Mechanisms and predictability of the AMOC: Progress and Challenges

Jon Robson

Thanks to the many collaborators: Pablo Ortega, Matt Menary, Irene Polo, Steve Yeager, Bablu Sinha, Rowan Sutton, David Thornalley, Tillys Petit, Alcide Zhao, Michael Lai, Annika Reintges, Laura Jackson…

And thanks to the wider AMOC community

University of Reading

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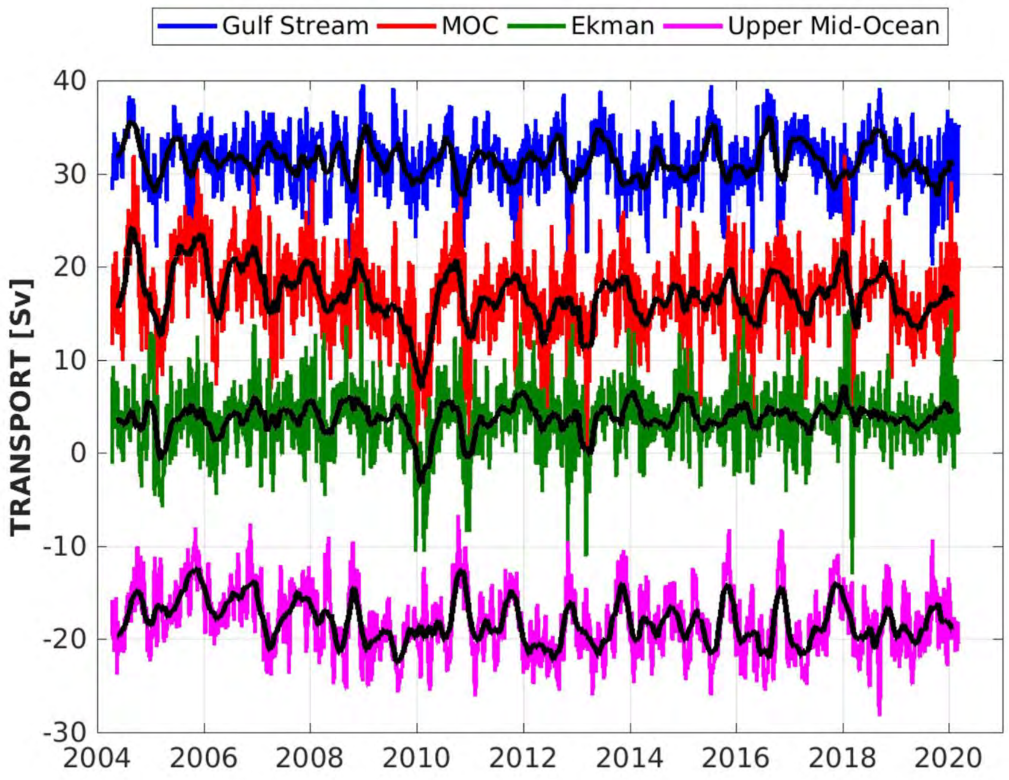
Motivation – why do we care about how and why the AMOC varies?

- AMOC is highly variable on a range of timescales – from days to millennium



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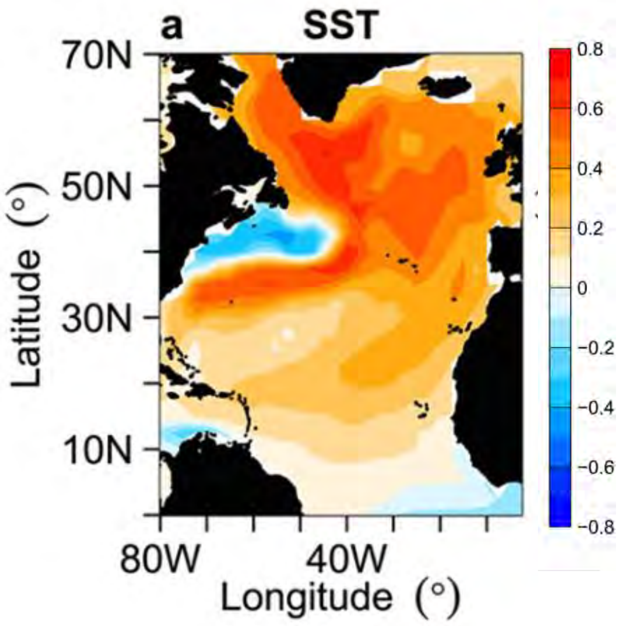
Motivation – why do we care about how and why the AMOC varies?

- AMOC is highly variable on a range of timescales – from days to millennium
- AMOC is linked to important climate variability and significant climate impacts

Correlation of SST and AMOC in CMIP5 models with strong AMOC variability



Yan et al., 2018; Zhang et al., 2019

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- AMOC is highly variable on a range of timescales – from days to millennium
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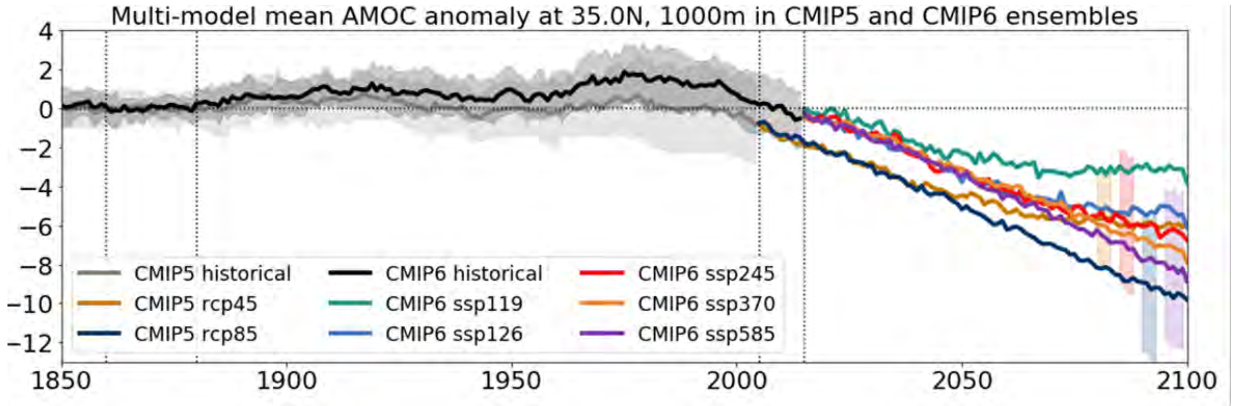

IPCC AR6, 2021, Fig 9.10

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Motivation – why do we care about how and why the AMOC varies?

- AMOC is highly variable on a range of timescales – from days to millennium
- AMOC is linked to important climate variability and significant climate impacts
- AMOC is expected to weaken significantly in the future due to climate change
- **To confidently predict AMOC we need to understanding how and why the AMOC is varying**

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Aim and Outline

Aim

Give a broad retrospective of some of the key progress in understanding mechanisms of AMOC variability and implications for predictability

Too many studies and processes to cover in one <25 minute talk, So I will:

- Focus on interannual and decadal timescales
- Focus on results from ocean and coupled models
- Discuss some implications for predictability
- Outline some important questions and uncertainty

- Will take speakers prerogative and, where possible, highlight work from UK-funded Projects VALOR, DYNAMOC, ACSIS, WISHBONE, SNAP-DRAGON

