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What drives the Arctic response to mid-latitude sulphate aerosol emissions?

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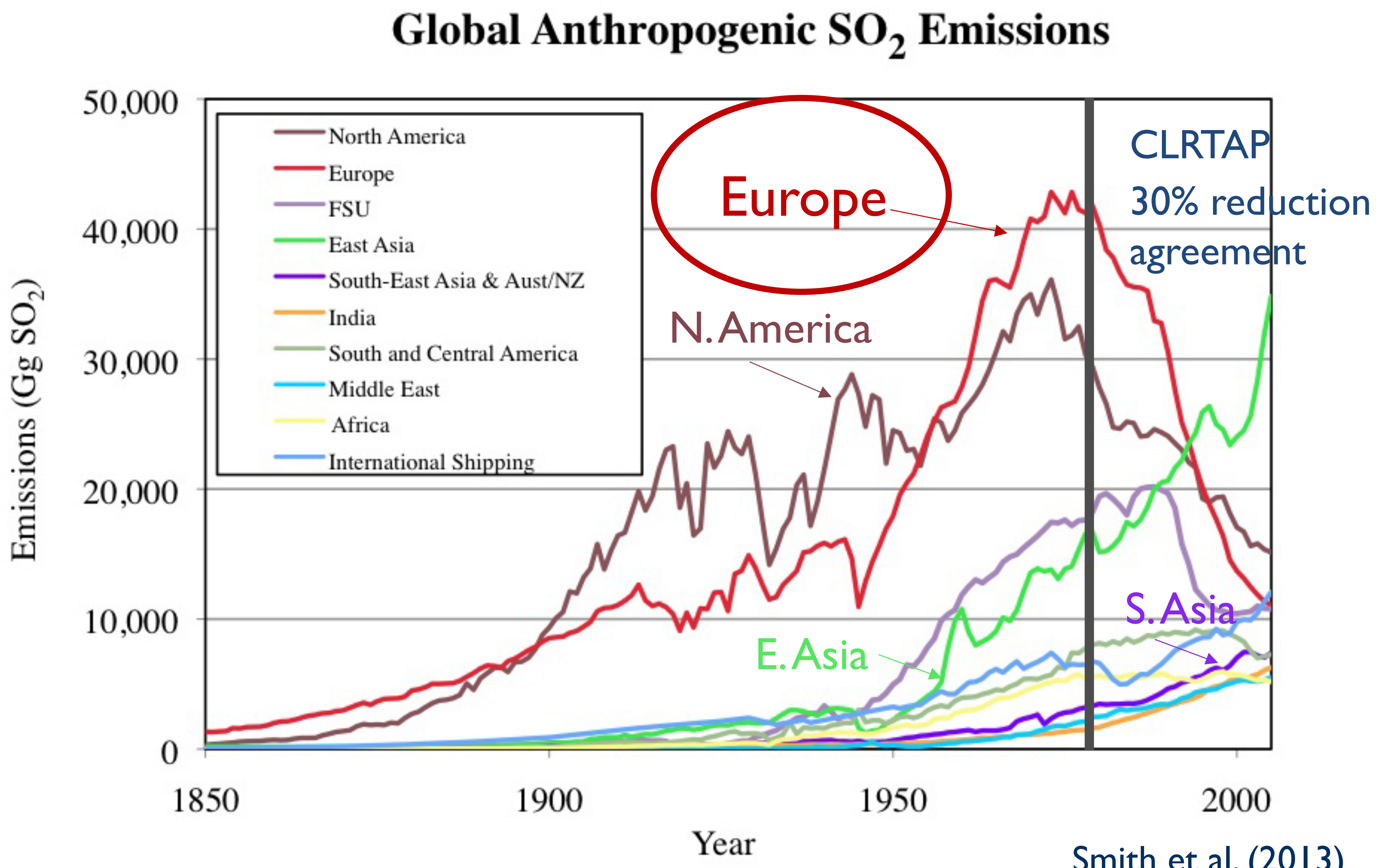
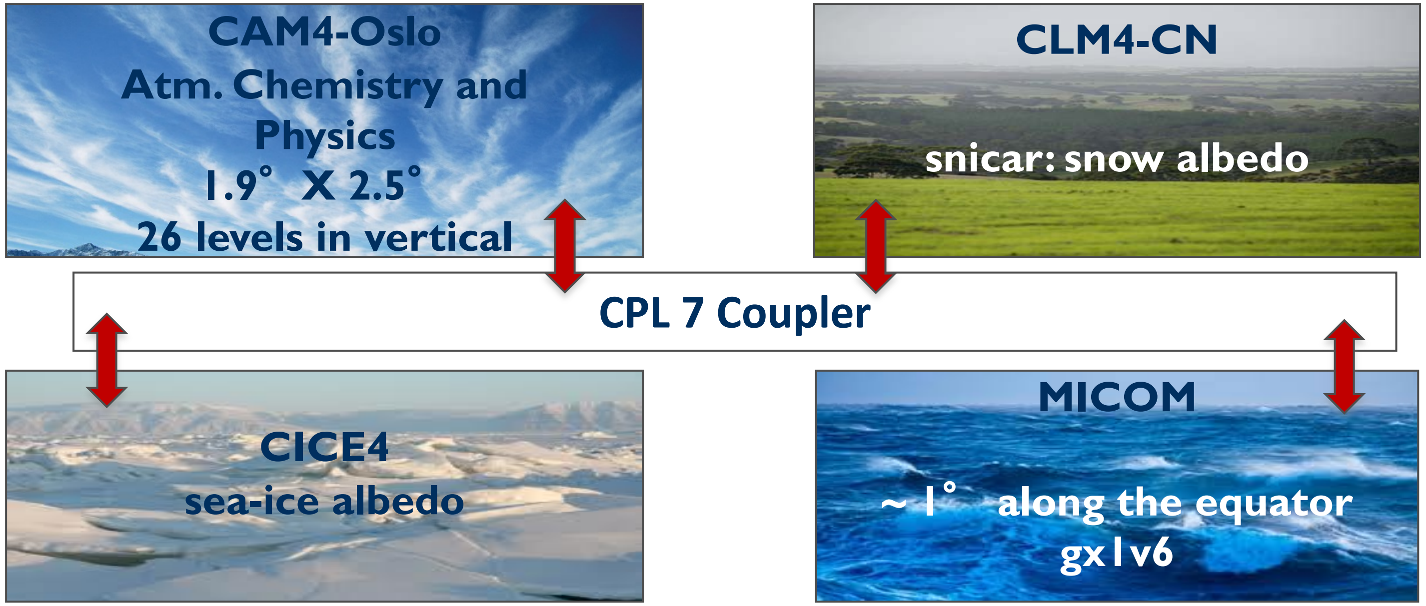
Motivation: Climate impacts of rapid reduction of SO_2 emissions in North America and Europe since 1980's



