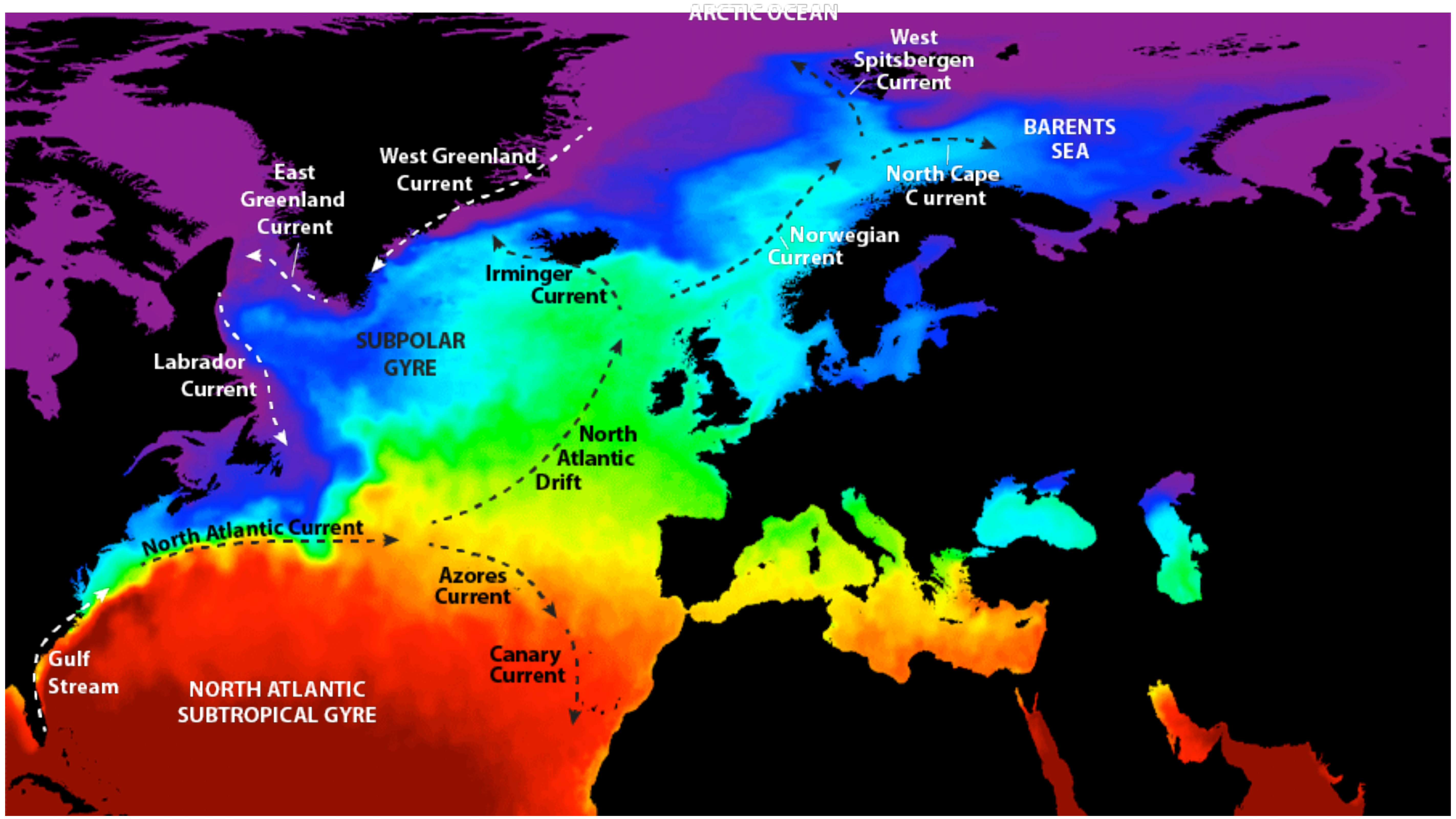
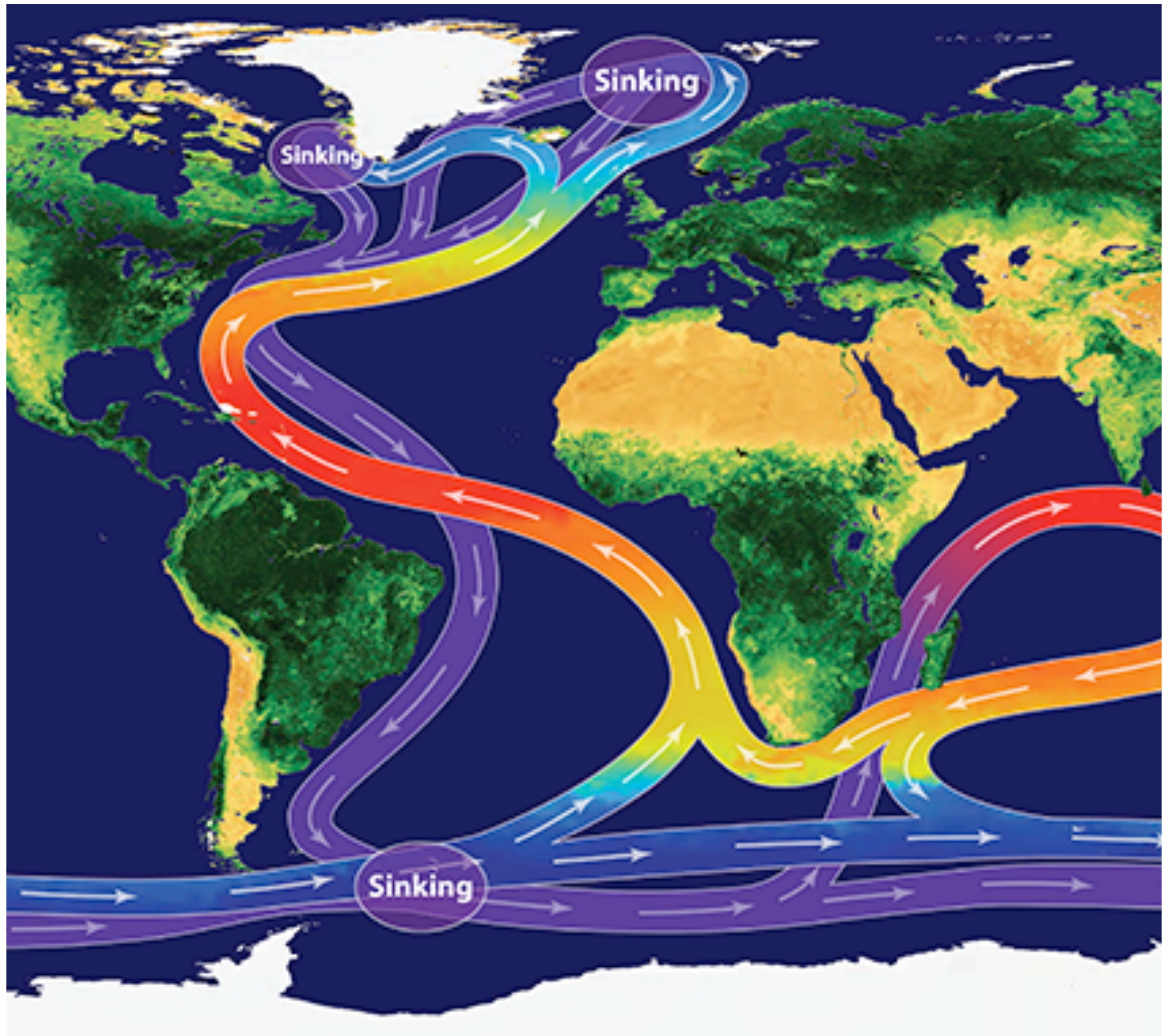
The role of anthropogenic aerosols in recent North Atlantic climate change

Laura Wilcox, Rowan Sutton, Jon Robson, Dan Grosvenor, Dan Hodson, James Keeble, Michael Lai, and members of the ACSIS project





Images from NOC

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LETTER

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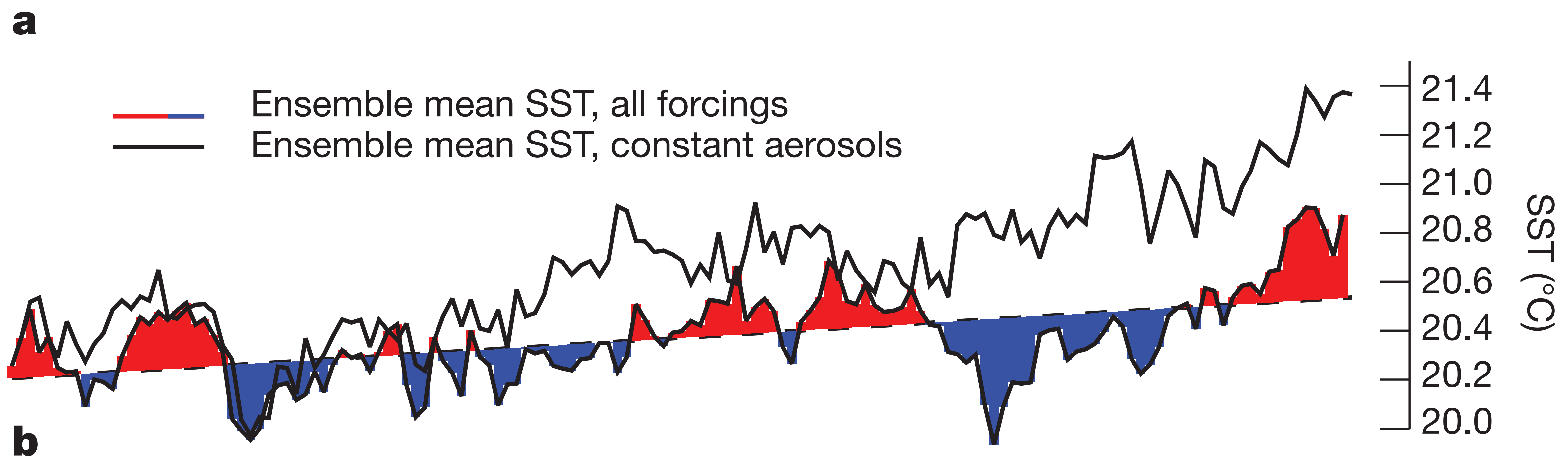
Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability

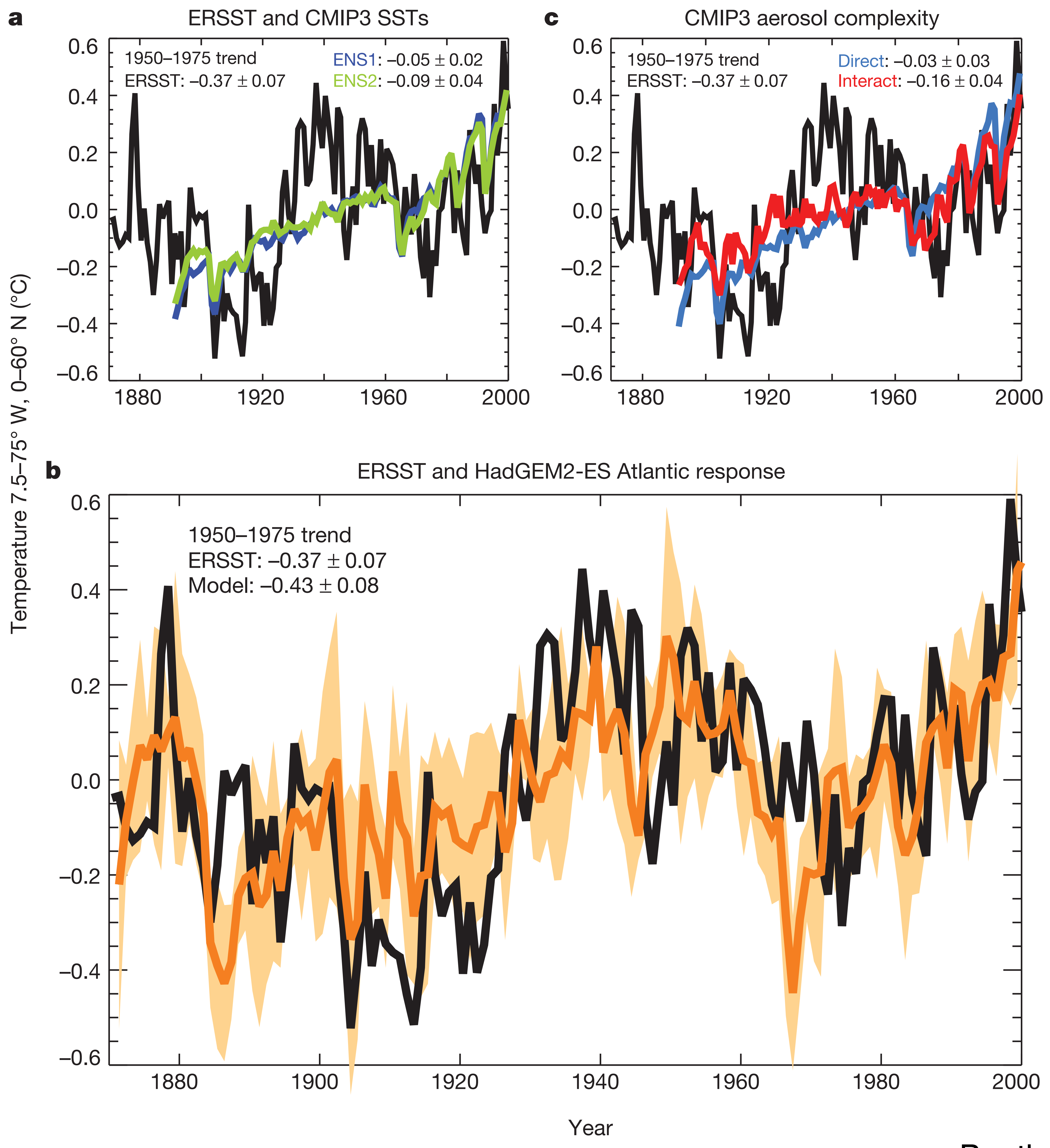
Ben B. B. Booth[1], Nick J. Dunstone[1]*, Paul R. Halloran[1]*, Timothy Andrews[1] & Nicolas Bellouin[1]

Consensus at the time: most variability in Atlantic SSTs due to the ocean's internal variability

CMIP3 models failed to capture SST variability, but it was well described in HadGEM2-ES

Simulations with constant aerosol did not show the same variability



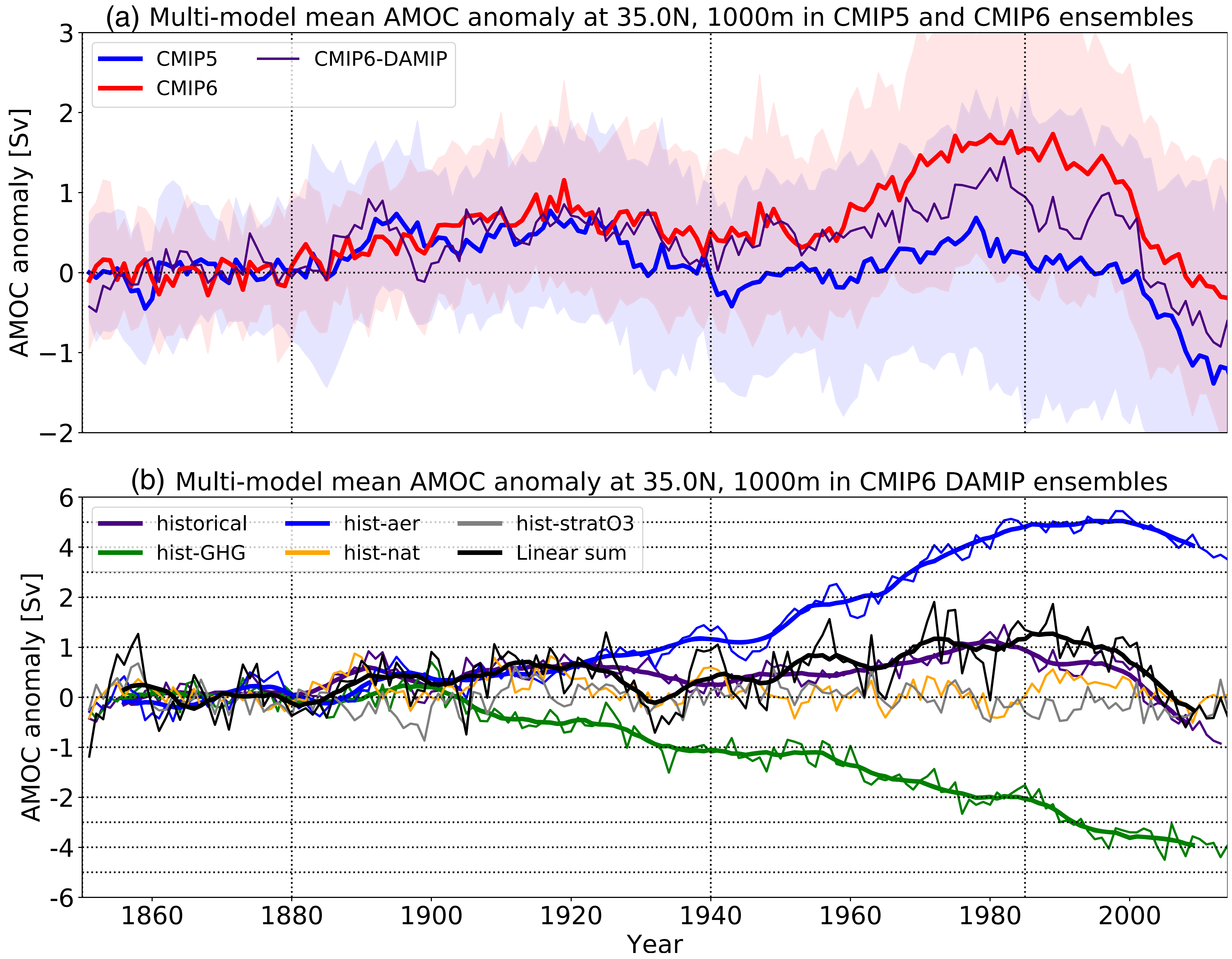


Booth et al., 2012

AMOC strengthens with increasing aerosol in CMIP6

Decadal variability in the Atlantic Meridional Overturning Circulation (AMOC) is influenced by changes in anthropogenic aerosol, but the **extent and mechanism of influence is uncertain.**

Differences between CMIP5 and CMIP6 attributed to differences in the strength of the aerosol forcing. We will come back to this!



Menary et al., 2020

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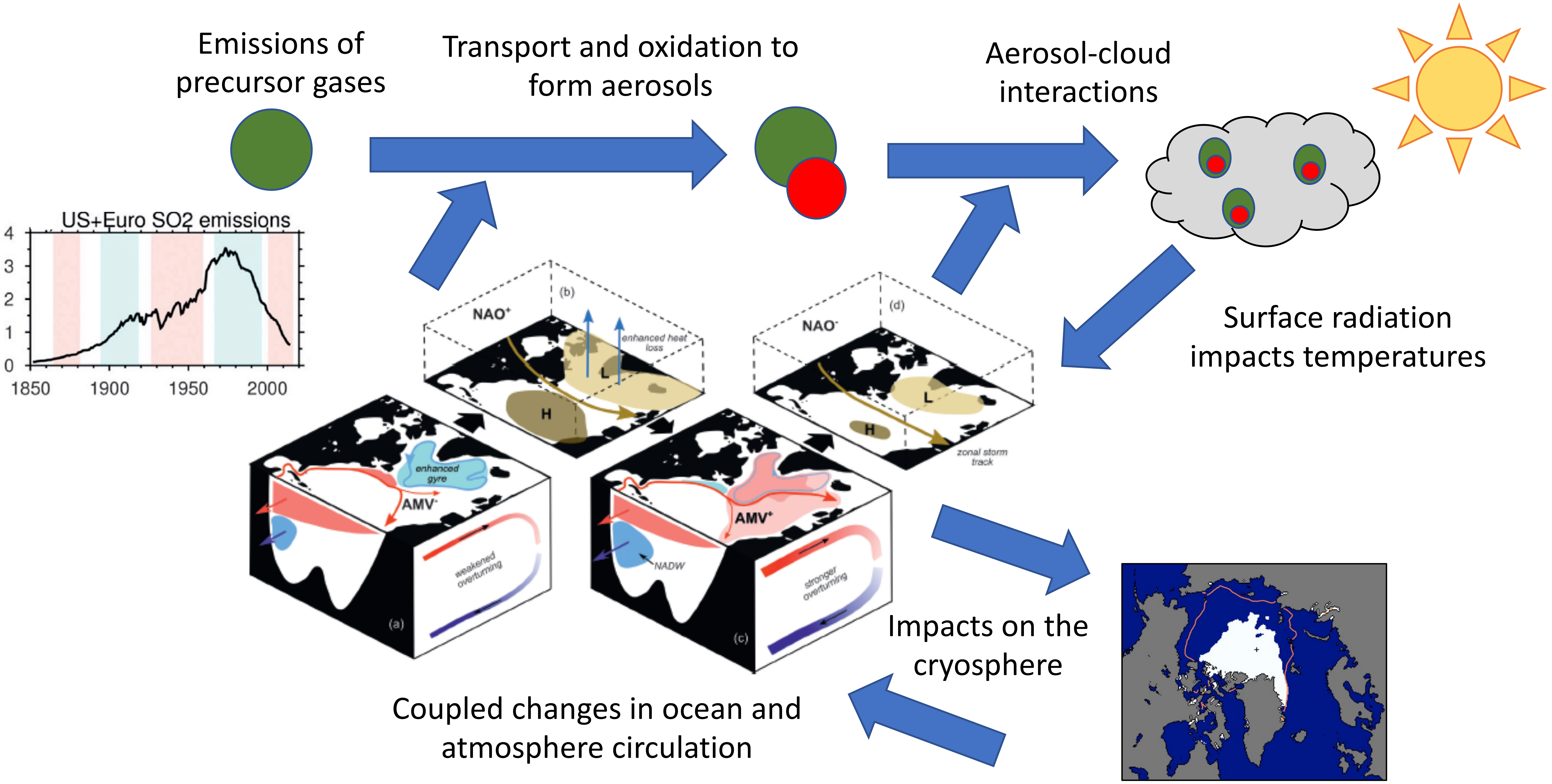
Lots of processes involved in the North Atlantic response to aerosol changes

Complexity an important factor in the uncertainty surrounding the role of aerosol in North Atlantic climate change



Motivation for the recently ended ACSIS project, which funded much of the research shown in this seminar

Sutton et al., 2018

Outline

Overview of the process chain in CMIP6-generation models
- Historical
- DAMIP
- AerChemMIP
- UKESM1 and HadGEM3-GC3.1

Mechanisms for the AMOC response to aerosol changes in CMIP6
- Ensemble mean results
- Model differences to understand processes contributing to uncertainty
- Constraint

A quick look at uncertainties
- Roles for process representation and model sensitivity
- The importance of model resolution

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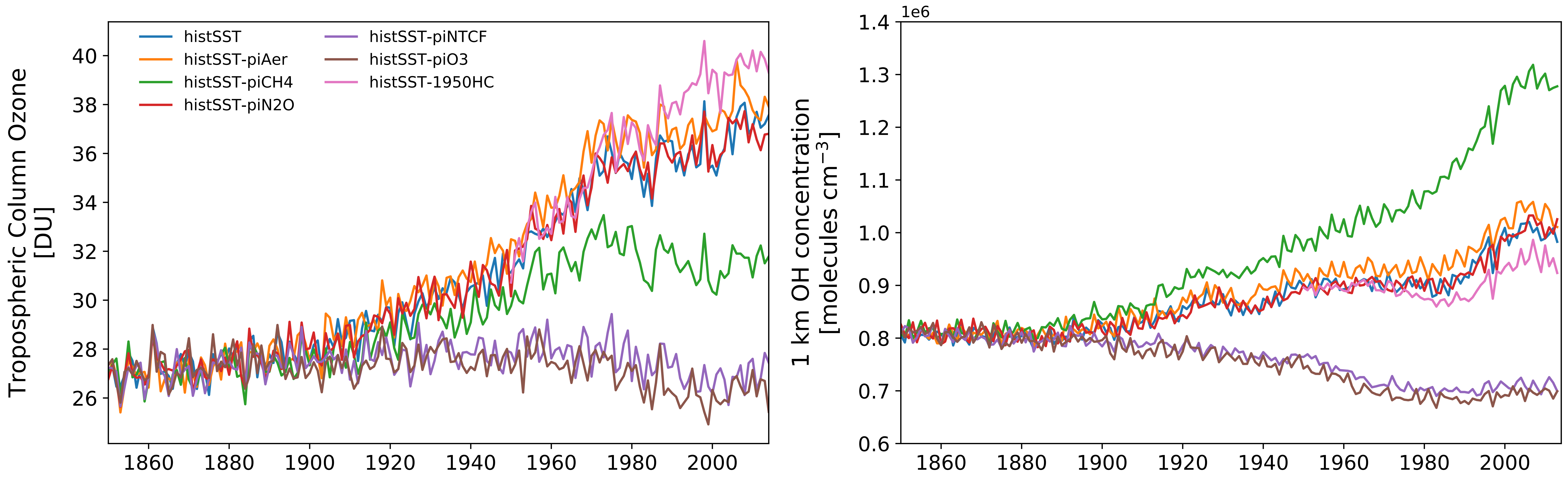
Formation of aerosol and cloud condensation nuclei - the role of oxidants



Formation of sulphate aerosol depends on the emission of aerosol precursors, and oxidants such as ozone

Different oxidants have different effects, e.g.:

- SO_2 interaction with O_3 increases the sulphate content of existing particles
- Gas phase reactions with OH result in new particle formation

histSST simulations enable the effect of different chemical species to be compared, without the effects of different background states (such as cloud distributions)

Wilcox et al., in prep.