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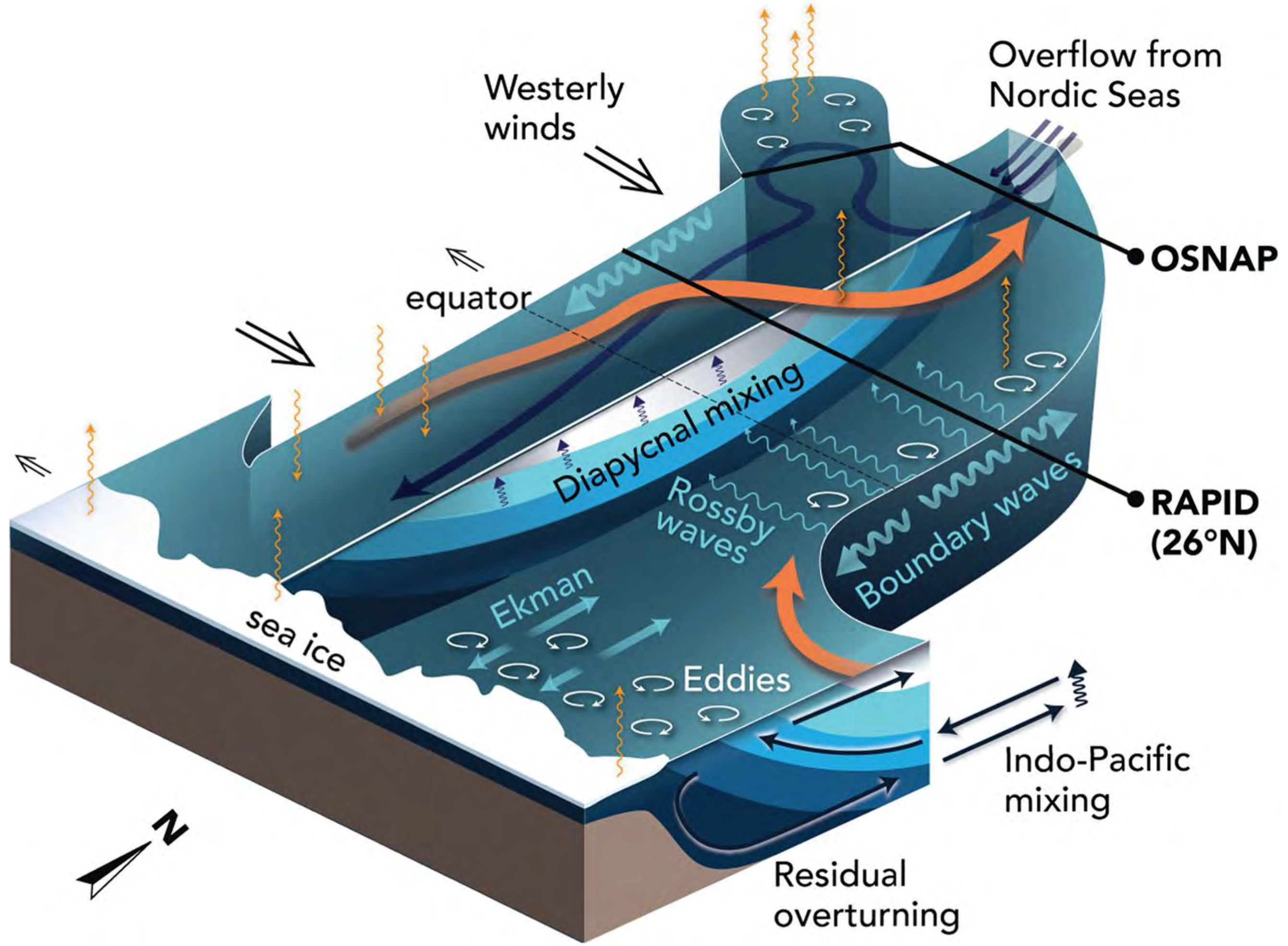
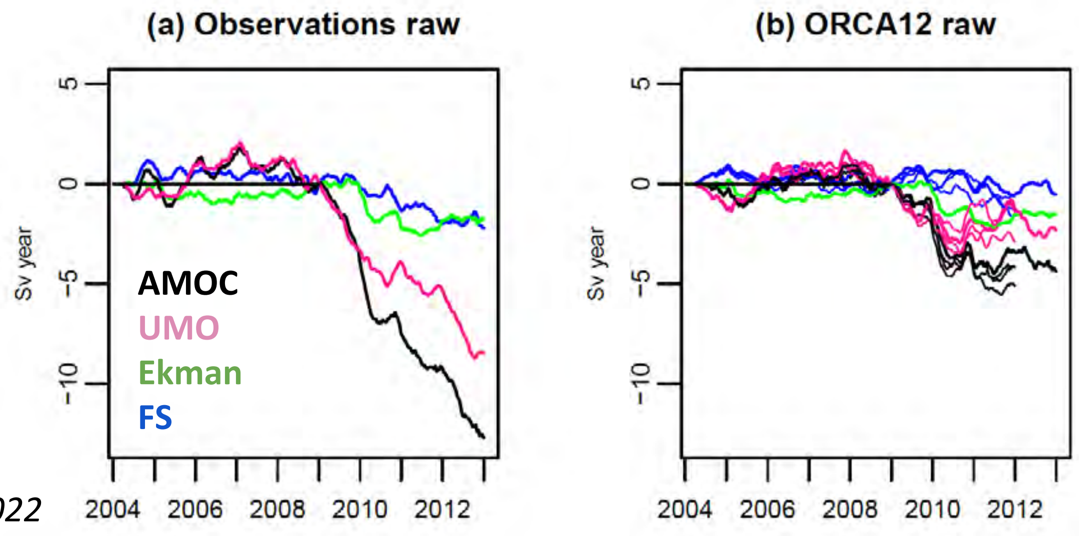
Many different processes play a role in AMOC variability



Johnson et al, 2019

- **Processes affecting AMOC variability depends on location and timescale**
- Processes can be broadly divided into internal "intrinsic" variability and surface forced variability

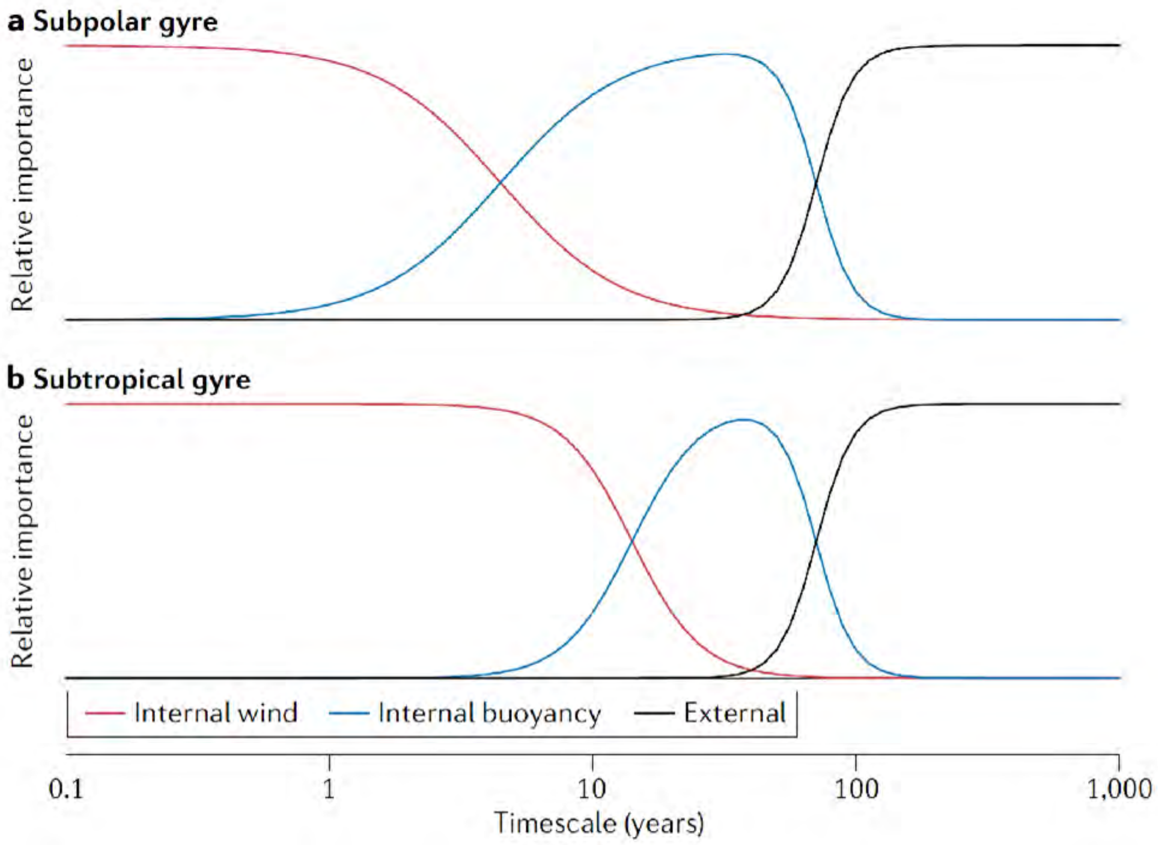
- However, model based estimates suggest that surface forced variability dominates



Germe et al, 2022

Role of surface forcing: Differing importance of Wind vs Buoyancy

Jackson et al, 2022



- The importance of mechanical Wind forcing vs buoyancy forcing also depends on location and timescale.

- Models suggest
  - wind forcing dominates shorter term variability especially in the subtropics
  - Buoyancy forcing dominates longer term variability

e.g., Biastoch et al., 2008; Robson et al., 2012; Yeager and Danabasoglu, 2014; Polo et al., 2014; Pillar et al., 2016; Kostov et al., 2021

