Impacts of North American forest cover changes on the North Atlantic ocean circulation

Final Author Response

Below we list the Answers to all Review Comments made in the Review Process including all relevant changes made in the manuscript.

Response to Referee Comments 1

Comment 0

The manuscript determines important impacts of North American forest cover changes on downstream North Atlantic ocean. Responses of ocean circulation and sea surface temperatures (SSTs) are investigated and the associated mechanisms are analyzed based on idealised forestation and deforestation simulation experiments with CESM2 under pre-industrial climate condition. The important role of short-lived cold air outbreaks (CAOs) in SSTs anomalies and ocean circulation changes induced by forest cover changes is highlighted. In the manuscript, the experiment simulations are reasonable, and results are well-presented. What's more, findings are of considerable interest. I recommend minor revisions of the manuscript. The detailed comments are as follows:

Response

Thank you for the positive evaluation of our study and the helpful comments. We address the comments made below and explain the modifications we made to the study.

Comment 1

The manuscript is entitled by "Impacts of North American forest cover changes on the North Atlantic ocean circulation", while "the objective of this study is to illuminate the processes involved in the formation of the NAWH -> SST anomalies downstream of large-scale forestation and deforestation across North America" is described in the introduction. Changes in ocean circulation and SST anomalies (eg, NAWH) are paid more attention throughout the manuscript. Even the latter seems to be mentioned more frequently. There are some confusions,

1) Does the manuscript focus on ocean circulation or NAWH, or both? It would be better if this was made clear. The corresponding parts in the introduction, results, and conclusions also need to be revised accordingly to highlight the focus of the manuscript.

Response

Thank you for this comment. The main focus of the study is to explore how land cover change imposed on a limited region influences the ocean circulation through air-sea interactions downstream of North

America. This involves the atmosphere, air-sea interactions, and the ocean circulation. We identify the NAWH as both a symptom and a driver of changes in ocean circulation and as such, it is also paid quite some attention throughout the manuscript.

We changed the sentence in the introduction "the objective of this study is to illuminate the processes involved in the formation of the NAWH" to "the objective of this study is to explore the impact of North American forest cover changes first on the atmosphere, on atmosphere-ocean interactions downstream of North America, and ultimately the ocean circulation." We went over the manuscript and made the following adjustments to reflect this:

- Line 96: play a crucial role for the ~~formation of the NAWH~~ downstream ocean circulation including SSTs
- Line 110: We will present the response of near surface temperature, wind and AMOC strength and compare this...
- Line 111: The following sections will explore how the found changes in temperature and wind over land drive the changes in the ocean circulation.
- Line 287: In this section, we turn to the mechanisms involved in forming the AMOC and SST response through...
- Line 442: on the ocean circulation.
- Line 480: These results suggest a positive SST – deep convection feedback mechanism initiated by the forest cover perturbations. In *forestNA*, a warmer atmosphere makes (strong) CAOs less likely. The ocean response to this is a cooling of Labrador Sea SSTs (Sect. 3.2) through changes in ocean circulation which in turn makes (strong) CAOs even less likely.
- Line 505: ...have been attributed an important role in ~~SST~~ ocean circulation changes in the North Atlantic
- Line 507: between surface wind stress and North Atlantic ~~SST anomalies~~ ocean circulation changes
- Line 580: the role of wind stress on ~~the NAWH~~ the changes in ocean circulation is more complicated
- Line 582: the effect of the atmosphere on the ocean circulation
- Line 599: from heat loss and enhancing AMOC decline
- Line 605: response of the North Atlantic ocean circulation

2) Although "The emergence of NAWH has been linked to changes in ocean circulation, in particular the AMOC" is mentioned in the introduction, what is the relationship between changes AMOC and the formation of NAWH, and how do the two influence each other, especially in this manuscript?

Response

We removed some of the literature review in the introduction in favor of making the connection of AMOC and SSTs clearer and added more details on this, note specifically:

> The emergence of NAWH has been linked to changes in ocean circulation, in particular the AMOC (Gervais et al. 2018, Caesar et al. 2018, Rahmstorf et al. 2015~~). Specifically, studies have pointed~~

~~towards a causal relationship between the concurrent cooling of North Atlantic SSTs and a potential slowing of the AMOC in response to global warming (~~van Westen et al. 2024, Ditlevsen and Ditlevsen 2023, Rahmstorf 2002, Armstrong McKay et al. 2022, Keil et al. 2020): ~~Research in the context of climate change, including the paleoclimate, has indicated that the ocean circulation may change drastically in response to atmospheric forcing with strong feedbacks on the terrestrial climate (Rahmstorf 2002, Ditlevsen and Ditlevsen 2023, van Westen et al. 2024). The cooling of the North Atlantic was shown to potentially cool large extents of the Arctic and Eurasia and lead to shifts in the climate system on the timescale of several centuries (Henry et al. 2016, Lynch-Stieglitz 2017, Lenton et al. 2008, Gervais et al. 2019).~~

~~From an energy budget perspective, a sufficiently large hemispherically asymmetric perturbation influences both atmospheric and oceanic heat transport (e.g. Portmann et al. 2022). Our study, however, does not focus on arguing with zonal mean budget constraints but local-scale processes instead.~~ Conceptually, in the subpolar North Atlantic, a warmer boreal atmosphere leads to reduced heat loss of the ocean to the atmosphere, which results in decreased deep water formation (DWF) and AMOC strength (Liu et al. 2020, Keil et al. 2020). ~~The subsequent decrease in warm water import into the North Atlantic results in a cold SST anomaly. Next to temperature, salinity is another main driver of deep water formation in the North Atlantic. For example, Liu et al. (2019) showed that the thermal and haline contributions to AMOC decline in response to Arctic sea ice decline were of similar magnitude. Specifically, increased buoyancy from enhanced freshwater influxes was comparable to the increase in buoyancy due to ocean warming, resulting from enhanced exposure to radiation. Conversely, Liu et al. (2020) found that manually reducing freshwater fluxes in anthropogenic warming simulations lead to a stabilization of the AMOC.~~ This leads to reduced transport of heat and salt into the North Atlantic as well as reduced mixing of warmer waters from below (Gelderloos et al. 2012, Drijfhout et al. 2012, Menary and Wood 2018, Putrasahan et al. 2019, Keil et al. 2020). Consequently, upper ocean heat content reduces (Stolpe et al. 2018), which is linked to reduced SSTs (Rahmstorf et al. 2015). The reduced SSTs can in turn be a positive feedback on AMOC slowdown through enhanced sea ice growth and subsequent insulation from the atmosphere that leads to cooler SSTs. Cooler SSTs result in the formation of a NAWH in a warmer climate. However, the relationship between AMOC strength and NAWH has been found to be strongly non-linear (Keil et al. 2020). Moreover, as the second large-scale ocean circulation pattern…

Comment 2

In the abstract, the introduction to the study is too long, and the significance of this study may be also missing. Besides, it would be better to make emphasis more prominent and conclusions more clear. Please rephrase the abstract to better present the significance and findings of the study.

