# “Dynamical Sensitivity in Response to a Wide Range of Abrupt $CO_2$ Forcings”

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- Variability in the extratropical atmospheric circulation is important for determining the behavior of weather extremes and for contributing most of the heat, momentum and moisture transport from low to high latitudes.

- The representations of various coupled atmosphere-ocean modes of variability have improved in more recent model versions submitted to the Coupled Model Intercomparison Project Phase 6 (CMIP6) (Orbe et al. (2020)).

- Improvement is most evident in modes like the Madden-Julian Oscillation and in the Quasi-Biennial Oscillation (QBO) (Richter et al. (2020)), but also suggested in the northern and southern annular modes, although this is sensitive to the season and mode considered (Lee et al. (2021)).

- Future projections of North Atlantic circulation changes exhibit large spread, reflecting both irreducible internal variability (~1/3) and model structural differences (~2/3) (McKenna and Maycock (2021)).

- Therefore, in addition to more thoroughly examining the role of internal variability, through use of large ensembles (Community Earth System Model (CESM-LE, Kay et al. (2015)), it is also necessary to better understand model structural differences, particularly individual models' feedback responses across a broad range of anthropogenic forcings.

- While idealized, the abrupt 4x$CO_2$ simulations submitted to CMIP6 afford a mechanistic look into the forcing and feedback response characteristics in models that can be unambiguously attributed to an increase in $CO_2$ (Grise and Polvani (2016)).

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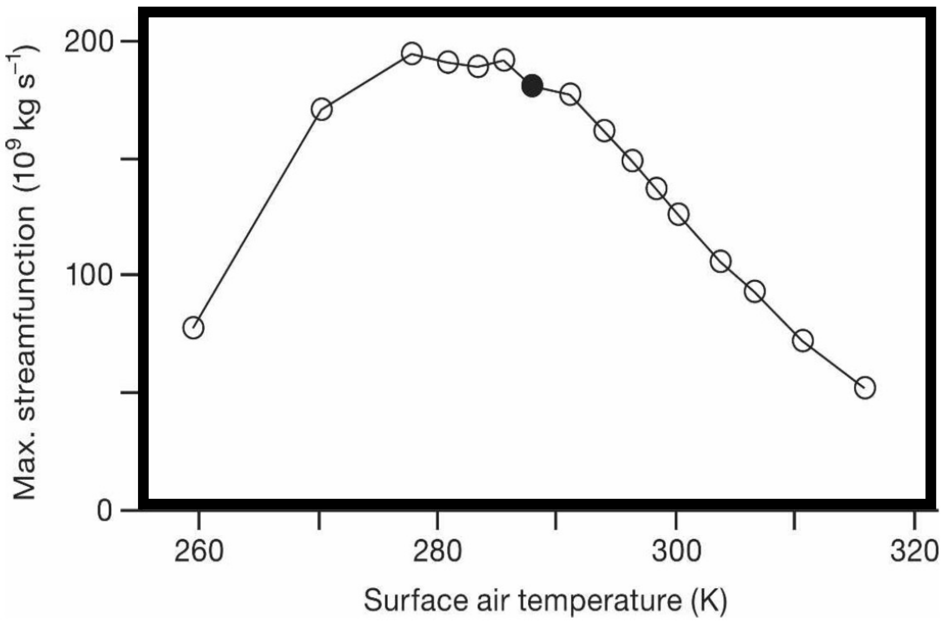
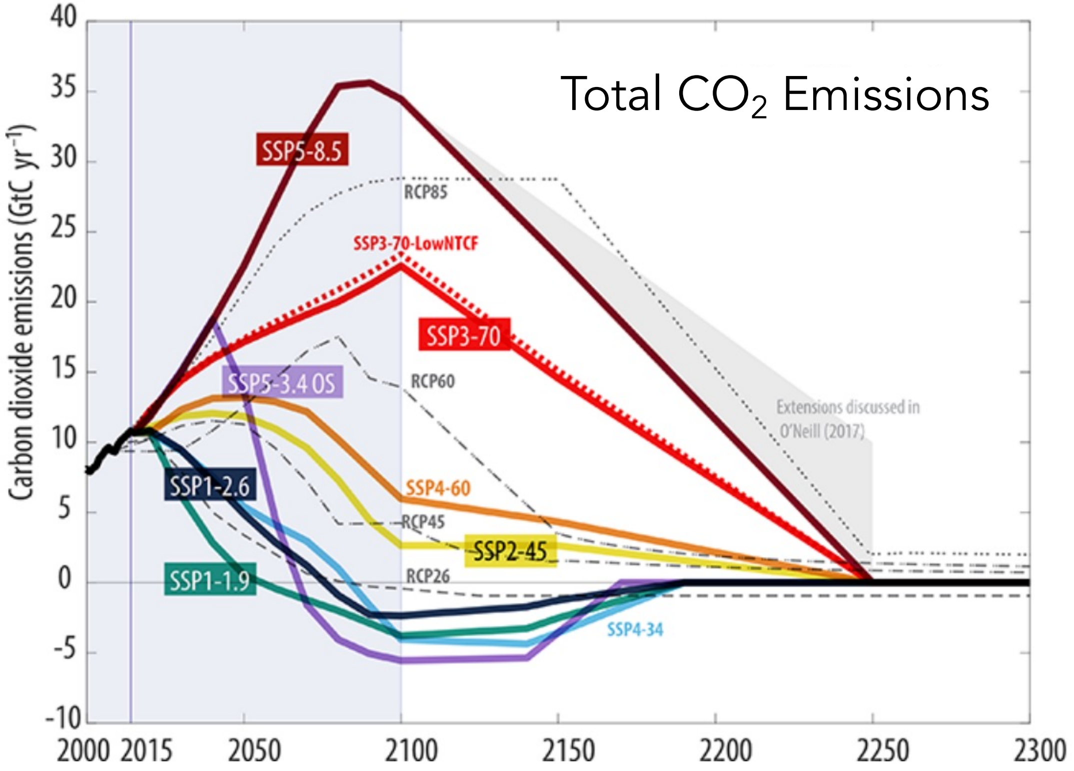
- Indeed, simpler models suggest that the $CO_2$-only response of the climate system is quite complicated, featuring bifurcations in oceanic flow regimes (Stommel (1961)) and non-monotonic behavior in global mean precipitation and Hadley Cell strength (O'Gorman and Schneider (2008), right; Levine & Schneider (2011)).



- To this end, we focus on the response of extratropical variability – primarily, the Northern Hemisphere (NH) storm tracks – to a broad range of abrupt $CO_2$ forcing experiments using the coupled atmosphere-ocean NASA Goddard Institute for Space Studies (GISS) Model E2.1-G (Kelley et al. (2020)) submitted to CMIP6.

- These results are then placed in the context of the more realistic Shared Socioeconomic Pathways (SSPs) emission scenarios (O'Neill et al. (2016)), also integrated using Model E2.1.

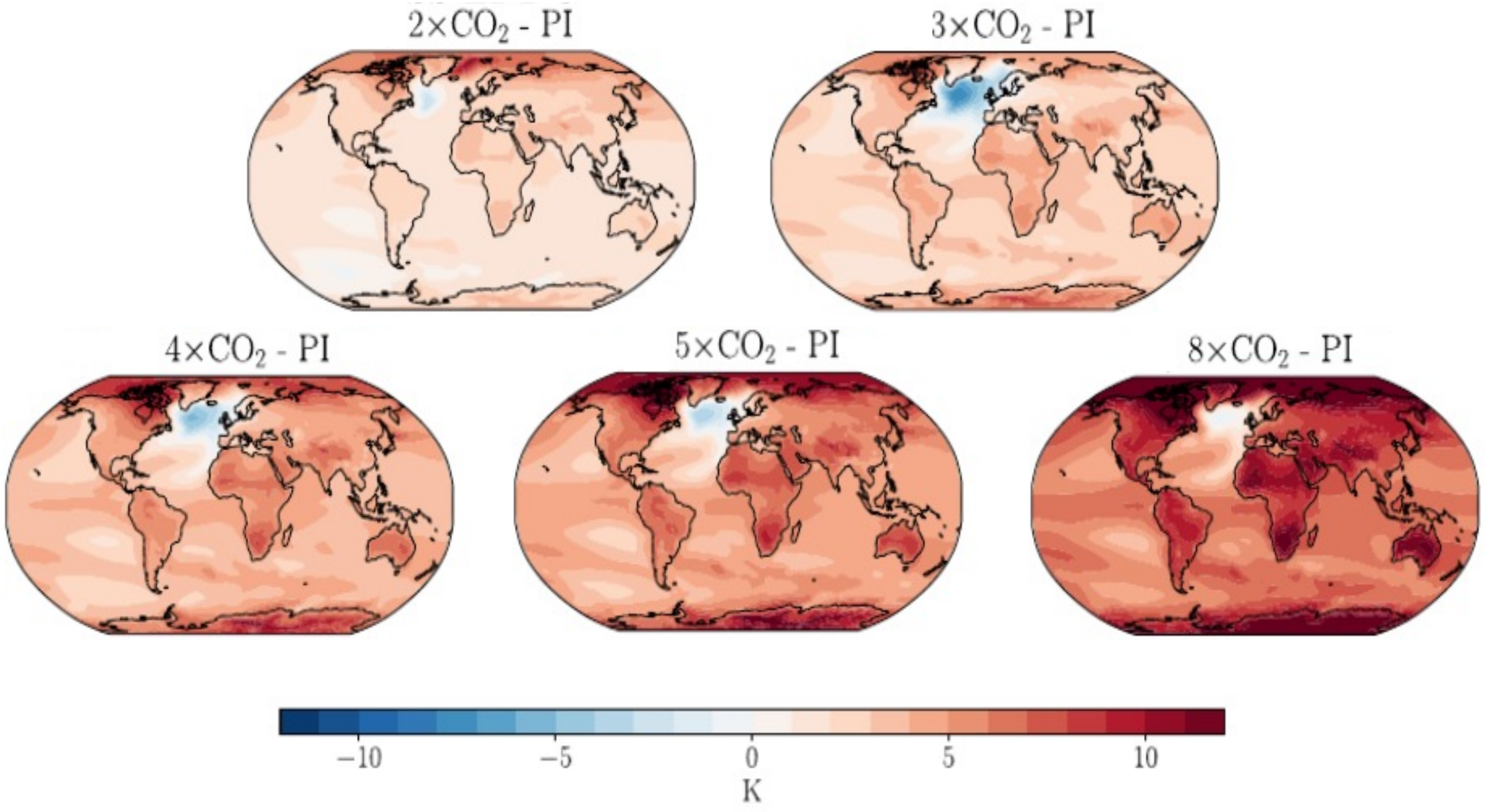
- In particular, we examine changes in the projected relationship between forcing and internal variability over the longer timescale response comprising the SSP "extensions" beyond 2100 over the 21st and 22nd centuries (Meinshausen et al. (2020)).



