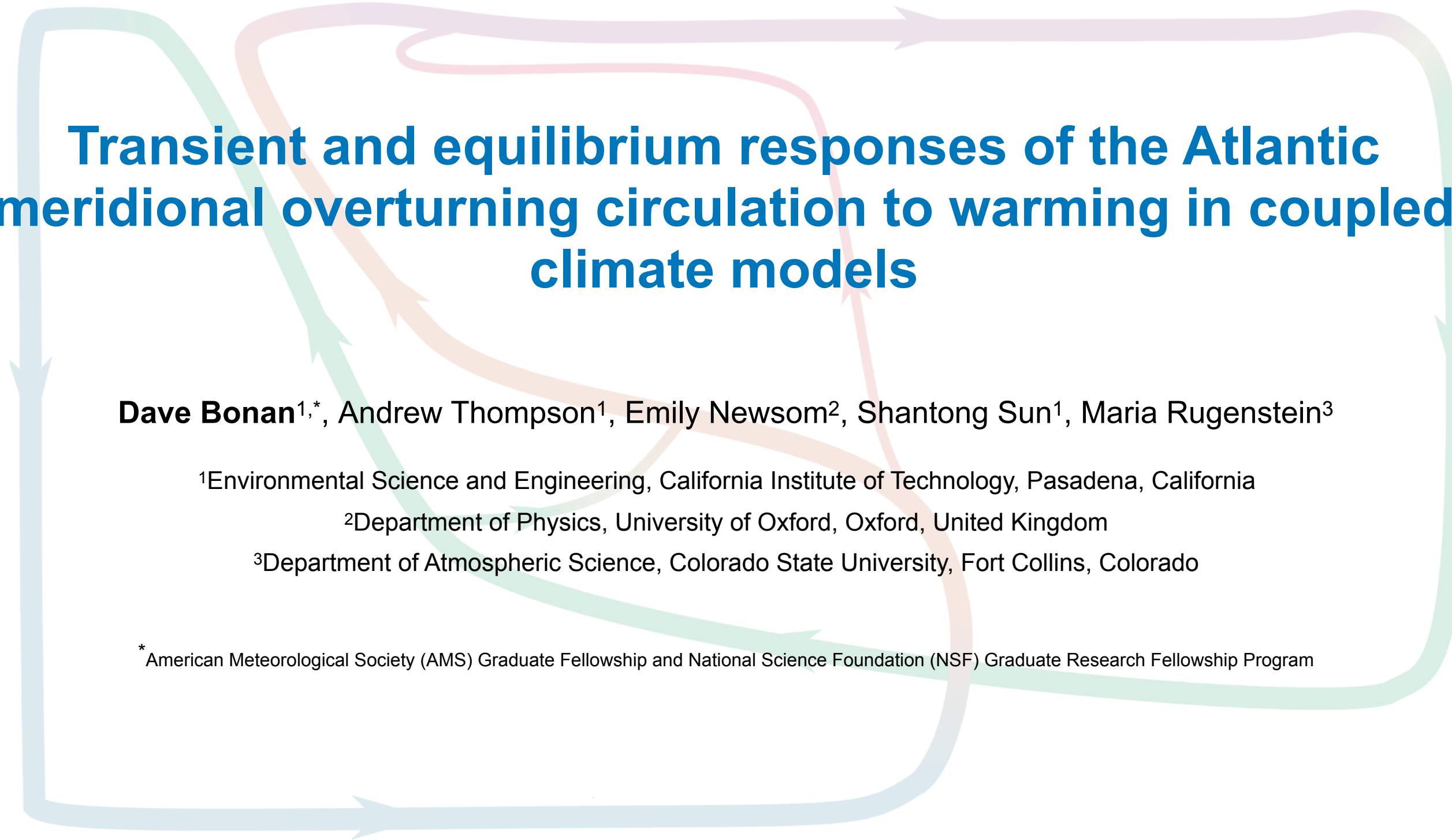




Transient and equilibrium responses of the Atlantic meridional overturning circulation to warming in coupled climate models

Dave Bonan^{1,*}, Andrew Thompson¹, Emily Newsom², Shantong Sun¹, Maria Rugenstein³

¹Environmental Science and Engineering, California Institute of Technology, Pasadena, California

²Department of Physics, University of Oxford, Oxford, United Kingdom

³Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

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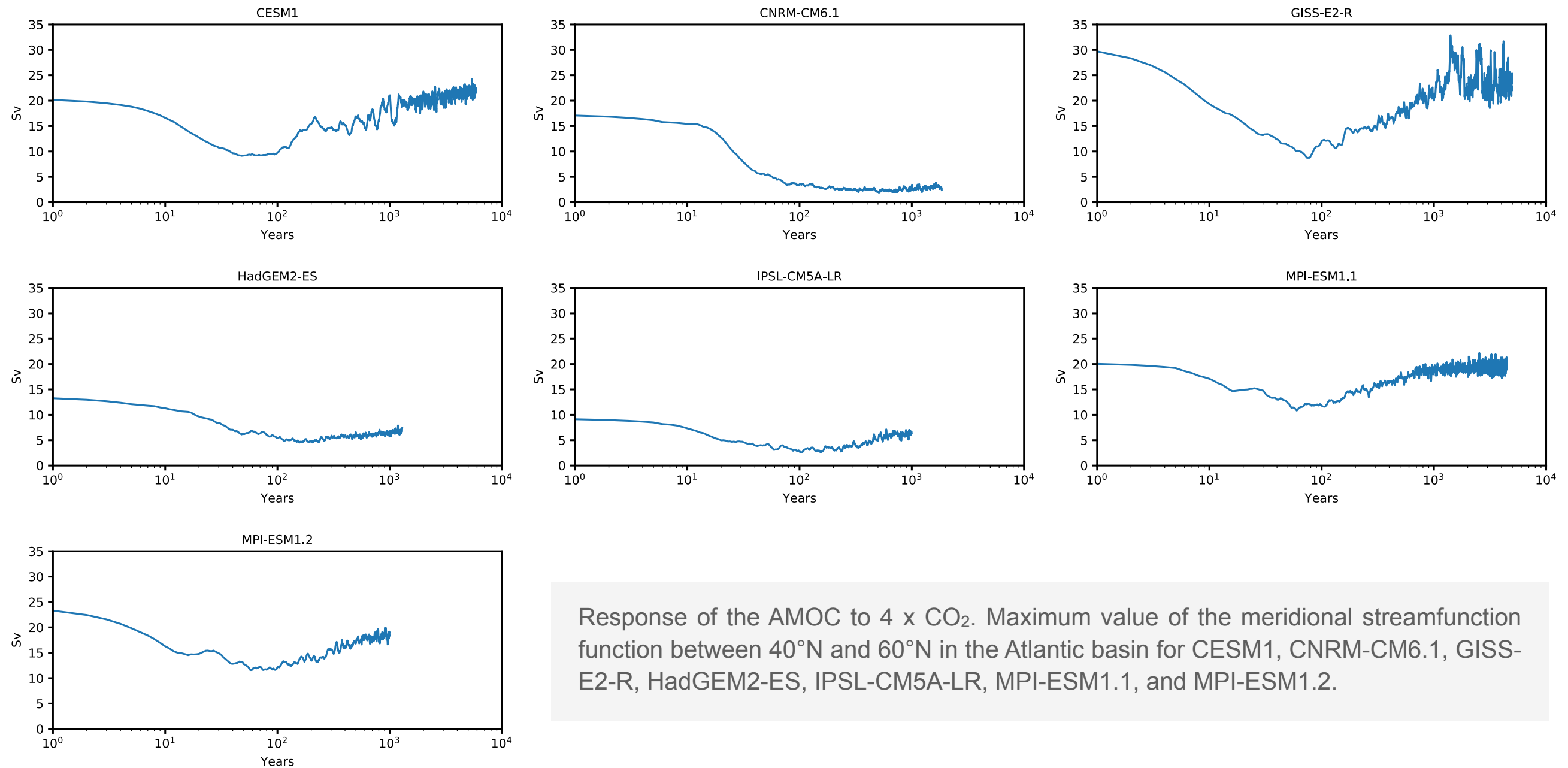
Motivation for this study