Smith et al. (2013)

We use the Norwegian Earth System Model (NorESM) ver. 1

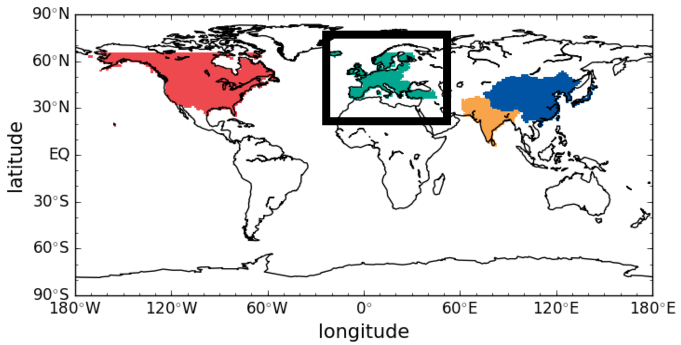


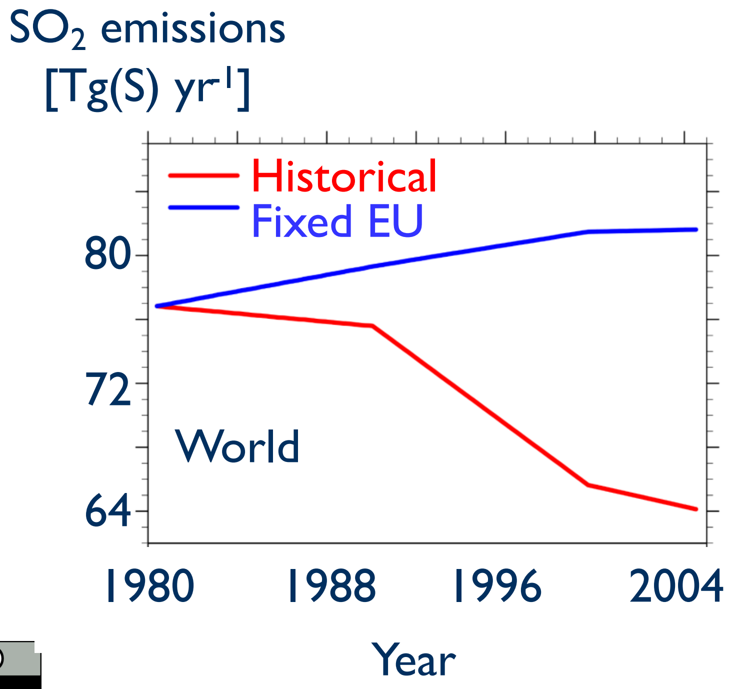
Bentsen et al., 2013; Iversen et al., 2013; Kirkevåg et al., 2013

