Effects of idealised land cover and land management changes on the atmospheric water cycle

Response to reviewers

29/01/2024

Reviewer 1

Reviewer 1 Comment 1

I found the studied subject really interesting. LCLMCs are widespread and has drawn the attention of the whole world for a long time. Yet, its impact on regional to global climate, in particular the moisture transport and rainfall, is still unclear. Studies in this field are very welcome to improve our understanding on this issue. However, after reading the manuscript I have a number of concerns, questions, and remarks on the methodology and conclusion. I hope that you find my comments useful and use them to improve your manuscript.

Response

We thank the reviewer for the positive appreciation of the study topic and for taking their time to comment on the manuscript. We think the comments can help improve the quality of this manuscript significantly. Below we provide answers to all comments and highlight the changes we intend to make to the manuscript in order to accommodate this feedback.

Reviewer 1 Comment 2

The large uncertainty among the three ESMs undermines the credibility of the conclusion drawn in this study. For example, LCLMCs-induced changes in precipitation, MFC and length scale (Figures 3-8) show considerable spread or even opposite signs between EMSs. Although the conclusions of this study may be intriguing, they lack robust support from ESMs.

Response

We acknowledge the large differences among the three different ESMs utilised in this study and a considerable part of the paper is dedicated to describing and understanding those differences (for example the results sections and the entire section 4.1: Different hydroclimatic responses of ESMs to LCLMC). Therefore, our conclusions are explicitly not intended strong: we claim that the effects induced by LCLMC are substantial but we also explicitly highlight that large differences between ESMs remain, e.g., in the absolute values of all moisture fluxes and the local recycling strength, and call for additional research. We highlight certain instances where some consistency (at least in sign of the change induced by LCLMC) exists between the different ESMs, specifically over land. However, by doing so we do not intend to ignore the large inter ESM-differences. Moreover, the LCLMC-induced drying and wetting trends found in these simulations are not new (as the reviewer also points out in a next comment). We believe that this study, being a multi-model analysis of idealised global LCLMC scenarios, is mostly valuable to illustrate how different ESMs handle these LCLMC changes and to learn from those to inform model development. The paper mentions several challenges associated with the study of LCLMC induced effects on the water cycle, both related to ESMs but also to the methods used to study them.

To accommodate this critique, we have carefully gone through the manuscript and have rewritten sections of the paper where we highlight consistent patterns across ESMs in their response to LCLMC to also more clearly state the important inter-ESM differences. Moreover, we made the inter-ESM differences and their implications more central in our conclusions to better demonstrate the new insights gained by this analysis. We specifically better clarify the large inter-ESM differences in precipitation and highlight better that the consistency we refer to is only related to the sign of change and not the absolute values of the changes.

Section 4, first paragraph:

> LCLMC can have substantial effects on atmospheric moisture fluxes and the local and continental recycling of moisture that determine water availability on land. ~~Common patterns emerge from our multi-model analysis, despite strong differences in the implementation of LCLMC and the simulation of the hydrological response in the different ESMs.~~ The different ESMs show large differences in their hydrological responses to the different LCLMC scenarios. However, some common patterns do emerge from this multi-model analysis. For cropland expansion, all three ESMs agree that there is a general decrease ~~over~~ in land ~~in~~ evaporation, for precipitation the patterns are less clear with large regional differences across ESMs. These changes in moisture fluxes affect the local recycling strength with a general decrease.~~ and precipitation over most regions as well as a decreased local recycling strength.~~ In contrast, afforestation and irrigation expansion show a general ~~an opposite pattern of both~~ increase~~d~~ in precipitation and evaporation over most regions. ~~with enhanced~~ Similarly, local recycling strength mostly increases despite large regional differences. Here we will discuss some of the discrepancies between the different ESMs and their implications on moisture fluxes and moisture recycling.