- The **Atlantic meridional overturning circulation (AMOC)** plays a fundamental role in shaping Earth's climate through its control on the northward transport of heat and freshwater, ocean heat uptake, and climate variability.
- In response to increased greenhouse gas concentrations, **global climate models (GCMs) consistently predict a weakening of the AMOC over the 21st century**. Beyond the 21st century, the response of the AMOC to increased greenhouse gas concentrations is less clear. **Because of the computational expenses associated with running GCMs to equilibrium, few studies have considered the long-term response of the AMOC to global warming** (e.g., Stouffer and Manabe, 2003).
- In recent years, idealized models of the ocean's overturning have significantly improved our understanding of the long-term response of the AMOC to global warming (Jansen et al., 2018). **While idealized models are convenient in that it costs relatively little to simulate the ocean circulation for multiple millennia, the lack of more sophisticated processes may inhibit a better understanding of the behavior of the AMOC**. GCMs, on the other hand, which include many of these sophisticated processes, are often only run for multiple centuries due to the computational expenses associated with simulating multiple millennia.
- **The goal of this study is to identify processes influencing the long-term evolution of the AMOC in response to global warming in more realistic climate models**. To do this, **we use a unique collection of millennial-length simulations from state-of-the-art GCMs** and examine the transient and equilibrium responses of the AMOC to an abrupt quadrupling of atmospheric carbon-dioxide above pre-industrial levels ($4 \times \text{CO}_2$).

LongRunMIP: millennial-length climate simulations

Rugenstein et al., (2019)

A collection of coupled climate models to study century and millennia time scales of atmosphere-ocean processes

