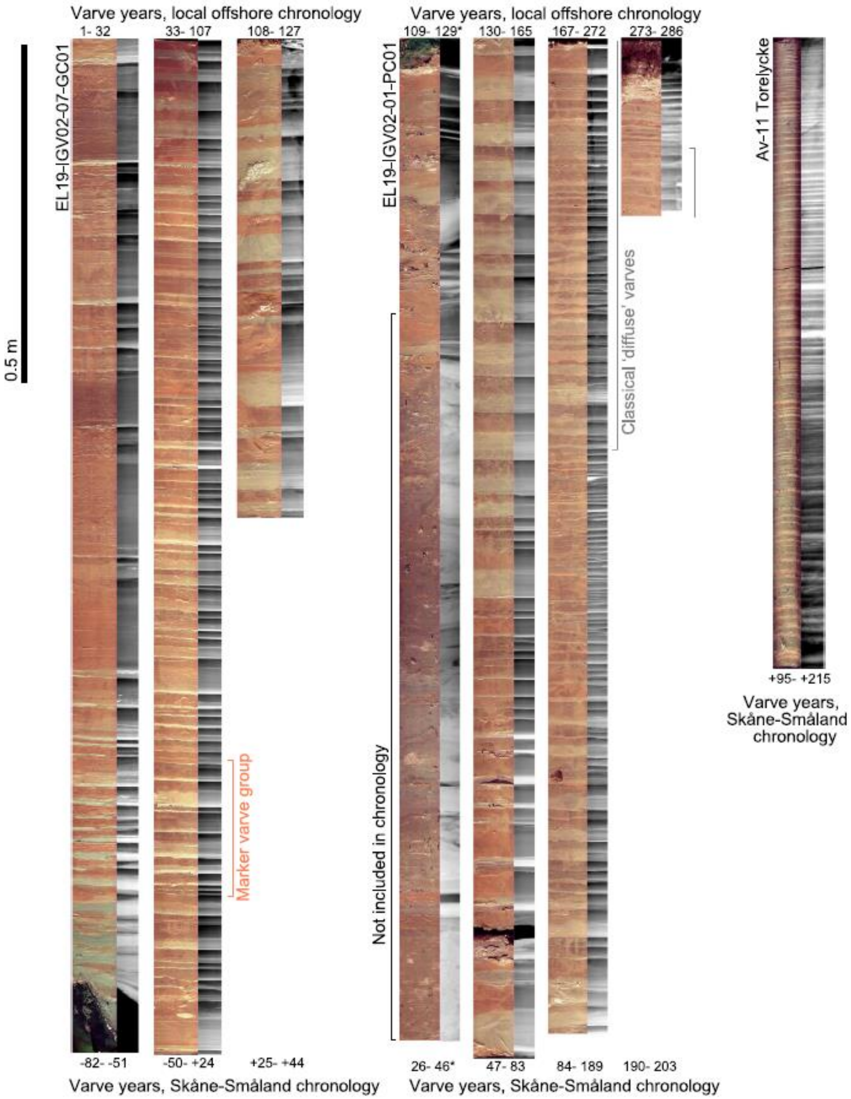




→ crucial to align and date rapid Lateglacial events via tephra layers
→ helps to identify local to regional deglaciation (Δice sheets)

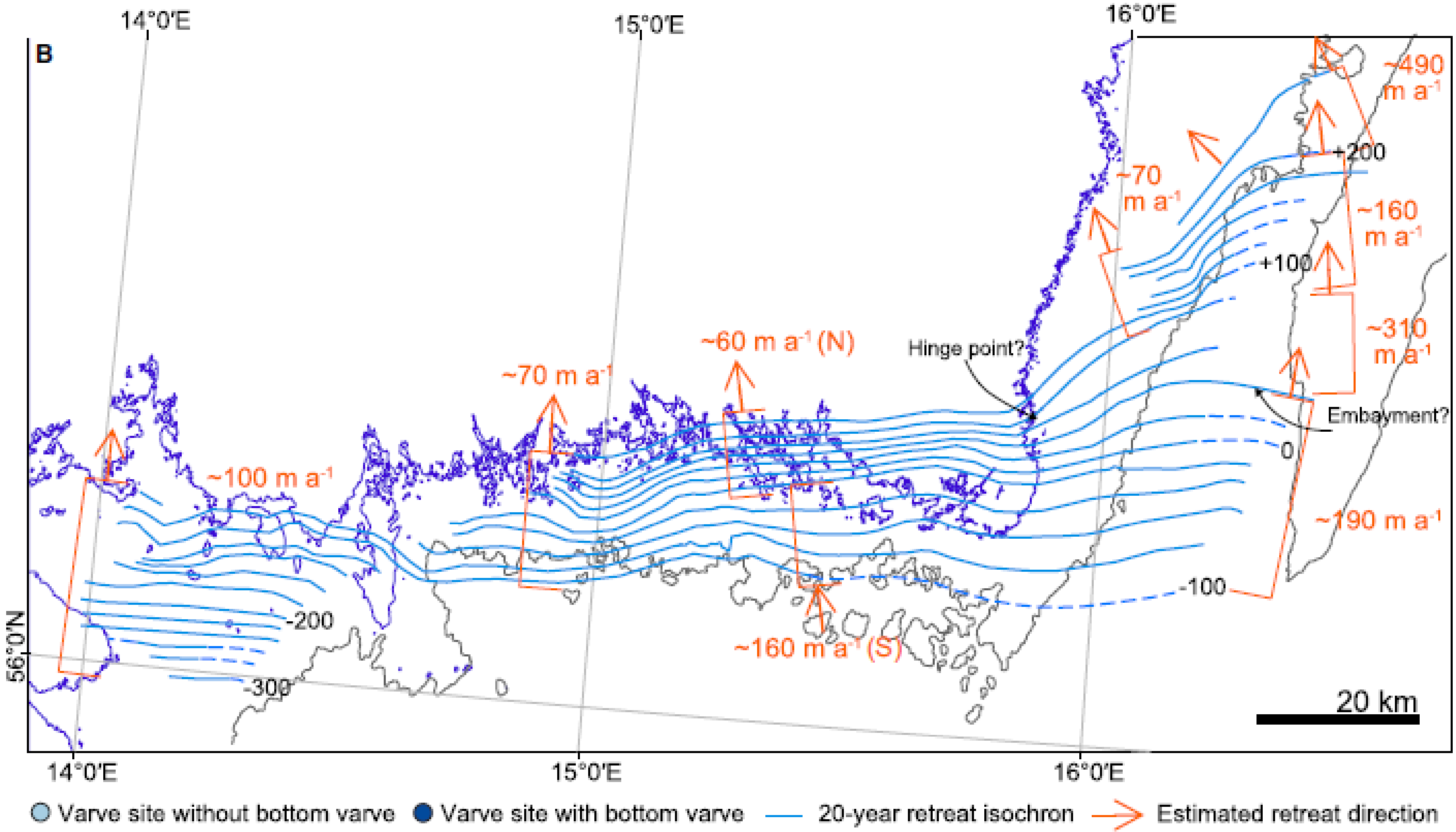
Varve chronologies: ice sheet retreat rates





Avery et al. 2020: A 725-year integrated offshore terrestrial varve chronology for southeastern Sweden suggests rapid ice retreat ~15 ka BP

Ice sheet retreat around 15,000 BP (pre-Bölling)

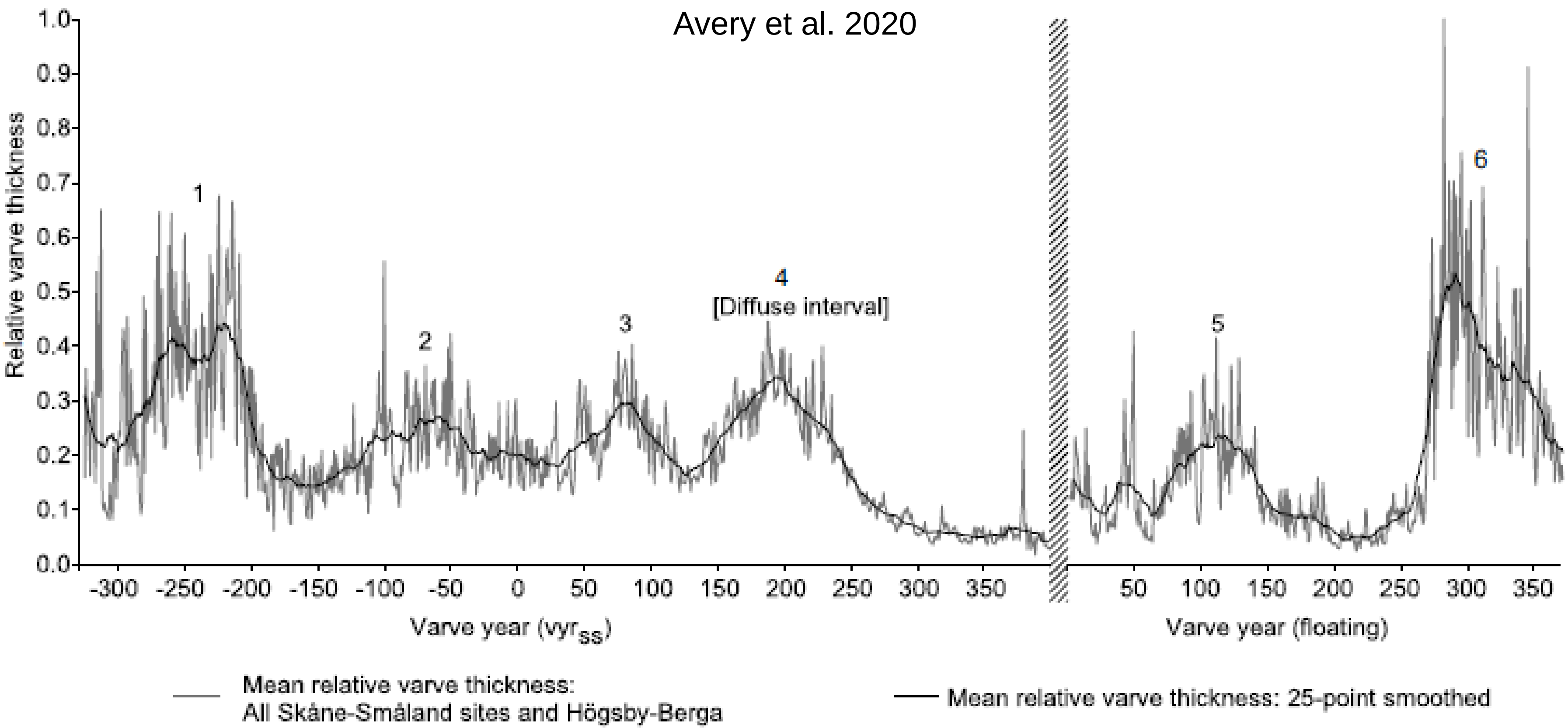


Avery et al. 2020

- very rapid ice sheet retreat already under stadial (cold) climate
- most likely driven by high summer orbital forcing with short warm summers

Multi-decadal oscillations in ice melting – paleo-AMO at 15 ka BP?

SMHI



AMO = Atlantic Multidecadal Oscillation (internal mode of the N-Atlantic)

→ according to recent studies (Mann et al. 2020; 2021), the AMO does not exist

→ Mann et al. claim: AMO-like variability due to volcanoes/CO_2/sulphate

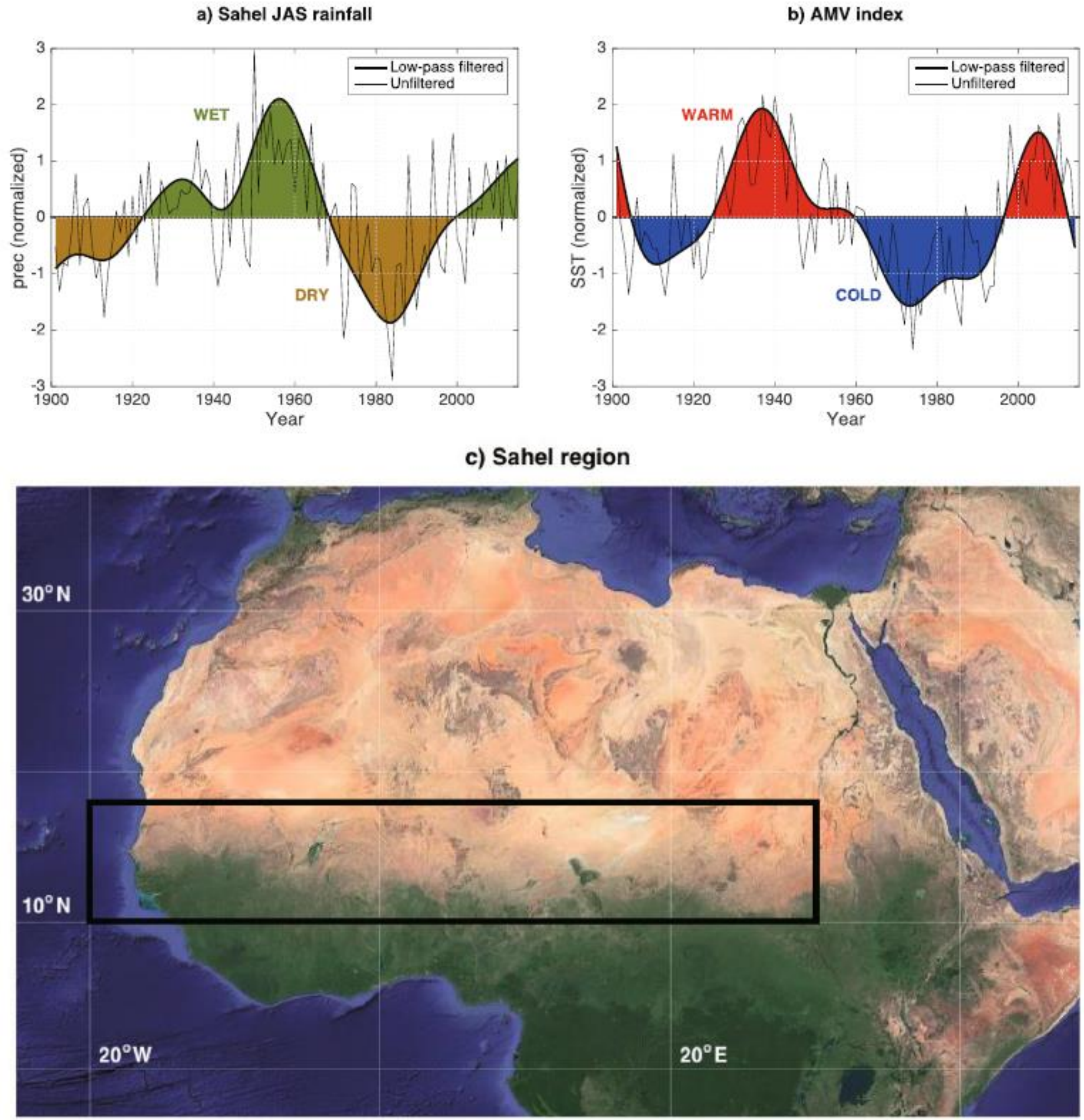
→ most control simulations (no Δforcing) show no AMO, but some do!

→ Greenland ice cores and marine cores show AMO for the last 8000 years

AMO and Sahel rainfall

The AMO – whether forced or intrinsic – plays a key role for multi-decadal climate variations and is clearly represented in paleo-records.

Decadal Climate Predictions e.g. with EC Earth 3 @SMHI show a good skill to predict the AMO for up to 10 years into the future.



Berntell et al. 2018: Representation of Multidecadal Sahel Rainfall Variability in 20th Century Reanalyses. Sci. Rep. 8: 10937

Part 3
Atmosphere-Ocean coupling: European summer extremes across timescales

- research example within RA5 linking climate models with proxies

- geological perspective on recent summer extremes
- weak North Atlantic Ocean overturning & climate

What is the meteorological explanation for persistent extreme events like 2018?

= atmospheric blocking

~ quasi persistent (high) air pressure pattern lasting > 5 days

The start of the heatwave and drought of 2018 in May

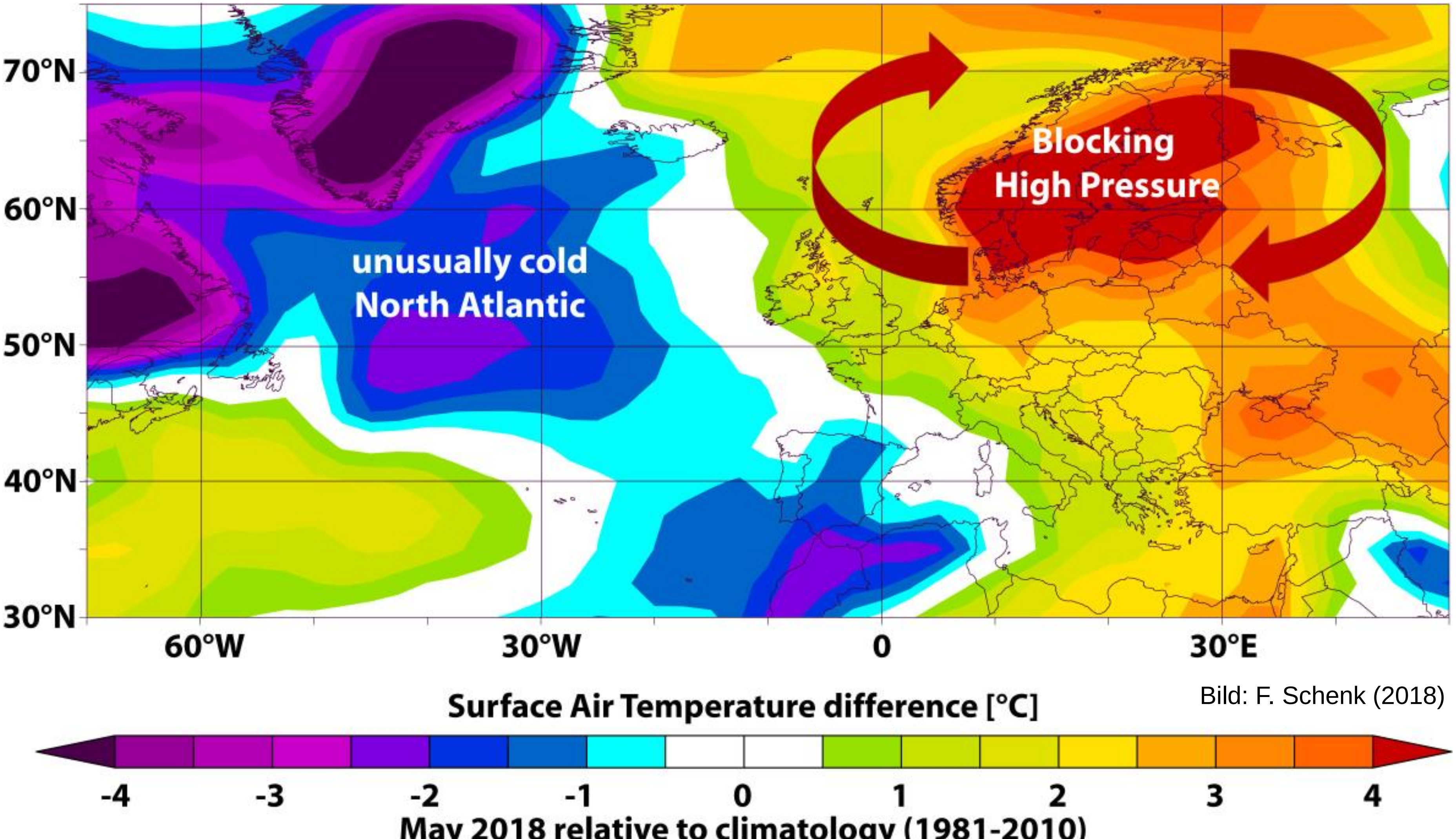
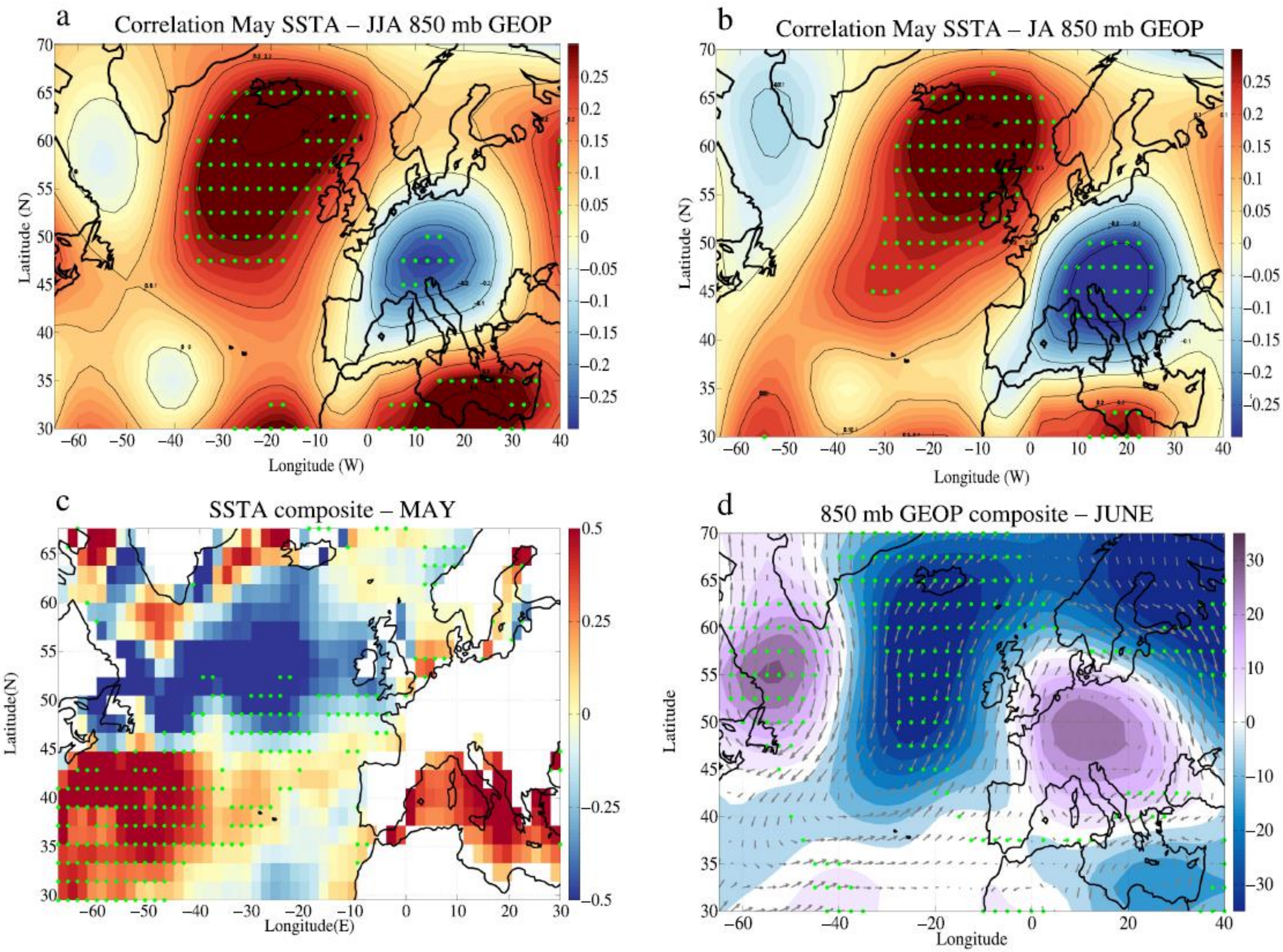


