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

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.

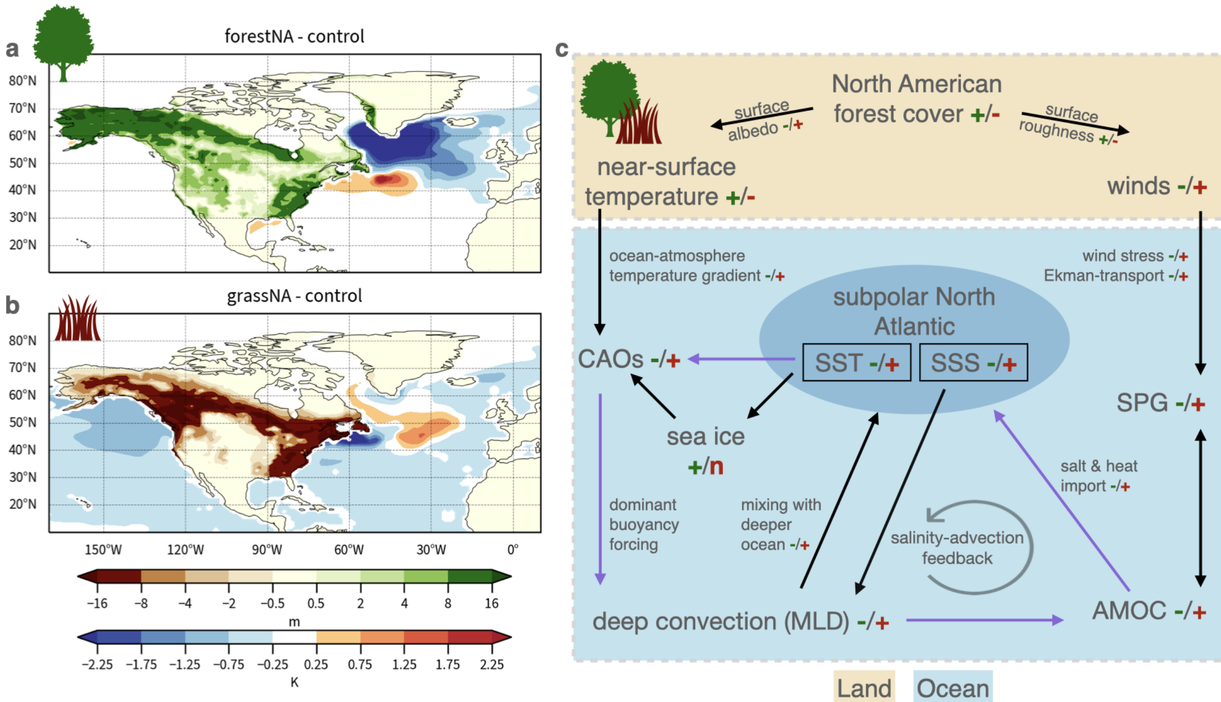

Figure RA1: Maps showing changes in canopy height on land and changes in SSTs over the ocean averaged over DJFMAM of the years 50 and 300 for (**a**) forestNA and (**b**) grassNA. (**c**) Proposed chain of processes how North American forest cover changes impact the North Atlantic ocean: Signs "+" and "-" 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

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