# Responses to Referee #1

We appreciate the detailed and constructive feedback provided by the anonymous reviewer, which has been valuable in enhancing the manuscript. The reviewer's comments are categorized into main comments and those directly on the manuscript. We respond to both categories. The reviewer comments are shaded and followed by our responses.

## General comment:

This paper investigates the impact of the intensive deforestation in favor of agricultural expansion on the hydro-climatic regime of the South America's Dry Chaco region. The paper addresses some important questions about the feedback of LULCC on the vegetation growth (LAI, albedo, stomatal resistance) and the hydro-climatic response (precipitation, soil moisture and runoff). This study uses WRF modelling to simulate hydro-climatic responses to deforestation scenarios. Analysing the impacts of deforestation in the Dry Chaco on local hydrology and climate, as well as in the neighbouring (which has been little affected by deforestation), is also interesting for understanding the effects at different spatial scales.

As the reviewer positively noted our study explores how the land use and land cover changes in the Dry Chaco alter the land-atmosphere interplay locally, but also investigates what are the non-local and/or remote effects of the agricultural expansion. The analysis is based on regional climate simulations, which consistently simulate the land-atmosphere interactions constraining the balances. This enables the simulation of the hydroclimate response to different lower boundary conditions and the analysis of the involved chain of processes.

I however have a number of comments that need to be addressed – please see below.

## Main comments:

1) (a) The simulations are carried out over a 2-year period (2014-2016 for the reference simulation) which seems very short to analyze the effects of deforestation on the hydro-climatic response.

If possible, I would recommend to validate WRF on the 2014-2016 period (to validate over a period with few changes in land use), and then to simulate the control and scenario simulations over a longer period (30 years or at least >10 years) so that the results are not affected by the inter-annual climate variability.

(a) We agree with the reviewer, longer simulations would allow us to investigate the impact of LULCCs under different large-scale atmospheric conditions (e.g. ENSO phase), providing more robustness to our results. Note that we conducted **a total of 12 simulations, each spanning 2.5 years**. The length of these simulations should suffice for assessing the land-atmosphere processes, which occur on shorter time scales. Conducting simulations spanning 10 years or more would provide information on the large-scale modulations of the surface processes but would not provide new understanding of them. Long-term simulations are impractical for our research due to computational constraints. Each simulation we perform is significantly resource-intensive in terms of computational time and storage, and extending the simulation period to such lengths is currently beyond our capabilities. For this reason, our work focused on the processes themselves while leaving out of the scope their large-scale modulation. It's worth noting that even NCAR, responsible for the WRF model development and a benchmark in our field, was recently able to produce just one 20-year-long simulation for South America (see it on the online model evaluation dashboard). As such, conducting 12 simulations spanning 30 years, as suggested, is not feasible and falls outside our research scope. The length of the simulations and the current computational constraints are now discussed on lines 428-438.

(b) The authors should at least specify whether the 2014-2016 simulation period corresponds to an El Nino or La Nina episode in order to know under which pattern of atmospheric circulation the simulations are being carried out.

The simulation period includes an El Niño event, developed between Sep 2014 and March 2016 according to the Oceanic Niño Index (ONI). However, it is important to note that our region of interest, the Gran Chaco, is not especially sensitive to the effects of El Niño, which have stronger impacts eastward for precipitation and northward for temperature (see the figure R1.1 below). Moreover, Vera and Osman (2018) reported that the impact of the El Niño 2015 event in South America has been weakened by the Southern Annular Mode.

The sensitivity of Gran Chaco to large-scale phenomena is now summarized in lines 94-98, while prevalent atmospheric conditions during the simulation period are now clarified in lines 224-228, providing a clearer context for our results.

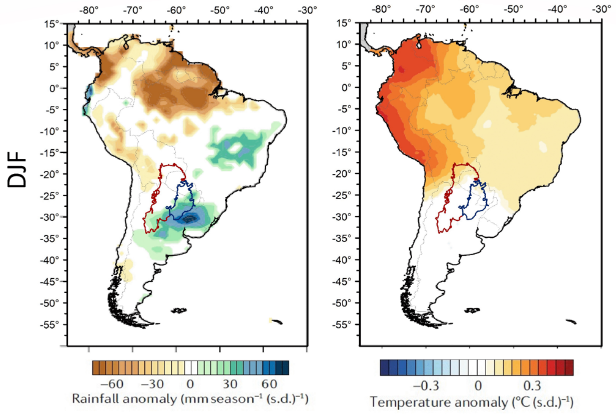


**Figure R1.1. ENSO-related precipitation (left) and temperature (right) anomalies for DJF during El Niño events adapted from Cai et al (2020). Cai et al. (2020) calculated the anomalies by regressing seasonally averaged variables on the normalized DJF Niño3.4 index, using data from the period 1948–2016. The coloured lines highlight the Gran Chaco subregions: Dry Chaco (red) and Humid Chaco (green).**

Cai, W., McPhaden, M.J., Grimm, A.M., Rodrigues, R.R., Taschetto, A.S., Garreaud, R.D., Dewitte, B., Poveda, G., Ham, Y.-G., Santoso, A., Ng, B., Anderson, W., Wang, G., Geng, T., Jo, H.-S., Marengo, J.A., Alves, L.M., Osman, M., Li, S., Karamperidou, C., Takahashi, K., and Vera, C. (2020). Climate impacts of the El Niño–southern oscillation on South America. *Nat. Rev. Earth Environ.*, *1*(4), 215-231.