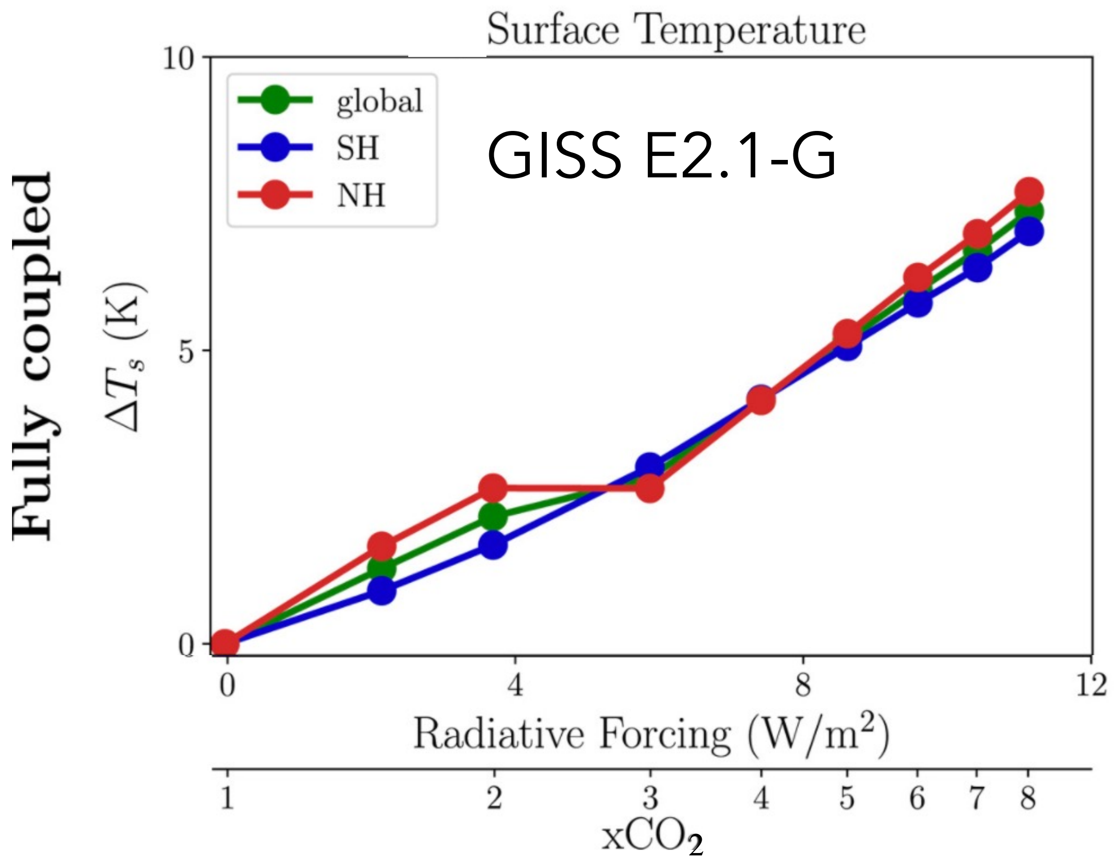
- Mitevski et al. (2021)* explored the climate system response to the range 1x- to 8x-$CO_2$ using two state-of-the art coupled climate models, including GISS E2.1-G and CESM-LE.

*U32B-07 - "Non-monotonic Response of the Climate System to Abrupt $CO_2$ Forcing,"
**Wednesday 12/15**

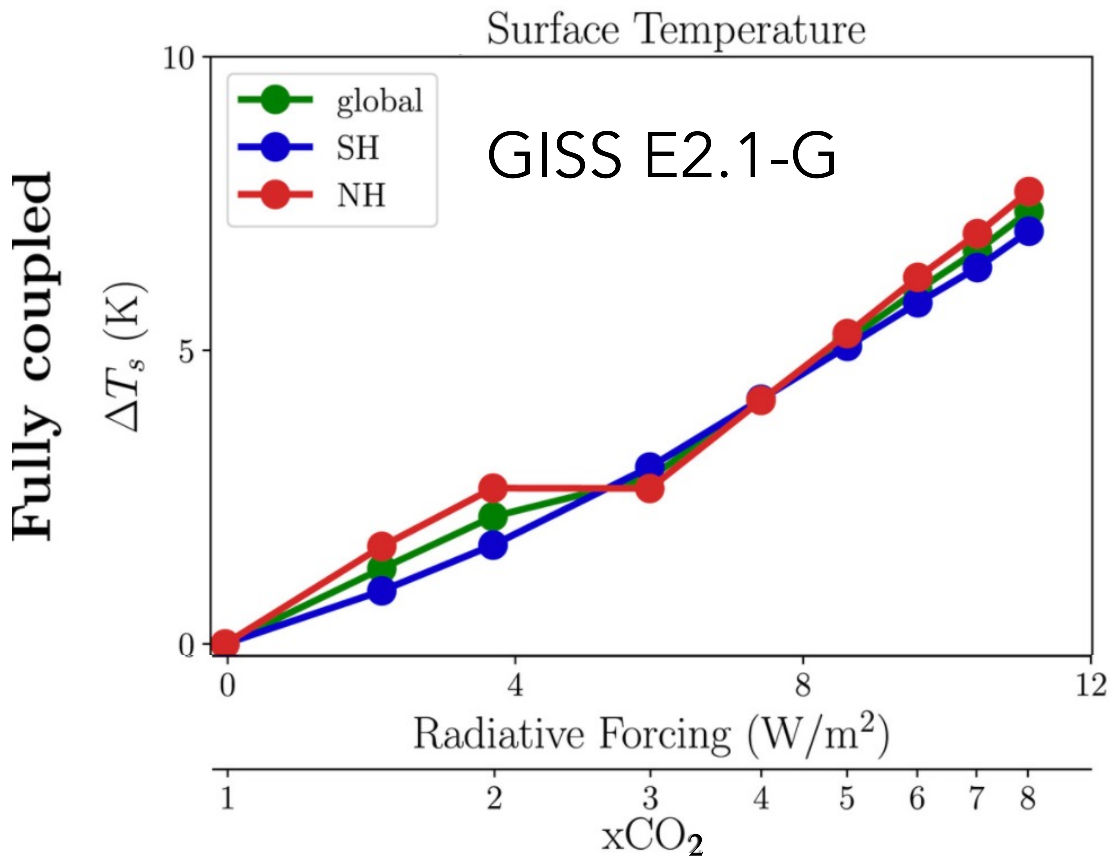
$\delta T_s$ Relative to Pi Control

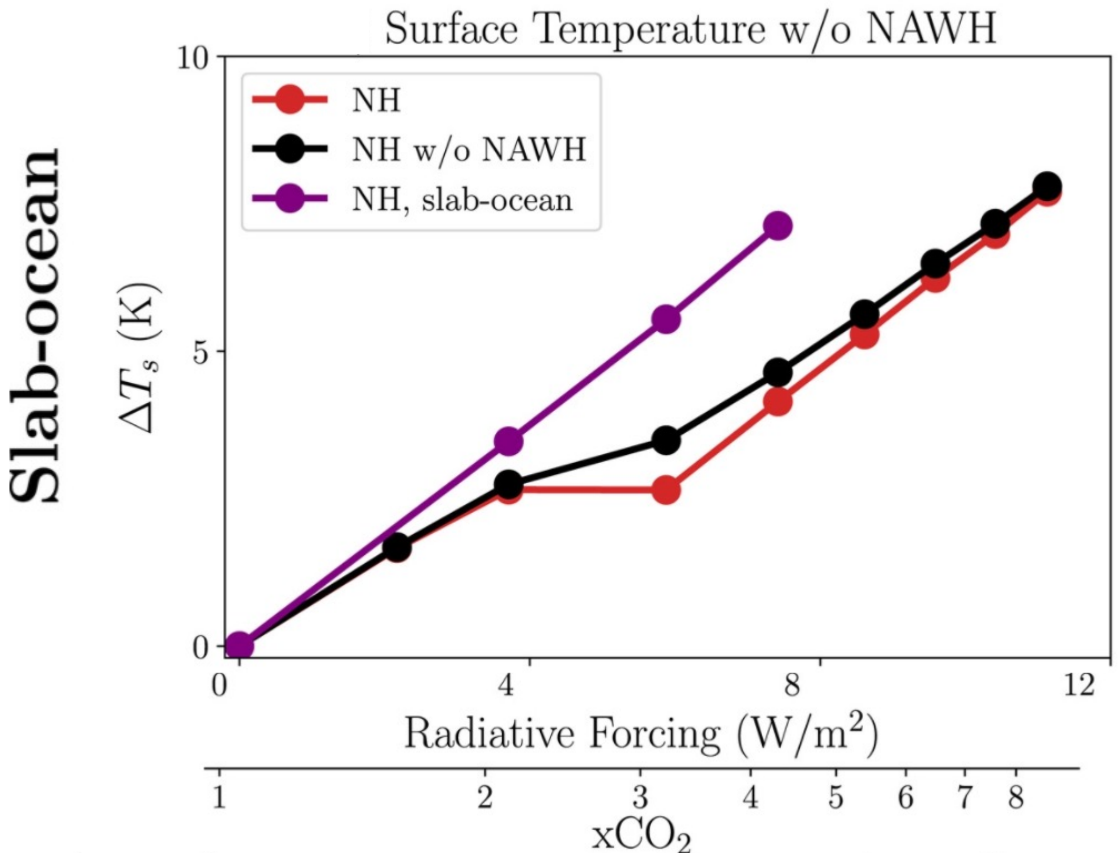


- Mitevski et al. (2021) showed that the effective climate sensitivity is a non-monotonic function of $CO_2$, minimizing at $3xCO_2$ ($4xCO_2$) in GISS E2.1-G (CESM-LE).

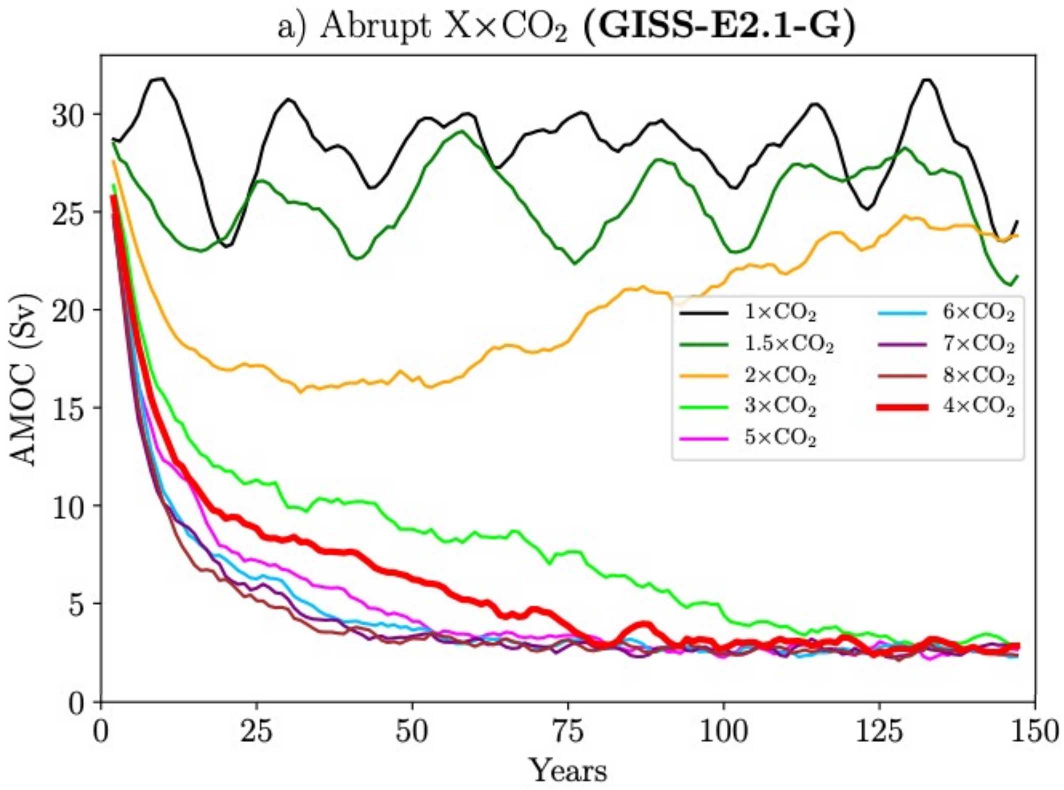


- Comparisons between fully coupled versus slab-ocean versions of both models reveal that this non-monotonic behavior is linked to changes in ocean dynamics associated with the North Atlantic Warming Hole (NAWH).