Response

Thank you for the suggestion, please find the revised abstract below. We shortened the introduction and highlighted the results and significance.

> ~~Atmosphere-ocean heat fluxes in the North Atlantic Labrador Sea region are a key driver of deep water formation and the Atlantic Meridional Overturning Circulation (AMOC). Previous research has shown that anthropogenic warming leads to reduced ocean heat loss and thereby reduced deep mixing in the North Atlantic. This results in AMOC decline and causes regional cooling of sea surface temperatures (SSTs) which has been referred to as the North Atlantic warming hole (NAWH). Similar responses of the AMOC and the formation of a NAWH have been found for changes in wind stress and fresh water forcing in the North Atlantic. Moreover, recent research has also revealed such an AMOC and North Atlantic SST response in global-scale forestation experiments and a reversed response in deforestation experiments.~~ Planetary-scale forestation has been shown to induce global surface warming associated with a slowdown of the Atlantic meridional overturning circulation (AMOC). This AMOC slowdown is accompanied by a negative North Atlantic sea surface temperature (SST) anomaly resembling the known North Atlantic warming hole found in greenhouse gas forcing experiments. The opposite holds true for deforestation. Here, we test the hypothesis that localised forest cover changes in particular over North America are an important driver of this response in the downstream North Atlantic ocean. Moreover, we shine light on the processes linking forest cover perturbations to ocean circulation changes. To this end, we perform simulations using the fully coupled Earth system model CESM2 where pre-industrial vegetation-sustaining areas over North America are either completely forested (*forestNA*) or turned into grasslands (*grassNA*) ~~and compare it to the control scenario without any forest cover changes~~. Our results show that ~~North American forestation and deforestation induce a North Atlantic warming and cooling hole, respectively. Furthermore, the response is qualitatively similar to previously published results based on global extreme land cover change scenarios.~~ North American forest cover changes have the potential to alter the AMOC and North Atlantic SSTs similar to global ones. North American forest cover changes mainly impact the ocean circulation through modulating land surface albedo and, subsequently, air temperatures. We find that comparably short-lived cold air outbreaks (CAOs) play a crucial role in transferring the signal from the land to the ocean: Around 80% of the ocean heat loss in the Labrador Sea occurs within ~~comparably short-lived cold air outbreaks (~~CAOs~~)~~ during which the atmosphere is colder than the underlying ocean. A warmer atmosphere in *forestNA* compared to the control scenario results in fewer CAOs over the ocean and thereby reduced ocean heat loss and deep convection, with the opposite being true for *grassNA*. The induced SST responses further decrease CAO frequency in *forestNA* and increase it in *grassNA*. Lagrangian backward trajectories starting from CAOs over the Labrador Sea confirm that their source regions include (de-)forested areas. ~~A closer inspection of the ocean circulation reveals that~~ Furthermore, the subpolar gyre circulation is found to be more sensitive to ocean density changes driven by heat fluxes than to changes in wind forcing modulated by upstream land surface roughness. In *forestNA*, sea ice growth and the corresponding further reduction of ocean-to-atmosphere heat fluxes forms an additional positive feedback loop. Conversely, a buoyancy flux

decomposition shows that freshwater forcing only plays a minor role for the ocean density response in both scenarios. Overall, this study shows that ~~forest cover changes over North America alter the frequency of CAOs over the North Atlantic and, as a consequence, the circulation of the North Atlantic. This highlights the relevance of CAOs for the formation of North Atlantic SST anomalies.~~ the North Atlantic ocean circulation is particularly sensitive to upstream forest cover changes and that there is a self-enhancing feedback between CAO frequencies, deep convection and SSTs in the North Atlantic. This motivates studying the relative importance of these high-frequency atmospheric events for ocean circulation changes in the context of anthropogenic climate change.

Comment 3

It would be better to give an overview of the purpose and significance of this study in the introduction, which may greatly enhance the interest of the manuscript.

Response

Thank you for pointing this out, we made adjustments to highlight the significance and purpose of the study:

- Line 54: However, the underlying drivers of the NAWH and NACH have not been further explored in these studies.
- We moved the introduction of the global forest cover experiments of Portmann et al. (2022) further down to make the significance of the study more clear, notably “the physical mechanisms responsible for these changes in ocean circulation in response to forest cover changes remain open.”
- We clarified the objective of the study as stated in the response to comment 1
- Line 108: Throughout this work, we aim to contextualise our findings in the broader picture of atmosphere-ocean dynamics in the subpolar North Atlantic. In particular, we compare our results to future climate simulations concerning ocean circulation changes and the NAWH and discuss the potential transferability of our conclusions regarding the identified physical mechanisms.

Comment 4

In the results, many variables are described and discussed, such as mixed layer depth, temperature, salinity, CAOs, etc. Although correlations between some variables are mentioned, such as “changes in MLD overlap well with the integrated ocean-to-atmosphere heat flux associated with strong CAOs”, “the negative SST anomaly overlaps with a strong MLD anomaly sea ice wind salinity”, etc., what is the specific causal relationship, and what is the logic chain of variables mentioned in 3.2? How much did each discussed factor contribute to the change in AMOC or the formation of NAWH? It would be better to present a logical diagram to briefly show the influence mechanism of each factor and its contribution, which would make findings more clear.

Response

Thank you for this suggestion. We added the logical diagram shown below (Fig. RA1) to the conclusions section. Note that a quantitative comparison for the importance of buoyancy vs mechanical forcing is given in section 3.4.

