Response to the reviewers' comments, esd-2023-44, García-Pereira et al.

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The authors would like to thank the reviewers for their constructive suggestions and the time they devoted to reading and evaluating the manuscript. We have tried to integrate all suggestions and think that the manuscript has improved with them. We do appreciate their contribution.

The next sections contain a detailed point-by-point response to the reviewers' comments. Comments are labeled by reviewers and in order of appearance, i.e. R2C3 is the third comment of reviewer 2. The original number by the reviewer is also preserved if it was given.

1 Anonymous Referee 1

GENERAL COMMENTS:

R1C0: *REVIEWER'S COMMENT:*

Summary: the study estimates the land heat uptake since the start of the industrialisation period based on borehole temperature profiles and surface temperature data and compares them with the magnitude derived from climate simulations. Climate models with a shallow soil model tend to understatement the heat uptake, whereas new model versions with a deep soil model produce heat uptakes much more in agreement with observational estimates. Another important conclusion is that the deeper soil model does not necessarily produce different surface temperature histories.

Recommendation: Although the land heat uptake is only a relatively small fraction of the heat taken up by the global ocean, this study is interesting since it points to deficiencies of soil models in Earth System Models that can be easily amended. Heat uptake can also be more relevant regionally, for instance, in eras of permafrost, where a more accurate estimation of the land-heat uptake can be critical to estimate permafrost melting in the future.

I have a few comments that the authors may want to consider, but in general terms, the manuscript can be published after some revisions.

AUTHORS' RESPONSE:

The authors welcome the positive perspective of the reviewer on the paper. We are grateful for the reviewer's comments.

Indeed, the point made by the reviewer here is one of the main motivations of the paper, as illustrated in the introduction. Even if the land heat uptake represents a small proportion of the net gain in the terrestrial energy budget, a proper estimate of it has an impact on the representation of different soil processes and ground-air feedbacks, including processes operating at global scales, such as radiative fluxes (latent, sensible, and ground heat flux) and evapotranspiration, and other mechanisms relevant at regional scales, for instance the subsurface thermal propagation in high-latitude permafrost regions. All these processes play a critical role in shaping the terrestrial carbon cycle, water availability, and biogeophysical characteristics of the land surface, ultimately influencing regional and global climate.

Please find below a comprehensive point-to-point response to your review.

R1C1: *REVIEWER'S COMMENT:*

I was slightly surprised by how the simulated heat uptake was calculated. The authors took an indirect detour by using the simulated surface temperature history and passing this history through a simple forward model. This forward model needs to include some assumptions about the thermal conductivity and capacity of the soil. Why not just use the simulated surface heat flux? Is there a hidden reason not to do so?

AUTHORS' RESPONSE:

We use ground surface temperatures as the input to derive land heat uptake estimates because we think that it is the most suitable approach to do so avoiding a bias in the estimates. ESMs prescribing a shallow LSM depth underestimate the ground heat flux since their representation of heat propagation is constrained by imposing a zero-flux boundary condition that is too close to the surface. Fig. S1 shows the P2k+d and P2k+s simulated global mean ground heat flux and its time-integrated value (i.e. the land heat uptake). As global warming intensifies from the second half of the 20th century onwards, the offset between deep and shallow simulations increases, the shallow simulation showing both a smaller ground heat flux and land heat uptake. Therefore, we consider surface heat flux is not an appropriate indicator to derive land heat uptake from ESMs, since it varies depending on LSM depth, whilst ground surface temperature does not, as portrayed by Fig. 1 and explained by Section 2.1.

