Reply to Referee #2
Groundwater in terrestrial systems modelling: a new climatology of extreme heat events in Europe

We thank the referee for the review and for the helpful comments and suggestions. We provide a point-by-point reply below, where the reviewer comments are repeated in black. The replies to the reviewer's comments are in blue. The revised text is given in italics and in quotation marks.

General remarks

Poshyvailo-Strube and colleagues investigated how the inclusion of groundwater modeling would affect heat wave characteristics in Europe. This is an important topic as groundwater plays a critical role in land-atmosphere interactions, but its modeling has been oversimplified or neglected in climate models. However, before I recommend publication, I have two major concerns that need to be addressed by the authors.

1. The title seems to suggest that this paper will be providing and evaluating a new climatology of extreme heat events in Europe.
   Thank you for this comment. The current title does not fully describe the main message we wanted to convey to the reader. Therefore, we decided to revise the title of the paper as follows *"The influence of 3D groundwater dynamics on heat events in a regional historic climate simulations"*.

2. I would expect the authors to compare their new climatology to observation-informed heat wave characteristics. However, I did not find any comparison with observations. The paper itself seems to discuss how groundwater modeling would affect heat waves just by comparing their model to other nogroundwater models. This seems not new to me as the authors have stated in line 60. An opportunity to improve probably is to add an observational perspective.
   In the paper, we present a new dataset from the coupled Terrestrial Systems Modelling Platform (TSMP), driven by MPI-ESM-LR GCM historical boundary information. The simulation was performed, in the context of GCM-RCM EURO-CORDEX long-term climate modelling, and, in particular, the climate change scenario control runs (until 2006). Thus, the model is informed at the boundaries with data from a GCM, and the simulation results can not be evaluated directly with observations. However, the evaluation of TSMP driven by the ERA-Interim reanalysis against observations has already been performed in the work of Furusho-Percot et al. (2019, 2022), which showed good agreement. This also holds for the large scale water budgets and anomalies (Hartick et al., 2021; Ma et al., 2022).

Long-term historic climate simulations of TSMP forced by GCM boundary information have not been previously presented. This is the first downscaled regional historic climate simulation from groundwater across the land surface to the top of the atmosphere, which has been put into context of the large EURO-CORDEX ensemble and analyzed for extreme heat events in this study.

We see a high potential for a dataset like TSMP driven by MPI-ESM-LR GCM, with explicit representation of groundwater dynamics. The characteristics of summer heat events from TSMP compared to the CORDEX ensemble members with oversimplified or neglected groundwater dynamics, discussed in this paper, not only adds important information to the existing ensemble, but also of existing uncertainties between the CORDEX ensemble due to explicit groundwater inclusion, which is is essential for drawing conclusions about the uncertainties to be expected in projection analyses. Also in the light of current groundwater drought in Central and Southern Europe, the results are of importance in the assessment of future temperature extremes.

In our opinion, this line of arguments was not clearly presented in the paper. Therefore, we have revised the introduction of the paper, following the rational above, and added a clear explanation of the objectives of the paragraph:
"...An important question remains: how will these findings be reflected in long-term regional climate simulations?
In this paper, we present a unique dataset from TSMP forced by the Max Planck Institute Earth System Model with Low Resolution MPI-ESM-LR (Giorgetta et al., 2013) historical boundary information in the context of EURO-CORDEX GCM-RCM long-term climate modelling, and, in particular, the climate change scenario control runs. We interrogate the statistics of the heat event characteristics (frequency, duration, intensity) of 1976-2005 with respect to the reference period 1961-1990 by comparing TSMP results with the EURO-CORDEX multi-model RCM ensemble driven by CMIP5 (Taylor et al., 2012) GCM control simulations, to understand the influence of 3D groundwater dynamics on simulated heat extremes for regional historical climate simulations and potential consequences for climate change projections. While the 1996-2018 TSMP evaluation runs nested within ERA-Interim reanalysis were examined for heat wave statistics (Furusho-Percot et al., 2019, 2022), long-term historical climate simulations of TSMP forced by GCM boundary information have not been previously presented. Thus, this is the first downscaled regional historical climate simulations from groundwater across the land surface to the top of the atmosphere placed in the context of the EURO-CORDEX ensemble and analyzed for extreme summer heat events."

3. Are the heat wave characteristics modeled by TSMP better agree with temperature observations than other models and by how much?
   Thank you for the questions. In the recent work by Furusho-Percot et al. (2022), it was shown that multiannual heat wave statistics from TSMP simulations forced by the ERA-Interim reanalysis are consistent with E-OBS observations and the ERA5 reanalysis. Moreover, TSMP heat wave metrics (intensity, extent, number of heat wave days) have consistently shown lower mean absolute deviations from observations compared to

RCMs with simplified groundwater representation, exhibiting a warm bias. It is explained by the explicit representation of 3D groundwater dynamics in TSMP.