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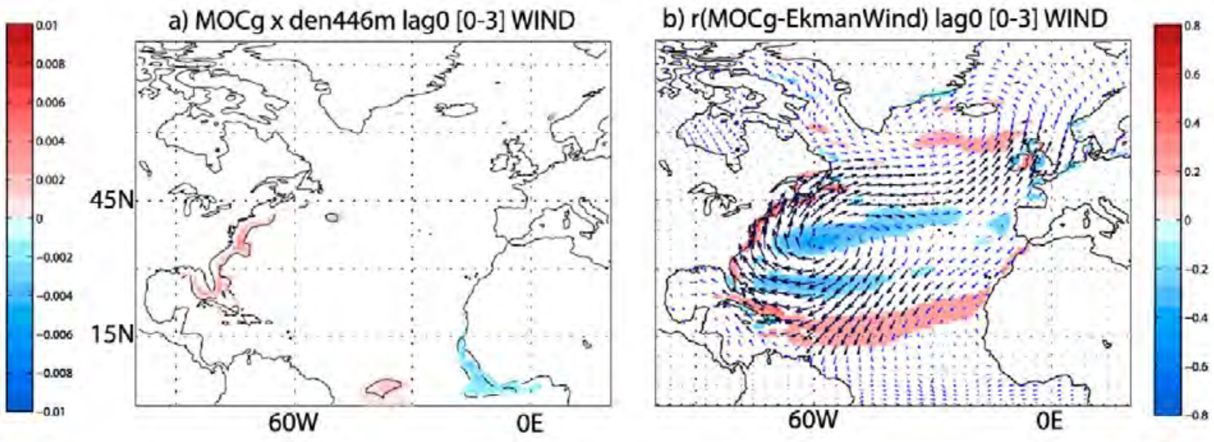
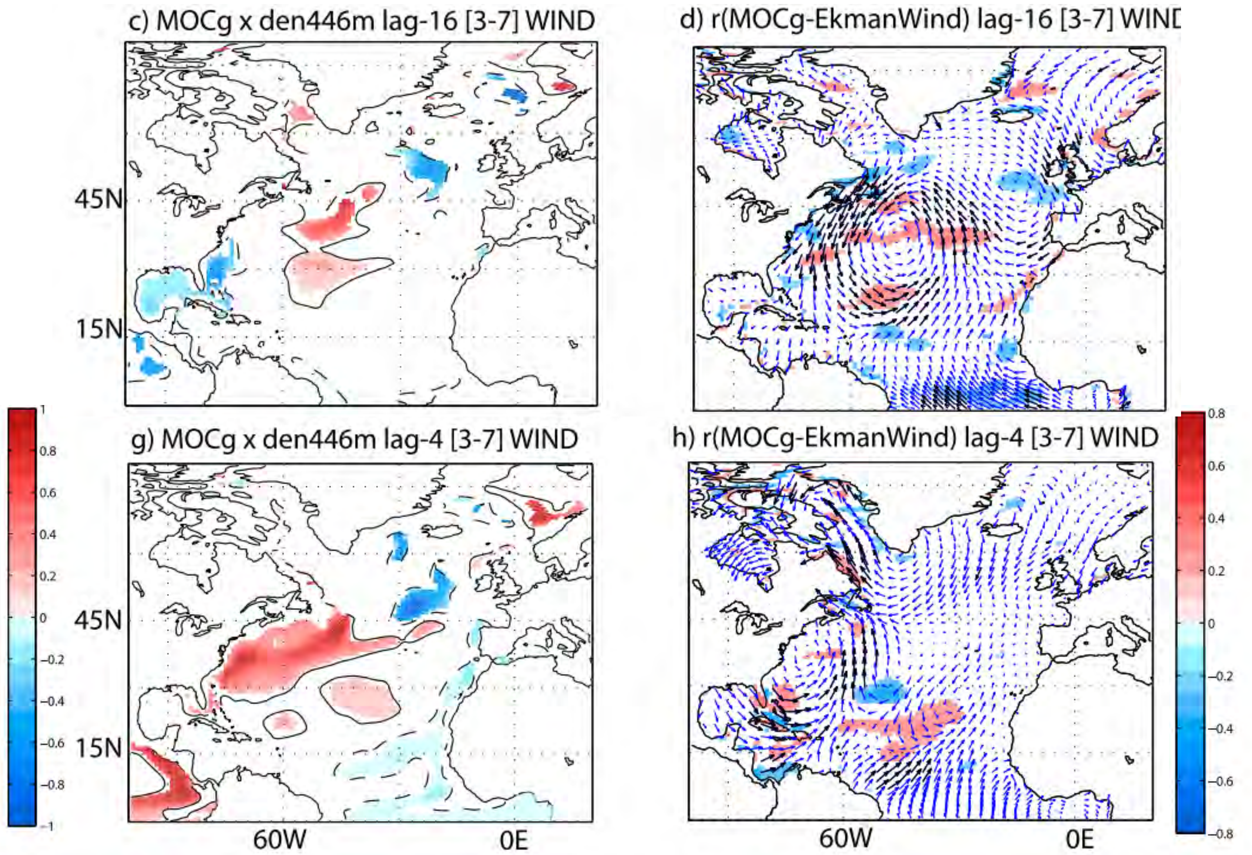
Interannual variability: Role of wind forcing

Wind forced variability 0-3 year filter



Wind forced variability >7year filter



- Wind driven Ekman changes play an important role in AMOC at 26N
- But, Wind can also be an important driver of geostrophic AMOC through a number of mechanisms
- Wind driven variability the dominant driver of AMOC at 26N on subdecadal timescales? E.g. Biastoch et al, 2008; Zhao and Johns, 2014; Kostov et al, 2021; Zou et al, 2021

Polo et al, 2014, JPO

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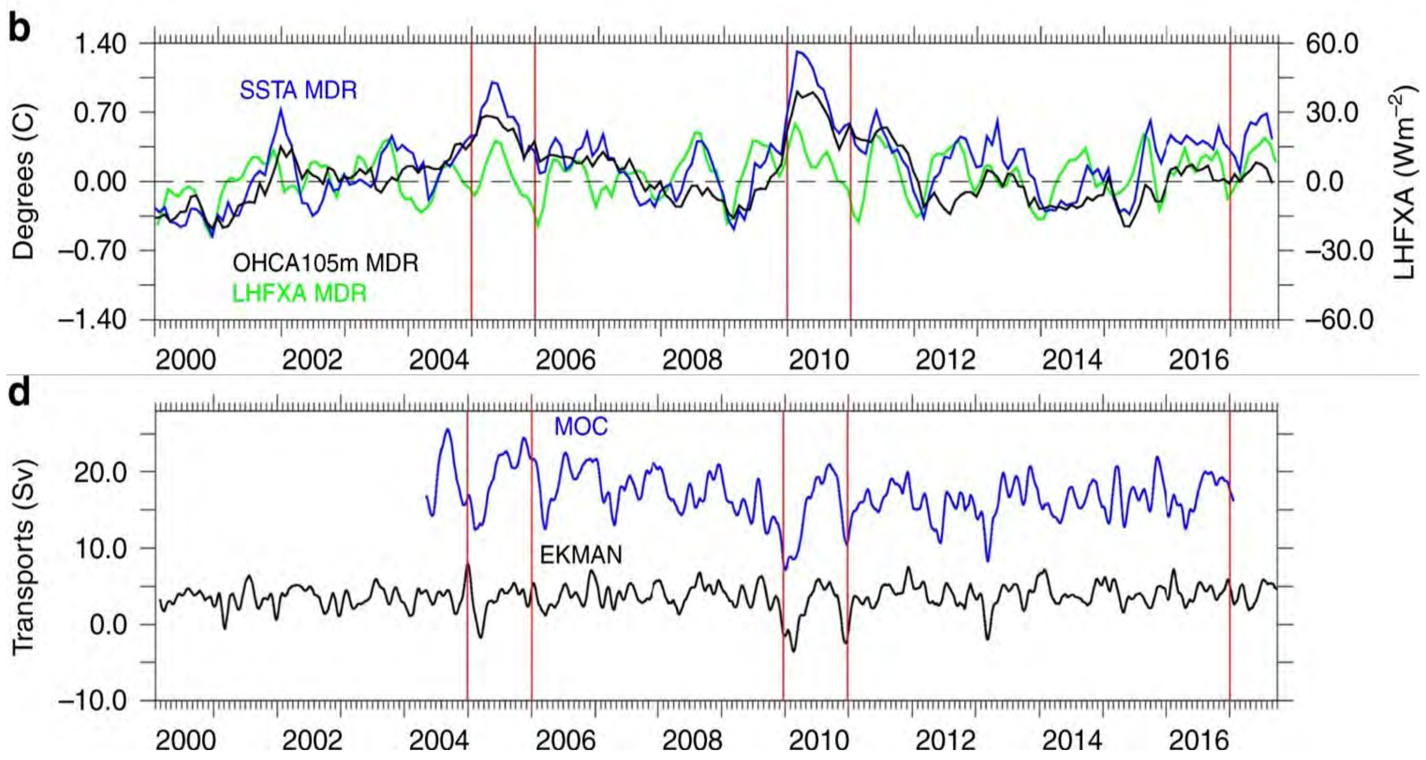
Interannual variability: Implications for predictability

- @26N Interannual AMOC variability shapes upper ocean temperatures (e.g. Cunningham et al, 2013)
- linked to high impact weather, including hurricanes etc
  (Hallam et al, 2019)

- If variability is largely wind-driven then the predictability of the ***atmosphere circulation*** is key
- Still important to adequately represent AMOC, its variability, and its impact.



Hallam et al, 2019

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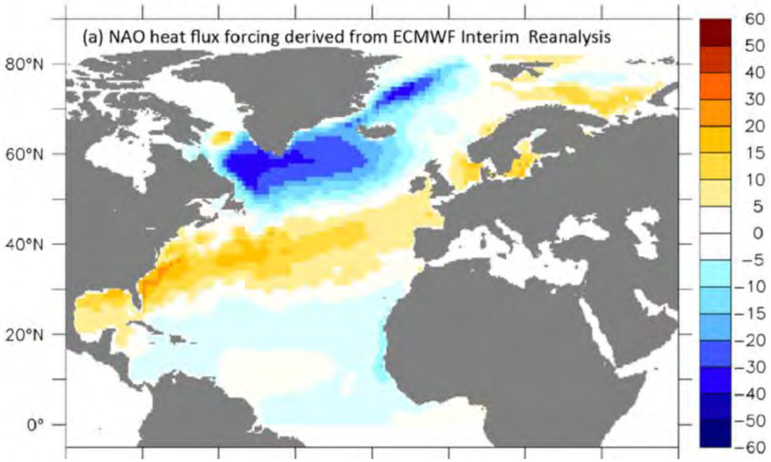
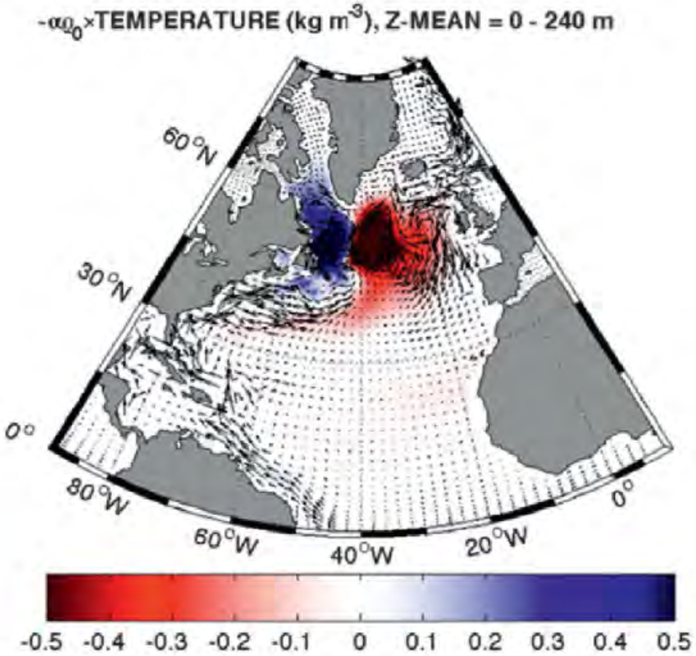
Decadal variability: Three main contenders?