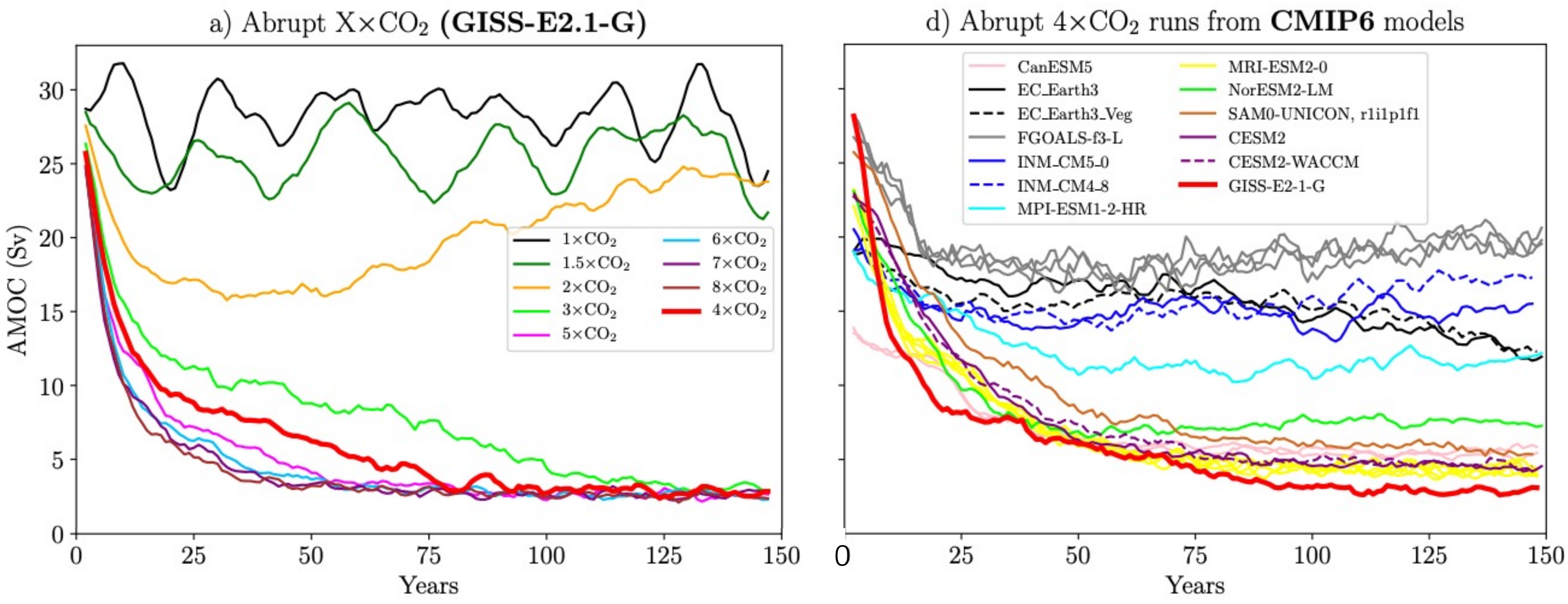


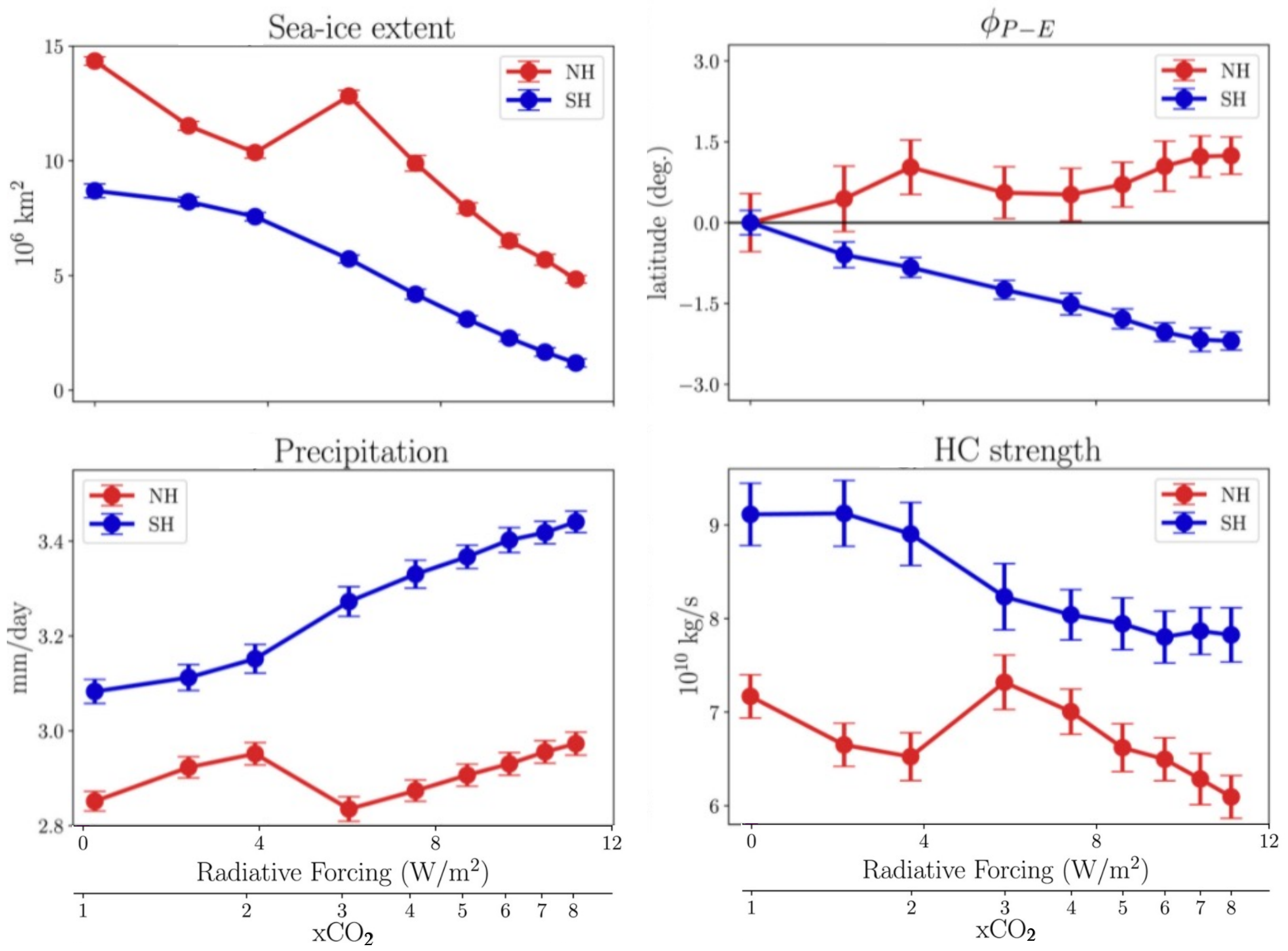
- The non-monotonic behavior in the NAWH reflects changes in the strength of the Atlantic Meridional Overturning Circulation (AMOC), which collapses in E2.1-G (CESM-LE) between 2x- and 3x-$CO_2$ (3x- and 4x$CO_2$).



- A sustained weakening and, in some models, entire collapse of the AMOC at similar forcing is also exhibited in the CMIP6 multi-model ensemble, with widespread global impacts on precipitation and the midlatitude jets (Bellomo et al. (2021)).

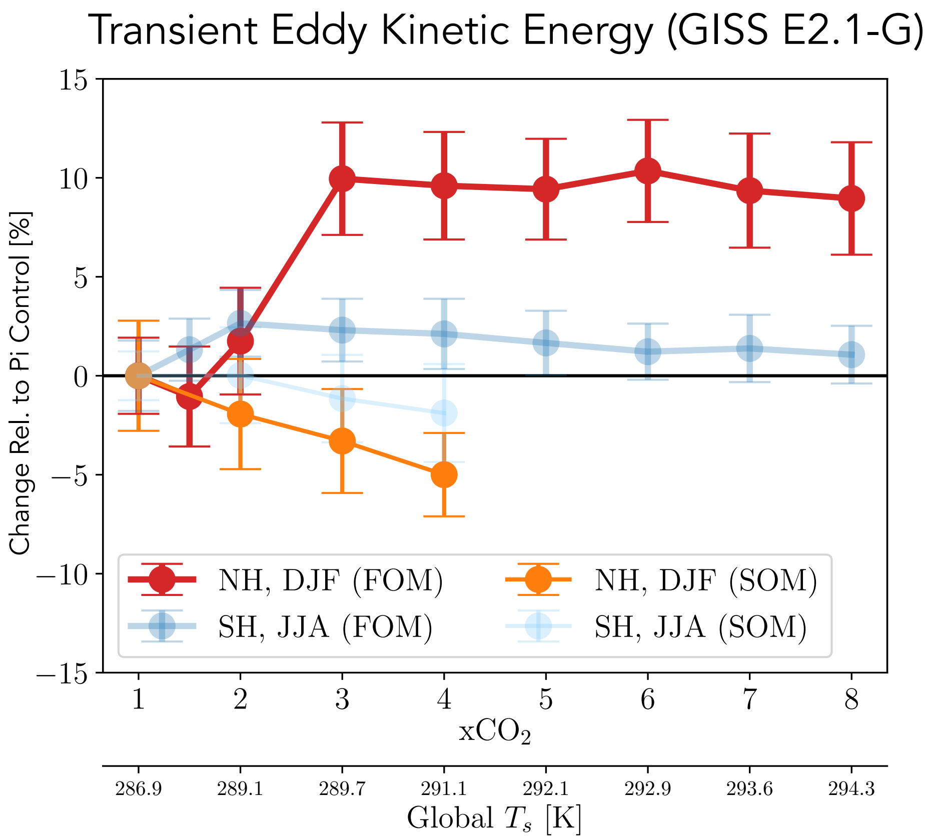


- Mitevski et al. (2021) went on to further identify non-monotonic behavior in precipitation, sea-ice, the edge of the dry zone and Hadley Cell (HC) strength.



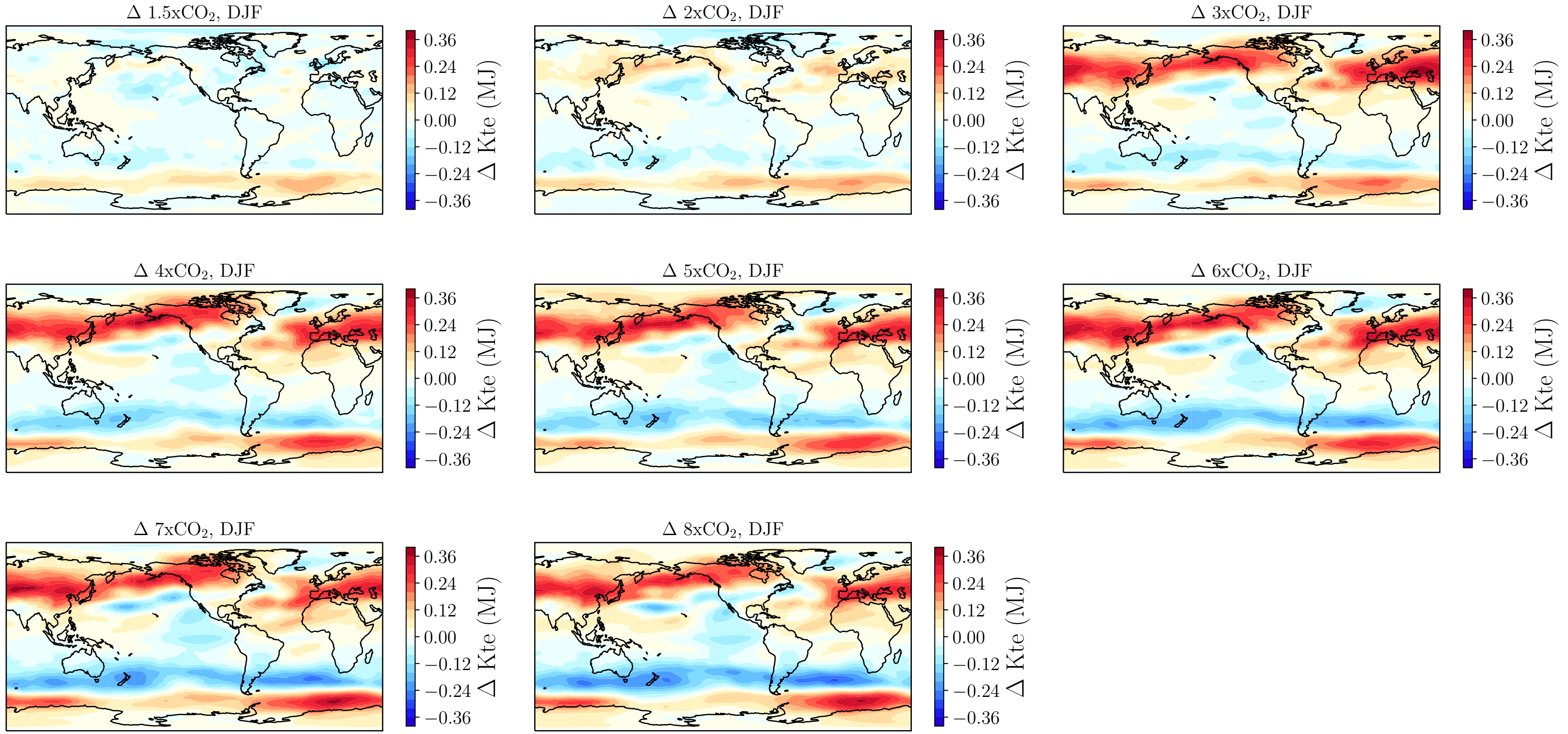
- In the NH winter storms are projected to strengthen (Chang et al. (2012); Harvey et al. (2020)), with studies highlighting the importance of ocean dynamical changes in affecting both storm track variability and their projected response to anthropogenic emissions (Woollings et al. (2012)).