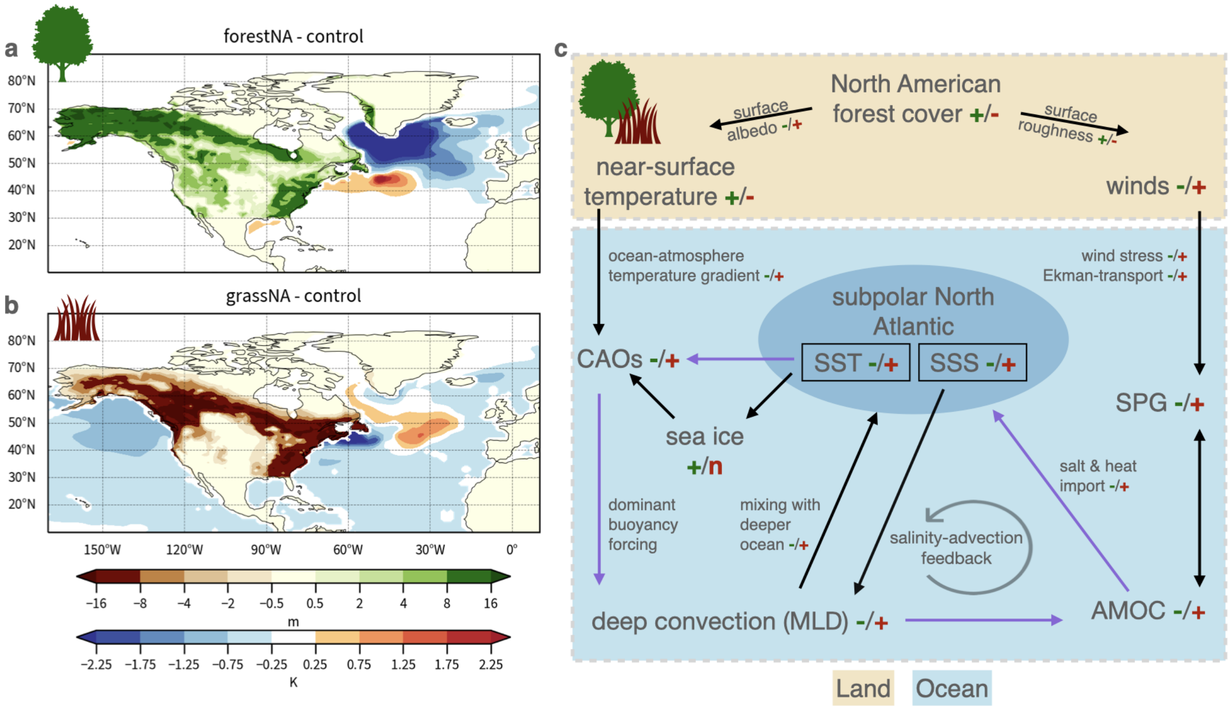

Figure RA1: Maps showing changes in canopy height on land and changes in SSTs over the ocean averaged over DJFMAM of the years 50 and 300 for (**a**) forestNA and (**b**) grassNA. (**c**) Proposed chain of processes how North American forest cover changes impact the North Atlantic ocean: Signs "+" and "-" indicate increase or decrease of the denoted variable while "n" indicates no change. Green signs indicate forestNA (always left) and brown grassNA (always right). Arrows marked in purple instead of black denote the positive feedback between CAOs, North Atlantic SSTs and the AMOC. CAOs = cold air outbreaks, MLD = mixed layer depth, AMOC = Atlantic meridional overturning circulation, SPG = subpolar gyre, SST = sea surface temperature, SSS = sea surface salinity.

This also leads to some added discussions in this section:

- Line 557: ...warming on the global scale, due to the dominant albedo effect at high latitudes
- Line 563: ...North Atlantic. The effective changes in canopy height from forest cover changes are shown with the resulting changes in SSTs in Fig.8a for forestNA and Fig.8b for grassNA.
- Line 569: The investigated physical processes and identified feedback loops are summarized in Fig. 8c. Through surface albedo and roughness changes, forests directly influence...
- Line 575: With reduced ocean-to-atmosphere heat fluxes, the MLD decreases which results in AMOC weakening in forestNA -- vice versa in grassNA. These changes in AMOC also go hand in hand with a reduction and strengthening of the subpolar gyre circulation in forestNA and grassNA, respectively. The changes in AMOC and gyre circulation imply changes in heat and salt transport

into the subpolar North Atlantic including the DWF regions. In forestNA, reduced salt import decreases the MLD further (which is not compensated by the density gain due to cooling) and vice versa in grassNA. We find that this salinity-advection feedback is subsequently intensifying AMOC and gyre circulation changes (but it is not the leading cause thereof, as it is …).

- Line 579: are ~~not large enough to be accountable for the gyre circulation changes~~ enhancing the respective subpolar gyre circulation changes but are not strong enough to be identified as the main driver.
- Line 594: This feedback is highlighted in Fig. 8 in purple arrows.

Comment 5

This manuscript focuses on the response of the ocean. Simulations with forest vegetation cover changes only run for 300 years. Has the climate system, especially the ocean, reached equilibrium?

Response

Thank you for this interesting question. We focus on the climate response in the 250 years after the initial response in the first 50 years (see Fig. 2c in the manuscript) of our simulations. We call this the long-term response. Depending on the definition, one could argue that an equilibrium state of the ocean circulation can take several millennia to establish (van Westen et al. 2023, Curtis & Fedorov 2024). We, however, are interested in the mechanisms driving the response of the ocean circulation on a centennial time scale similar to studies focusing on anthropogenic climate change (Rahmstorf et al. 2015, Liu et al. 2020, Keil et al. 2020). We added this explanation to section 2.1 model setup.

Specific comments

1. Line 42, “was been shown” should be “was shown”.
2. Line 179, “from from” should be “from”. Besides, a closing parenthesis is missing in this sentence, please complete it.
3. Line 195, “allows” should be “allow”.
4. Some variables in 2.2 and 2.3 lack unit descriptions, please complete them.
5. It would be better to note turbulent heat fluxes as THF in the description of Figure 4

Reponse

Thank you for these comments.

1. Yes, we implemented this.
2. Yes, we implemented this.
3. No, [the act of] starting trajectories… allow**s**
4. In section 2.2, we added units to the thermal expansion coefficient, the haline contraction coefficient and salinity. The remaining units are indicated in Tab. A1 and we refer from adding them

to the text for better readability. We added a reference to this table in line 158. We added the unit of potential temperature (K) an gridcell area (km^2) in section 2.3.

5. Yes, we implemented this.

References

1. Paul Edwin Curtis, & Alexey V. Fedorov (2024). Collapse and slow recovery of the Atlantic Meridional Overturning Circulation (AMOC) under abrupt greenhouse gas forcing. *Climate Dynamics, 62, 5949-5970*.
2. Renske Gelderloos, Fiammetta Straneo, & Caroline A. Katsman (2012). Mechanisms behind the Temporary Shutdown of Deep Convection in the Labrador Sea: Lessons from the Great Salinity Anomaly Years 1968–71. *Journal of Climate, 25, 6743-6755*.
3. Sybren Drijfhout, Geert Jan van Oldenborgh, & Andrea Cimatoribus (2012). Is a Decline of AMOC Causing the Warming Hole above the North Atlantic in Observed and Modeled Warming Patterns?. *Journal of Climate, 25, 8373-8379*.
4. Paul Keil, Thorsten Mauritsen, Johann Jungclaus, Christopher Hedemann, Dirk Olonscheck, & Rohit Ghosh (2020). Multiple drivers of the North Atlantic warming hole. *Nature Climate Change, 10, 667-671*.
5. Wei Liu, Alexey V. Fedorov, Shang Ping Xie, & Shineng Hu (2020). Climate impacts of a weakened Atlantic meridional overturning circulation in a warming climate. *Science Advances, 6*.
6. Matthew B. Menary, & Richard A. Wood (2018). An anatomy of the projected North Atlantic warming hole in CMIP5 models. *Climate Dynamics, 50, 3063-3080*.
7. D. A. Putrasahan, K. Lohmann, J.-S. von Storch, J. H. Jungclaus, O. Gutjahr, & H. Haak (2019). Surface Flux Drivers for the Slowdown of the Atlantic Meridional Overturning Circulation in a High-Resolution Global Coupled Climate Model. *Journal of Advances in Modeling Earth Systems, 11, 1349-1363*.
8. Stefan Rahmstorf, Jason E. Box, Georg Feulner, Michael E. Mann, Alexander Robinson, Scott Rutherford, & Erik J. Schaffernicht (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change, 5, 475-480*.
9. Martin B. Stolpe, Iselin Medhaug, Jan Sedláček, & Reto Knutti (2018). Multidecadal Variability in Global Surface Temperatures Related to the Atlantic Meridional Overturning Circulation. *Journal of Climate, 31, 2889-2906*.
10. René M. van Westen, & Henk A. Dijkstra (2023). Asymmetry of AMOC Hysteresis in a State-Of-The-Art Global Climate Model. *Geophysical Research Letters, 50, e2023GL106088*.

