Reply to Referee Review 1

We acknowledge the referee reviewer for those comprehensive and insightful comments. Our responses to the reviewers' comments are given below. The original comments from referee reviewer 1 were marked with blue color, and our response in black. The page and line numbers in our responses refer to those in the marked copy of the revised texts.

General comments

From the description provided in the methodology and materials section I argue that mHM and OGS, the mesoscale hydrological model and the groundwater model are decoupled. In fact, at line 13 of page 5 I read "The projected recharge from mHM calculations are fed to the groundwater model OpenGeoSys (OGS) for the assessment of groundwater quantity and travel time distribution." From this short description I concluded that vertical fluxes, including those of the unsaturated zone are modeled with mHM and that the resulting "deep" infiltration is used as recharge (i.e., as boundary condition) for OGS. In doing that the processes of infiltration and flow inside the aquifer are decoupled. This may be reasonable when the water table is deep, but I am wondering what is the impact of this assumption on the simulations showing significant rises of the water table. In this situation decoupling leads to significant errors as the water table gets close to the ground surface. This is relevant both for water levels and the following travel time analysis. The authors provide only limited information on this important point and do not discuss its implications in term of representativity of the model. Decoupling these two processes is a great advantage from a modeling point of view, but I am not sure it can be actually introduced at least in the scenarios showing the largest increase of groundwater levels.

Response:

We fully agree with the reviewer that groundwater dynamics can alter land surface response and feedback to the climate system, especially in cases that the groundwater level is shallow. The dynamic feedback from groundwater to land surface processes can introduce a second-order impact on the groundwater table and travel times. A fully coupled system, based on a mixed form of the Richards equation, is more realistic than the one-way system [1]. However, fully coupled model constantly suffers from expensive computational burden, which limits its applicability in large-scale real-world models. It also introduces extra parameters, which are essentially unknown at the catchment scale. Due to the above reasons, we didn't apply the fully coupled modeling approach in this study.

We think the current one-way coupling is appropriate in terms of investigating groundwater resources, because: (1) the current modeling method, although less accurate than the fully-coupled model, is computationally more efficient. It reduces the computational demand of this study. Besides, the Lagrangian particle tracking in the 3D model is computationally very expensive (total computational time is 20 days using 40 cores on a super computer for the ensemble simulations). (2) This method facilitates the use of currently established land surface models in the HOKLIM project to investigate large-scale groundwater levels and travel times, without re-establishing all the models [2,3]. (3) This one-way coupling method has been widely used by many other researchers [4,5,6].

We also agree with the reviewer that the limitation of the current method should be discussed in the manuscript. Accordingly, we modified the discussion section to include the following information: *"A potential limitation of the current modeling framework lies in the simple one-way coupling approach that neglects the feedback from groundwater level change to the land surface processes. The change in groundwater table can alter the partitioning of water balances, which further exerts a second-order impact on the groundwater level and travel times. The fully coupled system, based on a mixed form of the Richards equation to solve unsaturated and saturated zone flow simultaneously, is more realistic than the one-way coupled system. However, fully coupled model consistently suffers from expensive computational burden, which limits its applicability in large scale real-world models. It also introduces extra parameters that are essentially unknown at the catchment scale. The current one-way coupling, although less accurate than the two-way coupling, is computationally more efficient considering the huge computational demand with the Lagrangian particle tracking. The current approach also facilitates the extension of currently established land surface models in the HOKLIM project for investigating large-scale groundwater levels and travel times with minimal additional effort. The one-way coupling approach has also been widely used by many other researchers [4,5,6]…"*

Another aspect that is not fully explained is the validation of the groundwater simulations. The authors touch very briefly this point by saying that mHM has been validated at the European scale in a previous paper, but what about this specific small catchment or the larger, but still small compared to the European scale, Thuringian catchment? And what about the groundwater model? At page 8, line 17 I read: "The post-calibrated values of the hydraulic conductivity in each geological unit obtained from a previous study are assigned to the corresponding geological layers of the mesh (Jing et al., 2018a). Meanwhile, a uniform porosity of 0.2 is assigned to each geological layers (Table 2)". In a previous work (Jing et al., 2018a) the authors presented a comparison between observed and simulated heads at a number of observation wells (Figure 5 and related text on section 3.2.5) and for a number of recharge scenarios. The analysis is based on 400 calibrated Monte Carlo realizations and I am wondering if the authors used all the 400 realizations in the present work, or just one, in the latter case what was the criteria used to assign the hydraulic conductivity? Figure 5 of the previous paper shows apparently a good reproduction of the observed heads, but what puzzled me is that the standard deviation of the error is 4.6 m, a rather large portion of the variation presented in this manuscript as an effect of climate change.