Vera, C.S., and Osman, M. (2018). Activity of the Southern Annular Mode during 2015–2016 El Niño event and its impact on Southern Hemisphere climate anomalies. *Int. J. of Climatol.*, *38*, e1288-e1295.

2) This paper studies the effects of LULCC by analyzing the changes in various simulated variables (energy budget, precipitation, evapotranspiration, soil moisture, runoff, LAI, albedo, stomatal resistance) to different landuse conditions.

(a) However, the model is only evaluated using observed temperature, precipitation and soil moisture datasets. It is therefore difficult to draw any conclusions about the effects of deforestation on the other unvalidated variables.

(b) In my opinion the modelling experiment is not robust enough to draw general conclusions about the physical processes impacted by deforestation in the Dry Chaco. However, the modelling experiment remains interesting and the authors could instead present their results as a sensitivity analysis of WRF simulations to different initial landuse conditions.

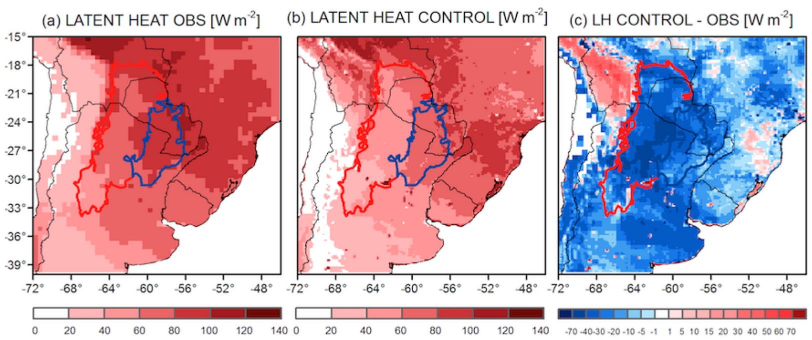
(a) Validation of simulated variables

The choice of temperature, precipitation, and soil moisture, and no other variables for evaluation serves a purpose. Temperature and precipitation observations are truly independent variables as they have relatively low uncertainty given the availability of multiple monitoring sources, both in-situ and remote. Indeed, climate model validation papers are typically based on these two variables (e.g. Smiatek et al. 2009, Sánchez et al. 2015, Marta-Almeida et al. 2016, Annor et al. 2018, Almazroui et al. 2021, Lovino et al. 2021, Ortega et al. 2021, etc.). On the other hand, soil moisture falls on the set of variables with recognized uncertainties due to the lack of in-situ observations and uncertainties in remotely sensed soil moisture estimates. However, we included it in the main manuscript due to its key role in land cover dynamics and land-atmosphere interactions.

Other data products (e.g., radiation, heat fluxes, runoff) may have an observational basis, but they are derived from algorithms or models with their own approximations and uncertainties. A proper validation of these data products is critical if they are to be used for model evaluation. Unfortunately, this is not possible. While some of the datasets are available globally, their quality at regional scales is questionable. The Gran Chaco region, examined in this study, lacks in-situ measurements of non-conventional variables, preventing an assessment of the data quality and making a comprehensive model validation even more unfeasible.

Still, following the reviewer's suggestion, we compared model energy variables against FLUXCOM (Jung et al., 2019), which is the successor dataset to global biosphere-atmosphere flux (GBAF) products that are used as a reference in the International Land Model Benchmarking System (ILAMB; Collier et al., 2018). The FLUXCOM observational estimates have been derived from FLUXNET energy flux measurements and remote sensing as well as meteorological data by training machine-learning algorithms. Figures R1.2 and R1.3 summarise the "validation" for latent heat flux and sensible heat flux. On the positive side, WRF produces similar longitudinal gradients compared to those of FLUXCOM and effectively reproduces the seasonal variability, showing a high correlation ($r = 0.95$) for latent heat, but exhibits less sensitivity to sensible heat, indicating a one-month lag in the seasonal cycle despite a correlation of 0.62. On the other hand, WRF underestimates latent heat $(RMSE = 20.2Wm^{-2})$ and overestimates sensible heat $(RMSE = 12.9Wm^{-2})$ in Gran Chaco. But does this imply that the biases are all in the WRF estimates? Impossible to say. There is only one FLUXNET tower (Ar-SLu) in the entire domain (please see https://fluxnet.org/sites/site-summary/) used to calibrate the machine-learning algorithms. Moreover, the FLUXNET observations are available for the period 2009-2011. In summary, the validation is reduced to a comparison between two disparate estimates without the inclusion of a ground truth.

