Responses to Referee #1

We appreciate the anonymous reviewer's feedback. Their comments highlighted in shaded are addressed below.

Comments:

In this revised manuscript, the authors have responded to all the comments made by the 2 reviewers. The changes made have improved the quality of the manuscript, in particular through:
- the addition of references in the introduction, providing a more complete and up-to-date bibliographic review
- the addition of information regarding the climatic context of the Chaco region
- the addition of information regarding the physical processes represented in WRF-Noah
- the addition of results and discussion on the uncertainty linked to the internal variability of the model
- the re-structuring of the paper with a section dedicated to the evaluation of the model and a discussion section.

We are pleased that the additions and restructuring have addressed the reviewers' concerns and improved the manuscript.

However, I do not always agree with the answers and modifications made by the authors concerning the 2 points discussed below. These 2 points do not undermine the method or the results of this study, but in my opinion some parts of the discussion section needs to rewritten and the results need to be more nuanced.
1) Both reviewers pointed out that the duration of the simulations (2.5 years) was too short to draw conclusions regarding the hydro-climatic impacts of LULCC, given that hydro-climatic regimes are generally assessed over periods of around 30 years. The authors rightly pointed out that the calculation times are too long to extend the simulation period considerably.
However, I do not agree with the sentence L432-435 (see below) which, in my opinion, minimizes this limit. The authors could also go further in the discussion section by giving some perspective for assessing the impact of climate variability on the simulation results (perhaps like repeating the experiment over another 3 years period with contrasted climatic conditions for initialization and boundary conditions).
The conclusion should also be more nuanced, pointing out that simulations lasting 2.5 years are too short to assess the impact on the hydro-climatic regime, and that further studies will have to be carried out to confirm these results.
L432-435 « While longer simulations could offer understanding under diverse large-scale atmospheric conditions, the length of these high-resolution simulations (determined by the computational capacity) provides valuable insights for assessing the land-atmosphere processes, which occur on daily to monthly time scales. »

We appreciate the reviewer's feedback and understand the concern regarding the duration of the simulations. We also agree that the discussion and conclusion sections should more explicitly address this limitation and suggest further studies for a more comprehensive assessment.

Below, we provide a revised text for lines L436-440 that better reflect these considerations: "Longer simulations could offer a more comprehensive understanding under diverse large-scale atmospheric conditions; in our case, the length of these high-resolution simulations (determined by computational capacity) provides valuable insights into land-atmosphere processes that occur on daily to monthly time scales. The role of background flow on interannual or larger scales is outside the scope of this study."

Also, the need for further experiments in future research is reinforced in the last paragraph (L511-514): "On the other hand, we also acknowledge that longer time scale simulations are needed to assess the impacts of LULCCs under diverse large-scale conditions. Future studies should extend the simulation period or repeat the experiments under different climatic conditions to provide a more nuanced understanding of the long-term impacts of LULCC."

We have made other minor adjustments to the Discussion section to smooth our findings and to put them in the context of our experiments.

2) Regarding the evaluation of the model on a broader set of variables, I do not agree with the sentence L442-445 (see below), as (i) I do not see why satellite products for variables such as LAI or albedo could not be used for model evaluation as they do not really differ from the SMOPS and HSAF products used to evaluate soil moisture in this study, and (ii) models inter-comparisons for the variables that cannot be directly measured could still provide some useful information about the modelling uncertainty of these variables.
The authors should point out in the discussion section that the impacts of LULCC are analyzed on simulated variables that have not all been validated (LAI, albedo, radiation, heat fluxes and runoff) which limits the ability to draw conclusions about the chain of processes affected. Although it was not possible to evaluate the model on a larger set of variables in this study, the authors could mention in the discussion that this will be an important issue to address in future studies in order to assess the uncertainty of the modelling on these variables and increase confidence in the results obtained.
L442-445 « Other variables (radiation, heat fluxes, runoff, etc) could be included in the evaluation. However, their derivation involves algorithms or models with inherent approximations and uncertainties, which cannot be verified by in-situ measurements given the lack of field observations of non-conventional variables in the Gran Chaco region. Thus, the validation of such variables would be reduced to a comparison between tow disparate estimates without the inclusion of ground truth. »

Thank you for your feedback on the evaluation of the model's performance across a broader range of variables. We appreciate your insights and agree with the points you raised (i and ii). We also acknowledge that some of the simulated variables have not been directly validated, which may limit the depth of conclusions drawn about the impacts of LULCC. Our evaluation focuses on the model’s final output products (precipitation and temperature). Evaluating all intermediate variables (like LAI or albedo), would be more adequate for a separate study with a different scope. It's important to note that assessment papers for WRF simulations are abundant in the literature, and such an endeavour may lack novelty. Thus, diverting the focus of our research from its primary objectives would not only be impractical but also may not contribute substantially to the existing body of knowledge. While we recognize the potential value of including additional variables for evaluation, it would significantly alter the scope and focus of our study.