Bild: F. Schenk (2018)

Note the **warming hole** in the North Atlantic in 2018:

- major heatwaves in Europe since ~1980 coincide with such unusally cold SST south of Greenland

European heatwaves coincide with cold SSTs after 1980



Anti-correlation:
warm Atlantic → cool EU
cold Atlantic → hot EU

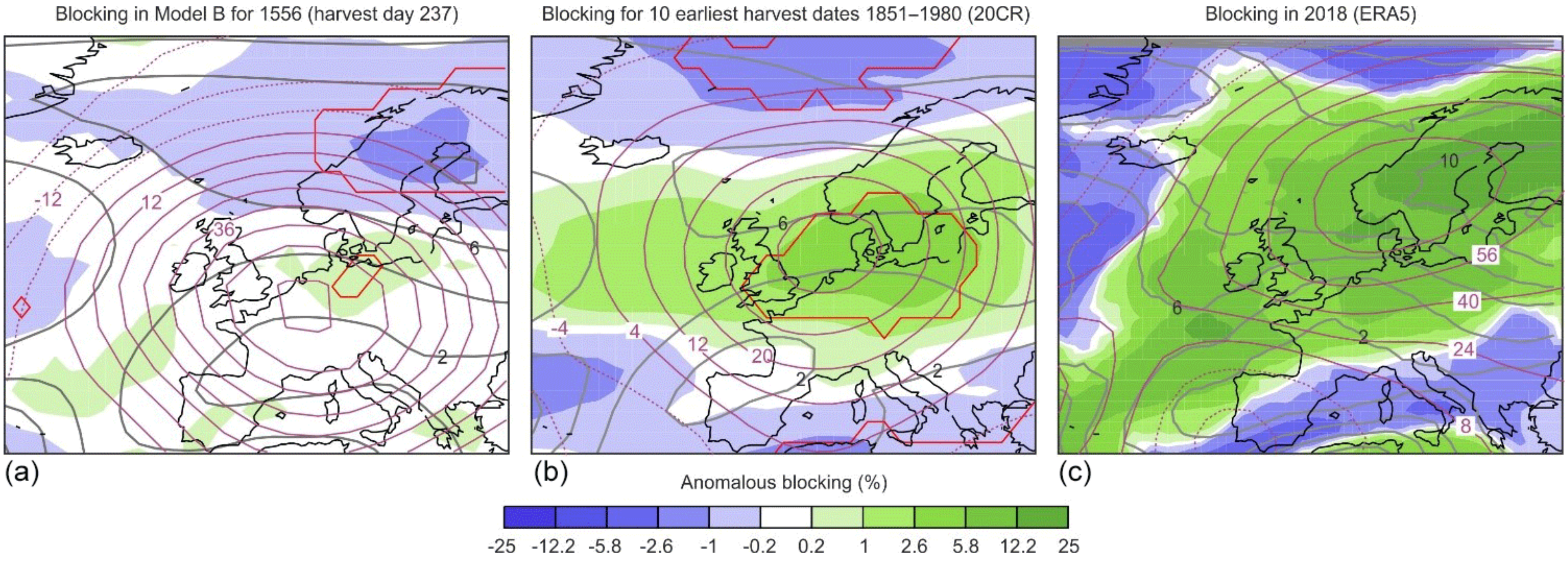
Composite = average over similar events

Cold Atlantic in May is followed by blocking **high pressure** over EU **in June** → heatwave

Duchez et al. 2016; composite for years with major heatwaves (1992, 1994, 2003, 2012, 2015)
→ compare „SSTA composite MAY" here with the previous pattern of May 2018 – it is the same!

Explanation for 1540 and other persistent heatwaves/droughts

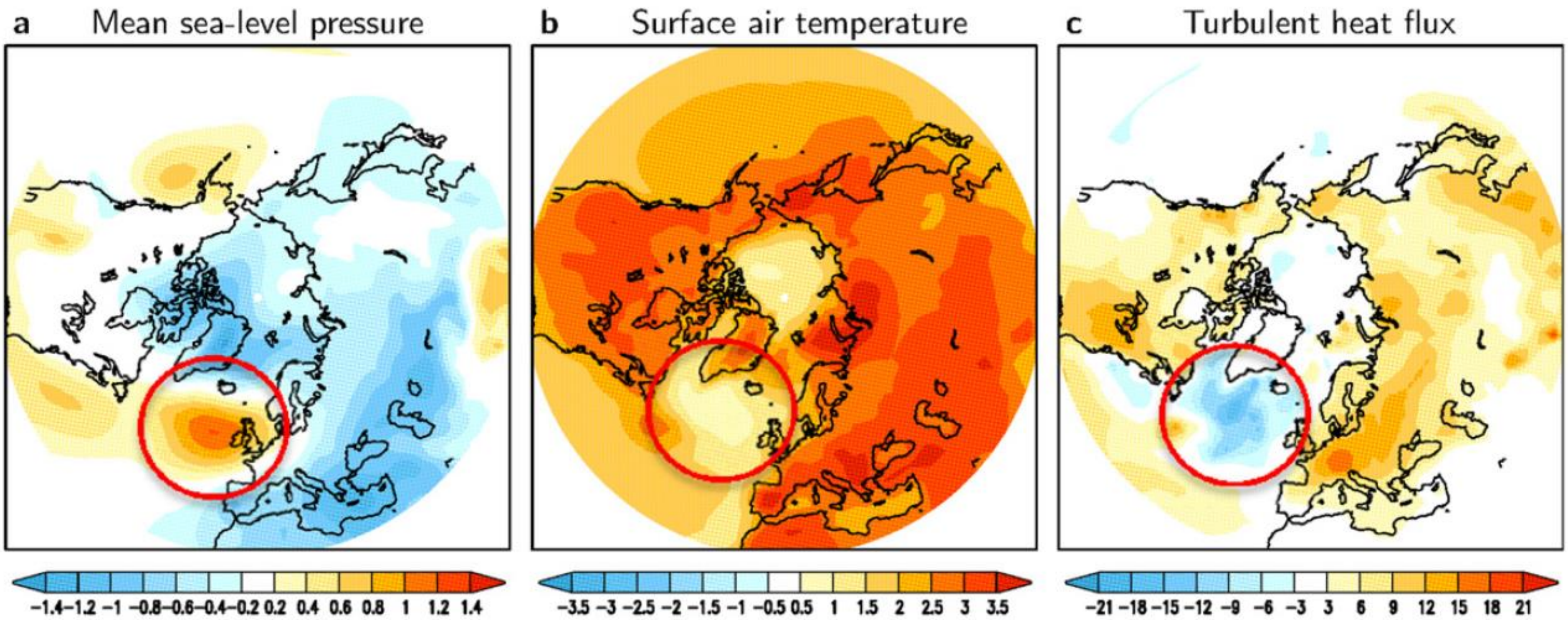
Labbé et al. 2019, Clim. Past 15, 1485–1501



Based on Jacobeit et al. (1999) in Wetter et al. (2014):

"…[1540] was characterised by a persistent diagonal south-west to north-east oriented blocking ridge of high pressure over continental Europe connected to the Azores High."

The *„warming hole“* during future warming (summer)



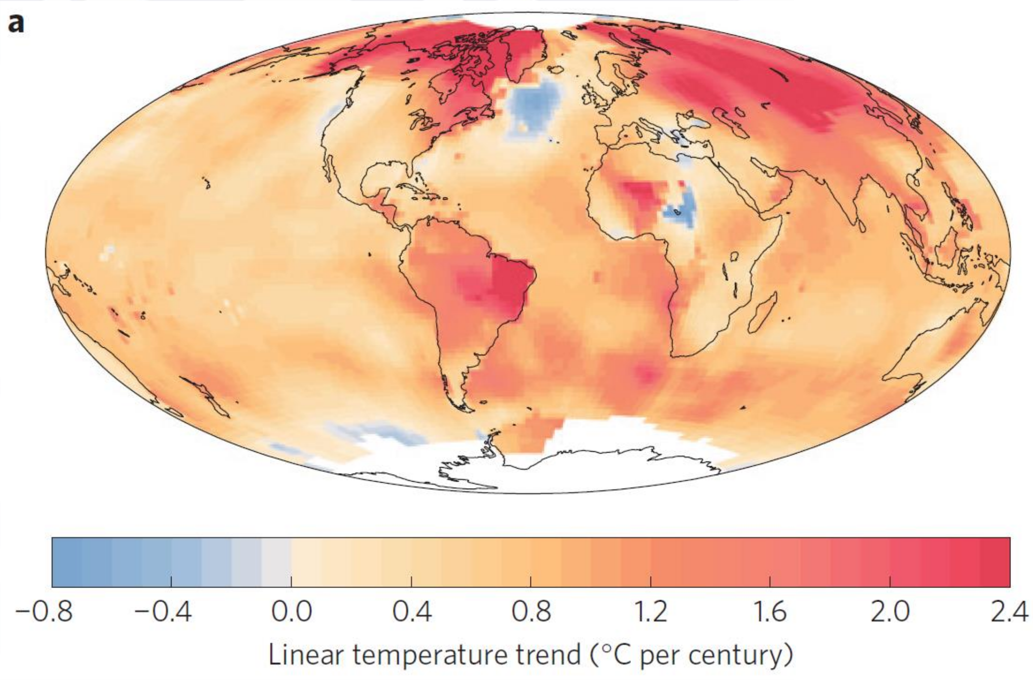
ΔSLP [hPa] Increased blocking tendency	ΔSAT [K] warming hole in surface air temperatures	ΔTHF [W/m²] decrease of turbulent heat fluxes

- CMIP5 model mean summer change under RCP4.5 (2071–2100)–(1971–2000)
- *„warming hole“* corresponds with high pressure tendency (models strongly underestimate blocking)
- atmospheric blocking and related heatwaves & droughts might get more persistent with a weak AMOC

Haarsma et al. 2015, ESL

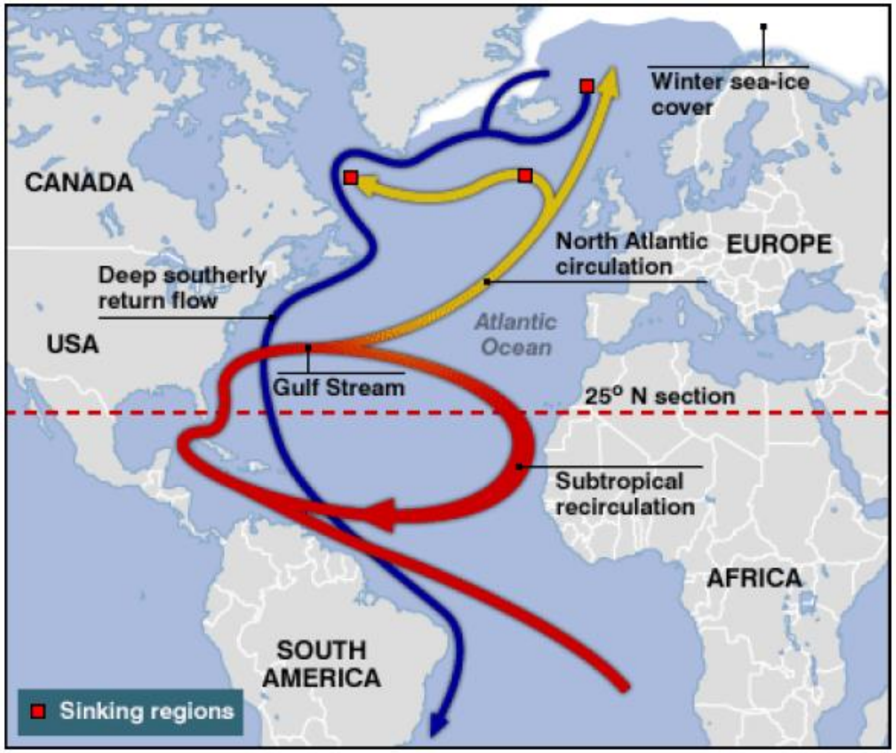
What is the cause for the cold North Atlantic sea-surface temperatures? Hence, the *warming hole?*

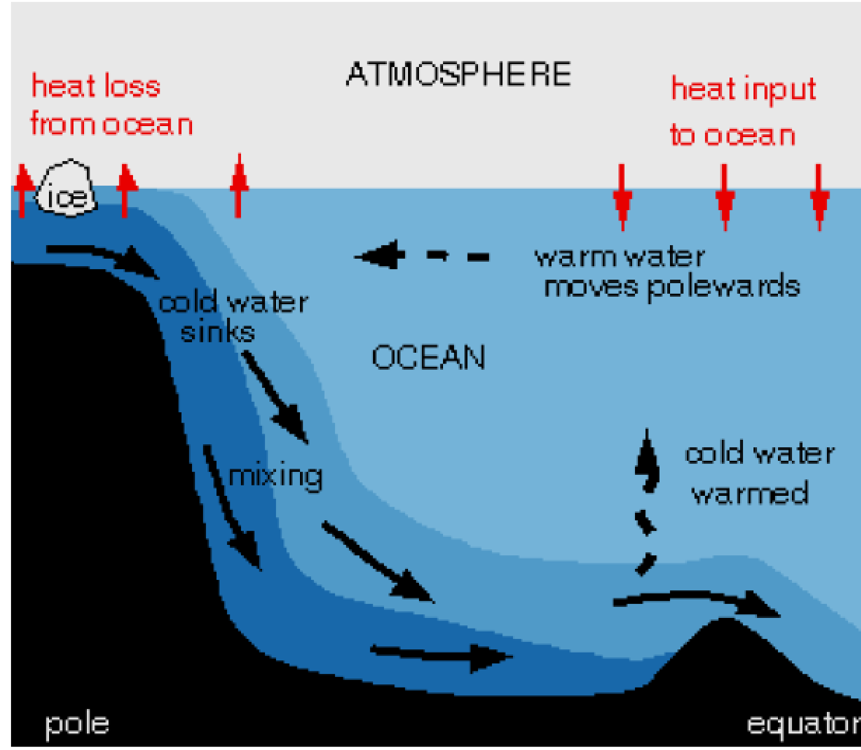
Why the *warming hole* is more than just weather



trend for 1901-2013; Rahmstorf et al. 2015

Atlantic Meridional Overturning Circulation (AMOC)



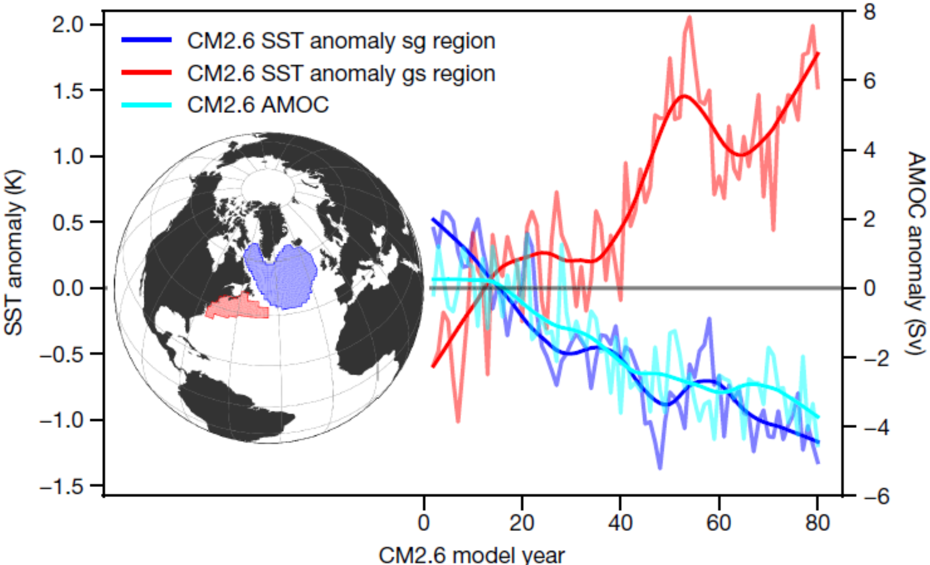


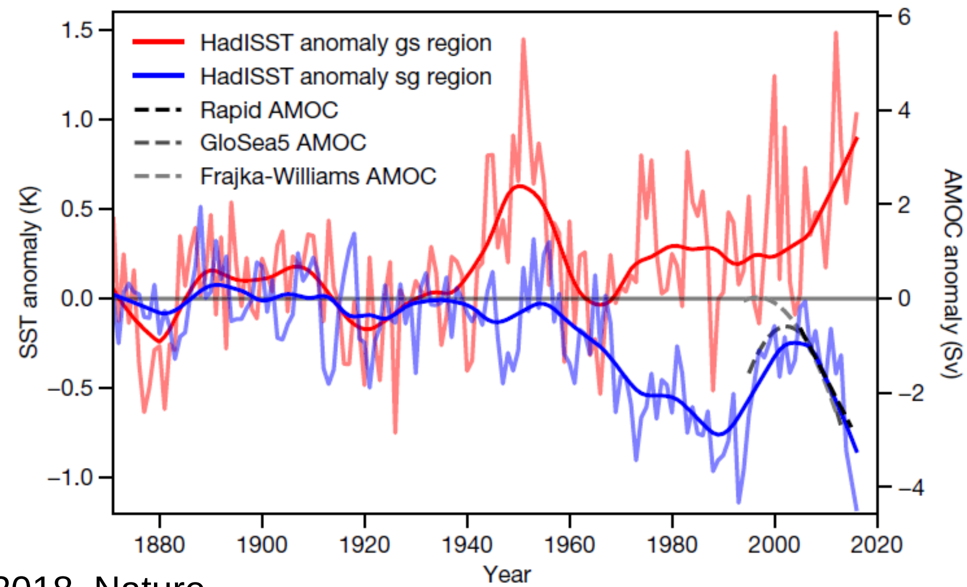
→ bi-stability or multiple equilibria, instability with hysteresis (theory)