Section 4.2, first paragraph:

> LCLMC strongly affects the redistribution of moisture over land in the ESMs. While the absolute length scales of moisture recycling differ among the ESMs, LCLMC-induced changes in local recycling are typically consistent in sign across the ESMs, with cropland expansion mostly causing decreased recycling and afforestation and irrigation expansion mostly causing enhanced local recycling (Figure 6 and Figure 7). The effects of LCLMC on continental recycling and the continental contribution to/from land precipitation/ ~~over land and~~ evaporation ~~from land~~ are less consistent across ESMs (Figure 8 and Figure 9), but also geographically more heterogeneous within the ESMs (Figure E1 and Figure E2). This is due to the complex interactions of local effects with non-local effects, such as advection and circulation changes, which all affect the redistribution of water globally.

Section 5, conclusion:

> In this study, we analysed the effects of land cover and land management changes (LCLMC) on the atmospheric water cycle in a slate of idealised simulations (cropland expansion,

afforestation and irrigation expansion) performed by three different Earth System Models (ESMs). We showed that the effects on moisture fluxes are substantial but differ strongly across the ESMs. ~~with, generally, decreased evaporation and precipitation over land due to~~ Cropland expansion typically causes a decrease in evaporation, while for precipitation the sign of change depends on the region and ESM. ~~and the opposite effects for~~ For afforestation and irrigation expansion there is generally an increase in both precipitation and evaporation although regional differences are important. ~~However,~~ The results presented here clearly illustrate that substantial discrepancies exist between the different ESMs ~~exist~~, with EC-EARTH displaying important local recycling and mesoscale circulation effects, while CESM shows a dominance of large-scale atmospheric circulation shifts. These differences can have various causes, such as model parameterisations of crucial processes (e.g., convection) or the extent to which different land cover types are implemented within the ESMs on a global scale. Because some of these effects might have been indirectly influenced by the checkerboard LCLMC pattern used in this study, we advocate for more research to assess the implications of possible checkerboard-induced climate effects and the applicability of this approach for signal separation into local and non-local effects. Despite the strong differences between ESMs, the effects on local recycling are generally consistent in sign (with notable regional exceptions), with cropland expansion causing a decreased recycling strength, and afforestation and irrigation expansion generally causing an increased recycling strength. Overall, we find that cropland expansion causes a net increase in water availability on land while afforestation and irrigation expansion cause a net decrease. However, these effects on water availability are caused by different changes in continental recycling due to LCLMC across the different ESMs. Our simulations show that changes due to atmospheric circulation patterns play an important role in explaining these patterns and should be taken into account when assessing the effects of future LCLMC on moisture recycling.

This is the first study – to our knowledge – to explicitly consider moisture recycling when assessing the LCLMC effects on moisture fluxes using multiple ESMs. Our results show that the effects of LCLMC on moisture recycling are substantial both on the local and global scale, with clear implications for water availability on land. Our results highlight that large differences between the ESMs remain, which require more research. However, despite these inter-ESM differences it is clear that LCLMC will substantially affect the atmospheric water cycle. Therefore, the inclusion of potential effects of LCLMC on the atmospheric water cycle should be considered in future land cover planning.

Reviewer 1 Comment 3

Many ESMs-based studies have investigated LCLMCs-induced water flux change, either with one model (Portmann *et al.*, 2022) or several models (Boysen *et al.*, 2020) as the authors have noted. It is not new to know cropland/grassland expansion causes drying and afforestation causes wetting. Please highlight your new findings or novelty in the abstract.

Response

We thank the reviewer for their comment. We agree that within the current version of the abstract some more novel aspects of our study could be delineated better, particularly related to the discussion of the results and conclusions. As the reviewer rightfully states, ESM-based studies focussing on LCLMC effects on water fluxes are not new, however these studies never assessed the effects on moisture recycling in these ESM simulations as we do here. At the same time, there exist many studies looking into the effects of LCLMC on moisture recycling but none of these apply ESMs. We believe that this combination of ESM experiments and moisture recycling is a valuable and novel aspect of our study. As ESMs explicitly model all processes caused by LCLMC, they can help us learn about potential effects of those LCLMC in the future, including, for example, LCLMC-induced circulation changes.