As a side note, our work builds upon prior research efforts (Lee and Berbery, 2012, Müller et al. 2014, Sörensson and Berbery 2015, Müller et al. 2016) that have consistently demonstrated the effectiveness of the WRF model in simulating different aspects of southern South America hydroclimate. In the revised manuscript, we will clarify the rationale behind our decisions to select variables for validation.



(d) Latent Heat in Gran Chaco

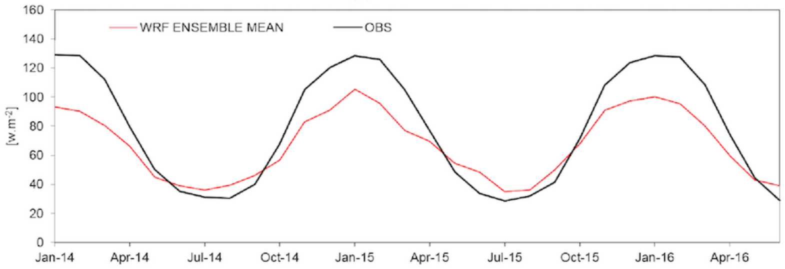
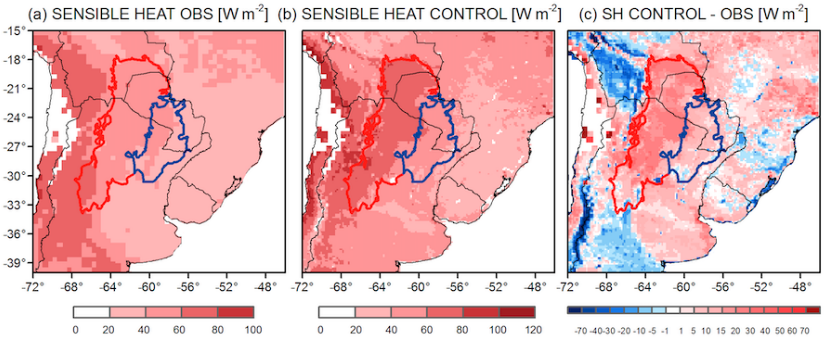


**Figure R1.2: Time average of (a) FLUXCOM latent heat, (b) the CONTROL ensemble latent heat, and (c) their differences. (d) Latent heat time series averaged over the Gran Chaco.**



(a) SENSIBLE HEAT OBS [W m$^{-2}$] (b) SENSIBLE HEAT CONTROL [W m$^{-2}$] (c) SH CONTROL - OBS [W m$^{-2}$]

(d) Sensible Heat in Gran Chaco

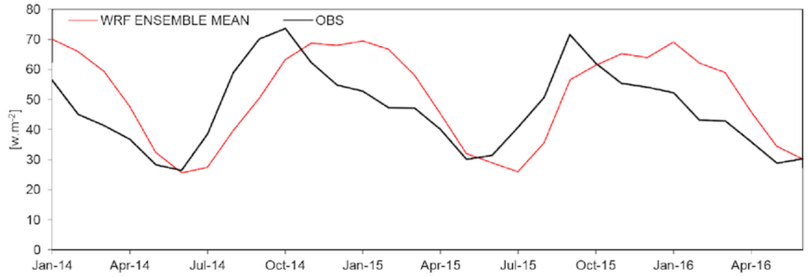


**Figure R1.3: As Figure R1.2 but for sensible heat.**

(b) Modeling experiments and physical processes

Climate models offer distinctive advantages, including the ability to maintain physical consistency within the Earth System, simulate a wide range of processes, and facilitate controlled experiments by modifying initial and boundary conditions. These features make climate models the only tool capable of exploring the intricate chain of processes affected by changes in initial and boundary conditions, an analysis that cannot be replicated using observed data or reanalysis. While we acknowledge the inherent uncertainties associated with models, it's essential to highlight that the WRF model exhibits a high level of skill, particularly in simulating fundamental variables such as precipitation, temperature, and soil moisture. Our extensive and documented experience with the WRF model further strengthens our confidence in its ability to capture underlying processes. Therefore, we assert that our experiments provide a valid and unique approach to analyzing the sensitivity of land-atmosphere physical interactions to different land cover scenarios. Moreover, our response to comment #3 clearly demonstrates the small internal variability of the WRF simulations providing robustness to our experiments.

Considering the previous argument, we have changed the manuscript as follows. The rationale behind the selection of variables to validate is now explained in the section 2.4 Evaluation datasets (lines 230-236). In the section 5 Discussion, we delineate the reasons preventing the validation of non-typical variables (lines 440-445), we expound on the consistency of our results with previous research (lines 450-453), and we delve into the potential and limitations of climate models for understanding processes related to land cover changes (lines 494-502).