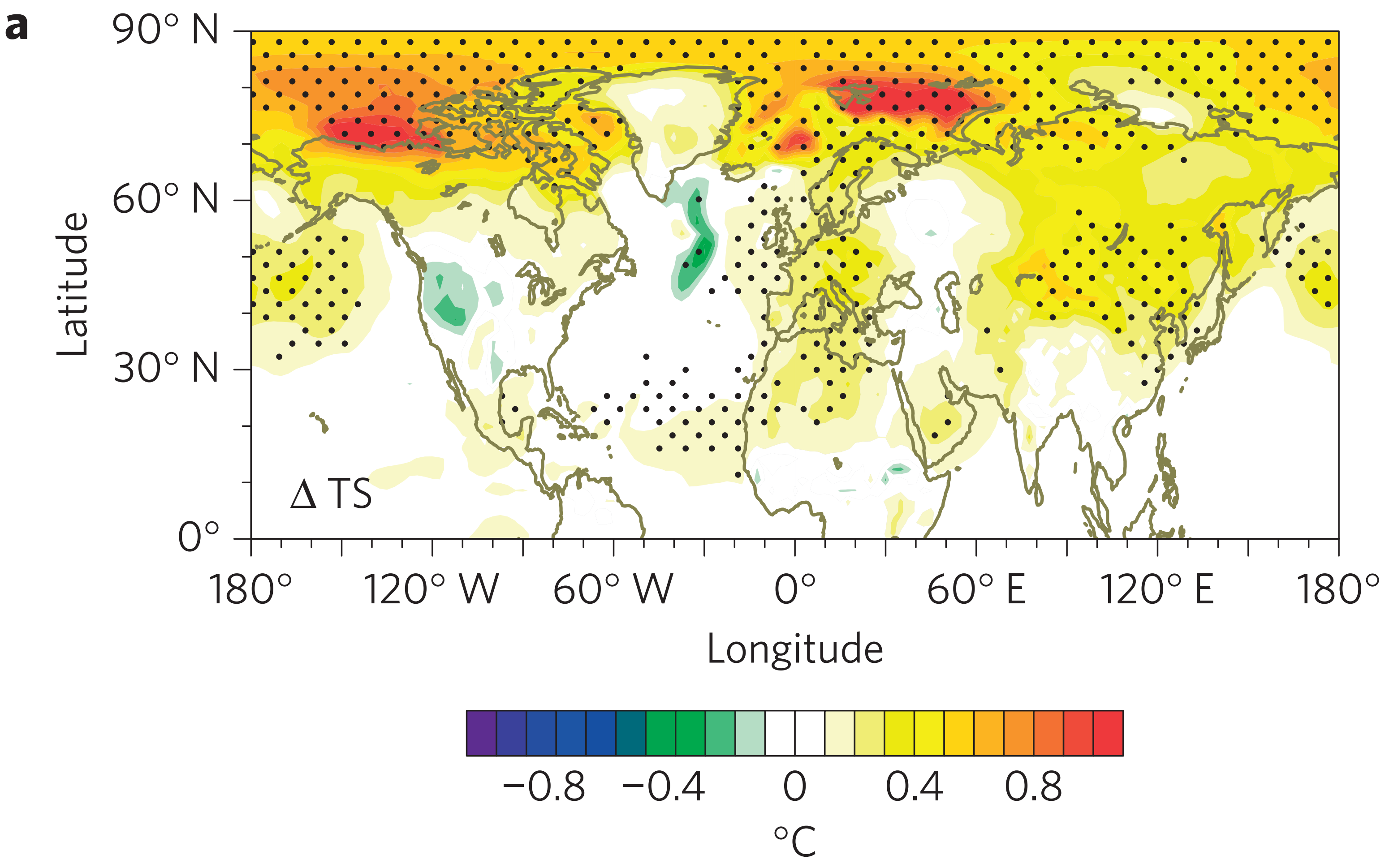
Aerosol module:

- Five aerosol compounds: sea salt, black carbon (BC), organic matter (OM), sulfate and mineral dust
- Aerosols can be both internally and externally mixed.
- Chemical and physical processing (i.e. the size distribution) of the aerosol population is described using 44 size bins.
- Aerosols are simulated online, i.e. they interact with radiation, meteorology etc.
- Both direct and indirect (cloud albedo and lifetime) aerosol effects are simulated.

Previous studies below have used NorESM to look at climate impacts using historical changes (since the1980s)