One of our key results is that the effects of LCLMC on the hydrological cycle can be substantial but depend strongly on the ESM, with some displaying more importance of local processes vs some highlighting the role of large-scale circulation processes. It is important to characterise and illustrate those inter-ESM studies to properly interpret their implications. Moreover, our research illustrates important caveats in common methods used in LCLMC studies, such as the issues found related to the checkerboard approach used for the signal separation in this study.

We have rewritten the abstract to better highlight the novelties of our study:

> Land cover and land management changes (LCLMC) play an important role in achieving low-end warming scenarios through land-based mitigation. However, their effects on moisture fluxes and recycling remain uncertain although they have important implications for the future viability of such strategies. Here, we analyse the impact of idealised LCLMC scenarios on atmospheric moisture transport in three different ESMs: the Community Earth System Model (CESM), the Max Planck Institute Earth System Model (MPI-ESM) and the European Consortium Earth System Model (EC-EARTH). The LCLMC scenarios comprise of a full cropland world, a fully afforested world, and a cropland world with unlimited irrigation expansion. The effects of these LCLMC in the different ESMs are analysed for precipitation, evaporation and vertically integrated moisture flux convergence to understand the LCLMC-induced changes in the atmospheric moisture cycle. Then, a moisture tracking algorithm is applied to assess the effects of LCLMC on moisture recycling at the local (grid cell level) and the global scale (continental moisture recycling). By applying a moisture tracking algorithm on fully coupled ESM simulations we are able to quantify the complete effects of LCLMC on moisture recycling (including circulation changes) which are generally not considered in moisture recycling studies. Our results indicate that cropland expansion is ~~LCLMC are~~ generally ~~inducing consistent effects on moisture fluxes over land in all ESMs. Cropland expansion causes~~ causing a drying and reduced local moisture recycling ~~in all ESMs~~, while afforestation and irrigation expansion generally cause wetting and increased local moisture recycling. However, the strength of this ~~influence~~ effect varies ~~in time and space and~~ across ~~the~~ ESMs and shows a strong dependency on the dominant driver: Some ESMs show a dominance of large-scale atmospheric circulation changes while other ESMs show a dominance of local to regional changes in the atmospheric water cycle only within the vicinity of the LCLMC. Overall, these results corroborate that LCLMC can induce ~~large~~ substantial effects on the atmospheric water cycle and moisture recycling, both through local effects and changes in atmospheric circulation. ~~but~~ However, more research is needed to constrain the uncertainty of these effects within ESMs ~~and better evaluate~~ to better inform future land-based mitigation strategies.

Reviewer 1 Comment 4

The authors added much details on precipitation and evaporation length scales, but this concept is still confusing and hard to understand, in particular the author wrote "they should not be interpreted as actual travel distance…". Hence, why not used a simple metric with explicitly physical meaning, such as the distance of water vapor transport before precipitating again over land in Staal *et al.* (2018).

Response

We thank the reviewer for bringing up this issue and the possible alternative of actual distance travelled as used in Staal et al. (2018). However, the travel distances would not be very meaningful as we are explicitly investigating local recycling strength between different ESMs. An actual travel distance is interesting in a regional study such as Staal et al. (2018) to see how different regions are linked. However, actual travel distances, which are often in the order of thousands of kilometres, are influenced by the environment the moisture travels over and thus do not represent an adequate metric of *local* moisture recycling strength (local being confined to the ESM grid cells), which is what we study here. The most straightforward concept to illustrate local recycling strength would be the local recycling ratio — however, as discussed at length in the methods of the manuscript, these are not directly comparable across different ESMs due to the different grid cell sizes.

Hence, we derive the length scale metric from the local moisture recycling ratios to quantify the local moisture recycling strength independent of the ESM grid cell size. As defined in the manuscript, these length scales represent a distance under the assumption of the same local hydrological and climatological conditions over the entire trajectory. Therefore, length scales do not represent an actual (physical) travel distance, which is dependent on the area the moisture will travel over (e.g. long distances over desert, short over mountain range). Instead, the length scales can be interpreted as a local process scale of moisture recycling strength at a given location, which is exactly what we want it to represent. Our study aims at illustrating different effects of LCLMC both due to local, grid-cell-based LCLMC and LCLMC that occurred elsewhere. For the moisture fluxes this distinction is made with the checkerboard signal separation approach while for moisture recycling, we illustrate this through the assessment of continental recycling ratios and the more on local conditions focussed length scales.