Almazroui, M., Ashfaq, M., Islam, M.N., Rashid, I.U., Kamil, S., Abid, M.A., O'Brien, E., Ismail, M., Simões Rivolta, M., Sörensson, A., Arias, P., Muniz Alves, L., Tippett, M., Saeed, S., Haarsma, R., Doblas-Reyes, F., Saeed, F., Kucharski, F., Nadeem, I., Silva-Vidal, Y., Rivera, J., Azhar Ehsan, M., Martinez-Castro, D., Muñoz, A., Arfan Alí, M., Coppola, E., Sylla, M.B. (2021). Assessment of CMIP6 performance and projected temperature and precipitation changes over South America. *Earth Syst. Environ.*, *5*(2), 155-183.

Annor, T., Lamptey, B., Wagner, S., Oguntunde, P., Arnault, J., Heinzeller, D., and Kunstmann, H. (2018). High-resolution long-term WRF climate simulations over Volta Basin. Part 1: validation analysis for temperature and precipitation. *Theor. Appl. Climatol.*, *133*, 829-849.

Jung, M., Koirala, S., Weber, U., Ichii, K., Gans, F., Camps-Valls, G., Papale, D., Schwalm, C., Tramontana, G., and Reichstein, M. (2019): The FLUXCOM ensemble of global land-atmosphere energy fluxes. *Sci. Data*, 6, 74.

Collier, N., Hoffman, F.M., Lawrence, D.M., Keppel-Aleks, G., Koven, C.D., Riley, W.J., Mu, M., and Randerson, J.T. (2018). The International Land Model Benchmarking (ILAMB) System: Design, Theory, and Implementation, *JAMES*, 10, 2731–2754.

Lovino, M.A., Pierrestegui, M.J., Müller, O.V., Berbery, E.H., Müller, G.V., and Pasten, M. (2021). Evaluation of historical CMIP6 model simulations and future projections of temperature and precipitation in Paraguay. *Clim. Change*, *164*, 1-24.

Marta-Almeida, M., Teixeira, J.C., Carvalho, M.J., Melo-Gonçalves, P., and Rocha, A. M. (2016). High resolution WRF climatic simulations for the Iberian Peninsula: Model validation. *Phys. Chem. Earth, Parts A/B/C*, *94*, 94-105.

Lee, S.-J., and Berbery, E.H. (2012). Land cover change effects on the climate of the La Plata Basin, *J. Hydrometeorol., 13*(1), 84-102.

Müller, O.V., Berbery, E.H., Alcaraz Segura, D., and Ek, M.B. (2014). Regional model simulations of the 2008 drought in southern South America using a consistent set of land surface properties, *J. Clim., 27*(17), 6754-6778, 2014.

Müller, O.V., Lovino, M.A., and Berbery, E. H. (2016). Evaluation of WRF model forecasts and their use for hydroclimate monitoring over southern South America. *Weather Forecast., 31*(3), 1001-1017.

Ortega, G., Arias, P.A., Villegas, J.C., Marquet, P.A., and Nobre, P. (2021). Present-day and future climate over central and South America according to CMIP5/CMIP6 models. *Int. J. Climat.*, *41*(15), 6713-6735.

Sánchez, E., Solman, S., Remedio, A.R.C., Berbery, H., Samuelsson, P., Da Rocha, R.P., Mourão, C., Li, L., Samuelsson, P., Da Rocha, R.P., de Castro, M., Jacob, D. (2015). Regional climate modelling in CLARIS-LPB: a concerted approach towards twentyfirst century projections of regional temperature and precipitation over South America. *Clim. Dyn.*, *45*, 2193-2212.

Smiatek, G., Kunstmann, H., Knoche, R., and Marx, A. (2009). Precipitation and temperature statistics in high-resolution regional climate models: Evaluation for the European Alps. *J. Geophys. Res. Atmos.*, *114*(D19).

Sörensson, A.A., and Berbery, E.H. (2015). A note on soil moisture memory and interactions with surface climate for different vegetation types in the La Plata basin. *J. Hydrometeorol., 16*(2), 716-729.

3) The uncertainties related to the model and its internal variability should be discussed. How can model parameterisation and initial conditions impact on the simulated results?

Regarding the uncertainty related to initial conditions, the authors mention in the presentation of the experimental design that each scenario was conducted with an ensemble of 4 members with identical parameterisations but different initial conditions that are 24-hr apart. But the simulations obtained with the 4 members do not appear in the results (only the average). It would be interesting to analyze and show some results about the sensitivity of the simulated variables (e.g. precipitation, soil moisture, runoff) to the different initial conditions.