Considering the reviewer’s feedback, we have revised the text to better reflect these considerations (L446-453): "Other variables such as radiation, heat fluxes, runoff, LAI, and albedo could potentially be included in an evaluation, however their derivation involves algorithms or models with inherent approximations and uncertainties, primarily due to the lack of field observations of non-conventional variables in the Gran Chaco region. Consequently, the validation of such variables without the inclusion of ground truth would be reduced to a comparison between two disparate estimates. Given these limitations, and to maintain the scope of the research, we focused on evaluating the model’s final output products, rather than its parameterizations and intermediate components.”

Technical remarks:

1) L74 Rephrasing suggestion to avoid the use of « more realistic scenarios » which is a bit confusing:
« In this way, this study considers both observed and possible future expansions of LULCCs, offering a nuanced understanding of the actual and potential impacts on regional climate. By considering these two scenarios of LULCCs, it is possible to hypothesize how agricultural expansion in one region influences the hydroclimate of another, which is crucial for effective regional land use planning on a topic prone to developing socio-ecological conflicts associated with LULCCs. »

Thanks for the suggestion, we adopted it in L74-L78.

2) L269-270 Please name the months instead of seasons to avoid confusions (e.g. JJA instead of winter)

We have clarified the corresponding months between parentheses. The text in L272-274 now states “The drier conditions arise from underestimated late austral summer and autumn (FMAM) rain, as shown in Figure 5d. Conversely, WRF notably improves the estimation in austral winter (JJA, the dry season) and spring (SON), showing almost the same peaks as observations for all years.”

3) L445 « two » instead of « tow ».

Done.

4) L511 Rephrasing suggestion: « The simulations indicate an average reduction of net surface radiation and surface energy fluxes, which in turn, lead to drier hydrological conditions overall in terms of precipitation and runoff. »

The sentence has been rephrased as suggested by the reviewer. L523-524 of the revised manuscript.

5) L519 Replace « may have not be » with « may not be »

Thanks for noting it. It has been corrected in L531 of the revised manuscript.

6) L525 Remove WFDEI dataset from the list and add url to ERA5 dataset

Done. The ERA5 URL is now included in the Data availability section.

7) L636 Please move the Flanagan et al. 2021 reference higher in the list to maintain alphabetical order.

Thanks for catching that. It is now correctly positioned in the references section.

8) L759 Replace WFDEI with ERA5

Done. The caption of Figure 5 has been fixed.

9) Figure 7: Does Fig7a show the mean between CRU and ERA5?

Exactly. It is now clarified in the caption of Figure 7.

10) Table in Fig7d replace « promedio » with « mean »

Done.

11) Figure 10: Boxplot values for runoff (10d) seem incoherent with text L350 « The reduced precipitation and drier soils end up affecting the total runoff, which presents a net reduction in the Dry Chaco of -2.1 % in local areas and -5.5% in non-local areas (Fig. 10d). ». Please check the consistency between Fig10d and L350.

The mean values indicated in the text appear inconsistent with the boxplot for runoff, as the mean values include outliers, which are common in this region due to small absolute changes in some grid cells producing large percentage differences. In contrast, the boxplot does not include these outliers. We have now removed the outliers from the calculations to maintain consistency and adapted the text accordingly (L353-354): "The reduced precipitation and drier soils end up affecting the total runoff, resulting in a net reduction of about 8% in the Dry Chaco (Fig. 10d)."

12) Figure 13: Same remark as Figure 10. Please check consistency between Fig13d and L386 « runoff is reduced by -5 % on average ».

The text has been updated to state “Similarly, runoff is slightly reduced by -1.2 % on average.” in L389-390, and “The overall drier conditions contribute to a reduction in runoff by about -4.2 % on average.” in L400.

Responses to Referee #2

We thank the anonymous reviewer for their feedback. The new comments (shaded) are responded to below.

Comments:

1) I appreciate the authors' efforts to incorporate the comments and make corresponding modifications. The newly added content and clarifications address most of my concerns and improve the quality of this work. However, some issues need further investigation.

We are pleased to have addressed your comments, which have helped improve our article.

2) Ln 260, the authors should elaborate on how the variation in sensible heat flux influences surface temperature.