- disturbance (warming, freshwater) can exceed a tipping point → (partial) collapse
- paleoclimate
    - AMOC was very stable in the last ~11,000 years
    - instable during rapid warming (late glacial) or warm states (Eemian)

AMOC is (and will be) slowing down (~15% since 1950)

SMHI





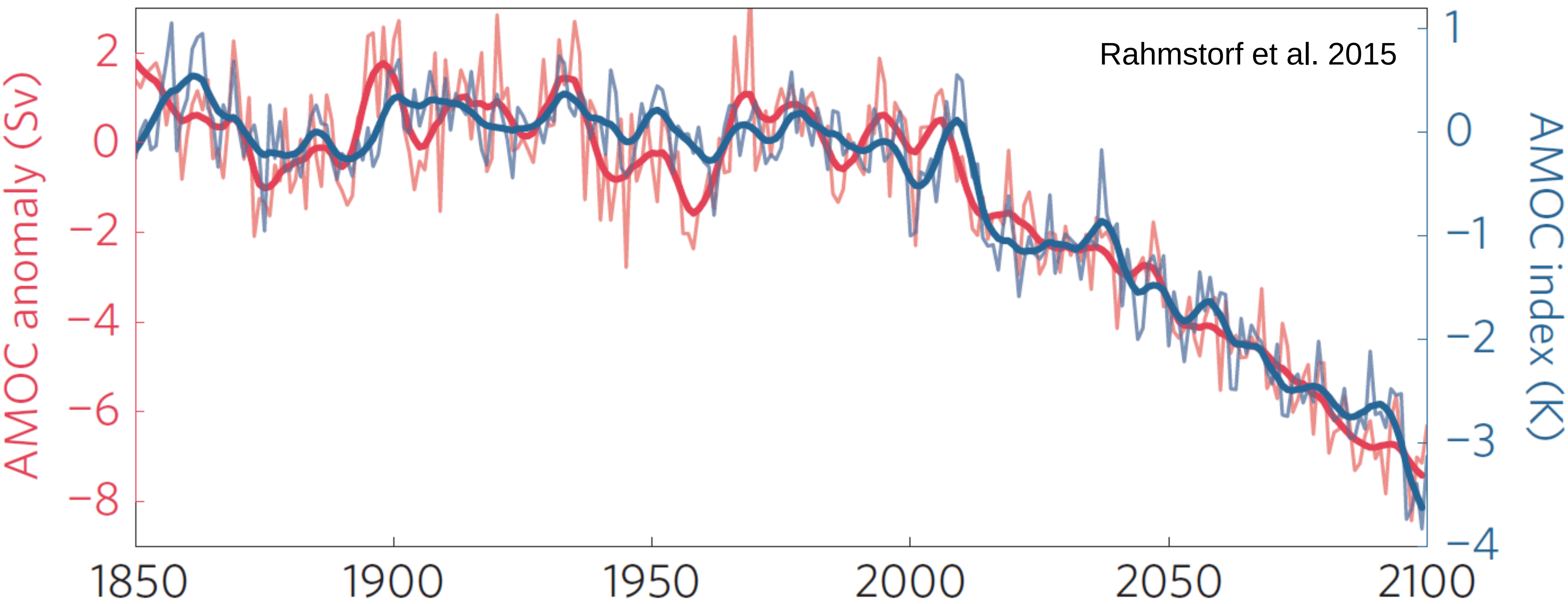
Caesar et al. 2018, Nature

The *warming hole* is a fingerprint for a weakening AMOC:

- same SST fingerprint for an AMOC slowdown in models & observations
  → cold tongue = subpolar gyre (sg) region southeast of Greenland
  → warm tongue = Gulf Stream (gs) region

➔ **divergent trends over both regions = slowdown of AMOC**

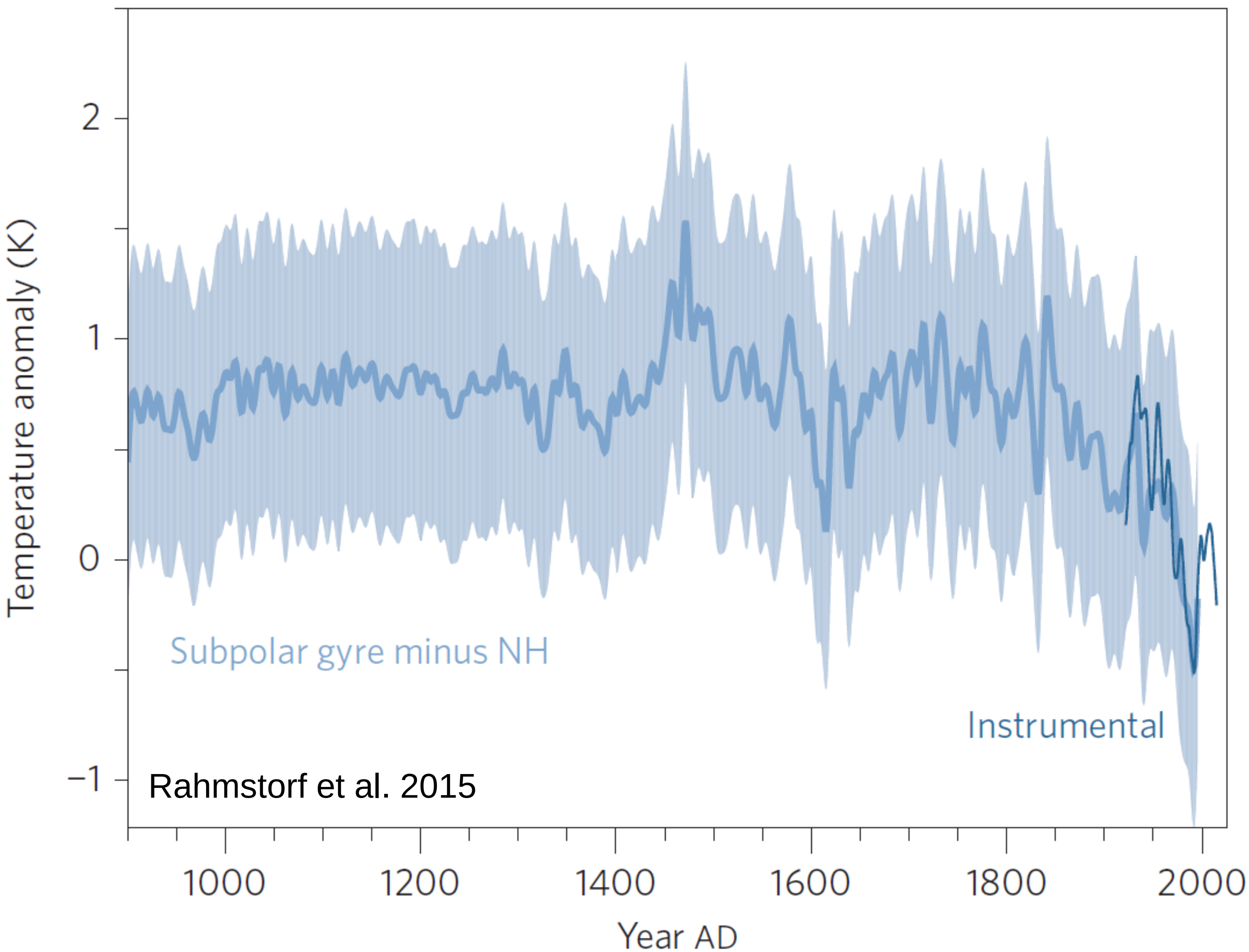
AMOC index [K] vs. simulated AMOC anomalies [Sv]



MPI-ESM-MR global climate model (Hamburg), RCP8.5

- ocean model: max. overturning stream function [Sv]
- index = subpolar gyre surface temperature minus NH temperature [K]
- AMOC slowdown under future warming projected by most CMIP5 models

Long-term AMOC index reconstruction 800-2000 AD



Surface temperature proxy reconstruction (data by Mann et al. 2008; 2009)

- AMOC index = subpolar gyre surface temperature minus NH temperature [K]

LETTER

https://doi.org/10.1038/s41586-018-0007-4

2018

Anomalously weak Labrador Sea convection and Atlantic overturning during the past 150 years

David J. R. Thornalley[1,2*], Delia W. Oppo[2], Pablo Ortega[3], Jon I. Robson[3], Chris M. Brierley[1], Renee Davis[1], Ian R. Hall[4], Paola Moffa-Sanchez[4], Neil L. Rose[1], Peter T. Spooner[1], Igor Yashayaev[5] & Lloyd D. Keigwin[2]

"Here we provide several lines of palaeo-oceanographic evidence that Labrador Sea deep convection and the AMOC have been anomalously weak over the past 150 years or so (since the end of the Little Ice Age, LIA, approximately ad 1850) compared with the preceding 1,500 years."

nature geoscience

BRIEF COMMUNICATION

https://doi.org/10.1038/s41561-021-00699-z

Check for updates

2021

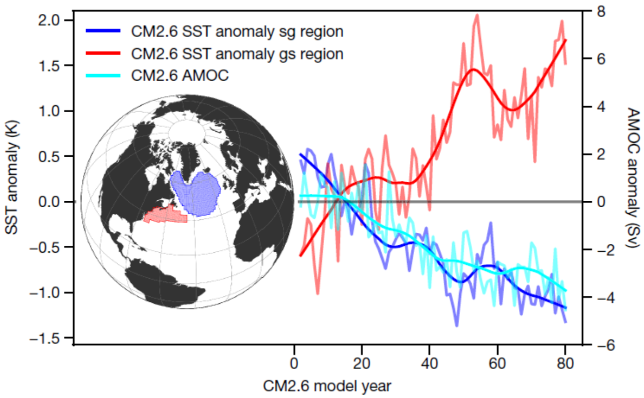
Current Atlantic Meridional Overturning Circulation weakest in last millennium

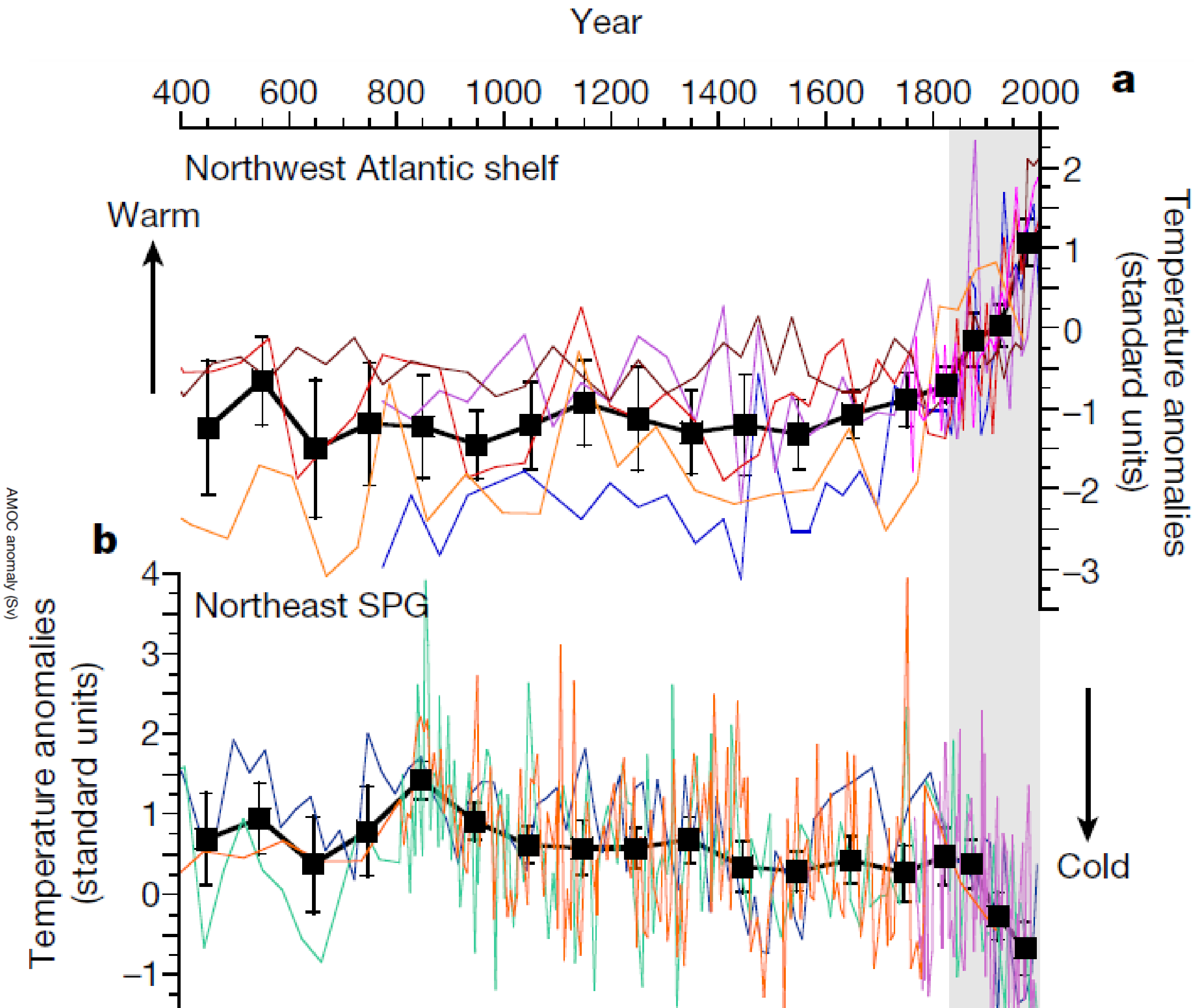
L. Caesar[1,2], G. D. McCarthy[1], D. J. R. Thornalley[3], N. Cahill[4] and S. Rahmstorf[2,5]

Reconstruction of AMOC-index (Thornalley et al. 2018)

SMHI

AMOC-index (modern)

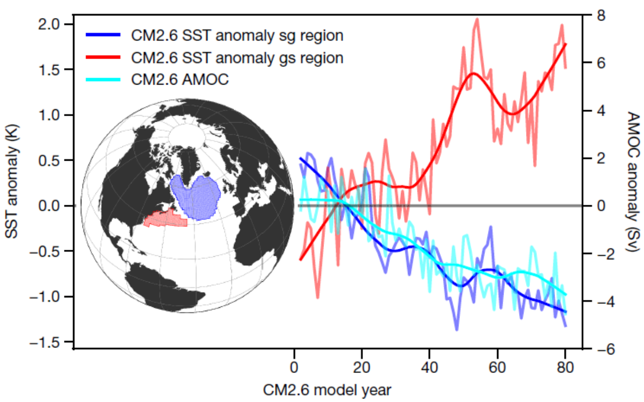


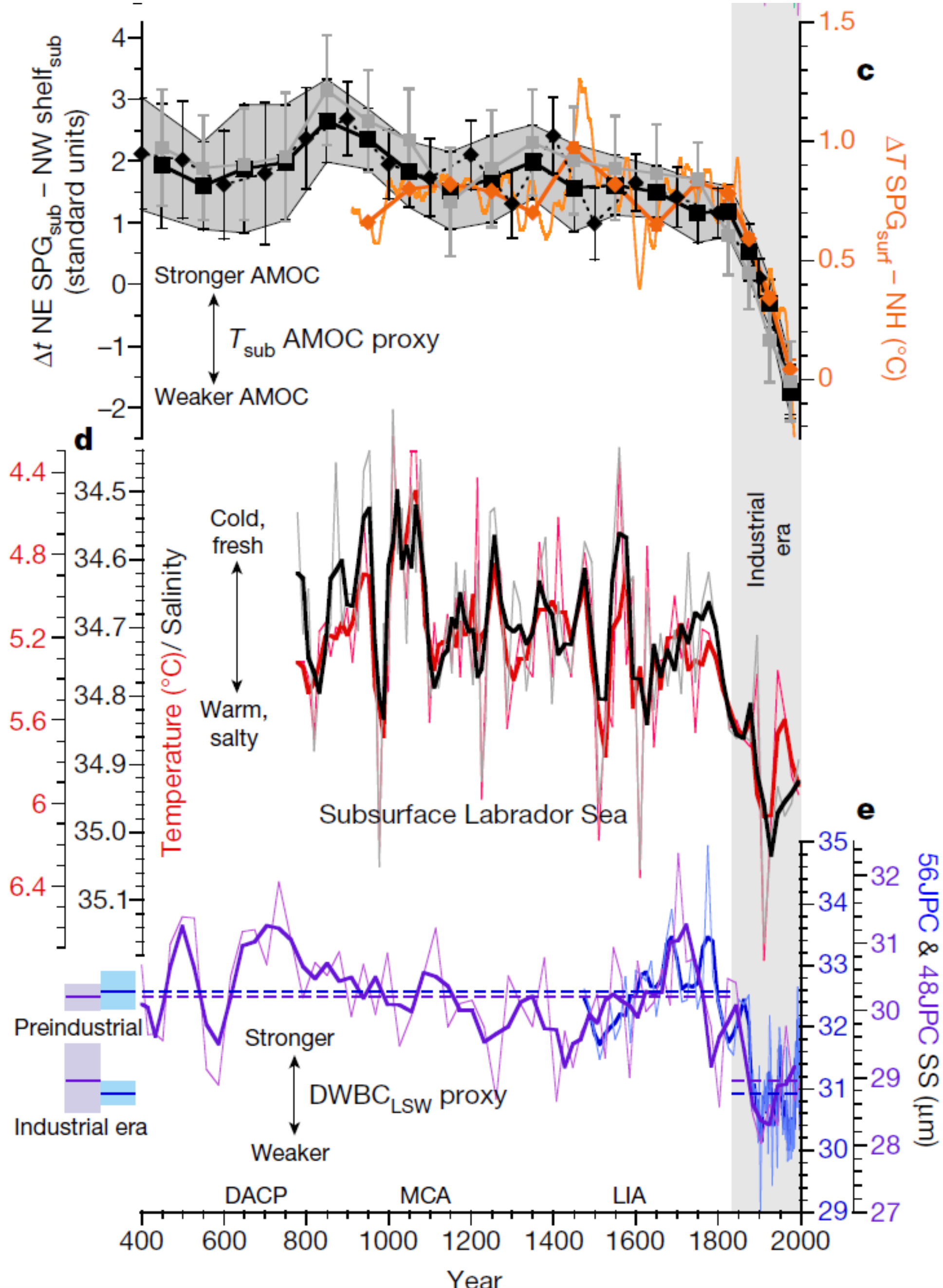


AMOC-index (past, reconstructions)