Buoyancy forcing



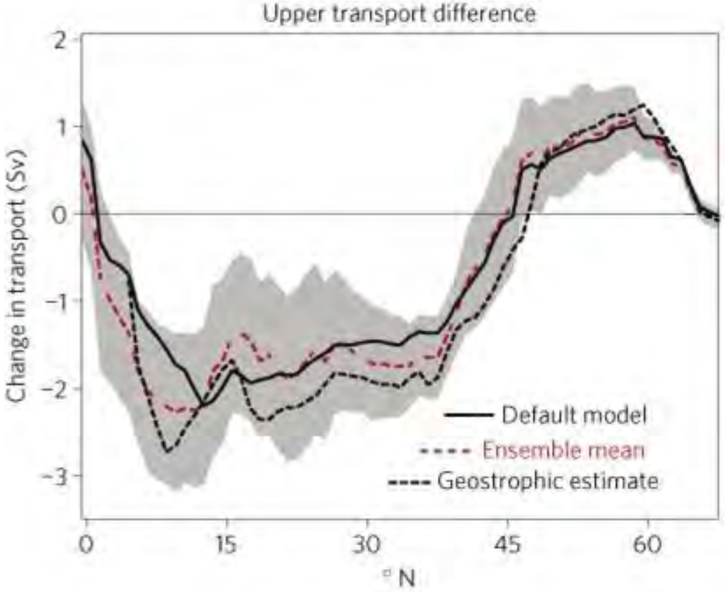
Delworth and Feng, 2016; Biastoch et al., 2008; Robson et al, 2012; Yeager and Danabasoglu, 2014;

Rossby Waves



Sevellec and Fedorov, 2013; Muir and Fedorov, 2017;

Wind forcing on decadal time-scales



Lozier et al, 2010; Williams et al, 2014; Zhao and Johns, 2012; Ortega et al, 2017;

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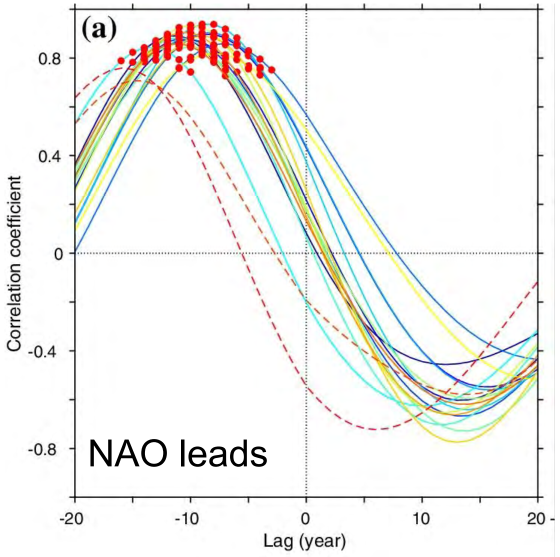
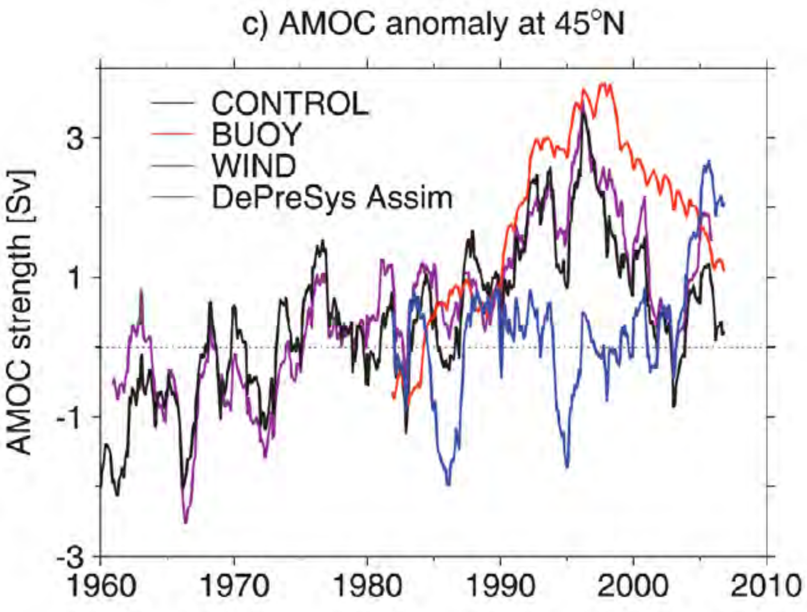
Decadal variability: Buoyancy forcing and role of the NAO

Lagged correlation of NAO and AMOC in ocean-only



Xu et al, 2019

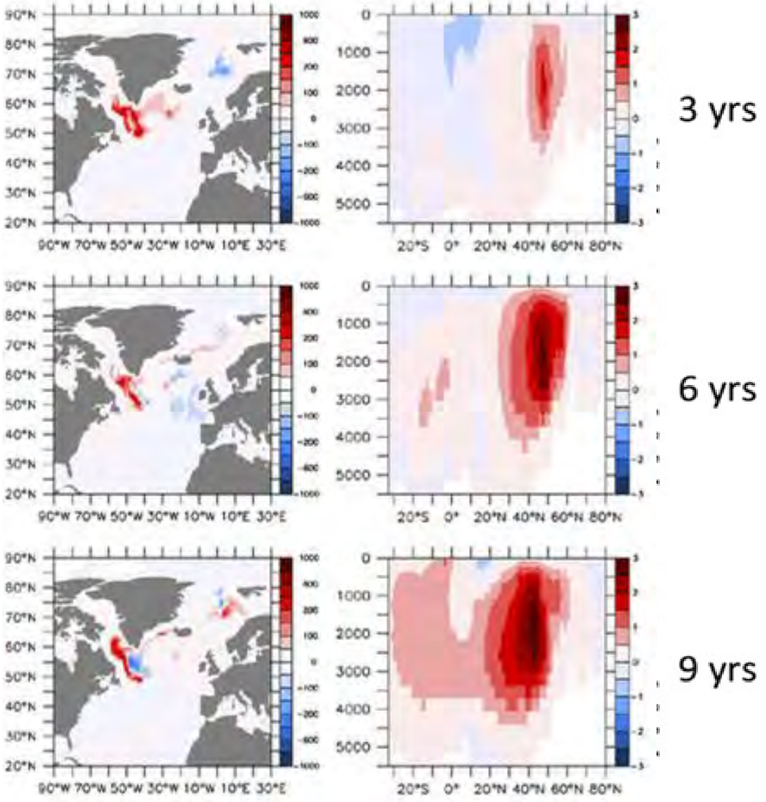


Robson et al, 2012

Mixed layer depth

AMOC

lag



Delworth and Feng, 2016

- NAO related buoyancy forced AMOC changes has remained the dominant paradigm for explaining decadal-to-multidecadal AMOC variability at subpolar latitudes.

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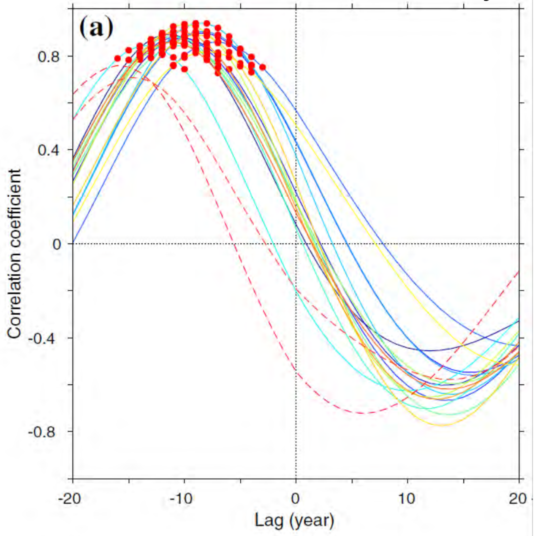
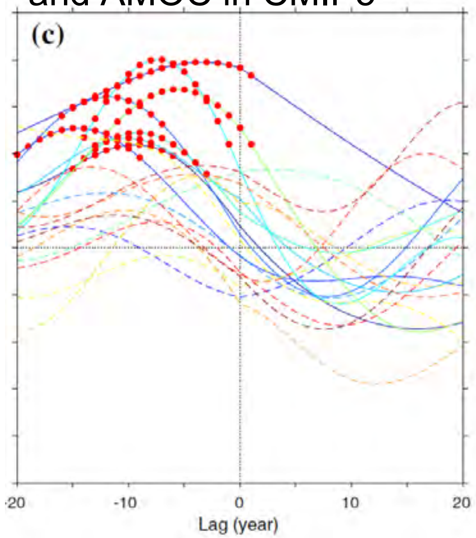
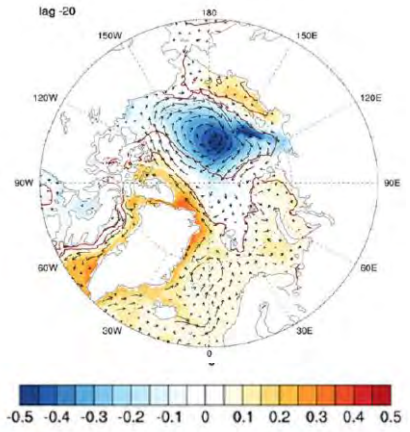
The menagerie of buoyancy forced variability