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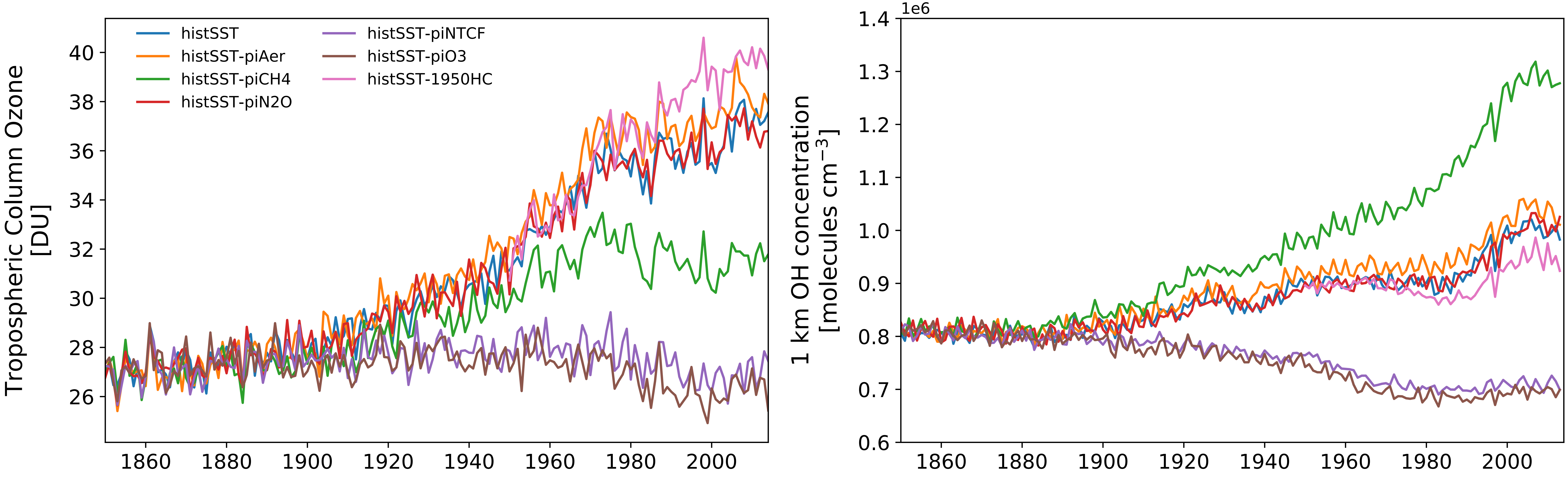

Tropospheric column ozone:

- piNTCF and piO3 show the importance of emissions of ozone precursors to ozone trends
- CH4 also plays an important role
- No influence from aerosol precursors of N2O, while the effects of stratospheric ozone depletion can be seen in 1950HC

Hydroxl radical:

- Similar clustering to tropospheric ozone
- OH rises rapidly when CH4 is held fixed as the OH sink through reaction with CH4 is lost
- When ozone precursors are held fixed, OH concentrations decrease. No ozone increases means that CH4 increases

Wilcox et al., in prep.

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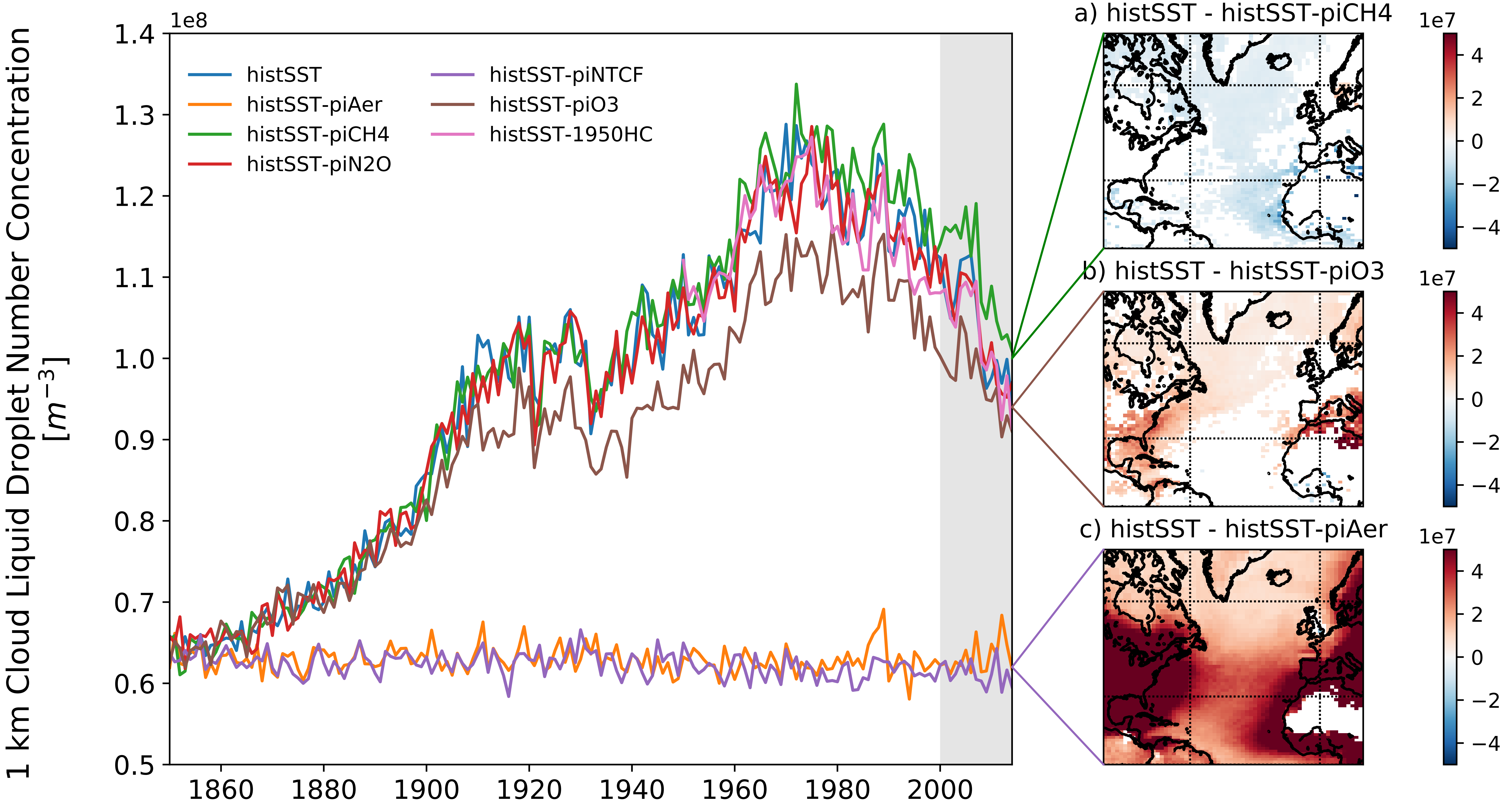
Formation of aerosol and cloud condensation nuclei - the role of oxidants

CDNC increased until the 1970s, before declining

Primarily influenced by emissions of aerosol and other near-term climate forcers

Smaller but marked effect of ozone



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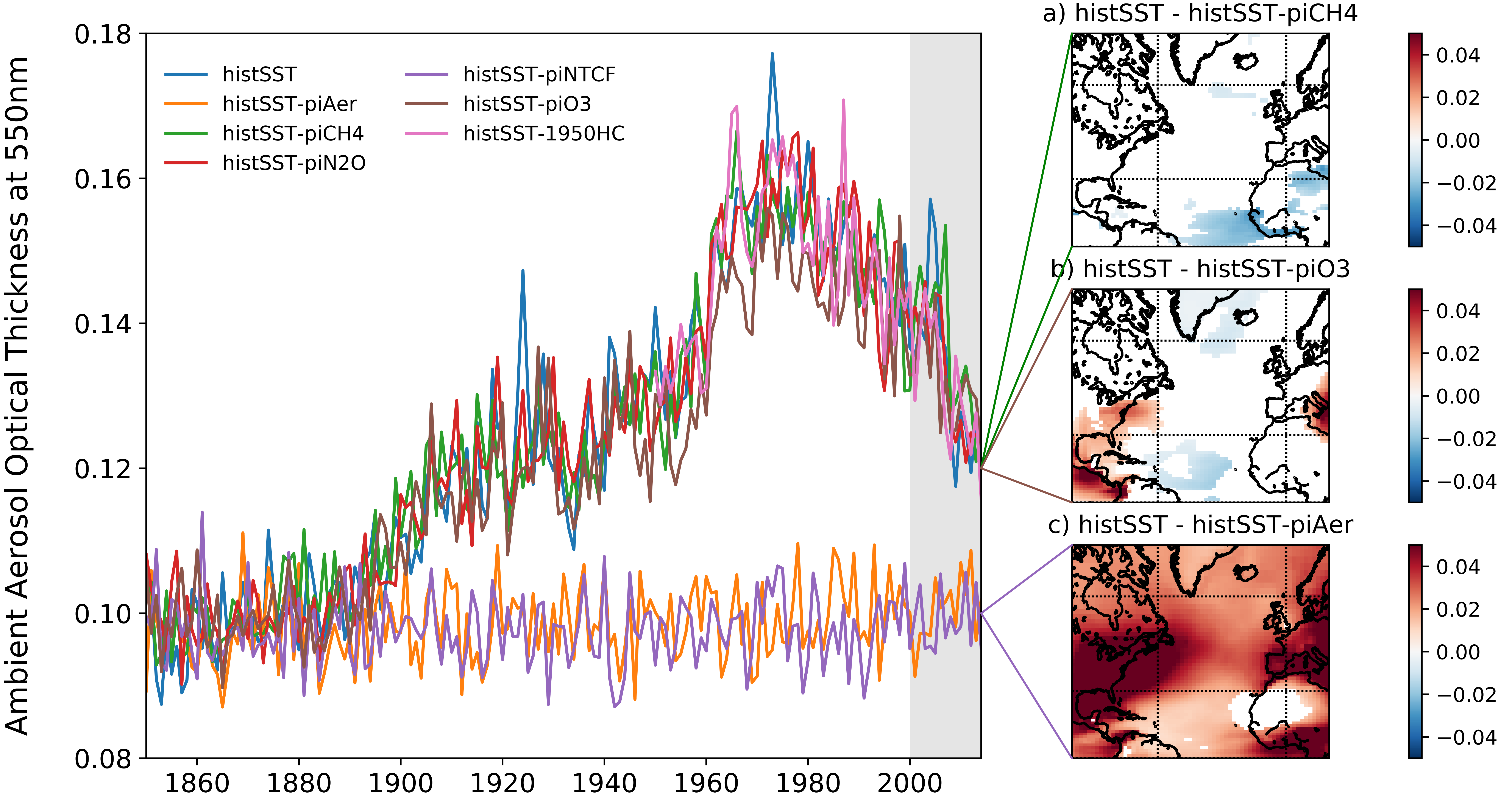
Formation of aerosol and cloud condensation nuclei - the role of oxidants

Influence of oxidants on aerosol optical depth is less clear



Wilcox et al., in prep.

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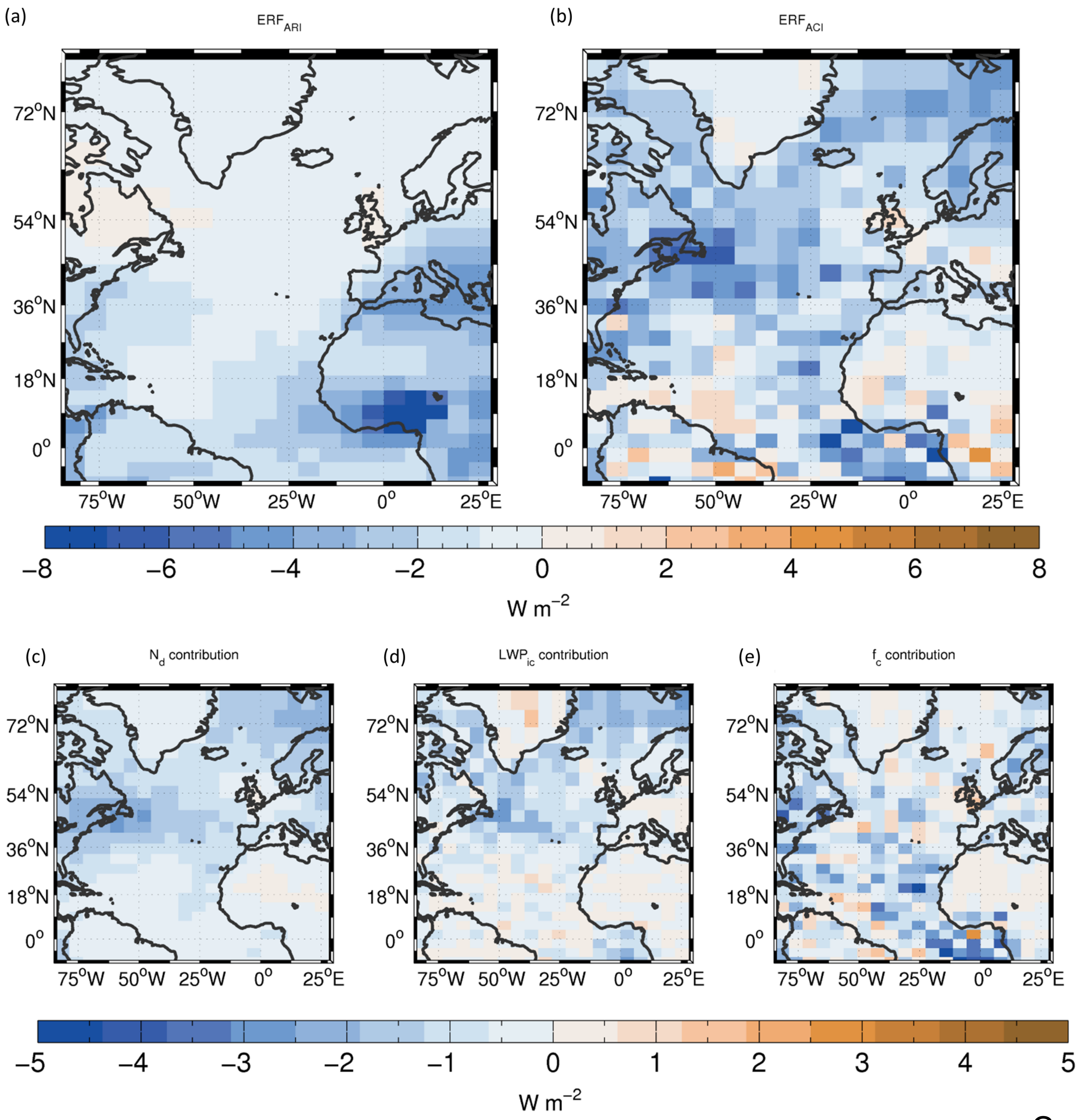
Effective radiative forcing

Aerosol cloud interactions are the main component of aerosol forcing over the North Atlantic. Aerosol radiation interactions more important over Europe and Africa

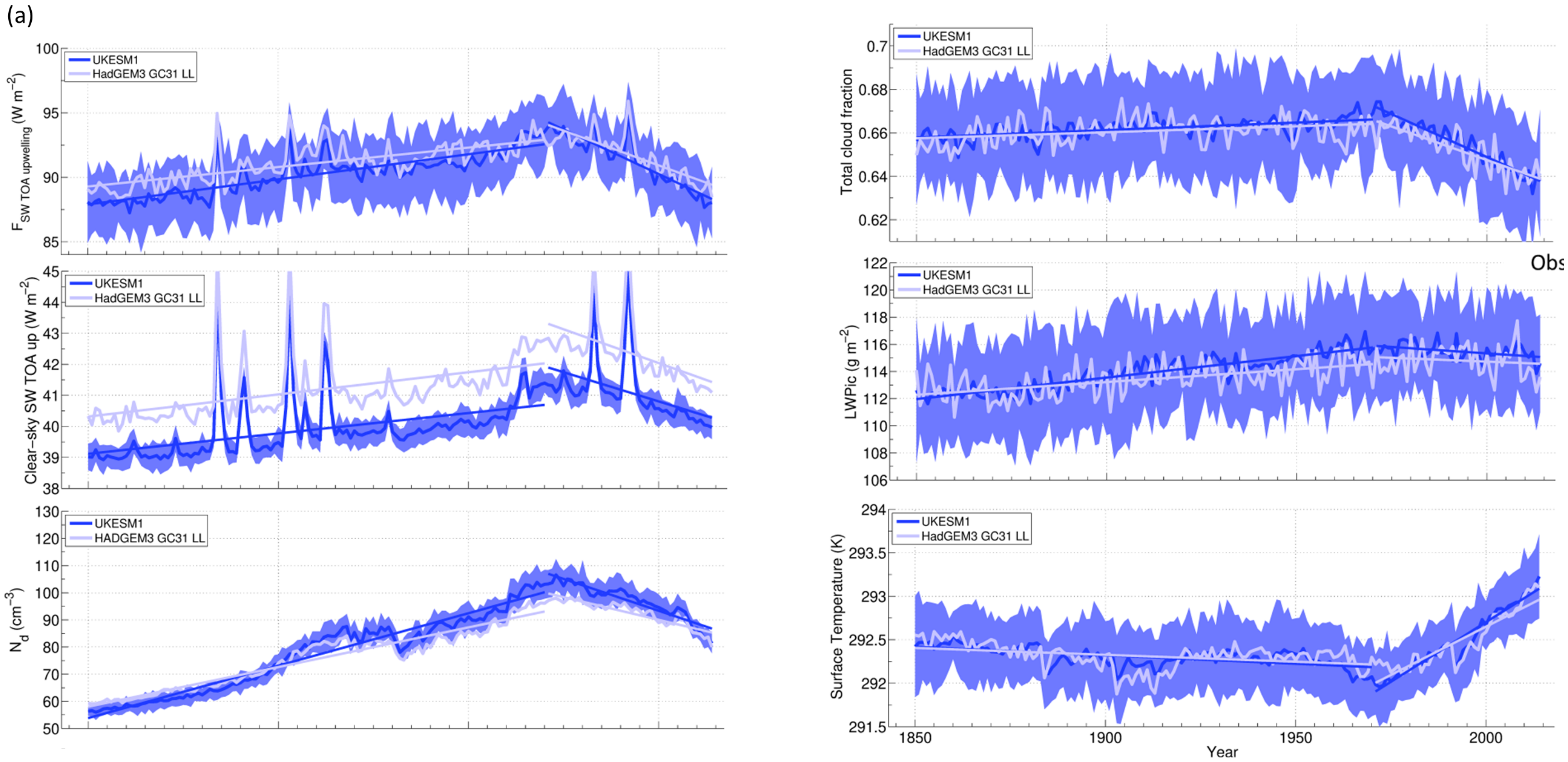
Deconstructing ACI forcing shows contributions from cloud droplet number concentration and liquid water path to be more important in the northern North Atlantic, while cloud fraction changes are more important in the south

Low altitude clouds account for most of the surface forcing



Grosvenor and Carslaw, 2020

Shortwave trends



Shortwave fluxes and surface temperature follow the temporal evolution of AOD and CDNC

CDNC, liquid water path, and cloud fraction also show similar patterns - **difficult to determine the relative importance of driving factors**

Grosvenor et al., 2022

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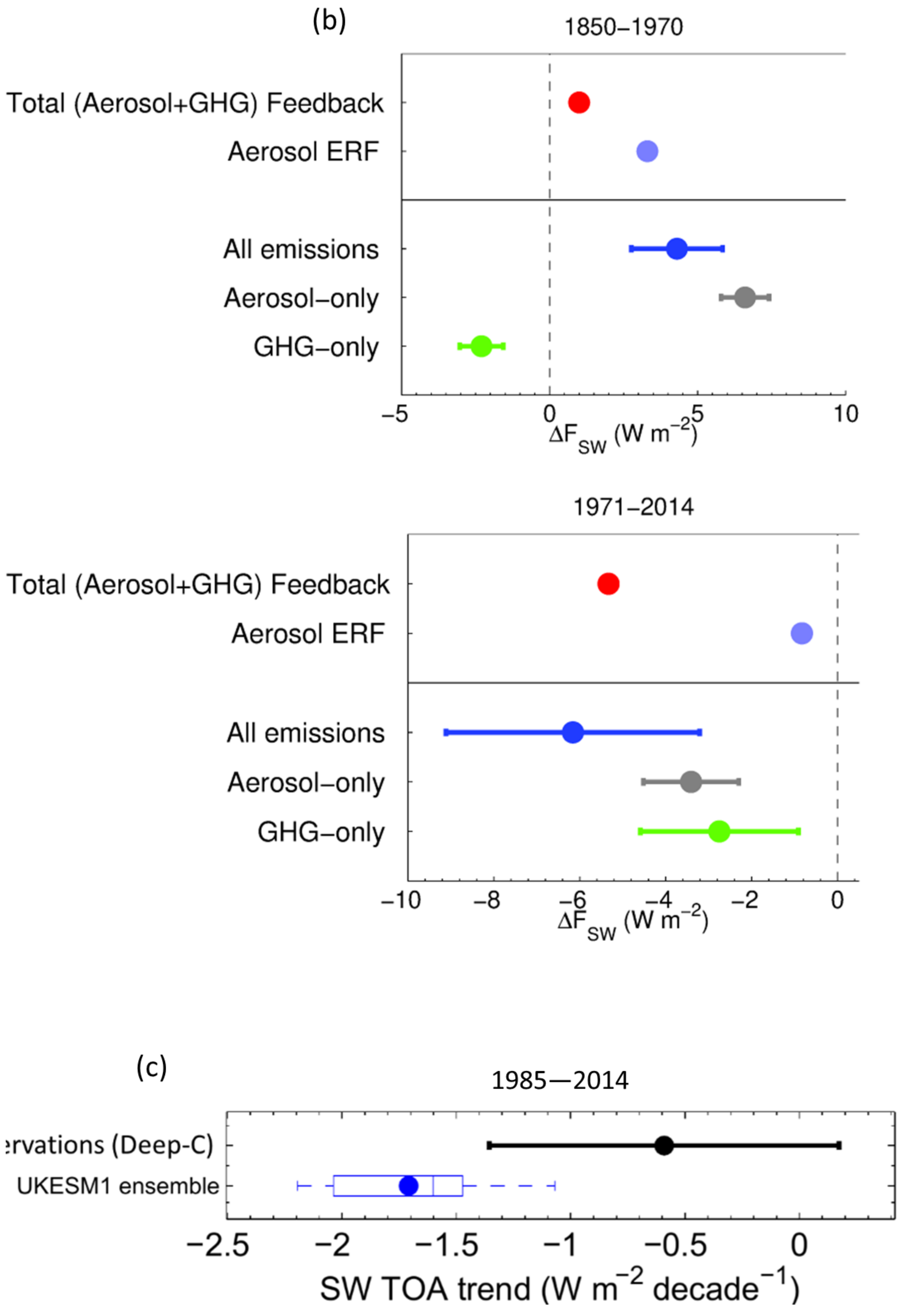
Shortwave trends