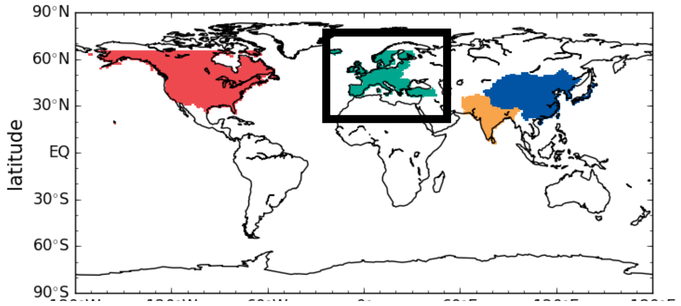




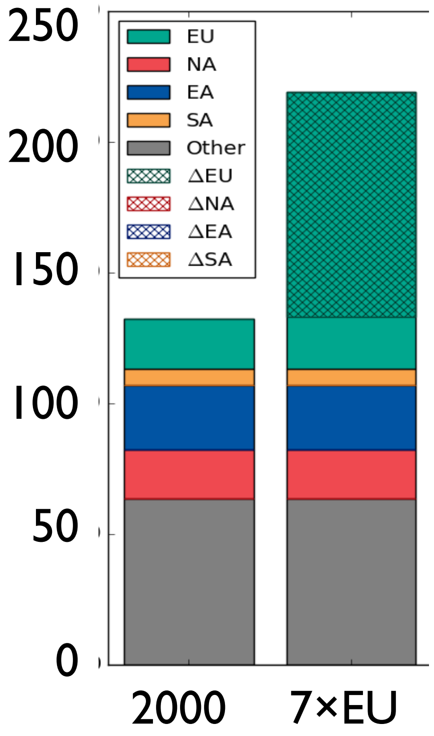


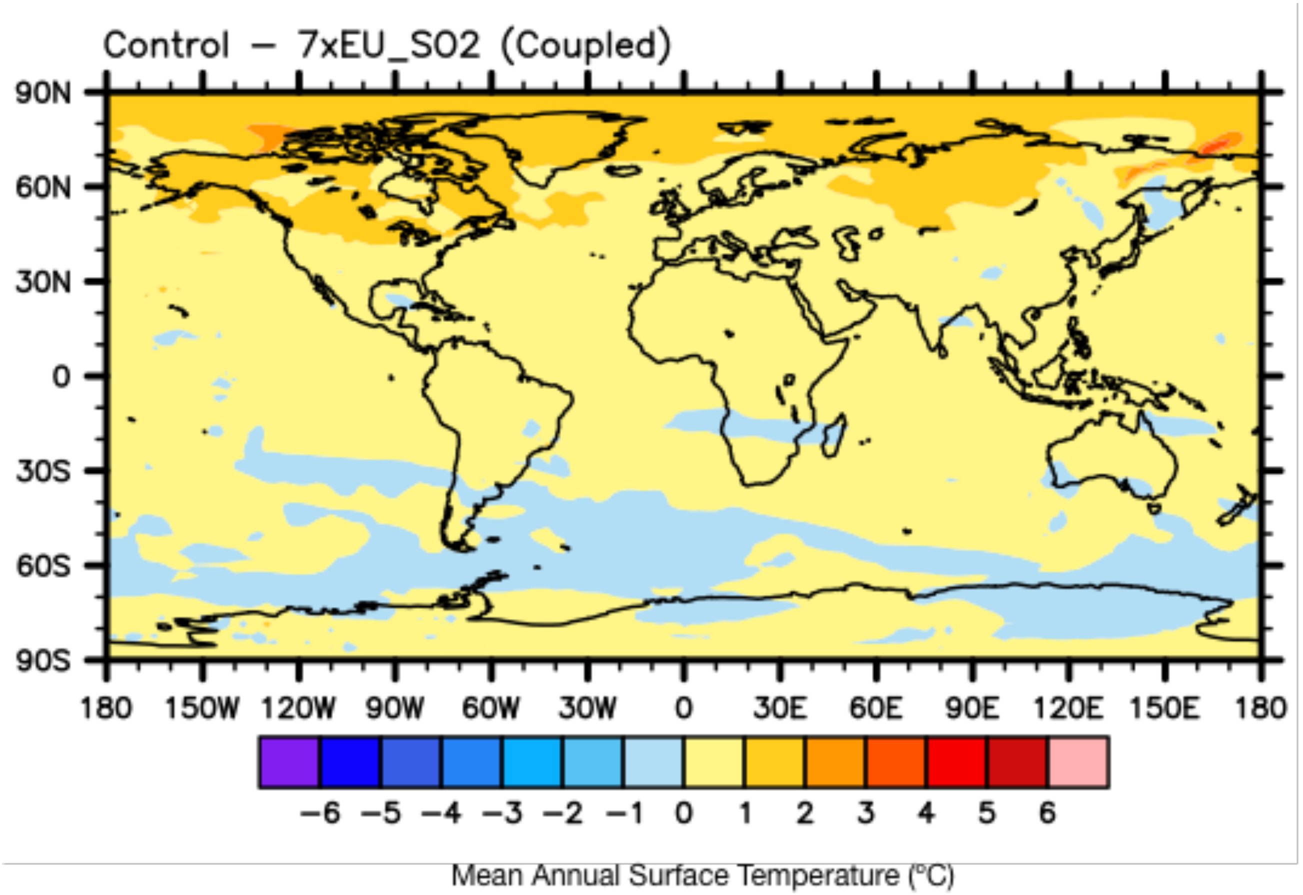
Acosta Navarro et al. (2016)

Previous studies below have used NorESM to look at climate impacts using idealized changes (7xEU SO_2)



SO_2 emissions [Tg yr^{-1}]