We realise that the length scale is a less intuitive metric, however, it is required to utilise such a metric to achieve the goals of our study, that is, a fair comparison of local moisture recycling strength across ESMs. As we realise that length scales remain a difficult concept to grasp (despite our previous effort to provide additional context in the methods section), we now edited Section 2.3 to include the argumentation on how the length scale compares to actual travel distances to further contextualise the length scale metric. In addition, we included an additional appendix chapter to clearly illustrate the difference between a length scale and an actual travel distance. We believe that this comparison can help illustrate the physical meaning of this concept.

> Length scales overcome one of the major shortcomings of local recycling ratios, which are dependent on the shape and size of the source region they are computed over (van der Ent and Savenije, 2011; Theeuwen et al., 2023)~~, which is normally problematic with~~ . This occurs when using regular latitude-longitude grids in which grid cells vary both in shape and size within a model as well as between models that apply different resolutions. Length scales of

local moisture recycling, in contrast, are designed to be area- and shape-independent at least for the region over which one can assume the same climatological conditions (i.e., the variables in Eq. 7 do not change much ~~across nearby~~ within a given grid cell~~s~~). The length scales give an indication of the distance over which moisture would travel on average to or from a given grid cell under the given local hydrological and climatological conditions (van der Ent and Savenije, 2011). Hence, they should not be interpreted as an actual travel distance, which depends strongly on environmental conditions over the thousands of kilometres moisture typically travels and thus do not represent recycling strength in the local scope which is aimed for here. The local scope (i.e., ESM grid cell size) is preferred as it allows us to understand changes to moisture recycling as much disconnected from remote changes in LCLMC as possible, thus giving an indication of the local sensitivity of moisture recycling to LCLMC independent on downwind/upwind environmental conditions (see also Appendix E). Length scales should thus ~~but rather~~ be interpreted as a local process-based metric of moisture recycling strength (Eq. 5) expressed in distance units (km). A short length scale indicates that local recycling is strong, and a long length scale indicates that local recycling is weak.

Appendix E: Difference between length scale and actual travel distance

The length scales are a shape- and size- independent metric defined to represent the local moisture recycling strength (van der Ent et al., 2011). They are represented in distance units (typically km) but should not be confused with actual travel distances, an actual travel distance of moisture is not representative of local recycling strength. The actual travel distances as inferred from an air parcel trajectory accumulates the influences of downstream regions on the moisture content of the air parcel along its trajectory, which is typically within the order of thousands of kilometers. The length scale, in contrast, retains solely the local impact and is further independent to other effects, such as the grid-cell size.

To illustrate the difference between actual travel distance and local moisture recycling strength we refer to Figure 2 from van der Ent et al. (2011), shown below. This figure shows the relationship between precipitation recycling strength and distance travelled by the moisture as derived by different authors (Figure E1). These relationship strongly differs among the different studies, which is to be expected, as each of these studies refers to a different region over which the recycling ratio is defined. However, they all illustrate a certain basic pattern of moisture recycling: the recycling ratio is low at small distances and becomes larger with distance travelled.

Here, we add three additional lines to the original figure of van der Ent et al. (2011) to illustrate the influence of the environment on the actual travel distance. These lines illustrate two hypothetical extreme cases where the moisture travels over a hypothetical infinite desert (purple full line) and a hypothetical mountain range (orange full line). For both these cases the local moisture recycling (i.e. moisture recycling ratio near the source region illustrated by the blue box) is the same as the black full line. However, in the case of the mountain range (orange full line) the atmospheric flow is blocked by the mountain. Consequently, the actual travel distance is low and due to the formation of precipitation the moisture recycling goes towards one (i.e. all water has left the air parcel) which is illustrated on Figure E1 at the distance of the orange dot striped line. For the case of the desert, the water particle reaches the hypothetical infinite desert at which no interaction with the ground occurs, hence the atmospheric flow is not blocked. All moisture is retained in the air parcel and no additional moisture exchanges are observed. Hence, the moisture recycling ratio remains constant while the actual travel distance will reach near infinite (purple dot striped line in Figure E1) .