For clarity, we have added this text in the revised version:
"... Furusho-Percot et al. (2019) showed that TSMP evaluation run (1996–2018) forced by the ERA-Interim reanalysis is able to capture climate system dynamics and the succession of warm and cold seasons on the regional scale for the PRUDENCE regions of Europe (Christensen and Christensen, 2007) consistently with E-OBS observations (Cornes et al., 2018). Another study by Furusho-Percot et al. (2022) demonstrated that TSMP multiannual simulations exhibit lower absolute deviations of summer heat wave indices from the E-OBS observational dataset, compared to ERA-Interim-driven RCM evaluation simulations of the EURO-CORDEX experiment (Jacob et al., 2020), which tend to simulate too persistent heat waves (Vautard et al., 2013). This particular behaviour of TSMP is attributed to the improved hydrology due to the explicit representation of 3D groundwater dynamics, namely the improved capacity to sustain soil moisture translates into more reliable latent heat flux and evapotranspiration, that, in turn, leads to a decrease in the heat wave amplitude, extent and the number of days with anomalously high near-surface temperatures, unlike in the CORDEX RCM ensemble with simplified groundwater representation."

4. The current paper lacks an investigation of which process the groundwater had the influence to change the temperature anomalies. The intuitive processes are soil moisture and evapotranspiration...
   Thank you for this comment. We agree with the referee that the link between groundwater and its impact on temperatures was not described well in the last version of the manuscript. In particular, the discussion of the previous studies on TSMP was missing. Note that the main objectives of this paper are not to demonstrate the impact of groundwater on temperatures, which has already been done in previous studies (e.g., Barlage et al., 2015; Keune et al., 2016). Instead we want to provide an overview of whether new GCM-RCM TSMP-MPI dataset is consistent with the CORDEX ensemble and arrive at a statement on the role of groundwater in RCMs for long-term climate simulations on the example of heat waves statistics.

   Taking all this into account, we (1) have extended the introduction of the paper in its revised version to include an overview of previous studies on TSMP (see below), (2) clearly stated the main objectives of the paper in its revised version (please see our response to point #2 of "General remarks").

   "The role of soil moisture in modelling extreme heat events is crucial (e.g., Seneviratne et al., 2006, 2010; Fischer et al., 2007), but due to the complexity of the feedbacks involved and related high computational cost, the explicit representation of hydrological processes is oversimplified or neglected in most RCMs. Commonly applied hydrology schemes are based on 1D-parameterizations in the vertical direction with gravity free drainage approach as the boundary condition at the bottom and runoff generation at the land surface; in such a parametrisation there is no lateral subsurface flow and only the

1D-Richards' equation is solved (e.g., Niu et al., 2007; Campoy et al., 2013). RCMs with simplified representation of hydrological processes are unable to reliably reproduce land energy flux partitioning and, consequently, near-surface air temperatures, leading to warm biases (Vautard et al., 2013; Barlage et al., 2021; Furusho-Percot et al., 2022). Hydrological parameters tuning (e.g., Teuling et al., 2009; Bellprat et al., 2016) or developing new parameterizations of groundwater dynamics (e.g., Liang et al., 2003; Yeh and Eltahir, 2005; Schlemmer et al., 2018) have been shown to improve model results. A physically consistent description of hydrological processes in RCMs can be achieved by an explicit representation of 3D subsurface and groundwater hydrodynamic together with overland flow, and accounting for a complete feedback loop over the terrestrial system (e.g., Maxwell et al., 2007), i.e., water and energy cycles from groundwater across the land surface to the top of the atmosphere, as in the regional Terrestrial Systems Modelling Platform (TSMP) (Shrestha et al., 2014; Gasper et al., 2014).

TSMP is a scale-consistent, highly modular, fully integrated soil-vegetation-atmosphere coupled regional climate model. TSMP comprises the hydrological model ParFlow v.3.2 (e.g., Kollet and Maxwell, 2008; Maxwell, 2013), the Community Land Model (CLM) v.3.5, and the atmospheric model Consortium for Small Scale Modelling (COSMO) v.5.01 (e.g., Baldauf et al., 2011), which are coupled externally via the Ocean Atmosphere Sea Ice Soil (OASIS, version 3.0) Model Coupling Toolkit (MCT) (e.g., Valcke, 2013) to exchange fluxes between independent component models of TSMP. Keune et al. (2016) demonstrated the link between groundwater and near-surface temperature in an analysis of the August 2003 European heat wave from the TSMP simulations nested within ERA-Interim (Dee et al., 2011) and set up over the the European domain of the COordinated Regional Downscaling EXperiment (EURO-CORDEX) (Gutowski et al., 2016; Jacob et al., 2020), with two different groundwater configurations: (i) simplified 1D free drainage approach and (ii) 3D physics-based variably saturated groundwater dynamics. The study clearly showed an impact of groundwater dynamics on the land surface water and energy balance: latent heat fluxes were higher and maximum temperatures were lower, especially in areas with shallow water table depth, in the 3D configuration compared to the simplified 1D free drainage approach. Keune et al. (2016) suggest that the 3D groundwater dynamics in TSMP alleviate the evolution of heat extremes due to weaker land-atmosphere feedbacks compared to the simplified 1D free drainage approach, at least during the investigated European heat wave of summer 2003. The ability of groundwater to decrease warm summer biases and moderate maximum air temperatures during a single seasonal heat wave in RCM simulations was also discussed in Barlage et al. (2015, 2021) and Mu et al. (2022).