Temperature change: -0.0056°C/TgS $year^{-1}$

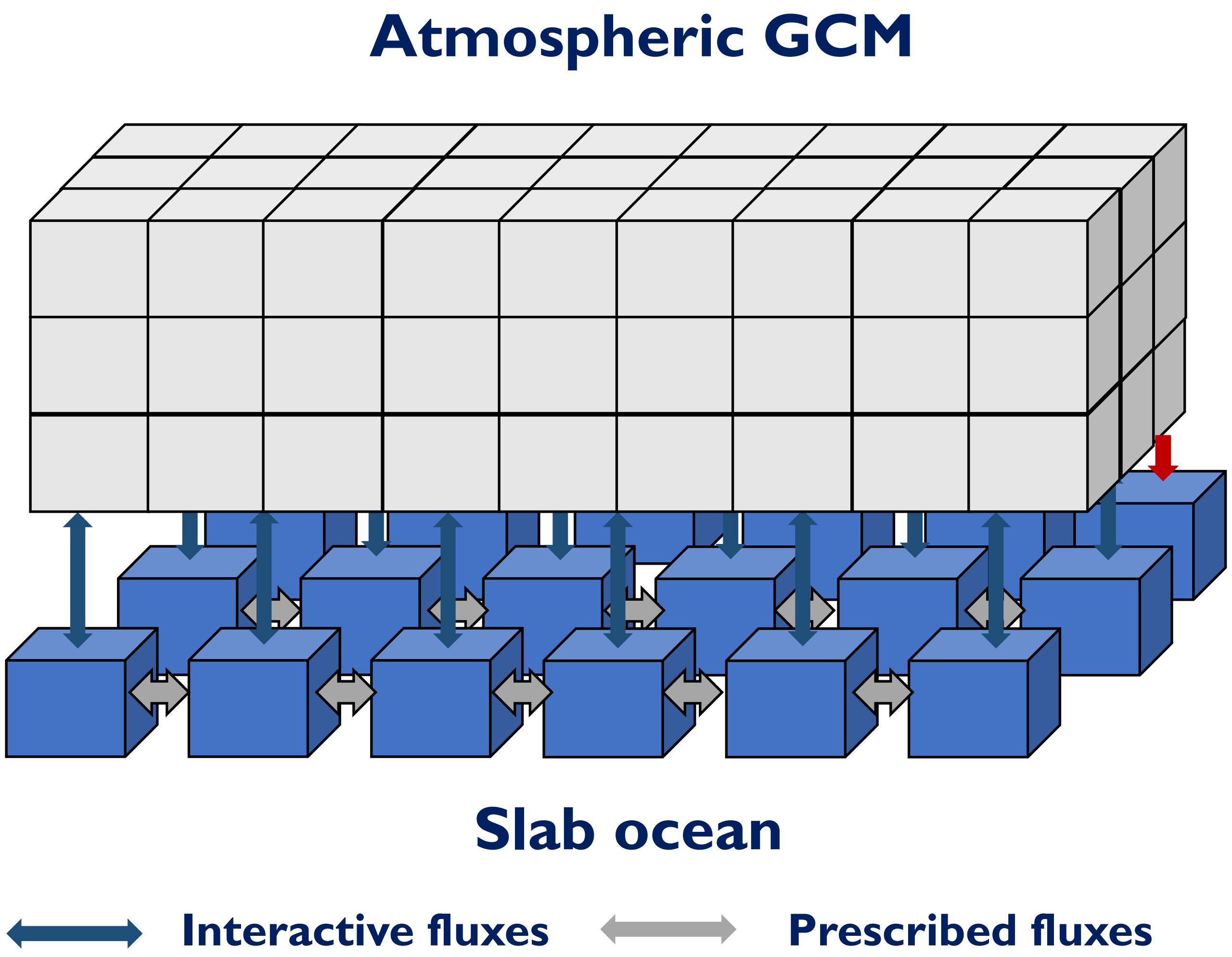
Lewinschal et al. (2019)

Questions

- Is the Arctic response in NorESM driven through atmosphere or the ocean?
  - *Run slab-ocean simulations to evaluate the changes driven by ocean-heat transport alone and atmospheric pathways*

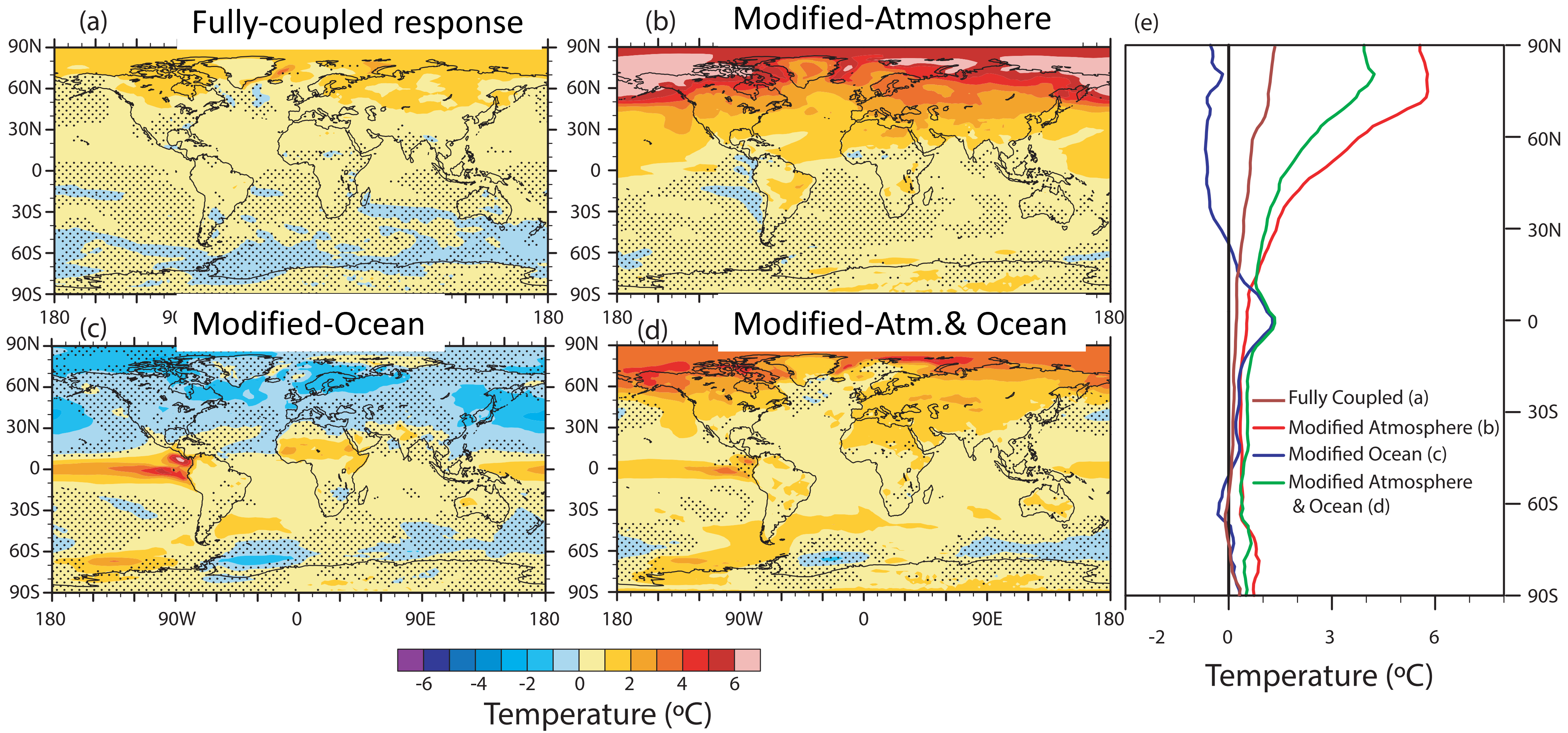
- What are the mechanisms that drives the initial Arctic response (first 50 years)?
  - *Run a series of initial-condition ensemble simulations with the modified aerosol forcing to get statistically robust changes that explain the Arctic response*