Consider two periods: 1850-1970, 1971-2014

Competition between aerosol and GHG prior to 1970, with most forcing due to aerosol

Competition results in small temperature changes, and small cloud changes and feedbacks



Grosvenor et al., 2022

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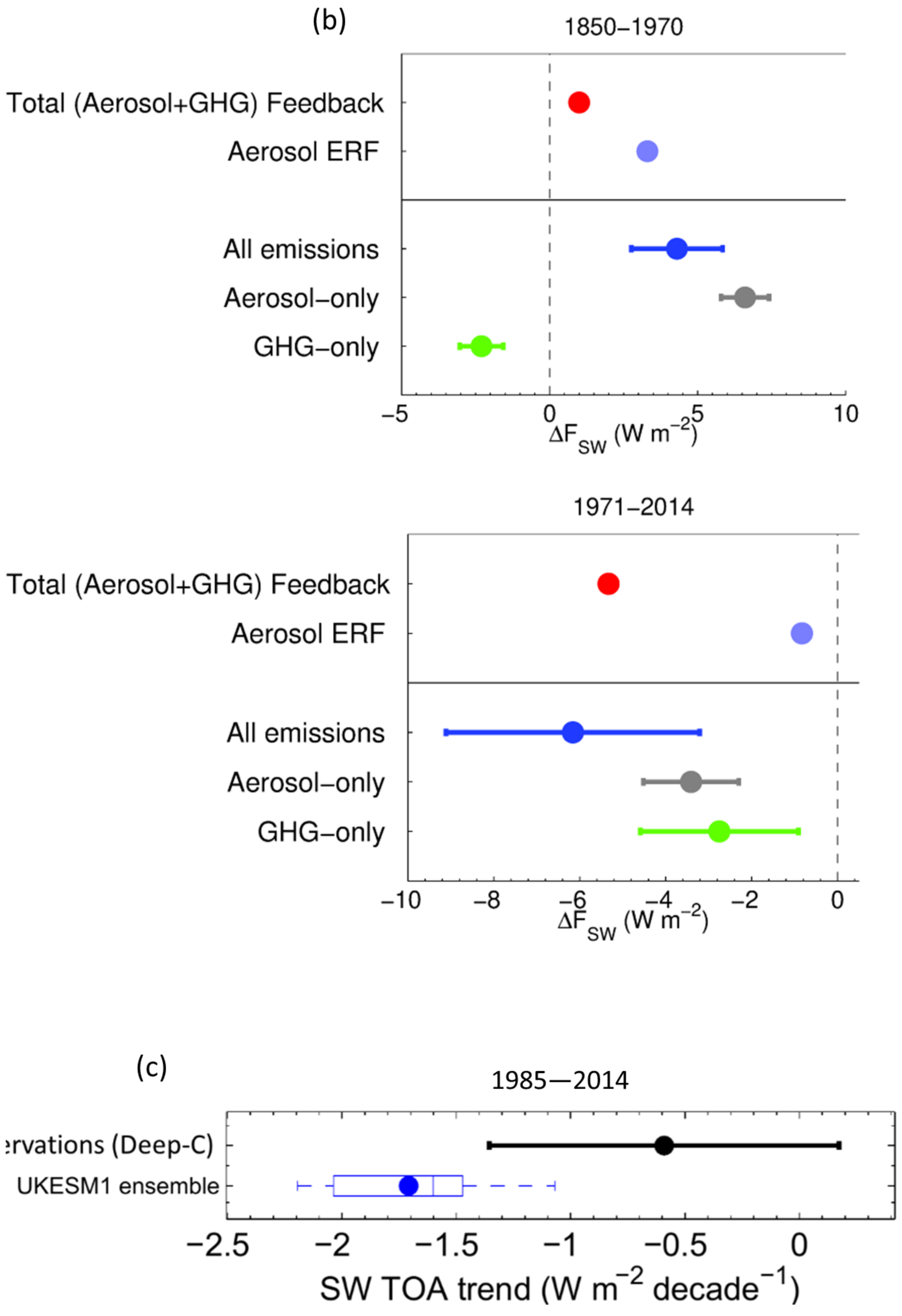
Aerosol and GHG push in the same direction post 1971

Temperature mediated **cloud feedbacks are the dominant driver of shortwave trends**



Grosvenor et al., 2022

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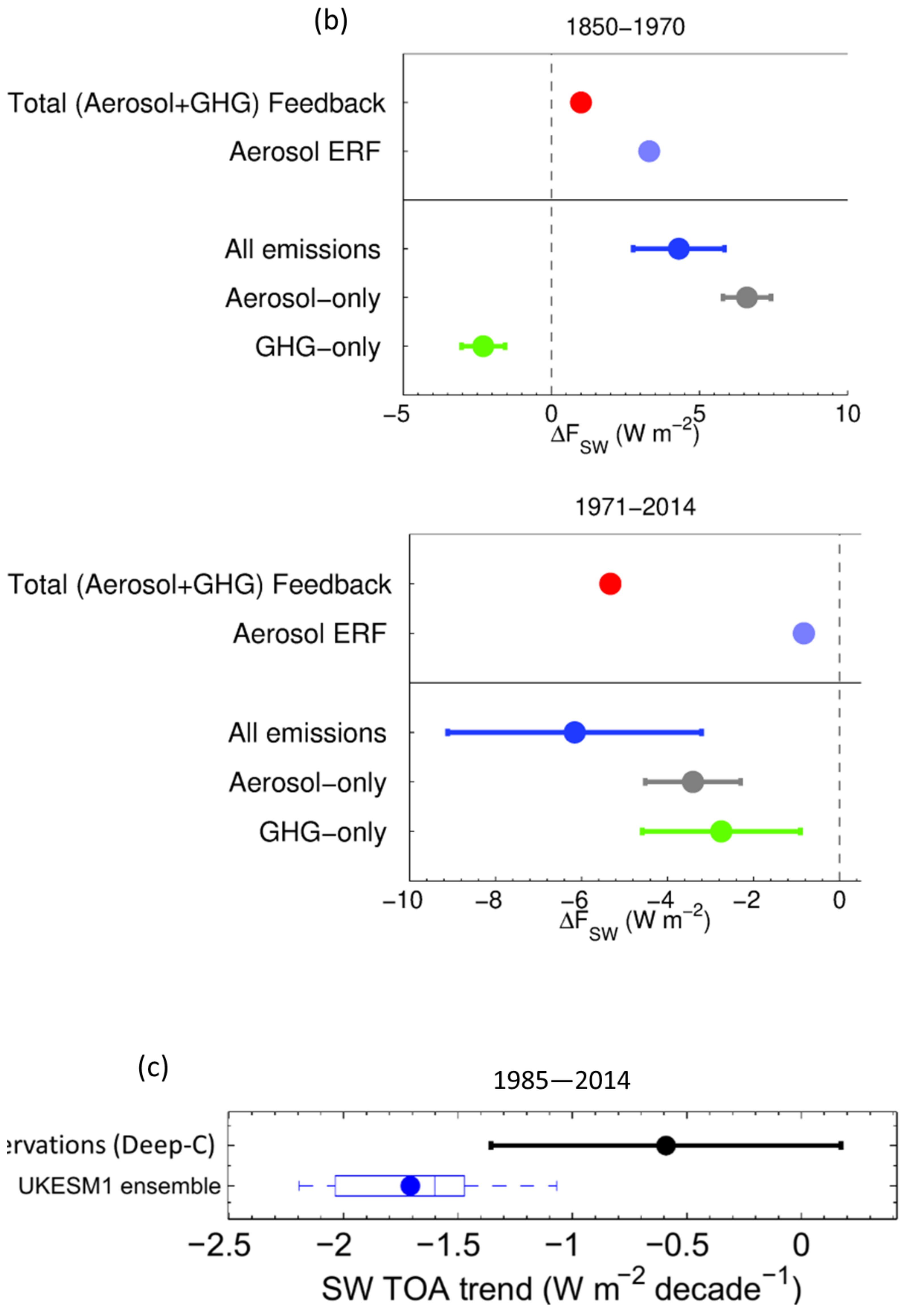
Recent shortwave **trend is overestimated in UKESM1**



Grosvenor et al., 2022

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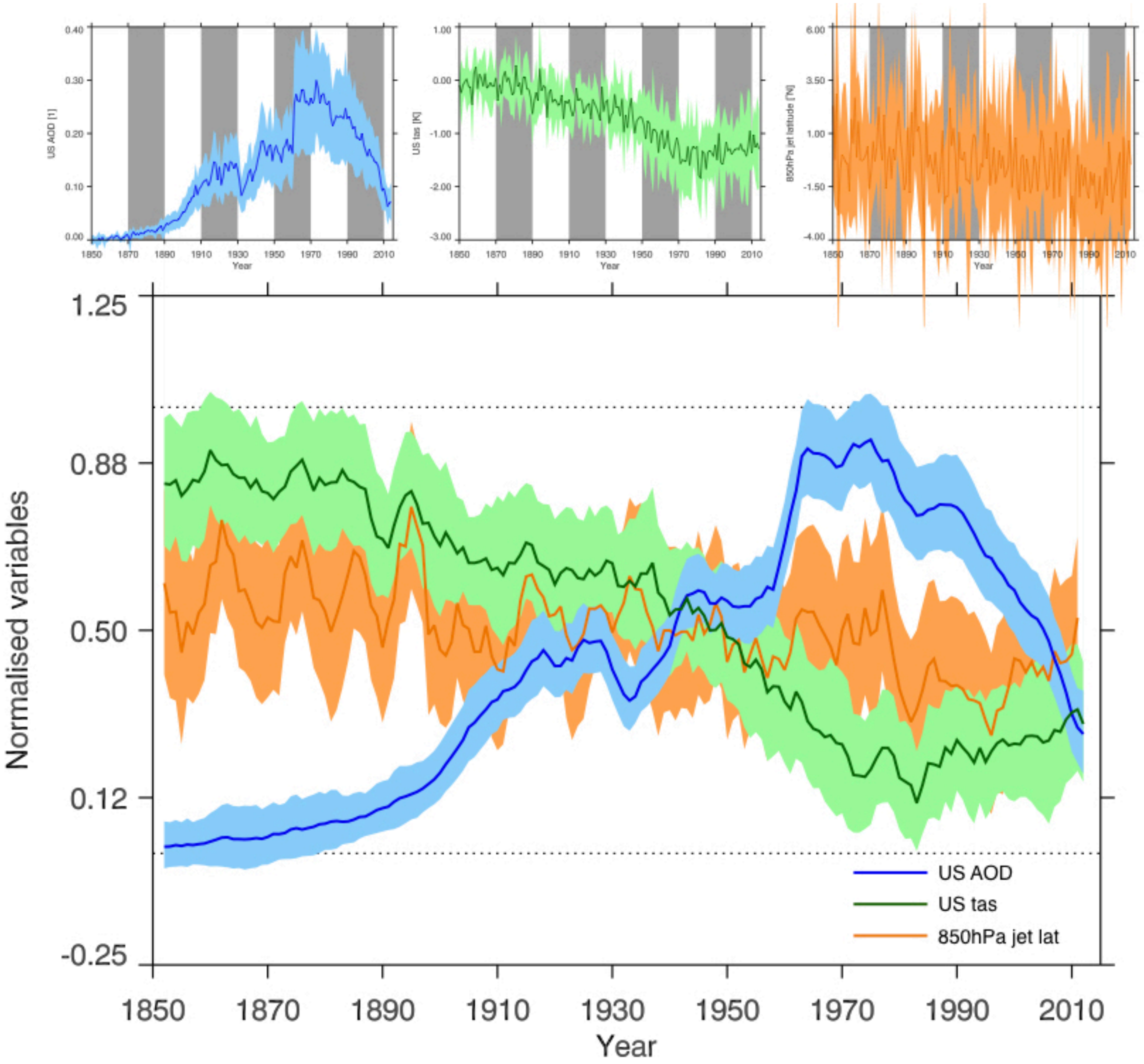
Changes in the North Atlantic atmosphere

Decadal variability in US temperature **follows decadal variability in US AOD**

Suggestion of similar variability in the North Atlantic jet, but the trend is small compared to variability



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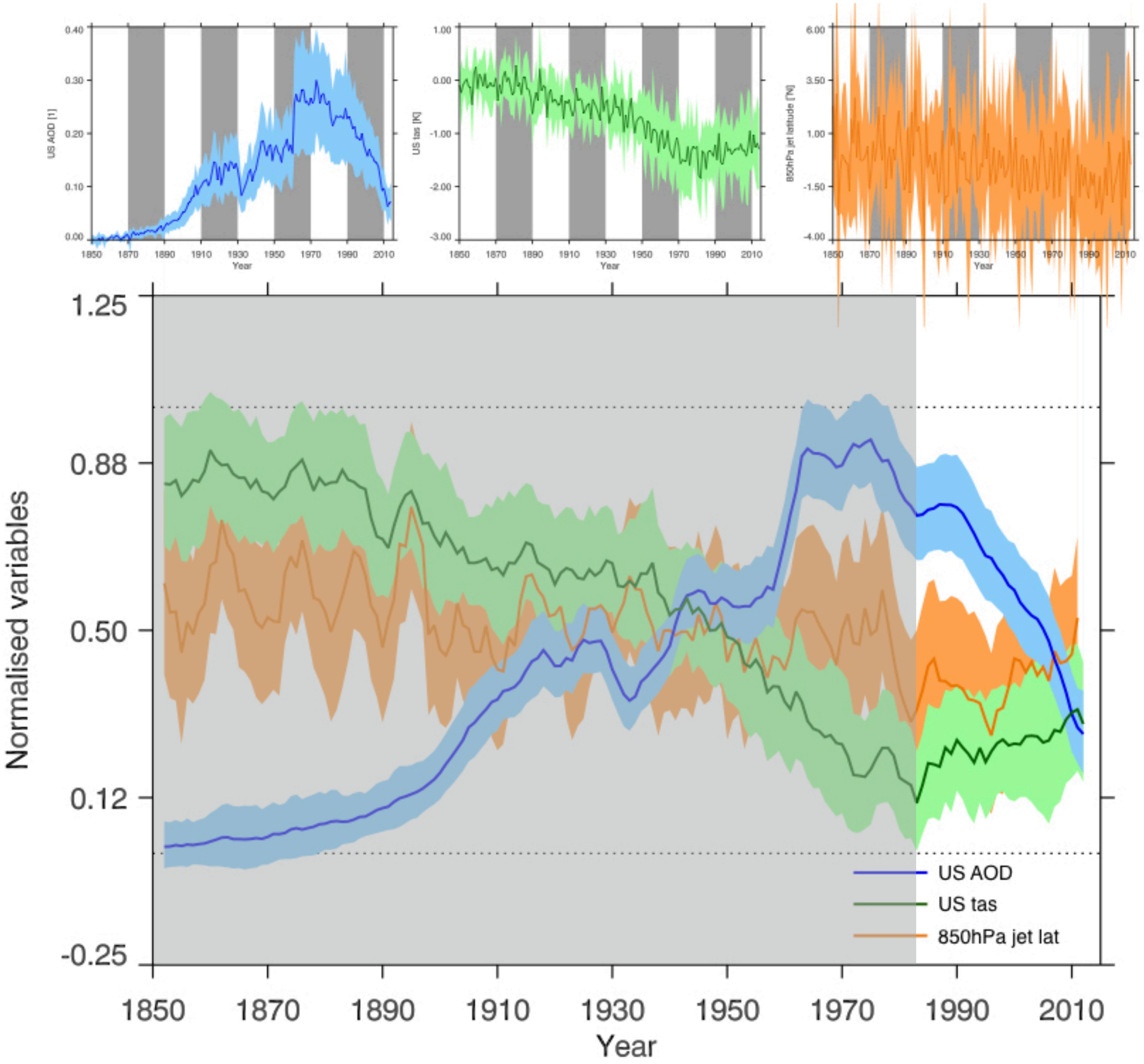
For analysis of linear trends, focus on: 1850-1985, 1985-2014



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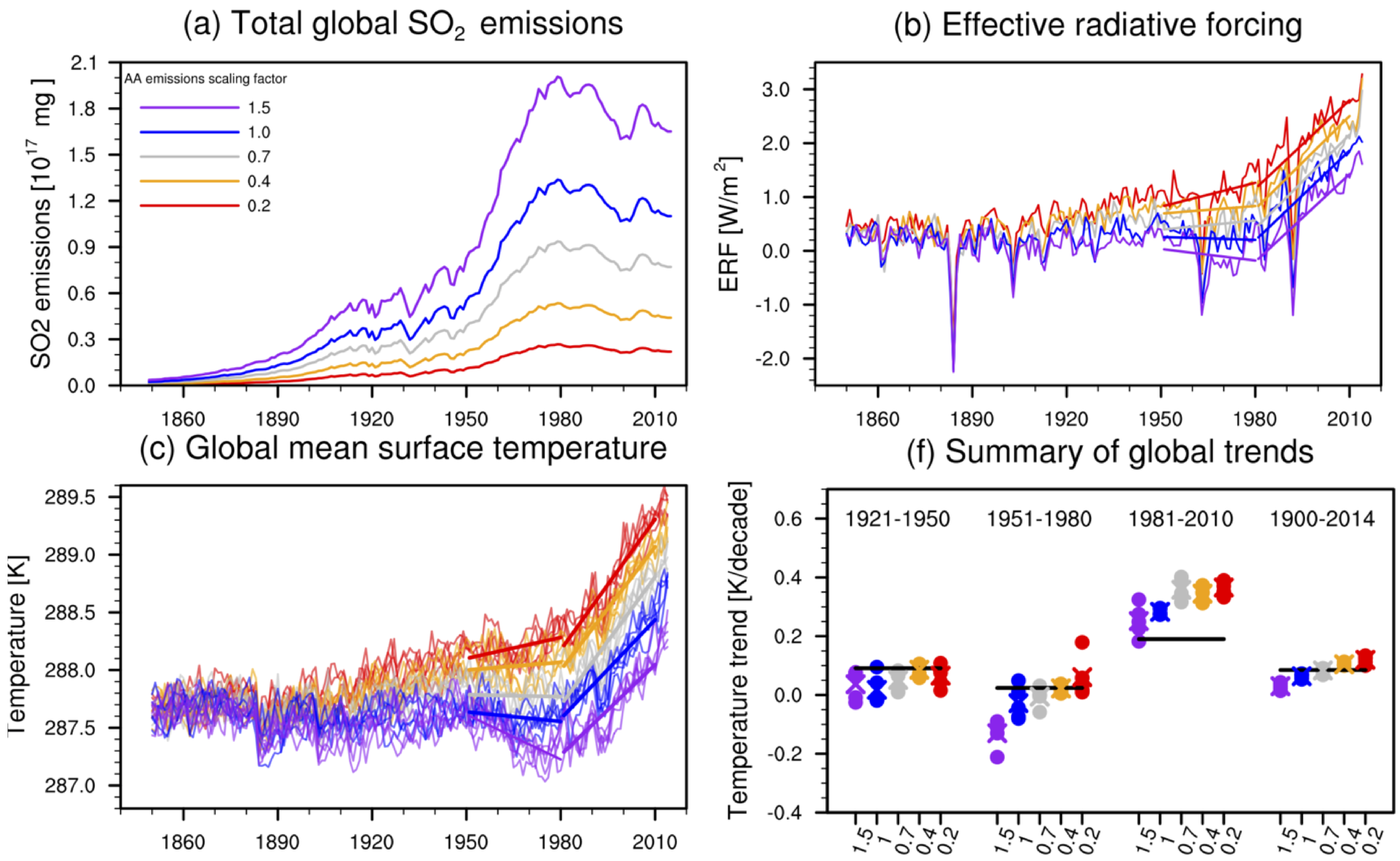
Circulation changes in the North Atlantic: model experiments

SMURPHS
HadGEM3-GC3.1 with scaled aerosol emissions
Aerosol-forced response from (1.5x and 1.0x) - (0.4x and 0.2x)



Scaling	ERF (W/m2)
0.2	-0.38
0.4	-0.60
0.7	-0.93
1.0	-1.17
1.5	-1.50

Wilcox et al., in prep.

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AerChemMIP
Multimodel mean (6 models)
Aerosol-forced response from historical - historical-piAer

UKESM1
9 member ensemble
Aerosol-forced response from historical - historical-1975Aer

Wilcox et al., in prep.