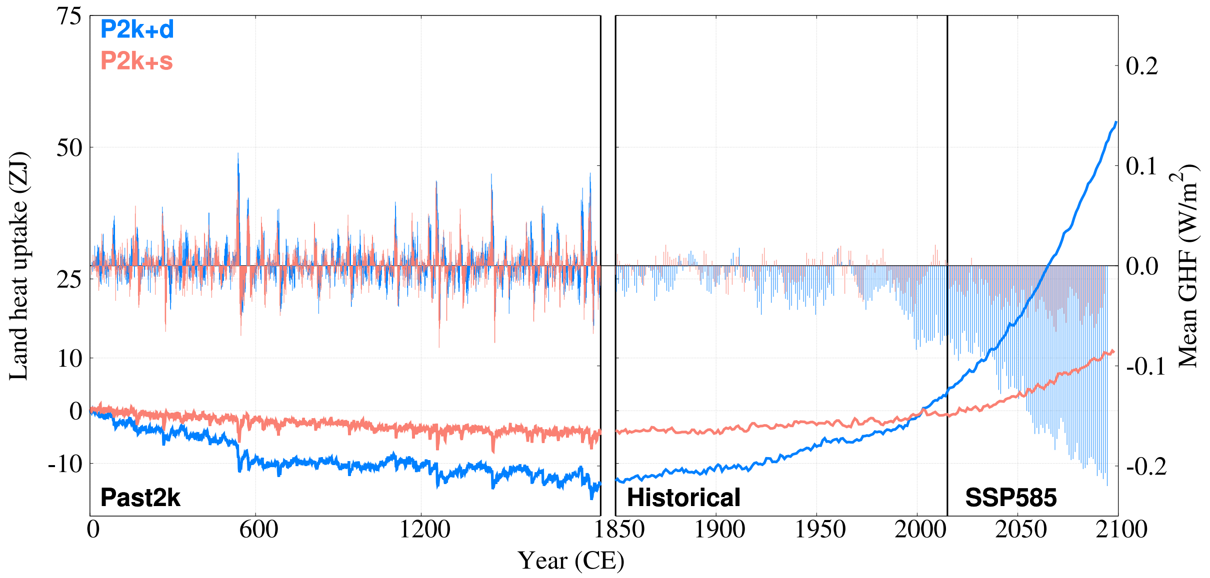

Figure S1. Land heat uptake in the MPI-ESM. 11-year moving average global mean (excluding glaciers) ground heat flux (GHF, W/m^2, impulses, right axis) in the P2k+d (blue), and P2k+s (red) simulations. The past2k era (0-1850) and historical and SSP585 scenario are separated to enhance the visibility of GHF evolution in the industrial period. Land heat uptake in yearly resolution is computed (ZJ, solid lines, left axis) as the grid area weighted time cummulative sum of yearly GHF values.

Moreover, ground heat flux data are not available for reanalysis products and observational gridded datasets and not directly yielded as an output by CMIP6 models, so the land heat uptake multi-source comparison would be severely hampered by using this variable as an input.

R1C2: *REVIEWER'S COMMENT:*

'The land contribution ranks second with the latest observational estimates based on borehole temperature profiles, which quantify the terrestrial energy surplus to be 6 % in the last five decades, whereas studies based on state-of-the-art climate models scale it down to 2 %.'

The reader might be interested in the range of uncertainty of the observational estimates. Could those cover the model value of 2 %?

AUTHORS' ANSWER:

The last terrestrial energy partition estimate stemming from von Schuckmann et al. (2023) based on observational data quantifies the contribution of the land to be 21 $\pm$ 2 ZJ in 1971-2020. Since the global heat accumulation in the same period is 381 $\pm$ 61 ZJ, the land contribution would range from 4.3 to 6.6 %, far above the CMIP5 multi-model mean land heat uptake contribution estimate of 2 % yielded by Cuesta-Valero et al. (2021a). A comment has been added to the manuscript, considering the reviewer's indication: "As a result of the energy imbalance at the

surface, the land stored around 6 % (4.3-6.6 %, 21 ± 2 ZJ) of the terrestrial energy surplus in the last five decades, as derived from observational estimates (von Schuckmann et al., 2020; Cuesta-Valero et al., 2021a, 2023), being the second largest contributor after the ocean (ca. 90 %, 324 ± 8 ZJ; Levitus et al., 2012; Abraham et al., 2013; von Schuckmann et al., 2020) to the total Earth System energy gain." (see lines 21 in the annotated manuscript).

R1C3: *REVIEWER'S COMMENT:*

'This approach yields values of 10.5-16.0 ZJ for 1971-2018,'

Comparing this number with the ocean heat uptake can be informative for the reader

AUTHORS' ANSWER:

A comment comparing this range to the ocean heat uptake value has been included in the introduction section of the manuscript, following the reviewer's indication: "As a result of the energy imbalance at the surface, the land stored around 6 % (4.3-6.6 %, 21 ± 2 ZJ) of the terrestrial energy surplus in the last five decades, as derived from observational estimates (von Schuckmann et al., 2020; Cuesta-Valero et al., 2021a, 2023), being the second largest contributor after the ocean (ca. 90 %, 324 ± 8 ZJ; Levitus et al., 2012; Abraham et al., 2013; von Schuckmann et al., 2020) to the total Earth System energy gain." (see line 21 in the annotated manuscript or R1C2).

R1C4: *REVIEWER'S COMMENT:*

'State-of-the-art climate models estimate land contribution to be 2 %, misrepresenting observational results.'

Misrepresenting is perhaps not the right word here, as the models' goal is not to represent the heat uptake but to simulate it.