Is it the Atmosphere? Is it the Ocean?
Slab-ocean model experiments



Simulation	Exp. Type	Atm. SO_2 levels	Ocean Heat Convergence Fluxes
Fully-coupled	Control	Year 2000	
Fully-Coupled	7xEU SO_2	7xEU SO_2	
Slab	Control	Year 2000	Year 2000
Slab	Mod. Atm	7xEU SO_2	Year 2000
Slab	Mod. Ocean	Year 2000	7xEU SO_2
Slab	Mod. Atm & Ocn	7xEU SO_2	7xEU SO_2

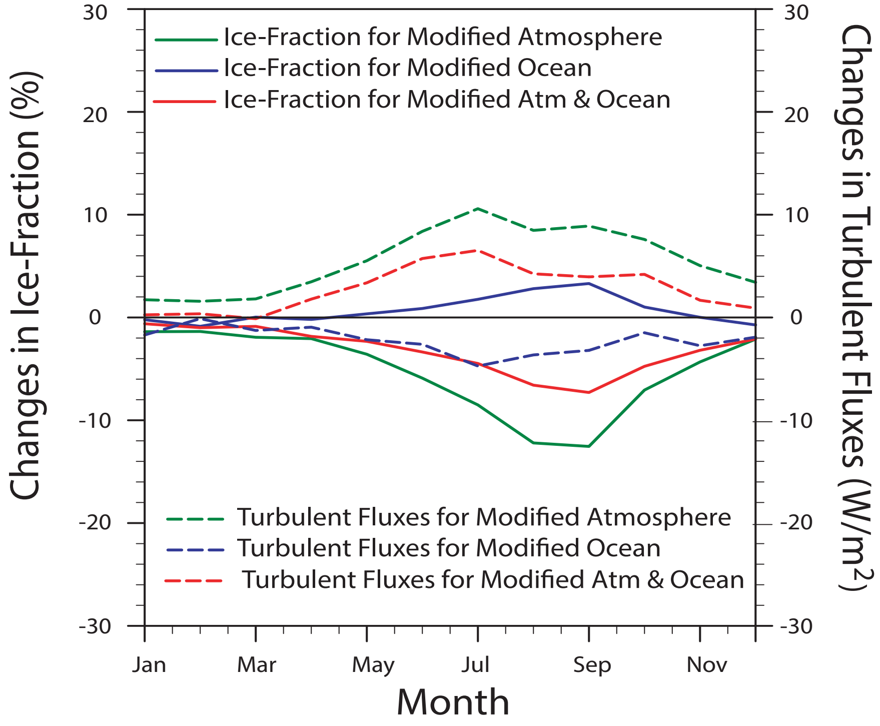
Question 1: Is it the Atmosphere? Is it the Ocean?