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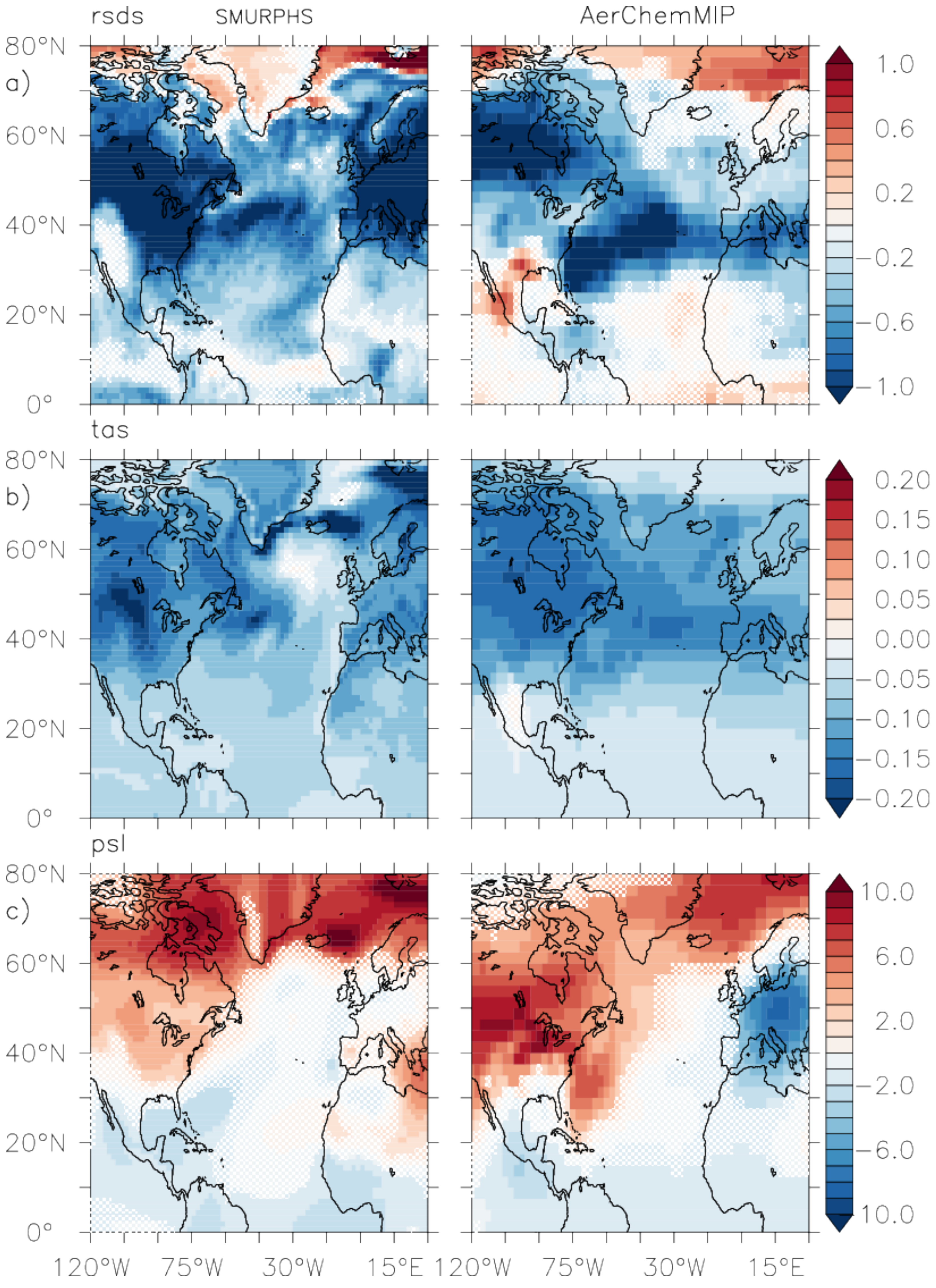
Atmospheric trends: JJA, 1850-1985

Shortwave reductions in aerosol emission regions, and cloudy regions downstream

Temperature trends largely follow shortwave

Sea level pressure increases at high latitudes

European response is very model dependent



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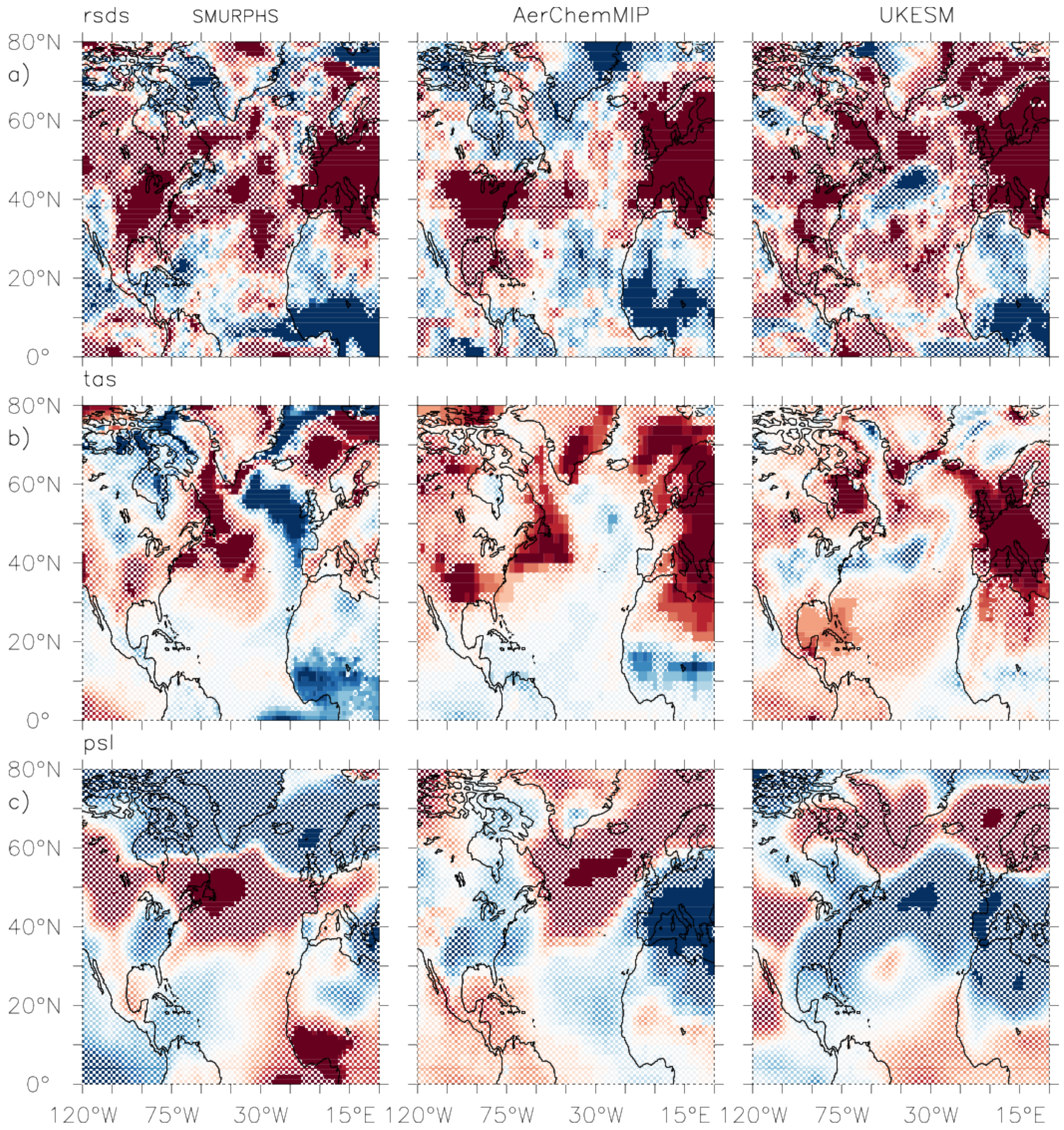
Atmospheric trends: JJA, 1985-2014

Shortwave trends largely reversed, but note the subtropical trends in UKESM

Temperature trends still largely follow shortwave trends in AerChemMIP and UKESM, but not so clear in SMURPHS

Strong European warming appears model dependent

Sea level pressure trends not really significant, and not robust



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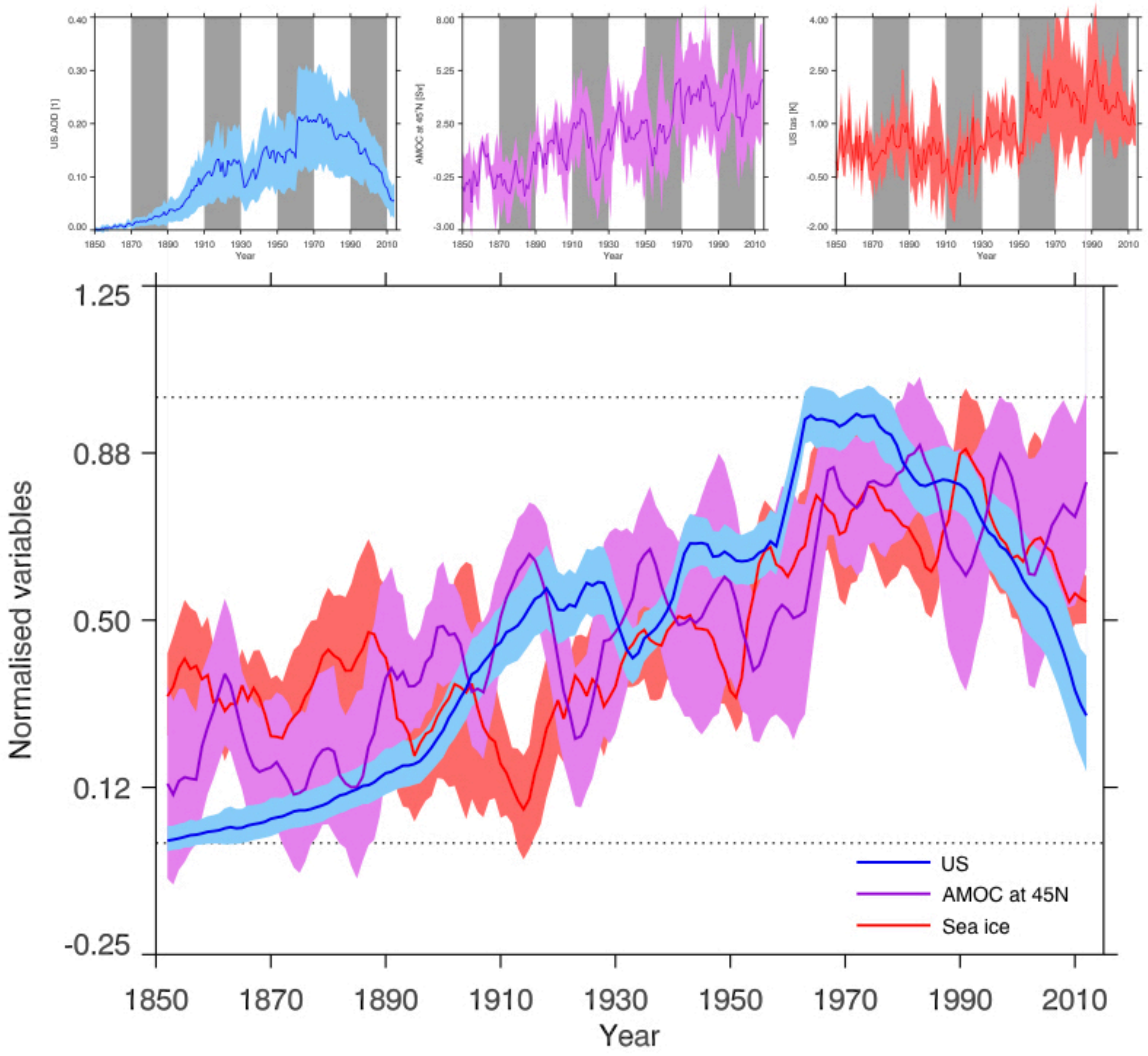
Changes in the North Atlantic ocean

Decadal variability in AMOC and sea ice extent **follow US AOD, but with a lag**

Suggestion of decline in sea ice extent as aerosols decrease, which isn't seen in AMOC



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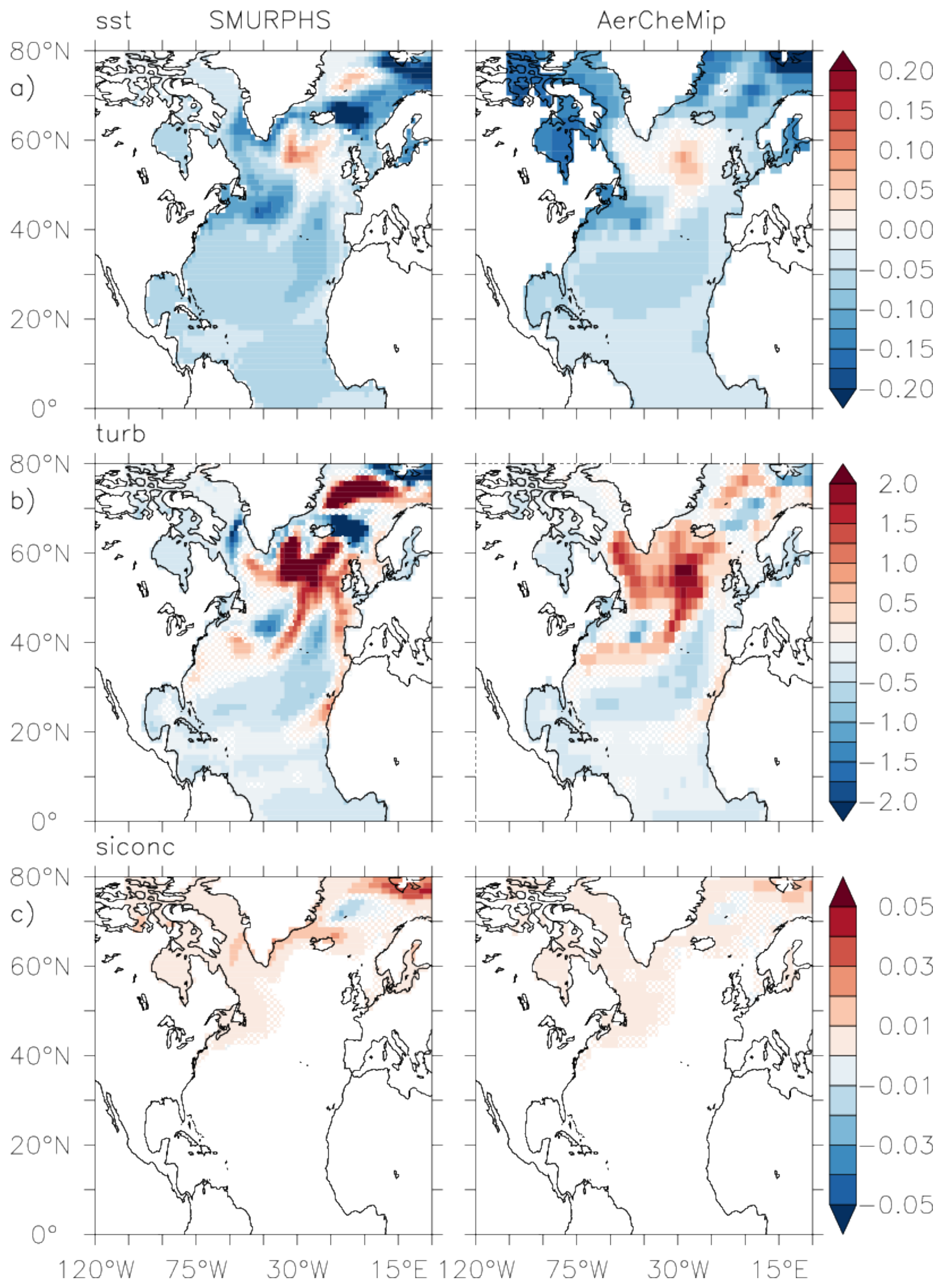
Oceanic trends: Ann, 1850-1985



General cooling in response to aerosol increases…

…except for a few patches of warming that are related to **increases in turbulent heat fluxes, and a spin up of the AMOC**

Wilcox et al., in prep.

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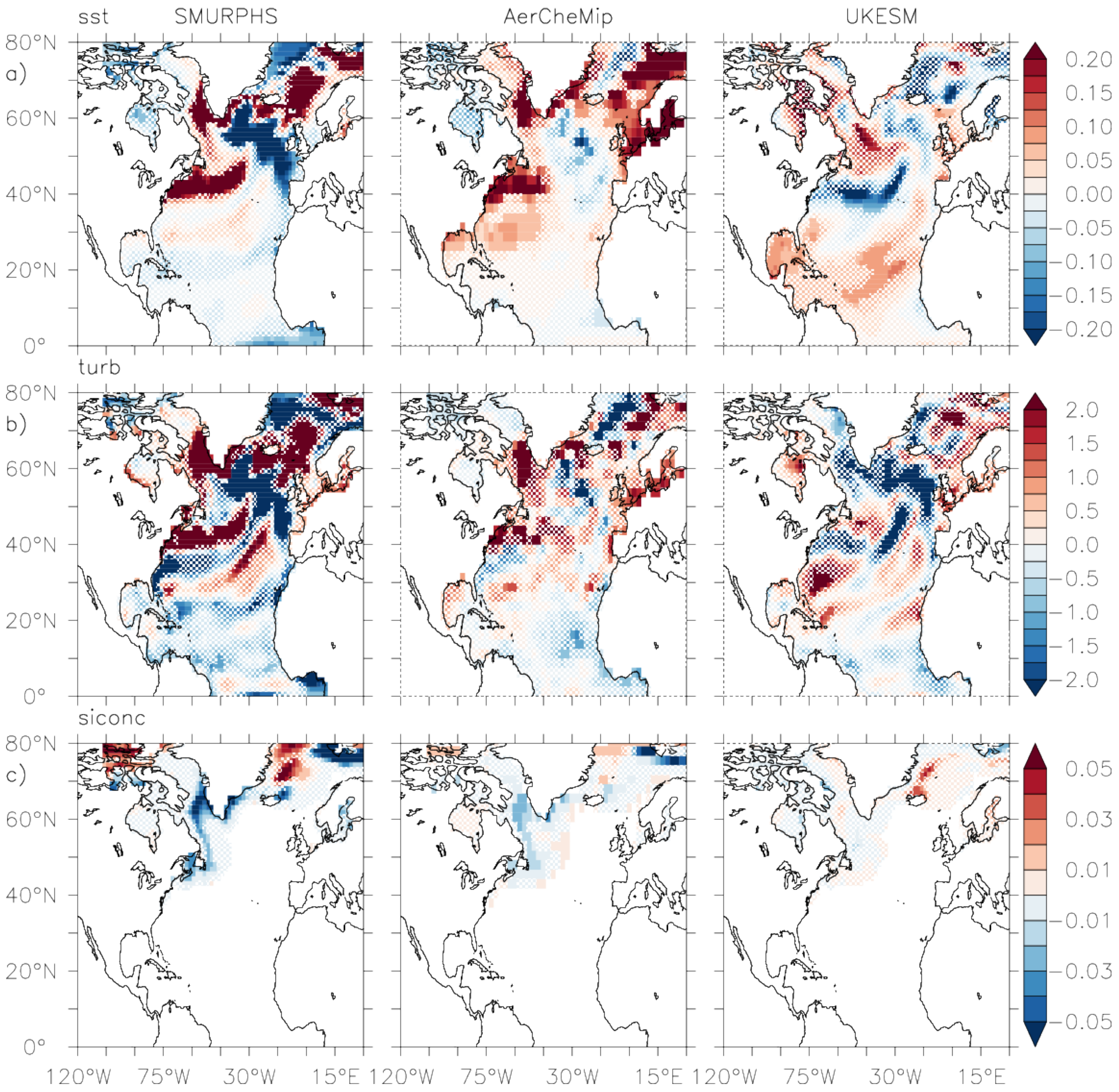
Oceanic trends: Ann, 1985-2014

Turbulent heat flux trends reversed as local aerosols are reduced

All approaches show negative trends over the sub polar gyre, but these are weaker in AerChemMIP, reflecting model diversity

Sea ice decline is stronger over the Labrador Sea



Wilcox et al., in prep.

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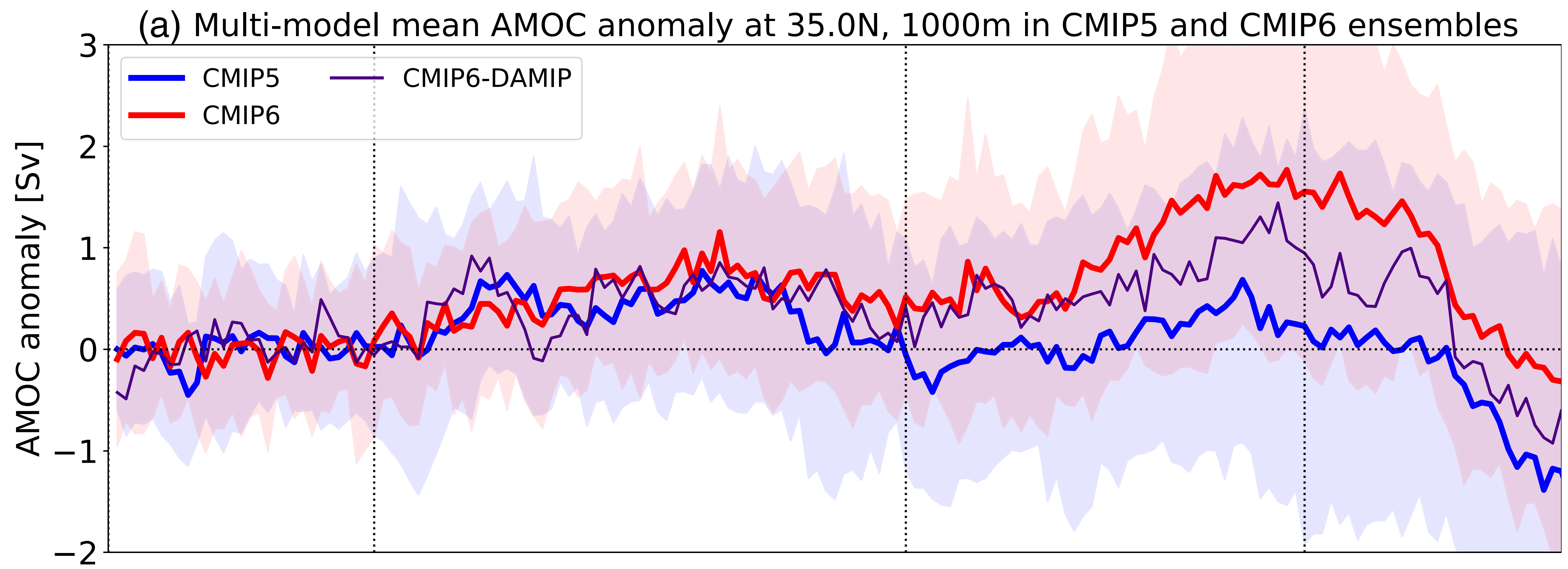
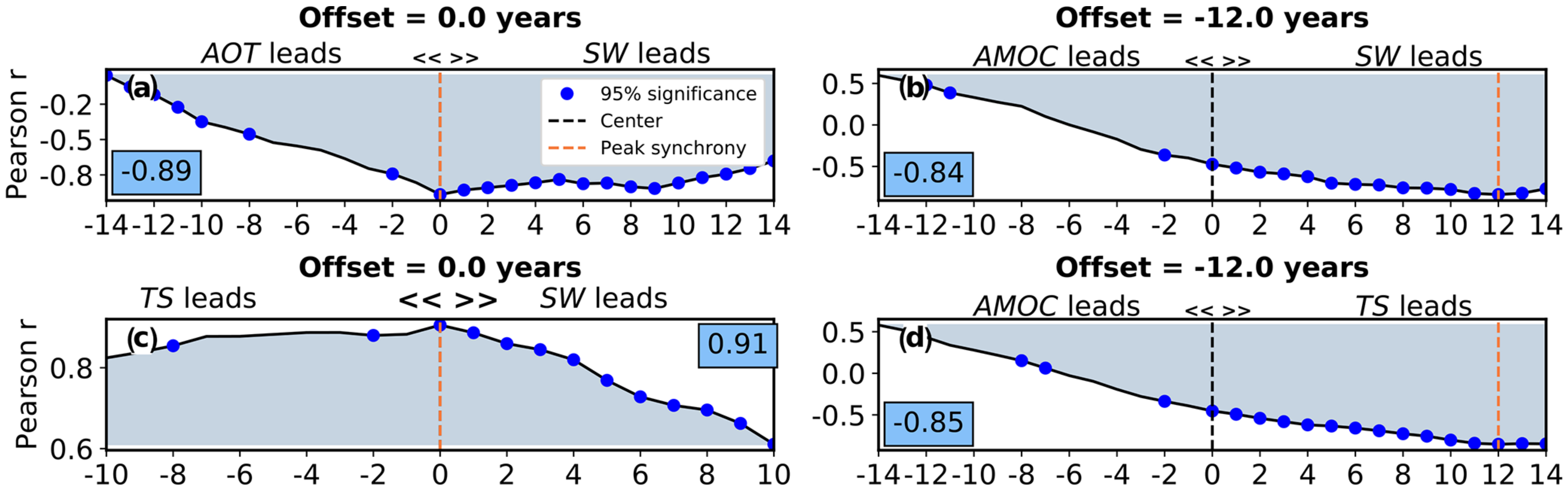
How does the AMOC respond to aerosol changes?





Stronger AMOC response to aerosol in CMIP6 vs. CMIP5. Attributed to stronger aerosol forcing.

