Summary

The authors use future projections from the NorESM2 climate model to drive the atmospheric moisture tracking model UTrack. The future projections represent four possible socioeconomic scenarios of varying severity, with the aim of estimating global responses in terrestrial precipitation recycling to different emissions pathways. The authors present their new version of the UTrack model in a Github repository. The paper is well written and a valuable addition to the literature. The introduction and discussion sections were especially good, however, the description of the results could be improved to help the reader make links between the text and the figures more readily, and to ensure your findings come across in the clearest possible way.

We thank the reviewer for their kind words and the constructive and detailed comments. They will help us improve the manuscript, in particular te clarity and readability of the Results. Below we respond briefly to the individual comments and how we propose to deal with them.

Line by line comments

Line 74 – add some examples of studies that use moisture tracking models to assess precipitation recycling

We will add several examples, from local to global examples, and with different purposes such as understanding the role of ecosystem services.

Line 97 – can you add further explanation for why 100 parcels are released at random locations above the starting area? For evaporation, shouldn't parcels come from the surface, and precipitation higher up in the atmosphere? You say further up in the paragraph that the number of parcels that is tracked from a certain area and time step depends on the evaporation…or precipitation… from the respective location or area at the respective time step. Is the number of parcels 100 or does it vary? Would be good to make this paragraph a bit clearer to fully understand what's happening in the lagrangian model. Could consider adding in a schematic figure?

Although we agree that, in principle, surface release is more realistic, given the specific set-up of UTrack surface or profile release does not really matter. UTrack contains a random mixing parameter such that even with surface release, a parcel would be assigned a random vertical position within 24 hours anyway. Still, it may have some effect, which was tested by Tuinenburg & Staal (2020). From here, we can show that the difference in moisture transport distance between the two modes of release is considerably (about 4-5 times) less than the size of an individual grid cell in NorESM2.

The number of parcels per mm of evaporation (or precipitation in case of moisture tracking backward in time, but this is not applicable in the current study) can vary, because it is a parameter in the model framework. As default (Tuinenburg & Staal 2020, https://doi.org/10.5194/hess-24-2419-2020) it is 100 parcels per mm. Here, we chose to

release 1000 parcels per mm, but distributed across the globe. We will revise this paragraph for clarity.

You add further information under the 'Simulation settings' section. Perhaps these sections could be combined / adjacent for clarity?

We will consider this when revising and possibly restructuring our Methods.

Line119 – did you calculate vertically integrated moisture fluxes?

We did not, because of the added randomized vertical mixing in UTrack, which is done to compensate for known underestimation of vertical fluxes. This means that the vertical moisture fluxes in the forcing data lose most of their relevance. Indeed, including vertical moisture flows additional to the mixing scheme is optional in UTrack. However, the forcing data at multiple pressure layers are still very important to account for differences in horizontal wind speed and direction.

Again we will clarify this shortly and refer to the references in which the model framework was introduced.

Line 158 – can you add more information on this basin-level analysis. Do you calculate trajectories for multiple locations within each basin? How does this differ from the rest of your analysis. E.g. couldn't you just subset your existing trajectories you calculated for the whole globe? Add a statement on what additional insight this basin-level analysis provides.

In our revision, we will clarify the methods and merits of the basin-level runs. Subsetting existing trajectories is possible but not cost-effective, because it would have meant we needed many more parcels per run in the global analysis that additionally would have required much more information to keep track of.

Line 159 – 100 parcels vs 1000 parcels mentioned in line 152. Is that correct? If so, why the difference?

We will make it more clear in the revision that this decision is based on different areas of global versus basin masks.

Line 171 – add definition of evaporation recycling and how this differs from P recycling

We will do this.

Line 213 – here you discuss changes in precipitation, but the figure you point to (Fig. 3a) shows changes in precipitation recycling, which isn't the same thing. Maybe double check.

Thank you for pointing this out. Indeed, in this sentence, Figure A1 should be referred to, and Figure 3a only in the sentence following it.

Having read further on in the paper – you show the annual P changes in Figure A1. Would be good to direct to this in relevant parts of the text. In fact, it might be better to move A1 to

the main paper given its importance to the rest of your results – it will allow the reader to identify drying and wetting areas more easily. Make sure all supplementary figures are referenced somewhere so they don't get overlooked.