Response: We thank the reviewer for these insightful comments. We agree with the reviewer that the validation of groundwater model is very important, and will add more information on the validation of groundwater model in the revised manuscript.

The mHM model has been validated both on the European scale and the catchment scale. The validation result of mHM model on the Thuringian basin is included in previous publications [7,8].

The groundwater model was validated using the observed groundwater levels in many monitoring wells. For the steady state model, a long-term average of observed groundwater levels is compared to the simulation results. The simulation results show a good correspondence to the observations (Fig. 1).

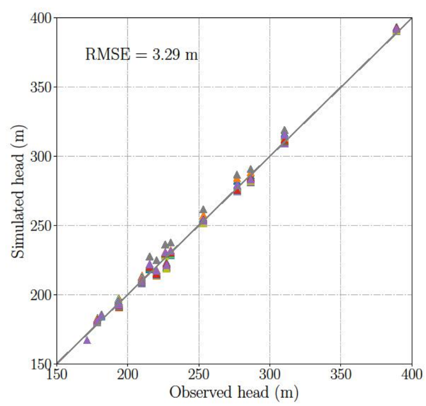

Fig. 1 Validation of groundwater model

The current hydraulic conductivity values for groundwater model are randomly sampled from the 400 parameter sets [9]. The reviewer pointed out that parameter values and its uncertainty can be critical to study results, with which we fully agree. In order to further investigate the parametric uncertainty in groundwater model, we expanded the current parameter set from only one set to 80 different sets. Those 80 parameter sets are all compatible with the groundwater level observations. The 80 parameter sets are randomly sampled from the parameter dataset used in our previous study [9].

The standard deviation of the residuals between observed and simulated groundwater table is 3 to 5 m, which seems to be large. However, the topography is complex in the study area, and the groundwater level difference between the highest and lowest monitoring wells is around 220 m. The CV (coefficient of variation) of the residuals is 2.09%, which is quite low, demonstrating a good reproduction of groundwater dynamics.

According to these important comments, we modified the manuscript to include simulations using many realizations of hydraulic conductivity fields (80 members in total). We also expanded the study to investigate the parametric uncertainty in groundwater model associated with 80 different hydraulic conductivity fields. We presented a comprehensive uncertainty study in the revised manuscript.

The third issue I would like to comment is uncertainty. My impression is that combining a large number of GCM-RCM pairs introduced a large variability of the meteorological forcing and therefore to water levels and travel time distributions, which should be validated in some way. According to the presented analysis it is very difficult, if not impossible, to sort out unrealistic scenarios, or weight less them in the ensemble. On the other hand, uncertainty in the hydrological models is neglected, in particular that related to the groundwater model.

Response: This is another important observation by the reviewer. Substantial uncertainty persists about the impacts of climate change on mean precipitation from general circulation models (GCMs) [10, 11]. A large spread in projections occurs in many regions and variables due to a combination of variations in the climate sensitivity that determines the magnitude of the average global response, and large variations in the spatial patterns of change – particularly for precipitation [10]. It is a widely-used approach to set up a large ensemble of GCMs and greenhouse-gas emissions scenarios to generate recharge projections, which is also the case of this study [4, 12, 13]. Besides, it is clear that when exploring the potential impact of climate change scenarios, ensemble spread provides some important, if incomplete, information about the range of plausible future climate changes. This uncertainty information significantly improves the usefulness of climate projection and impact information by (a) allowing policy makers to consider a plausible range of eventualities and (b) informing the appropriate use of uncertain climate projections [10]. We use a large ensemble of GCM-RCP combinations to assess the climate uncertainty, and we also use the summary statistics (e.g., mean and SD) to show the highest possible scenarios in the future.