Regarding the uncertainty related to the model parameterisation, it would be interesting to include simulations to test the sensitivity to few selected model options or parameter, or at least discuss the results referring to studies from the literature that conducted a full internal variability analysis of the WRF model.

Uncertainty related to initial conditions:

The analysis of our WRF/Noah-MP simulations reveal minimal uncertainty associated with variations in initial conditions. In response to the reviewer's suggestion, we updated the figures of the Model Evaluation section, specifically focusing on Fig. 5d, 6g, and 7d, which presented ensemble mean precipitation, soil moisture, and temperature, respectively. To better capture the uncertainty, these panels now include a surrounding band illustrating the spread of ensemble members around the mean. In the updated panels, the time-series demonstrate relevant uncertainty only during the first month of precipitation simulation, after which the dispersion consistently remains in a narrow range. Notably, the model uncertainty is comparable to or even smaller than the observational uncertainty. In particular, the result for soil moisture is consistent with Sörensson and Berbery (2015), who found that the initialisation of WRF/Noah-MP in wet months (e.g. January) favour a quick stabilisation of soil conditions. A discussion of these findings is provided in the corresponding figure descriptions (lines 274-276, lines 291-294, lines 305-307).

Uncertainty related to the model parameterisation:

We have previously conducted extensive discussions about WRF parameterization in our earlier publications. For instance, in Lee (2010) and Lee and Berbery (2012), a comprehensive set of ten WRF simulations combining different surface layer schemes, atmospheric boundary layer schemes, cumulus parameterization schemes, and microphysical schemes, have been conducted to identify the configuration that exhibited the highest skill for southern South America. This optimal configuration was subsequently employed in Müller et al. (2014) to assess droughts and in Müller et al. (2016) to evaluate the model's performance in short-term forecasts. In both cases, the selected parameterisations were well-suited to represent the hydroclimate in South America. In summary, while we acknowledge that different WRF simulations may be sensitive to specific parameterisations, we have demonstrated in our previous experience that this configuration produces realistic simulations for our region of interest. We now describe these antecedents in lines 142-148.

Lee, S.-J. (2010). Impact of land surface vegetation change over the La Plata Basin on the regional climatic environment: A study using conventional land-cover/land-use and newly developed ecosystem functional types. Ph.D. dissertation directed by E. H. Berbery, University of Maryland, 153 pp.

Lee, S.-J., and Berbery, E.H. (2012). Land cover change effects on the climate of the La Plata Basin, J. Hydrometeorol., 13 (1), 84-102.

Müller, O.V., Berbery, E.H., Alcaraz Segura, D., and Ek, M.B. (2014): Regional model simulations of the 2008 drought in southern South America using a consistent set of land surface properties, *J. Clim.*, 27(17), 6754-6778.

Müller, O.V., Lovino, M.A., and Berbery, E.H. (2016): Evaluation of WRF model forecasts and their use for hydroclimate monitoring over southern South America, *Weather Forecast.*, 31(3), 1001-1017.

4) The paper would benefit from a more detailed literature review and a proper discussion section to discuss the above points. The results of the first part concerning the observed changes in the Dry Chaco between 2001 and 2015 and future trends of deforestation should also be discussed and compared with other studies from the literature.

Thank you for your valuable feedback. To address the referee's specific concern, we have enhanced the literature review in the introduction by incorporating relevant and more recent publications. On the other hand, papers of lesser relevance have been removed. This revision improves the context and provides an expanded overview of the relevant research.

Additionally, we have divided the original “Discussion and Conclusions” section into two separate sections: “Discussions” and “Concluding Remarks.” The “Discussion” section has been expanded to provide a comprehensive analysis of our research findings within the broader context of climate models and their capabilities. In this revised section, we also discuss about model validation and model internal variability and compare our results with findings from other studies when relevant, adding depth and perspective to our research outcomes.

**In-manuscript reviewer comments:**

1) Introduction section: The reviewer suggests adding more recent references and removing a few non-relevant papers.

Our response to this comment is provided in the response to the main comment 4.

2) Figure 2d: It is difficult to find the numbers on Fig 2d. Can you make Fig 2d easier to read? Perhaps use the names of the LULC classes instead of the numbers. You could also perhaps use the same classes than in Fig 2.b with the same color code.

We appreciate the reviewer's suggestion. To enhance the interpretation of Fig. 2d, we now utilize the same colour code for land cover classes in the panel's headings as in Fig. 2b. Additionally, we have adjusted the format of cell numbers to [1000 $km^2$] rounded up to one decimal, for example, expressing 155376 as 155.4. This change allows for an increased font size and improved legibility.

3) L134: Add reference to the WRF model.

The following reference have been added (line 140):

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Wang, W., and Powers, J.G. (2008). A description of the Advanced Research WRF version 3. Technical report, NCAR., http://dx.doi.org/10.5065/D68S4MVH.

