Response to comments made by Reviewer 1 on a manuscript entitled 'Changes in mean evapotranspiration dominate groundwater recharge in semi-arid regions'

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General comment 1: A major conclusion seems to misrepresent actual recharge changes. Namely, it is concluded that mean ET has a bigger influence on recharge than P, but the latter is only true when the ratio of recharge to precipitation is considered, but absolute (in mm/y) or relatively (in %) changes in recharge are very likely much bigger due to precipitation changes. Such an amplifying effect of precipitation on recharge (versus PET on recharge) is because changes in precipitation both the ratio of this precipitation becoming recharge, and the total amount of precipitation that can become recharge. In contrast, changes in PET only affect the ratio of precipitation becoming recharge. The latter is also highlighted in cited most recent work on the climate sensitivity of recharge.

Reply to general comment 1: *Indeed, our choice to focus on changes in the ratio highlights the nonlinear effects rather than the actual changes in the recharge (R). Actual changes in the recharge are meaningless without relating them to the changes in the precipitation (P). Even the simplest linear models assume that*

$$R = cP$$

would predict a change in the actual recharge when the precipitation changes. However, when the relation is nonlinear, it is not clear what would be the response to different changes in P, and this is the point we wish to emphasize. To provide the requested information, we added to the SI figures showing the actual recharge as requested.
In this study, we do not attempt to predict the changes to the precipitation and the potential evapotranspiration (E_p). Rather, we focus on modeling the response of the groundwater recharge to assigned changes in the P and the E_p statistics.

We added an explanation of this point at the beginning of the Methods section of the revised MS. We added figures presenting the actual recharge fluxes.

General comment 2: The model claims to be accurate within 5% of recharge but given that recharge/rainfall is typically very low in these arid places so being within 5% can still mean the recharge is off by a lot (for example several 100%). These uncertainties are not reflected in the projections. In addition, several data points appear to exceed the 5% error? More generally it is unclear why the climate projections can be considered accurate?

Reply to general comment 2: *We thank the reviewer for the comment. We double-checked our code and found that due to a typo, 7 locations in Africa showed an error that was larger than 0.05 in the ratio. Therefore, we corrected the code and redid the entire analysis. The corrections resulted in the removal of the 7 locations and the addition of 3 other locations in Africa that were within the 5% error.*

As for the second part of the comment, indeed, for locations where the ratio between the recharge and the precipitation is small, the relative error (associated with absolute errors in the ratio of 0.05) may be very large. However, in most locations with reported small R/P ratios the uncertainty of the measurements is very large. To illustrate this issue, we show in the figure below the measured ratios in the locations in Africa together with the associated uncertainties Taylor et al. (2013). As shown in the figure below, an error of 0.05 in the R/P ratio is still within the reported uncertainty range for these locations. While we do not have the data regarding the uncertainties in all locations considered, we believe that the uncertainties show similar patterns.

We never claimed that climate projections are accurate, nor have we used them. The CRU data is not based on climate projections but, rather, on reanalysis data. The latter is effectively an interpolation of meteorological measurements.

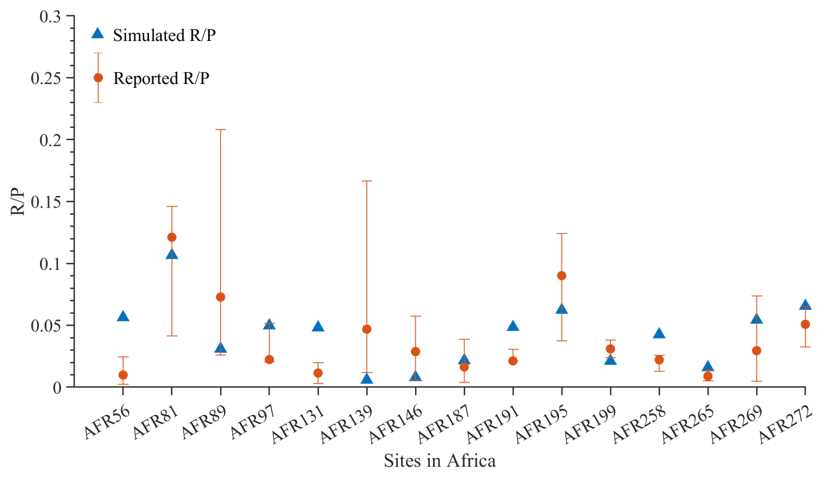

Figure 1. A comparison between reported GR/Rain ratio ranges and simulated ratios. Note that the name of each site used in our study, as reported by Taylor et al. (2013), is designated in the x-axis tick labels.

