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

*Response to reviewers*

*25/07/2023*

We would like to thank all reviewers for their dedicated time reviewing the manuscript and for their useful and constructive suggestions. We carefully addressed all comments by the reviewers and believe that the manuscript has strongly benefited from the proposed changes. We highlight that on top of the changes requested by the reviewers we also changed some aspects of the text in order to improve readability, by a.o. adding a summarising table of the moisture flux responses across the different LCLMC.

## Reviewer 1

### Reviewer 1 Comment 1

This paper presents results from three climate models forced by three different land use changes (a cropland expansion, a global afforestation, and an irrigation expansion) and details the changes to the global water cycle driven by these land use changes. The paper is well written and I believe the experiments are an interesting addition to the literature on this subject, which, as the authors note, is typically limited to one model performing a suite of land use change experiments.

The main part of the paper that I believe needs improvement is the methods section. I found the description of some of the analyses difficult to follow, which in turn made the paper's results difficult to evaluate. I also feel like the authors presented a lot of results without attempting to understand them in detail, I'll make some suggestions on this below.

#### Response

We thank the reviewer for the appreciation of the study topic and the work done to enable a multi model study. Below we address every comment in detail and explain the corresponding changes made to the manuscript.

### Reviewer 1 Comment 2

One issue is the different length scales (the evaporation vs. precipitation length scale). I didn't understand how these were calculated or how they're different from one another. It seems like a major effort went into these calculations with the Eulerian tracking algorithm applied to the climate model output, but I didn't fully understand i) the distinction between the two length scales, or ii) what these length scales actually correspond do in physical terms. I think a more detailed description (and maybe a schematic) is required for readers to understand the results in Figs. 5/6.

## Response

We thank the reviewer for highlighting this issue. We acknowledge that length scales are not a widely used metric for this type of study, and hence the text benefits from a better description of the meaning of these metrics. We now try to clarify both the physical meaning and the difference between both length scales. Below we include the changes made to the dedicated methods section (Section 2.3.3).

> To assess local moisture recycling independently of the ESM, we compute the length scale of the moisture recycling process as introduced by van der Ent and Savenije (2011). Length scales overcome one of the major shortcomings of regional recycling ratios, which are strongly dependent on the shape and scale of the source region they are computed over (van der Ent and Savenije, 2011). Length scales of local moisture recycling are scale-independent and give an indication of a process-based distance over which moisture would travel on average to or from a given grid cell ~~under local~~ in case upwind (precipitation recycling length scale) and downwind (evaporation recycling length scale) hydrological and climatological conditions (van der Ent and Savenije, 2011) would be the same. Hence, they should not be interpreted as actual travel distance, but rather as a local process-based metric of moisture recycling strength expressed in distance units (km). Length scales can be linked to the strength of land–atmosphere feedbacks and they are comparable to other metrics of land–atmosphere feedbacks (e.g. Seneviratne et al., 2010; Santanello Jr et al., 2018). A short length scale indicates that moisture does not travel far and that local land–atmosphere feedbacks may play a role. On the other hand, a long length scale indicates that moisture originates from far away or travels far once evaporated, and that local recycling is lower. Like local recycling ratios, the length scales can be calculated from a precipitation- or an evaporation-centric perspective (i.e., precipitation recycling ratios $\lambda\rho$ or evaporation recycling ratios $\lambda\epsilon$). Here the precipitation length scale represents the length scale of precipitation raining down in a given grid cell, and the evaporation length scale represents the length scale of evaporation that travels from a given grid cell before precipitating. Both length scales can be derived from the local recycling ratios presented above (see section 2.3.2), which are computed at the grid scale level, and the distance travelled along an atmospheric streamline (Dominguez et al., 2006). For the complete derivation of how length scales are defined we refer to van der Ent and Savenije (2011).

## Reviewer 1 Comment 3

A second issue is the description of the checkerboard pattern, and how this particularity of the experiments is leveraged to understand the local versus non-local effect of the land use change. I'm confused about how the plots in Figs. 2-4 are different from those in Appendix A. Is the "non-local" change just the change in grid cells where the land use change was not applied? It seems like this conflates "non-local" with "downstream" or "teleconnections" which are two other areas of interest for land-atmosphere coupling people. I think a better description of why these checkerboard experiments were used is important for readers to understand the results.