Response to Referee Comments 2

Comment 0

The authors of this study investigate the Atlantic response to (admittedly extreme) forestation and deforestation scenarios applied only to North America. Warming in the forestation experiments drives a reduction in the strength of AMOC, while cooling over land in the deforestation experiments (*grassNA*) drives an increase in its strength. Consideration is also given to the formation of a North Atlantic Warming Hole, its location, and sign. The importance of cold air outbreak events is found to be pivotal. Overall, the study is well structured and of broad interest. I suggest minor revisions, detailed below.

Response

Thank you for the positive evaluation of our study and the helpful comments. We address the comments made below and explain the modifications we made to the study.

Comment 1

It's not clear that there's been any kind of statical significance testing conducted to determine differences in *forestNA* and *grassNA* relative to control, but that would lend much more credibility to the findings of the study. It would be particularly useful in contour plots such as in Figures 1 and 2.

Response

Thank you for this comment. We added significance testing (two-sided Wilcoxon rank-sum test with Benjamini–Hochberg correction to Figures 1 and 2 (see Fig. RB1 and RB2 below).

Please note the added details in the methods section:

> #### Statistical significance testing
>
> To test statistical significance of differences between the two experiments forestNA and grassNA to the control run, we employ the same approach as in Portmann et al. (2022): a two-sided Wilcoxon rank-sum test (Wilks 2011) is applied on the time-series of annual or seasonal means in the considered period on each grid-cell separately. The null-hypothesis tested is that a randomly drawn value from the experiment time-series is equally likely to be larger or smaller than a randomly drawn value from the control time-series. To control for the false discovery rate when testing multiple hypotheses on a field, we employ a Benjamini-Hochberg correction (Wilks 2016), with the false discovery rate set to $\alpha_{\{FDR\}} = 0.05$.

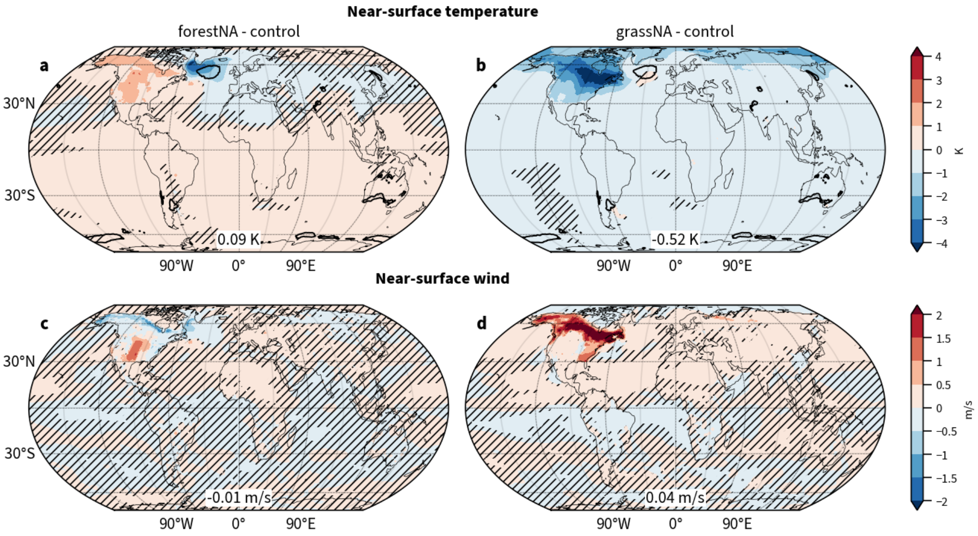

Figure RB1: As Figure 1 in the manuscript, where hatching indicates statistically insignificant differences. The black contour in (**a**) and (**b**) denotes the 0K/century trend in monthly ERA5 reanalysis near-surface temperature from 1950 to 2023 (Hersbach et al. 2023) to indicate the extent of the historical North Atlantic warming hole.

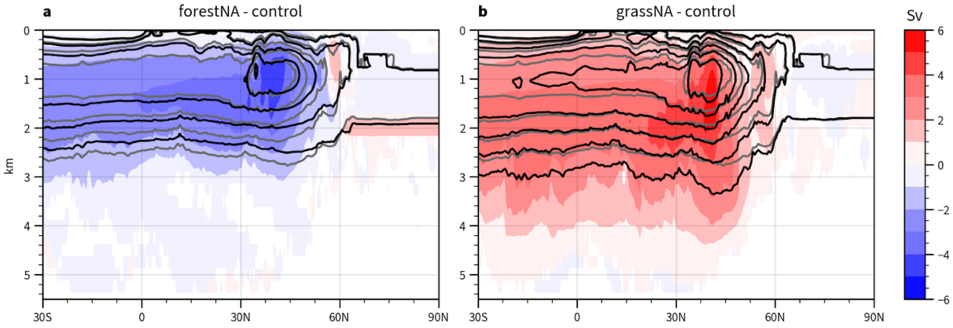

Figure RB2: As Fig. 2 a and b in the manuscript, with statistically insignificant changes of AMOC masked in white.

This leads to small adjustments in the text:

- Line 224: ...large parts of the Southern Hemisphere ~~ocean~~ exhibit a slight warming response.
- Line 226: In contrast, deforestation significantly cools...

Comment 2

In general, comparison is made to both observations and to simulations with global land cover changes but neither is plotted. As possible, it would be helpful to show the global-change results and/or observations, so that interested readers can find all the relevant comparisons in a single paper. For example:

1) Lines 239-246: For comparison to observations as here, it would help to show the observations themselves; maybe in Fig 1a,c as a contour?

Response

Thank you for the suggestion. We added a contour to Fig. 1a & b of ERA5 reanalysis data (2m temperature, see Fig. RB1).

This leads to adjustments in the text:

- Line 239: A qualitative comparison of the *forestNA* historical warming hole to the NAWH found in ~~observations (Rahmstorf et al., 2015; He 240 et al., 2022; Gervais et al., 2018)~~ ERA5 reanalysis data Hersbach et al. 2020, Hersbach et al. 2023, black contour in Fig. 1a, b)
- Line 245 f.: historical data and anthropogenic warming ~~observations and~~ projections
- Line 358: to what is found in ~~observations~~ reanalysis data (Fig. 1 a,b), where the warming hole is shifted more into the central North Atlantic, similar to the cooling hole in *grassNA* ~~(Rahmstorf et al., 2015; He et al., 2022; Gervais et al., 2018)~~
- Line 600: in ~~observations~~ reanalysis data and future climate simulations
- Acknowledgements: Thanks also go to Martin Hirschi for swiftly providing regridded ERA5 data.