We understand this reasoning, but if allowed, we prefer to show in the main text only original results. We consider non-original results that facilitate understanding of the novel findings to be supplementary.

"In 45.4% of the grid cells that are projected to become drier (representing 1.1% of all land grid cells)" are these figures correct? Does this mean that in 1.1 % of land grid cells the drying is caused by a reduction in P recycling? This value seems quite low looking at the shaded areas in Fig 3, but perhaps that's because you're showing significant and no-significant changes, but only talking about the significant changes. Maybe consider rewording this paragraph and subsequent paragraphs or at least clarify in the text that only a very small land fraction shows statistically significant changes.

Exactly, this low number is because of the small area of significant drying in the SSP1-2.6 scenario: 0.087 * 0.272 * 0.454 = 0.011. In Figure 3, we show also non-significant areas, as the reviewer remarks. In the revision, we will make sure this will be clear to the reader.

Line 214 "…this drying is dominated by a decrease in the precipitation that originates from land." Point to a figure / evidence for this.

We will refer to Figure 3a here (as mentioned above in response to the point raised about referencing Figure A1).

Lines 211-245 I wonder if the information presented in these paragraphs would be better summarised in a table? The text gets a bit repetitive here and it might be more useful to focus the reader's attention on your most important findings, e.g. perhaps the worst case scenario of SSP5-8.5 could be highlighted in the text? Just an idea.

This is a useful suggestion which we will implement.

Line 248 – Are you considering 'all global grid cells' or just land? As all your figures show land only, perhaps it makes sense to only refer to results over land throughout your description of your results. Check here and elsewhere.

We meant all global land grid cells. Thank you for pointing this out. We will check throughout the text whether we did not confuse this elsewhere.

Line 255 – please indicate a figure after the first sentence so the reader immediately knows where to look for evidence for this statement.

We will refer to Figure 6 after the first sentence.

Line 264 – again please be clearer with your figure indications. How is it possible for recycling to exceed actual precipitation? You indicate the regions where this occurs but

would be useful to add a line to explain if this is simply an artefact of the model or if this is a physical result (and if so how that might arise).

We will add explanation of how this is possible. It is an artefact of the model, where sometimes (especially in dry grid cells and months) too many forward-tracked moisture parcels end up in a grid cell relative to the precipitation in that grid cell in that month. This can be due to the stochastic nature of the model, the fact that some parcels are tracked across two months, and/or due to a non-closed water balance in the forcing data.

We also will add in the Discussion that this robustness and associated artefacts could also be tested in the future with different members of the NorESM runs (i.e. replicate runs with similar forcings and scenarios but with small different initial conditions)

Line 270 – consider removing the word 'one' or even the whole phrase in brackets – not sure if it's needed here and sounds a bit confusing

We will remove 'one' as it is redundant.

Line 272 – 'In SSP2-4.5, global forest cover remains 25%' insert 'at' after 'remains'

Thank you, we will do that.

Line 279 – 'a larger proportion of the 26 major…'

Good suggestion.

Line 280 – unclear what the distinction is between basin precipitation recycling ratio and terrestrial precipitation recycling ratio. In line 165 you state: "We calculate the global terrestrial precipitation recycling ratio as the percentage of precipitation on land that evaporated from land." Can you also clarify in caption for Table 2?

We will be more clear about the distinction between basin precipitation recycling ratio and terrestrial precipitation recycling ratio in both the main text and the caption of Table 2.

Line 289 – "Both changes in basin recycling ratio increases in SSP1-2.6 are an increase." Not sure what you mean here. Possibly: "The two basins that showed statistically significant changes in basin recycling ratio by the end of the century in SSP1-2.6 both showed increases from the baseline"?

This was a typo, thank you for spotting it. The suggested revision captures the intended meaning.

Line 289 – From Table 2 it looks like the change is from 19 % to 20% for Amur? Similarly it looks like Ob changed from 11 % to 13 % (not 11 to 12 as written in the text). Possibly double check these and other values referenced in the text in case the numbers have updated since an earlier draft of the paper.

Numbers have indeed changed from an earlier version of the manuscript. We appreciate the detailed checks by the reviewer and we will double-check all numbers before resubmitting the manuscript.