Lagged correlation of NAO and AMOC in ocean-only

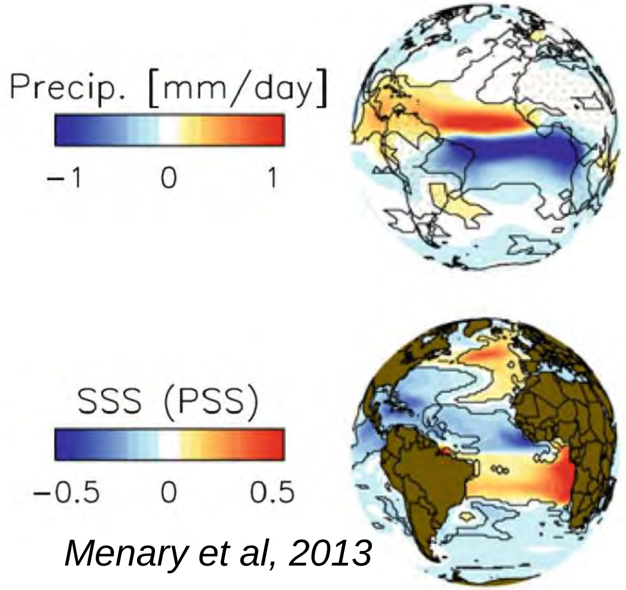


Lagged correlation of NAO and AMOC in CMIP5





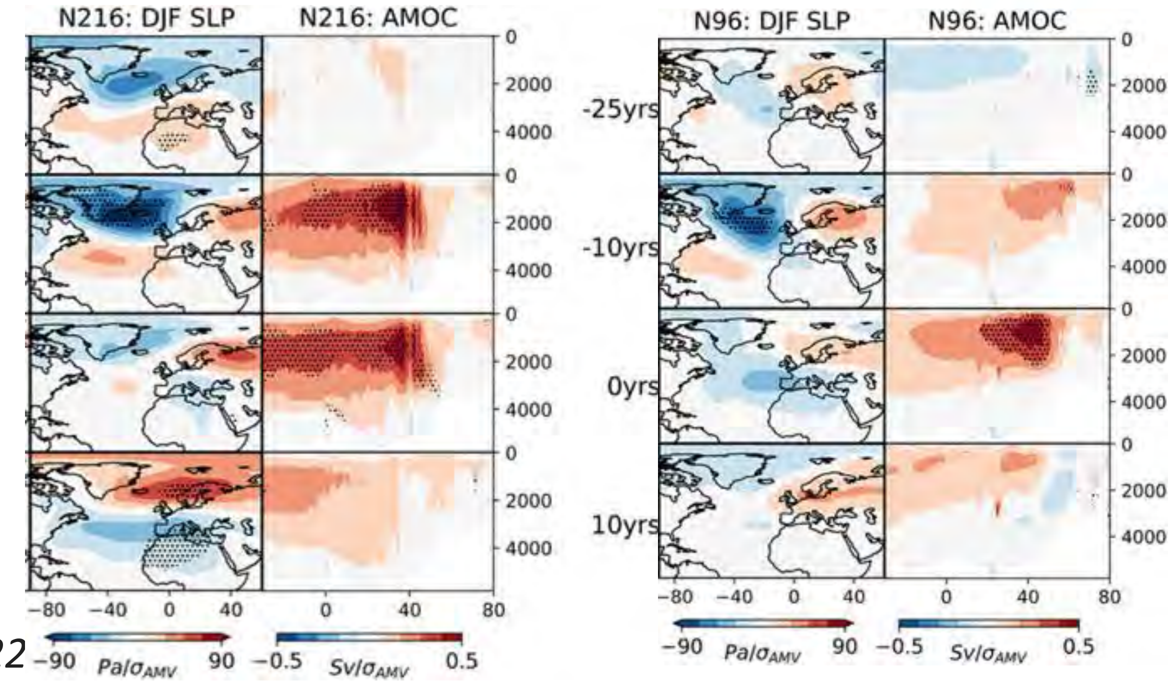
Jiang et al, 2021



Menary et al, 2013

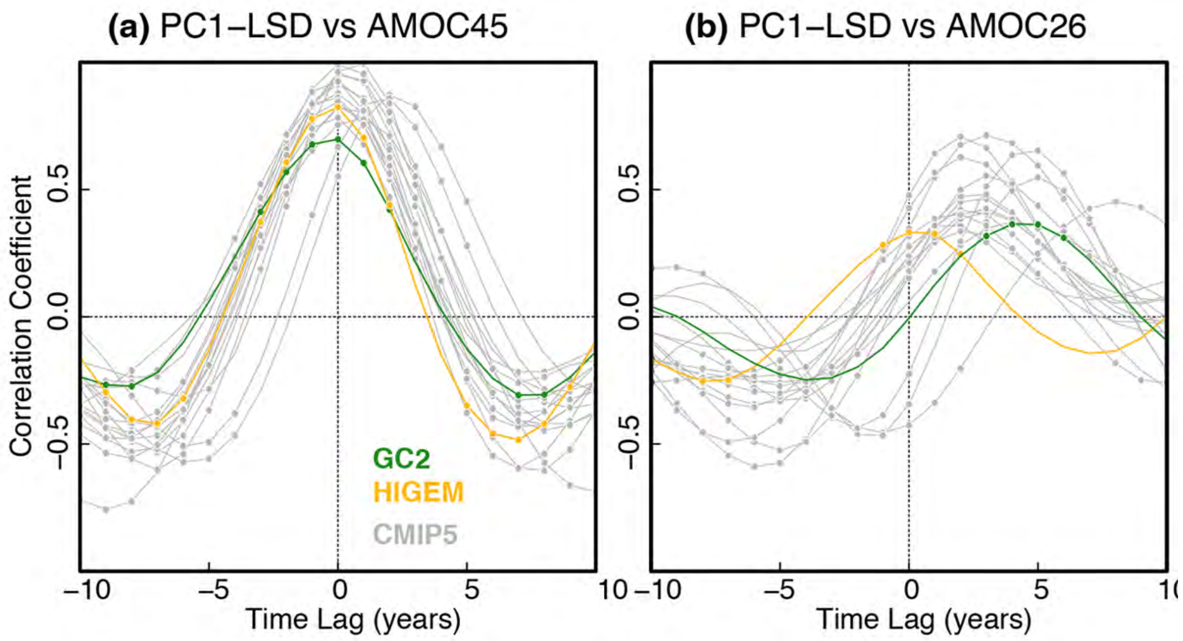
Although NAO is the dominant driver of decadal variability in ocean-only simulations, coupled models support a broad range of mechanisms

See Posters by Annika Reintges on simulation of the NAO-AMOC relationship in CMIP6

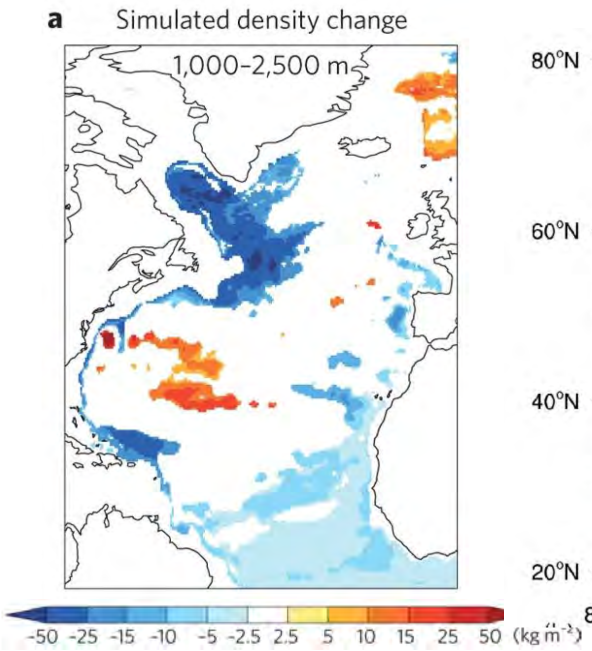


Lai et al, 2022

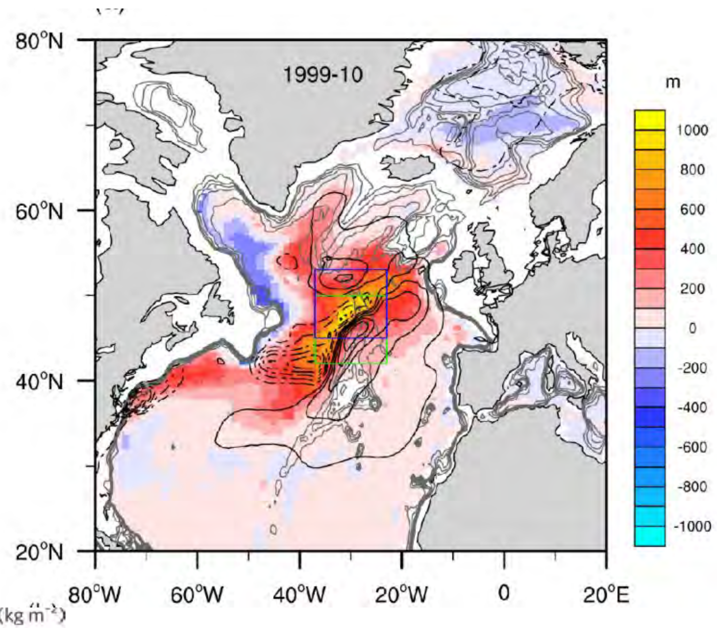
Decadal variability: Subsurface density anomalies and coherence of AMOC



Ortega et al, 2021



Robson et al, 2014



Yeager, 2020

- Subpolar sub-surface density anomalies are a key predictor of the AMOC further south in models
- Interaction with the western boundary or mid-Atlantic ridge necessary for a AMOC / THC response.