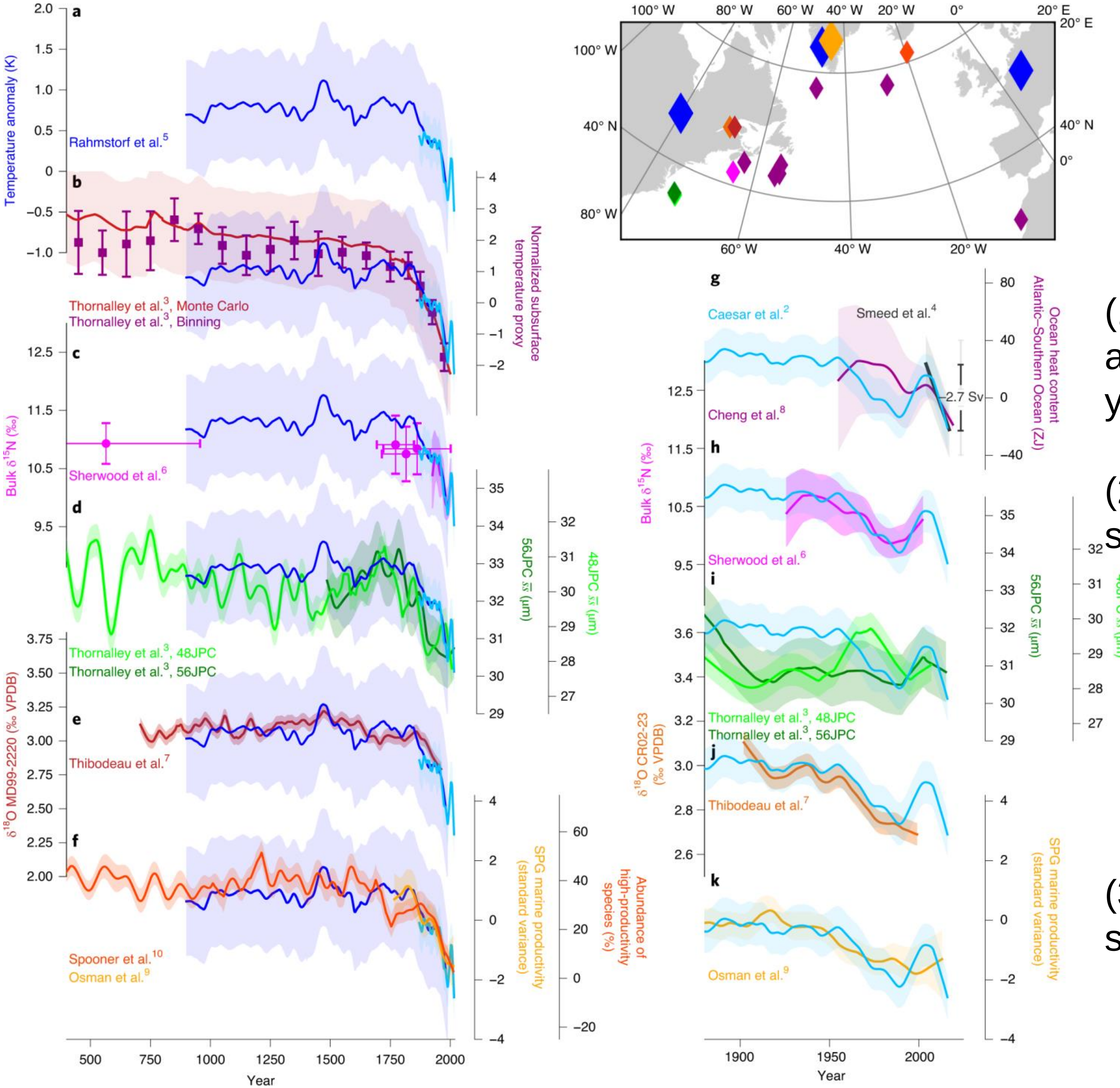
Reconstruction of AMOC-index

AMOC-index (modern)





AMOC-index (past, reconstructions)



SMHI

Caesar et al. 2021

(1) Slowdown started already around 200 years ago

(2) Large fraction of slowdown after 1950

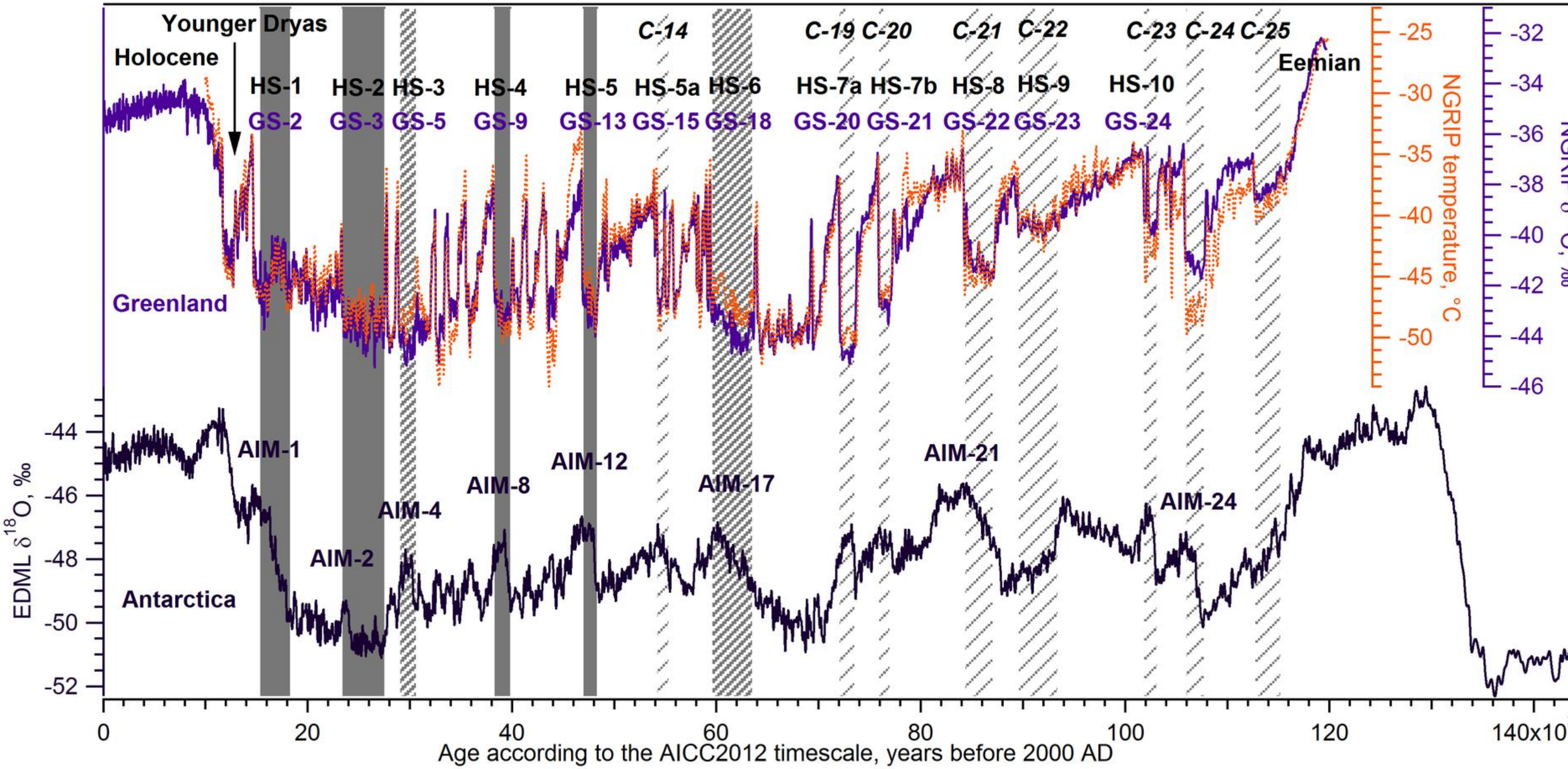
(3) Earlier papers: slowdown is ~15%

Deglacial timescale
A geological perspective on the *warming hole*

Abrupt climate change and extreme events

Climate instabilities during the last rapid warming
= late glacial period & the time ~12,000 years ago

Pleistocene: Heinrich/Greenland Stadials & „bipolar seesaw“



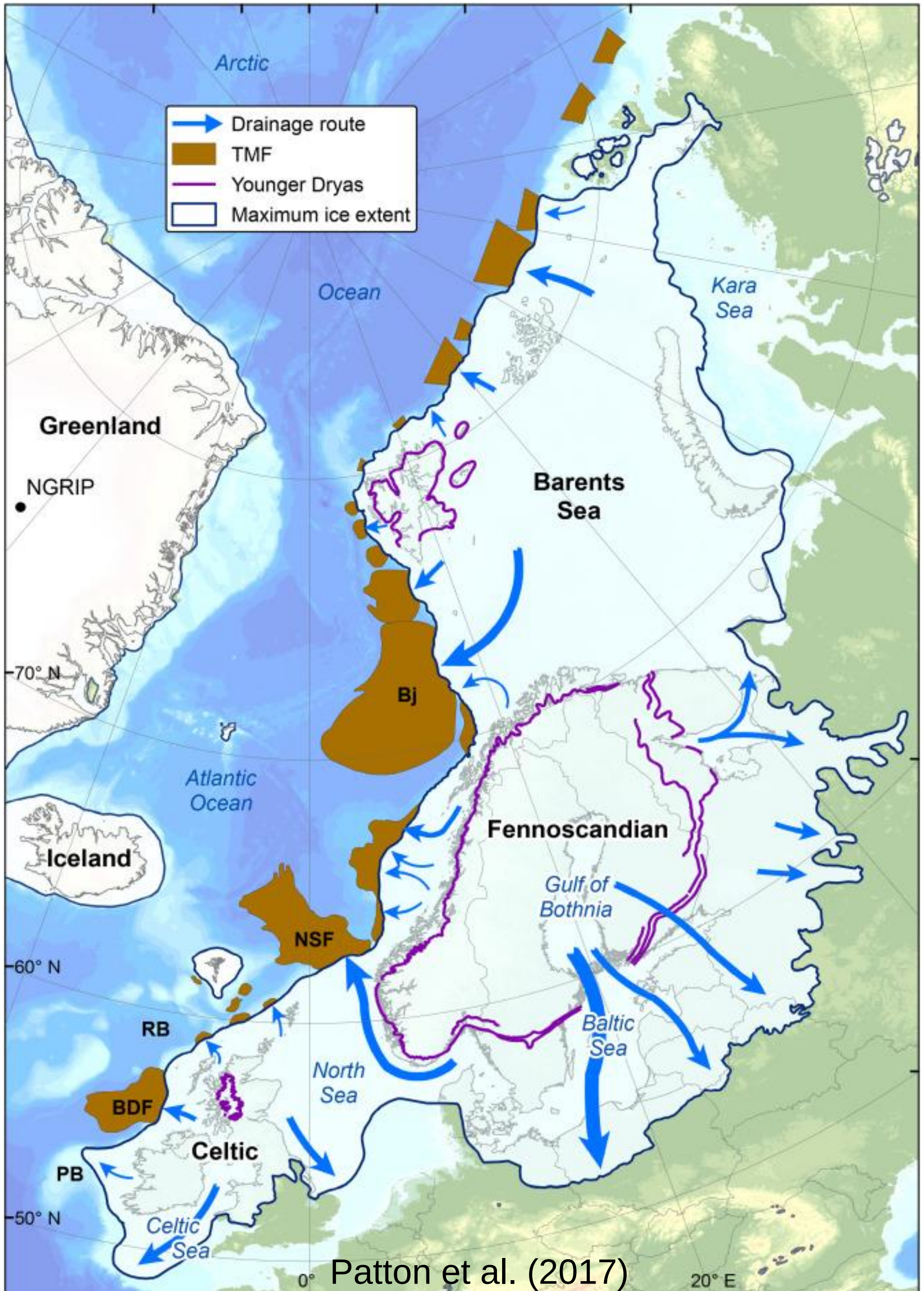
Greenland Stadials (GS) = cold period within an ice age

Greenland Interstadials (GI) = warm period within an ice age

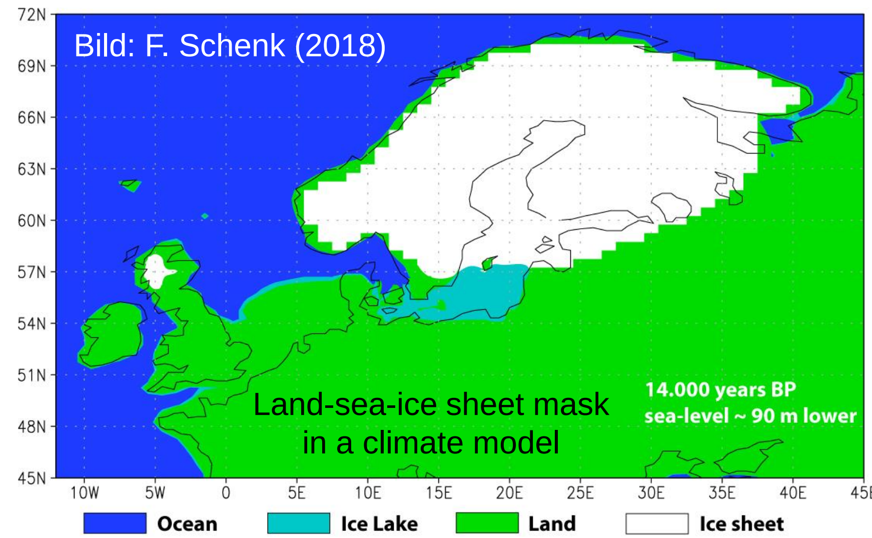
Antarctic Isotope Maximum (AIM) ~ ± in sync with Heinrich Stadials ~ **bipolar seesaw**

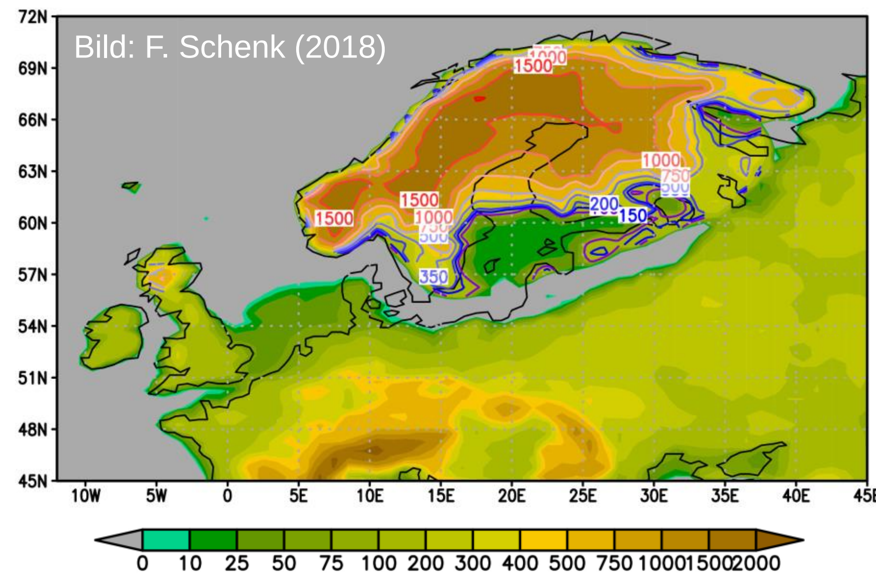
Melting ice sheets produce huge amounts of fresh water

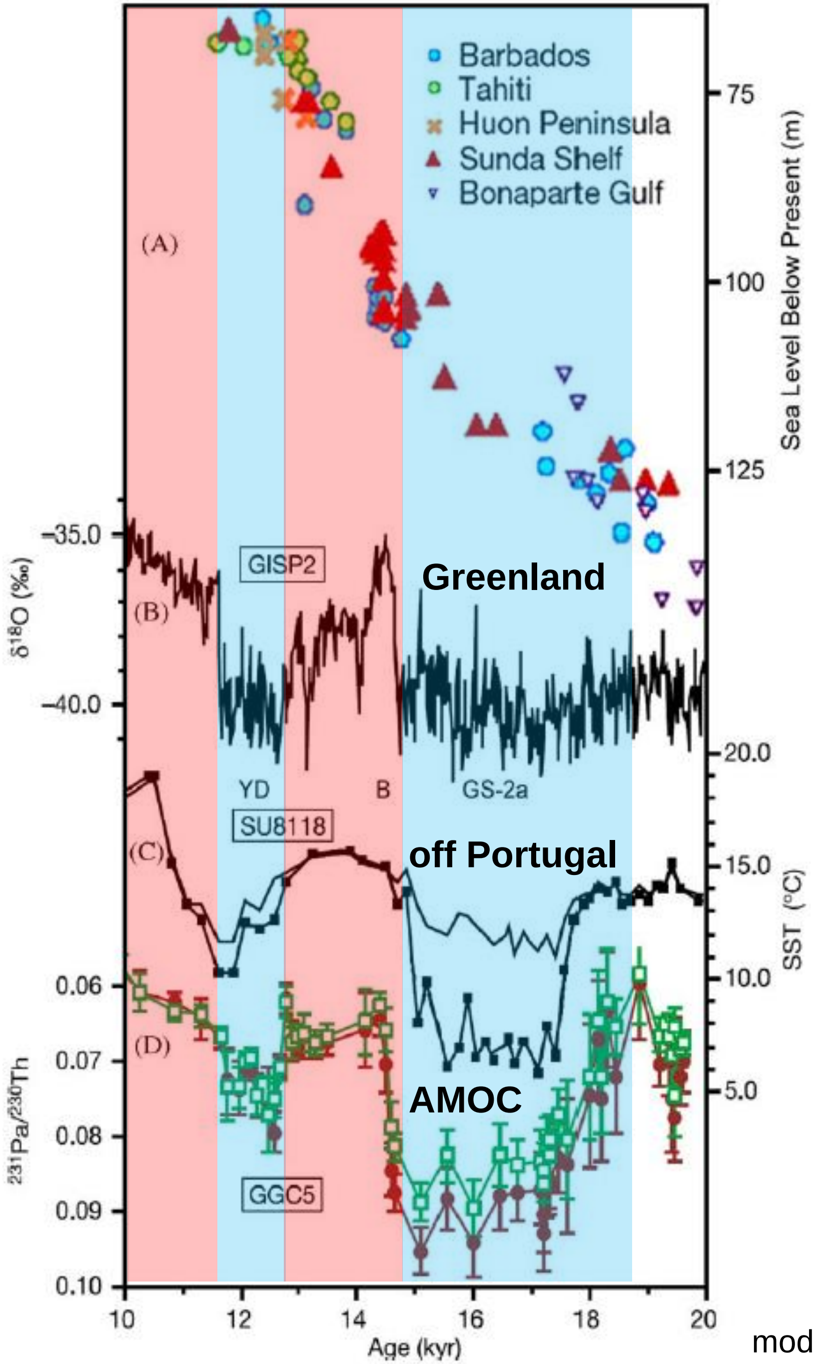
SMHI



Patton et al. (2017)







Euro-Atlantic paleoclimate

SMHI

Deglaciation ~15.000 to ~11.700 years BP
- rapid warming and cooling events
- huge amount of meltwater (+ pulses)

→ rapid sea-level rise
(based on many different sites)

→ abrupt ΔTemperature Greenland ($\delta^{18}O$)
(proxy dominated by winter & North Atlantic sea-ice extent)

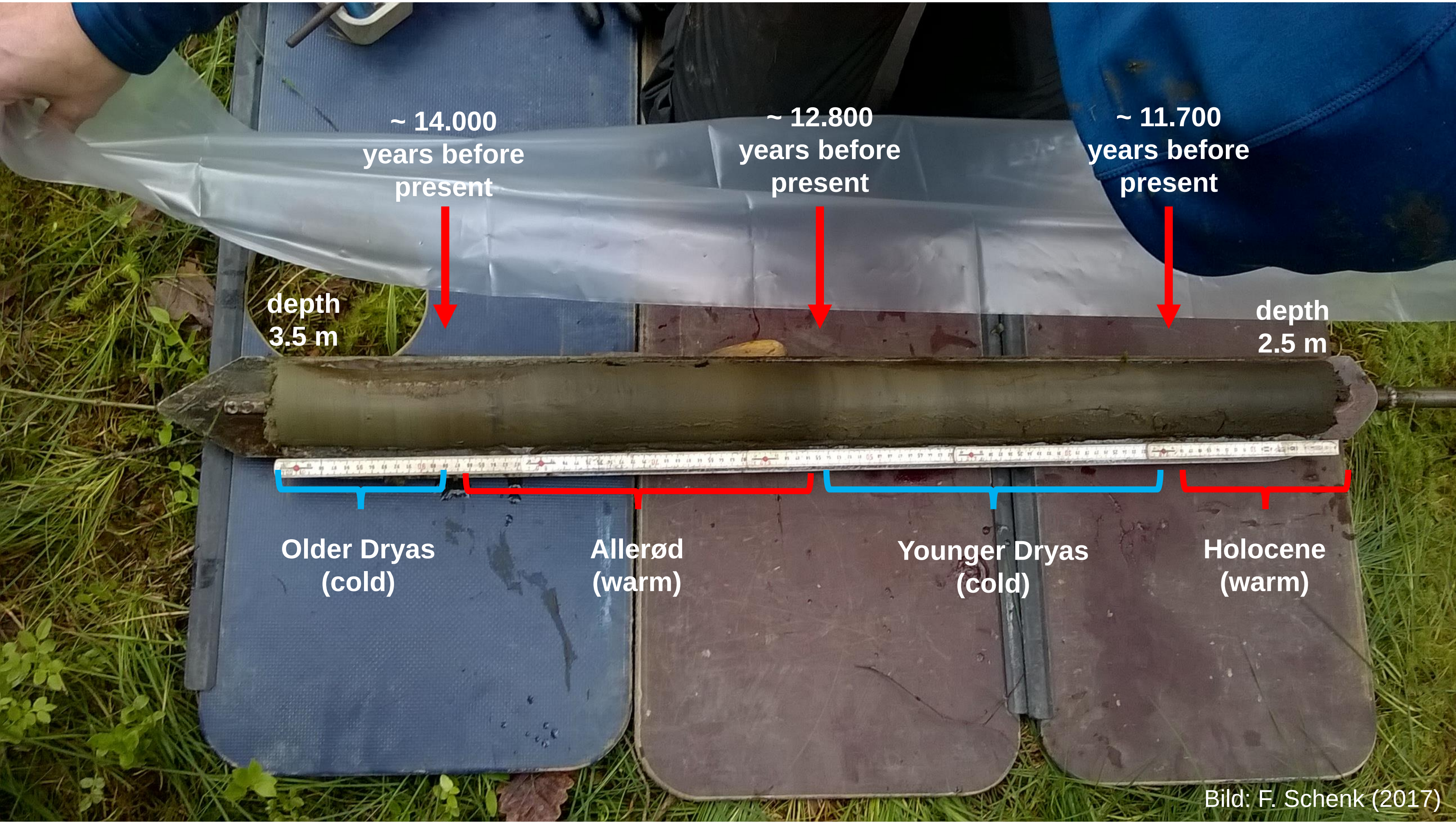
→ abrupt ΔSST North Atlantic (alkenones)
(absolute sea-surface temperature (SST) cooling is uncertain)