Rapid shortwave and temperature responses to aerosol, but the AMOC response lags by about a decade

Menary et al., 2020; Hassan et al., 2021

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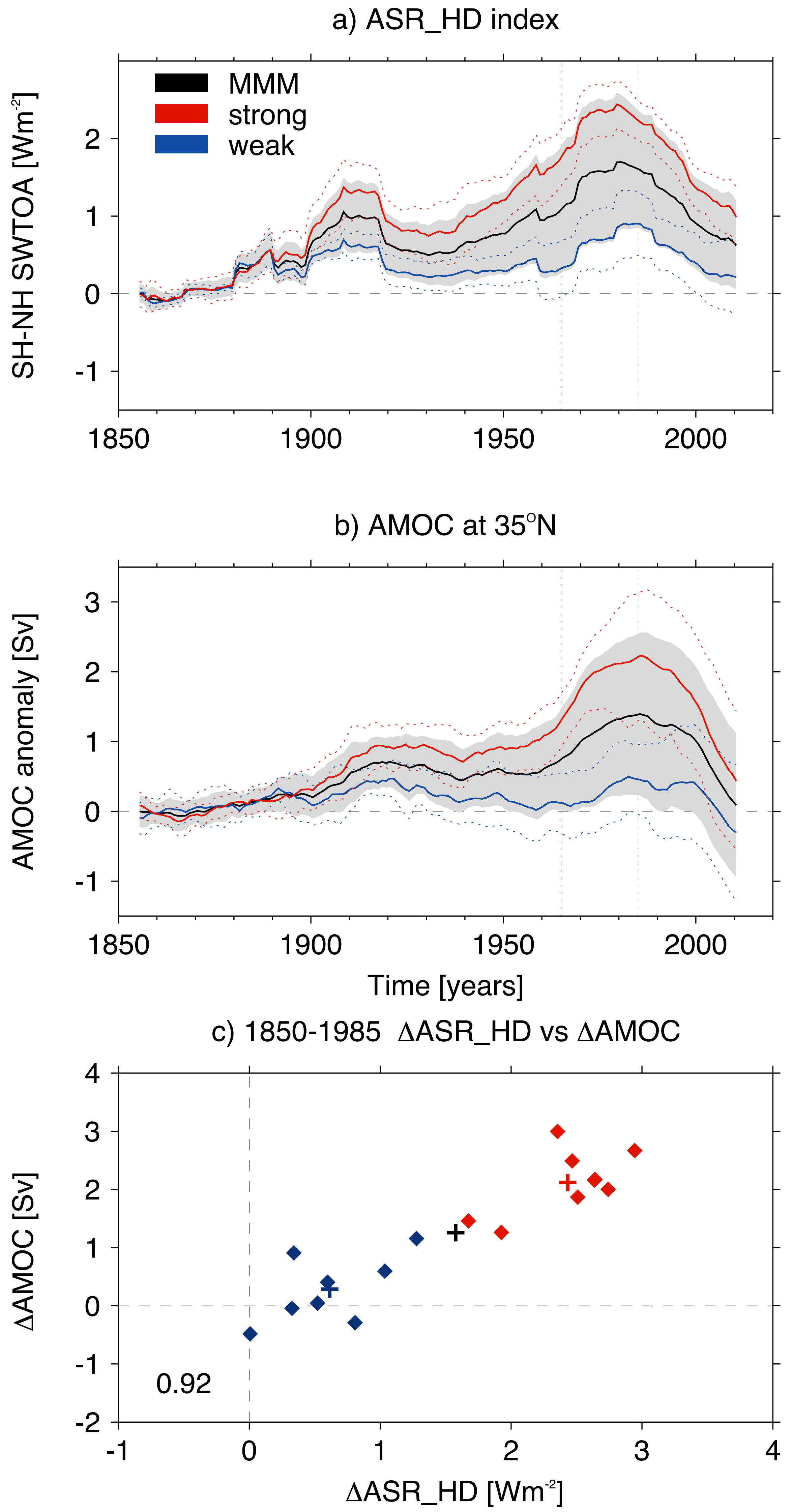
The effect of ‘strong’ and ‘weak’ aerosol forcing on the AMOC



ASR_HD: SH - NH net solar radiation at the top of the atmosphere
-> positive values indicate less radiation absorbed by NH

Strong models have a linear change in ASR_HD between 1850 and 1985 **greater than 1.5 Wm^{-2}**
-> 9 strong models and 8 weak models

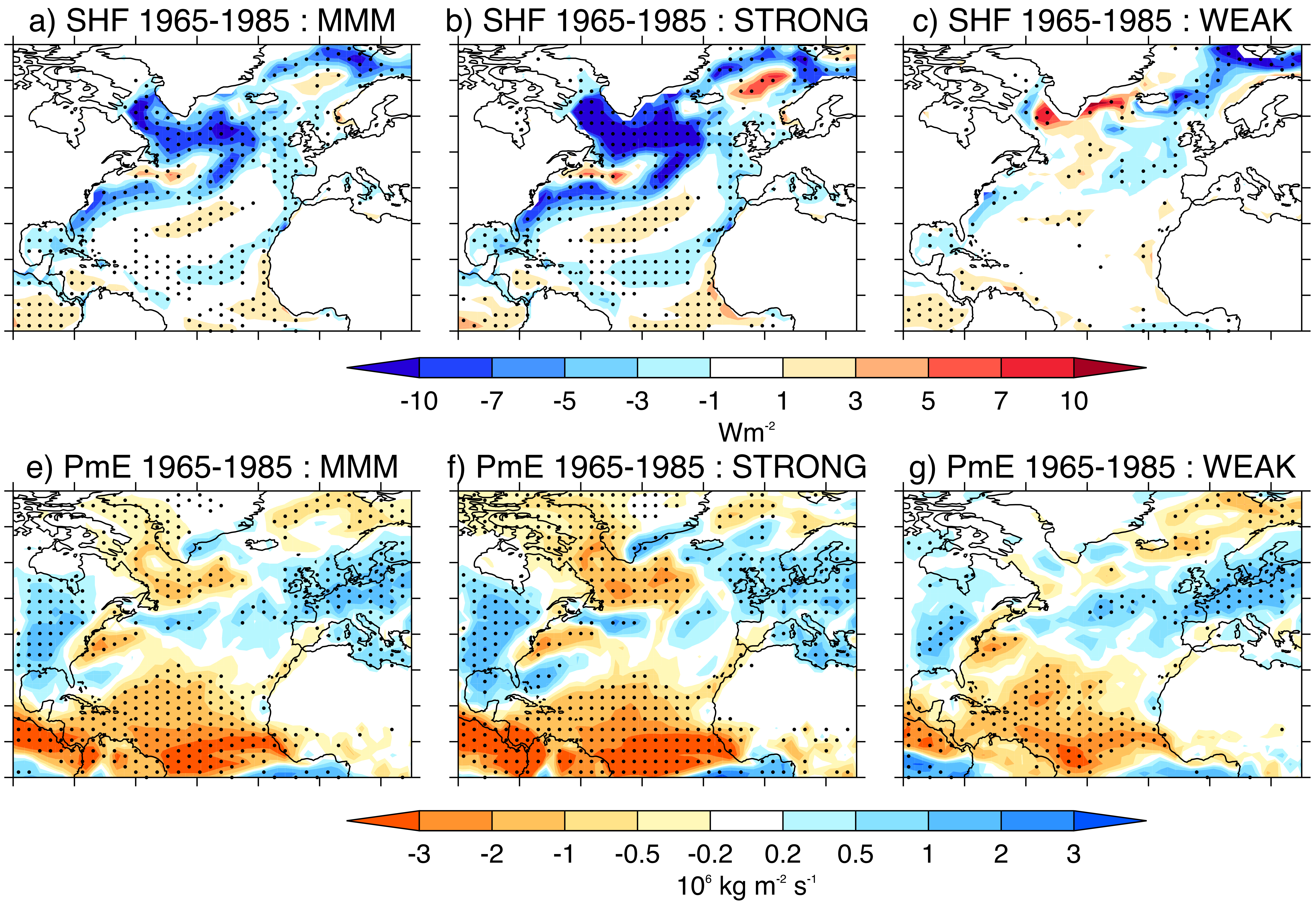
Increase in both ASR_HD and the AMOC from 1850–1985 with the fastest increase over ~1940–1985

Strong models have **4x larger anomaly in ASR_HD**, and **8x larger anomaly in AMOC**, vs. weak models for 1965-1985 relative to 1850-1879.

ASR_HD and AMOC are correlated

Robson et al., 2022

The effect of 'strong' and 'weak' aerosol forcing on surface fluxes



SHF: net surface heat flux into the ocean -> blue indicates increased heat loss from the ocean

SHF anomalies **dominated by strong** models

Changes in surface fluxes over the subpolar North Atlantic expected to drive AMOC

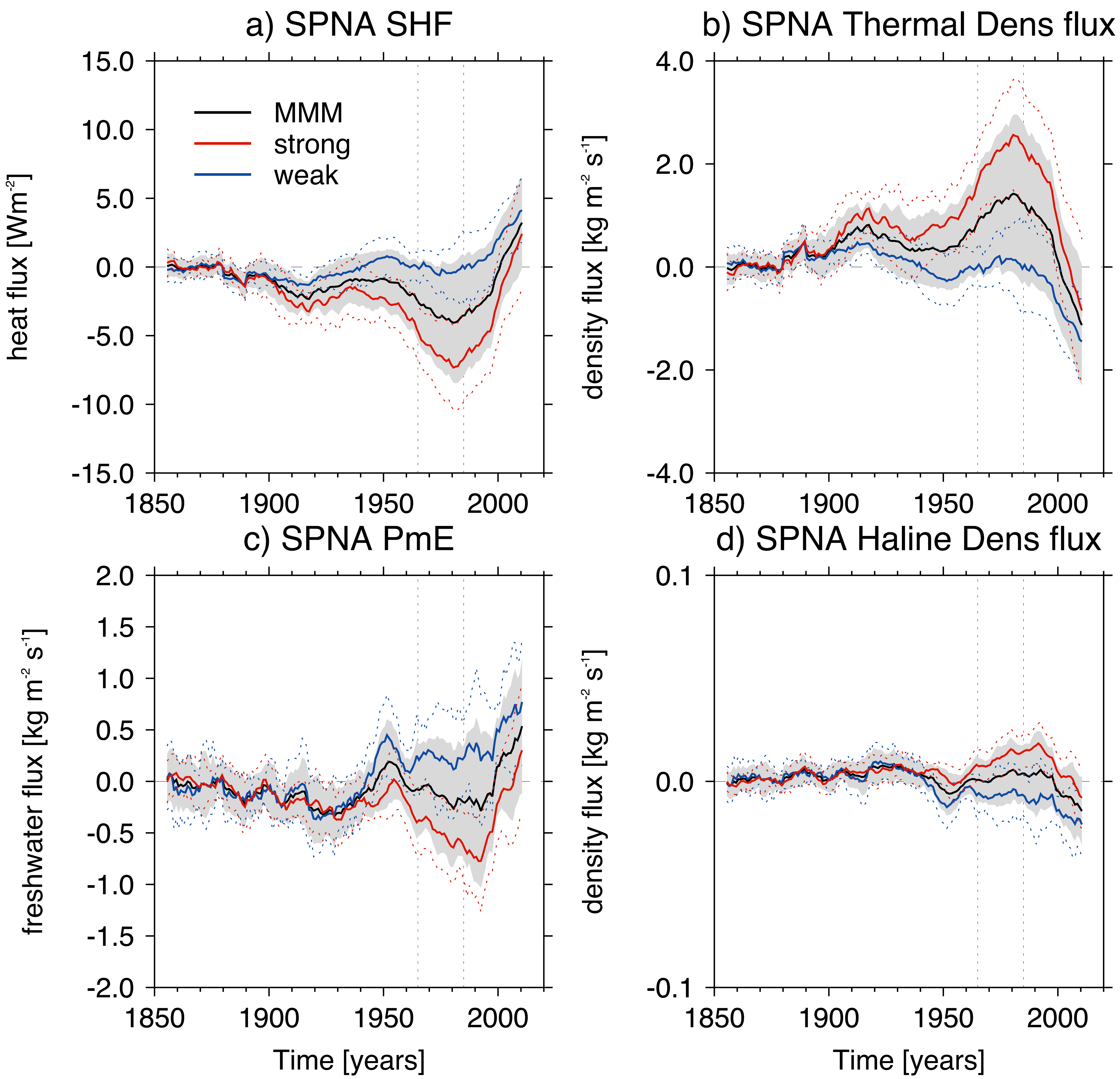
PmE: precipitation minus evaporation

Subpolar reduction in PmE **only seen in strong models**

Subtropical reduction in PmE due to increased evaporation

Robson et al., 2022

The effect of ‘strong’ and ‘weak’ aerosol forcing on surface fluxes



SHF anomalies **dominated by strong models**

SHF dominates the overall surface density flux anomalies

AMOC anomalies in CMIP6 are consistent with the evolution of SPNA **surface heat fluxes, and their impact on surface density fluxes, driving the AMOC** in the ‘strong’ models

PmE decreases due largely to increased evaporation

PmE anomalies diverge after 1940
-> Anomalous evaporative cooling likely contributing to SHF anomalies in this period

Robson et al., 2022

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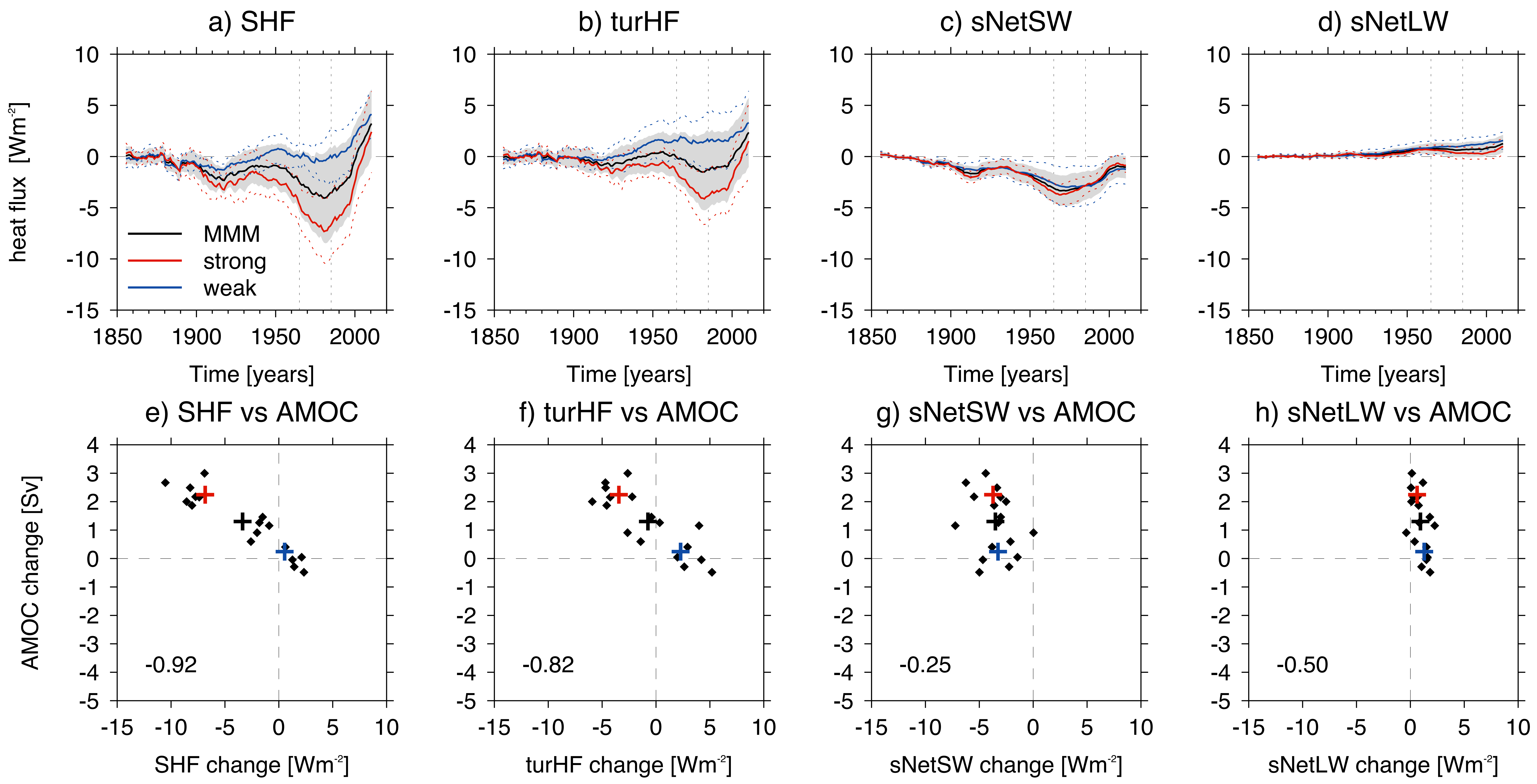
Breakdown of surface heat flux



turHF: turbulent heat flux
sNetSW: surface net shortwave
sNetLW: surface net longwave

MMM SHF dominated by sNetSW

Differences in SHF anomalies between *strong* and *weak* models are **dominated by differences in turHF**

Relationship between AMOC and SHF is **due primarily to turHF**

Robson et al., 2022

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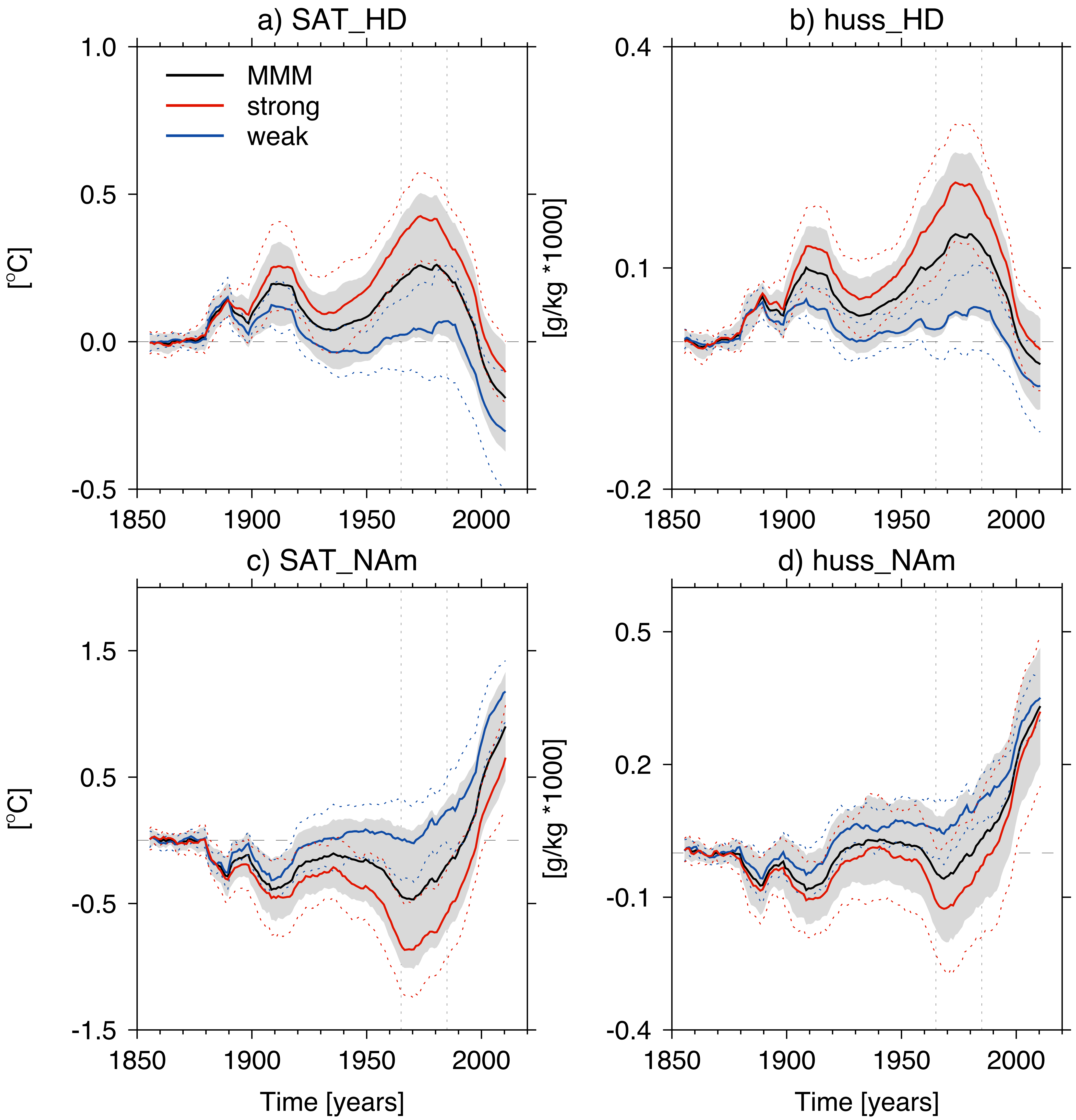
Increased aerosol results in a colder, drier atmosphere



The atmosphere is **colder and drier** relative to the sea surface in models with **strong aerosol forcing**

Cooler, drier atmosphere over the subpolar North Atlantic consistent with larger Northern Hemisphere and North American cooling in strong models

Cooling and drying over North America played an important role in shaping the subsequent evolution of the externally-forced AMOC through its **impact on the air-sea contrast** in temperatures

Robson et al., 2022

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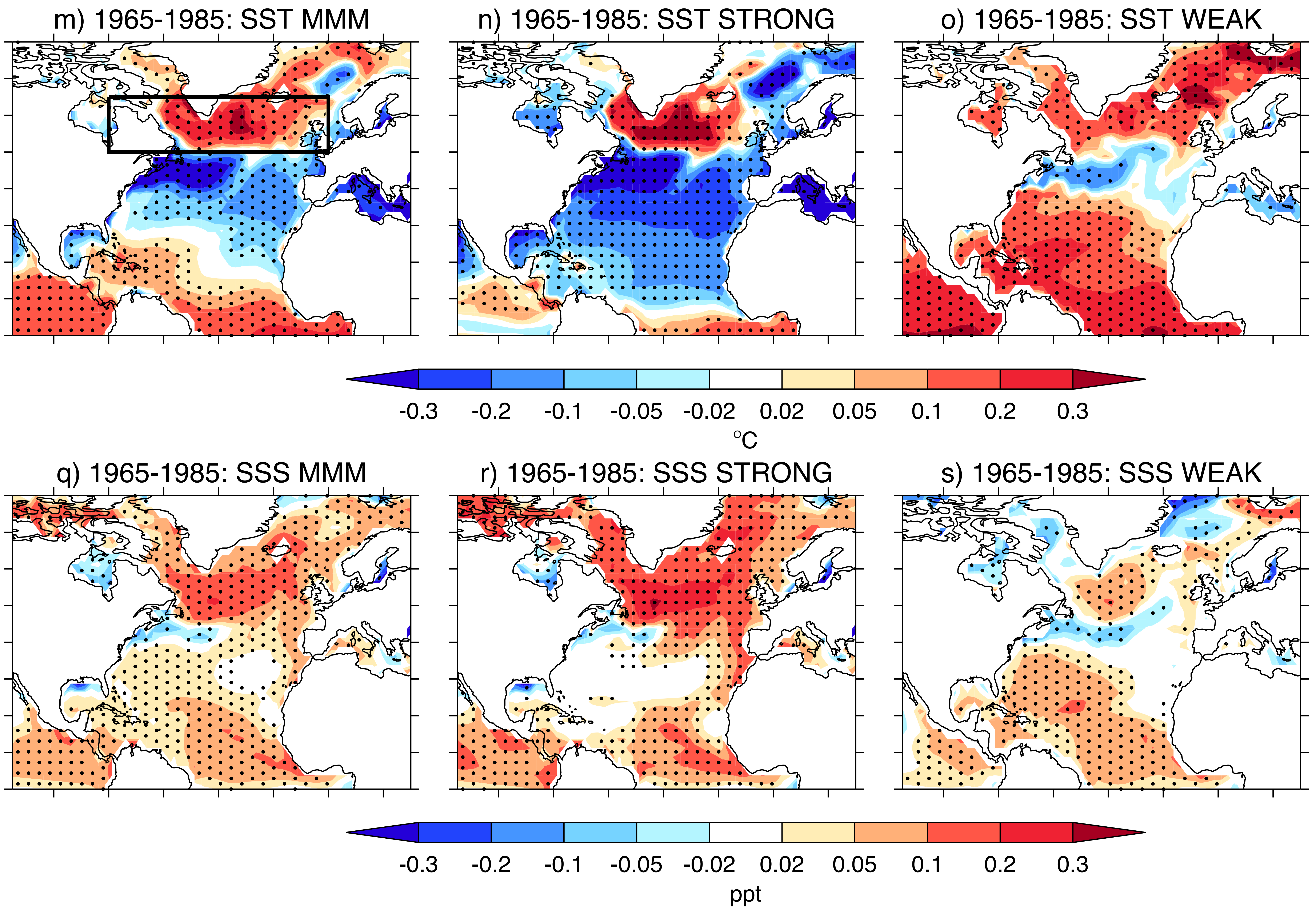
Ocean feedbacks strengthen the AMOC response to aerosol