2) Lines 247-248 “Compared to global forestation and deforestation…”: Can there be some added figure element to show the response in the global runs of Portmann et al. 2022, rather than asking readers to have both documents handy? Maybe overlay the global signals as contours, or add more panels?

Response

After adding significance hatching and ERA5 contours we think that the Figure would become too busy with more contours. We added the results of the global simulations into the Appendix for convenience. We revised the corresponding references to point towards this new figure.

Comment 3

Line 44 “…found to also induce anomalies in the ocean”: Could be more specific than just “anomalies” – temperature anomalies, circulation, etc?

Response

We concretized:

> Beyond the named biogeophysical effects, forestation has been found to also induce anomalies in ~~the ocean~~ SSTs.

Comment 4

Line 59 “w.r.t.”: Please spell out “with respect to” rather than adding acronyms.

Response

Yes, thank you we implemented this.

Comment 5

Lines 61-62 “Hereby, it is important to note that recent studies have found considerable model dependency of the climate response to vegetation changes (De Hertog et al., 2024, 2023).”: Please expand; this seems like an important point.

Response

Thank you for this valuable comment. In order to keep the introduction concise, we removed this sentence from the introduction and added a detailed discussion in section 2.1 (Model Setup):

> It is important to note that recent studies have found considerable model dependency of the climate response to vegetation changes: De Hertog et al. (2023) have shown that CESM reacts to afforestation with a stronger warming over land and stronger cooling in the North Atlantic than two other models (MPI-ESM and EC-EARTH) they compared. Notably, the two other models showed no cooling in the North Atlantic. De Hertog et al. (2024) showed similar model dependencies for the atmospheric water cycle. On the other hand, Boysen et al. (2020), explored the reaction of several CMIP6 models to idealised global deforestation. In their analysis, six of the nine models analyzed show a cooling hole and the global mean temperature response of CESM is close to the model mean. Moreover, CESM has been shown to simulate more DWF in the Labrador Sea and is more sensitive to changes in the Labrador Sea than has been historically observed (Gervais et al. 2018, He et al. 2022).

Please also note that this is again discussed in the Conclusion and Discussion section from Line 611 onwards.

Comment 6

Lines 99-100: The second research question posed could reasonably be removed, or should be rephrased. The others are scientific questions, the second is contextualizing results (which should be an assumed piece of the work)

Response

This is a valid point; we removed this research question. However, we want to stress that our findings are also of interest in the context of anthropogenic climate change as the driving mechanisms of changes in ocean circulation we identify are to some extent transferable to any upstream warming signal, thus we added the following:

- Line 108: Throughout this work, we aim to contextualize our findings in the broader picture of atmosphere-ocean dynamics in the subpolar North Atlantic. In particular, we compare our results to future climate simulations about ocean circulation changes and the NAWH and discuss the potential transferability of our conclusions regarding the identified physical mechanisms.
- Line 608: We want to stress that this likely also extends to other cases with upstream temperature forcing. In greenhouse gas forcing simulations, the faster warming of high latitudes known as Arctic amplification resembles the warming response in forestNA (e.g. Rahmstorf 2024). In principle, we would expect a similar response in CAO frequency and therefore reduced heat loss in regions of DWF. However, the additional freshening by Greenland melt-water might be more important for the salinity-advection feedback. Furthermore, changes in wind stress patterns might differ. Nevertheless, the CAO-SST feedback described in this study is likely at play.
- Line 621: ... melt-water fluxes. This in turn could facilitate assessing the relative contribution of CAOs to changes in ocean circulation and the formation of a NAWH in CO2 forced simulations.

Comment 7

Line 121: "Vegetation-sustaining areas" – would be helpful to elaborate on what qualifies as a vegetation sustaining area. Are there water or nutrient limitations on where the forests or grasslands can exist? Are urban areas converted as well?

Response

Vegetation-sustaining areas are here all areas without deserts (e.g. Sahara) or ice deserts (e.g. Greenland) and urban areas are excluded as well. We added this information to the revised version. Regarding water limitations please note our reply to comment 14.

> Line 121: Vegetation-sustaining areas, here all areas without deserts (e.g. Sahara), ice deserts (e.g. Greenland), or urban areas, ...

Comment 8

Line 130 "...and the north western USA": Should probably include mention of the eastern half of the US

Response

Yes, thank you, this should be the eastern USA here, not western. We implemented this.

Comment 9

Line 176-177 "The resulting CAO masks include for example the center of a CAO of 9 K in the (4, 8] category..." : Please explain? Shouldn't a 9 K CAO fall into the (8,12] category?

Response

Yes, thank you. This is the revised text:

> The resulting CAO masks include the center of a CAO of 9 K in the ~~(4, 8]~~(8, 12]K category ~~while the surrounding areas are attributed to the weaker categories~~. Surrounding this center, there is an area in the (4,8]K category, which in turn is surrounded by an area in the (0,4]K category.

Comment 10

Line 178: “Summing up the heat fluxes…” : Are these summed in time or space (or both)?

Response

They are summed up in both time and space. We revised this sentence as follows:

> ~~Summing up the heat fluxes associated with CAOs and dividing them by the total upward heat flux in the Labrador Sea […] results in the fraction of positive upwards heat flux associated with CAOs with respect to the total heat flux.~~ The resulting masked heat fluxes are summed up in time and space and divided by the total upward heat flux in the Labrador Sea […]. This gives the fraction of positive upwards heat flux associated with CAOs with respect to the total heat flux in this area.

Comment 11

“Sverdrup balance is not fully accurate in the subpolar North Atlantic” – could the authors give a sense of how large of a difference might be expected between the balance and observations? Is this something like a 10% difference or a 100% difference?

Response

Thank you for the interesting comment. Take for example the barotropic streamfunction of the control simulation (grey contours in Fig. 7e) and compare it to the estimated winddriven streamfunction (grey contours in Fig. 7c). The differences between these two give an estimate for how much of the ocean circulation is wind-driven or more strongly determined by, e.g., the bathymetry (ocean topography). As becomes clear from this comparison, the deviation from Sverdrup balance can locally be well above 100%.
Even if these discrepancies are large, we seek a quantitative estimate of the influence of wind changes on the ocean circulation on the scale of the entire subpolar North Atlantic. In particular, we focus on the changes of the barotropic and wind-driven stream function. We argue that in terms of change in the circulation strength (in Sverdrup), changes in the winddriven streamfunction would have to be comparable to changes in the barotropic streamfunction (on the scale of the subpolar North Atlantic) if wind were the dominant driver. To further justify the choice of method, this estimate a) is comparably practical to compute and b) has been previously applied in other studies. One can argue that the latter is not a justification for its application, however it is applied for comparability with those studies as mentioned in the main text.