As discussed in the first revision, land use and land cover changes modify biophysical properties that are key to the radiation balance, such as albedo, emissivity, and leaf area index. For instance, reduced vegetation cover leads to lower latent heat flux and increased sensible heat flux. This change means that less energy is used for evapotranspiration (latent heat), and more energy is available to heat the surface (sensible heat). A higher surface albedo, resulting from decreased vegetation, reflects more solar radiation, but the net effect is often an increase in net shortwave radiation absorbed by the surface. This extra radiation that is absorbed by the ground leads to an increase in surface temperature. In summary, the increase in sensible heat flux due to reduced vegetation cover and higher albedo results in more heat being retained at the surface, thereby raising the surface temperature. This increase in surface temperature subsequently warms the air close to the ground, leading to higher near-surface temperatures.

The text in the manuscript has been updated (L335-345) to state: "The changes in net radiation alter the main components of the energy balance, i.e., the sensible heat flux and the latent heat flux. The spatial distributions of these fluxes play important roles in determining near-surface temperature, as variations in these fluxes affect the amount of energy used for heating the surface as opposed to being released through evapotranspiration. Figures 9d-e reveal that changes in sensible heat and latent heat have a similar spatial pattern but with opposite signs. As with the radiation terms, the changes are of the order of ±10 W m-2. Furthermore, Fig. 9f shows that the deforested areas in the northern and central eastern zones of Dry Chaco experience warming, while the southern area exhibits cooling. Both of these changes can be attributed to variations in sensible heat flux. On average, the changes in net radiation lead to an average decrease of -3.5 % in sensible heat at the local level and 0.6 % in the remaining Dry Chaco (Fig. 9e). Latent heat exhibits minor or negligible changes over the whole Dry Chaco (Fig. 9d). Despite the presence of locally strong signals (up to ±0,4 °C), the spatially averaged temperature changes present a slight rise due to the compensatory warming and cooling effects."

3) Ln 348, please quantify the changes in MSE or CAPE.

As expressed in the first revision, unfortunately, due to computational constraints, we did not store all WRF output variables for the 12 simulations, including the 3-dimension variables required to estimate CAPE and MSE. Thus, we relied on interpreting changes in energy variables and precipitation, supporting our analysis with the precipitable water field. We recognize that precipitable water does not replace CAPE nor MSE, they both contribute to our understanding of atmospheric conditions. The revised manuscript submitted on 19 February explains our interpretation of the involved processes in L421-430.

4) (a) Ln 385, by comparing the LULCC in Figure 2 f and temperature changes in Figure 9 f, it looks like the warming is the most significant over the northwest where deforestation is not significant. Meanwhile, deforestation is most severe in the central east where warming is not concrete. I would suggest the authors to explain this. (b) Also, the cooling effect is obvious in the south over grids experiencing “others” LULCC. It looks to me that the “others” LULCC matters a lot, and I wonder what kind of LULCC causes the cooling.

Thanks for pointing this out. To address this point, we split the comment into (a) and (b).

(a) We stand by our assertion that deforestation is significant in the northwest and the central east of Dry Chaco. These regions are among the most anthropized areas, with substantial expansion of pastures in the north for cattle ranching and agricultural lands in the central east for cultivation, as evidenced in Fig. 2f and Fig. 8, as well as by other studies such as Maertens et al. (2021) and Mosciaro et al. (2022) (see Fig. R2.1 below).

(b) We agree with the reviewer that LULCCs classified as “others” in the southern area of Dry Chaco produce a local cooling effect, and the affected area is considerable. The main land cover changes in this area involve conversions from open shrublands and grasslands to savannas. Unlike deforested areas, these changes result in an overall increase in the Leaf Area Index (LAI), enhancing transpiration and shading, which lead to cooling.

Based on the previous analysis we rephrased the text (L476-478) as follows: “…Spatially, changes in sensible heat influenced near-surface temperature, leading to warming in deforested areas and cooling in areas affected by other LULCCs. For instance, the conversion from open shrublands and grasslands to savannas resulted in an increased LAI, which enhanced transpiration and shading, thereby producing a cooling effect. …”