→ abrupt ΔAMOC ($\Delta^{231}Pa/^{230}Th$)
(proxy for AMOC from marine sediments)

modified after Denton et al. (2004) & McManus et al. (2004)

Hässeldala Port (Southern Sweden, 56°N / 15°E, 60 m)

SMHI



Distinct sediment sections in grey (cold, low organic matter) and brown (warm, productive) are clearly visible

Simulating the extreme climate of the Younger Dryas (~12,000 BP)

High-resolution Community Earth System Model (CESM1)

Community Earth System Model 1 (CESM1.0.5 paleo)

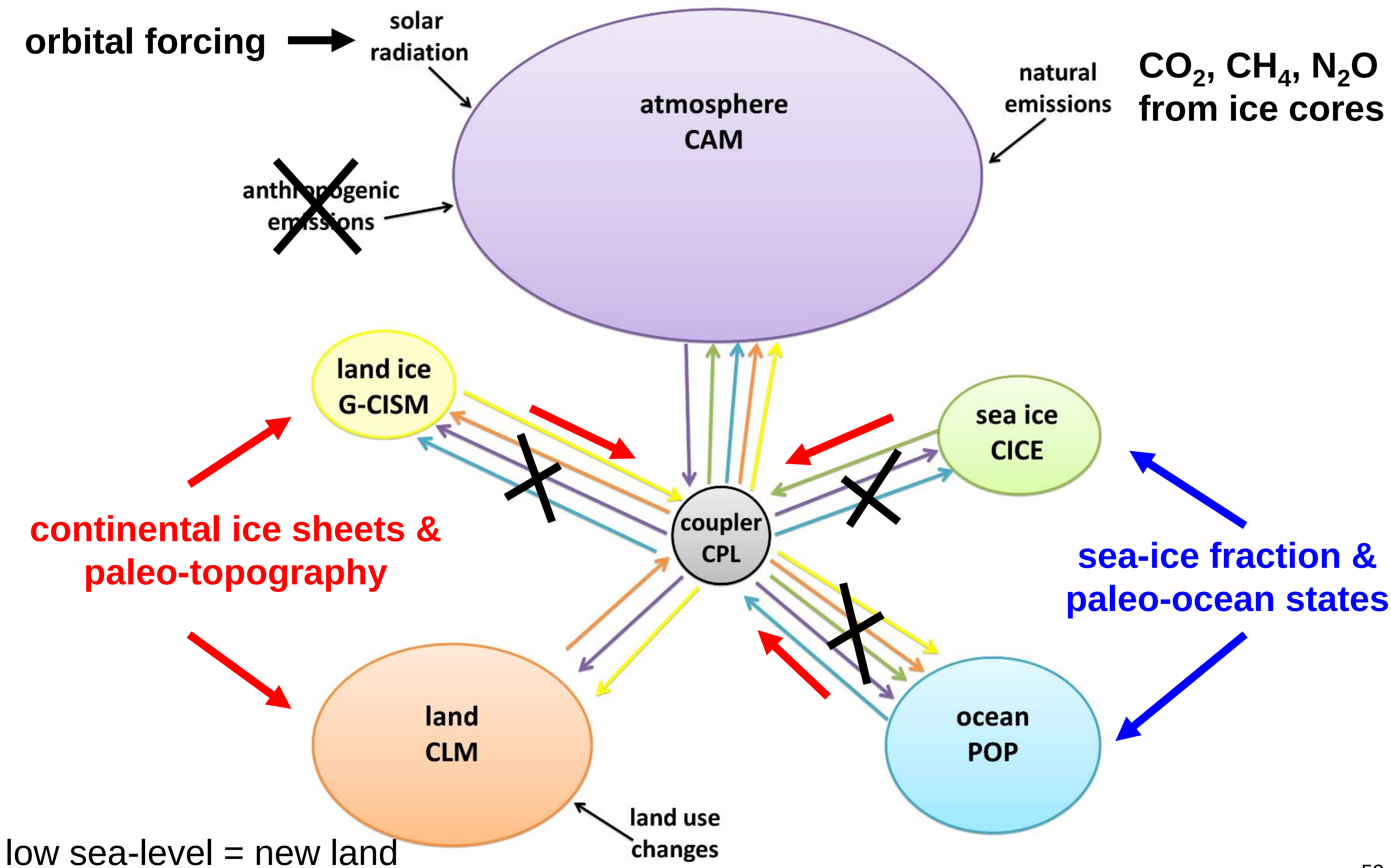
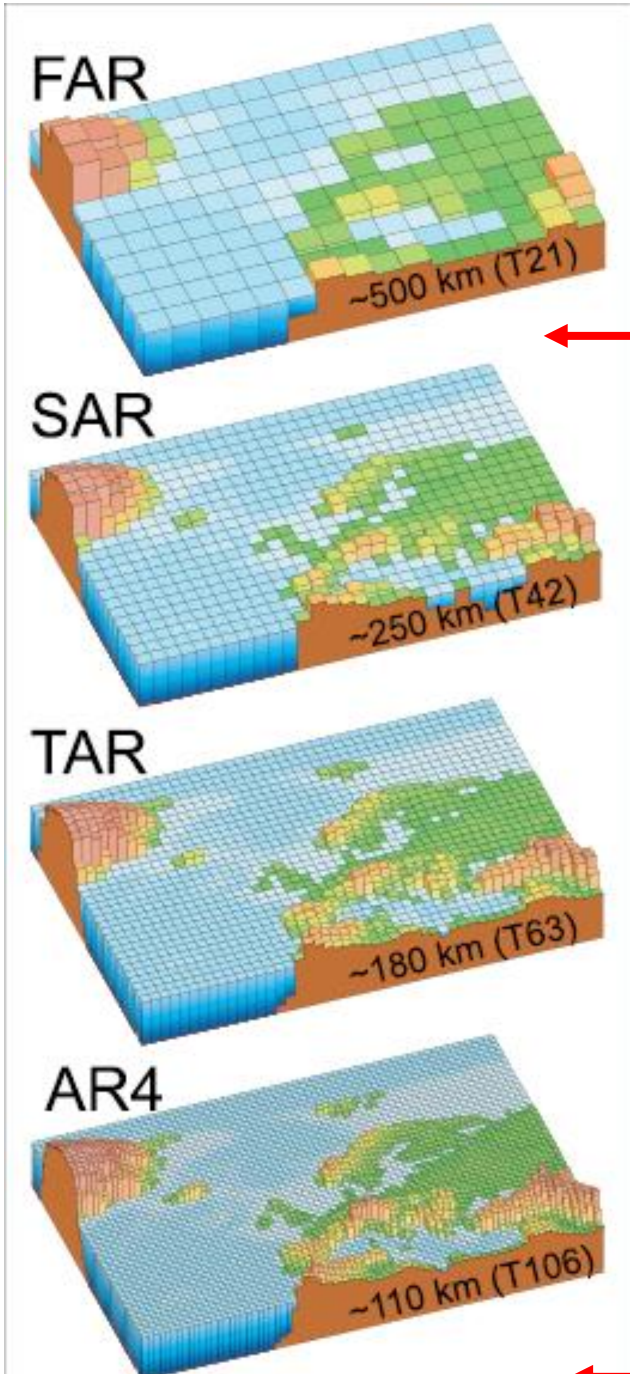


Bild: climatesight



Model resolutions are getting better

previous simulations

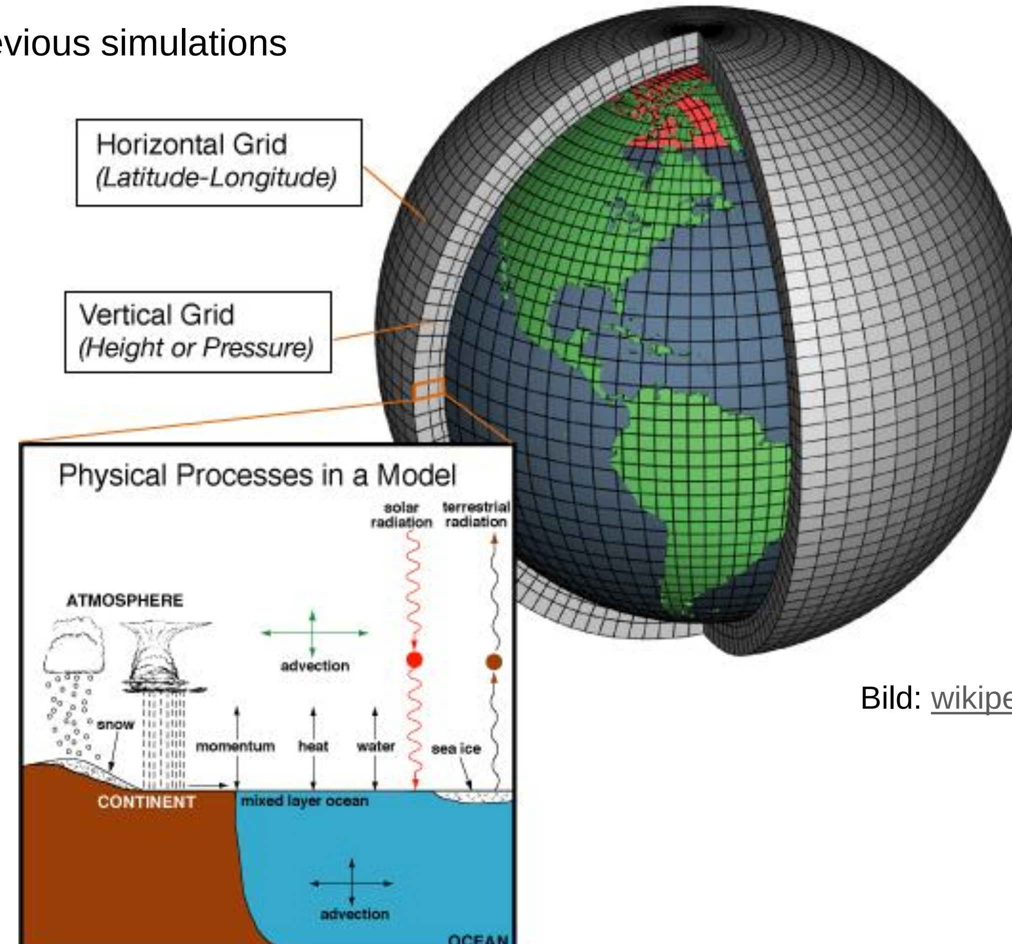


Bild: wikipedia

CESM1 simulations (Schenk et al. 2018)

Bild: IPCC 2007, WG1, Chapter 1, p 113

Stadial and Interstadial climates simulated by CCSM3

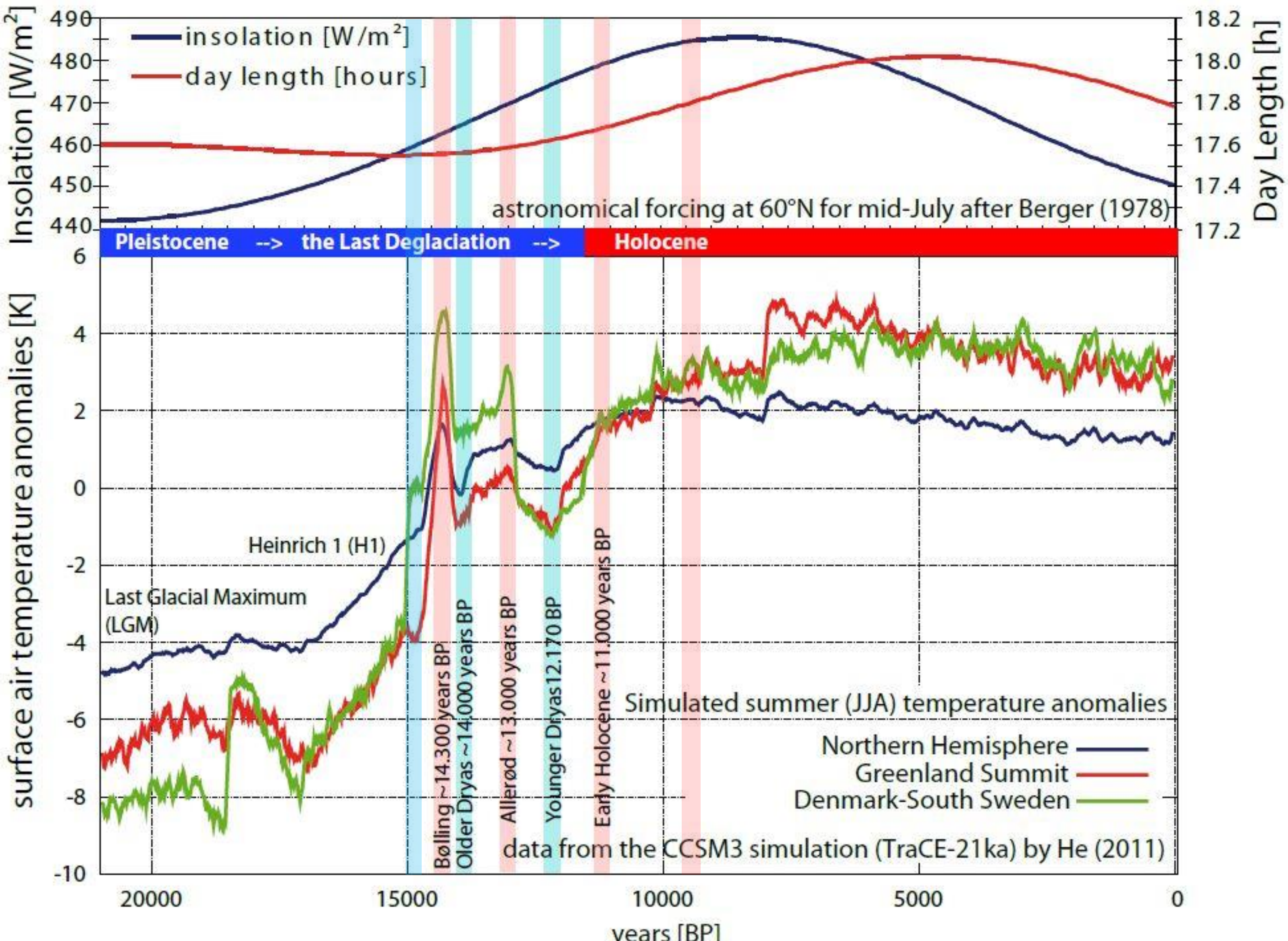
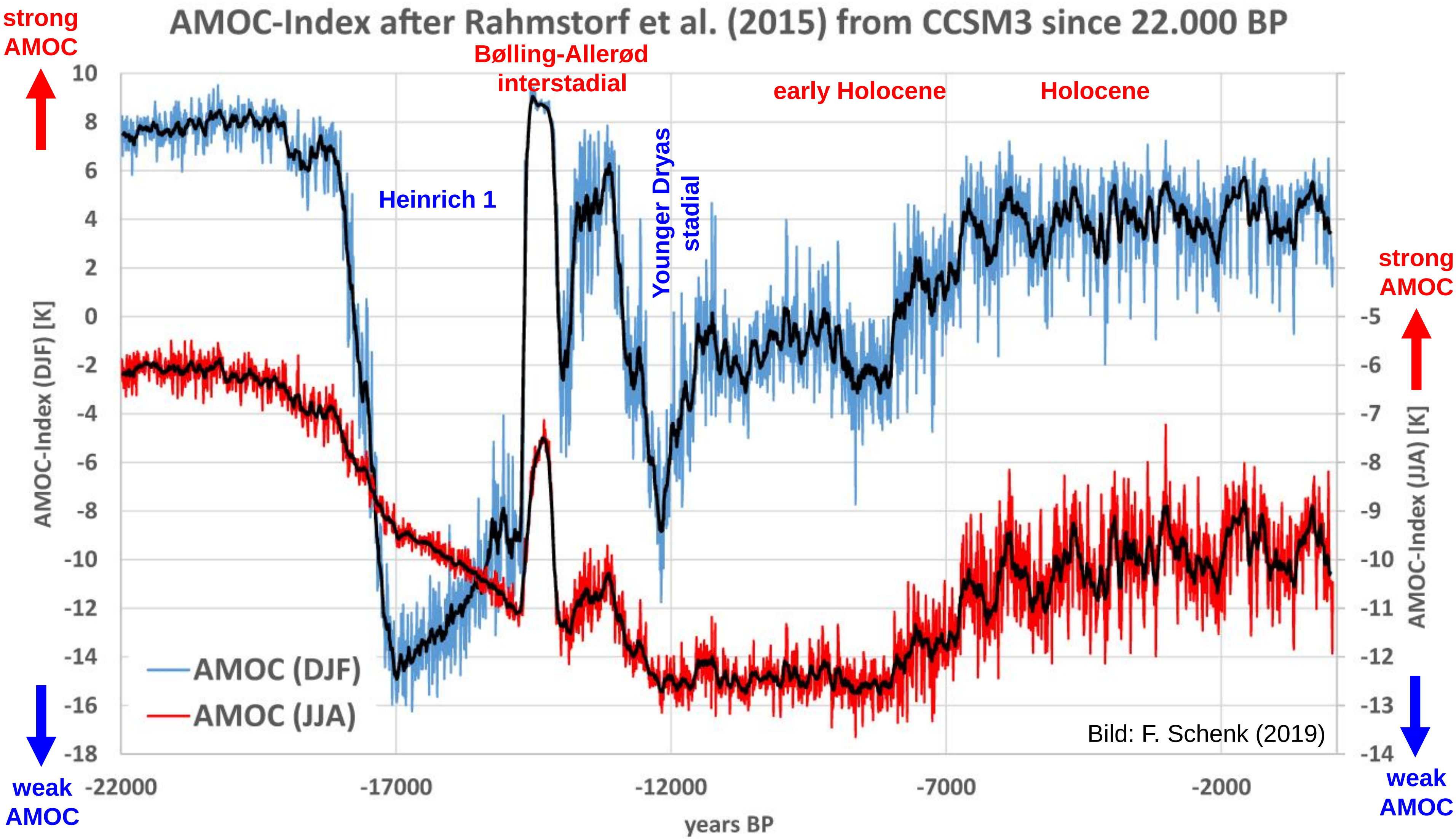


Bild: F. Schenk (2019)

Surface Temperature as AMOC proxy (ΔT NH-SPG)