## Response

We thank the reviewer for their feedback and agree that the signal separation in local and non-local effects is poorly contextualised within the initial submission of the manuscript. We referred to an earlier study (De Hertog et al., 2023) within the manuscript, where this is described and explained in detail. However, despite the checkerboard pattern being implemented within the simulations presented here we do highlight that we focus mainly on the raw ESM output and a moisture tracking analysis on those. The separation into a local and non-local signal of evaporation and precipitation is not the focus of the paper, and hence we do not feel that this method needs to be explained in all details in the main text methods section. However, we added an additional appendix chapter where the signal separation approach using the checkerboard pattern is explained in more detail (also included here below) and refer to this in appendix in the main text. Also, to further clarify the purpose of the study and the implications of the checkerboard pattern in the LCLMC implementation we also rewrote the last paragraph of the methods section 2.1. as follows:

> This ~~checkerboard-like~~ implementation of the LCLMCs in the ESM land cover maps following a checkerboard pattern enables a signal separation of the ESM response into local and non-local components (Winckler et al., 2017a; De Hertog et al., 2023). The local effects refer to changes directly induced by the LCLMC within the grid cell, while the non-local effects refer to changes induced by LCLMC elsewhere through changes in atmospheric circulation or advection. The approach has been explained in detail in previous studies (Winckler et al, 2017; De Hertog et al, 2023) and is summarised here in Appendix A. 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 is not applied to the ~~results for which~~ atmospheric variables ~~were used~~. As this analysis focusses 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, 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 ~~figures~~ in Appendix ~~A~~B to support interpretations of these signals. All calculations are applied at each ESM'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°x 0.7°).

Appendix:

> The checkerboard approach was developed by Winckler et al. (2017) for the signal separation into local and non-local effects within dedicated simulations with the MPI-ESM. Subsequently it has been applied to the LCLMC simulations performed within the LAMACLIMA project in a multi-model framework (De Hertog et al., 2023). 'Local effects' are defined as the direct climate effect due to the changes in land surface properties within a given grid cell. While 'non-local effects' are climate effects caused by changes in atmospheric circulation or advection as a consequence of LCLMC elsewhere (Winckler et al., 2017). Here we summarise the approach and highlight technical processing steps taken to extract the local and non-local signal from the raw ESM output.
>
> The checkerboard approach allows a robust signal separation of local and non-local effects by implementing the LCLMC in a checkerboard pattern, i.e. alternating 'change' grid cells, where LCLMC occurs, with 'no change' grid cells, which retain the CTL land cover (see Fig X). It can then be assumed that any effects in climate variables over the 'no change' grid cells can be

attributed as a non-local effect while in the 'change' grid cells of the raw model output both local and non-local effects occur (Winckler et al., 2017).

The 150 year-simulation with constant external forcings is split into 5 slices of 30 years each. To account for natural variability, we treat each slice as a member of a perturbed initial condition ensemble. In order to apply the signal separation, a multi-year monthly mean is computed over each of these ensemble members (De Hertog et al, 2023). (1) We subtract a reference member from the LCLMC member of interest, i.e., for CROP and FRST this reference member is CTL while for the IRR simulation it is CROP. (2) We mask the LCLMC grid cells of this difference map, hence, retaining only those grid cells where only non-local effects occur. (3) The grid cells with only non-local effects are spatially interpolated to fill the masked LCLMC grid cells in order to create a global map of the non-local effect. Consequently, to create a global map of the local effects, we mask all 'no change' grid cells from the difference map created in (1), thus only retaining the grid cells where both local and non-local effects occur. The values of these grid cells are then corrected by the interpolated non-local values in order to only retain the local effects. Subsequently, the values of the resulting grid cells are again spatially interpolated in order to attain a full global map of local effects. Finally, the sum of both, the local and non-local effects, then represents the total effect. This is the effect we would expect if an actual idealised LCLMC simulation had been performed without an LCLMC checkerboard pattern, although it should be noted that this total effect can be considered a lower limit as the non-local effects represent only a 50% change simulation (Winckler et al., 2017).