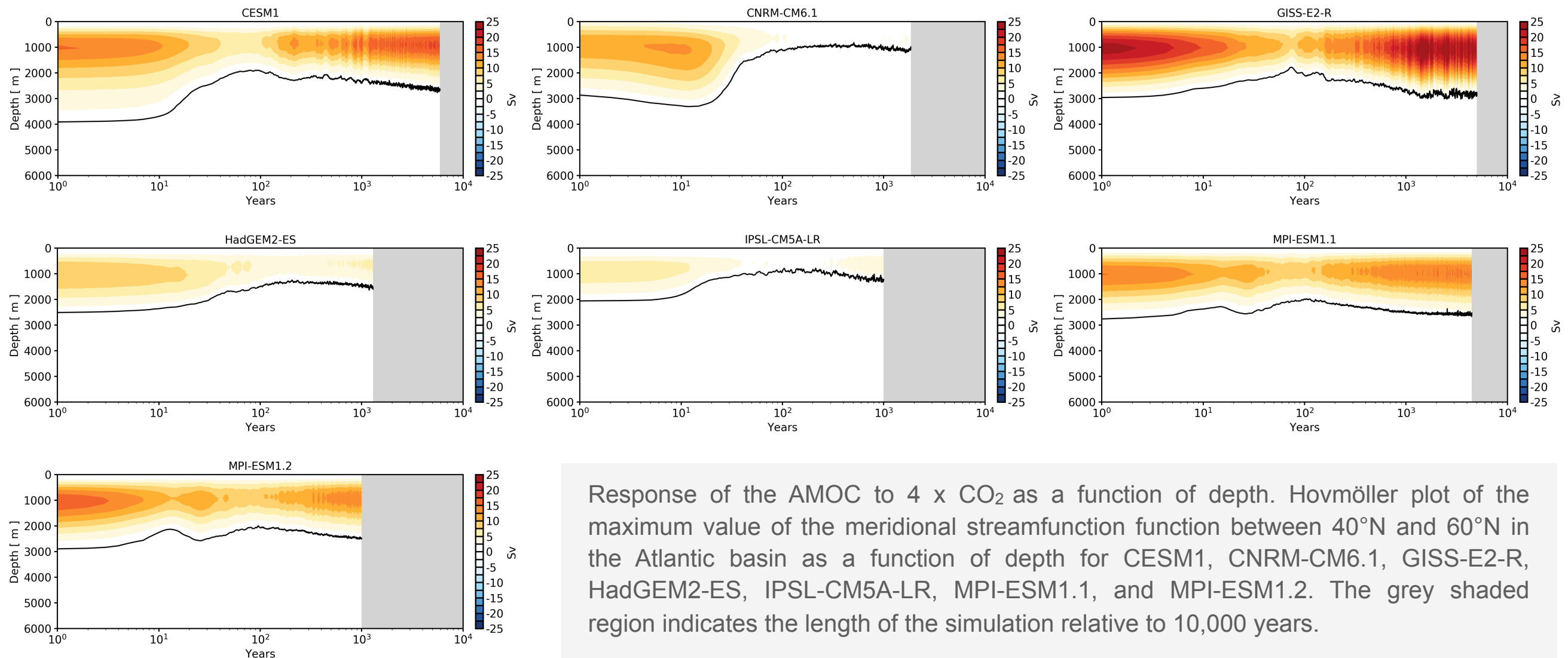


- In response to increased greenhouse-gas concentrations the AMOC weakens on centennial timescales across all GCMs. After the initial weakening, most GCMs show a recovery of the AMOC. The recovery occurs much quicker in some GCMs (e.g., CESM1) when compared to others (e.g., CNRM-CM6.1). After approximately 3000 years, the AMOC is stronger than the initial state in some GCMs.

LongRunMIP: millennial-length climate simulations

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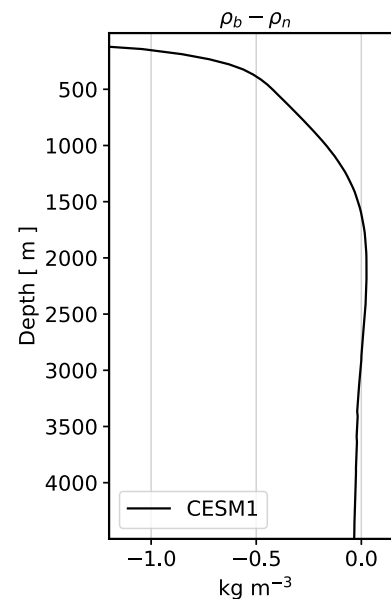
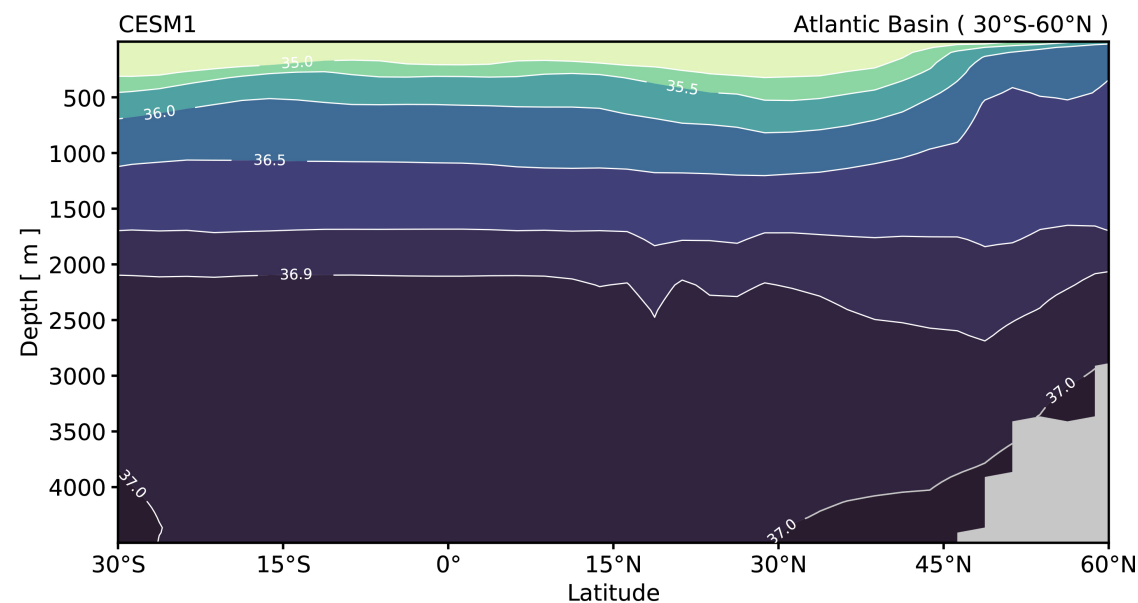


Response of the AMOC to 4 x CO₂ as a function of depth. Hovmöller plot of the maximum value of the meridional streamfunction function between 40°N and 60°N in the Atlantic basin as a function of depth for CESM1, CNRM-CM6.1, GISS-E2-R, HadGEM2-ES, IPSL-CM5A-LR, MPI-ESM1.1, and MPI-ESM1.2. The grey shaded region indicates the length of the simulation relative to 10,000 years.

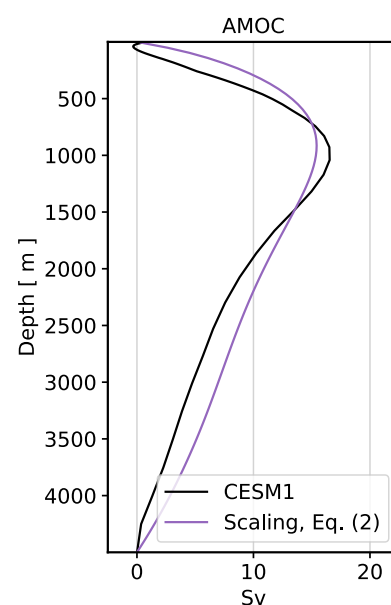
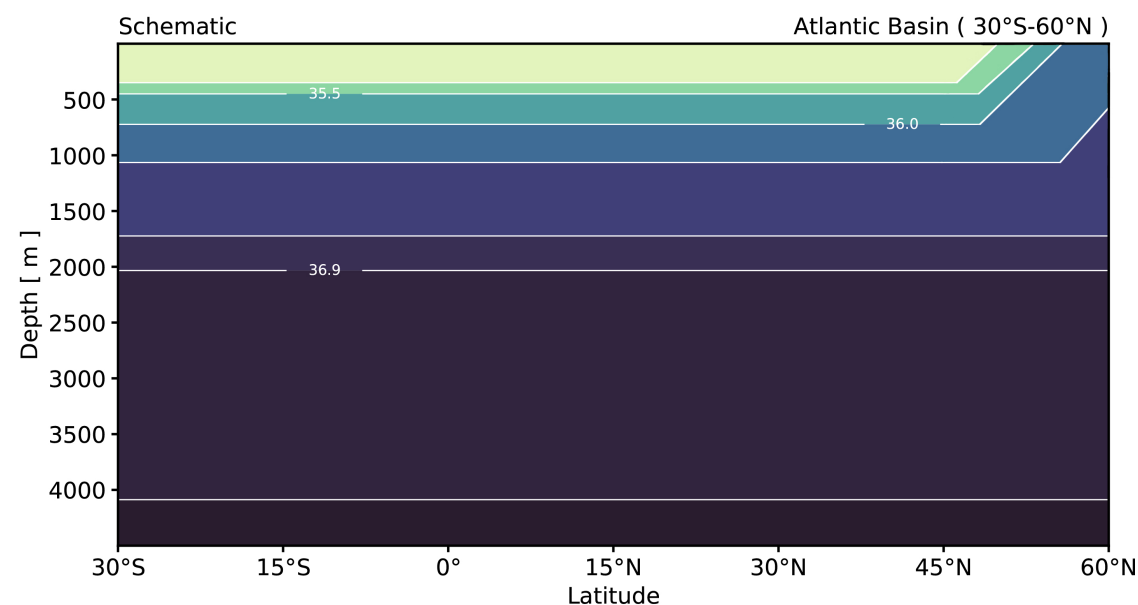
- All GCMs exhibit a shoaling of the AMOC in addition to a weakening on centennial timescales. The depth at which the transport of the upper cell equals zero shoals by 500-3000 meters in each GCM (see black line). In most GCMs, the AMOC restrengthens and deepens over the next millennia, though to varying degrees (e.g., compare CESM1 and CNRM-CM6.1).
- What processes set the strength and depth of the AMOC in each GCM?