This example clearly illustrates the local nature of the length scale, as this metric is not affected by the different environments across the trajectory which do strongly affect the actual travel distance. The length scale will only be influenced by the local changes (i.e. within the small distance of an ESM grid cell as illustrated by the blue box) and represents the distance moisture would travel if the conditions over this local area would continue along the entire trajectory. This is illustrated by the thin black line which results in a length scale of 2500 km here (as indicated by the dotted line). This local scope is preferred in this study as it provides the local sensitivity of moisture recycling to local LCLMC, without considering any other upstream effects.

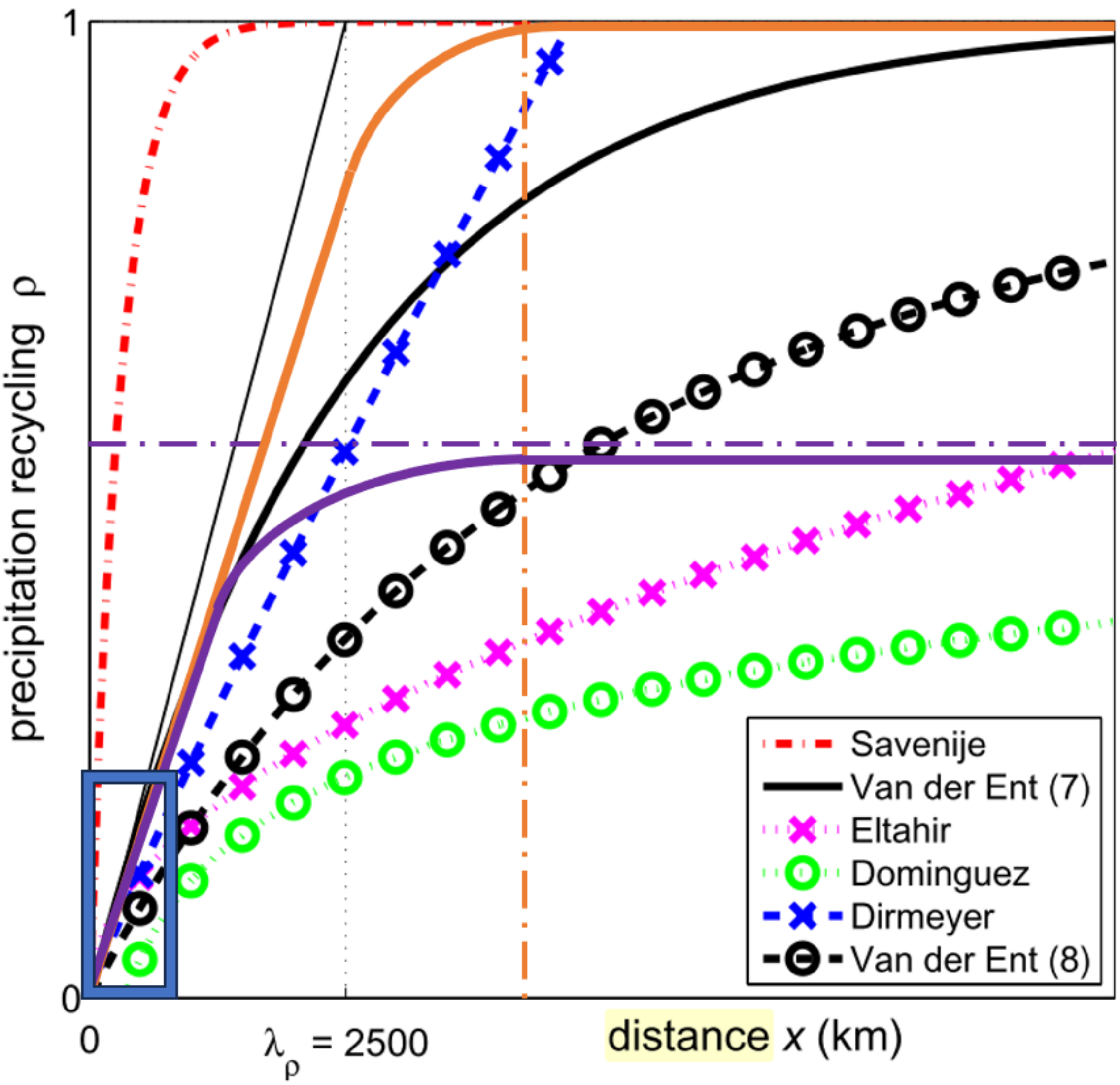

Figure E1: The relationship between the precipitation recycling ratios and distance using different formulas as was shown as Figure 2 in van der Ent et al. (2011). The orange and purple full lines are added here as they illustrate an extreme cases where moisture travels over a desert and mountain range respectively. They have the same local recycling as the black full line but the distance travelled is very different. The orange dot striped line indicates the distance at which the atmospheric flow is blocked by the mountain range and the purple dotted line indicates the moisture recycling ratio while the atmospheric flow travels the desert. Both illustrate very different moisture recycling patterns at a large distance but have the same local recycling (blue box). The length scale then represents *the distance if those local conditions would be extrapolated (thin black line) which results in a distance of 2500 km for this case (dotted black line).*

Reviewer 1 Comment 5

L45-49 and L414-415: The authors may have a misunderstanding on one-way/two-way interaction (offline vs coupled) and reanalyses. Although moisture tracking model is offline, but the analyses are observation-based, i.e. including realistic LCLMC-induced circulation changes. In this case, moisture tracking model indirectly includes the impact of these circulation changes on water fluxes (two-way). Unless in a scenario in which reanalyses do not include these circulation changes (the LCLMCs are not realistic), it is a one-way interaction. In this sense, Tuinenburg and Staal (2020) and Cui *et al.* (2022) are two-way studies.

Response