The checkerboard approach is implemented to each model grid at its native resolution. Hence, grid cell sizes vary across the different ESMs. As we have five ensemble members of 30 years for each simulation, we can extract local and non-local signals for each ensemble member, which are then used as a measure of uncertainty coming from natural variability (De Hertog et al., 2023).

Within this study we focus on interpreting the raw ESM output (as this is used in the moisture tracking analysis) and only apply the signal separation for completeness and to support the interpretation of the presented results.

## Reviewer 1 Comment 4

Lines 225-226: The increase in evaporation over CESM seems confined to the southern hemisphere, which is an interesting result that the authors do bring up later. I think "mostly an increase in evaporation" in the CESM is a bit of a mischaracterization of the results from Fig. 2b.

### Response

We thank the reviewer for highlighting this issue, we have adapted the text to better reflect the model results:

Regarding afforestation, CESM and MPI-ESM show opposite patterns compared to cropland expansion, with mostly an increase in evaporation (Figure 2b,e). However, in CESM this increase is only apparent over the Southern Hemisphere tropics while the Northern Hemisphere extratropics and the Sahel show a clear increase in annual evaporation due to afforestation. Whereby it should be noted that the ~~increase~~ decrease in the extratropics is clearly ~~seasonal (JJA)~~linked to the boreal summer season (FigureB1 and Figure B2).

## Reviewer 1 Comment 5

Lines 246-248: I like this discussion, but the authors haven't discussed the local vs. non-local difference between the two models, which seems really important for interpreting the results and (to me) is the most interesting thing about the paper. The fact that two models forced by very similar land use change scenarios produce very different local vs. non-local results seems like something that would be of very broad interest to the community and is worth a more thorough investigation that is presented here. I think a whole analysis could likely be written about this result -- it seems very important for understanding the distinctions between two models

### Response

We thank the reviewer for their appreciation of the signal separation approach to the study of land cover and land management change induced climate effects and agree that this is a highly valuable tool for increasing our understanding. However, we would like to highlight that a study specifically focussing on the signal separation results of these simulations has recently been published in this same journal (De Hertog et al., 2023). That paper focussed mainly on temperature but also looked at the different surface energy fluxes including latent heat flux (from which evaporation in this study is derived). In contrast, the focus of the present study is on the application of the moisture tracking algorithm on the ESM simulations and their implications (both on the resulting values and the methods used). We fundamentally agree with the reviewer that there remain interesting results which can be further analysed within the simulations, such as the implications of differences in local and non-local precipitation within the different ESMs. However, this would require the development of an analogous methodology for atmospheric variables (see our previous reply) that is beyond the scope of this study. We highlight that the data underlying this study will be made available before final publication of this paper and hope that the data will be taken up in future follow up analyses.

## Reviewer 1 Comment 6

The discussion of moisture flux convergence (MFC) is difficult to follow, and makes statements about causality that are difficult to prove in this modeling context (for example, the ITCZ shift that the authors discuss are likely driven by MFC changes in response to atmospheric circulation patterns, not the other way around as lines 266-268 claim). In the discussion of Indian MFC changes, the authors claim that reductions in temperature lead to a reduction in MFC, but I think an extra causal step is necessary because temperature doesn't appear in the MFC equation.

### Response

We would like to thank the reviewer for highlighting this issue. We agree that the initial version of this paragraph did not explain the changes and causality well. We note that the explanations regarding the Indian MFC changes were made within the context of previous statements in the description of the precipitation results. However, we acknowledge that the causality was not clear. We rewrote this part as shown below:

The effects of LCLMCs on MFC show substantial regional differences between CESM and MPI-ESM (Figure 4). Overall, the patterns in MFC are highly similar to those seen for precipitation (Figure 3) which indicates that these precipitation changes are likely driven by the changes in MFC. Under cropland expansion, ~~there is a clear influence of the~~ the shifts in precipitation bands for CESM are likely caused by the changes in MFC over those areas. ~~These shifts in precipitation cause a decrease~~ Decreases in MFC appear linked to changes in precipitation over the Amazon and India, while an increase in precipitation appears linked to increased MFC over Central South America and Central Africa. In MPI-ESM, there is generally a decrease in MFC as a consequence of cropland expansion (Figure 4a,c), which appears to be related to changes in the areas where the largest LCLMC occurred (which confirms the mostly local precipitation changes shown in Figure 4B). In EC-EARTH, we see a general increase of P −E, used here as proxy for MFC, over the unaltered patches while the deforested patches show a clear decrease over the tropics (see Figure C1g). Regarding afforestation (Figure 4b,e), the patterns in MFC are less strong in CESM, with an increase over Brazil and parts of East Africa and a decrease over the Sahel and southern Africa. In MPI-ESM, there is a general increase in MFC over land. Following irrigation expansion (Figure 4c,f), there is an overall decrease in MFC over land for both ESMs~~, which is likely due to the strong cooling induced by irrigation (De Hertog et al., 2022)~~. This decrease in MFC is especially strong over Southeast Asia in CESM but is also apparent for MPI-ESM, and could explain the precipitation decreases shown over this region in Figure 3 further, confirming the weakened Indian Summer Monsoon hypothesis.