- GISS E2.1-G (and CESM-LE) also project an increase in NH* winter storm track intensity with increased $CO_2$ (right), albeit only in fully coupled ocean-atmosphere integrations.

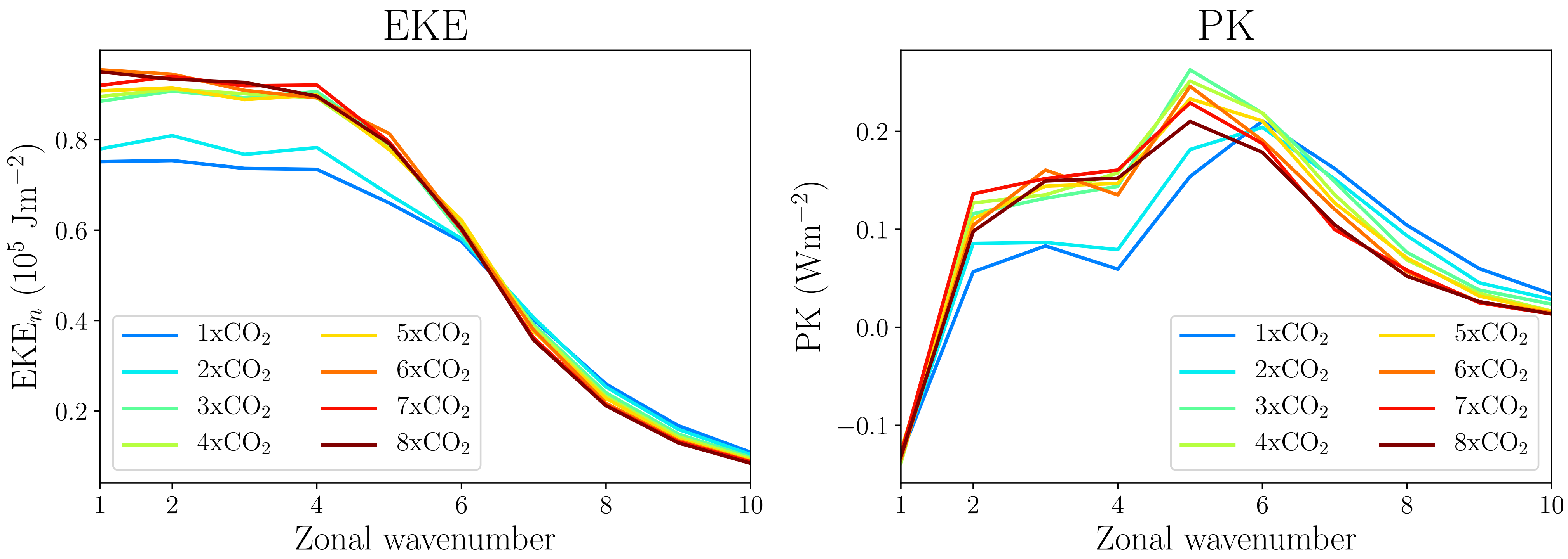



*A52H-09 - Southern Hemisphere Winter Storms Respond Differently to Low and High $CO_2$ Forcing, **Friday 12/17**

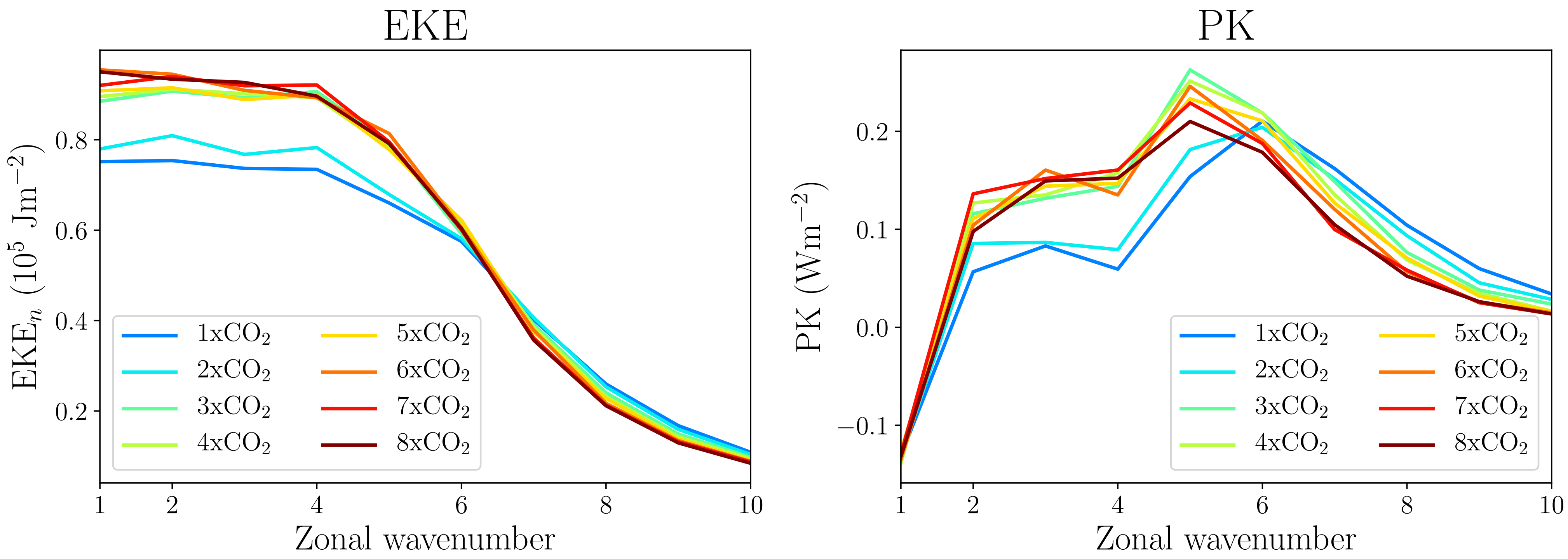
- NH transient eddy kinetic energy increases non-monotonically with $CO_2$, consistent with the response in precipitation, Hadley Cell strength, etc. (Mitevski et al. (2021).



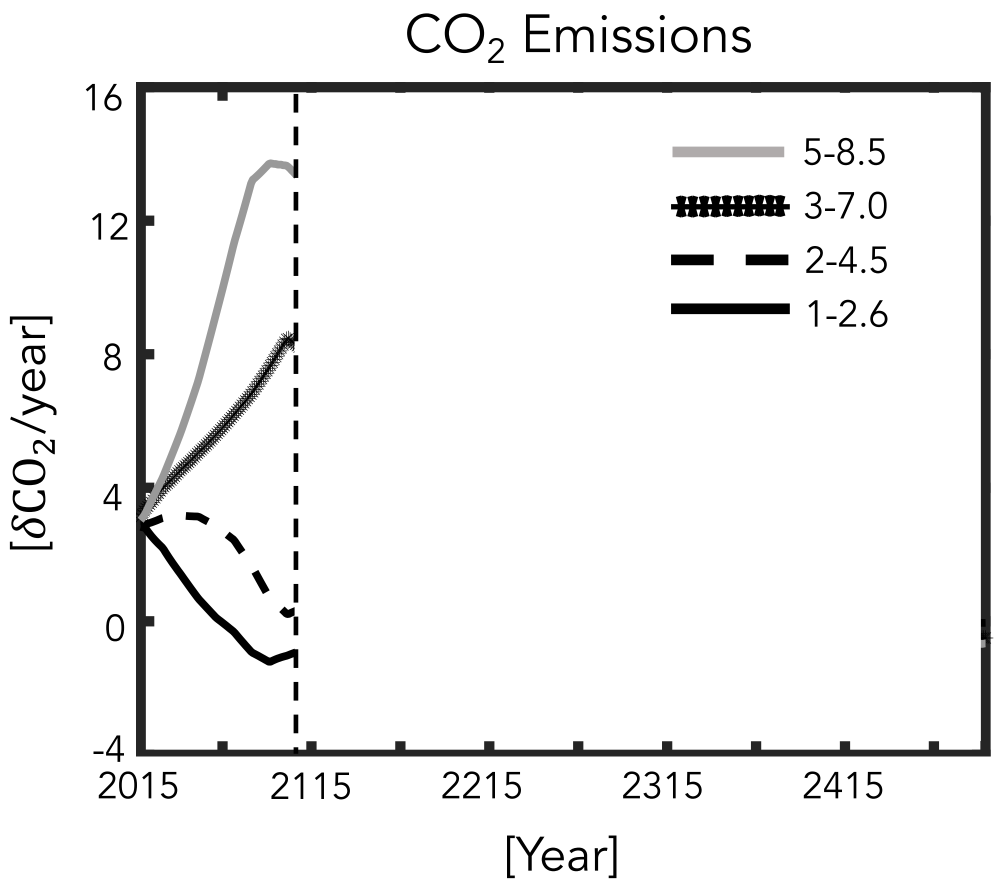
- The $CO_2$-induced changes in NH eddy kinetic energy and the conversion of eddy potential energy to EKE (PK) primarily reflect increases over wavenumbers 1-5 and 2-8, respectively.

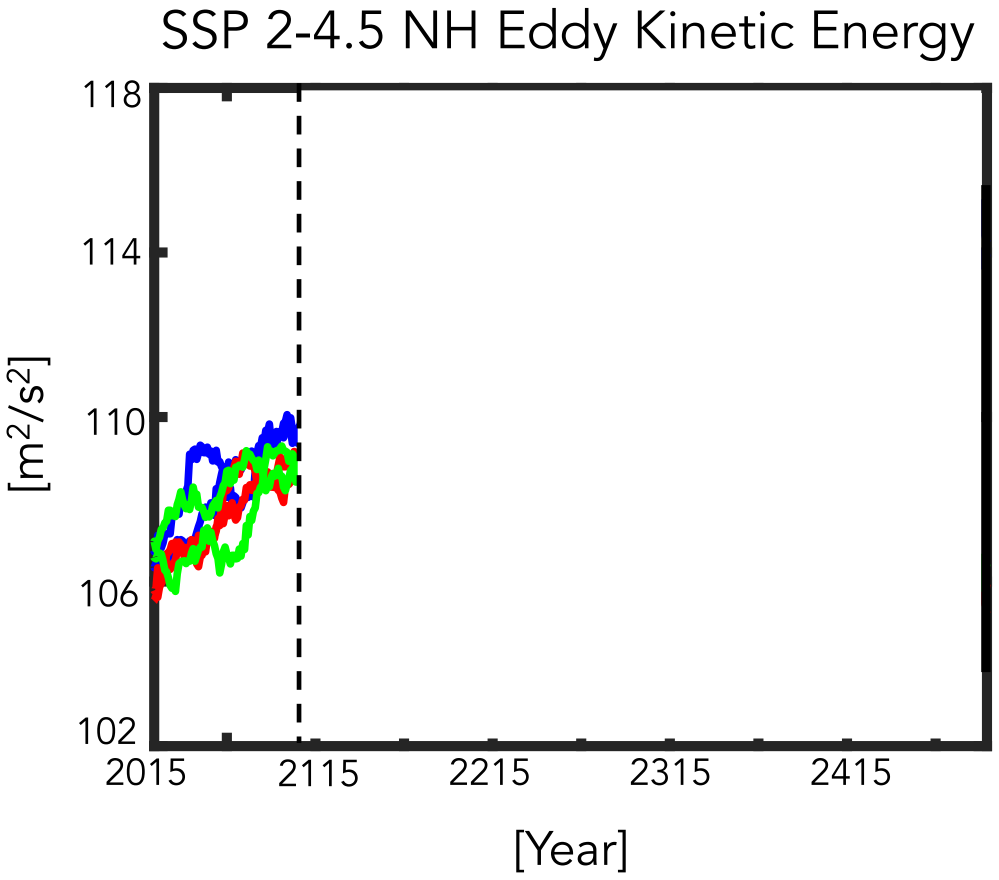


- A similar non-monotonic increase in NH EKE occurs in response to 1%$CO_2$ (transient) forcing in both GISS E2.1-G and CESM-LE.