Mechanisms controlling the strength and depth of the AMOC

Thermal-wind expression relates basin-wide stratification to overturning in the North Atlantic



$$\frac{\partial^2 \psi}{\partial z^2} = \frac{g}{\rho_0 f} \left(\underbrace{\rho_b}_{\text{basin } 30^\circ\text{S}-60^\circ\text{N}} - \underbrace{\rho_n}_{\text{north } 40^\circ\text{N}-60^\circ\text{N}} \right)$$



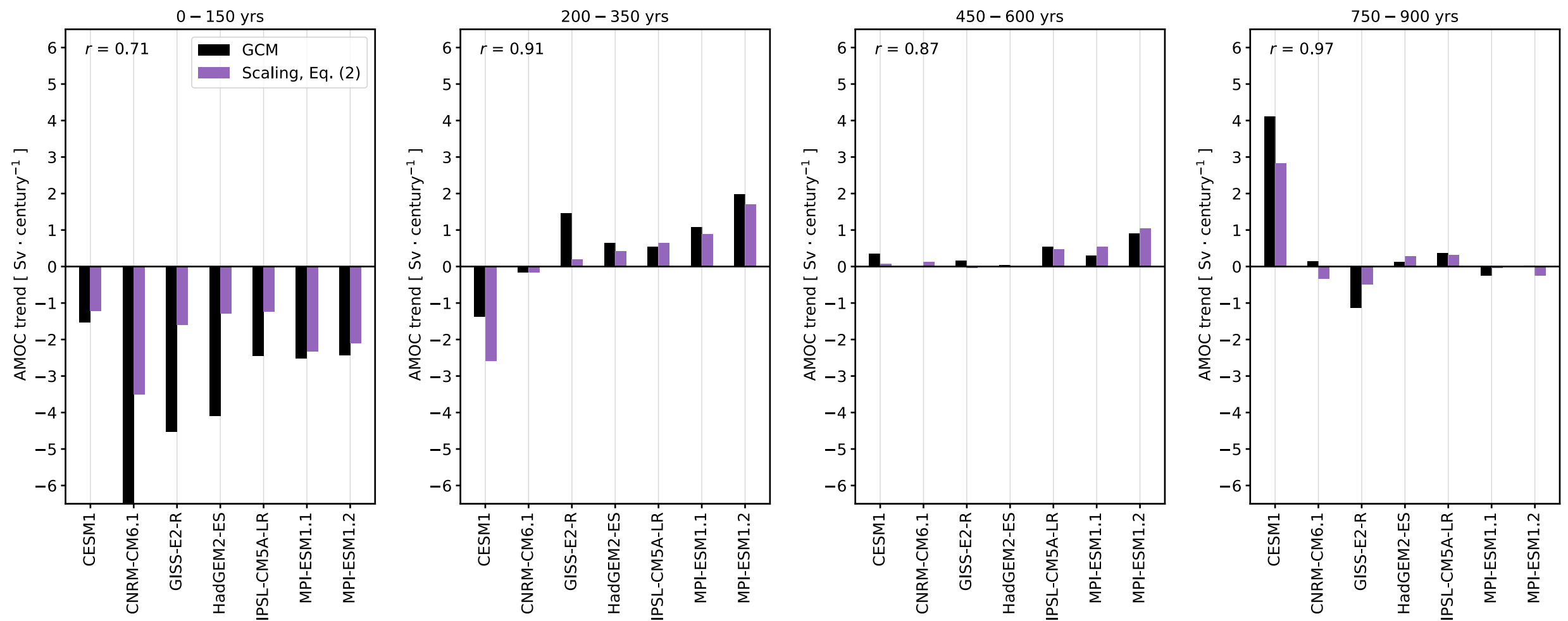
Meridional section of isopycnals averaged zonally across the entire Atlantic basin in CESM1 and a schematic of the isopycnals in the Atlantic basin which remain relatively flat throughout the Atlantic basin and outcrop in the North Atlantic. Difference between the density profile in the Atlantic basin (30°S-60°N) and in the North Atlantic (40°N-60°N) in CESM1 and the associated overturning streamfunction from the thermal-wind expression.

- To provide a more mechanistic interpretation of the AMOC responses in each GCM, we relate the overturning circulation in the North Atlantic to the density difference between the interior of the Atlantic basin and the region of deep-water formation. A comparison of the streamfunction produced by the thermal-wind scaling and the streamfunction diagnosed from CESM1 shows that magnitude and structure of the AMOC can be well approximated.