## Reviewer 1 Comment 7

In discussion of Figs. 7-8, I'm not sure how the fractional changes associated with local (land-atmosphere coupling) processes are evaluated, so it's hard to interpret these results.

### Response

We would like to highlight that the values shown in Figs 7–8 are derived from the continental recycling ratios. Hence the moisture recycling referred to within this section is not local but continental. Within this section we take a different scope than in the preceding section using the length scales (which can be seen as a proxy for land–atmosphere coupling). This is also clearly highlighted in lines 317–318 at the start of section 3.3. in Results. The continental recycling values and the global bulk values presented in Figs 7–8 are indeed difficult to evaluate in terms of local recycling, as they are a compound response caused by both local changes and larger-scale circulation changes causing a redistribution of moisture between land and ocean within the simulations. In fact, these values are intrinsically difficult to interpret without additional analyses and are mainly presented to illustrate inter-model consistency and to assess the importance of moisture recycling (here defined at the continental scale) for understanding the climate effects of LCLMC on the atmospheric water cycle.

## Reviewer 1 Comment 8

Lines 414-416: This also seems like an important finding, but since reanalyses do have interactive connections between the land surface and the atmosphere I'm not sure what the authors are implying here.

### Response

We thank the reviewer for this remark. The issue we wanted to highlight here is that most studies of the effects of LCLMC on moisture recycling (e.g., Tuinenburg et al., 2020, Theeuwen et al., 2023, Wunderling et al., 2022, Cui et al., 2022) use reanalysis derived moisture recycling ratios as a basis for their assessments of the effect of LCLMC without considering LCLMC climate feedbacks. In other words, most studies that evaluate the effect of LCLMC on moisture recycling are based on reanalyses and do not compare simulations employing different LCLMC scenarios in fully coupled models. We agree with the reviewer that reanalyses do have interactive connections between land and atmosphere — however, moisture tracking models driven with reanalyses can only estimate the effects of LCLMC on precipitation downwind via moisture recycling and cannot account for indirect feedbacks, such as LCLMC-induced circulation changes (among others) that further impact all water fluxes and could also modify the recycling ratio. Studies, such a Tuinenburg et al. (2020) are reanalysis-driven studies that estimate how evaporation would change due to LCLMC and then translate this change to precipitation downwind, assuming a constant recycling ratio and no other feedbacks. To study the full impact of LCLMC on moisture recycling, LCLMC model simulations must be compared to a control simulation (as is done here). To better clarify this issue, we have rephrased this sentence in section 4.2:

> Although the effects of LCLMC on the precipitation and evaporation changes are substantial, they are not as large as ~~previously assumed within~~ 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 ~~the case~~ 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 feedback. 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 feedbacks that are not considered when basing the studies on reanalysis are not negligible.~~it is likely also because these studies base themselves on reanalysis-based recycling ratios, which do not include the two-way feedbacks of circulation changes and changed recycling strengths due to LCLMC, which are shown to be substantial.~~ As LCLMC becomes increasingly relevant as a climate mitigation strategy, it is important to ~~include the potential side effects~~ 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 2

## Reviewer 2 Comment 1

This manuscript by De Hertog et al. presents an interesting analysis on the precipitation effects of idealized land cover and land management changes (LCLMCs) in three ESMs. The results are largely consistent, but also show some contrasts among regions and models, which shows that the effects of LCLMCs are not straightforward. Some results appear to be linked to artefacts related to the checkerboard pattern of LCLMCs, as the authors acknowledge when they mention that the assumptions behind the checkerboard approach are not met, but in my opinion this should not preclude publication of the manuscript. I do, however, have some (generally minor) remarks.