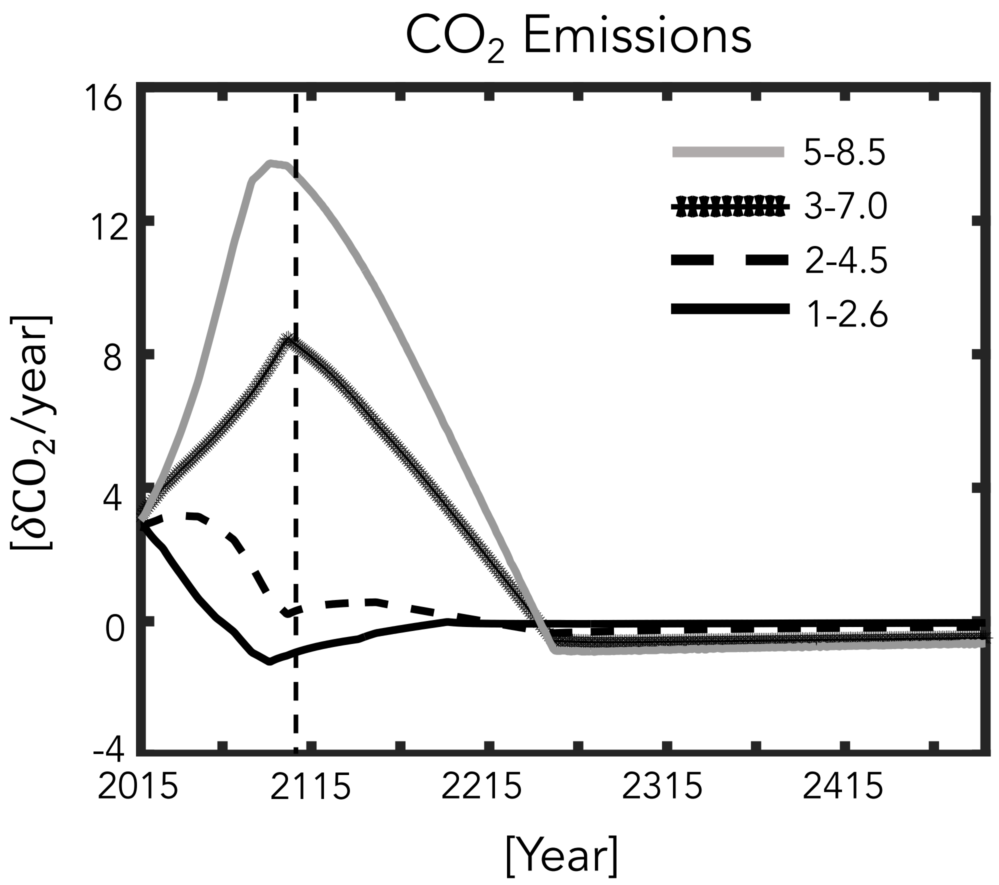


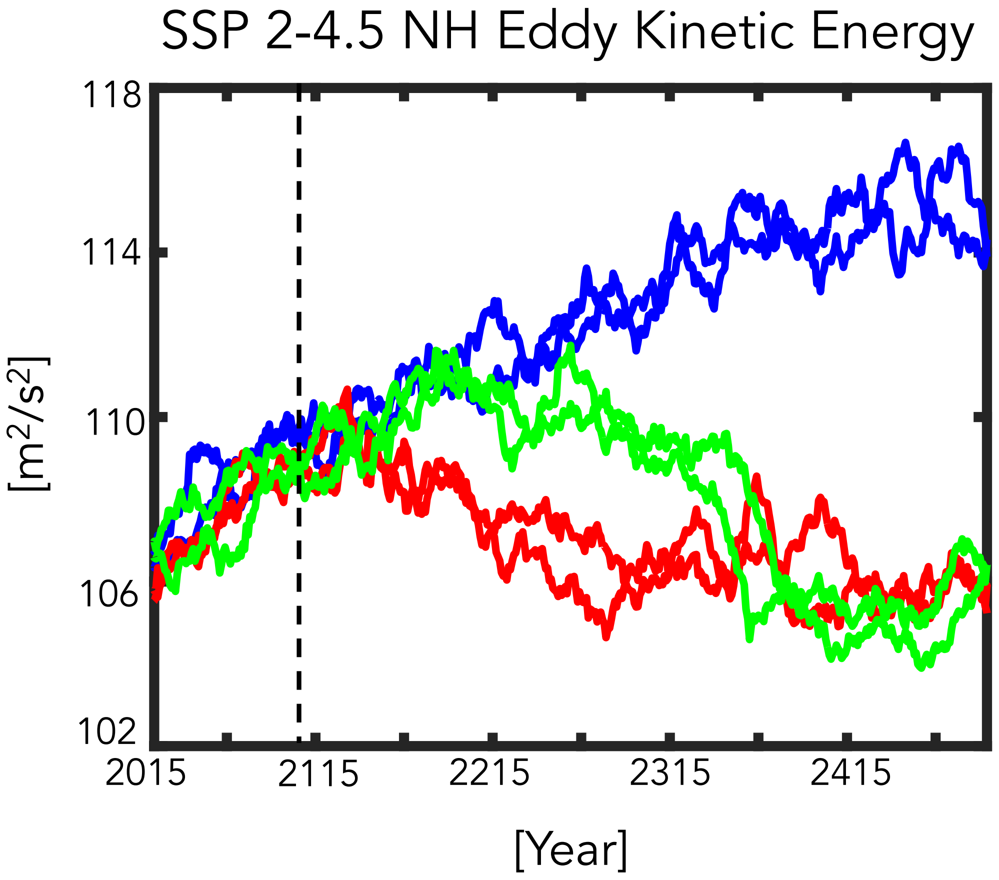
- More comprehensive forcing scenarios (i.e. SSP 2-4.5) using GISS E2.1-G also exhibit an increase in NH storm track intensity in response to anthropogenic emissions…



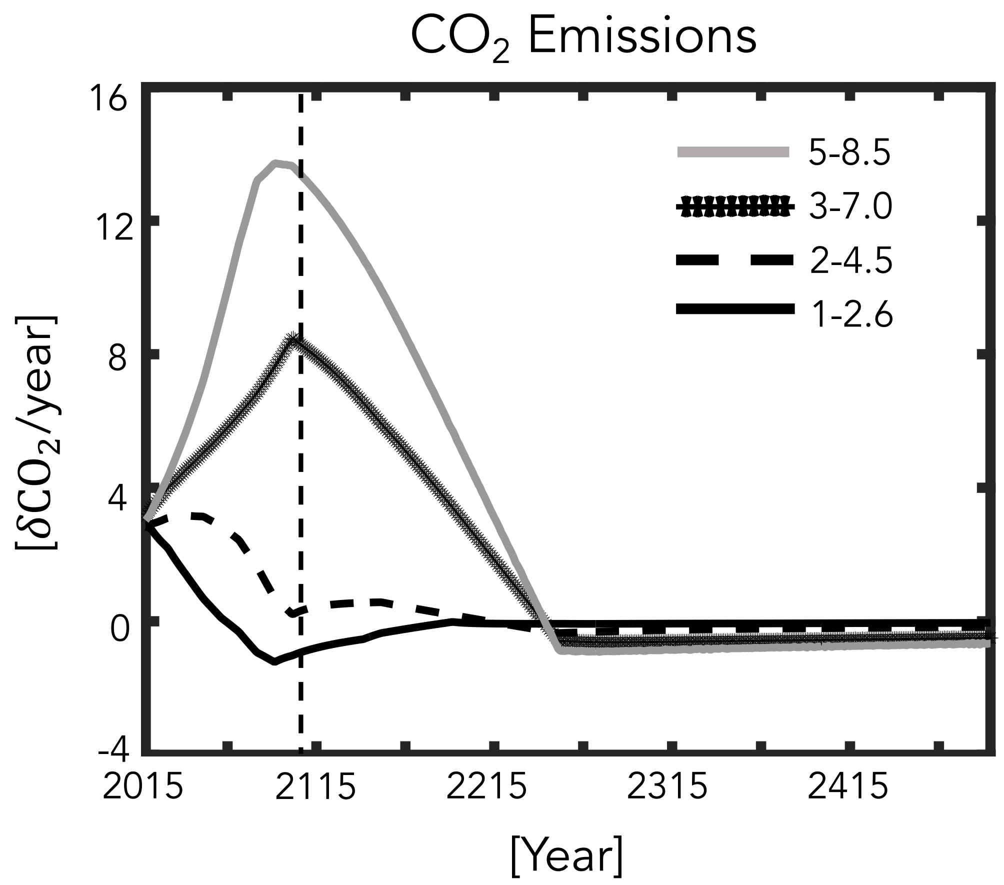



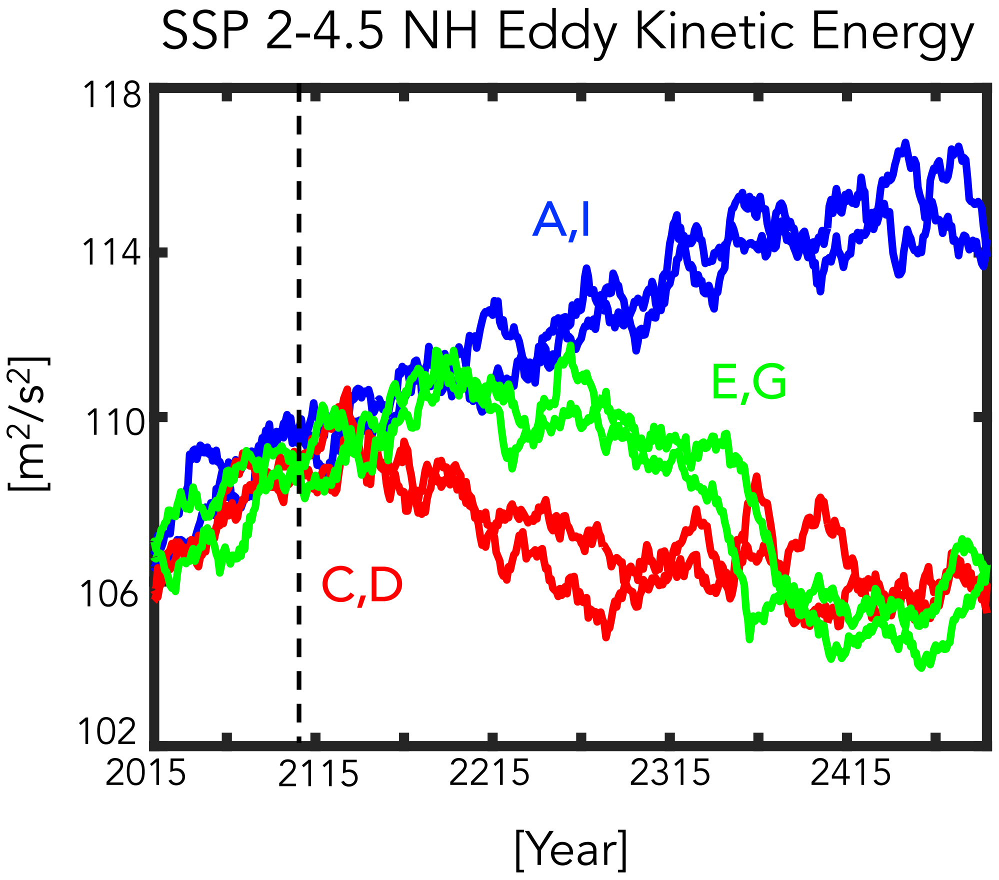
- Extension to far-future changes (>2100), however, reveal non-linearities in the system, similar to those suggested from the 1x- to 8x$CO_2$ abrupt $CO_2$ integrations.