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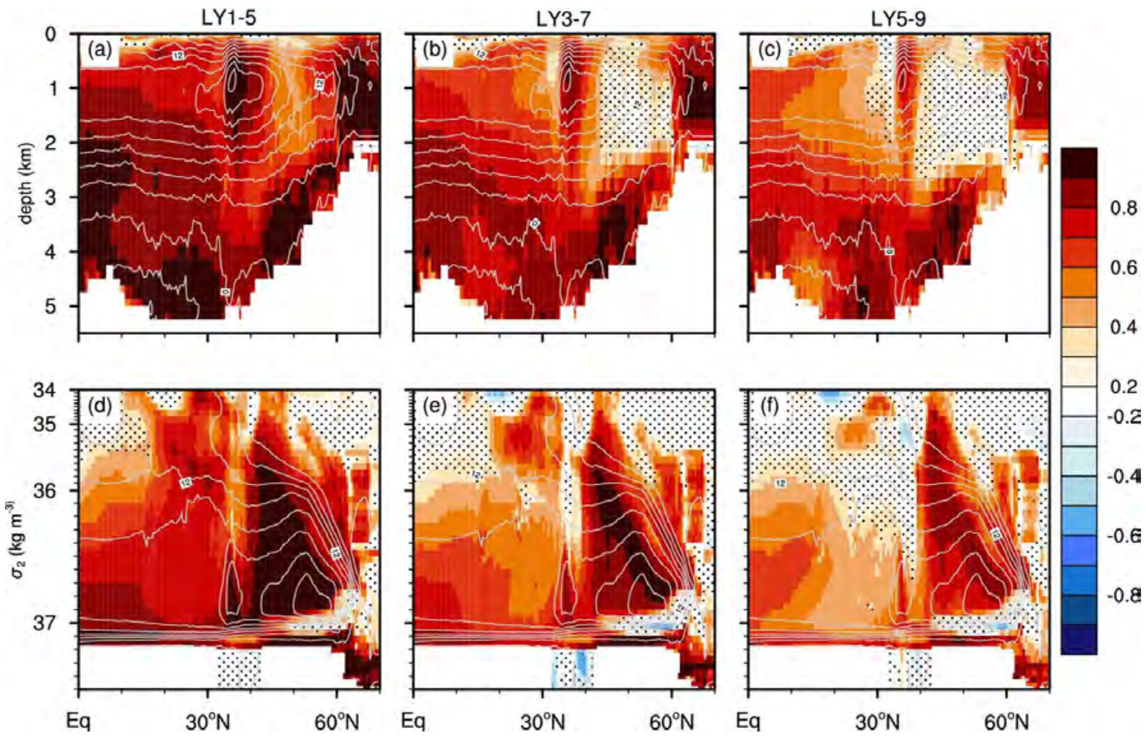
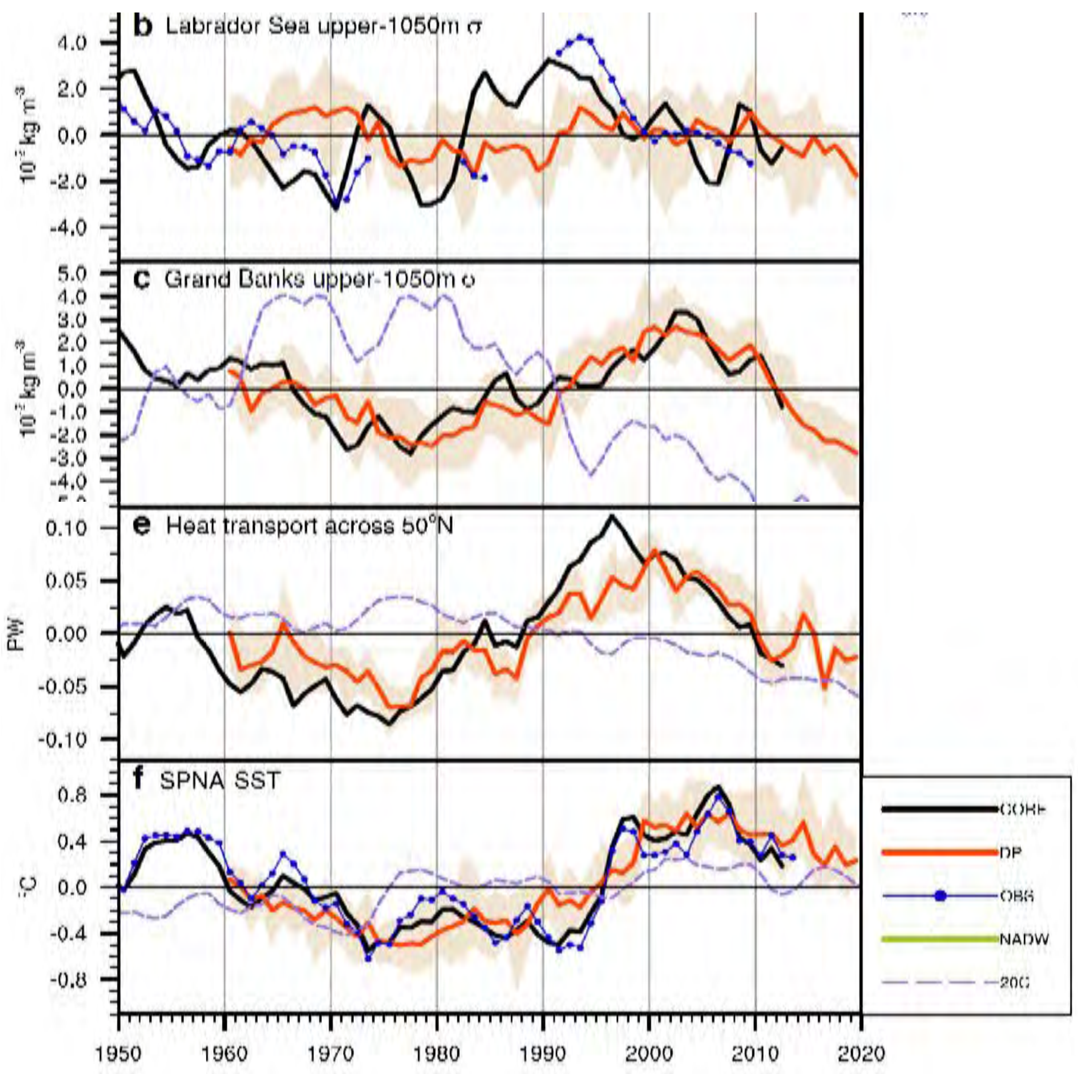
Decadal variability: predictability



Yeager, 2020



Yeager and Robson, 2017

- Little work on AMOC prediction but some predictability on multi-year timescales
- Skill is very sensitive to drifts (*Menary et al, 2016*)
- Initialisation of subsurface density anomalies key for delivering successful predictions of upper ocean subpolar North Atlantic
    - *E.g., Robson et al., 2012, 2014, 2018; Yeager et al., 2012; Msadek et al., 2014; Yeager, 2020;*

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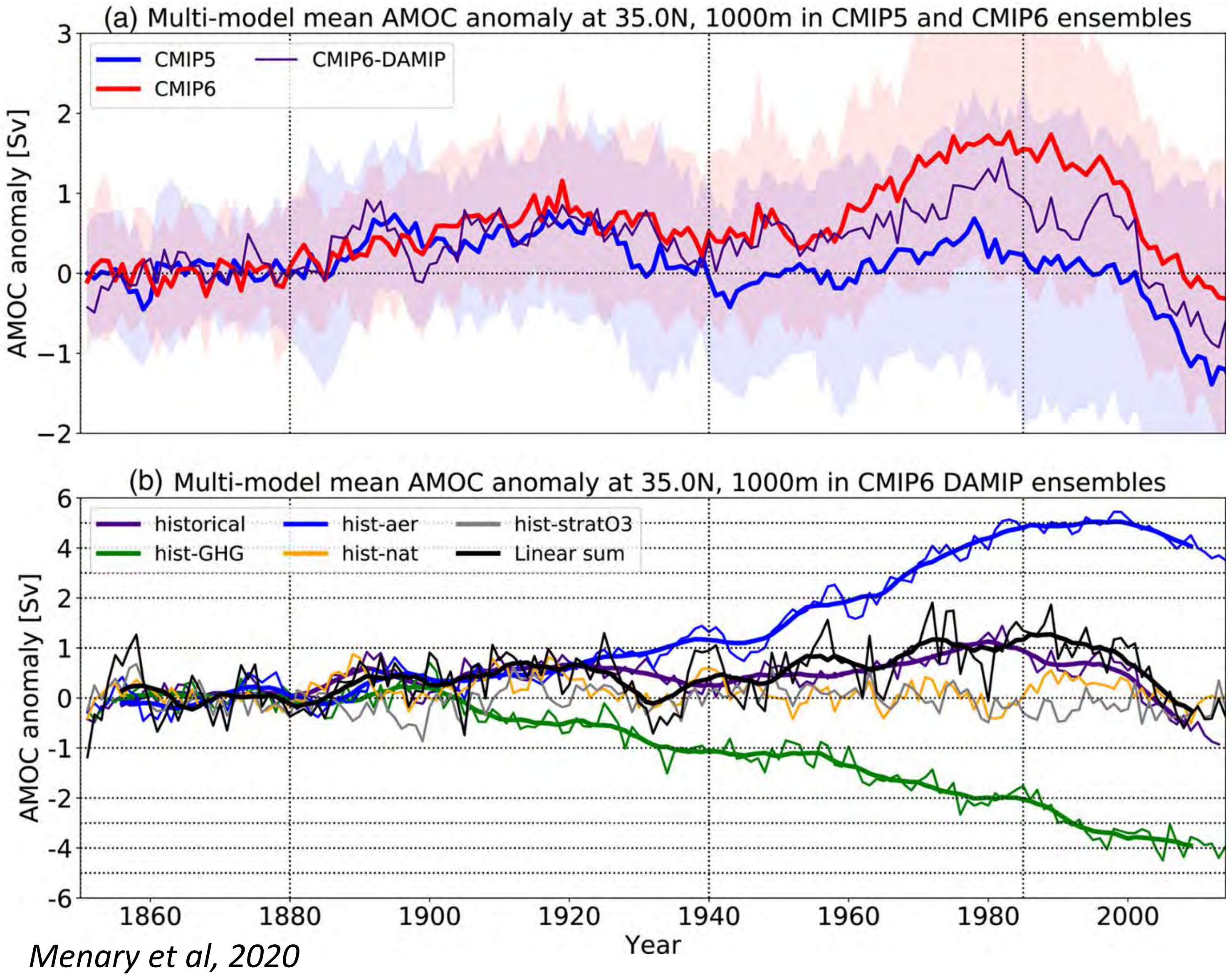
The role of external forcing