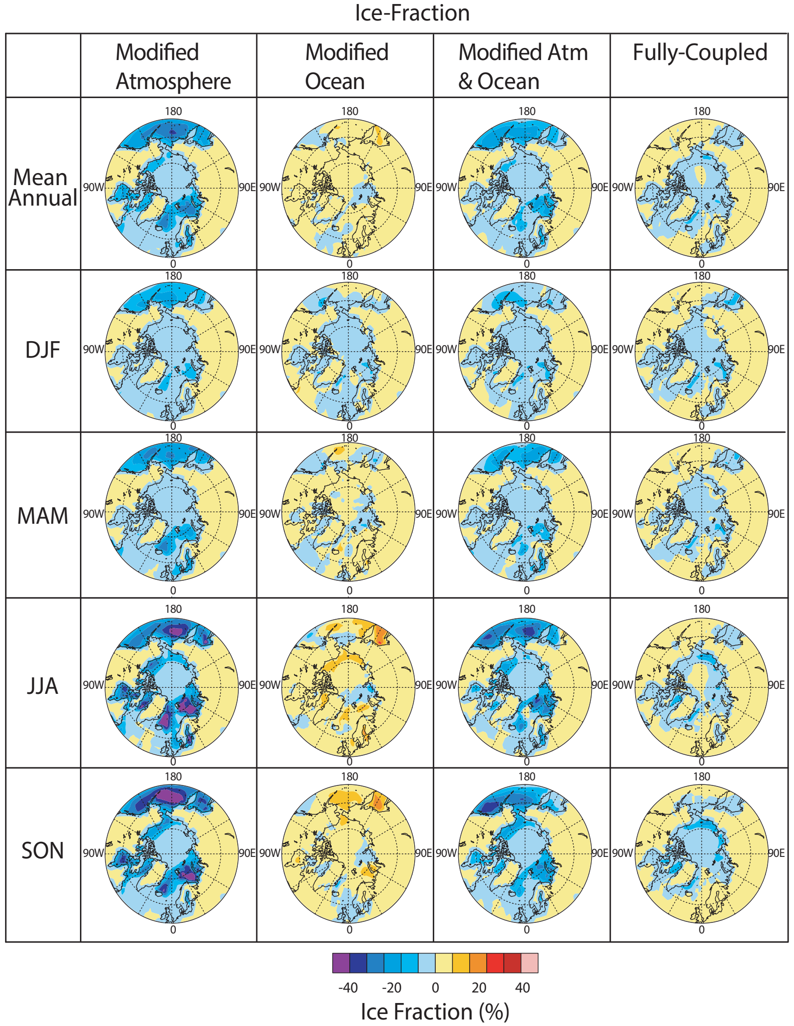


Largest changes are observed in simulations where the atmosphere is perturbed. Changes in ocean heat transport play a secondary role and even counters the changes – as seen in the modified Atm & Ocean run. These changes are still larger than that predicted by the fully-coupled model.

Krishnan et al., 2020 (GRL)

Probably the Atmosphere… But why?





Changes in Arctic temperatures are driven by changes in turbulent fluxes – related to changes in the sea-ice fraction. This suggests that the Arctic response is modulated by changes in Arctic sea-ice.

Question II: What drives the sea-ice changes and Arctic response through atmospheric changes?

- Proposed plan
  - To run a set of initial-condition ensemble simulations with the fully-coupled model and perturbed aerosol forcing from Europe
- Initial-condition Ensemble: Individual member simulations differ by small perturbations, which grow with time due to the unpredictable variability (“chaos”).
- Allows the ensemble to capture uncertainty in initial conditions, and the variability in changes driven by the modified aerosol forcing

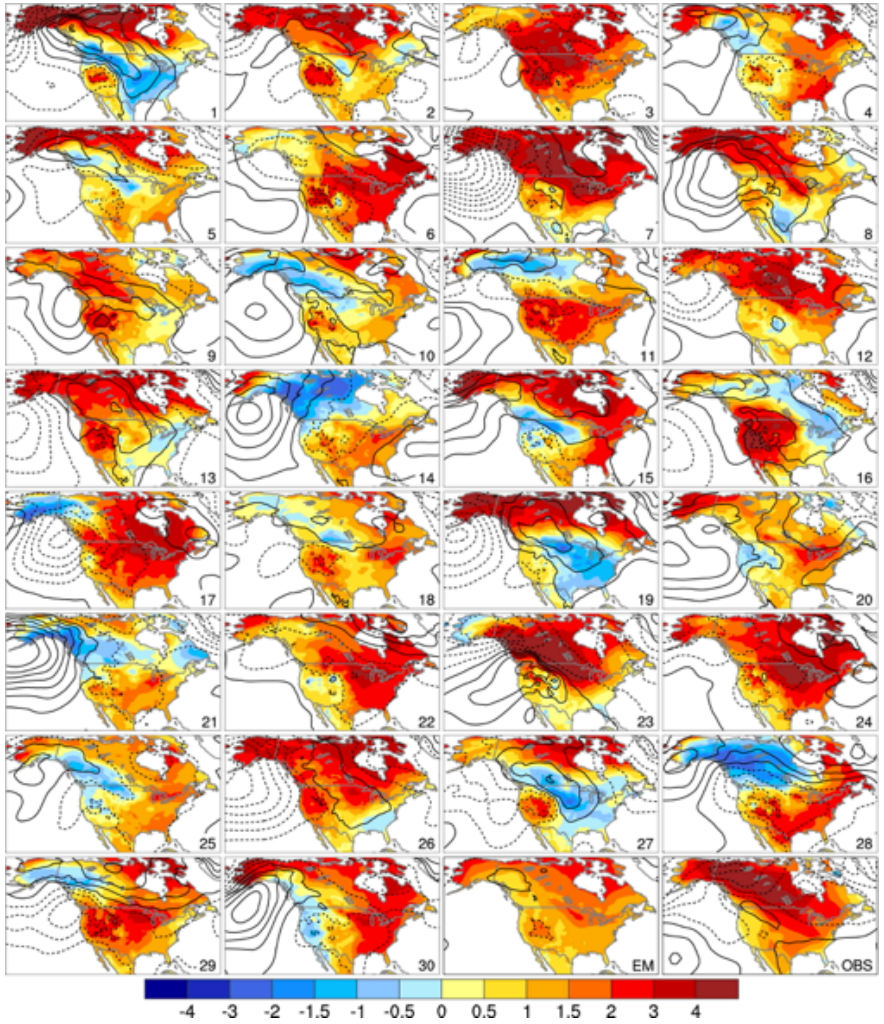


Fig. 1. DJF SAT [color shading; °C (50 yr)−1] and SLP [contours; hPa (50 yr)−1] trends (1963–2012) for each member of the CESM-LE (labeled 1–30), the CESM-LE ensemble-mean trend (labeled EM), and observations (labeled OBS). SLP contour interval is 1 hPa (50 yr)−1 starting at ±0.5 hPa (50 yr)−1, with solid (dashed) contours for positive (negative) values. SAT and SLP observation are from MLOST and 20CR, respectively. (Deser et al., 2016)

Goal II: What drives the sea-ice melt and Arctic response through atmospheric changes?