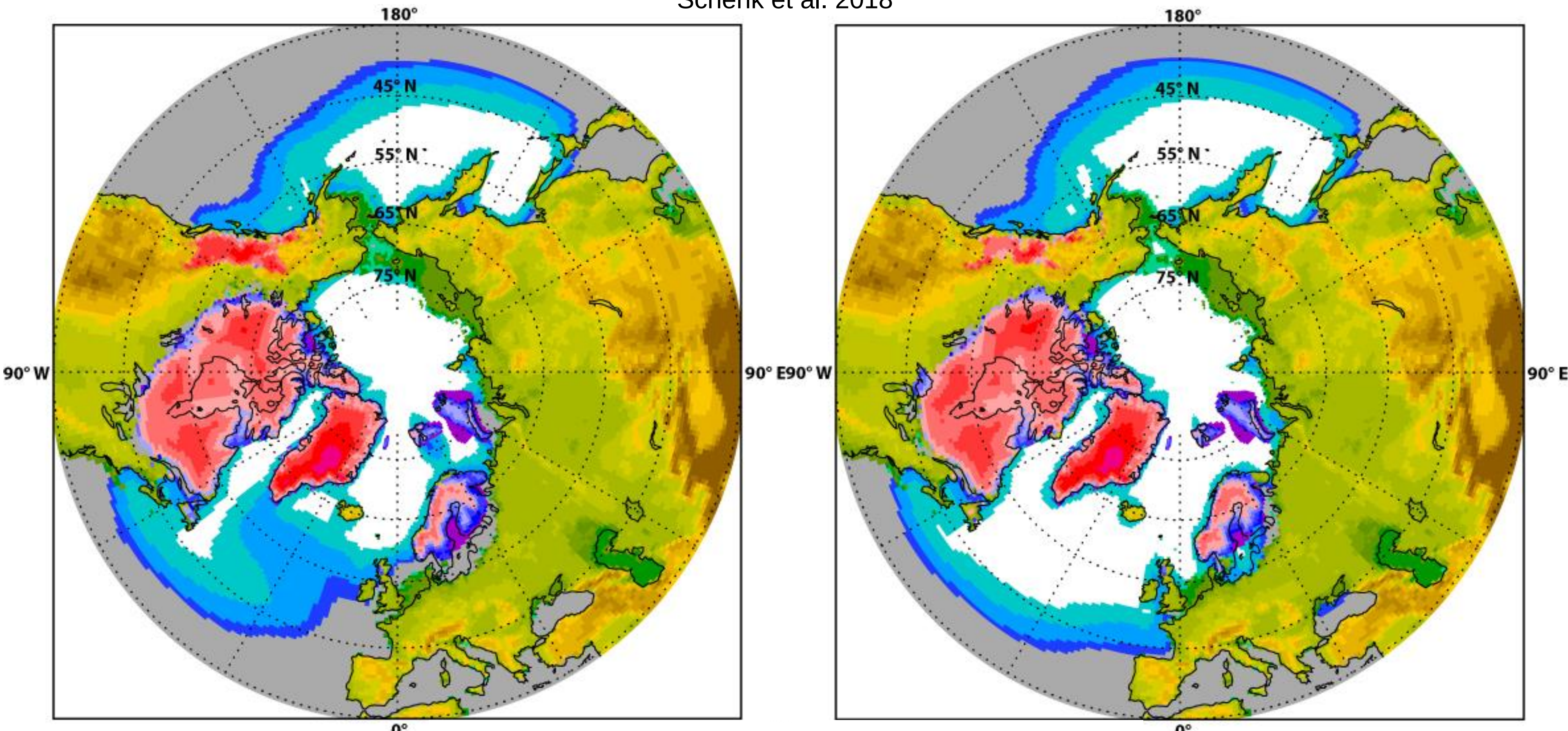


AMOC definition based on surface air temperatures:
temperature difference of Northern Hemisphere (NH) minus Sub-Polar Gyre (SPG) region south of Greenland

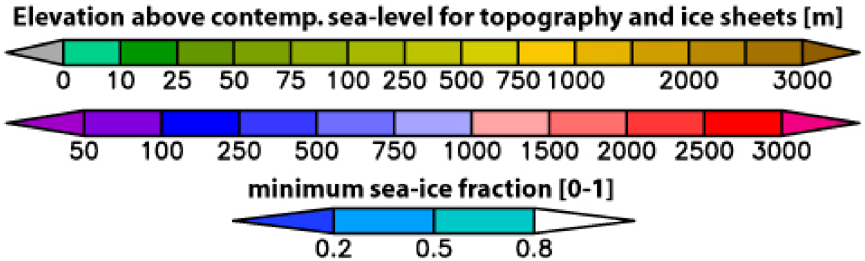
ΔAMOC → Δsea-ice extent – winter maximum (March)

SMHI

Schenk et al. 2018



Allerød
(13,000 BP)
= strong AMOC

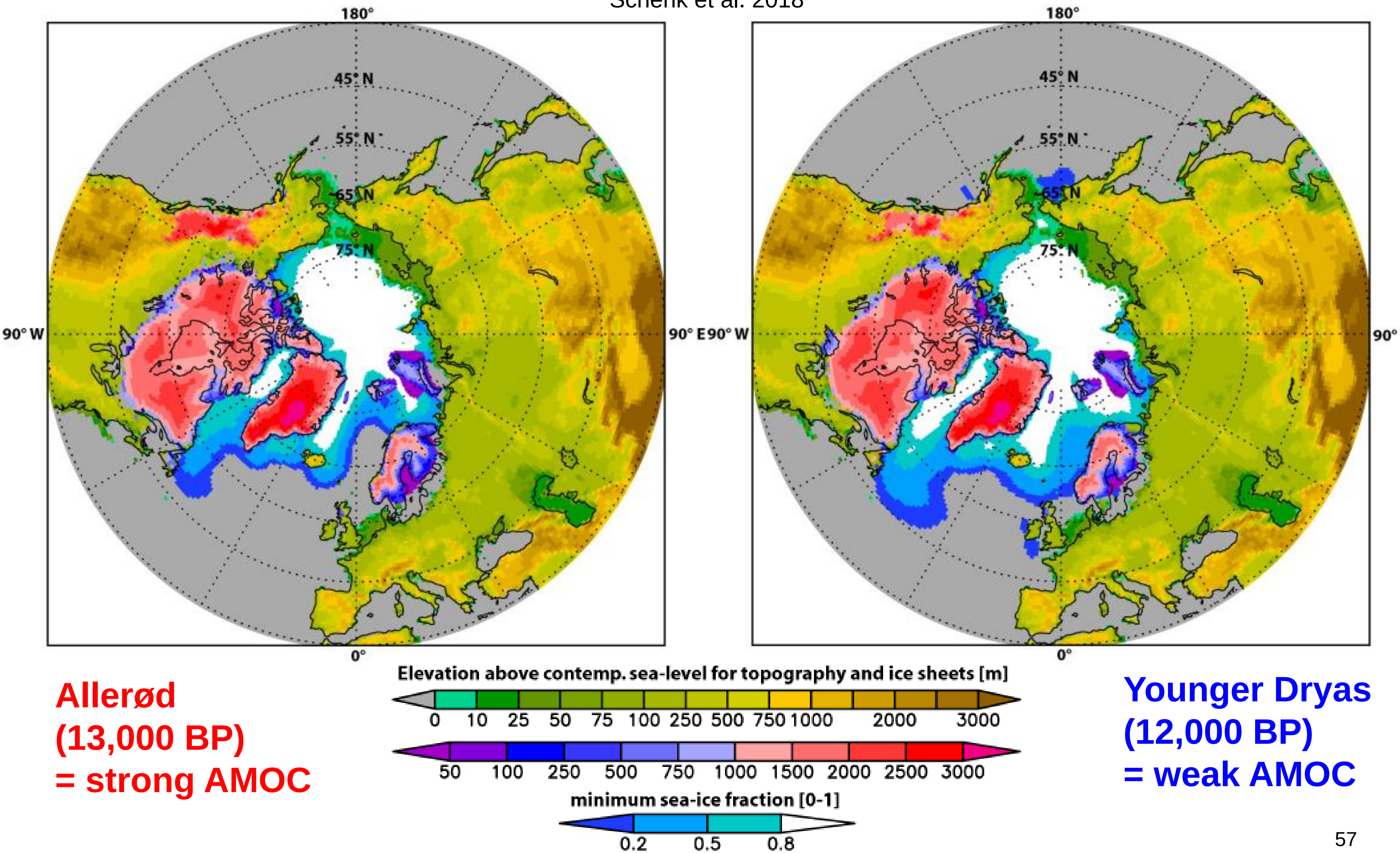


Younger Dryas
(12,000 BP)
= weak AMOC

ΔAMOC → Δsea-ice extent – summer minimum (September)

SMHI

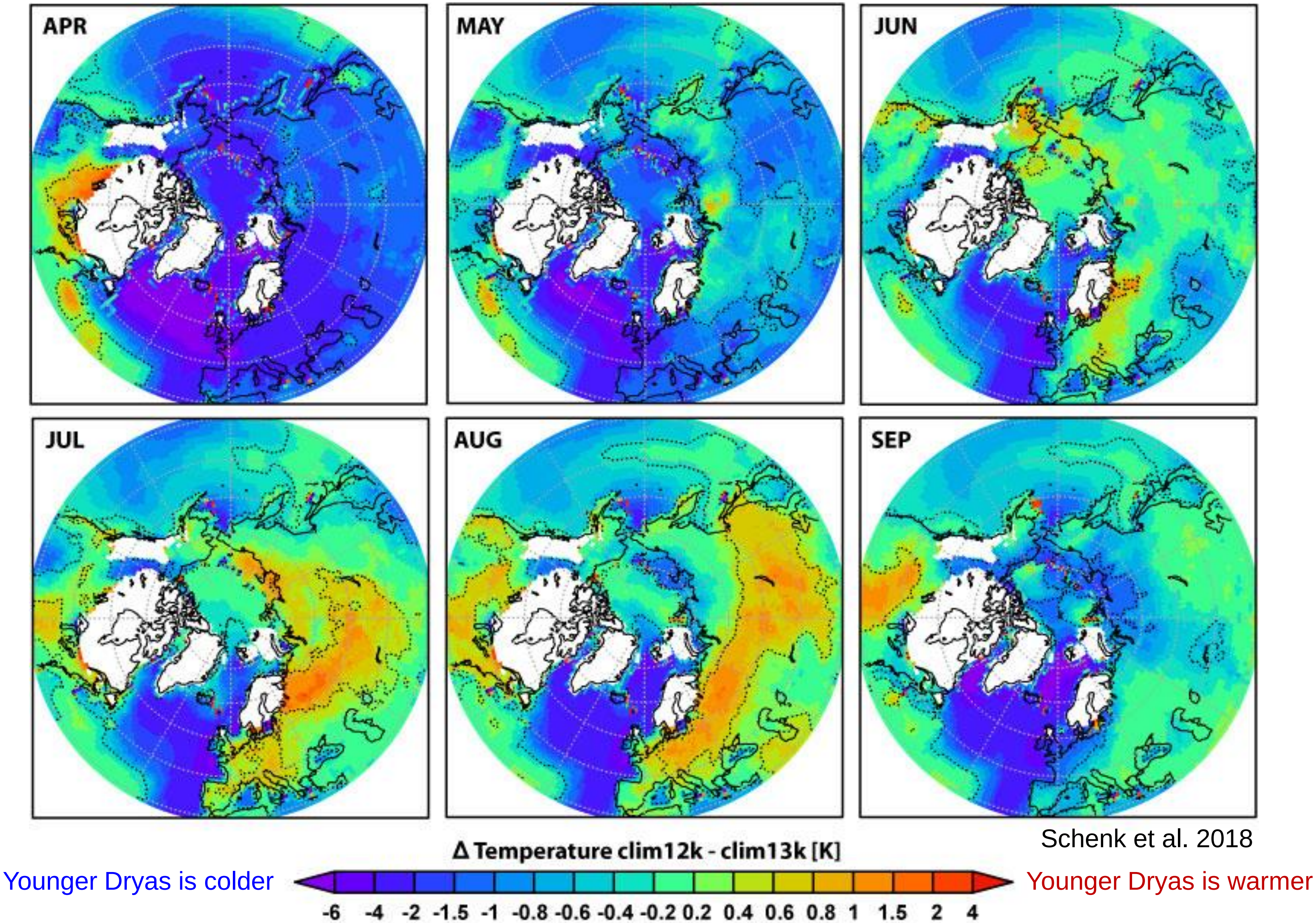
Schenk et al. 2018



Allerød (13,000 BP) = strong AMOC

Younger Dryas (12,000 BP) = weak AMOC

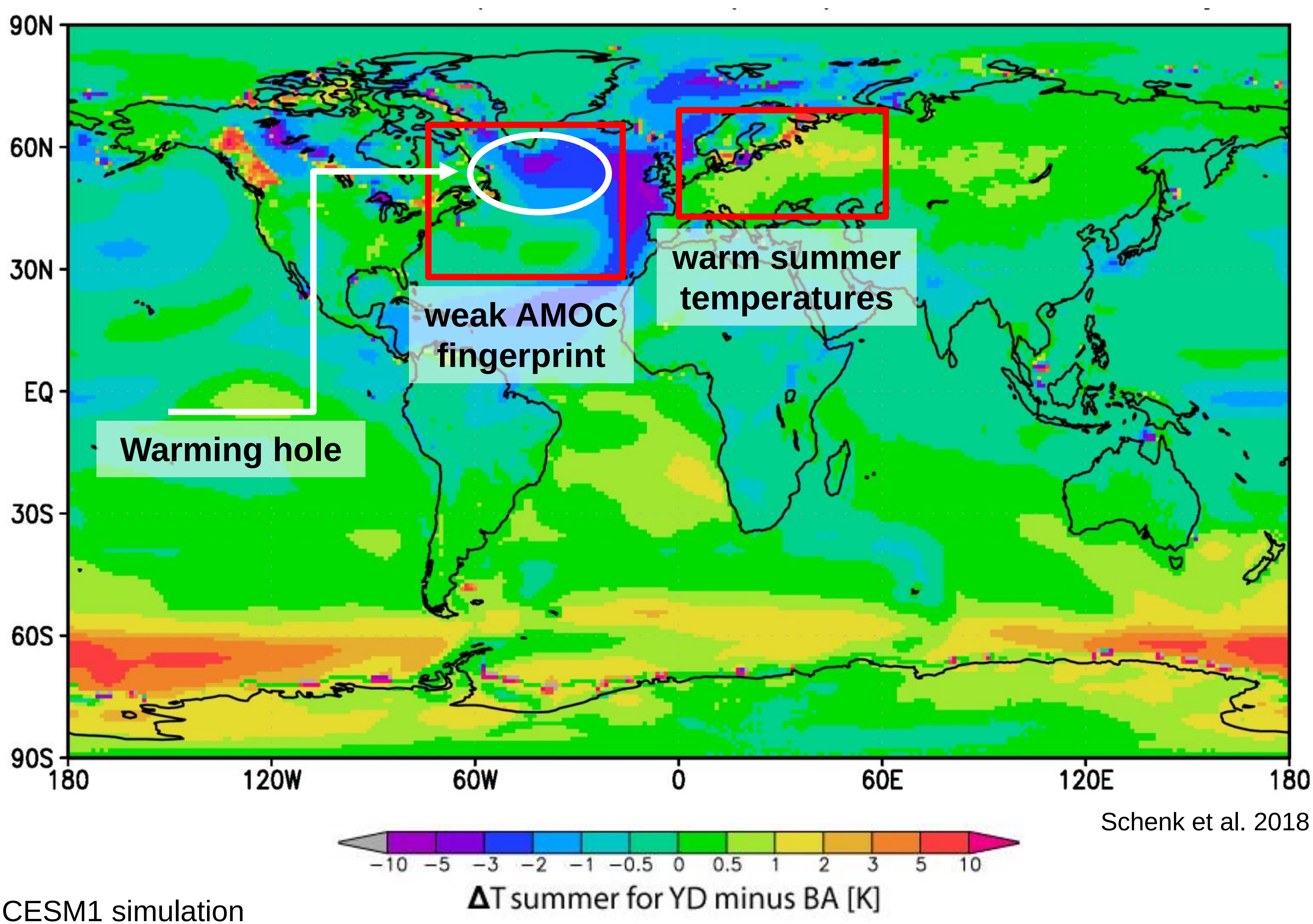
Simulated $\Delta T_{surface}$ Younger Dryas minus Allerød



Schenk et al. 2018

The *warming hole* again! But now 12,000 years ago
ΔT summer for AMOC slowdown during Younger Dryas

SMHI

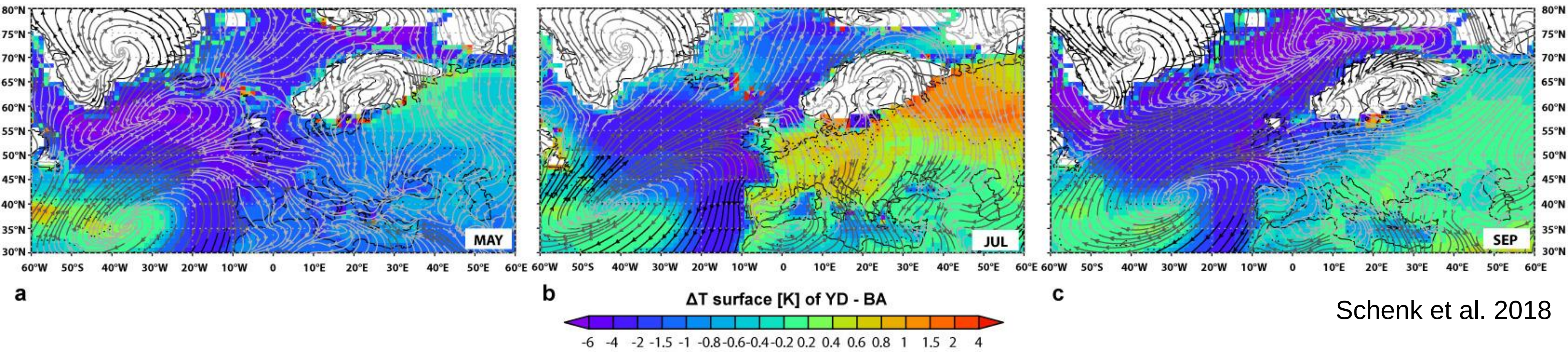


Schenk et al. 2018

CESM1 simulation

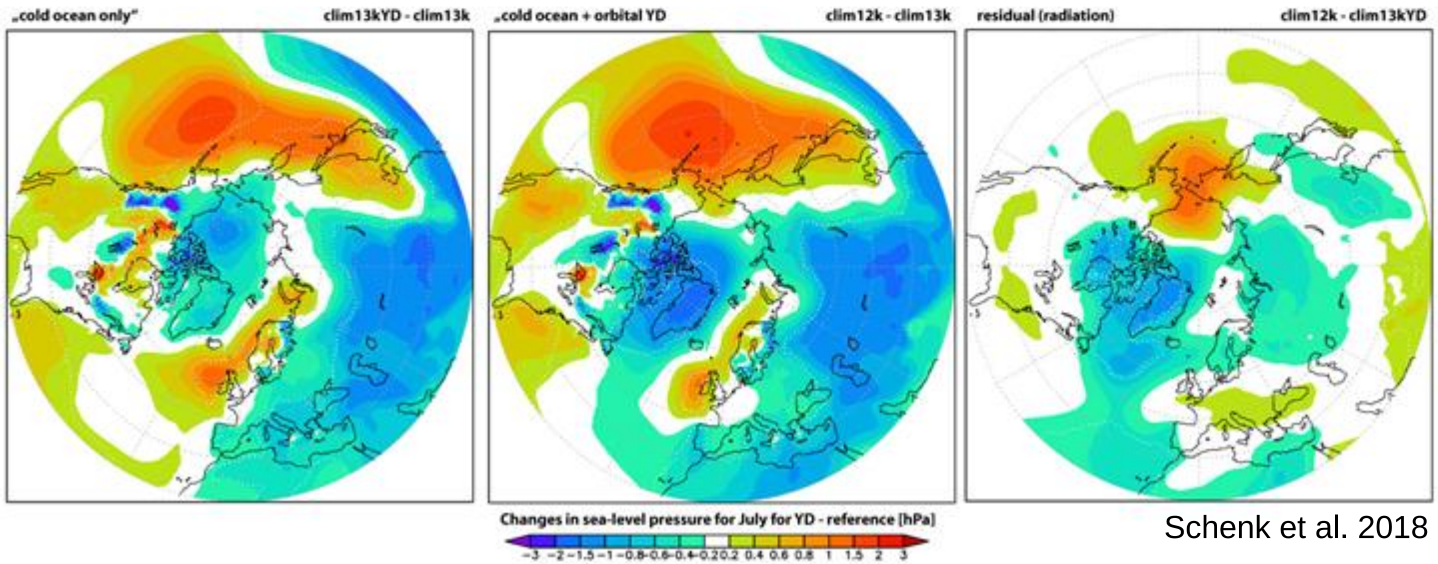
SMHI

westerlies = cold **blocking = warm** **westerlies = cold**



Schenk et al. 2018

Δsea-level pressure in response to strong North Atlantic Ocean cooling



Schenk et al. 2018

(1) a very cold North Atlantic Ocean increases blocking by high pressure during summer (left)
(2) increasing solar/orbital forcing during summer weakens this effect (middle)