4) L151: The results don't show the 4 members of the ensemble (e.g. Fig.5, 6, 7). Can you explain the method: do you use the average of the 4 members? Can you discuss (or even show on a figure) the differences between the results obtained with the 4 members in order to show the uncertainty linked to the initial condition?

Figures 5, 6, and 7 show the ensemble mean. That is now clarified in the corresponding captions. As stated in our response to main comment 3, the internal model variability (as explained by the spread of the ensemble members) is now shown and discussed in the revised manuscript.

5) L154-L161: What is the time horizon (of the FUTURE ensemble)? Could you give more details about your method to compute the future expansion? What trend did you use (% of agricultural expansion per year)? Can you discuss here (or in the discussion section) if your future projection of agricultural expansion consistent with other studies that simulated future scenarios of landuse change in the Dry Chaco, such as:

Mosciaro, M.J., Calamari, N.C., Peri, P.L. et al. Future scenarios of land use change in the Gran Chaco: how far is zero-deforestation?. Reg Environ Change 22, 115 (2022). https://doi.org/10.1007/s10113-022-01965-5

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, https://doi.org/10.5194/hess-25-4099-2021, 2021.

Thanks for bringing these publications to our attention. We employed a method known as 'dilation' to compute the expansion imposed in the FUTURE ensemble, as indicated in the original manuscript. We have now expanded the technical explanation and put the proposed scenario in the context of the scenarios proposed by Mosciaro et al. 2022. The text in lines 197-209 states:

"… The FUTURE ensemble assumes an intensive agricultural expansion within Dry Chaco (Fig. 4b), mimicking what could be expected in the future if current expansion trends are to continue in a global-low scenario. This scenario considers a strong global market opening with low state regulation of LUCC, where the conditions favour great agricultural expansion (Mosciaro et al. 2022).

The corresponding FUTURE land cover map is a modified version of the 2015 land cover map in which all crop/grassland areas are expanded through a dilation process (Gonzalez and Woods, 1993). Dilation is a morphological method commonly used in digital image processing to expand target areas by adding surrounding pixels to boundaries and filling gaps. In this study, dilation is first applied to the crop category by adding ten lines, and subsequently, dilation is applied to grassland pixels by the addition of five lines. In the resulting land cover map, croplands cover 29.4% while grasslands cover 19.1% of the Dry Chaco area, meaning that the areas occupied by crops and pastures have been expanded by 5 and 2.5 times, respectively. Based on the rate of change of the global-low scenario proposed by Mosciaro et al. (2022), which is ~7800 $km^2 yr^{-1}$, the time horizon of our FUTURE scenario is 2065."

6) I suggest a change in the paper structure: (a) change the "2.4 Model evaluation" subsection into a section "3. Model evaluation" because it contains results and therefore does not form part of the method section. And move "2.4.1 Evaluation datasets" to 2.4. (b) A proper section for discussion should be included here. (this reviewer's comment referred to the original section "4 Discussion and conclusions").

Following the reviewer's suggestion, the structure will change as follows:

| Original structure | New structure |
|---|---|
| 1 Introduction | 1 Introduction |
| 2 Data, model, and experiments | 2 Data, model, and experiments |
| 2.1 Study region | 2.1 Study region |
| 2.1.1 Geographical features | 2.1.1 Geographical features |
| 2.1.2 Land cover and its evolution in DC | 2.1.2 Land cover and its evolution in DC |
| 2.2 The WRF model and its configuration | 2.2 The WRF model and its configuration |
| 2.3 Experimental design | 2.3 Experimental design |
| 2.4 Model evaluation | 2.4 Evaluation datasets |
| 2.4.1 Evaluation datasets | 3 Model evaluation |
| 2.4.2 Precipitation | 3.1 Precipitation |
| 2.4.3 Soil Moisture | 3.2 Soil Moisture |
| 2.4.4 Temperature | 3.3 Temperature |
| 3 Experiments' results | 4 Experiments' results |
| 3.1 Scenario OBS_LULCC: Actual LULC … | 4.1 Scenario OBS_LULCC: Actual LULC … |
| 3.1.1 Effects on the energy budget | 4.1.1 Effects on the energy budget |
| 3.1.2 Effects on the water budget | 4.1.2 Effects on the hydrological response |
| 3.2 Scenario AG_INT: Intensive … | 4.2 Scenario AG_INT: Intensive expansion … |
| 3.1.1 Effects on the energy budget | 4.2.1 Effects on the energy budget |
| 3.1.2 Effects on the water budget | 4.2.2 Effects on the hydrological response |
| 3.3 Process-based analysis | 4.3 Process-based analysis |
| 4 Discussion and conclusions | 5 Discussion |
|  | 6 Concluding remarks |

7) How do you explain this spatial heterogeneity?