Menary et al, 2020

- Increased evidence that external forcings can contribute significantly to historical AMOC variability
  - Not just greenhouse gases, but solar, volcanic and anthropogenic aerosols (*Menary et al, 2013, 2014, 2020; Ottera et al, 2010; Hassan et al, 2021; Swingedouw et al, 2015)*
- CMIP6 simulations simulate an increase in AMOC over 1850—1985 due to increasing aerosol forcing.

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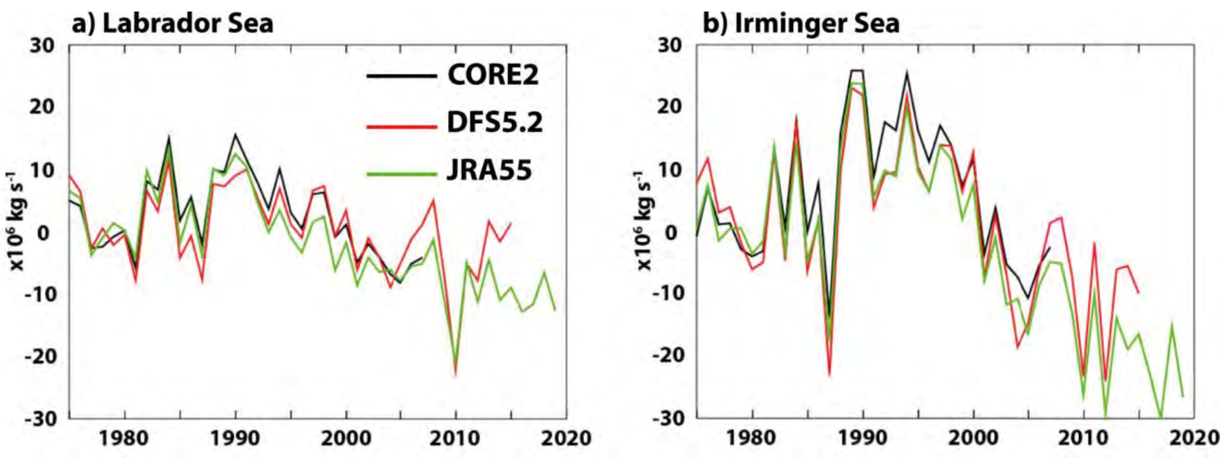
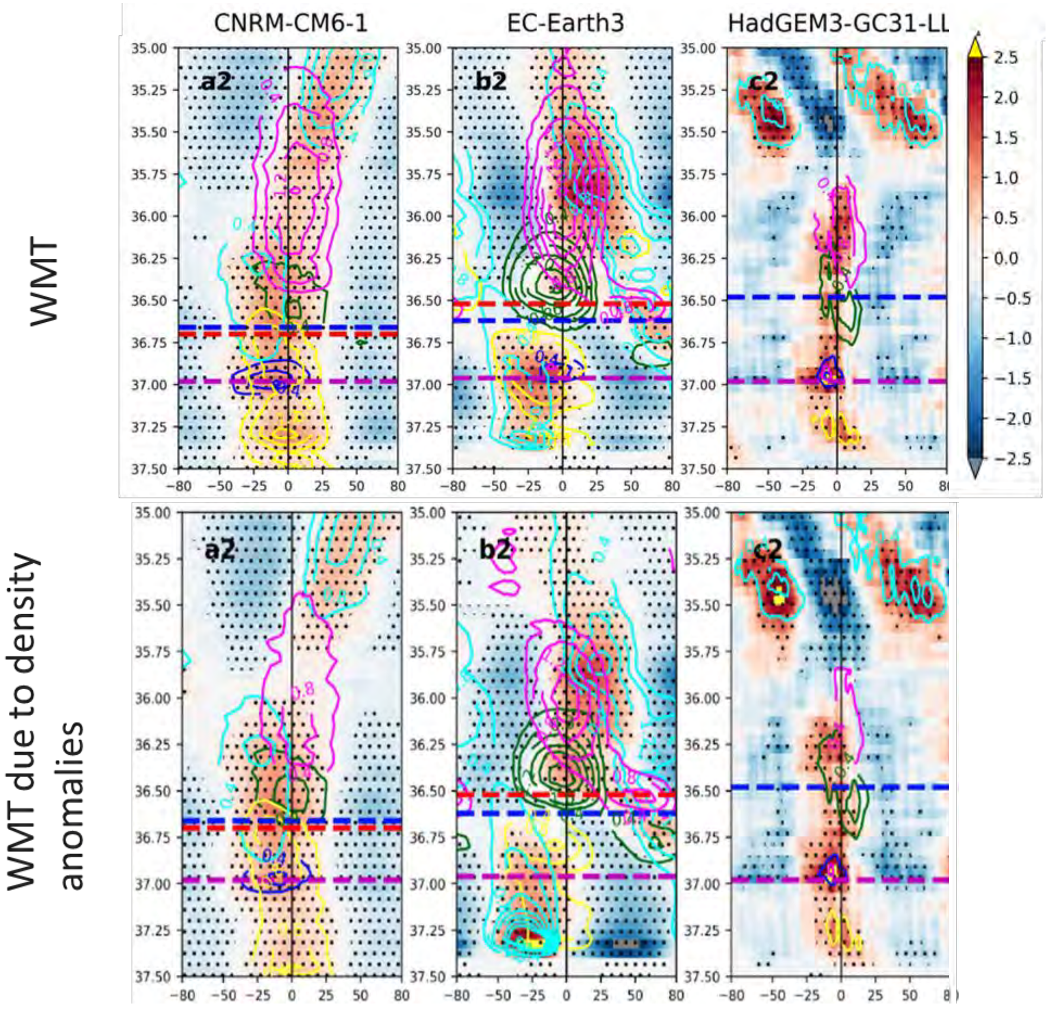
Ongoing questions and challenges

Challenge to constrain the details of buoyancy forced variability



Megann et al, 2021

Zhao et al, in prep



- What regions are most important for decadal variability, and water mass transformations vs dense water formation? (*Megann et al, 2021; Yeager et al, 2020*)
- Role of buoyancy forcing, deep convection, dense water formation and AMOC still not fully understood.
- What is the role of surface fluxes vs surface density? (*e.g. Petit et al, 2022*)

See Who Kim's poster on consistency of response to NAO heat fluxes

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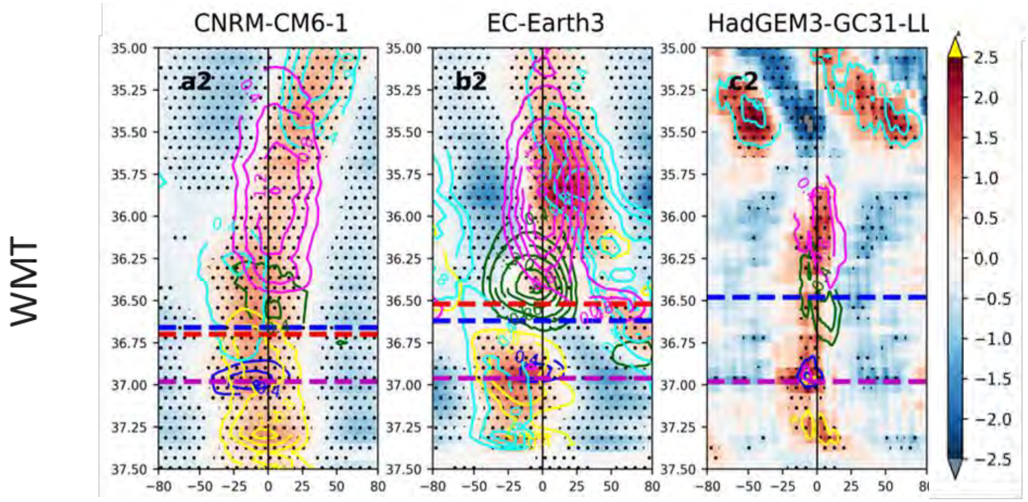
Emergent variability and *constraining* the menagerie of buoyancy forced variability

- Buoyancy forced AMOC variability is an emergent phenomena related to densification
- Many different processes drive densification / water mass transformations
- Representation of the processes, the mean state, and the interaction between processes all important

- **Should we be surprised that models simulate a broad range of mechanisms and timescales (even within the same model)?**