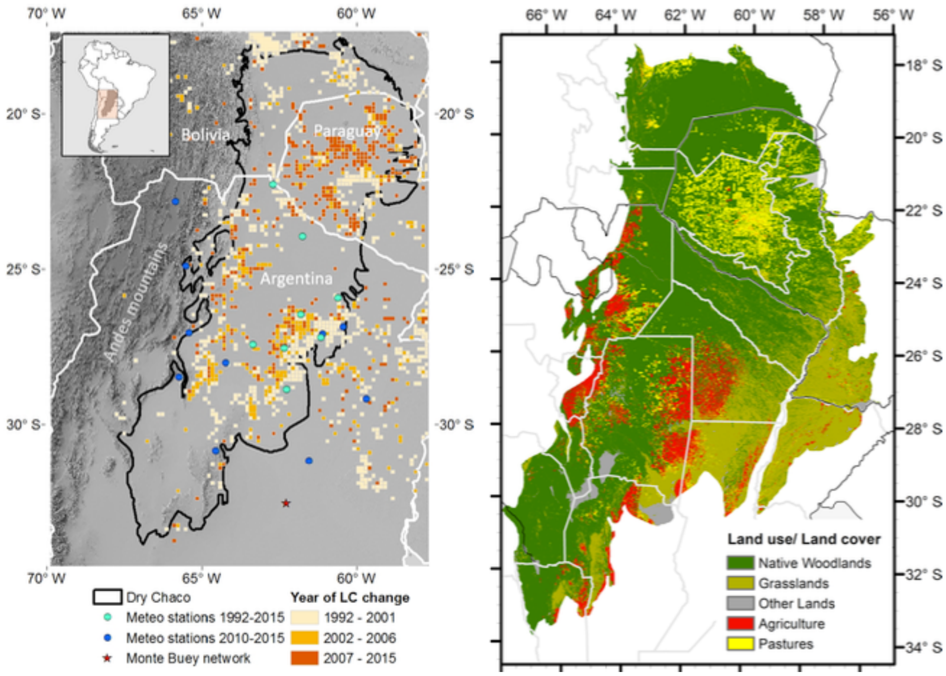

Figure R2.1: Left: Figure 1 of Maertens et al. (2021) showing land cover changes within Dry Chaco. Brown colors highlight deforested areas. Rigth: Figure 2 of Mosciaro et al. (2022) showing land cover changes in the Gran Chaco (Dry and Humid Chaco). Red highlights agriculture expansion, while yellow represent the replacement of native vegetation by pasture mainly for cattle ranging.

Maertens, M., De Lannoy, G. J. M., Apers, S., Kumar, S. V., and Mahanama, S. P. P.: Land surface modeling over the Dry Chaco: the impact of model structures, and soil, vegetation and land cover parameters, Hydrol. Earth Syst. Sci., 25, 4099–4125, doi:10.5194/hess-25-4099-2021, 2021.

Mosciaro, M.J., Calamari, N.C., Peri, P.L., Flores Montes, N., Seghezzo, L., Ortiz, E., Rejalaga, L., Barral, P., Villarino, S., Mastrangelo, M., Volante, J.: Future scenarios of land use change in the Gran Chaco: how far is zero-deforestation?. Reg. Environ. Change., 22, 115, doi:10.1007/s10113-022-01965-5, 2022.

5) Ln 615, in Figure 10 a, the precipitation decreases significantly at the northern boundary where LULCC is neglectable. In other words, the precipitation-decreasing areas do not overlap the deforestation, which does not agree with the conclusion that deforestation causes drying. In Figures 9 and 10, for the box plots showing the local and non-local changes, does the local change area include all types of LULCC (deforestation and others in Figure. 2)?

Indeed, the term "local" in the OBS_LULCC experiment (including Figs. 9 and 10) includes all types of LULLC (deforestation, illogic, and others). As explained in our response to the previous comment we do not consider that LULCCs are insignificant in the north. Just in the adjacent northern area of the north limit of Dry Chaco there is a clear deforestation hotspot (Fig. 2c and Fig. R2.1 left). Additionally, it is important to note that the processes we are examining are complex and nonlinear. The interaction between the land surface and the atmosphere involves feedback mechanisms that are not always localized due to atmospheric circulation, particularly for precipitation, as changes in land cover can influence rainfall patterns through the movement of air masses and changes in horizontal gradients. Our work aims to identify the most relevant mechanisms, although we acknowledge they may not apply uniformly to every individual grid cell.

6) I would suggest the authors elaborate on the reasons for using dynamic vegetation which has significant uncertainties in simulating LAI.

Note that the rationale for enabling vegetation dynamics is already provided in the revised manuscript submitted on 19 February. We have expanded the explanation as follows (L180-186): "Our simulations enable vegetation dynamics, i.e., the model simulates changes in vegetation properties, such as LAI, surface roughness, and other land surface characteristics, as they naturally evolve over the simulated period due to seasonal changes and vegetation growth cycles. These dynamic properties allow the model to capture the seasonality of vegetation and its impact on land-atmosphere interactions. We chose to use dynamic vegetation to reflect the natural variability and feedback mechanisms more accurately between vegetation and climate. Although simulating LAI dynamically involves uncertainties, it provides a more realistic representation of how vegetation responds to and influences climatic conditions than using fixed LAI values."