We thank the reviewer for bringing up this point and acknowledge that our choice of words might have caused a misunderstanding here. We do not claim that ratios derived from reanalysis do not include the two-way coupling of contemporary land cover. However, we highlight that studies with the aim of assessing potential LCLMC induced effects do not take LCLMC-induced changes in circulation into account when applying those metrics. This distinction has been clearly explained by te Wierik et al. (2021) - in their recent review related to the impacts of land use change on moisture recycling they state that:

'moisture recycling models address mostly "first-order" hydrological processes (e.g., evaporation fluxes, source-sink relationships). "Second-order" effects may occur when first-order processes affect atmospheric properties and processes'.

This is exactly the caveat of these second order effects that we want to highlight here and that can only be analysed with fully coupled ESMs as these explicitly model those potential circulation changes. As our analysis is based on idealised global LCLMC scenarios, these represent an extreme case of these potential circulation effects.

Further, we wish to highlight that the aforementioned deforestation/afforestation-based studies apply moisture tracking models based on reanalyses data but do not evaluate the historical land cover change as embedded in the reanalyses. Instead, they typically aim to evaluate the impact of (potential) de- or afforestation on downwind precipitation through a change in evaporation modelled by, e.g., a land surface or hydrological model; however, they typically use constant moisture recycling ratios derived from reanalyses to do so. Embedded in these analyses are two key assumptions: First, it is assumed that the land cover change does not impact circulation. Second, any other secondary effects are ignored, but local LCLMC does not only affect downwind precipitation. The simulated change in precipitation downwind further affects evaporation downwind, which in turn also affects precipitation in other regions... and so on. These feedback mechanisms in the hydrological cycle are not included in reanalyses-based studies which only evaluate the effect of LCLMC induced evaporation changes on the first-order precipitation downwind. However, both effects of LCLMC, on the circulation and subsequent hydrological fluxes, are modelled in ESM simulations. By applying moisture tracking models, such as WAM2layers, to the output of idealised LCLMC ESM simulations, we can assess the impact of LCLMC on the hydrological cycle in a more complete manner and disentangle the drivers of local changes. However, modelling these more complex interactions comes at the cost of large difference in all hydrological fluxes induced by LCLMC among the ESMs. We understand that the current text can be confusing in this regard, hence we have rewritten the paragraphs where these points are highlighted. In the introduction:

> Most studies that quantify the effects of LCLMC on the atmospheric moisture cycle focus on the changes in moisture fluxes, but often cannot unravel the role of local and continental moisture recycling in these differences (Tuinenburg et al., 2020; Hoek van Dijke et al., 2022; Baudena et al., 2021; Wunderling et al., 2022; Staal et al., 2018). Those studies that do account for moisture recycling in assessing the effects of future LCLMC (Staal et al., 2018; Hoek van Dijke et al.,2022; Baudena et al., 2021; Wunderling et al., 2022) generally apply reanalysis based recycling ratios (such as those presented in Tuinenburg et al., 2020) ~~Hoek van Dijke et al., 2022; Baudena et al., 2021; Wunderling et al., 2022; Staal et al., 2018)~~ which do not include the second-order effect on moisture recycling caused by LCLMC induced ~~two-way interactions of~~ circulation changes (te Wierik et al., 2021) ~~and the water cycle~~. By analysing dedicated ESM simulations for LCLMC we are able to address these shortcomings and include the potential effects of atmospheric circulation changes on moisture recycling.

And also in the discussion (second paragraph of section 4.2) we further clarify this point:

> Although the effects of LCLMC on the precipitation and evaporation changes are substantial, they are not as large as could be expected based on literature (Tuinenburg et al., 2020; Hoek van Dijke et al., 2022; Baudena et al., 2021; Wunderling et al., 2022; Staal et al., 2018). This could partially be due to the less extensive LCLMC scenarios considered here (only 50% change due to checkerboard approach). However, differences are expected because most previous studies are based on reanalyses and can only estimate the impact of upwind LCLMC changes on downwind precipitation using constant recycling ratios, neglecting any other interactions such as through changes in atmospheric circulation. Therefore, to fully capture the impact of LCLMC on moisture recycling, LCLMC model simulations should be compared to a control simulation, as done here. In fact, the resulting (substantial) differences in recycling ratios show that the interactions that are not considered when basing the studies on reanalysis are not negligible (at least within the context of extensive LCLMC scenarios as considered here). As LCLMC becomes increasingly relevant as a climate mitigation strategy it is important to consider a more holistic view of the influence of these strategies on the water cycle. Consequently, more research is needed to better constrain the effects of LCLMC on moisture recycling, aiming to support science that can guide future land cover planning.

Reviewer 1 Comment 6

In many places, it is hard to follow, please be concise.

Response

We thank the reviewer for this comment, we have revised several sections of the paper in order to improve the readability of the manuscript. These adaptations will be included in the revised manuscript.

Reviewer 1 Comment 7

In the beginning of abstract, the author noted "their effects on moisture fluxes and recycling remain uncertain…". At the end of abstract, "more research is needed to constrain the uncertainty…", it sounds like the situation did not change much after the significant amount of work by the authors?

Response

We thank the reviewer for bringing up this point; it is true that uncertainty is large related to the effects of LCLMC on moisture fluxes and moisture recycling and that large uncertainty remains after the work presented in this study. However, our study is a first attempt at using dedicated ESM simulations to analyse the effects of LCLMC on moisture recycling, and as discussed before, it includes all first- and secondary effects of LCLMC, which further induce uncertainty. While uncertainty remains large, our study brings up many interesting results: the important differences in how different ESMs hydrological cycles treat the LCLMC is one example, where some ESMs such as CESM cause large scale circulation changes which strongly determine the changes while other ESMs show a stronger importance of more local to regional effects (such as EC-EARTH). These inter-ESM differences are important to report as it can help guide future development in order to improve the next generation of ESMs. Additionally, these results highlight the potential importance of changes in atmospheric circulation for changes in moisture fluxes and moisture recycling, which have to be taken into account in future studies given the large dependence of low-emission scenarios on land-based mitigation.