Changes in SST due to forced changes in AMOC act as a positive feedback
-> warm SST increases atmosphere-ocean contrasts and turbulent heat flux cooling

Salinity changes also consistent with strengthened AMOC

Salinification of the subpolar North Atlantic drives an increase in surface density
-> positive feedback on AMOC

Robson et al., 2022

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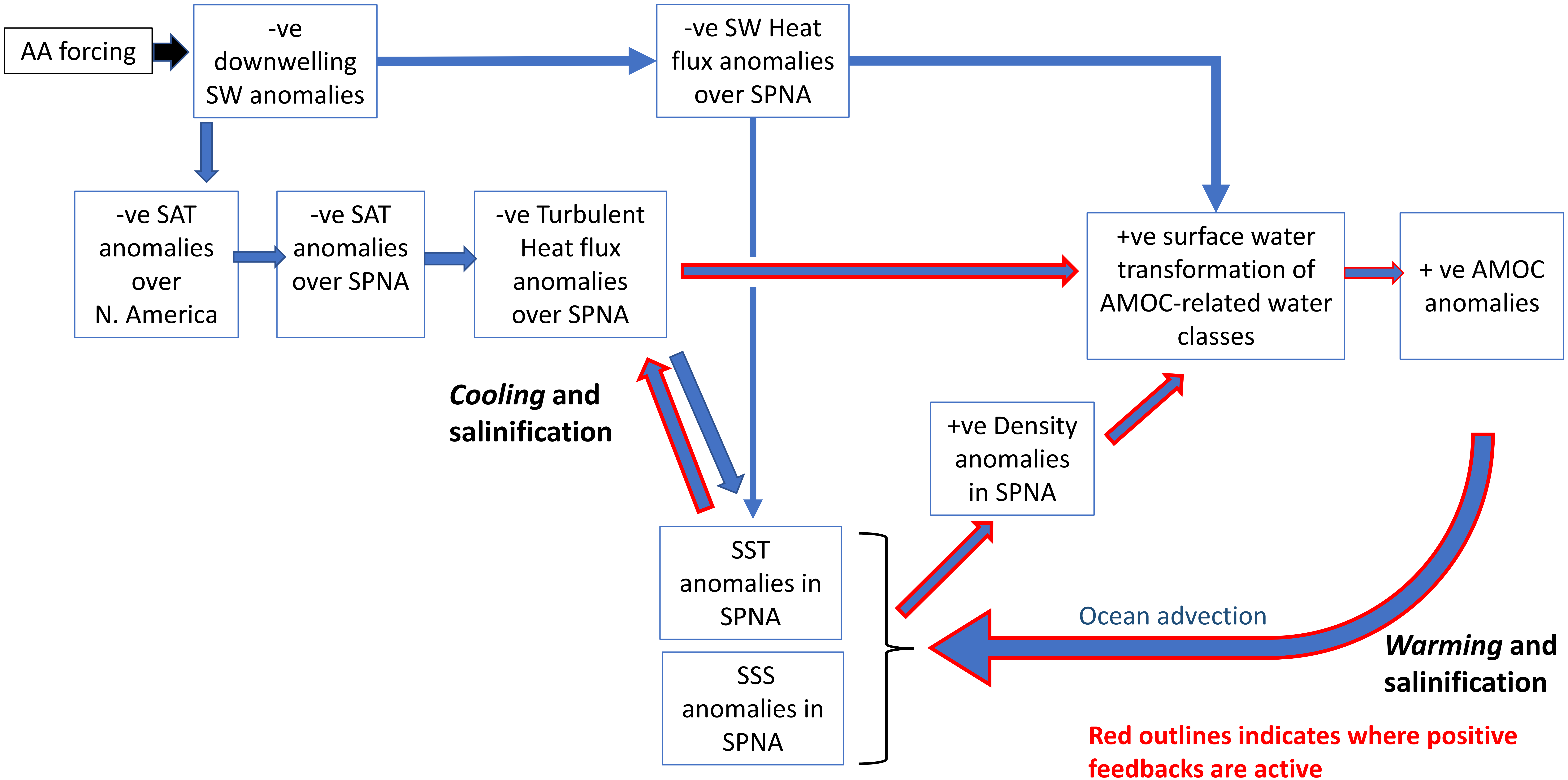
Proposed mechanism for the AMOC response to aerosol



Red outlines indicates where positive feedbacks are active

Robson et al., 2022

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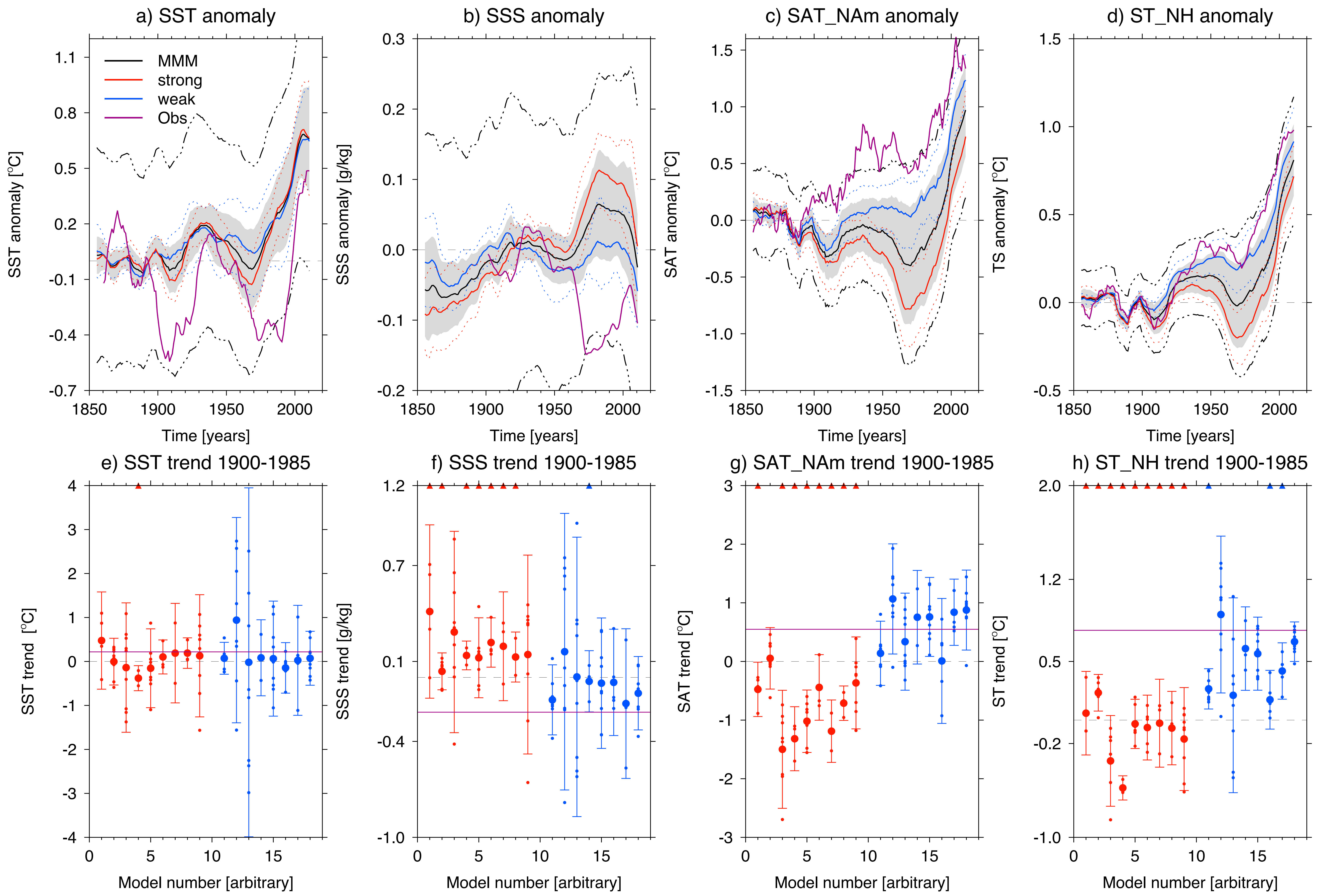
Constraining forced AMOC changes



Subpolar SST is a weak constraint

Increased salinity in strong models **inconsistent with observations**

North American cooling, and weak trends in Northern Hemisphere temperature are **inconsistent with observations**

Forced AMOC strengthening in strong models not consistent with observations
-> aerosol forcing, or the response to it, is too large in strong models

Robson et al., 2022

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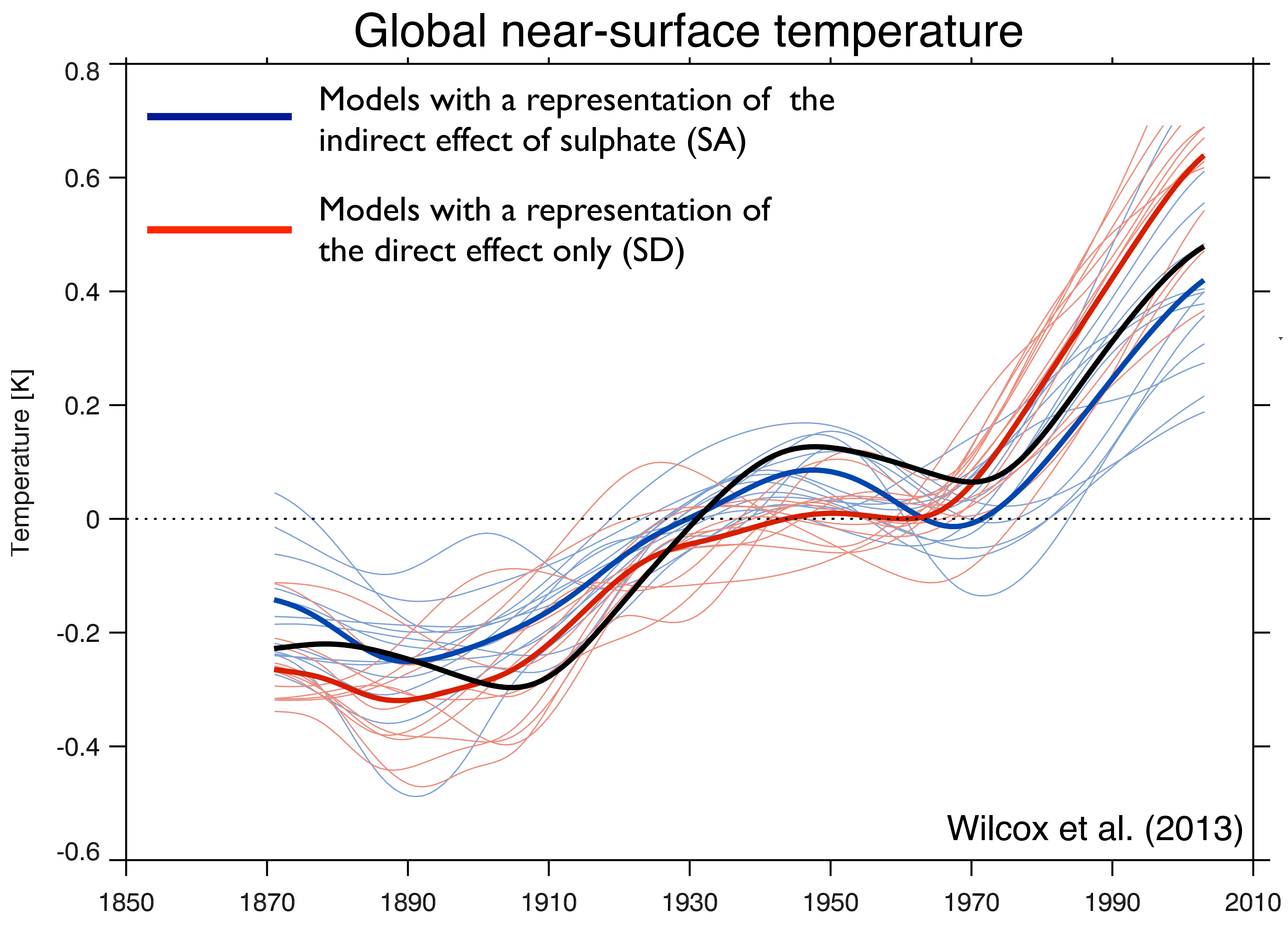
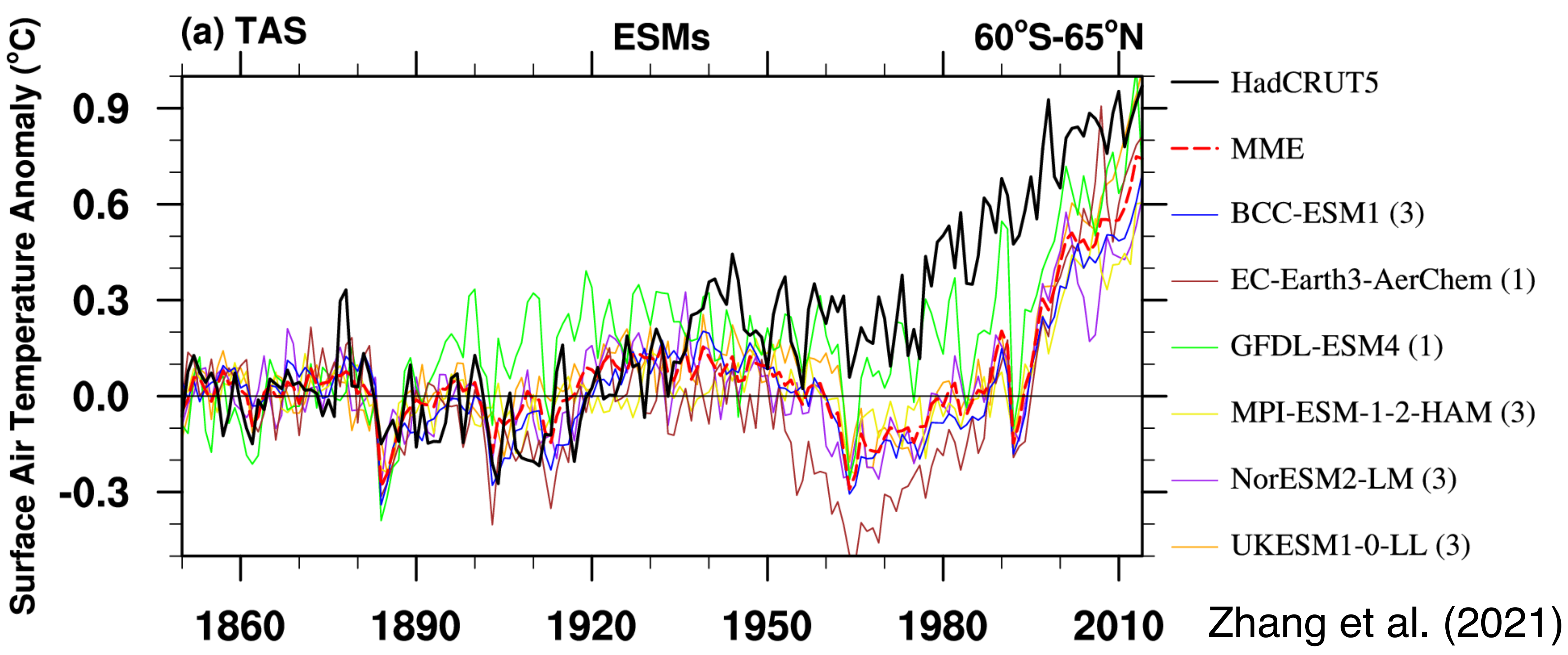
How we represent aerosol processes in models can influence multi-decadal variability





- CMIP5 contained an unprecedented number of models with a representation of the indirect effect
- These models give a better reproduction of historical trends due to greater aerosol cooling

- Earth system models cool too much in the mid-twentieth century
- Linked to large sensitivity to aerosol changes in these models

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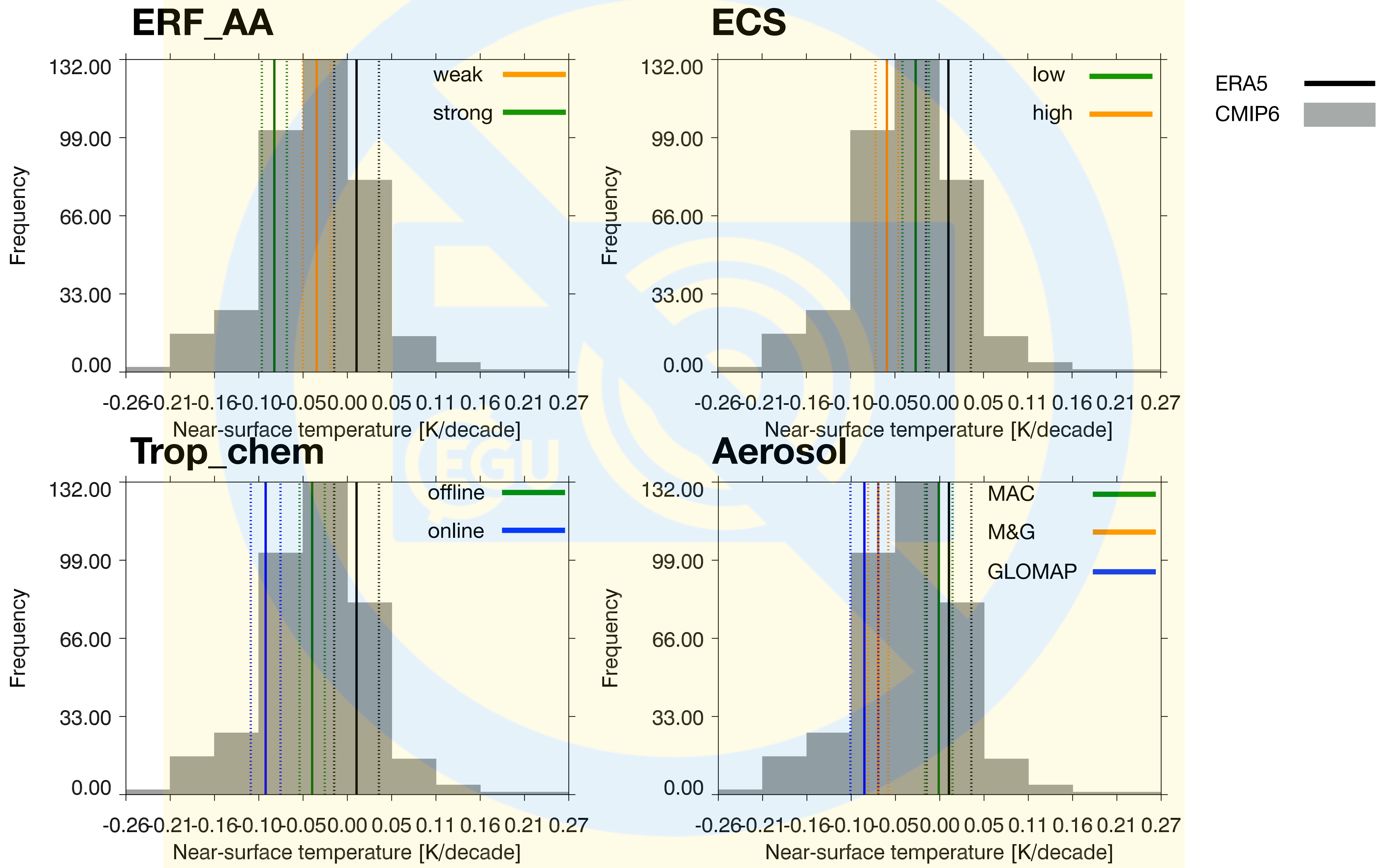
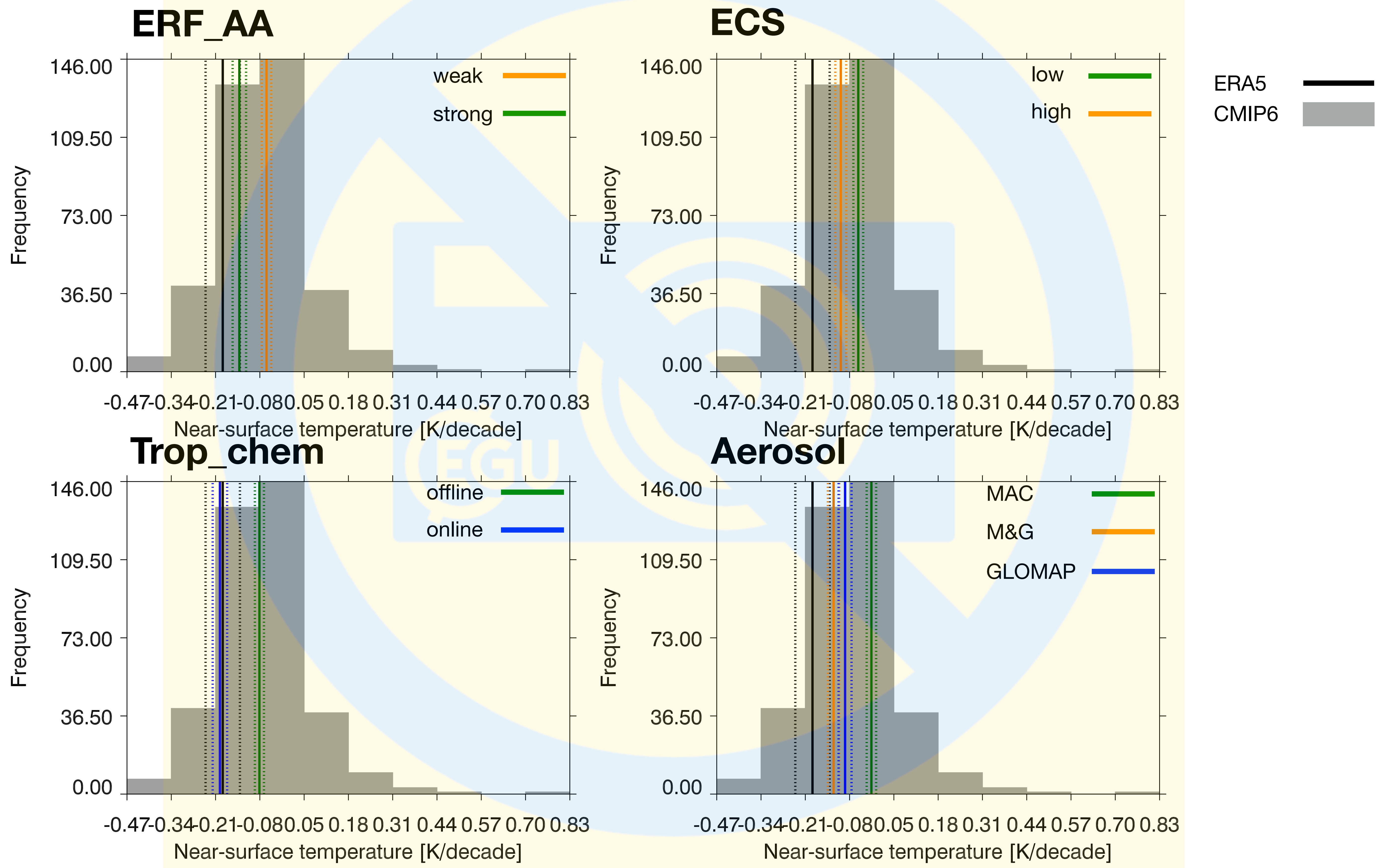
Global temperature trends, 1950:1975