The corresponding text has been rephrased as follows (lines 285-289):
"The simulated root-zone soil moisture also presents a notable overall resemblance to the HSAF satellite estimates, with slight dry biases towards east (Fig. 6d-e). Focusing on the Gran Chaco, the area-averaged WRF soil moisture presents a similar evolution to HSAF but with a systematic negative bias (Fig. 6g). This bias is explained by the differences in Humid Chaco, where RMSE reaches 0.091 $m^3m^{-3}$, likely in response to the underestimated precipitation (Fig. 5d). Instead, the Dry Chaco presents a strong spatial agreement with HSAF (RMSE=0.035 $m^3m^{-3}$)."

8) LAI, albedo, runoff, stomatal resistance and energy budget are not validated for the CONTROL simulation. Can you explain why? Since there are some observed datasets (e.g. MODIS) for these variables, could you extend the validation of the CONTROL simulation to other variables?

Our response to this comment is provided in the response to the main comment 2a.

9) Section "Experiments' results" A general comment for this section is that it is difficult for the reader to assess the significance of the changes on the energy budget and hydrological response compared to the model's internal variability.

As explained in our response to the main comment 3, the model internal variability is now discussed in the new version of the manuscript. In summary, given the negligible internal variability of the WRF model, the differences between ensembles, either small or large, are directly attributable to the LULCCs imposed with the different land cover maps. Moreover, following your suggestion in comment #12, we incorporated boxplots to illustrate the distribution of the changes. This addition provides a clearer idea of the extent to which LULCCs alter the various hydrometerological variables at the local, non-local, and remote levels.

10) Change “Effects on the water budget” to "Effects on the hydrological response". The effects are only studied during the DJF period and the term "water cycle" is misleading and suggests that these results show changes on the hydrological regime (i.e. all year hydrology). Also, even though it is mentioned line 236 that the analysis is conducted during the DJF period, it could be helpful to remind it later on, particularly in the titles of the figures.

We agree with the reviewer, “Effects on the hydrological response” is more adequate given that we just evaluate the changes in austral summer. The caption of the corresponding figures explicitly states that the differences correspond to the summer season (DJF).

11) Please explain what these uncertainties are and what are the model limitations in the discussion section.

As stated in our response to the main comments 3 and 4, the model limitations and uncertainties are now discussed in the “Discussion” section. In particular, the revised the manuscript includes an analysis of the uncertainty related to the internal variability of WRF for the region of interest, while the uncertainty related to the model parameterization is supported by previous publications.

12) Figures 9, 10, 12, 13: Instead of the average over the pixel grids, could you show 2 box plots (one for local and one for Non-local grid cells) to show the difference between the 2 distributions of grid cells? (same comment for next figures).

We thank the reviewer for this valuable idea. The arrows in the insets have been replaced by boxplots in the new Figures 9, 10, 12, and 13, giving more information about the effects of the LULCCs on the different hydroclimatic variables.

13) Figure 10 is averaged per month whereas Fig5 are averaged per day. It would help to show results with the same time aggregation in order to better assess the significance of these changes.

Figure 5 is now shown in $[mm\ month^{-1}]$ consistently with the units used in Figure 10.

## Responses to Referee #2

We appreciate the detailed and constructive feedback provided by the anonymous reviewer, which has been valuable in enhancing the manuscript. The reviewer's comments are categorized into main comments and those directly on the manuscript. We respond to both categories, with reviewer comments in shaded text and our responses in black.

### General comment:

This manuscript conducts a set of WRF-Noah simulations to examine the impacts of historical land use and land cover change (LULCC) and potential agriculture expansion in the future. By comparing historical, control, and future cases, this work illustrates the drying climatology and land conditions (e.g., warming surface temperature and decreased precipitation and soil moisture). However, several problems and limitations exist; thus, a major point-to-point revision is needed. For example, at least several months of spin-up are needed to initialize the soil moisture and allow the surface fluxes to respond to LULCCs; however, the manuscript doesn't mention if the authors spin up the WRF-Noah before the formal runs. Also, the authors haven't confirmed if WRF-Noah can simulate the specific mechanisms discussed. For example, the authors should confirm if WRF-Noah can resolve the remote effects of LULCC.

We acknowledge the reviewer's comment. First, we should clarify that our experiments do have an 11-month spin-up period that was dismissed from the analysis, ensuring the stabilization of all variables. Our simulations span from Jan 2014 to July 2016, with a specific focus on the austral summer season (DJF), encompassing the 2014/2015 and 2015/2016 summers. The validation of the CONTROL ensemble involves a comparison of simulated and observed variables for the entire period, including the spin-up months. The updated version of this section's plots will incorporate the ensemble member dispersion. This addition provides a clear illustration of how our model simulations rapidly stabilize their values within the first month of simulation, which is noticeable for soil variables that traditionally take longer to reach equilibrium. Further details on this aspect can be found in our response to comment 3 of Data, model, and experiments.