### Response

We thank the reviewer for the appreciation of the study topic. Below we address every comment in detail and explain the corresponding changes made to the manuscript.

## Reviewer 2 Comment 2

It needs to be better explained how the signal separation (lines 101-102) in the checkerboard procedure works exactly. For example, in lines 215-216, the results are definitely not as "clear" to me as they are to the authors. Section 4.3 mentions artefacts resulting from the checkerboard approach, but this could be expanded upon: how exactly do which artefacts come about?

### Response

We thank the reviewer for their feedback and agree that the signal separation in local and non-local effects is poorly contextualised within the initial submission of the manuscript. We referred to an earlier study (De Hertog et al., 2023) within the manuscript, where this is described and explained in detail. However, despite the checkerboard pattern being implemented within the simulations presented here we do highlight that we focus mainly on the raw ESM output and a moisture tracking analysis on those. The separation into a local and non-local signal of evaporation and precipitation is not the focus of the paper, and hence we do not feel that this method needs to be explained in all details in the main text methods section. However, we added an additional appendix chapter where the signal separation approach using the checkerboard pattern is explained in more detail (also included here below) and refer to this in appendix in the main text. Also, to further clarify the purpose of the study and the implications of the checkerboard pattern in the LCLMC implementation we also rewrote the last paragraph of the methods section 2.1. as follows:

> This ~~checkerboard-like~~ implementation of the LCLMCs in the ESM land cover maps following a checkerboard pattern enables a signal separation of the ESM response into local and non-local components (Winckler et al., 2017a; De Hertog et al., 2023). The local effects refer to changes directly induced by the LCLMC within the grid cell, while the non-local effects refer to changes induced by LCLMC elsewhere through changes in atmospheric circulation or advection. The approach has been explained in detail in previous studies (Winckler et al, 2017; De Hertog et al, 2023) and is summarised here in Appendix A. 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 is not applied to the ~~results for which~~

atmospheric variables ~~were used~~. As this analysis focusses 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, 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 ~~figures~~ in Appendix ~~A~~B to support interpretations of these signals. All calculations are applied at each ESM'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°x 0.7°).

Appendix:

The checkerboard approach was developed by Winckler et al. (2017) for the signal separation into local and non-local effects within dedicated simulations with the MPI-ESM. Subsequently it has been applied to the LCLMC simulations performed within the LAMACLIMA project in a multi-model framework (De Hertog et al., 2023). 'Local effects' are defined as the direct climate effect due to the changes in land surface properties within a given grid cell. While 'non-local effects' are climate effects caused by changes in atmospheric circulation or advection as a consequence of LCLMC elsewhere (Winckler et al., 2017). Here we summarise the approach and highlight technical processing steps taken to extract the local and non-local signal from the raw ESM output.

The checkerboard approach allows a robust signal separation of local and non-local effects by implementing the LCLMC in a checkerboard pattern, i.e. alternating 'change' grid cells, where LCLMC occurs, with 'no change' grid cells, which retain the CTL land cover (see Fig 1). It can then be assumed that any effects in climate variables over the 'no change' grid cells can be attributed as a non-local effect while in the 'change' grid cells of the raw model output both local and non-local effects occur (Winckler et al., 2017).

The 150 year-simulation with constant external forcings is split into 5 slices of 30 years each. To account for natural variability, we treat each slice as a member of a perturbed initial condition ensemble. In order to apply the signal separation, a multi-year monthly mean is computed over each of these ensemble members (De Hertog et al, 2023). (1) We subtract a reference member from the LCLMC member of interest, i.e., for CROP and FRST this reference member is CTL while for the IRR simulation it is CROP. (2) We mask the LCLMC grid cells of this difference map, hence, retaining only those grid cells where only non-local effects occur. (3) The grid cells with only non-local effects are spatially interpolated to fill the masked LCLMC grid cells in order to create a global map of the non-local effect. Consequently, to create a global map of the local effects, we mask all 'no change' grid cells from the difference map created in (1), thus only retaining the grid cells where both local and non-local effects occur. The values of these grid cells are then corrected by the interpolated non-local values in order to only retain the local effects. Subsequently, the values of the resulting grid cells are again spatially interpolated in order to attain a full global map of local effects. Finally, the sum of both, the local and non-local effects, then represents the total effect. This is the effect we would expect if an actual idealised LCLMC simulation had been performed without an LCLMC checkerboard pattern, although it should be noted that this total effect can be considered a lower limit as the non-local effects represent only a 50% change simulation (Winckler et al., 2017).