As an explanation, the 3D groundwater dynamics in TSMP leads to shallower groundwater levels compared to 1D approach, causing wetter soils, and a reduction in the Bowen ratio (sensible heat flux to latent heat flux) due to an increase in surface latent heat flux and a decrease in surface sensible heat flux, i.e., an increase in evapotranspiration (Maxwell and Condon, 2016). On the one hand, such an increase in a latent heat flux causes moistening of the lower atmosphere and increases downward longwave radiation *due to the greenhouse effect of water vapor, on the other hand, it cools the surface and reduces outgoing surface longwave radiation (Pal and Eltahir, 2001). In addition, increased evapotranspiration may cause moist convection or rainfall, which further affects soil moisture (Eltahir, 1998; Yang et al., 2018). In its turn, the simplified representation of groundwater dynamics with the 1D free drainage approach leads to the opposite effect, namely an overestimation of the land surface-atmosphere coupling via shallow soil moisture and strengthening of the feedback mechanisms, i.e., deeper groundwater levels cause drier soils, an increase in the Bowen ratio by reducing latent and increasing sensible heat fluxes, a decrease in cloud cover and enhance of incoming shortwave radiation, and, as a result, higher near-surface temperatures, which in turn further enhances latent heat flux and reduces soil moisture (Vogel et al., 2018).*

Further studies were carried out to understand whether the observed differences in simulated near-surface temperature due to differences in groundwater configuration (3D physics-based in TSMP and simplified in RCM ensemble) persist over longer time periods, and how this manifests itself for heat waves in the EURO-CORDEX realm. Furusho-Percot et al. (2019) showed that TSMP evaluation run (1996–2018) forced by the ERA-Interim reanalysis is able to capture climate system dynamics and the succession of warm and cold seasons on the regional scale for the PRUDENCE regions of Europe (Christensen and Christensen, 2007) consistently with E-OBS observations (Cornes et al., 2018). Another study by Furusho-Percot et al. (2022) demonstrated that TSMP multiannual simulations exhibit lower absolute deviations of summer heat wave indices from the E-OBS observational dataset, compared to ERA-Interim-driven RCM evaluation simulations of the EURO-CORDEX experiment (Jacob et al., 2020), which tend to simulate too persistent heat waves (Vautard et al., 2013). This particular behaviour of TSMP is attributed to the improved hydrology due to the explicit representation of 3D groundwater dynamics, namely the improved capacity to sustain soil moisture translates into more reliable latent heat flux and evapotranspiration, that, in turn, leads to a decrease in the heat wave amplitude, extent and the number of days with anomalously high near-surface temperatures, unlike in the CORDEX RCM ensemble with simplified groundwater representation. An important question remains: how will these findings be reflected in long-term regional climate simulations?.."

5. The comparison between TSMP and other RCMs may not be entirely due to groundwater. Other factors such as forcing, and structure differences (how they model vegetation) may also contribute to the difference. An opportunity to address this is to run the TSMP without the groundwater component and compare the affected processes within TSMP rather than across different RCM settings.

   We agree that the differences between the various RCMs and driving GCMs need to be honored in the analyses and discussion when making the comparison. At the beginning of Section 3.2, we discussed these limitations already:

   "Due to connections of various factors other than groundwater coupling in the multi-model CORDEX ensemble (e.g., various model setups, conceptual and structural model uncertainties, different physical parameterizations, internal variability, representation of

subsurface-land-atmosphere interactions, lower and lateral atmospheric GCM boundary conditions), it is challenging to reveal the exact cause and effect relationship of the explicit groundwater representation for simulated hot days and the associated heat events characteristics in RCMs. Moreover, the ensemble of EURO-CORDEX climate change scenario RCM control runs is not intended for direct comparison between individual models, as it includes different RCMs in combination with different driving GCMs. However, as has been shown in previous studies, the consideration of an extended period, e.g., 30-years, allows to draw statistically conclusions."

To improve the manuscript further, we will (1) expand the discussion on the selection of RCMs-GCMs in the CORDEX ensemble, (2) clearly formulate the main objectives of the paper (please see our response to point #2 of "General remarks").

We would like to point out that Keune et al. (2016) with dedicated TSMP simulations (with and without 3D groundwater flow) clearly demonstrated the impact of groundwater on the land surface water and energy balance including temperature. In our study, the model was used in the same version (including groundwater) and with improved geology and topographic slopes. Repeating the dedicated simulations with/without groundwater at the climate time scale is computationally not feasible. Our rational and its limitations will be also discussed in detail in the revised manuscript.

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