General comment 3: The mathematical derivation (Eq. 6-9) is applicable for ET but not for ETref. The argument that is made (that ET is proportional to the ETref) to circumvent this problem is not valid in semi-arid systems. If we follow the Budyko framework as a reference, one can see that in extremely energy-limited systems indeed ET is expected to (almost exactly) linearly (and one-on-one) scale with ETref. However, in more arid places changes in ETref will not be associated will similar ET changes, nor will be their relationship be linear.The expectation of how this behaves can be exemplified using simplified version of the Budyko framework: E/P = 1-exp(-ϕ) = E/P= 1-exp(-Eref/P). Thus: E= P*(1-exp(-ETref /P)). Thus, dE/d(ETref)= P/(P - exp(ETref/P) P + ETref), which is a nonlinear function for ETref > P. Therefore, the physical relevance of the derivation provided in the manuscript remains unclear to me.

Reply to general comment 3: *We thank the reviewer for this helpful comment. Indeed, we find that in many locations there is no linear relationship between the actual evapotranspiration (E_a) and the potential evapotranspiration (E_p). However, we also found that the Budoyko formula does not explain the observed relationship between the two quantities. In the revised text, we explain that under the assumption of $E_a = f(E_p/P)$, with f being any function, the effects of changes in E_p or in P are expected to be the same as long as the ratio, E_p/P, remains constant (which is the kind of changes we considered in our paper). We believe that the observed difference in the responses to changes in E_p and changes in P is due to the fact that the E_a depends on the water content of the top soil layer. The water content of the top soil layer is a function of the specific temporal fluctuations of the precipitation and the potential evapotranspiration as well as of the soil hydraulic parameters.*
We revised the paragraph to reflect the changes outlined above.

General comment 4: The model assumes that all evaporation is soil evaporation and no overland flow. It is unclear why this is realistic even with somewhat sparse vegetation. Most of these regions will still have vegetation that evaporates relevant parts of total ET.

Reply to general comment 4: *We find that using the global soil parameters and the CRU TS climate data for the locations with sparse vegetation, results in similar simulated groundwater recharge and independently reported groundwater recharge. Therefore, it is justified to neglect the specific details of vegetation transpiration (information that we do not have for all the locations considered) within the scope of our study.*

General comment 5: The manuscript states surprise that the extreme ETref statistics have much weaker effects on the GR than changes in extreme rain statistics. Isn't this a result in line with obvious expectation?

Reply to general comment 5: *We found that changes in the mean E_p have a greater impact on R/P than changes in the mean precipitation. Therefore, we find it interesting that for changes in the extreme value statistics, the impact of changes in E_p is weaker than the impact of changes in P.*

General comment 6: The use of symbols is highly confusing with GR standing for "recharge" and R for "rain". However, to readers it would make interpretation a lot easier if a single letter was used for a process, and maybe a subscript is needed for further specifications. This avoids that GR reads as G times R. In addition, the use of P for precipitation, and R for recharge seems slightly more conventional. Such formulation would also come in handy when the symbols are used to derive new equations (Eq. 6-9).

Reply to general comment 6: *We accept the comment.*
We changed the notation. In the revised MS, R represents the groundwater recharge rate, P represents the precipitation rate, E_p represents the potential evapotranspiration and E_a represents the actual evapotranspiration.

References

Taylor, R. G., Todd, M. C., Kongola, L., Maurice, L., Nahozya, E., Sanga, H., and MacDonald, A. M.: Evidence of the dependence of groundwater resources on extreme rainfall in East Africa, Nature Climate Change, 3, 374–378, https://doi.org/10.1038/nclimate1731, 2013.