The checkerboard approach is implemented to each model grid at its native resolution. Hence, grid cell sizes vary across the different ESMs. As we have five ensemble members of 30 years for each simulation, we can extract local and non-local signals for each ensemble member, which are then used as a measure of uncertainty coming from natural variability (De Hertog et al., 2023).

Within this study we focus on interpreting the raw ESM output (as this is used in the moisture tracking analysis) and only apply the signal separation for completeness and to support the interpretation of the presented results.

Finally, regarding the artefacts mentioned in Section 4.3., we wish to clarify that with artefacts we mean any climate effects that are caused by the specific implementation of the LCLMC in a checkerboard pattern and thus would not occur in a full 100% LCLMC implementation. Hence this implies that our results might not be representative of a full LCLMC, therefore calling these results an artefact. A clear example of this is the mesoscale convection in EC-EARTH which clearly occurs at the level of the checkerboard implemented LCLMC and thus appears to be a feature caused by the implementation of the LCLMC in a checkerboard pattern. For our study these artefacts need to be taken into account when interpreting these results. However, it has wider implications for the applicability of the checkerboard approach as a signal separation approach in general, which are also discussed in Section 4.3. In order to fully investigate these artefacts an additional full LCLMC simulation would be needed which is beyond the scope of this study.

| Reviewer 2 Comment 3 |
|---|
| Line 139 mentions that the evaporation and precipitation length scales represent the average distance that moisture travels, but I believe these length scales are not the same as averages. Please explain more carefully what these length scales are and how they should be interpreted. |

## Response

We thank the reviewer for highlighting this issue. We acknowledge that length scales are not a widely used metric for this type of study, and hence the text benefits from a better description of the meaning of these metrics. We now try to clarify both the physical meaning and the difference between both length scales. Below we include the changes made to the dedicated methods section (Section 2.3.3).

To assess local moisture recycling independently of the ESM, we compute the length scale of the moisture recycling process as introduced by van der Ent and Savenije (2011). Length scales overcome one of the major shortcomings of regional recycling ratios, which are strongly dependent on the shape and scale of the source region they are computed over (van der Ent and Savenije, 2011). Length scales of local moisture recycling are scale-independent and give an indication of a process-based distance over which moisture would travel on average to or from a given grid cell ~~under local~~ in case upwind (precipitation recycling length scale) and downwind (evaporation recycling length scale) hydrological and climatological conditions (van der Ent and Savenije, 2011) would be the same. Hence, they should not be interpreted as actual travel distance, but rather as a local process-based metric of moisture recycling strength expressed in distance units (km). Length scales can be linked to the strength of land–atmosphere feedbacks and they are comparable to other metrics of land–atmosphere feedbacks (e.g. Seneviratne et al., 2010; Santanello Jr et al., 2018). A short length scale indicates that moisture does not travel far and that local land–atmosphere feedbacks may play a role. On the other hand, a long length scale indicates that moisture originates from far away or travels far once evaporated, and that local recycling is lower. Like local recycling ratios, the length scales can be calculated from a precipitation- or an evaporation-centric perspective (i.e., precipitation recycling ratios $\lambda\rho$ or evaporation recycling ratios $\lambda\epsilon$). Here the precipitation length scale represents the length scale of precipitation raining down in a given grid cell, and the evaporation length scale represents the length scale of evaporation that travels from a given grid cell before precipitating. Both length scales can be derived from the local recycling ratios presented above (see section 2.3.2), which are computed at the grid scale level, and the distance travelled along an atmospheric streamline (Dominguez et al., 2006). For the complete derivation of how length scales are defined we refer to van der Ent and Savenije (2011).

## Reviewer 2 Comment 4

It is not clear why the length scales differ so strongly among models (lines 281-282). Please elaborate on this and provide some quantifications. How do these length scales correspond to those in the literature?