We added the following note to the text:

> Line 208: … 2015). Discrepancies between the estimate of the wind-driven circulation and the actual barotropic flow arise mainly due to the complex bathymetry and can locally be on the order of 100% (Yeager 2015). However, we argue that changes in the wind-driven streamfunction would have to be comparable to changes in the barotropic streamfunction (averaged across the subpolar North Atlantic) if wind were the dominant driver of subpolar gyre circulation changes.

Comment 12

Line 223 "…over parts of Asia.": Could be more specific; where in Asia? This is somewhat hard to see on the map.

Response

We specify (including information from the significance testing):

> In *forestNA*, the negative near surface temperature anomaly near the North Atlantic ocean surface extends downstream over Europe ~~and even further downstream over parts of Asia~~ with still significant cooling in North Africa as well as regions east of the Caspian Sea and eastern China.

Comment 13

Line 223 "The impact of forestation on the Northern Hemisphere surface temperature is confined to North American land." : This seems to directly contradict what was just discussed (cooling over N Atlantic). Please clarify/rephrase.

Response

Thank you, this should say "the **warming** impact" but we removed this sentence as it is not important.

Comment 14

Lines 250-253 "Potentially, this very dry region…": Is there no way to confirm the ability of the vegetation to survive? If the forests are dying out, does the model simulate *no* vegetation there, which seems to be the implication?

Response

As stated, the canopy height in this region stays relatively constant as compared to control (Fig. B1c in the manuscript), indicating no forest growth. The fact that this region is very dry climatologically is a proposed explanation for this. In this region, the model simulates less productive vegetation (decreased leaf area index - not shown) and albedo changes are weak (Fig. B1e).

Comment 15

Lines 253-254 “However, the impact of these changes is local and it is reasonable to assume that this increase in wind speed has only a weak downstream influence on the North Atlantic”: Is there evidence to back up the assertion that the impact is local and not impactful for the North Atlantic?

Response

The trajectory analysis in section 3.3 in the manuscript shows that the regions of origin of CAO air parcels are similar between forestNA and grassNA, suggesting that near surface wind changes do not significantly impact the formation of CAOs in the North Atlantic. Moreover, wind stress changes downstream of this region are small (Fig. 7 a in the manuscript), also making a mechanical influence on the ocean circulation unlikely.

Comment 16

Fig 2 discussion: It might be helpful to show the control, forestNA and grassNA depth profiles themselves, not just the differences. Otherwise, it would be helpful to the reader to add more description to the paragraph starting on Line 269 – for example, how can one see that the overturning has shallowed in forestNA from 2a? How does the positive anomaly at 60N suggest a shift equatorward?

Response

The depth profiles themselves can be seen in the contours in Fig. 2a and b of the manuscript, where black lines indicate the profiles for forestNA or grassNA and grey ones the profile of control. The shallowing can be seen in the black contours (forestNA) being above the grey contours (control). The dipole of a negative anomaly in the south and a positive one in the north suggests a shift. However, it should say poleward instead of equatorward. We adjusted this.

Comment 17

Discussion of Fig 2c: I don’t see any note regarding the impact of the relatively fast and extreme increase in AMOC maximum for the grassNA simulation; this seems like a big shock to the system. Is that initial shock expected? In general, discussion around this panel should be expanded.

Response

Thank you for this comment, please note the revised discussion below:

> … Portmann et al. 2022). In grassNA, the AMOC strength increases very rapidly during the first 25 years of the simulation, to a peak value of 39 Sv, about 11 Sv or 40% above its long-term median. This large increase in grassNA (compared to the reaction of forestNA) may be attributable to the fact that albedo and temperature changes over land are stronger in grassNA (Fig. B1 f, Fig. 1 b) and

> that the anomalously cold branching point may favor increases in deep convection. Moreover, there might be a positive feedback of warmer and saltier ocean waters and the sensitivity of deep convection to atmospheric forcing, as further explored in Sect. 3.2. While such fast AMOC increases have been found in other studies as well (Haskins et al. 2019, van Westen et al. 2023), explaining the initial phase of the AMOC reaction remains a challenge due to many effects overlapping over a very short time period. In forestNA, the AMOC declines in comparison to control. This reaction is slower than the one in grassNA and is likely connected to a slowly building sea-ice feedback explored in Sect. 3.2. Note, however, that this manuscript focuses primarily on the mechanisms governing the long-term response of the AMOC. Nevertheless, we want to show the initial response for comparability and possible future studies.

Comment 18

Line 310 "...SST fingerprint in response AMOC changes": Missing a word somewhere?

Response

Yes, we changed this to "in response to AMOC changes".

Comment 19

Lines 337-338 "...cold temperatures in grassNA on land lead to increases in sea ice along the coasts (Fig. 3f)...": Sea ice fraction doesn't seem to increase markedly in the Davis Strait along the coasts, so I'm not sure how it limits the MLD response. Can this be described more to help the reader see what the authors are suggesting?

- This also seems to be contradicted in the next few sentences ("Sea ice anomalies are however small..."), perhaps suggesting a more detailed discussion is needed.

Response

Thank you for pointing this out. We revised this paragraph as follows:

> Compared to forestNA, only a thin band of anomalous MLD reaches into Davis Strait in grassNA and MLD even deepens slightly along the southern and eastern coast of Greenland. This is due to the fact that ~~cold temperatures in grassNA on land lead to increases in sea ice along the coasts~~ the cooling of Greenland in grassNA leads to slight increases in sea ice along its coast (Fig. 3f) and increasing freshwater fluxes there (Fig. 3d). This narrows the region of increased MLD to the pattern we see in Fig. 3d and leads to decreased SSTs around the southern and eastern coast of Greenland. ~~Sea ice anomalies are however small compared to forestNA.~~ However, the increased import of warm water by the AMOC in grassNA prevents sea ice from growing extensively, allowing for more heat loss of the ocean to the atmosphere and thus enhanced DWF. ~~Since there is less shielding of the ocean from the atmosphere by sea ice, AMOC reacts faster in grassNA (Fig. 2c).~~

We also removed this last sentence as sea ice does not start to grow in forestNA until after the initial response.

Comment 20

Line 345 “The same SST and MLD patterns as in…”: This comparison to Gervais et al. (2018) is somewhat hard to follow and to see the benefit/relevancy of. Suggest reworking this.