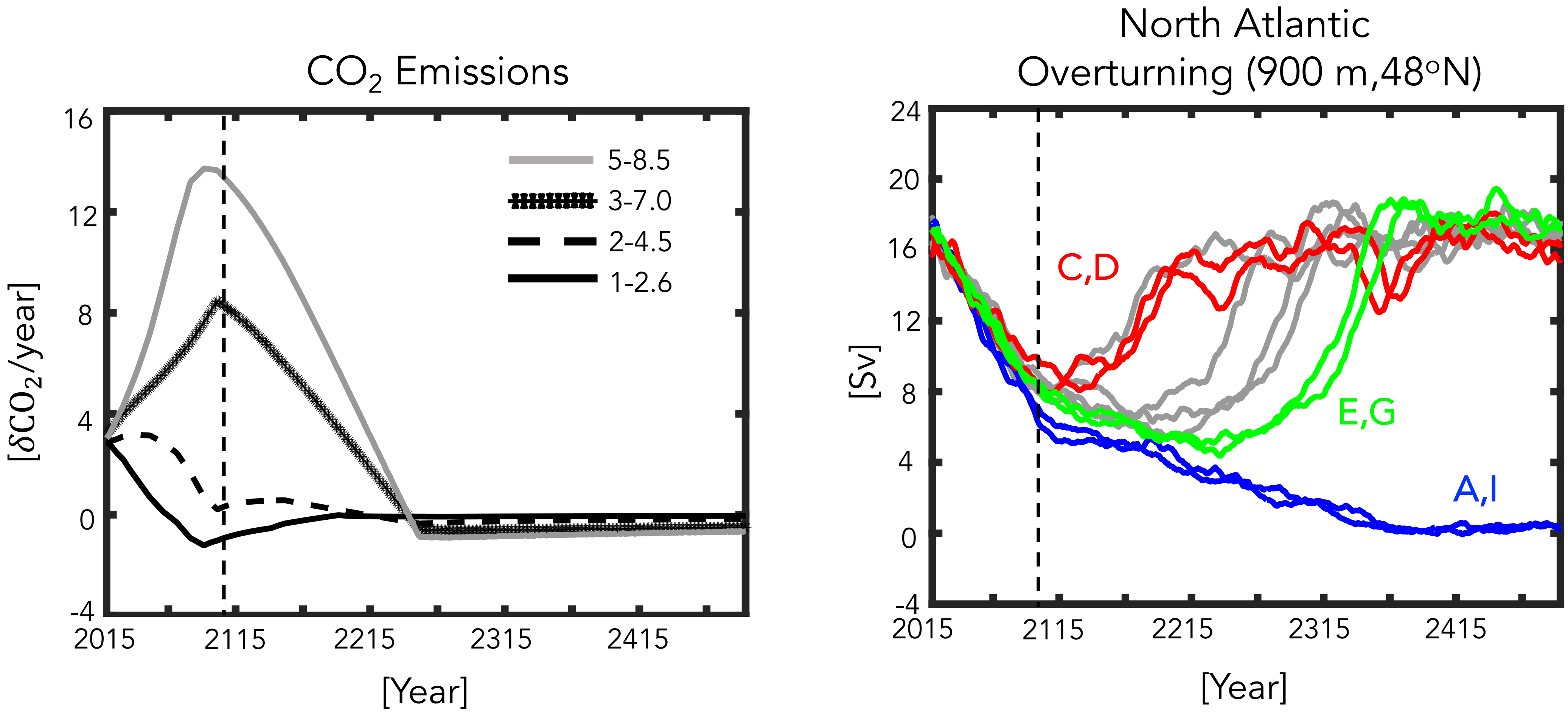



- In particular, two members (A,I) out of a ten-member ensemble exhibit a continued increase in NH EKE > 2100 under SSP 2-4.5. By comparison, the remaining eight members project an overall decrease in NH EKE, albeit at different rates (C,D vs. E,G).

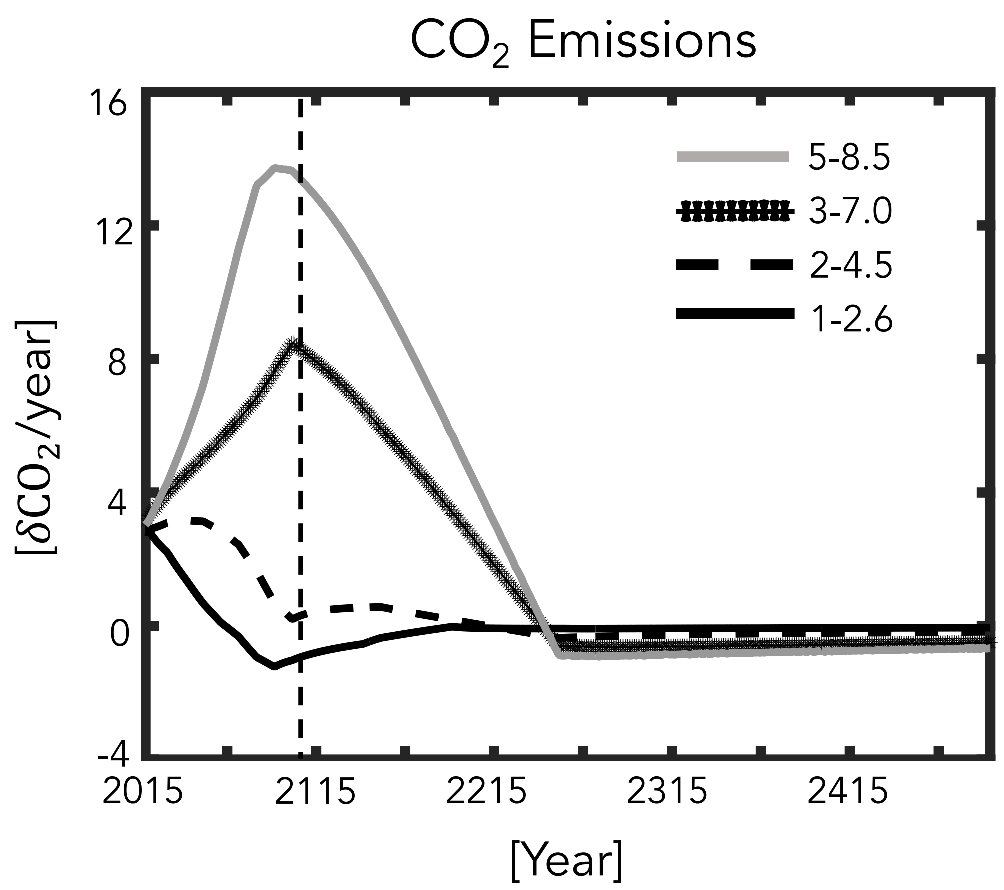


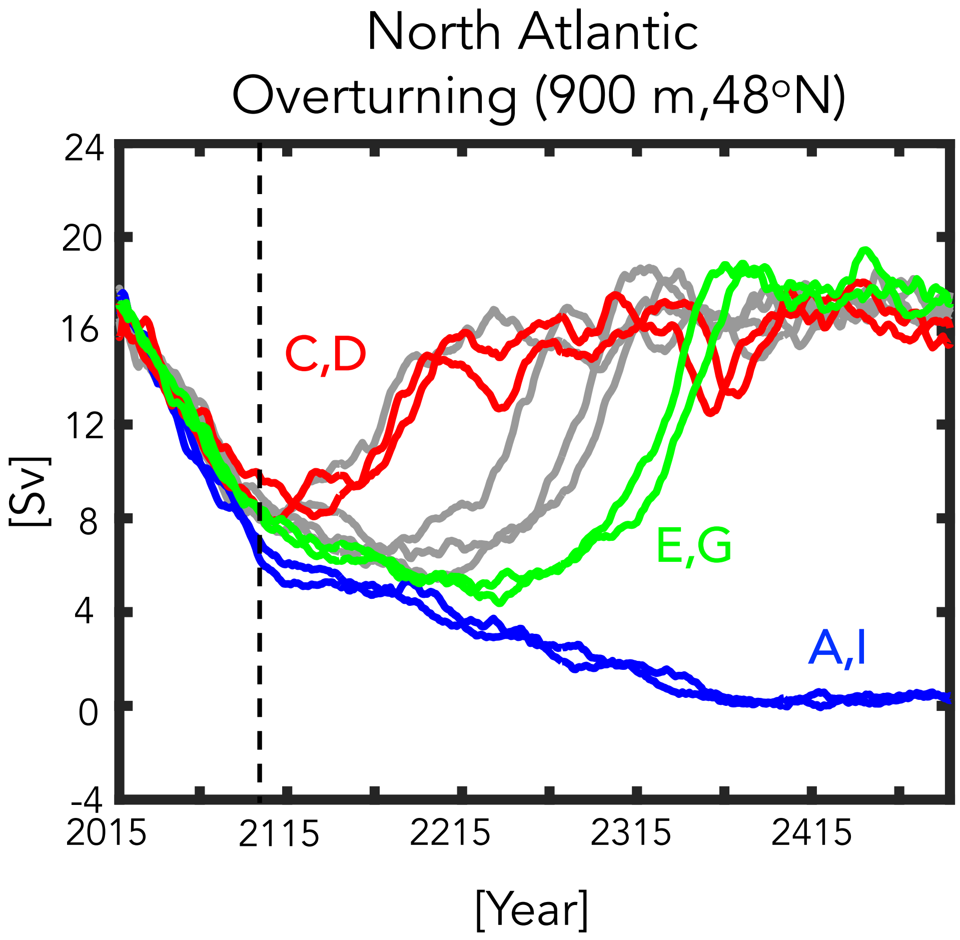



- All 10-members under the SSP2-4.5 scenario feature a decline in AMOC strength over the 21st century (Weijer et al. (2021)); thereafter individual members recover at different times, with 2 members weakening to a near-complete collapse (A,I).