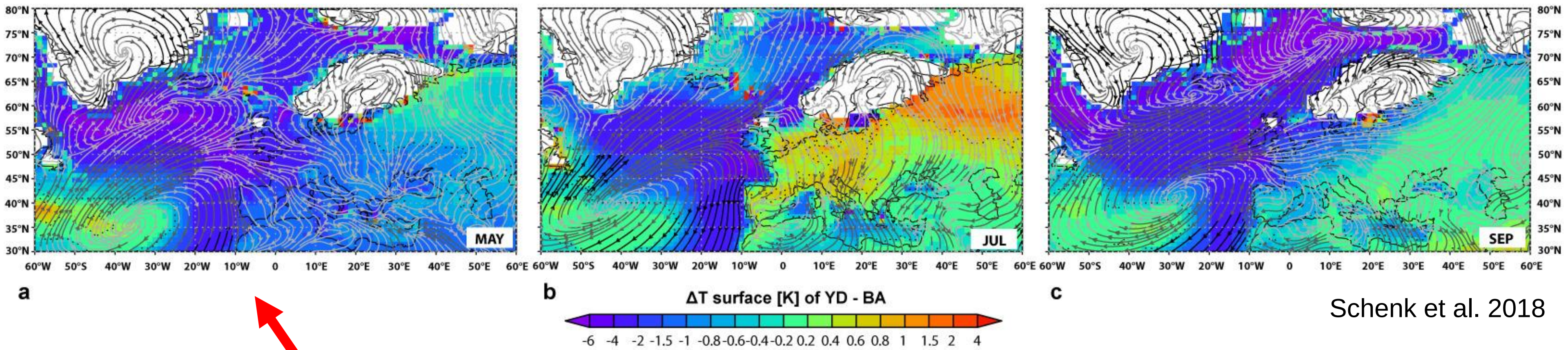
stronger ocean cooling causes warmer summers

Proxy-Model-Comparison

Summer temperature reconstruction for Europe
→ compare response to the *warming hole* with climate model
= response to weak AMOC in the past

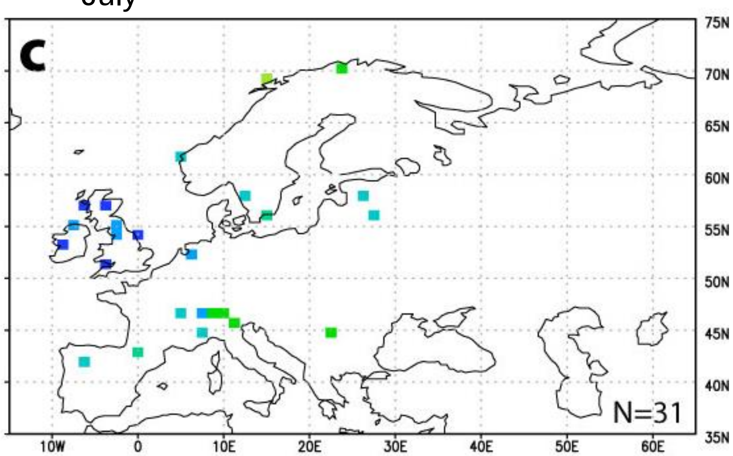
ΔT_{July} in response to ΔAMOC for stadial vs. interstadial

SMHI



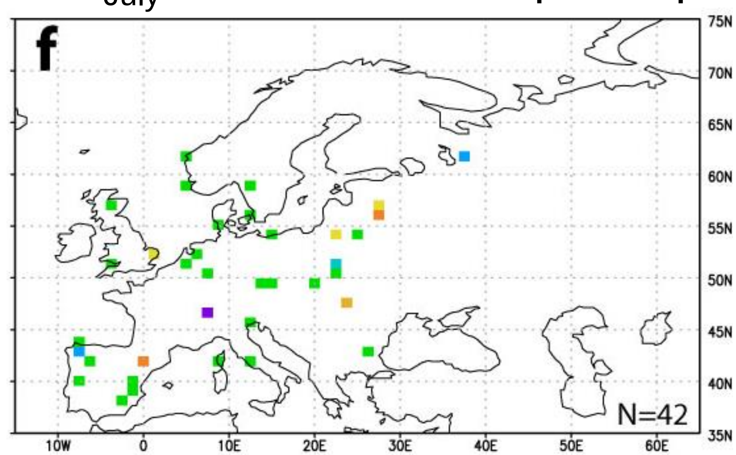
Schenk et al. 2018

ΔT_{July} chironomid data



pattern & values fit cold ocean + westerlies

ΔT_{July} climate indicator plant species

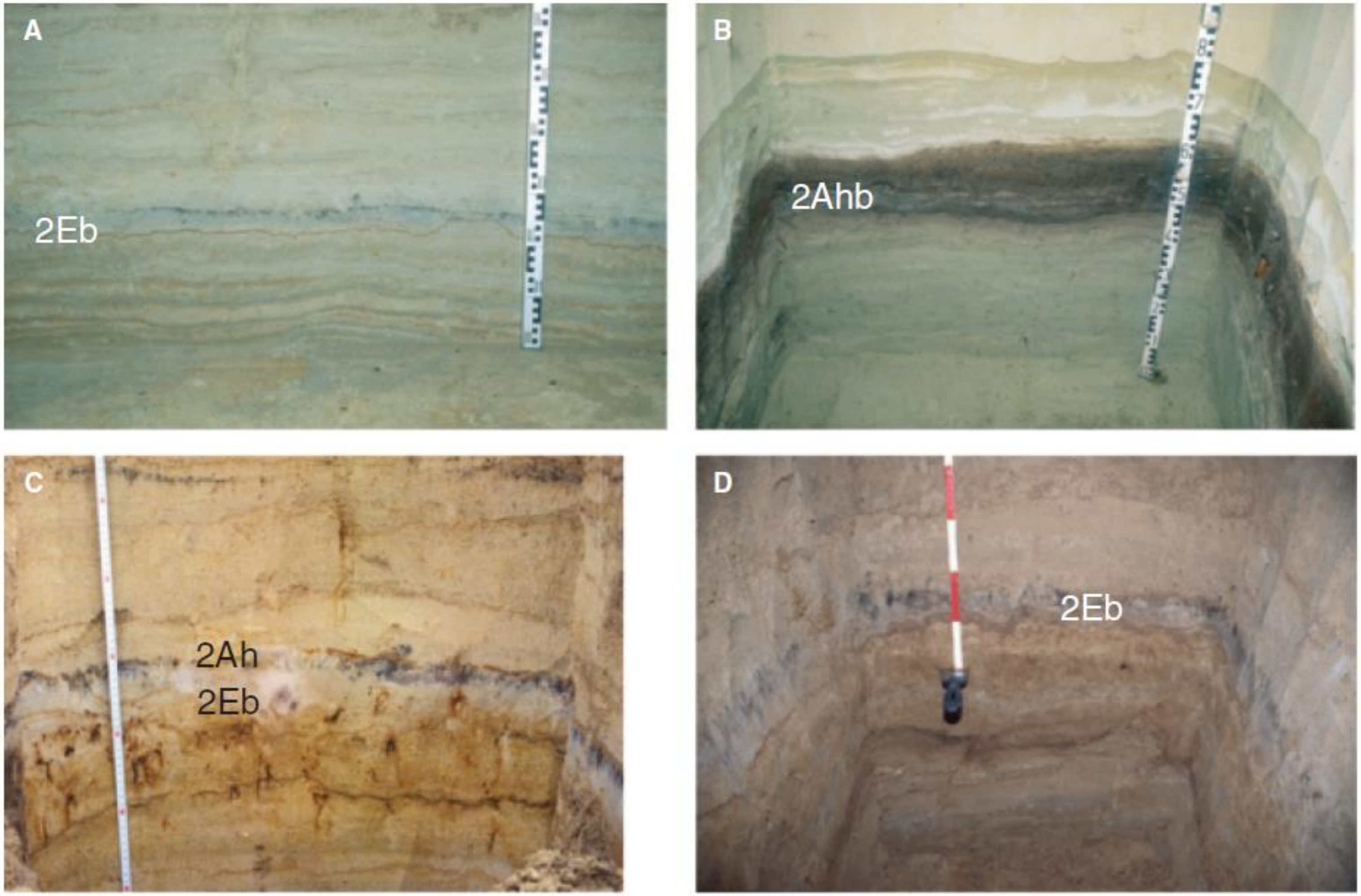


pattern represents warm summers + no westerlies

What about heatwaves and droughts?

Limitation: Proxy data typically reflects only mean states

Usselo soils – very dry & fires in the Netherlands/Belgium AL/YD

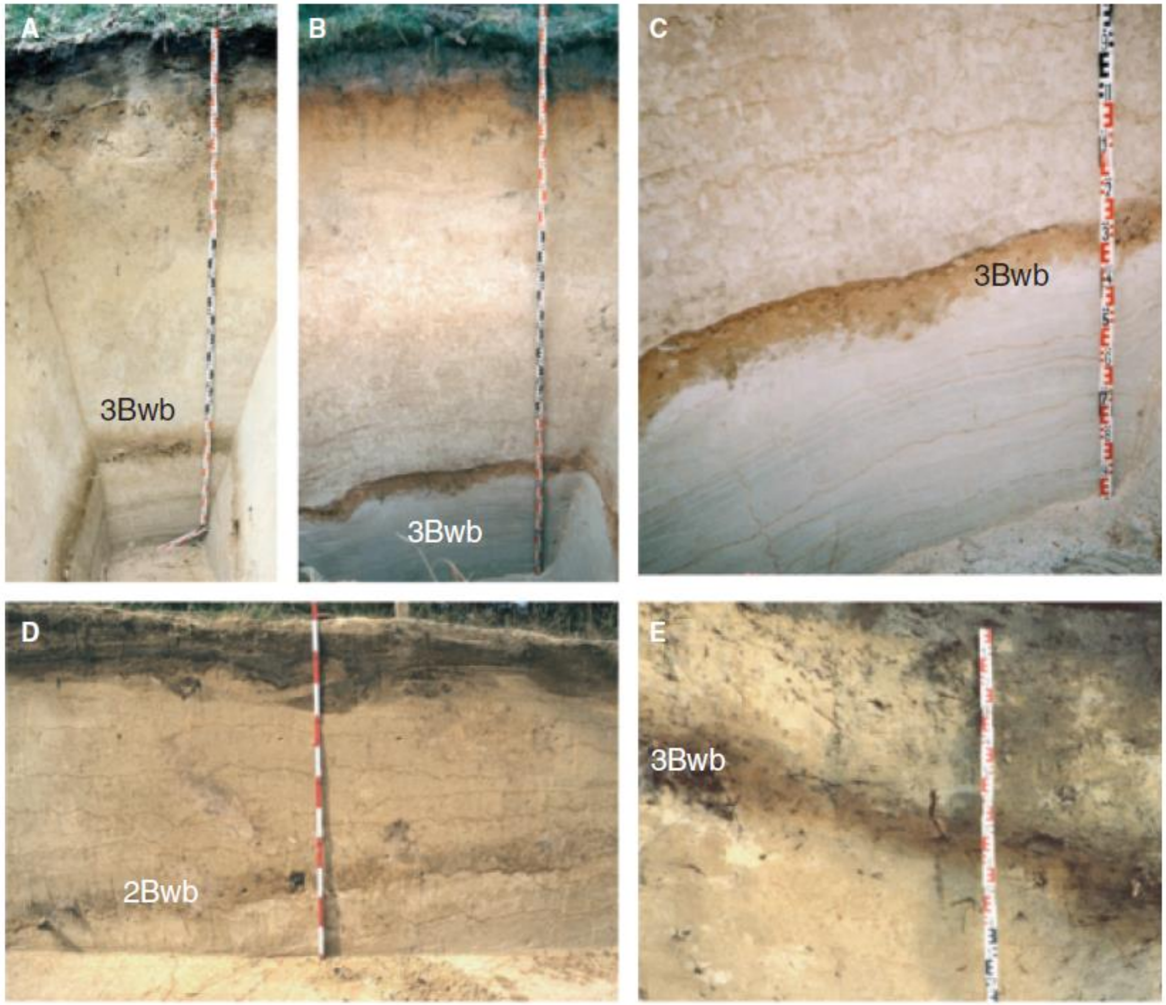


Kaiser et al. (2009), Boreas

Wind blown sand layers with high charcoal content (= dry + fires)

Finow soils – very dry & fires in N-Germany and Poland AL/YD

SMHI

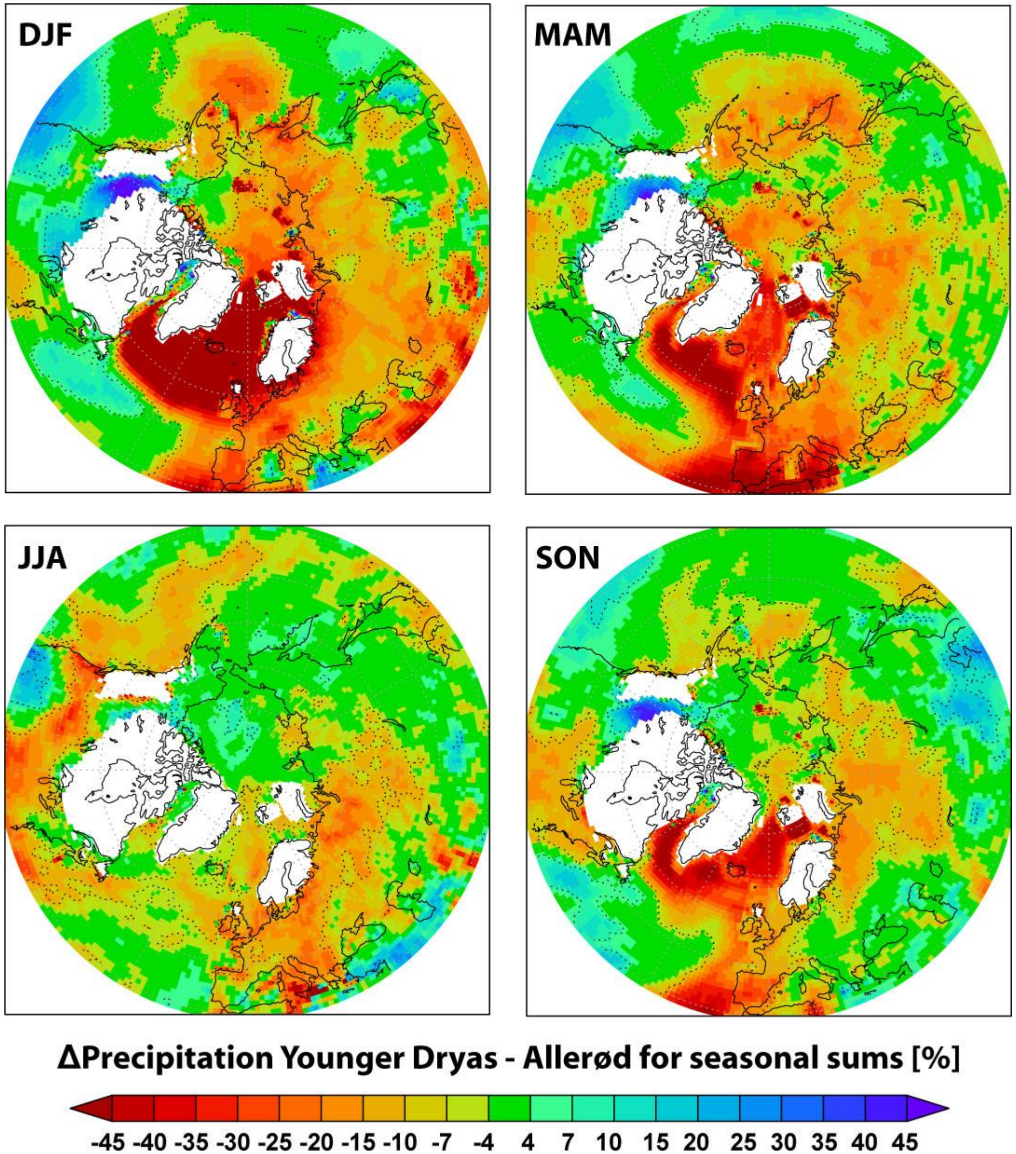


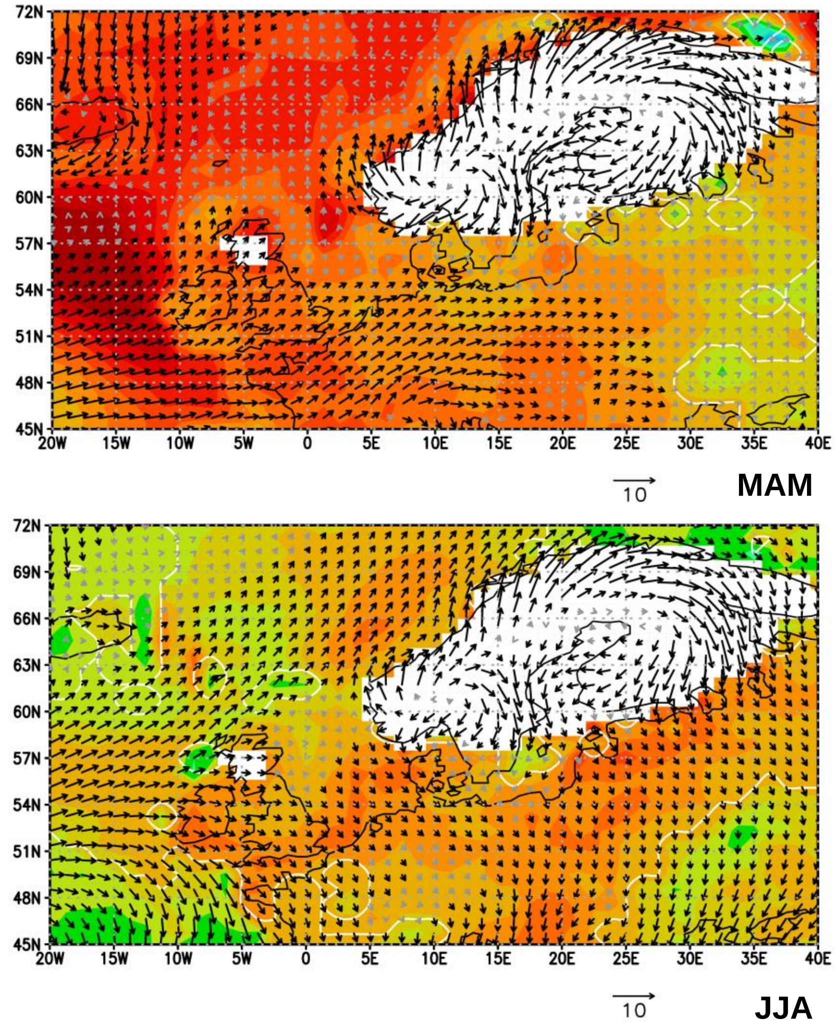
Kaiser et al. (2009), Boreas

Wind blown sand layers with high charcoal content (= dry + fires)

ΔPrecipitation [%] simulations – YD stadial gets very dry

Schenk & Wohlfarth 2019



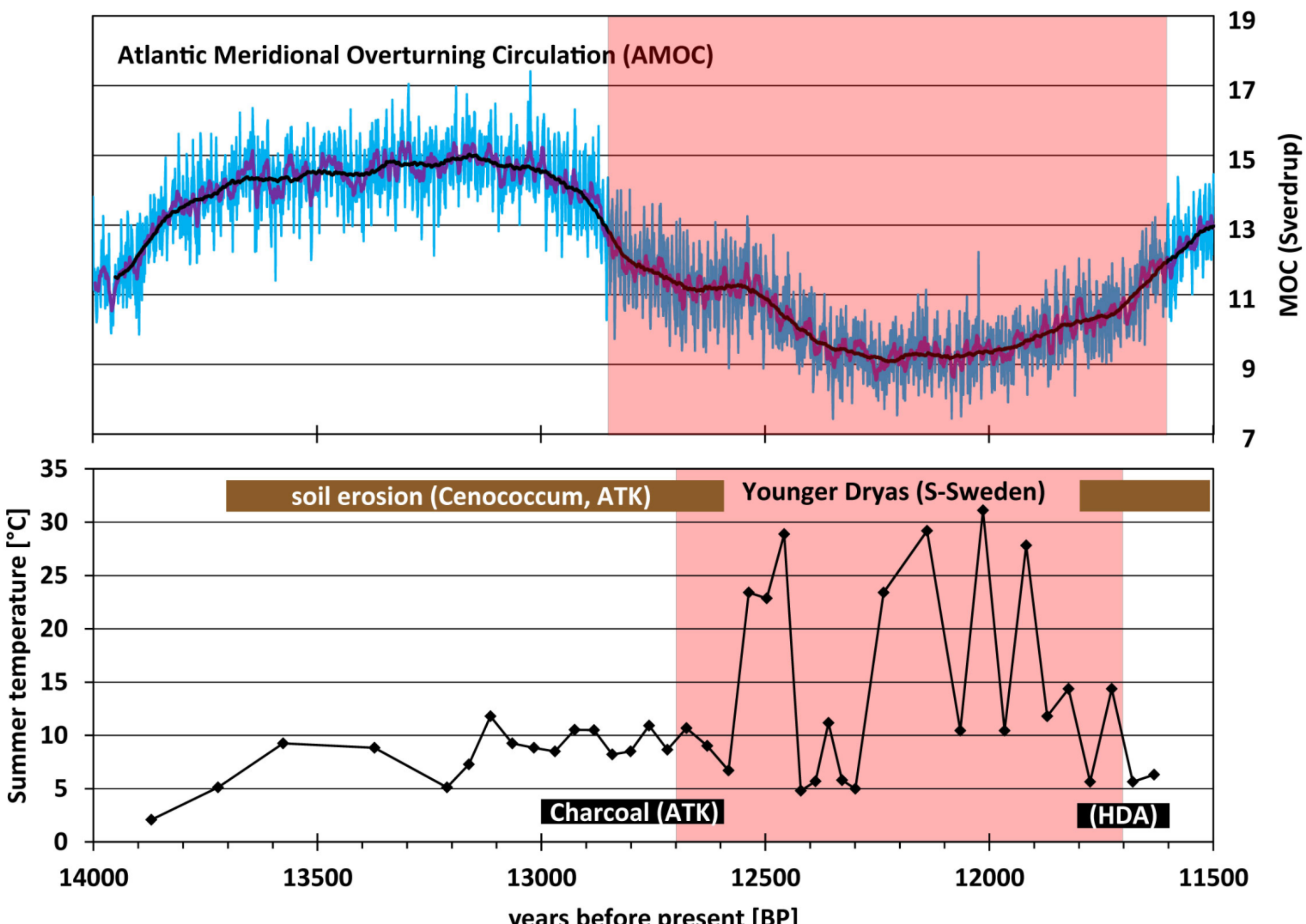


consistent with hydroclimate proxies

Weak AMOC as a cause for paleo-heatwaves/droughts?