Nikurashin and Vallis, (2012); Jansen et al., (2018)

Mechanisms controlling the strength and depth of the AMOC

$$\frac{\partial^2 \psi}{\partial z^2} = \frac{g}{\rho_0 f} \left(\underbrace{\rho_b}_{30^\circ\text{S}-60^\circ\text{N}} - \underbrace{\rho_n}_{40^\circ\text{N}-60^\circ\text{N}} \right)$$



Comparison of the meridional streamfunction estimated from GCMs and calculated from the thermal-wind scaling. Linear trend of the maximum value of the meridional streamfunction function in GCMs between 40°N and 60°N in the Atlantic basin (black) and of the thermal-wind scaling (purple) from 0-150 years, 200-350 years, 450-600 years, and 750-900 years.

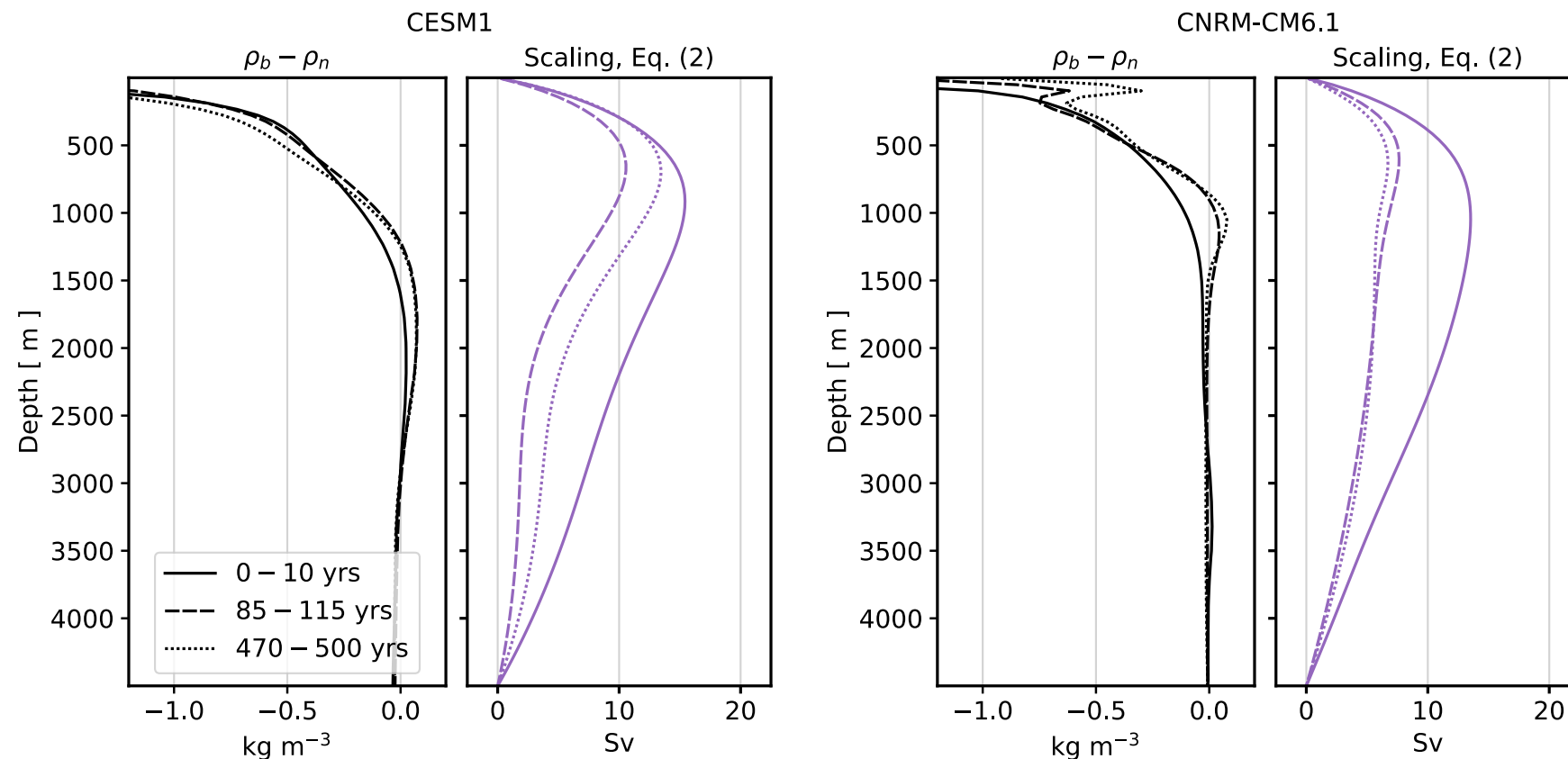
- The thermal-wind scaling also explains the inter-model spread in the AMOC responses to 4 x CO₂, capturing AMOC trends during the initial weakening, gradual recovery, and eventual strengthening. This suggests we can use the scaling to examine processes determining the AMOC responses in each GCM.

The weakening and recovery phase of the AMOC in response to 4 x CO₂

$$\frac{\partial^2 \psi}{\partial z^2} = \frac{g}{\rho_0 f} \left(\underbrace{\rho_b}_{30^\circ\text{S}-60^\circ\text{N}} - \underbrace{\rho_n}_{40^\circ\text{N}-60^\circ\text{N}} \right)$$

AMOC recovery

no AMOC recovery



Difference between the density profile in the Atlantic basin (30°S-60°N) and North Atlantic (40°N-60°N) averaged between 0-10 years (solid), 85-115 years (dashed), and 470-500 years (dotted) and (right) the associated overturning stream function as calculated by the thermal-wind scaling in CESM1 (which has an AMOC recovery) and CNRM-CM6.1 (which experiences a prolonged AMOC weakening).