Table 2 – It might be nice to somehow indicate (possibly through additional columns, or by colouring the numbers red and blue) which basins were showing statistically significant increases and which decreases in P recycling. At present the reader can quickly pick out the values with asterisks next to them but not the direction of changes.

This is a good suggestion. We will explore options to show the differences between increases and decreases in a clear way.

Line 302 – check the wording here as it seems a bit contradictory. You say that Chad has an "increase in basin recycling ratio between the middle and end of the century" but in the next sentence you say "the Chad basin does not have a significant decrease by the end of the century". This whole paragraph might be a bit clearer if you first focus on the changes by the middle of the century, and then subsequently describe the changes that occur from mid to late century. I appreciate there is a lot of detail to try to capture, but at the moment it gets a bit muddled and the message gets lost.

Thank you for pointing this out. We will restructure the paragraph to improve its clarity.

Line 319 – I'm not familiar with the expression "the one percentage point level" which comes up here and elsewhere. Is the point you want to make that in some instances there are changes in P recycling where there are no changes in forest cover or cropland cover? Possibly rewording could improve clarity.

We will rephrase this. What we meant is that the ratios are rounded to percentages and there is no difference between those rounded numbers.

Line 321 – where land cover changes are small and P recycling changes are high, is this related to changes in e.g. plant stomatal conductance in response to rising atmospheric CO_2? Or other aspects of climate? I know this is only the results section, not results and discussion, but might be nice to just add in a line or so to briefly explain this finding.

It may be related to increased residence times of moisture in a warmer atmosphere, as explained in the Discussions section (lines 396-408). We will add a note about that also here in the Results.

Lines 317-330 Maybe restructure this paragraph or split into multiple paragraphs. For example, the first line of the paragraph really relates to what is described in the second half of the paragraph – i.e. regions where changes in recycling are related to changes in land cover

We will restructure and/or split it up.

Line 345 – missing word 'relative' for panel a description. Could start the paragraph with the current second sentence (rephrased!) and focus on areas with no LCC that see changes in

recycling, then have a separate paragraph that looks at areas that do see large differences in LCC.

Thank you, we will add “relative” to the caption.

We assume that the second part of the comment belongs to the previous comment about lines 317-330. We will take this into account when restructuring it.

Lines 332-336 Maybe reword. I think the point you are trying to get across is: “In the Amazon and Congo river basins, end-of-century recycling ratios are the same in SSPs with different land cover distributions. For example, in the Amazon under SSP 3-7.0 and SSP5-8.5 the estimated basin recycling ratio is 24% and the terrestrial recycling ratio is 40%, despite forest cover of 75% in SSP3-7.0 and 82% in SSP5-8.5. Similarly in the Congo…. etc. etc.”

Thank you for this specific suggestion; it is indeed the point that we were trying to get across.

Line 349 – specify ‘absolute’ differences in ΔTPR

This figure displays the differences in relative recycling, not absolute, which we will specify in line 349.

Line 355 – missing word ‘ratio’ after recycling. Not sure if this is intended given the change in units from Figure 2 to Figure 3?

Figure 3 shows absolute recycling, not ratios. We will add “absolute” to prevent misunderstanding.

Line 420 – can you speculate on why the Danube might show opposite behaviour?

We will delete the sentence starting with “Interestingly, though”, as the Danube is in fact not so different from the general pattern; it just has a particularly strong decrease in terrestrial precipitation recycling ratio.

Line 423 – consider citing papers by Christopher Skinner and Rob Chadwick here. E.g. DOI: https://doi.org/10.1175/JCLI-D-16-0603.1

Thank you, this is a useful suggested reference and we will look for possible other ones.

Line 444 – underestimated…. In the current generation of climate models? Or specifically in this study?

We mean in our study, which we will make more clear.

Line 461 “We call drying land-dominated if it coincides with a significant increase in terrestrial precipitation recycling ratio and we call it ocean-dominated if it coincides with a significant decrease in terrestrial precipitation recycling ratio.” This definition could come earlier as it would help understand the description of these results.

We agree, this definition should be provided in the first paragraph of section 4.2.

Line 524 – maybe repeat here that NorESM2 was the only model that provided the required variables at the time frequency required for your moisture tracking model.

Thank you, we will do this.