We again acknowledge that despite the work done here, uncertainty remains large. However, we are convinced that the insights reported here can help guide future research in LCLMC-induced climate effects which can hopefully build on the experiences from this study to start narrowing down the uncertainty. Finally, our results further highlight that LCLMC has the potential to massively disturb the atmospheric water cycle and moisture recycling (even if further model development is needed to quantify these changes robustly across ESMs) - an important insight that allows decision-making on LCLMC to expand their frameworks to account for these impacts.

Reviewer 1 Comment 8

L29-32: Add some recent refs, such as Smith *et al.* (2023) and Cui *et al.* (2022).

Response

We thank the reviewer for suggesting to add these references, we agree that they are highly relevant and added them in the text.

Reviewer 1 Comment 9

L58: the ref missed title in the bibliography

Response

We thank the reviewer for spotting this mistake, the reference will be corrected in the revised manuscript.

Reviewer 1 Comment 10

L117: we are not able to separate?

Response

We thank the reviewer for highlighting this sentence. It is indeed a bit confusing and actually a repetition of what has already been explained earlier in the previous paragraph. Therefore, we removed the sentence to avoid this confusion. The paragraph now reads as follows:

> This separation is only applicable to (near-)surface variables and not to variables representing processes that extend higher into the atmosphere, as there is lateral mixing between different adjacent atmospheric grid cells above the surface. Therefore, the signal separation approach is not applied to the atmospheric variables (i.e. variables that have a vertical dimension into the atmosphere). ~~As t~~The analysis presented here focuses on atmospheric processes, specifically moisture recycling, which is computed through a moisture tracking algorithm requiring atmospheric variables~~, we are not able to separate local and non-local effects for all results in this study. Instead~~. Therefore, we analyse the raw ESM output directly, which represents an extreme case of LCLMC applied in a checkerboard pattern. For the variables where signal separation can be applied, we provide those results to support interpretations of these signals. All calculations are applied over the last 30 years of the simulations and at each CESM's native spatial resolution (latitude x longitude) (i.e., MPI-ESM: 1.88° x 1.88°, CESM: 0.90° x 1.25°, EC-EARTH: 0.7°x0.7°).

Reviewer 1 Comment 11

L190-194: given the limitations of local recycling, why not only use continental recycling?

Response

In this study, we have decided to report both local recycling and continental recycling. As the LCLMC scenarios considered here are idealised global changes (global deforestation, afforestation and irrigation), they also cause large-scale changes in atmospheric circulation. Therefore, the responses in both moisture recycling and moisture fluxes are potentially both caused by LCLMC elsewhere and locally. For the moisture fluxes we apply the checkerboard signal separation approach to better understand the role of remote LCLMC and local LCLMC. However, we cannot apply this approach on moisture recycling results. That makes that the continental recycling ratios and the changes thereof are very hard to interpret as we cannot explicitly know whether they are caused by local LCLMC or by large scale circulation changes due to LCLMC elsewhere. However, the length scales, which are derived from local recycling ratios and represent that local recycling strength are a metric that is easier to interpret as they, by definition, only take the local climatic changes into account which makes them much easier to interpret.

As our multi-model study shows large changes between the different ESMs, we opted to show a wide range of these results to characterise and illustrate the strongly different changes in the hydrological cycles in the different ESMs both through local changes and changes in atmospheric circulation.

Reviewer 2

Reviewer 2 Comment 1

I thank the authors for their revisions. In my previous review, I named two issues that had not been resolved yet in the first revision. These were 1) insufficient discussion of length scales; and 2) inappropriate use of the term 'feedback'. In the current version, these issues have been resolved. Proper discussion is provided about the results relating to length scales and the authors refrain from 'feedback' (except where appropriate). Congratulations on this interesting study.

We thank Arie Staal for his positive appreciation of the study and would also like to thank the reviewer for his useful comments during the review phase. These comments led to interesting discussions both among co-authors and in the review process and we believe that these have greatly increased the quality of the manuscript.