We agree with the reviewer that the uncertainty in groundwater model should be considered. We modified the manuscript to include simulations using many realizations of hydraulic conductivity fields (80 members in total). We also expanded the study to investigate the parametric uncertainty in groundwater model associated with 80 different hydraulic conductivity fields. We also presented a comprehensive uncertainty study in the revised manuscript.

Overall I feel that the manuscript, although interesting and pleasant to read, cannot be accepted for publication in the present form. As it is the manuscript reads like an application of previously published modeling efforts, with little analysis of the results. However, I see value in what the author presented and I think that with some extra effort they may accommodate the above drawbacks, by explaining more the underlying hypotheses and limitations of the current analysis and improving and enriching the discussion of simulation results. With these changes I think this manuscript will be a valuable contribution to the community.

Response: We are modifying the manuscript thoroughly according to the reviewer’s comments. We will post a revised manuscript soon for HESS.

Minor comments Page 9 line 6: The recharge seems to increase almost linearly with the temperature, which is strange considering the many nonlinearities involved in the infiltration process;

Response: Yes, but it only indicates that the spread in projected recharges increase in a near-linear way. If we look at the ensemble average of projected recharges, it shows a nonlinear relationship between the recharge and warming level (8.0%, 8.9%, and 7.2% for the 1.5, 2, and 3 degree).

We already stated this in the current manuscript: "*The ensemble simulations do not show a systematic relationship between the predicted change and the warming level, but they indicate an increased variability in predicted changes with the enhanced warming level from 1.5 to 3 degree.*'' (Page 1, Line 10-11)

Page 9, line 9: "The projected....." This seems to suggest that the number of combinations of GCM and RCM can be reduced, or even that similar results can be obtained by using only the GCM. Please elaborate a bit more.

Response: We use different pairs of GCMs and RCPs to provide the degree of spread in future climate projections. It is clear that when exploring the potential impact of climate change scenarios, ensemble spread provides some important, if incomplete, information about the range of plausible future climate changes.

We nonetheless fully agree with the reviewer that this point should be elaborated in detail. Accordingly, we added the following information into the manuscript:*" Nevertheless, differences in recharge induced by different RCPs can still be witnessed in Figure 3, indicating the necessity of considering multiple GCM/RCP combinations for providing a plausible range of predictive uncertainty."*

Page 14, line 17 and following: this sentence is vague. Have these shallow local flow pathways actually been observed in the simulations and how realistic are they?

Response: These shallow local flow pathways exist in areas with complex topography and dense drainage network. In areas with complex topography and dense drainage network, rising groundwater level may activate shallow groundwater flow paths and intensify shallow local flow pathways. This effect is evidenced by the simulation results. We modify the revised manuscript accordingly to clarify this point.

Page 15 line, 25: this disclaimer, saying that uncertainty may be even larger, since some uncertainty sources have not been considered is somewhat alarming because it casts doubts on the interpretation of the results.

Response: We agree with the reviewer that the more uncertainty sources, e.g., uncertainty in groundwater model, should be considered. We modified the manuscript to include simulations using many realizations of hydraulic conductivity fields (80 members in total). We also expanded the study to investigate the parametric uncertainty in groundwater model associated with 80 different hydraulic conductivity fields. In doing so, a more comprehensive coverage of multiple uncertainty sources is achieved. We presented a comprehensive uncertainty study in the revised manuscript.

Page 16, line 20: How can be that first-order effects of climate change are small and second-order effects are not negligible? If for not negligible you mean that they are however smaller than first-order effects, what is the reliability of their estimate considering the large uncertainty affecting these simulations? Please elaborate more

Response: In the context of this paragraph, the term “first-order effect” means the direct effect of climate change on recharge, and the term “second-order effect” means the effect on groundwater quantity and travel times introduced by the change of recharge. We want to deliver the information that although the relative change in recharge rate seems to be indistinctive, its further effect on groundwater levels and travel times can be significant according to our simulation results.

This original expression, as pointed out by the reviewer, may be somehow misleading. We modified this sentence as the following one: *“To summarize, climate change can significantly alter the quantity and travel time behavior of regional groundwater system through the modification of recharge, especially for the long term. Ensemble simulations indicate remarkable predictive uncertainties in regional groundwater quantity and travel times, which are introduced by both climate projection and groundwater model.”*

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