- Proposed plan
  - To run initial-condition ensemble with perturbed aerosol forcing
  - Similar to the CESM-Large ensemble approach
  - Apply random perturbations to 3-D temperature field and start from Year 2000 using pertlim (i.e. a random T perturbation is generated for each vertical level based on user-specified conditions)
  - Initiate the model at different time points during the year (winter vs. summer start)

THE COMMUNITY EARTH SYSTEM MODEL (CESM) LARGE ENSEMBLE PROJECT

A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability

BY J. E. KAY, C. DESER, A. PHILLIPS, A. MAI, C. HANNAY, G. STRAND, J. M. ARBLASTER, S. C. BATES, G. DANABASOGLU, J. EDWARDS, M. HOLLAND, P. KUSHNER, J.-F. LAMARQUE, D. LAWRENCE, K. LINDSAY, A. MIDDLETON, E. MUNOZ, R. NEALE, K. OLESON, L. POLVANI, AND M. VERTENSTEIN

By simulating climate trajectories over the period 1920–2100 multiple times with small atmospheric initialization differences, but using the same model and external forcing, this community project provides a comprehensive resource for studying climate change in the presence of internal climate variability.

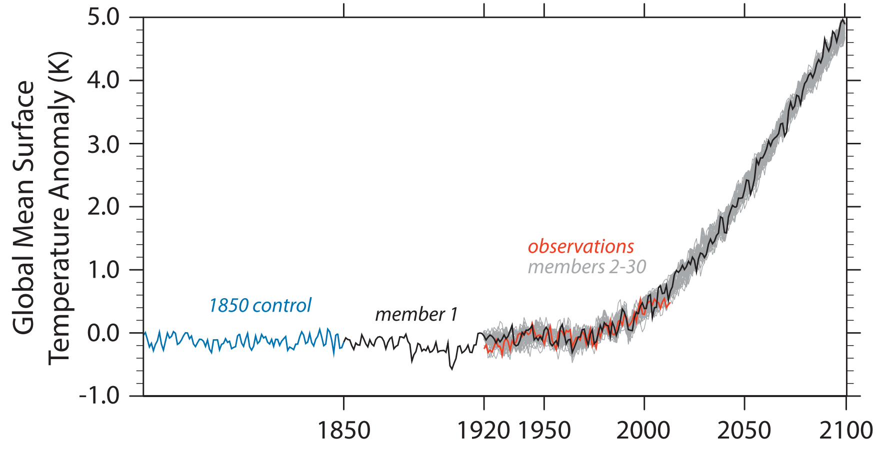
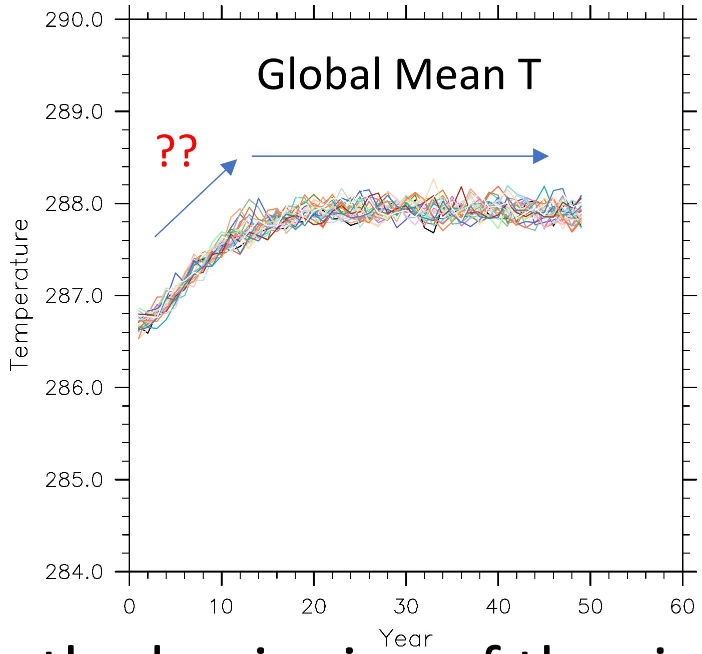


FIG. 2. Global surface temperature anomaly (1961–90 base period) for the 1850 control, individual ensemble members, and observations (HadCRUT4; Morice et al. 2012).

Goal II: What drives the sea-ice melt and Arctic response through atmospheric changes?

Unfortunately, Technical Issues!



- Global mean temperatures in the beginning of the simulations start much colder, followed by a warming of 10 years to reach “equilibrium”
- <u>Possible Issues</u>
  - Random perturbation being too large
  - Model not in an equilibrium state to begin with
  - Wrong compiler flags, initial condition files, ocean set-up

Conclusions

- In NorESM, the Arctic response is primarily driven by the atmospheric pathway
- This response is modulated by changes in Arctic sea-ice fraction, which alters the turbulent flux and energy exchanges between the ocean and the atmosphere.
- We propose to conduct a series of initial-condition ensemble simulations with modified aerosol forcing to constrain the mechanisms that drive the initial Arctic response!