### Response

We thank the reviewer for this suggestion, and we agree that the differences in length scales among different ESM are remarkable. However, there exists only one study prior to ours where these length scales have been quantified, the study that presented the concept of lengths scales (van der Ent and Savenije, 2011). This study computed the precipitation and evaporation length scales using ERA-Interim reanalysis data over the period 1999-2008 (see Figure R1 taken from that paper below). The values presented in this study lie within the broad range of values captured by the three ESMs in our study, even if the results are not directly comparable. Yet, more interestingly, it should be noted that — despite very large differences between the absolute length scales in all ESMs — the spatial patterns are quite similar among the ESMs and comparable to those in van der Ent and Savenije (2011).

However, in the paper we deliberately do not directly compare our length scales to the reanalysis-based values from van der Ent and Savenjije (2011), as an evaluation of the length scales is not the main purpose; instead our study focusses on the quantification of the effects of LCLMC on moisture recycling. It is, however, a remarkable result that the effects of LCLMC on length scales (i.e., the differences of length scales between the LCLMC scenario and the control run) are much more consistent than the length scales themselves between the ESMs. These different absolute length scales in the ESMs are likely linked to how the processes relevant to moisture recycling are modelled within the ESMs, such as how, for example, convection is parameterised and how atmospheric circulation is resolved, and how these lead to strongly different evaporation and precipitation responses across the ESMs. Within the discussion of the paper (lines 377–381) we highlight this as well as the potential role of spatial resolution in these differences. Our calculations only allow to illustrate this difference, more research should further investigate the causes for these very large differences of length ratios and thus recycling strengths across different ESMs, but this is beyond the aim of this research.

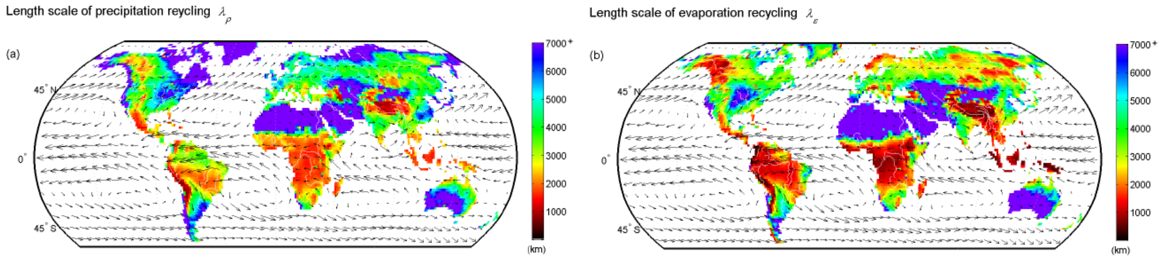


*Figure R1: Average length scales of moisture recycling (1999-2008): (a) length scales of precipitation recycling, and (b) length scale of evaporation recycling. These are local characteristics of feedback strength, which can be interpreted as travel distances of atmospheric water, under local conditions of a grid cells. Figure was taken from van der Ent et al. (2011).*

## Reviewer 2 Comment 5

The way in which Lagrangian tracking models are portrayed is not entirely accurate. Computational demand scales with number of parcels, not area (lines 152-153), and in contrast to what is claimed in lines 203-204, parcels can be released simultaneously and therefore all continental moisture can be tracked at the same time.

### Response

We thank the reviewer for pinpointing us to these sentences, which are indeed not entirely accurate in their formulation. Carefully reviewing these parts, we realised that a comparison to Lagrangian models is not needed in these paragraphs at all — hence, we deleted the entire sentence in lines 152–153 and the subsentence in lines 203–204 that refers to Lagrangian models.

## Reviewer 2 Comment 6

The manuscript is well-written overall, but please fix the following language-related issues:

Throughout the manuscript, the authors mention “feedbacks” where these are not really feedbacks – often, if not always, “effect” seems to be the more appropriate term.

Line 233: “boreal latitudes”. I believe “high latitudes” are meant, as boreal latitudes would mean the latitudes of the Northern Hemisphere.

Lines 251 and 344: “is causing” should be “causes”.

### Response

We thank the reviewer for these suggestions and have implemented them as suggested in the revised manuscript.

## References

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