Response

Thank you for this comment. Note the revised version below:

> ~~The same SST and MLD patterns as in grassNA have been found for anthropogenic warming experiments in Gervais et al. (2018) albeit with opposite sign. Using CESM, they also find that under an RCP8.5 scenario, the Arctic will be ice-free at the end of the 21st century. Correspondingly, freshwater from melting ice is the main driver of a reduction in DWF at the beginning of their simulations. In our simulations it seems the warming over land is not strong enough to induce widespread melting. As a consequence, a feedback loop of reduced DWF, cooling SSTs and enhanced insulation of the ocean from the atmosphere by sea ice and thus reduced heat loss lead to the cooling pattern over the North Atlantic observed in forestNA.~~ We want to point out that the role of sea ice for AMOC decline and the SST anomalies in our forestNA simulation is somewhat different from anthropogenic warming simulations: In forestNA, the warming over land is not strong enough to lead to basin-scale melting of sea ice. Thus, freshwater fluxes are not the main driver of the reduction of MLD and AMOC strength here as they are in several anthropogenic warming simulations (Gervais et al. 2018, Liu et al. 2020) or hosing experiments to investigate AMOC decline (Martin et al. 2022, Jackson et al. 2023). Instead, the changes in buoyancy fluxes in forestNA are dominated by turbulent heat fluxes and sea ice growth acts as a secondary (positive) feedback.

Comment 21

Lines 353-355 “Moreover, the North Atlantic is anomalously fresh and cold…”: It seems that a hypothesis is both offered and refuted here, which makes it confusing for the reader to know what to take away. Perhaps phrase this section differently to highlight the relevant points.

Response

Thank you for the suggestion, here is the revised text:

> ~~Moreover, the North Atlantic is anomalously fresh and cold at the branching point, which makes a strong reaction of sea ice in forestNA more likely. However, significant forestNA sea ice growth only happens after about year 100 onwards (not shown), speaking against this hypothesis.~~ Note that sea ice in forestNA only starts to grow after around year 100 onward (not shown). This supports that the

atmosphere is the primary driver of the SST change in forestNA. Albeit the cold starting conditions at the branching point might prevent sea ice from melting in the beginning.

Comment 22

Fig 4 caption: Define “THF” somewhere, as it’s used in subplot titles.

Response

Thank you, we put the definition in the caption.

Comment 23

Fig 5: I’m not sure what the green/brown shading adds to the interpretation of the figure; suggest removing it for clarity (would be easier to focus on the rainbow contours)

Response

The shading indicates canopy height, green is for increased canopy height (i.e. increased forest in forestNA) and brown is for decreased canopy height (i.e. forest to grass in grassNA). This is to point out where the air parcels are coming from in direct comparison to where the land cover changes occurred. This is important for the argument that air parcels resulting in CAOs over the ocean do not necessarily stem from regions that directly experience forest cover changes. Removing the shading would make it hard for the reader to compare the regions of origin of CAO air parcels with regions with land cover changes. Thus we refrain from removing it.

Comment 24

Lines 448-449: “...suggests that forest cover change does not only directly influence the air parcels upstream but does so by also influencing the surrounding regions.”: I don’t see the evidence for this claim.

Response

We refined this statement and added a figure in the Appendix to support it. By including this figure, we can further strengthen another point in the manuscript in lines 480 to 489. Note the revisions below:

> These regions are not necessarily regions with forest cover changes. ~~This suggests that forest cover change does not only directly influence the air parcels upstream but does so by also influencing the surrounding regions.~~ Consequently, we investigate areas within 50°N and 90°N and 120°W and 60°W that did not experience forest cover changes. Latitudinally averaged vertical profiles show that the air above these grid-cells (which are largely overlapping with the trajectory source regions) experiences significant temperature changes (Fig.RB3 / Fig.B6 in the revised manuscript). The

> warming response in forestNA is stronger in the first 50 years and extends up to 350hPa while the cooling response in grassNA is stronger in the long-term response but extends over the entire column in both time periods. The median pressure level of trajectories at -96 hours is around 830 hPa. This means that forest cover changes impact the origin regions of CAO trajectories also through remote effects. ~~Thus, very high latitude forest cover changes also over Eurasia could lead to a similar ocean response as in Guo et al. 2024 , who found a similar cooling hole response as in grassNA for an Eurasian deforestation experiment.~~ This is also supported by Guo et al. 2024, who find warming North Atlantic SSTs in response to Eurasian deforestation.

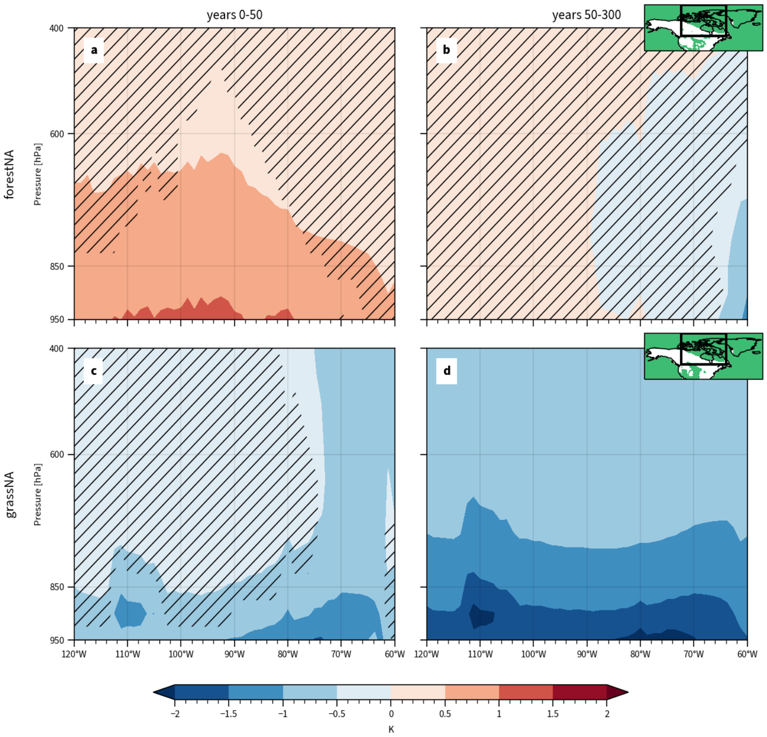

Figure RB3: Differences in DJFMAM temperature at pressure levels between 120°W to 60°W, averaged over latitudes between 50°N and 90°N. **a** and **b** show differences between forestNA and control while **c** and **d** show grassNA minus control. Left panels are averaged over the years 0 to 49 and right panels over the years 50 to 300. Vertical columns spanning all pressure levels above grid-cells with absolute forest cover changes <= 0.5m were excluded. Insets show the area (black box) over which the latitudinal mean is taken for forestNA and grassNA, respectively. Excluded grid-cells are shown in white and included ones in green. Hatching shows statistical insignificance (same testing procedure as for Fig.RB1).

This further leads to adjustments in lines 487 ff.:

> ~~Regarding the argument that this SST feedback is initiated by warming due to forestation, it is unfortunately not meaningful to study the first few decades of the simulations. The cold bias at the branching point of the simulations (Sect. 2) makes interpreting temperature distribution changes highly complicated.~~ This is supported by the warming of the atmospheric column over regions without forest cover changes in the trajectory source region during the first 50 years of forestNA (Fig

> B8 a). In the long-term response, the cooling signal of the NAWH transfers far up into the troposphere and the warming upstream is mitigated (Fig. B8 b).

Comment 25

Lines 522-524: “Here, annual averages are chosen over DJFMAM…”: Would be helpful to confirm that differences between annual and winter-half year averages are small. Or explain what some of the differences are, if not.