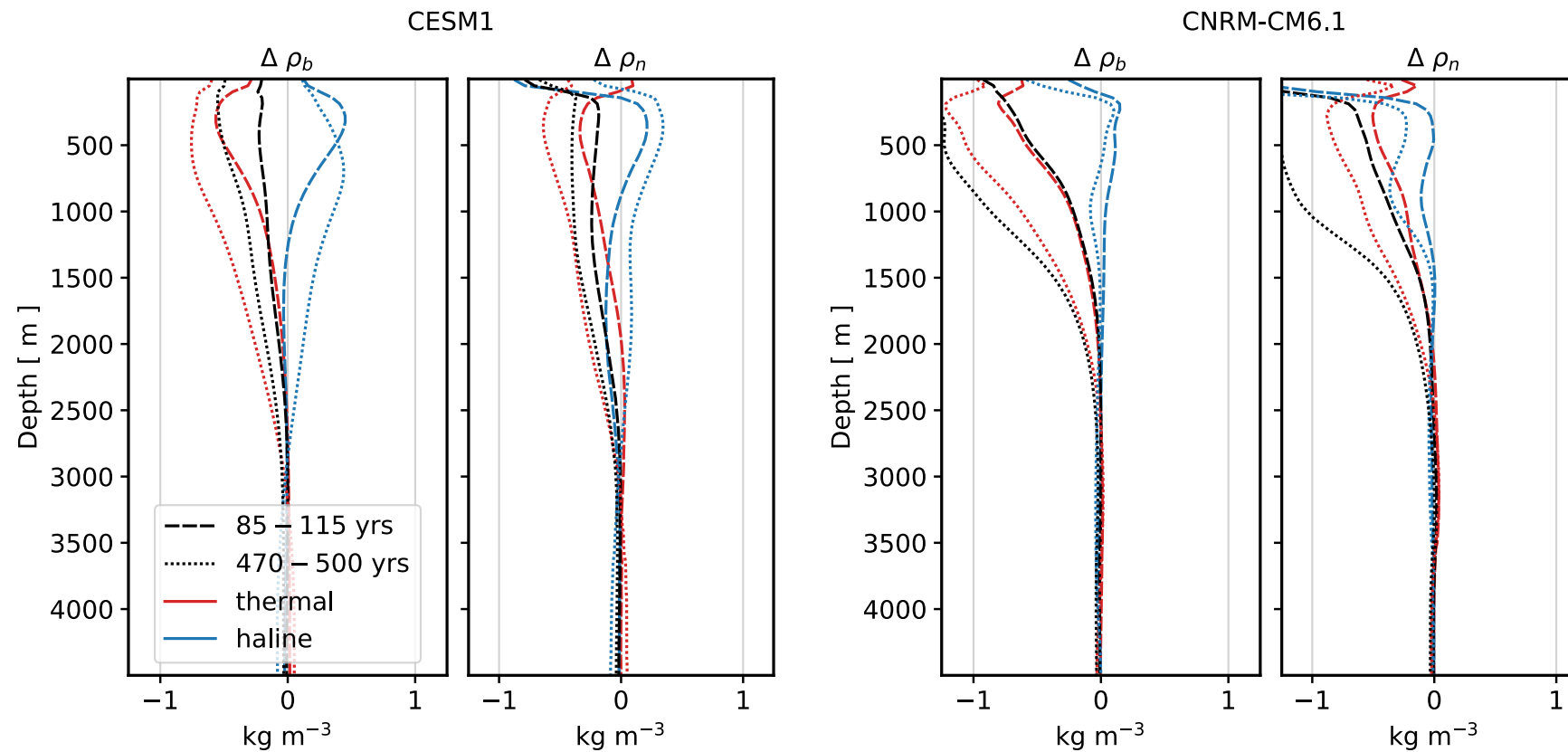
- We focus on a GCM where the AMOC recovers (e.g., CESM1) and a GCM where the AMOC stays weakened (e.g., CNRM-CM6.1). Both GCMs show the weakening phase (i.e., 85-115 years) is associated with a decrease in the basin-wide density gradient between 500-2000 meters, while the recovery phase (i.e., 470-500 years) is associated with an increase in the basin-wide density gradient between 500-1000 meters. Note, this increase is absent in CNRM-CM6.1.

The weakening and recovery phase of the AMOC in response to 4 x CO₂

$$\frac{\partial^2 \psi}{\partial z^2} = \frac{g}{\rho_0 f} \left(\underbrace{\rho_b}_{30^\circ\text{S}-60^\circ\text{N}} - \underbrace{\rho_n}_{40^\circ\text{N}-60^\circ\text{N}} \right)$$