- Larger cooling in models with larger aerosol forcing and more complex representation of aerosol-cloud interactions
- Larger cooling in models with online tropospheric chemistry
- Slightly larger cooling in models with high ECS

Wilcox et al., also in prep

North Atlantic temperature trends, 1950:1975



- Larger cooling in models with larger aerosol forcing and more complex representation of aerosol-cloud interactions
- Larger cooling in models with online tropospheric chemistry
- Slightly larger cooling in models with high ECS

- Qualitatively similar to the global picture (note expanded x-axis)

Wilcox et al., also in prep

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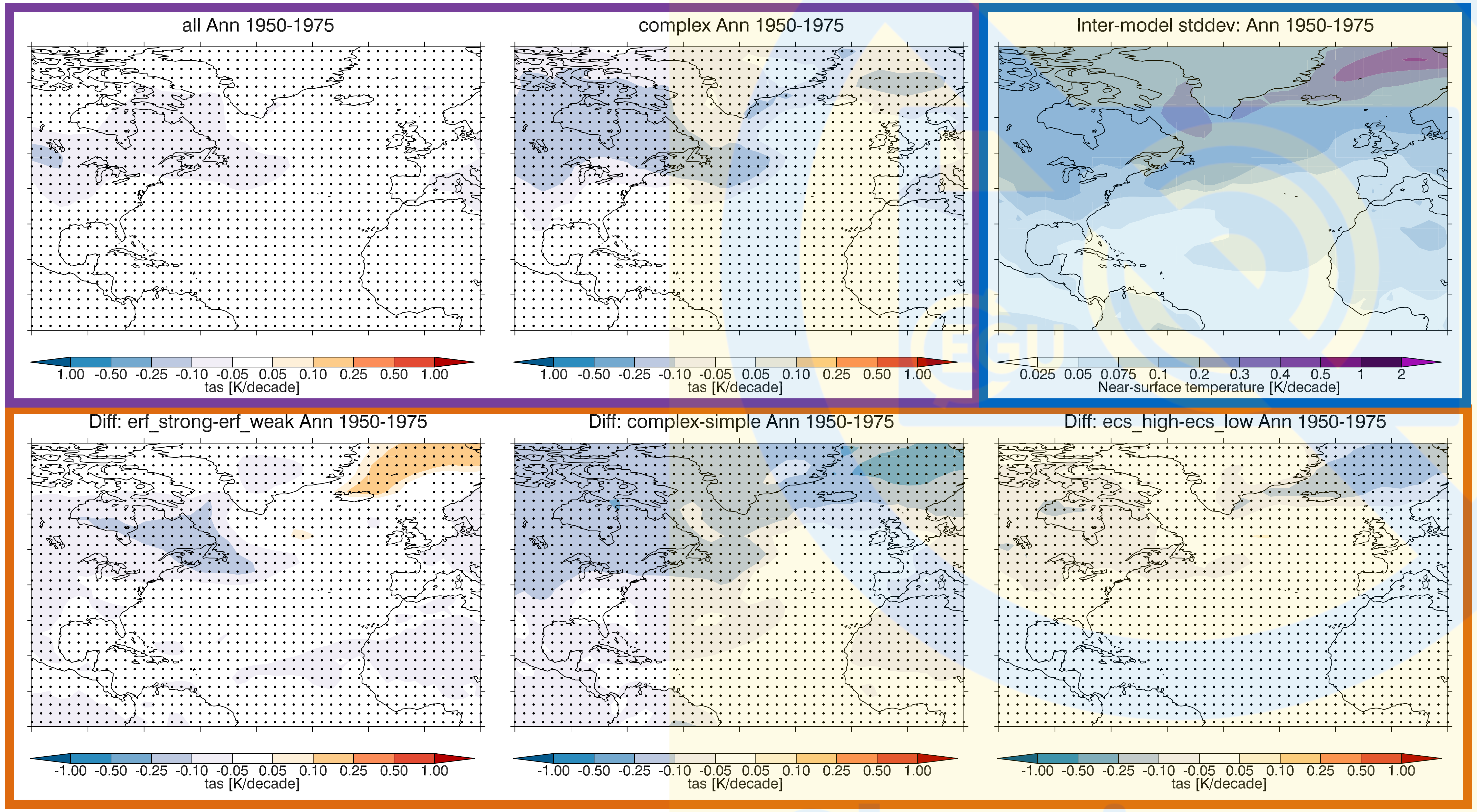
Influence of aerosol process representation: temperature trends, 1950-1975



- Different groups produce trends with different magnitude and pattern
- Differences between groups are significant…
- …but comparable in magnitude to the inter-model standard deviation

- Difficult to attribute differences in the pattern of trends to specific physical processes

- Similar picture is seen for other periods and variables

Wilcox et al., also in prep

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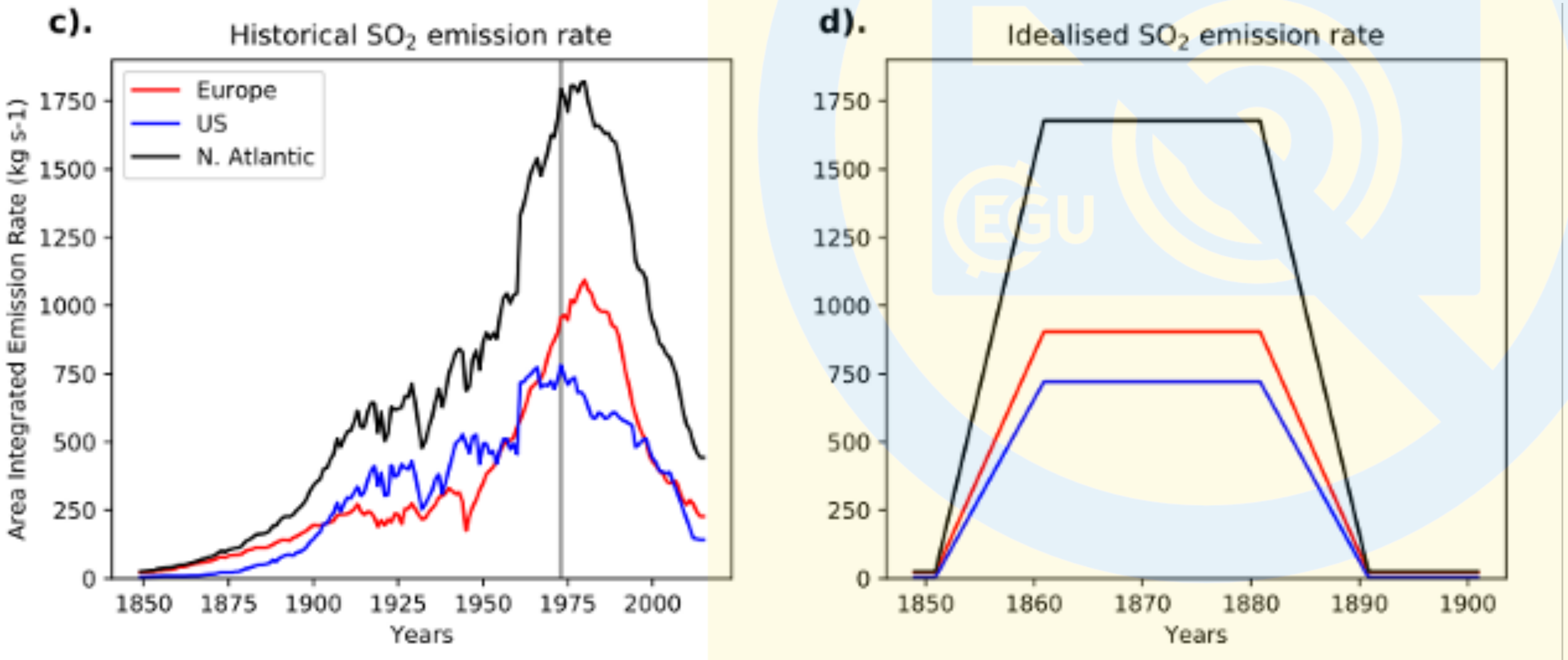
Influence of horizontal resolution: idealised experiments in HadGEM3-GC3.1



Ramp up, ramp down experiments designed to capture the magnitude of historical aerosol changes

Run with two identical versions of HadGEM3-GC3.1 at N96 Orca 1 and N216 Orca 0.25

Lai et al., in prep

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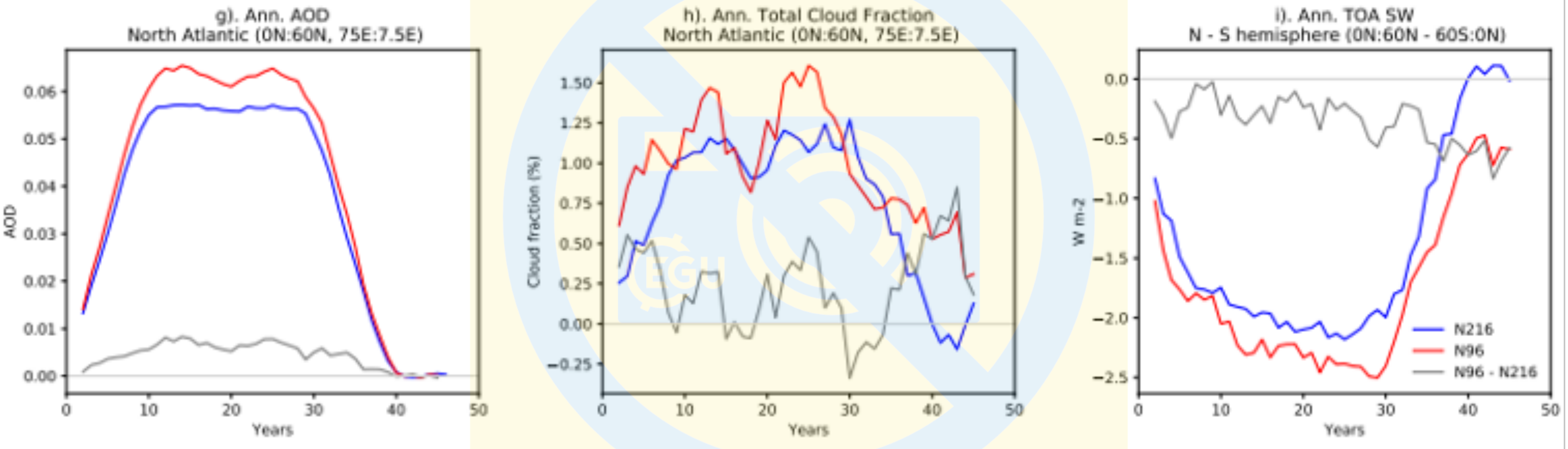
Influence of horizontal resolution: idealised experiments in HadGEM3-GC3.1



Slightly larger AOD and cloud fraction changes in N96

Larger interhemispheric imbalance in TOA shortwave in N96

Lai et al., in prep

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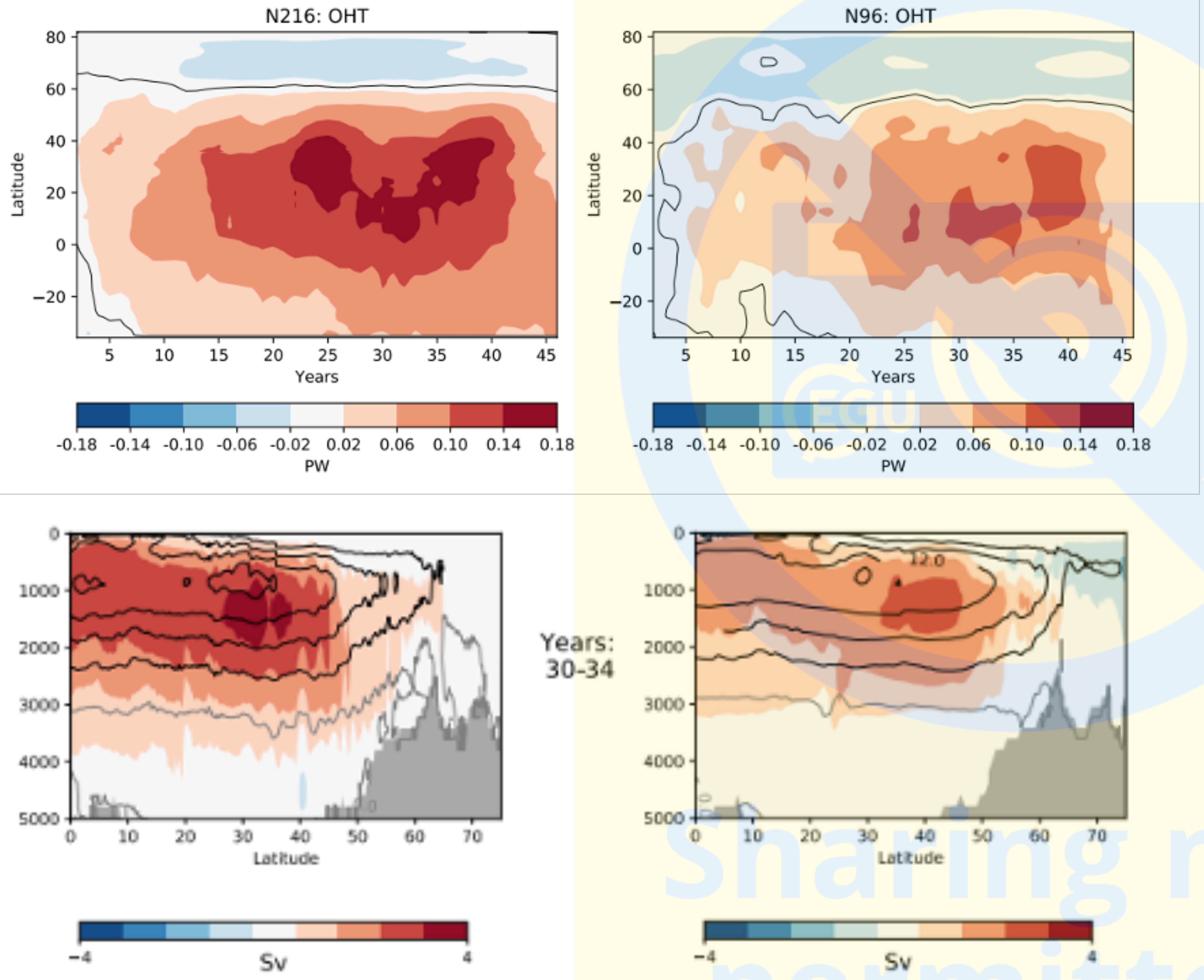
Influence of horizontal resolution: idealised experiments in HadGEM3-GC3.1



Larger aerosol and flux changes in N96, but the ocean response is much stronger in N216

Difference related to differences in sub polar North Atlantic buoyancy forcing and sea ice growth in the Labrador Sea

Greater ice growth in N96 inhibits air-sea interaction and anomalous density fluxes

Differences reflect model climatology: N96 is cooler with more sea ice

Lai et al., in prep

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Summary

- **Large AMOC response to anthropogenic aerosol in CMIP6 historical simulations**
  - Large spread related to the spread in the strength of aerosol forcing
  - Multi-model mean response is dominated by models with strong aerosol forcing

- **Relationship between aerosol and AMOC less clear in last 40 years**
  - Complicated by GHGs, cloud feedbacks, remote aerosol changes

- **Surface density fluxes due to surface heat flux cooling over the subpolar North Atlantic dominate the simulated increase in AMOC**
  - This can be sensitive to model resolution

- **Differences in downwelling shortwave radiation do not explain the different evolution of AMOC in models**
  - Turbulent heat fluxes dominate the spread in AMOC responses
  - Aerosol does not act directly on the AMOC through changes in the radiation balance alone

- **AMOC is primarily driven by a colder and drier atmosphere**
  - Anomalies in turbulent heat flux are dominated by changes in temperature and humidity, rather than wind speed

- **Strong models cool too much compared to observations, so the AMOC increase is likely to be overestimated**
  - Difficult to attribute differences in sensitivity in CMIP6 to specific physical processes due to model complexity

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More details

Sutton et al. (2018): https://journals.ametsoc.org/view/journals/bams/99/2/bams-d-16-0266.1.xml
Grosvenor and Carslaw (2020): https://acp.copernicus.org/articles/20/15681/2020/
Grosvenor et al. (2022): https://acp.copernicus.org/preprints/acp-2022-583/
Menary et al. (2020): https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020GL088166
Robson et al. (2022): https://journals.ametsoc.org/view/journals/clim/35/20/JCLI-D-22-0124.1.xml
Dong et al. (2022a): https://link.springer.com/article/10.1007/s00382-022-06438-3
Dong et al. (2022b): https://www.nature.com/articles/s41467-022-28816-5

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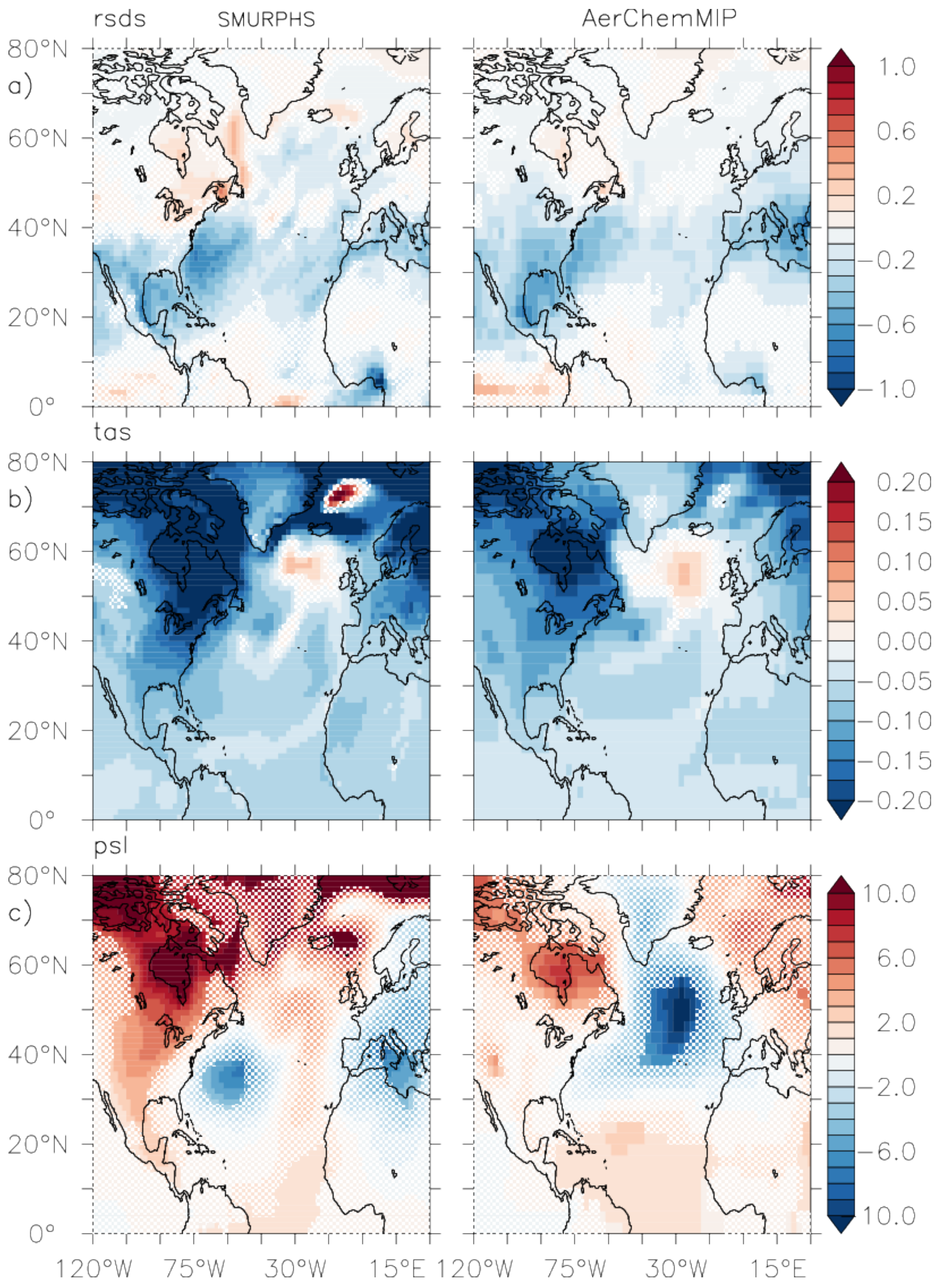
Atmospheric trends: DJF, 1850-1985

Weaker shortwave trends in winter

Strong cooling, especially over Hudson Bay, Labrador Sea, and Nordic seas

Warming sub polar gyre due to AMOC spin up

Limited significance in sea level pressure trends

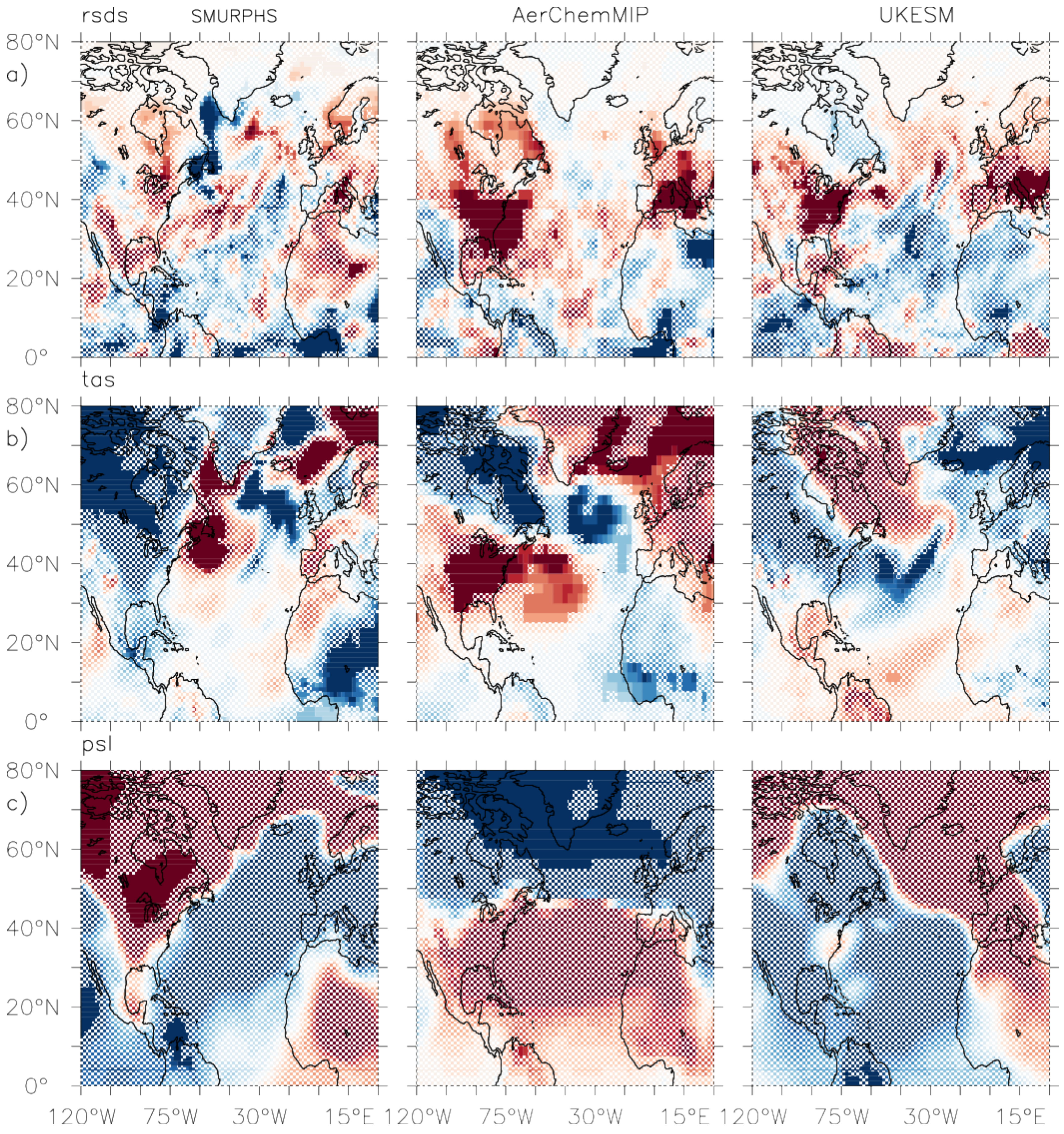


Wilcox et al., in prep.