SMHI

Ongoing research! (Schenk et al., unpublished)



Ongoing research:

- a new paleothermometer proxy (brGDGT) shows very warm spikes during a very weak AMOC period
- possible explanations: either very warm summers (heat waves) or erosion (droughts?)

Part 4
Summary

General summary and reflection on RA5 research topics

SMHI

Climate system: always tries to balance incoming/outgoing energy (± fails)

Last ~11,700 years (Holocene) have been unusually stable

- still large changes i.e. in summer orbital forcing over northern hemisphere
- relatively small changes in greenhouse gas concentrations
- system had enough time to respond to *transient climate change*

  → not too many bad things happen (of epic geological dimension)

  Historical timescales (~500 to 1000 years)

  → already small variations had negative impacts on human societies

Last ~40 years with unusually rapid warming

- driven by anthropogenic emissions of greenhouse gases (± epic dimension)
- regional to continental-scale extreme events appear to increase
- difficult to explain:
  - statistically: not enough data, time series usually too short
  - physically: limited understanding, models are „conservative“

Paleoclimate as part of Earth Sciences allows studying past extreme states

- Multi-proxy climate reconstructions & climate modelling

Historical/Holocene: transient change = ± stable
Deglaciation: strong + rapid ΔT_{Earth} → abrupt Δclimate/ecosystem

Main difference Holocene vs. Deglaciation (or Pleistocene)

Holocene = transient changes (but e.g. spikes in storminess and peat records)

Glacial climate = abrupt changes and instabilites (i.e. ice sheets & ocean)

Abrupt climate shifts during Deglaciation

External forcing: gradual increase in summer insolation and GHG during Lateglacial

Climate response: abrupt shifts between warm and cold climate states

Ecosystem impacts: often catastrophic (no time to adapt or migrate)

= non-linear response of the climate system to gradual forcing

= rate of change from one state to a new state >> Δexternal forcing

→ makes the ongoing rapid warming increasingly dangerous and unpredictable

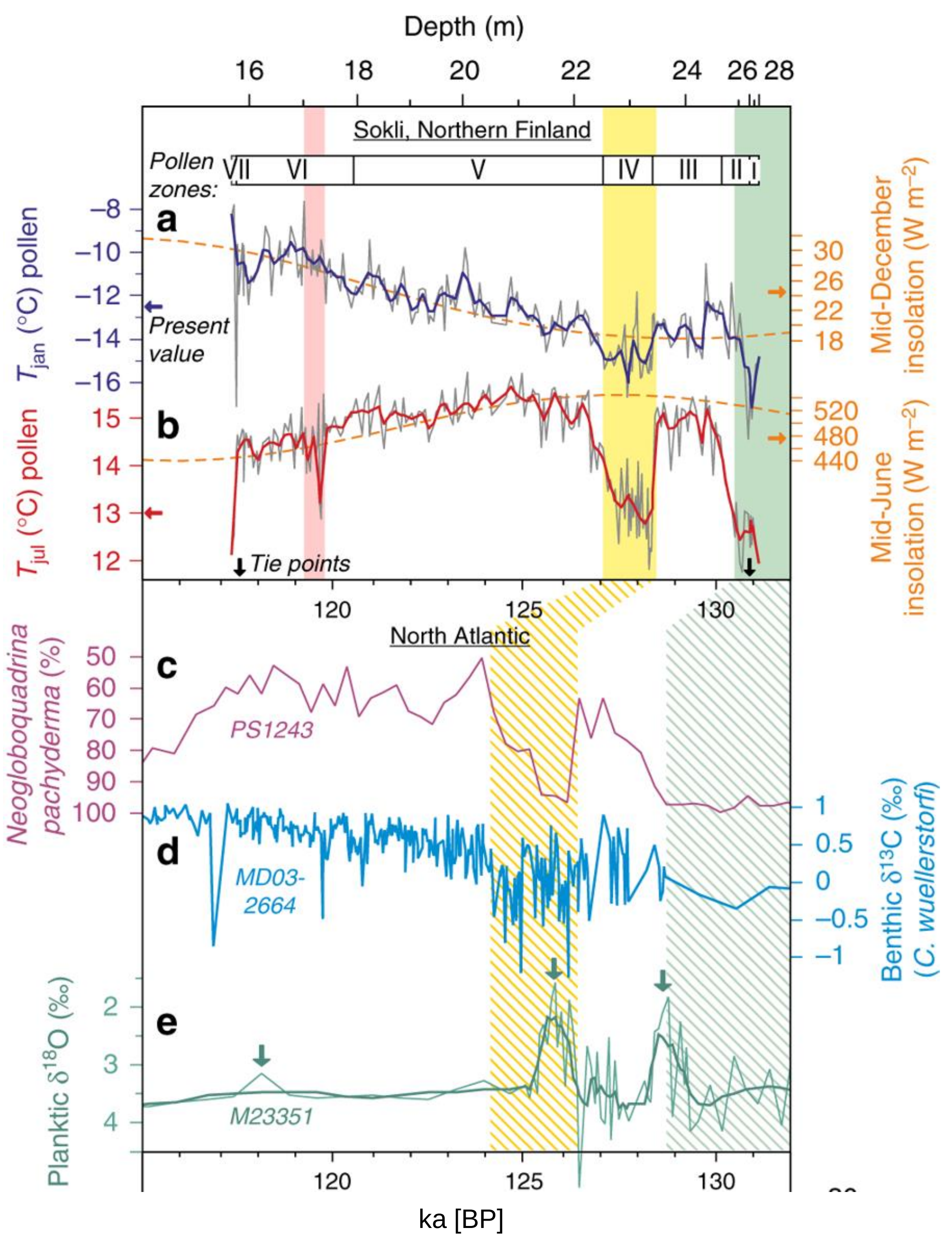
→ are our climate models fit to predict future warm states? Evaluate for past states

Typical explanations:

tipping points, non-linear responses and/or positive feedbacks

→ AMOC slowdown and abrupt increase of extreme events is only one possibilty

Geological perspective – unstable AMOC when it is warmer?
Climate instabilities also during the Eemian…



AMOC and climate instabilities not limited to late-glacial conditions

→ abrupt ΔAMOC also during warmer than today climates

→ AMOC disturbance without glacial meltwater

→ AMOC might be also instable under (too) warm climates?

Solonen et al. 2018
(several more events: Tzedakis et al. 2018)

Further reading

(1) How do we know that the Gulfstream (AMOC) is slowing down already? How can we see this in surface ocean temperatures?
→ e.g. Rahmstorf et al. 2015; Caesar et al. 2018; Thornally et al. 2018

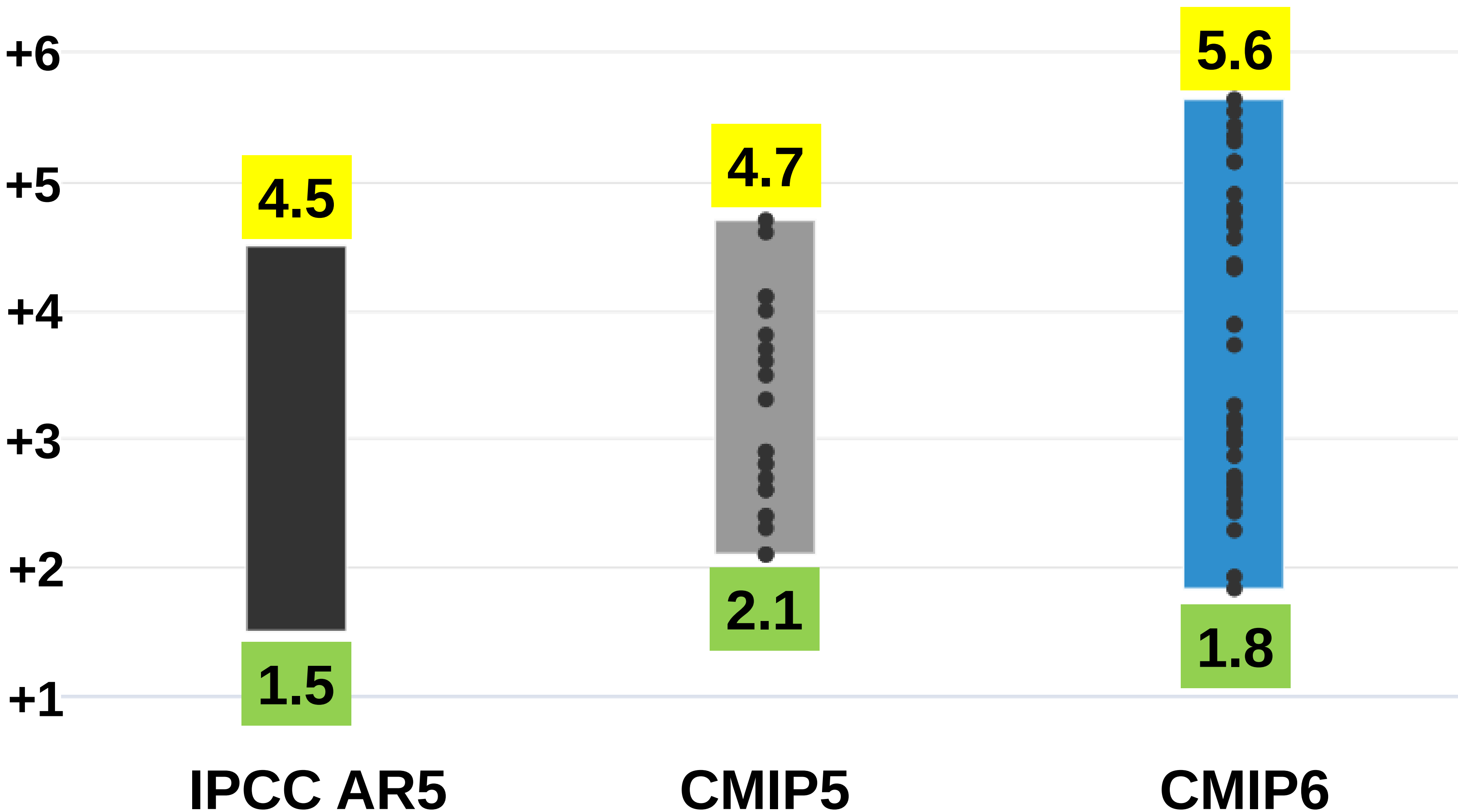
(2) What is the expected impact of a weakening AMOC on the European climate (past, present, future)?
→ e.g. Haarsma et al. 2015; Drijfhout 2015; Schenk et al. 2018

(3) An alternative explanation for why future summers might look like 2018.
→ Coumou et al. 2018

(4) Do some own research!
→ e.g. google "*warming hole*" (cold blob) and see what others think about it

In case of questions or if you cannot access a publication:
frederik.schenk@smhi.se

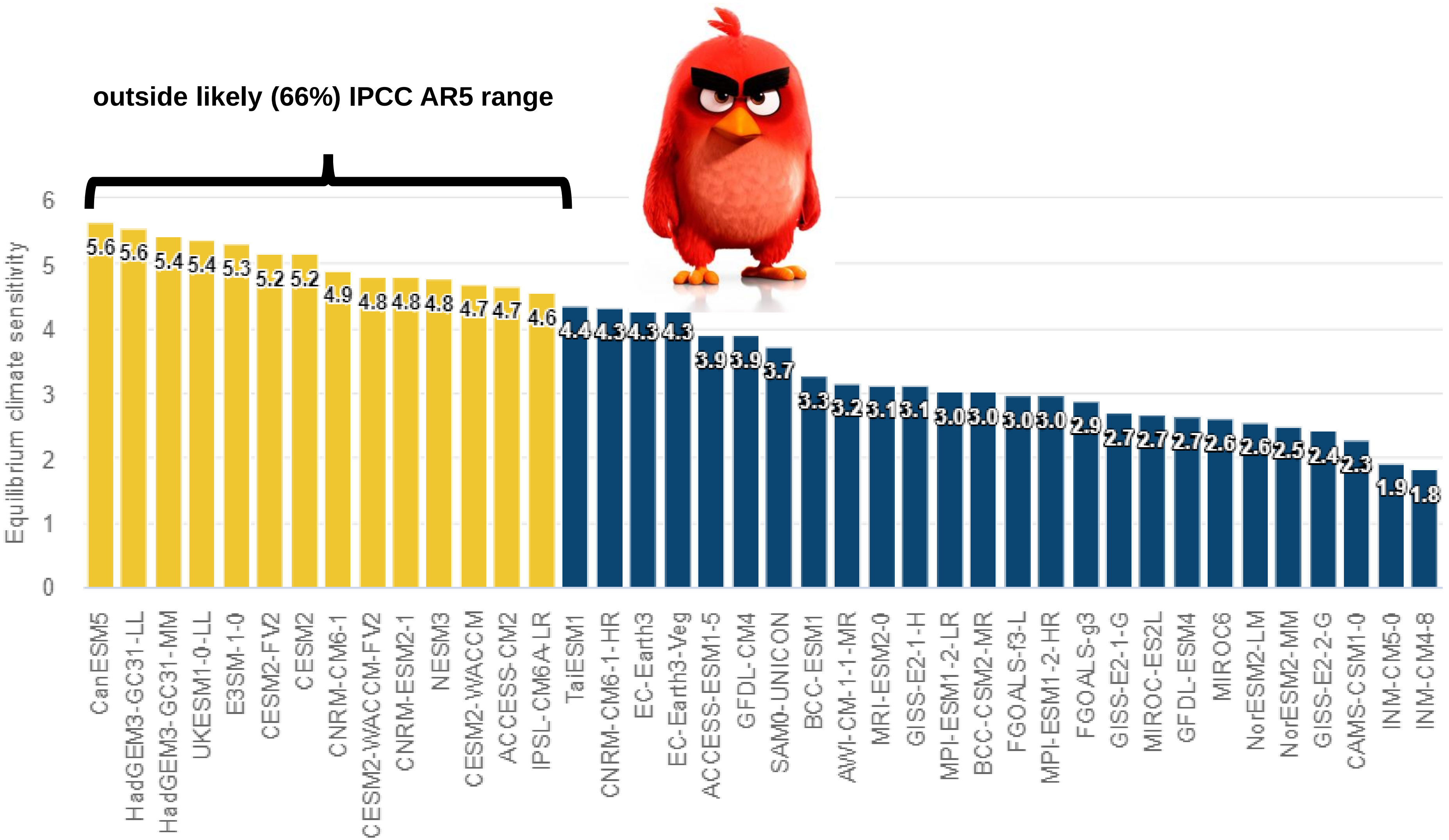
Equilibrium Climate Sensitivity – how much does Earth warm with 2x CO_2?



Zeke Hausfather, https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained

ECS for the new CMIP6 models (May 2020)

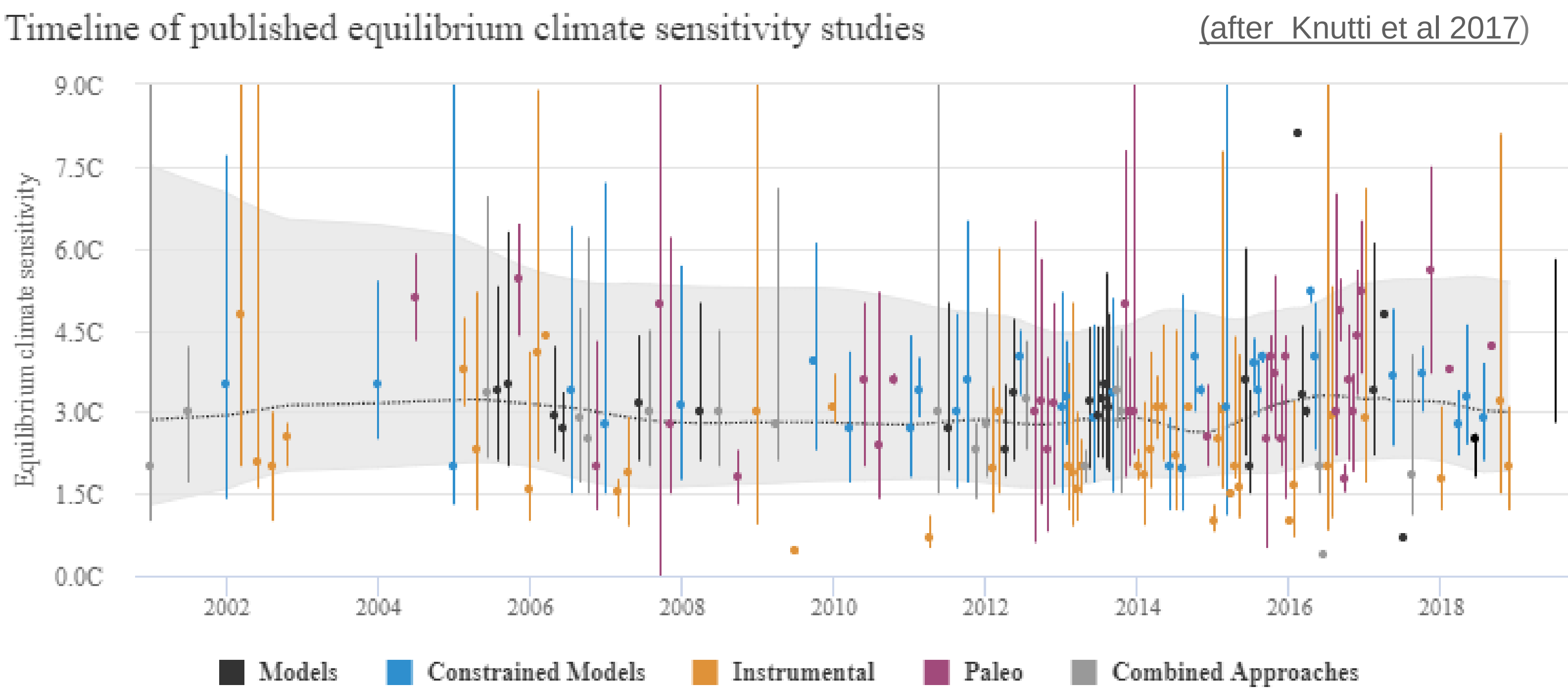
SMHI



Zeke Hausfather, https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained

Models run (too?) hot – paleoclimate studies are very important

SMHI



*…many scientists are skeptical, pointing out that past climate changes recorded in ice cores and elsewhere **don't support the high climate sensitivity**—nor does the pace of modern warming. […]*

*In assessing how fast climate may change, the **next IPCC report probably won't lean as heavily on models as past reports did**, says Thorsten Mauritsen.*

(in: Voosen 2019, Science)