AMOC recovery

no AMOC recovery



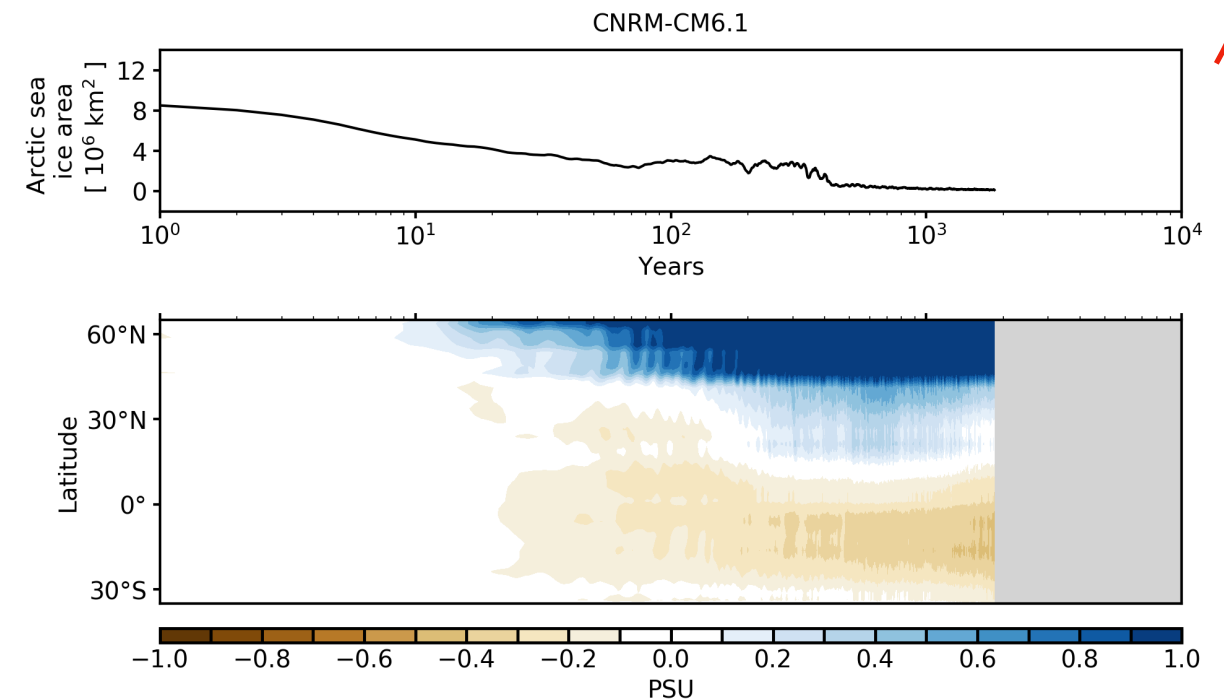
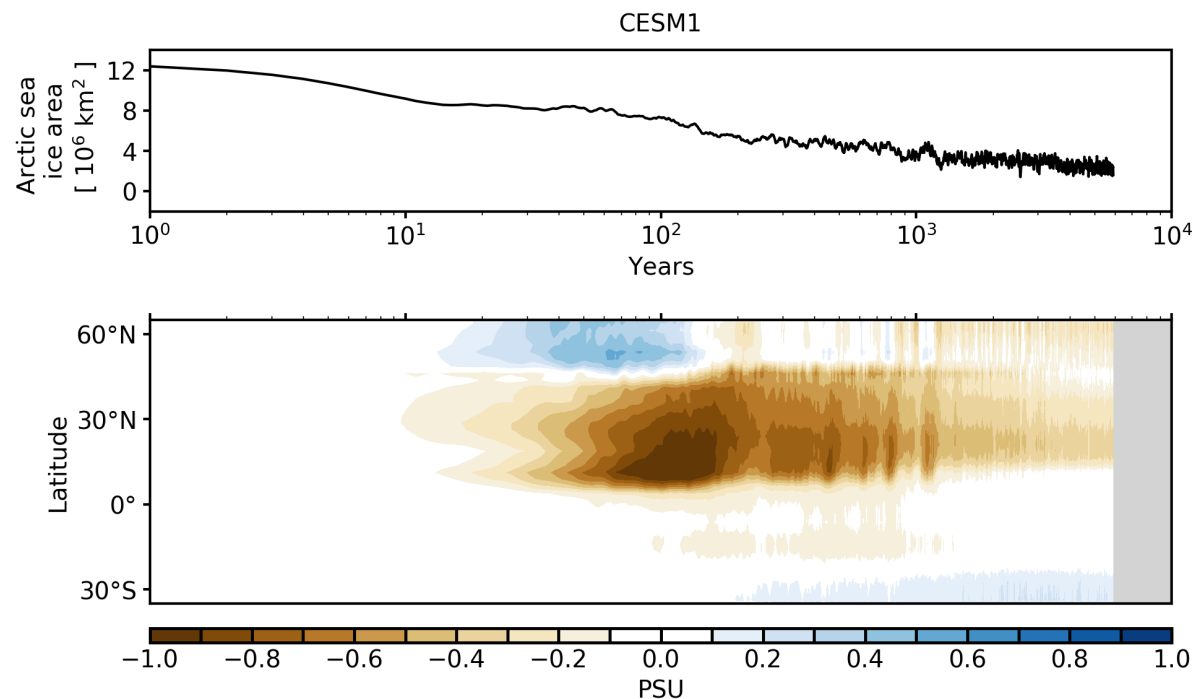
Decomposition of density changes in the (left) Atlantic basin (30°S-60°N) and (right) North Atlantic (40°N-60°N) averaged between 85-115 years (dashed) and 470-500 years (dotted) into contributions from temperature (red) and salinity (blue) for CESM1 and CNRM-CM6.1. All anomalies are relative to the first 10 years of each simulation.

- The weakening phase (i.e., 85-115 years) is attributed to warming of the northern convection region (ρ_n), which decreases the basin-wide density gradient.
- The recovery phase (i.e., 470-500 years) is attributed to an increase in salinity between 500-1000 m in ρ_n , which increases the basin-wide density gradient. GCMs with a stronger weakening tend to warm more, and GCMs with a weaker AMOC recovery tend to have weaker salinity anomalies.

The recovery phase of the AMOC in response to 4 x CO₂

no AMOC recovery

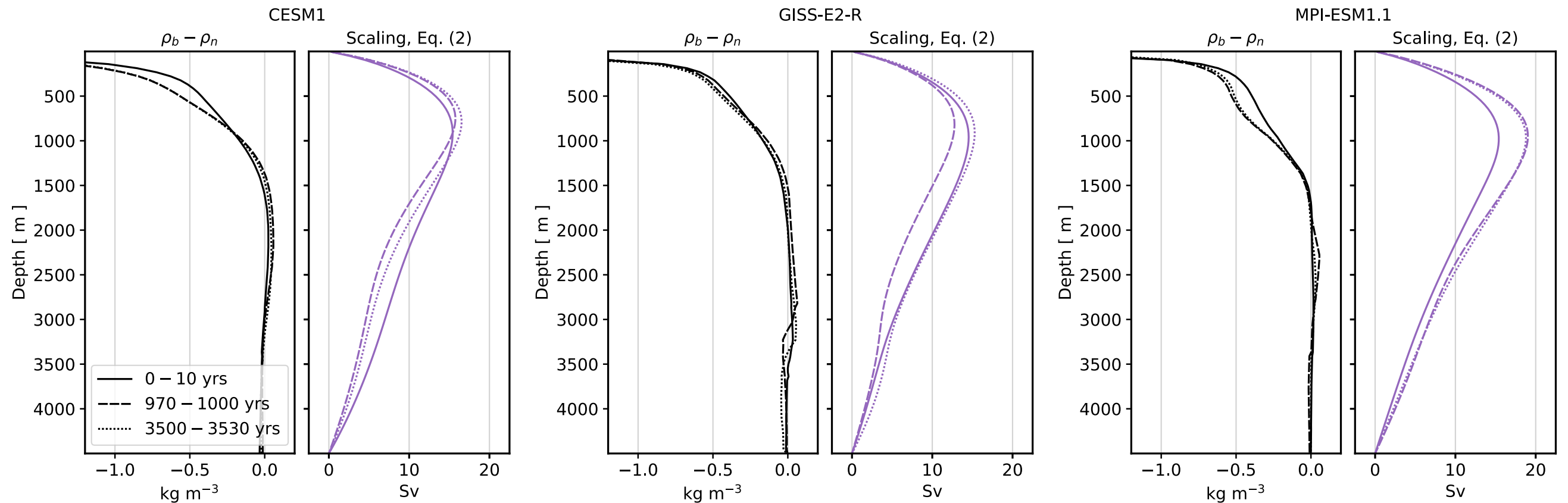
AMOC recovery



Hovmöller plot of the anomalous zonal-mean salinity in the Atlantic basin averaged from 500-1500 meters for CESM1 and CNRM-CM6.1. A Savitzky-Golay filter with a window size of 11 years was applied to all timeseries. The grey shaded region indicates the length of the simulation relative to 10,000 years. All anomalies are relative to the first 10 years of each simulation. The upper plot shows annual Arctic sea ice area for each GCM.