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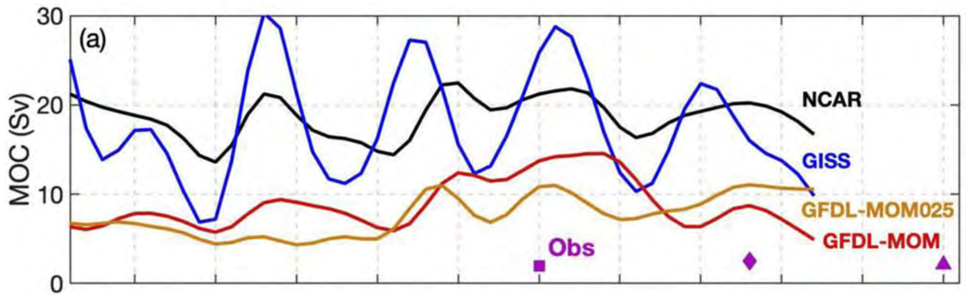
The representation of the AMOC in models and the balance of mechanisms

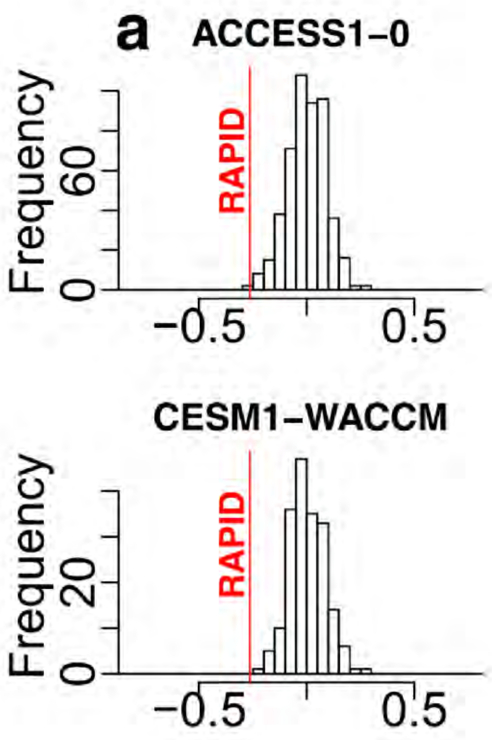
Models are not perfect, and they have several issues:

- Too much overturning in the Labrador sea (li et al., 2019)
- wrong relationships between deep convection and dense water formation in low resolution (Katsman et al, 2018)
- Too little interannual and decadal variability in AMOC (Yan et al., 2018)
- Too little decadal variability in NAO and North Atlantic jet (Kim et al., 2020; Bracegirdle et al., 2020)
- Signal-to-noise problems in atmospheric circulation (e.g., Scaife and Smith., 2018)
- Mean state biases in ocean and atmosphere affects variability (Menary et al, 2015; Bracegirdle et al, 2021)

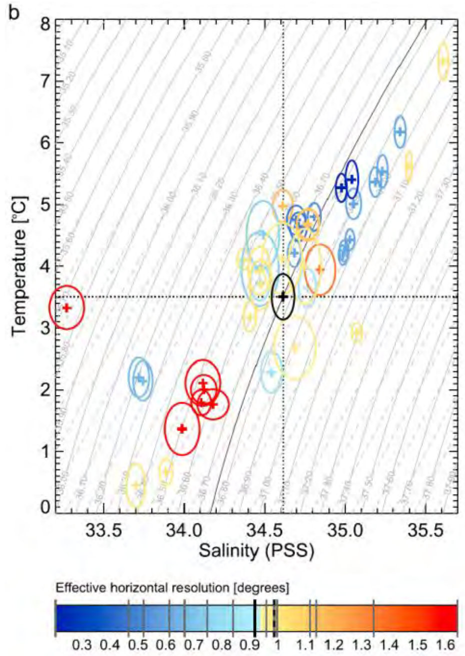
We are not sure about the relative role of different processes and mechanisms



Li et al, 2019

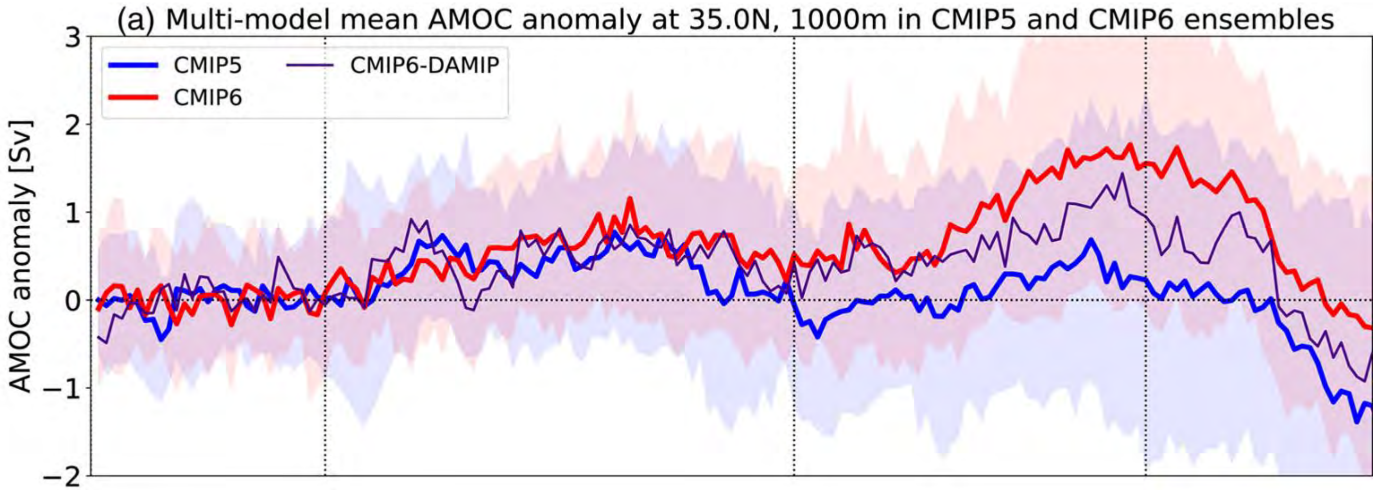


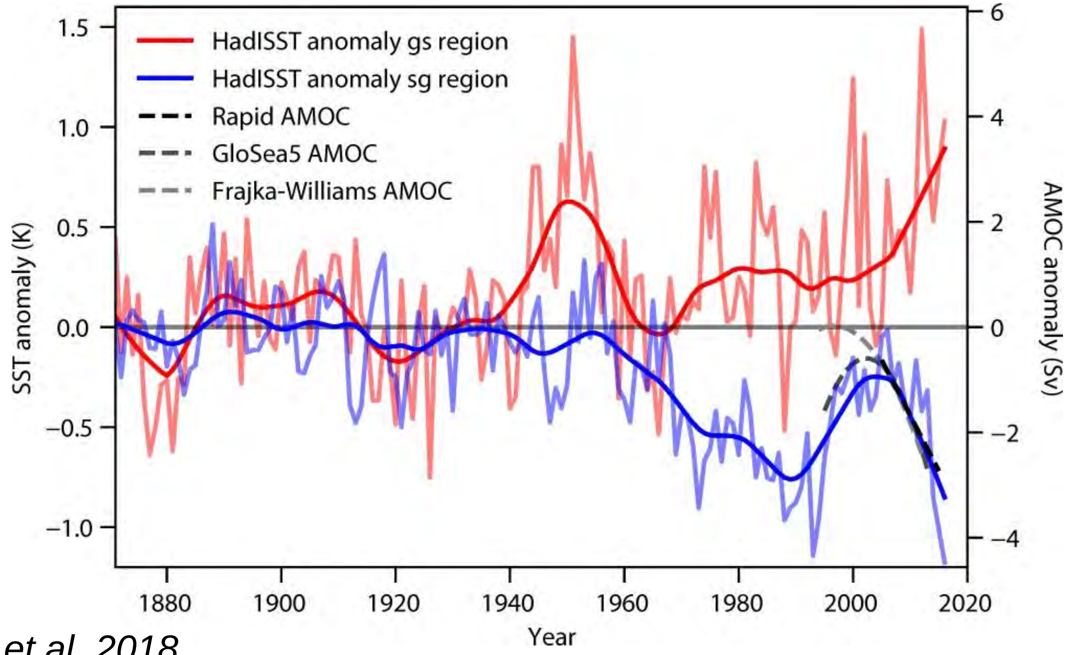
Yan et al, 2018



Menary et al, 2015

The representation of the externally forced AMOC





Caesar et al, 2018

Many questions on the role of external forcing in AMOC changes over the next few decades

- Mismatch between simulated and implied historical AMOC
- Still a large spread in the rate of future AMOC declines across models (Weijer et al., 2020)
- Historical aerosol mechanism still not clear
- Important processes (Greenland ice melt) not well represented
- Impact on atmospheric circulation

For more on the role of anthropogenic aerosols
See Posters by *me* and Michael Lai

Thoughts on ways forward

- Move to higher resolution coupled models (e.g., Roberts et al., 2020; Yeager et al. 2021)?
- Continue to evaluate and constrain short-term AMOC variability against observations
- Need to better constrain decadal buoyancy forcing and related mechanisms?
  - New tools and targeted experiments?
- Analyse multiple models where possible and look for observed constraints

See Poster by Tillys Petit on high-resolution modelling

- Consistent (and easy to apply) analysis tools of key diagnostics.
- Need collaborative research programs/fora to bring ocean-modelers, climate modellers, physical oceanographers and paleo together

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Conclusions

- The AMOC varies on a range of timescales due to a range of processes and mechanisms.
- On interannual time-scales wind forced changes in AMOC dominate and can lead to important upper ocean changes
- On decadal timescales buoyancy forcing dominates
  - role of surface forced AMOC changes related to the NAO is still the dominant paradigm for decadal AMOC variability
- However many questions remain unanswered
  - What is the relative importance of different mechanisms?
  - How do we constrain the buoyancy forced decadal variability?
  - How do models respond to external forcing, and what feedbacks are operating?

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