Atmospheric trends: DJF, 1985-2014

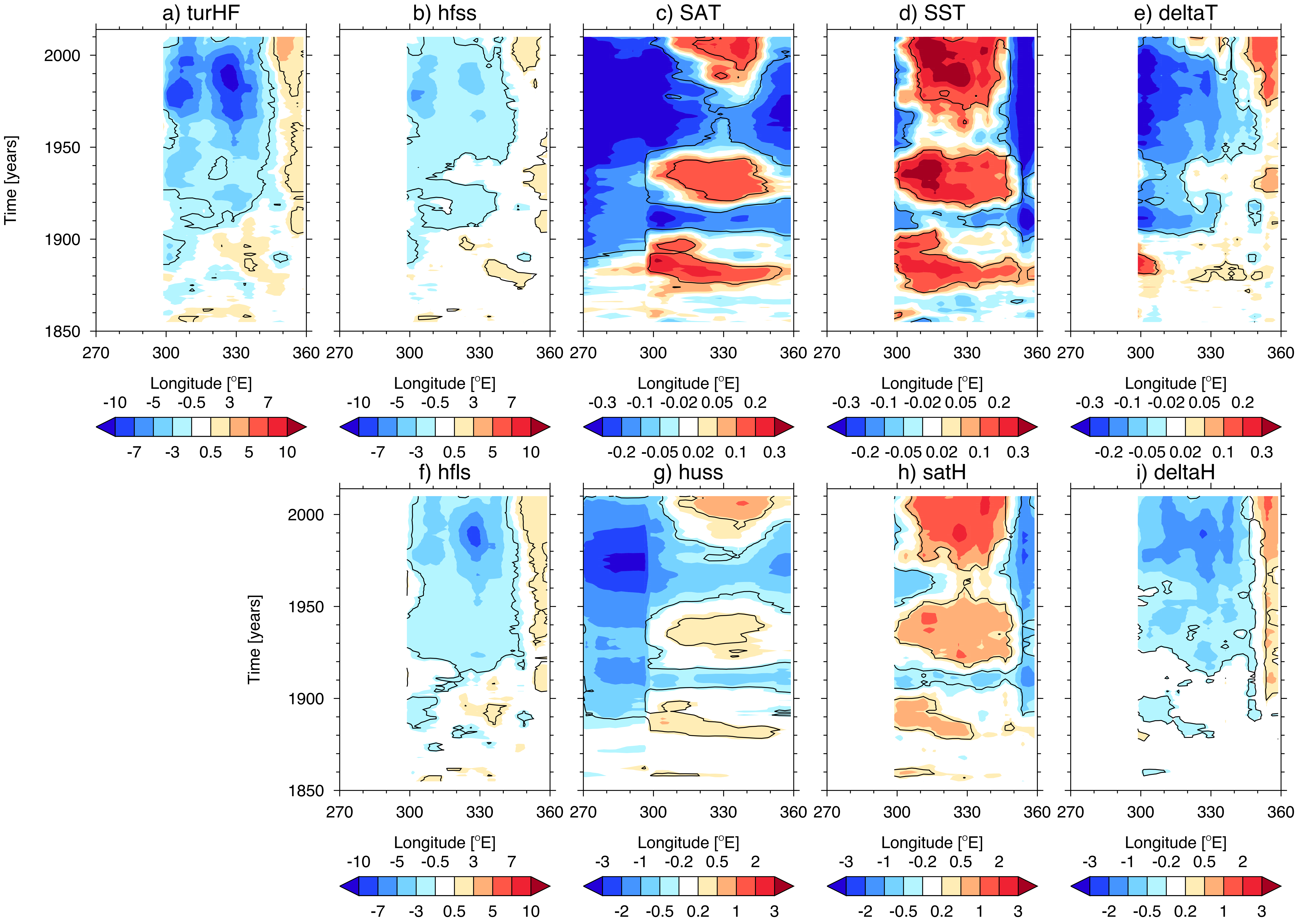
Shortwave trends largely reversed, but no clear/significant picture from SMURPHS

Temperature and sea level pressure trends largely insignificant and not robust across models/methods



Wilcox et al., in prep.

‘Strong’ and ‘weak’ aerosol forcing in CMIP6



The cooling and drying of the atmosphere over the North American continent is substantially larger than the cooling and drying over the SPNA

Continental cooling leads the atmospheric cooling over the SPNA

Anomalous heat fluxes are first seen in the western SPNA, especially in the sensible heat fluxes, and then in the East

-> initial anomalies in the west consistent with **cold advection**

-> later anomalies in the east consistent with **intensification of cold dry signal** over North America, and the expected **warming from an intensified AMOC**

Robson et al., 2022

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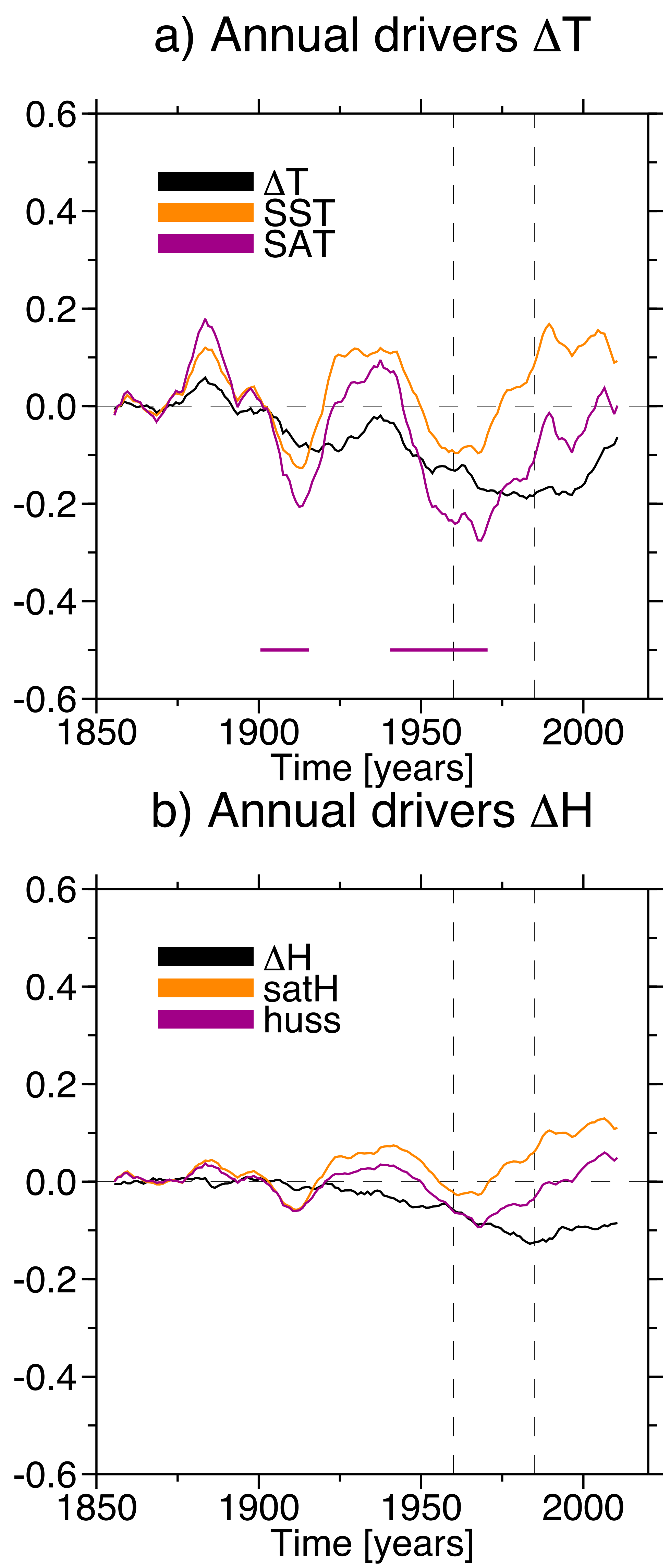
The atmosphere is the main driver of turbulent heat flux anomalies



ΔT mainly from decreases in air temperature

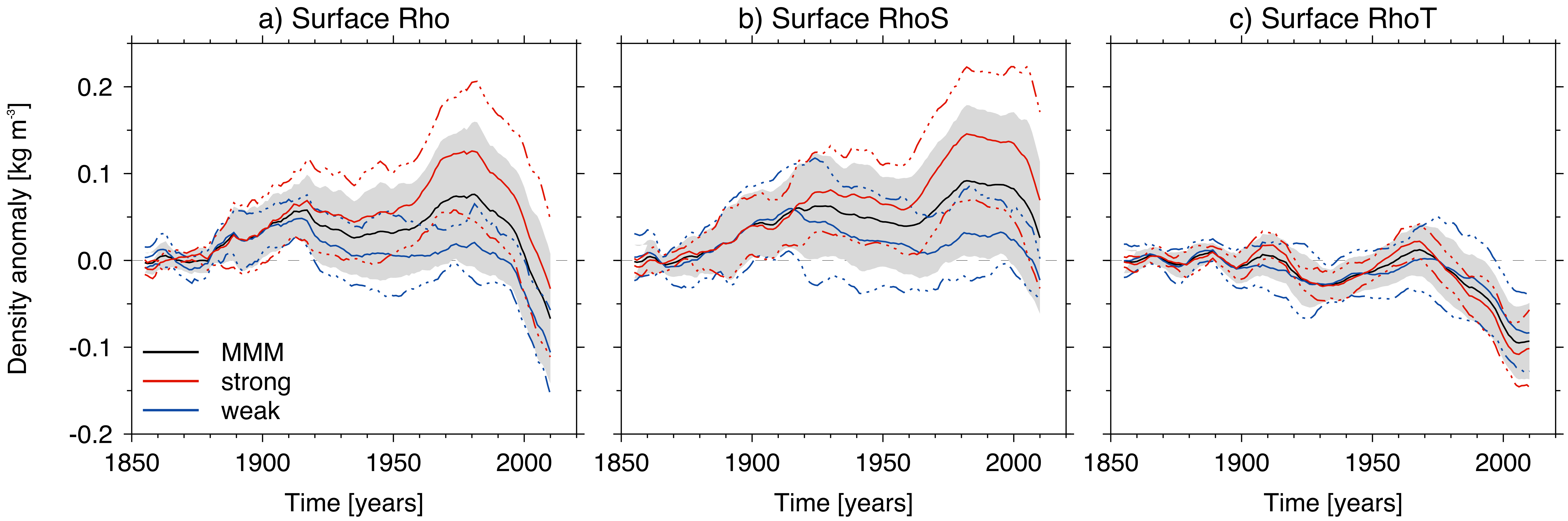
ΔH mainly from changes in surface specific humidity

Consistent with surface heat fluxes driving AMOC, and not vice versa

But… SST changes broaden and delay the peak in turbulent heat flux cooling

Robson et al., 2022

Surface density increases dominated by salinity changes



Surface density changes in the subpolar North Atlantic **match the evolution of the AMOC**

Long-term increase in density prior to 1970 is **dominated by increased salinity**

SPNA warming post-1970 causes a fast decrease in surface density anomalies

Robson et al., 2022

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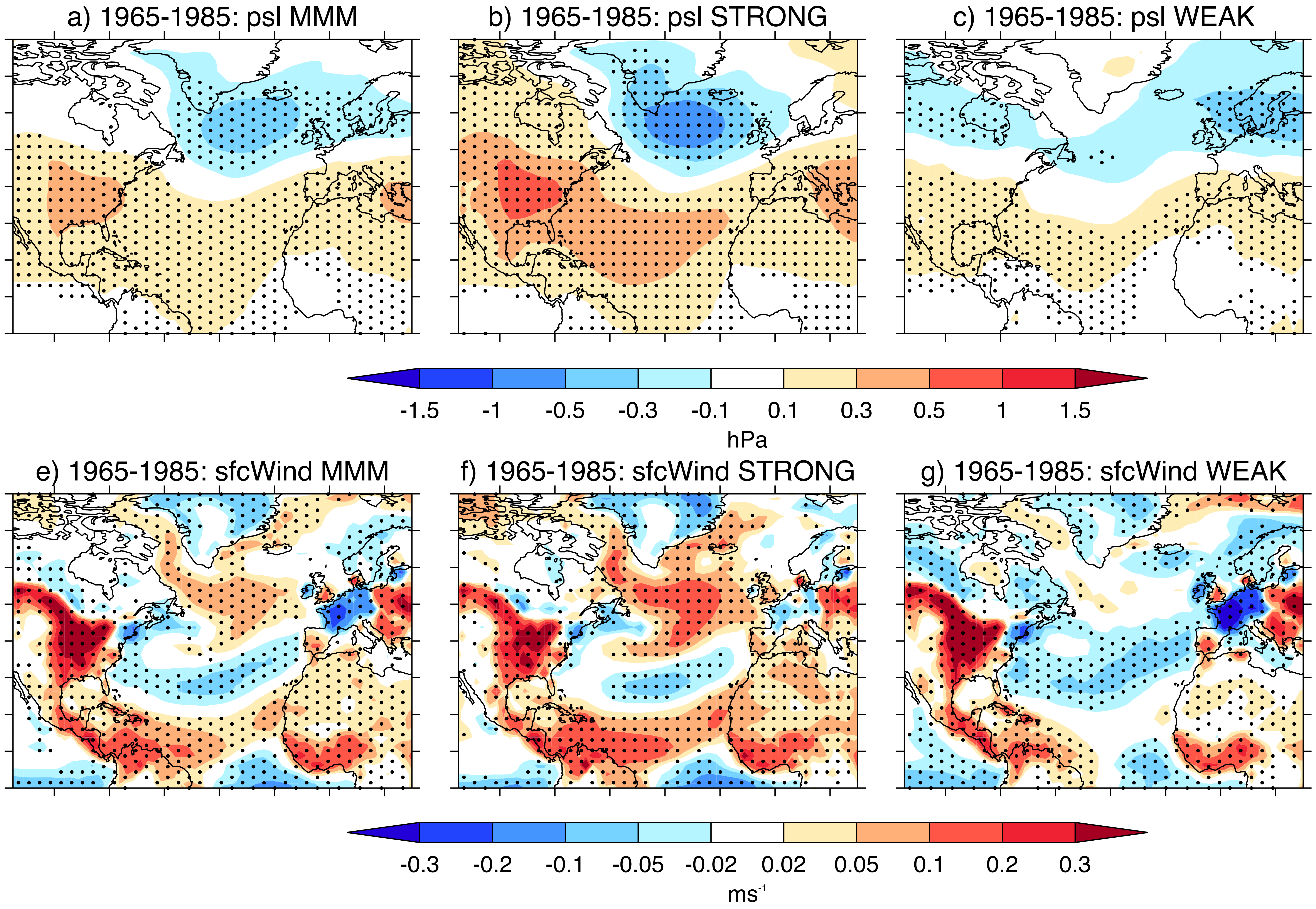
Atmospheric circulation anomalies



Increased meridional pressure gradient and **strengthened westerly winds**

Circulation response dominated by strong models

Does the stronger circulation response account for the stronger AMOC response?

Robson et al., 2022

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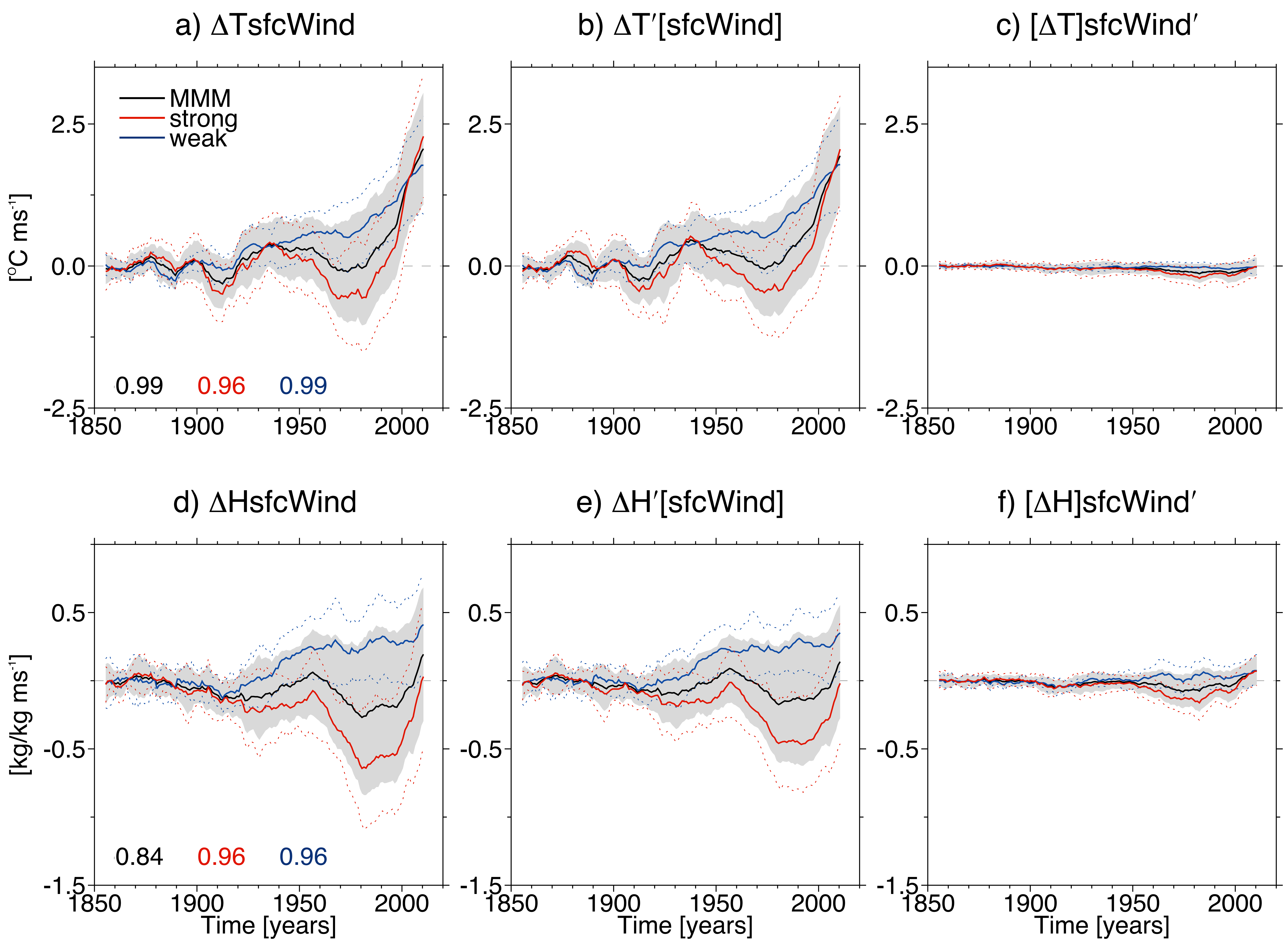
Linear decomposition of turbulent heat flux drivers



Turbulent heat fluxes are driven by changes in wind speed, and contrasts in temperature (ΔT) and humidity (ΔH) at the air-sea interface

ΔTsfcWind is strongly correlated with sensible heat flux, ΔHsfcWind is strongly correlated with latent heat flux

Simple linear decomposition of the form:

$$AB = A'[B] + [A]B' + A'B'$$

Thermodynamic changes drive the anomalies turbulent heat fluxes, and the difference between strong and weak models

Robson et al., 2022

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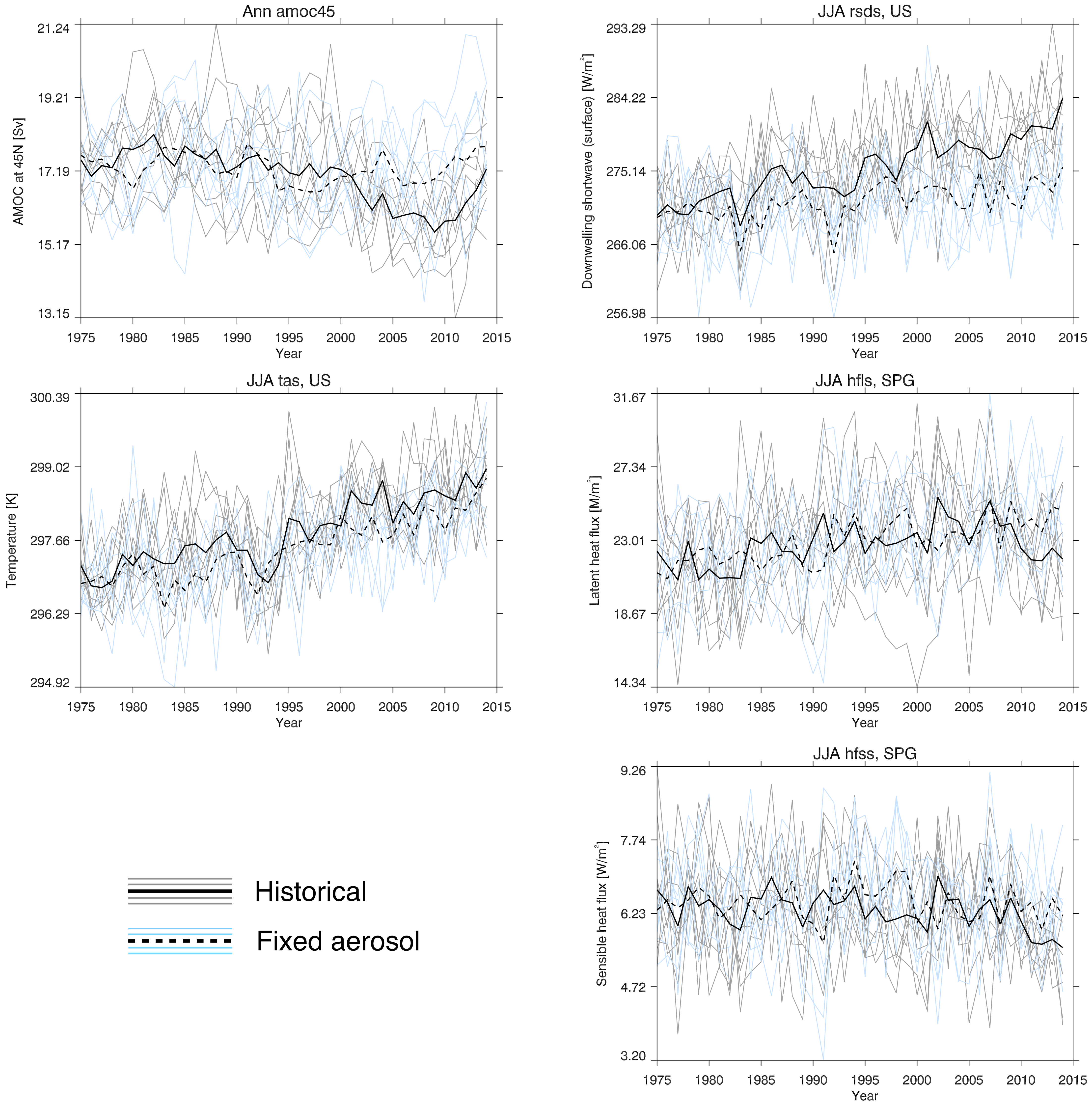
Complex picture post 1985



Wilcox et al., in prep.

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