Response

Differences between DJFMAM and yearly data are small for wind stress, wind-driven streamfunction and the barotropic streamfunction. Overall, changes in DJFMAM are slightly stronger than in the yearly average, specifically around 2 kg/(m^2s^2) in the Labrador Sea for wind stress and around 4 Sv for wind-driven streamfunction and barotropic streamfunction. The spatial pattern and the ratio between wind-driven and barotropic streamfunction remains the same. We added the following to the manuscript:

> Here, annual averages are chosen over DJFMAM… Note that changes in wind stress, wind-driven streamfunction, and barotropic streamfunction are slightly stronger during DJFMAM but not qualitatively different (not shown).

References

1. D. S. Wilks (2016). “The Stippling Shows Statistically Significant Grid Points”: How Research Results are Routinely Overstated and Overinterpreted, and What to Do about It. *Bulletin of the American Meteorological Society, 97, 2263-2273.*
2. Daniel S. Wilks (2011). *Statistical Methods in the Atmospheric Sciences*. (Vol. 100) Academic Press.
3. Stephen Yeager (2015). Topographic Coupling of the Atlantic Overturning and Gyre Circulations. *Journal of Physical Oceanography, 45, 1258-1284.*
4. René M. van Westen, & Henk A. Dijkstra (2023). Asymmetry of AMOC Hysteresis in a State-Of-The-Art Global Climate Model. *Geophysical Research Letters, 50, e2023GL106088.*
5. Raphael Portmann, Urs Beyerle, Edouard Davin, Erich M. Fischer, Steven De Hertog, & Sebastian Schemm (2022). Global forestation and deforestation affect remote climate via adjusted atmosphere and ocean circulation. *Nature Communications 2022 13:1, 13, 1-11.*
6. Stefan Rahmstorf (2024). Is the Atlantic Overturning Circulation Approaching a Tipping Point?. *Oceanography*.
7. Jiaqi Guo, Yonggang Liu, & Yongyun Hu (2024). Climate Response to Vegetation Removal on Different Continents. *Journal of Geophysical Research: Atmospheres, 129, e2023JD039531.*
8. H. Hersbach, B. Bell, P. Berrisford, G. Biavati, A. Horányi, J. Muñoz Sabater, J. Nicolas, C. Peubey, R. Radu, I. Rozum, D. Schepers, A. Simmons, C. Soci, D. Dee, & J-N. Thépaut. (2023). ERA5 monthly averaged data on single levels from 1940 to present..
9. Hans Hersbach, Bill Bell, Paul Berrisford, Shoji Hirahara, András Horányi, Joaquín Muñoz-Sabater, Julien Nicolas, Carole Peubey, Raluca Radu, Dinand Schepers, Adrian Simmons, Cornel Soci, Saleh Abdalla, Xavier Abellan, Gianpaolo Balsamo, Peter Bechtold, Gionata Biavati, Jean Bidlot, Massimo Bonavita, Giovanna De Chiara, Per Dahlgren, Dick Dee, Michail Diamantakis, Rossana Dragani, Johannes Flemming, Richard Forbes, Manuel Fuentes, Alan Geer, Leo Haimberger, Sean Healy, Robin J. Hogan, Elías Hólm, Marta Janisková, Sarah Keeley, Patrick Laloyaux, Philippe Lopez, Cristina Lupu, Gabor

Radnoti, Patricia de Rosnay, Iryna Rozum, Freja Vamborg, Sebastien Villaume, & Jean Noël Thépaut (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society, 146, 1999-2049.*

10. Rosalind K. Haskins, Kevin I.C. Oliver, Laura C. Jackson, Sybren S. Drijfhout, & Richard A. Wood (2019). Explaining asymmetry between weakening and recovery of the AMOC in a coupled climate model. *Climate Dynamics, 53, 67-79.*
11. Steven J. De Hertog, Felix Havermann, Inne Vanderkelen, Suqi Guo, Fei Luo, Iris Manola, Dim Coumou, Edouard L. Davin, Gregory Duveiller, Quentin Lejeune, Julia Pongratz, Carl-Friedrich Schleussner, Sonia I. Seneviratne, & Wim Thiery (2023). The biogeophysical effects of idealized land cover and land management changes in Earth system models. *Earth System Dynamics, 14, 629-667.*
12. Steven J. De Hertog, Carmen E. Lopez-Fabara, Ruud van der Ent, Jessica Keune, Diego G. Miralles, Raphael Portmann, Sebastian Schemm, Felix Havermann, Suqi Guo, Fei Luo, Iris Manola, Quentin Lejeune, Julia Pongratz, Carl-Friedrich Schleussner, Sonia I. Seneviratne, & Wim Thiery (2024). Effects of idealized land cover and land management changes on the atmospheric water cycle. *Earth System Dynamics, 15, 265-291.*
13. Lena R. Boysen, Victor Brovkin, Julia Pongratz, David M. Lawrence, Peter Lawrence, Nicolas Vuichard, Philippe Peylin, Spencer Liddicoat, Tomohiro Hajima, Yanwu Zhang, Matthias Rocher, Christine Delire, Roland Séférian, Vivek K. Arora, Lars Nieradzik, Peter Anthoni, Wim Thiery, Marysa M. Laguë, Deborah Lawrence, & Min-Hui Lo (2020). Global climate response to idealized deforestation in CMIP6 models. *Biogeosciences, 17, 5615-5638.*
14. Melissa Gervais, Jeffrey Shaman, & Yochanan Kushnir (2018). Mechanisms Governing the Development of the North Atlantic Warming Hole in the CESM-LE Future Climate Simulations. *Journal of Climate, 31, 5927-5946.*
15. Chengfei He, Amy C. Clement, Mark A. Cane, Lisa N. Murphy, Jeremy M. Klavans, & Tyler M. Fenske (2022). A North Atlantic Warming Hole Without Ocean Circulation. *Geophysical Research Letters, 49.*
16. Laura C. Jackson, Eduardo Alastrué De Asenjo, Katinka Bellomo, Gokhan Danabasoglu, Helmuth Haak, Aixue Hu, Johann Jungclaus, Warren Lee, Virna L. Meccia, Oleg Saenko, Andrew Shao, & Didier Swingedouw (2023). Understanding AMOC stability: the North Atlantic Hosing Model Intercomparison Project. *Geoscientific Model Development, 16, 1975-1995.*
17. Torge Martin, Arne Biastoch, Gerrit Lohmann, Uwe Mikolajewicz, & Xuezhu Wang (2022). On Timescales and Reversibility of the Ocean's Response to Enhanced Greenland Ice Sheet Melting in Comprehensive Climate Models. *Geophysical Research Letters, 49, e2021GL097114.*
18. Wei Liu, Alexey V. Fedorov, Shang Ping Xie, & Shineng Hu (2020). Climate impacts of a weakened Atlantic meridional overturning circulation in a warming climate. *Science Advances, 6.*