AUTHORS' ANSWER:

Both terms 'misrepresenting', and 'misrepresentation' in the next sentence have been substituted by 'underestimating' and 'underestimation', respectively, following the reviewer's indication: "State-of-the-art climate models ~~estimate~~quantify land contribution to be roughly 2 % (Cuesta-Valero et al., 2021a), ~~misrepresenting~~underestimating observational results. ~~A misrepresentation~~This underestimation of land heat uptake in climate models..." (see line 26 in the annotated manuscript or R1C2).

R1C5: *REVIEWER'S COMMENT:*

'Temperature anomalies are calculated by subtracting the temperature value at t1 from the temperature values of the trimmed series to depart from equilibrium initial conditions.'

There is something strange in this sentence that makes it hard to understand.

AUTHORS' ANSWER:

The sentence has been rephrased to improve its clarity, according to the reviewer's indication: "Temperature anomalies are calculated by ~~subtracting the temperature value at the~~computing annual anomalies with respect to the temperature value of the first year of the trimmed interval, t1~~, from the temperature values of the trimmed series to depart from equilibrium initial conditions~~. This allows for departing from equilibrium initial conditions." (see line 123 in the annotated manuscript).

2 Anonymous Referee 2

GENERAL COMMENTS:

R2C0: *REVIEWER'S COMMENT:*

Summary: In this work the authors aim to quantify the energy absorbed by the land surface globally using model simulations. They start with an evaluation of sub-surface terrestrial heat storage in one model that has its lower soil thermal boundary at a conventional shallow depth and in a version where this is extended to much deeper. They use the findings from this to correctly forward model the outputs from other Earth System models with shallow bottom soil thermal depths and produce an ensemble of estimates across these.

The paper is well written, is very thorough and provides useful insights into the problem. I have only a small number of recommendations.

AUTHORS' RESPONSE:

The authors acknowledge the good perspective of the reviewer on the paper. Please find below the comprehensive point-to-point response to your review.

SPECIFIC COMMENTS:

R2C1: *REVIEWER'S COMMENT:*

There are far too many acronyms in this text for a easy reading. For example FTP, P2k, STP, FTP, BBCP, 30ENS, GST, SAT, ST5, BTP, FM, LSM, etc. Please consider reducing the number of acronyms in order to make this work more accessible.

AUTHORS' ANSWER:

The authors have cautiously revised the manuscript to seek for redundant or unnecessary abbreviations and acronyms. Some of the acronyms mentioned by the reviewer are of general knowledge in the climate community, such as GST or SAT. Some other acronyms related to soil and subsurface climatology have extensively been used in the previous literature, such as BTP, or LSM. Further, other acronyms are defined by coherence with some of the previously mentioned, such as ST5, STP, or FTP. Therefore, we have decided to suppress some of the acronyms that can be easily substituted by other more simple terminology, e.g. BBCP (either by LSM depth or zero-flux bottom boundary condition), or the least used across the manuscript, e.g. FM (simply forward model).

R2C2: *REVIEWER'S COMMENT:*

Abstract: The last sentence states that "This approach yields values of 10.5-16.0 ZJ for 1971-2018, slightly smaller than the latest borehole-based estimates (18.2 ZJ)."

I would be more specific and say this is 12-42 % smaller than the latest borehole estimate (18.2 ZJ).

AUTHORS' ANSWER:

An explicit indication of the difference in percentage between the values stemming from this study and the previous state-of-the-art land heat uptake estimate has been included in the abstract, according to the reviewer's suggestion: "This approach yields values of 10.5-16.0 ZJ for 1971-2018, ~~slightly~~which are 12-42 % smaller than the latest borehole-based estimates (18.2 ZJ)" (see line 13 in the annotated manuscript).

R2C3: *REVIEWER'S COMMENT:*

However, looking at figure 4, I can't see where the range of 10.5-16.0 is derived from. The corrected CMIP6 models are in the range from 0 to 25?

AUTHORS' ANSWER:

The range of 10.5-16 ZJ for 1971-2018 (Fig. 4c) indicated in the abstract refers to the results stemming from applying the forward model correction to all the available sources used in this work, i.e. reanalysis, observational, and CMIP6 datasets. This interval is obtained considering CMIP6 mean value (13.9 ZJ) as an indicator and not the individual simulations, since the ensemble spread due to the different internal variability of the individual models is really large, as it is shown in terms of temperature trend in Table 2. Therefore, we consider the CMIP6 mean land heat uptake to be a good trade-off estimate of the different models, since averaging a large number of simulations reduces the effect of their individual realization of internal variability (Fernández-Donado et al., 2013).

R2C4: *REVIEWER'S COMMENT:*

Figure 4: for clarity I would recommend you move the BBCP depth (m) grey arrow to outside the figure as otherwise I was at first trying to interpret it in terms of the y-axis.