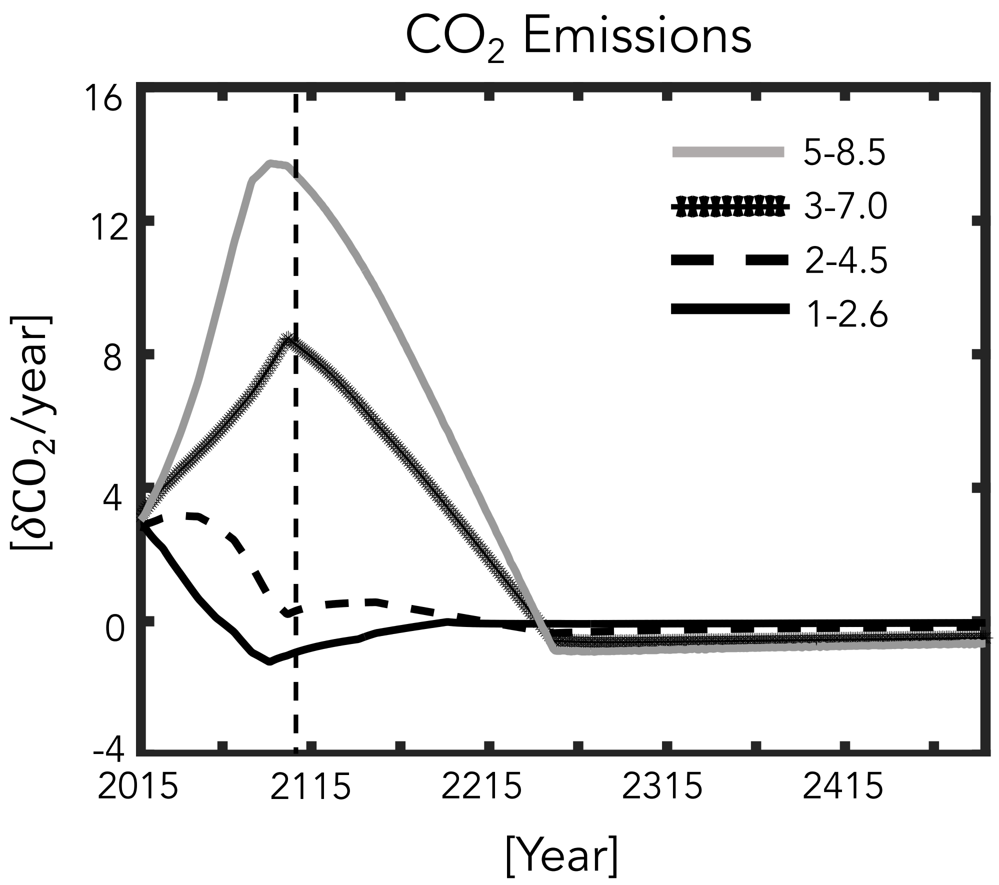


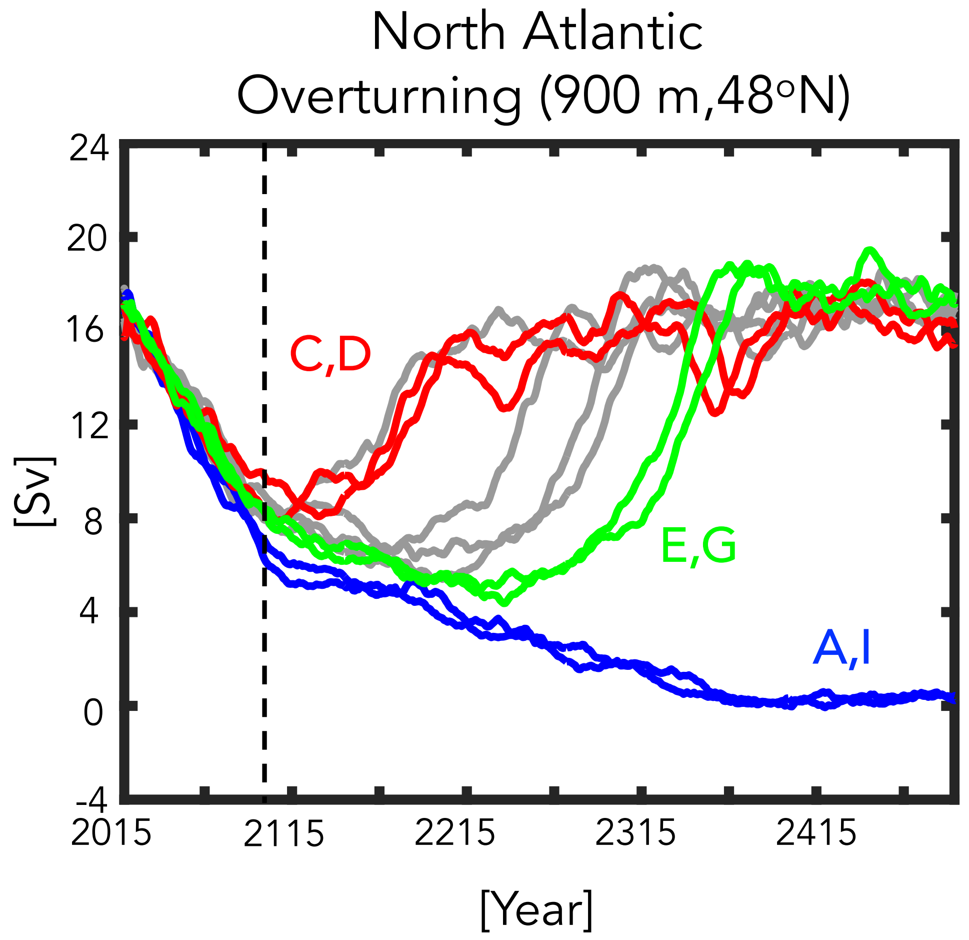
- The differences in NH EKE among ensemble members reflect differences in ocean heat transport related to feedbacks that either strengthen or weaken the AMOC.



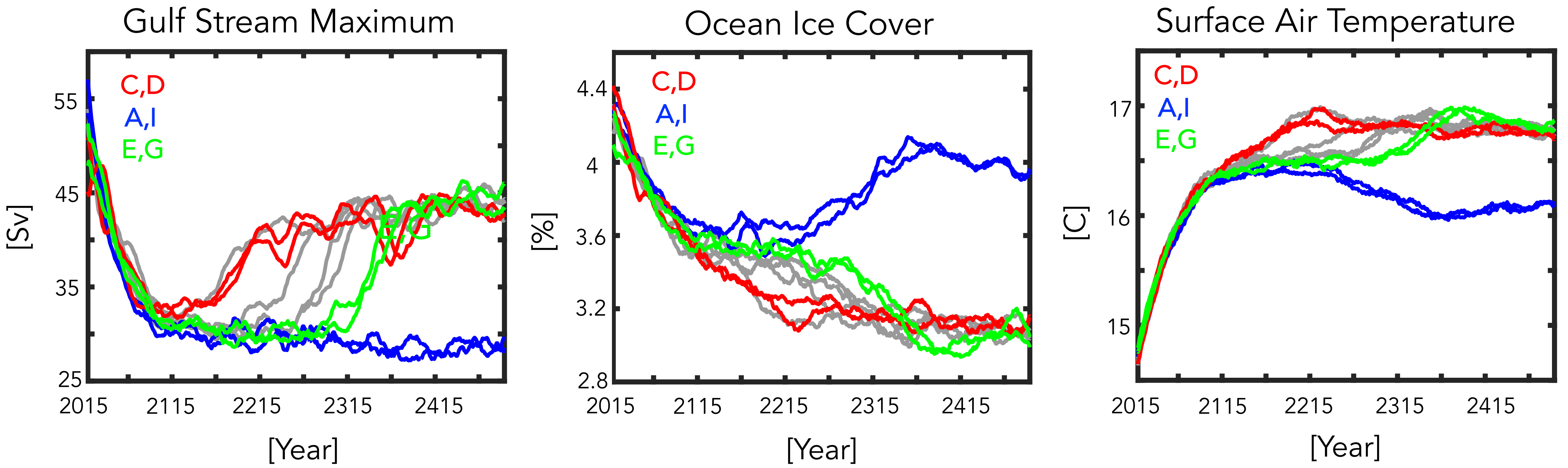



- Here the recovery/collapse of the AMOC reflects the presence of a model "threshold" around which unforced variability pushes some members into distinct climate trajectories (Stommel et al. (1961)).

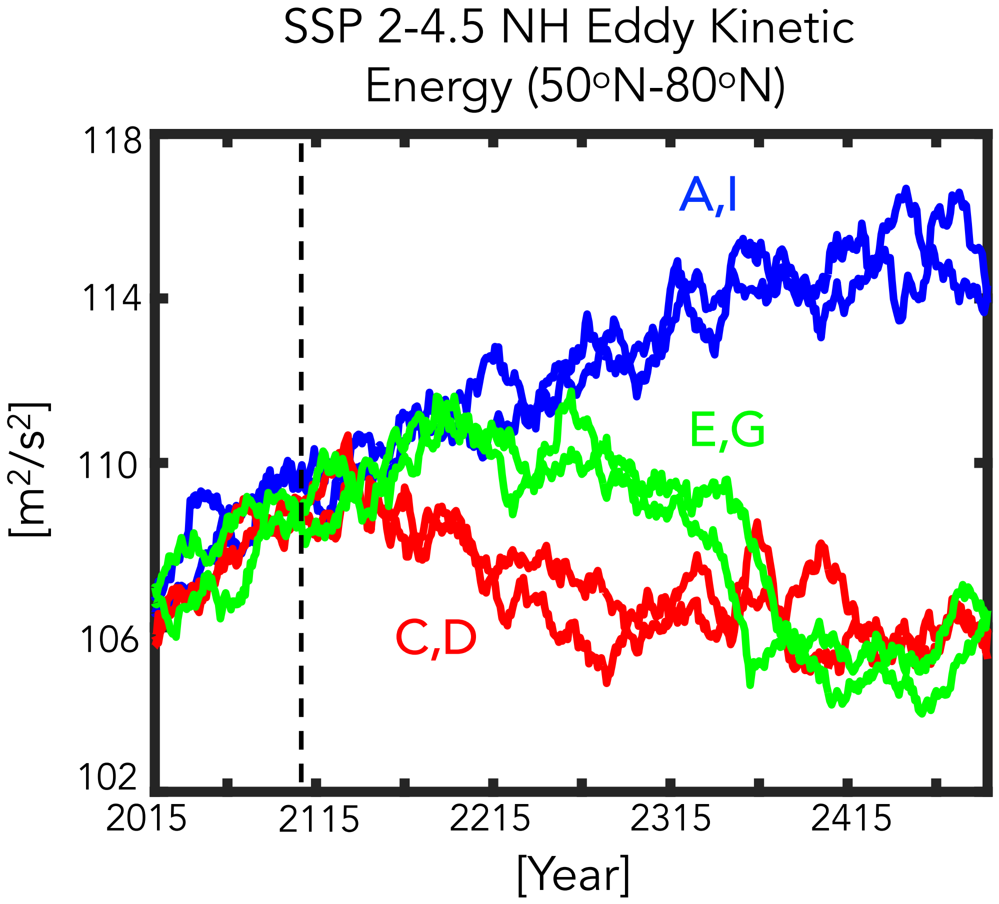


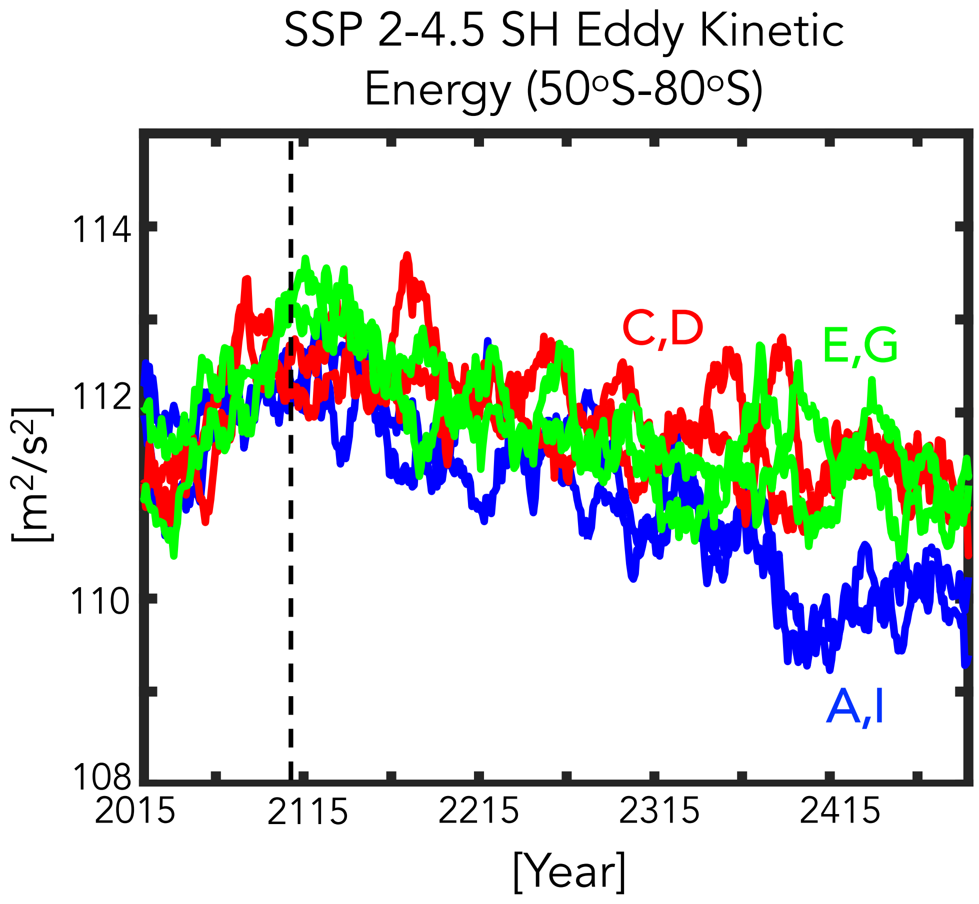



- The changes in ocean heat transport have widespread impacts on other basins and global atmospheric measures (i.e. sea ice extent and surface air temperature).