- A positive salinity anomaly accumulates in the subtropical Atlantic basin, when the AMOC is weakened, and moves poleward.
- This salinity anomaly reduces North Atlantic stratification and reinvigorates deep convection.
- GCMs with more Arctic sea ice loss (e.g., CNRM-CM6.1) tend to have little-to-no AMOC recovery, since the large input of freshwater from sea ice loss mixes with the poleward moving subtropical salinity anomaly.

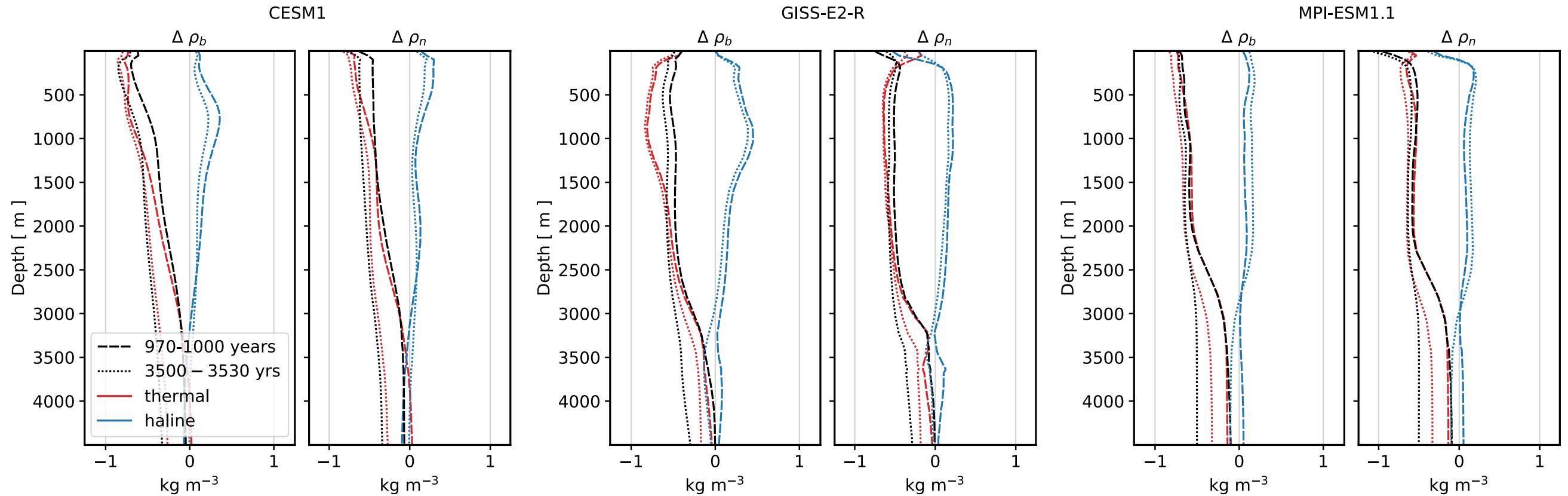
The re-strengthening phase of the AMOC in response to 4 x CO₂



Difference between the density profile in the Atlantic basin (30°S-60°N) and North Atlantic (40°N-60°N) averaged between 0-10 years (solid), 970-1000 years (dashed), and 3500-3530 years (dotted) and (right) the associated overturning stream function as calculated by the thermal-wind scaling in CESM1, GISS-E2-R, and MPI-ESM1.1.

- The re-strengthening phase (i.e., 970-1000 years) and the new equilibrium state (i.e., 3500-3530 years) is associated with an even larger increase in the basin-wide density gradient. Between 250-1250 meters, the density gradient increases in most GCMs and implies a stronger AMOC than the initial state by 1-5 Sv.
- After 3000 years, the AMOC is slightly deeper in GISS-E2-R and MPI-ESM1.1, but not CESM1.
- What is setting this increase in the basin-wide density gradient?

The re-strengthening phase of the AMOC in response to 4 x CO₂



Decomposition of density changes in the (left) Atlantic basin (30°S-60°N) and (right) North Atlantic (40°N-60°N) averaged between 85-115 years (dashed) and 470-500 years (dotted) into contributions from temperature (red) and salinity (blue) for CESM1 and CNRM-CM6.1. All anomalies are relative to the first 10 years of each simulation.

- The re-strengthening phase (i.e., 970-1000 years) and the new equilibrium state (i.e., 3500-3530 years) are associated with a warming of the low-latitude Atlantic basin. Salinity plays a negligible role on these timescales.
- This warming increases the basin-wide density gradient between 500-1500 meters and implies a stronger overturning circulation.

Key points

- We use a collection of millennial-length simulations from state-of-the-art GCMs to examine the transient and equilibrium responses of the AMOC to $4 \times \text{CO}_2$.
- We find that an expression — which relates the overturning circulation in the North Atlantic to the density difference between the basin interior and the region of deep-water formation — explains the inter-model spread of the AMOC responses, capturing the initial weakening, gradual recovery, and eventual strengthening.
- The evolution of the AMOC on different time scales is attributed to distinct changes in temperature and salinity.
- The initial shoaling and weakening occurs on centennial timescales and is attributed to the warming of the northern convection region.
- The recovery of the AMOC results from a pile-up of salinity in the Atlantic basin, when the AMOC is weakened, that propagates northward and reduces subsurface stratification. A weaker AMOC recovery is associated with a smaller salinity anomaly due to increased Arctic sea ice loss.
- The full strengthening of the AMOC is linked to warming of the low-latitude Atlantic basin.
- These results highlight the importance of considering the role of temperature and salinity dynamics in the evolution of the AMOC during and beyond the 21st century.

dbonan@caltech.edu
www.davebonan.com

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