AUTHORS' ANSWER:

According to reviewer's recommendation, the arrow is now displayed horizontally over the CMIP6 chunk of the panel above in order to prevent its repetition in every panel and confusion with the y-axis.

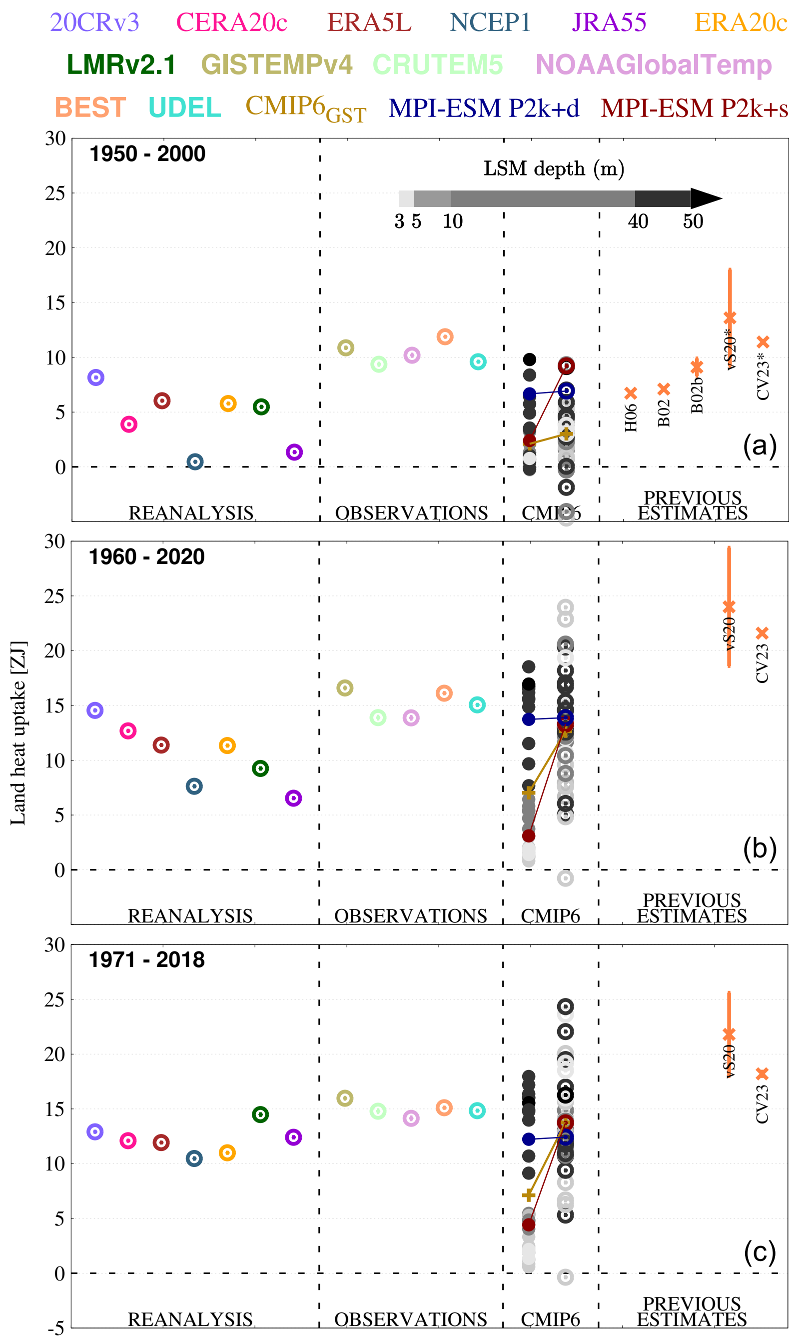

Figure S2. Land heat uptake estimates from different sources and periods. Land heat uptake during 1950-2000 (a), 1960-2020 (b), and 1971-2018 (c) derived from FTPs (hollow points) of reanalysis and observational databases (Table 1), CMIP6 FTPs (right hollow) and direct integration of CMIP6 STPs (left solid points, Table 2), and previous estimates: B02 (Beltrami, 2002), B02b (Beltrami et al., 2002), H06 (Huang, 2006), vS20 (von Schuckmann et al., 2020), and CV23 (Cuesta-Valero et al., 2023), orange crosses. The vS20 and CV23 estimates for 1950-2000 refer in fact to 1960-2000 and are marked with a star. ~~BBCP~~LSM depth for every CMIP6 model used in this work is given by a grey shading (see legend above), while the multi-model mean both for the STP and FTP-based values is given by gold crosses. MPI-ESM P2k+d (P2k+s) estimates are plotted in dark blue (red).

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