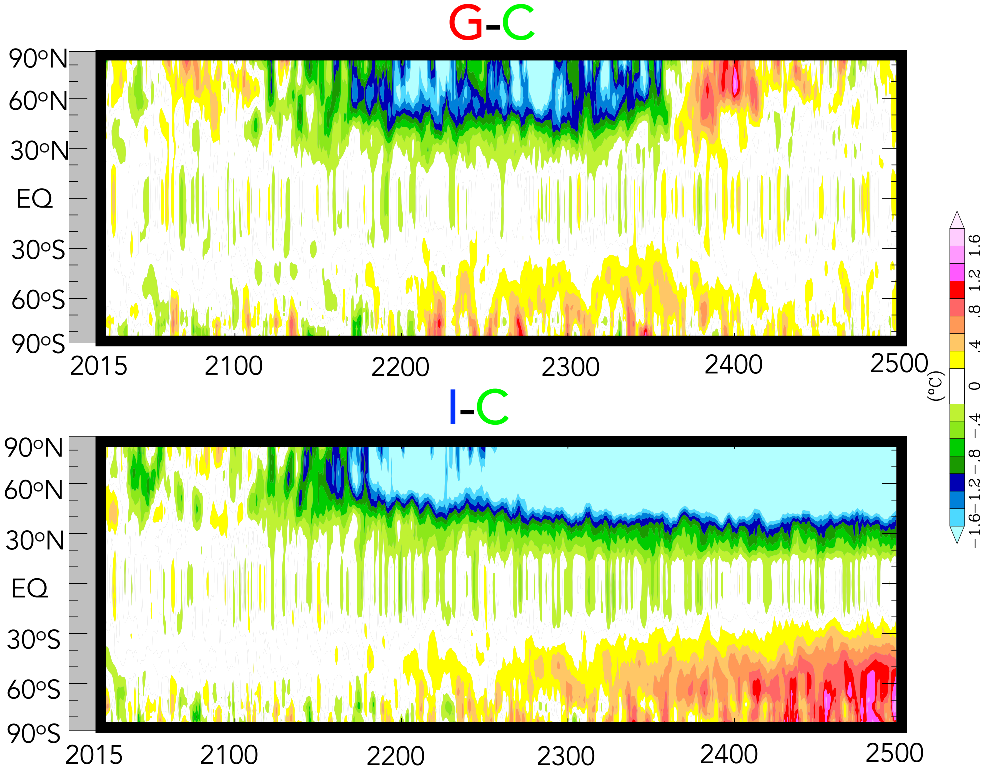
- Differences in projections of storm track intensity even appear in the Southern Hemisphere, where the members in which the AMOC exhibits a sustained collapse (A,I) exhibit an overall decrease in EKE, relative to 2015.



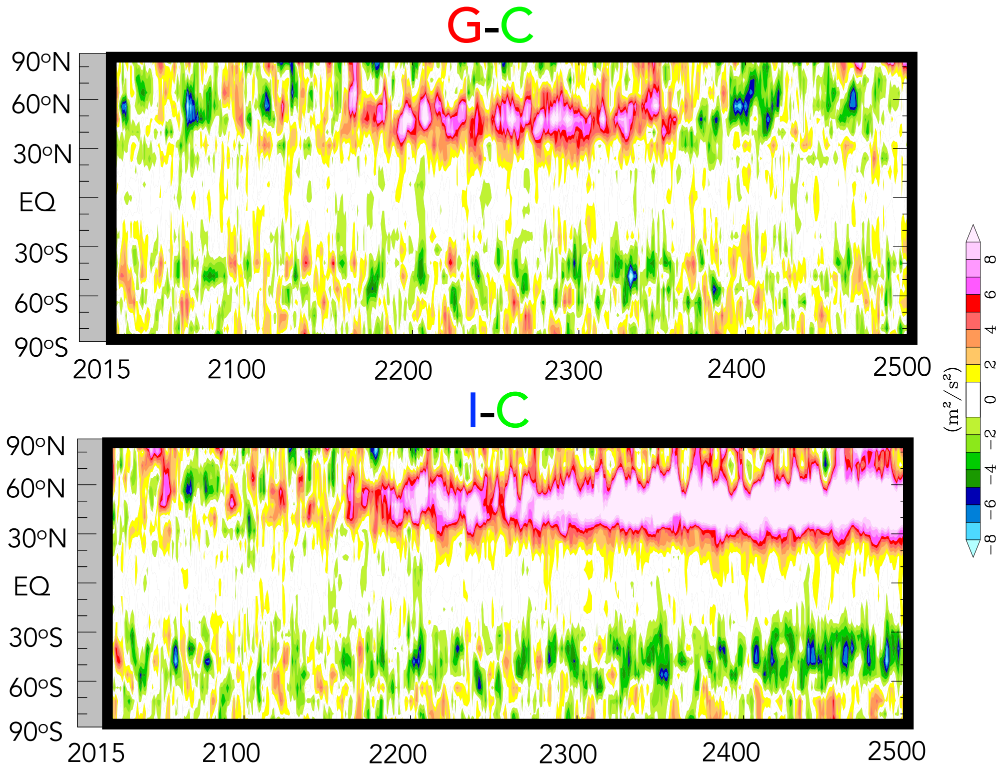



- The changes in storm track intensity are consistent with changes in the lower tropospheric meridional temperature gradient (below) and exhibit similar spectral characteristics as the abrupt 1x- to 8x$CO_2$ integrations (not shown).

800 mb Temperature

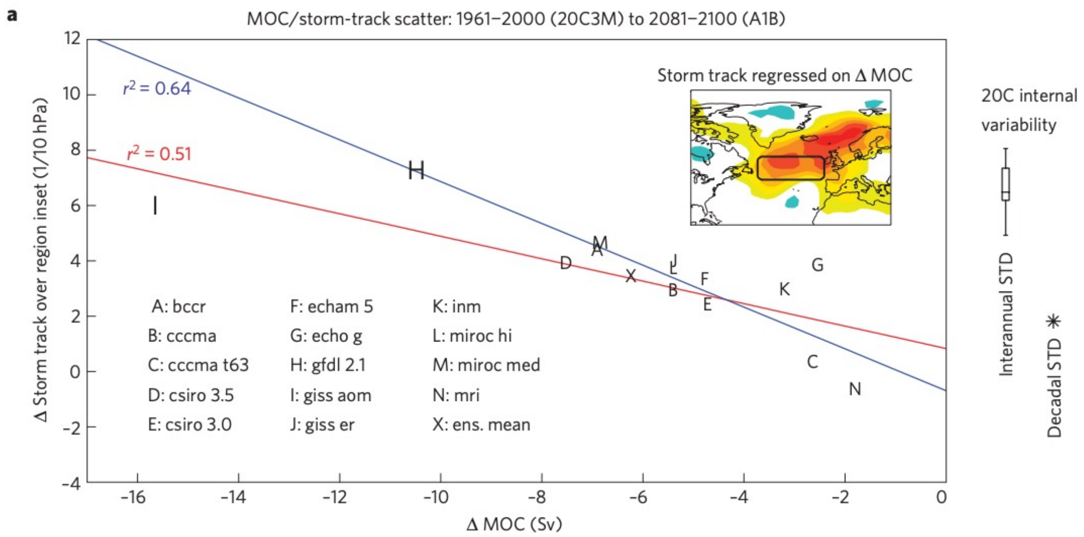



SSP 2-4.5 Transient EKE



- Previous studies have suggested that the AMOC modulates the intensification of North Atlantic winter storm tracks in CMIP3 (Woollings et al. (2012)) and jet position across the CMIP5 and CMIP6 models (Bellomo et al (2021)).

- It is not clear whether this spread in projections is driven by different formulations in ocean heat transport among models or is due to internal variability.

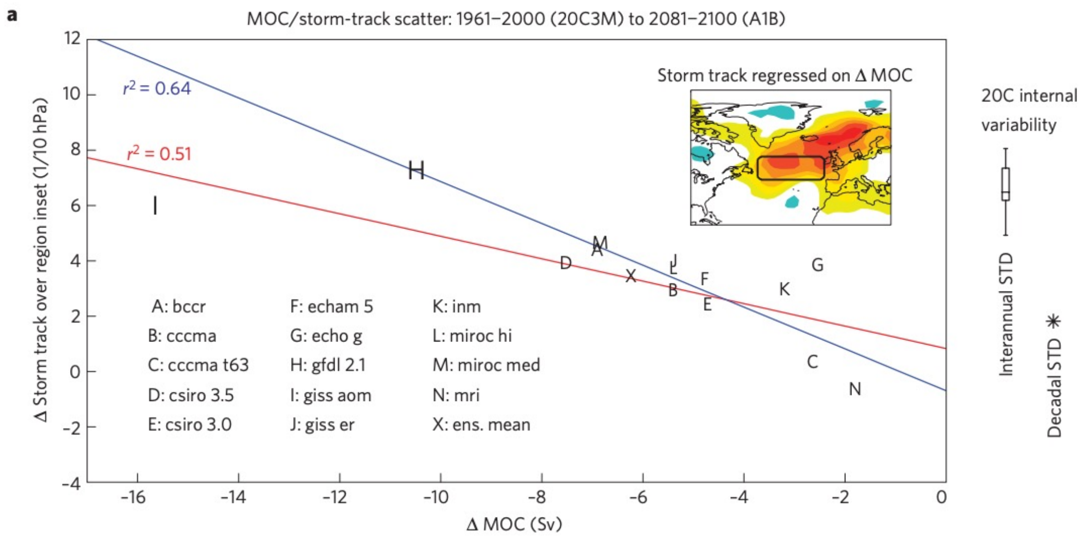



Woollings et al. (2012)

- Our results suggests that the contribution due to internal variability depends subtly on the evolution of the forcing, particularly in the presence of model "thresholds".

- More precisely, internal variability emerges for years > 2100 as a key determinant of the NH storm track – and overall climate system – response to anthropogenic emissions under certain extended SSP scenarios.

- This emergence of variability stresses the fact that climate change adaption strategies be continuously modified as greenhouse gas forcing continues.




Woollings et al. (2012)

Exploration of the climate system response to a wide range of $CO_2$ forcing reveals:

- Non-monotonic changes in NH extratropical variability (EKE), indicative of thresholds in the climate system associated with changes in ocean heat transport. These thresholds occur in several models, albeit at different $CO_2$, and in response to both abrupt and transient (1%$CO_2$) forcing.
- The "extension" (>2100) period of certain SSP scenarios also reveals the presence of such thresholds, around which unforced variations are capable of pushing certain ensemble members along a vastly different climate trajectory.
- How close are models to these thresholds? How close is this to the real world? What implications does this evolving relationship between forcing and internal variability raise for future projections of atmospheric variability?

# Thank you for your attention!

Please note the following related presentations:

U32B-07 - “Non-monotonic Response of the Climate System to Abrupt $CO_2$ Forcing,” **Wednesday 12/15**

A43B-05 - “Asymmetric Climate System Response to $CO_2$ Induced Warming and Cooling,” **Thursday 12/16**

A52H-09 - “Southern Hemisphere Winter Storms Respond Differently to Low and High $CO_2$ Forcing,” **Friday 12/17**

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