Unlike typical land surface or hydrologic models, climate models do simulate non-local effects of LULCC. Land surface models (LSMs), in our case Noah-MP, solve equations in isolated columns. However, they play a crucial role by providing the boundary conditions in all time-steps to the atmospheric component of the climate model, where the grid volumes are completely connected. Thus, LULCCs have a direct and immediate local impact on the soil, modifying the surface fluxes, which in turn, can alter the local and non-local atmospheric variables, influenced by the atmospheric dynamics.

In summary, climate models stand as the ideal and singular tool capable of unravelling the intricate chain of processes affected by changes in initial and boundary conditions, an analysis that cannot be replicated using observed data or reanalysis.

This is explained in more detail in our response to comment 7 of “Data, model, and experiments”.

**Comments about Introduction:**

1) The introduction lacks enough paper review. For example, Georgescu et al. (2013) also use WRF to simulate the LULCC over South America.

In response to the referee's concern, we have strengthened the literature review in the introduction by integrating pertinent and up-to-date publications, while irrelevant papers have been excluded. This revision enhances the context and offers a more thorough overview of the pertinent research.

2) The impacts of LULCCs have been widely studied in WRF. For example, Lee et al. (2012) had a similar experiment design, study region, and results. Therefore, the authors should emphasize their novelty and new insights compared with previous studies.

We appreciate the reviewer's observation and acknowledge the antecedent work of Lee and Berbery (2012). Indeed, our work advances on those results, now providing new insights into a specific ecoregion. It's essential to highlight the distinctiveness and advancements offered by the current study in comparison. Specifically:

<u>Study Region and temporal scope</u>: Our focus extends beyond the La Plata Basin to the Gran Chaco, which is recognized as one of the most threatened ecoregions in South America concerning agricultural expansion rates. Moreover, our study spans a comprehensive 30-month period (2014-2016), providing a more extensive analysis of the impacts of land use and land cover changes (LULCCs) over time compared to the 3-month simulations in 2002 by Lee and Berbery (2012).

<u>Experiment Design</u>: While Lee and Berbery (2012) considered extreme LULCCs (all natural vegetation, all crops), our study considers both observed and realistic expansions of LULCCs, offering a nuanced understanding of the actual and potential impacts on regional climate.

<u>Novel Insights</u>: By considering more realistic scenarios, 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. This focus on uncovering the processes behind such remote effects is a relatively unexplored aspect in existing literature, making our study particularly novel and relevant.

In summary, our study offers valuable insights into the hydroclimate patterns arising from LULCCs, providing a clearer perspective on the potential outcomes of agricultural expansion in Dry Chaco over the entire Gran Chaco. We believe these distinctions underscore the significance and originality of our work in advancing the current understanding of regional climate dynamics impacted by land use changes. The key aspects discussed here are now part of the revised introduction (see lines 55-78).

3) Because the results are all derived from WRF-Noah, the author should introduce how WRF-Noah simulates land-use changes and discuss its limitations. For example, which processes can be resolved, and which cannot.

The Noah-MP LSM assigns a dominant land cover type to each grid point, and this assignment remains constant over time (Li et al., 2013). In turn, each land cover is associated with a set of 15 biophysical properties. The properties can either be values fixed on time or can vary seasonally or dynamically when vegetation dynamics is activated. Our simulations enable vegetation dynamics, i.e., the model simulates changes in vegetation properties, such as leaf area index ($LAI$), 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. By default, the model employs the land cover map derived from the Moderate Resolution Imaging Spectroradiometer (MODIS), which classifies the land cover following the 20 categories proposed by the International Geosphere-Biosphere Programme (IGBP). **Then, the land cover changes in our experiments are implicitly imposed by the change of land cover map among the various ensembles**. It is worth noting that other studies for different regions of the world have applied a similar approach with WRF to assess the impact of LULCCs on the overlying atmosphere (e.g. Lal et al. 2021, Flanagan et al. 2021).

Noah-MP comprises four soil layers with a thickness from top to bottom of 10, 30, 60 and 100 cm (2 m total depth), and includes representations of the root zone, vegetation categories, monthly vegetation fraction, soil texture, among others. It simulates soil moisture, soil temperature, skin temperature, canopy water content, and the energy flux and water flux terms of the surface energy balance and surface water balance. Different options of schemes for various physical processes that are key in the soil-atmosphere interaction, are available in Noah-MP. These processes include dynamic vegetation; canopy interception; soil moisture factor controlling stomatal resistance, *b* Factor; runoff and groundwater; surface exchange coefficient for heat; and radiation transfer. The vegetation and soil components are closely coupled and interact with each other via complex energy, water, and biochemical processes. The recent publication of He et al. (2023) describes in detail the above processes, including equations and schematic diagrams.

To enhance clarity, we now (a) introduce how climate models deal with LULCCs in the introduction (lines 58-66), (b) provide a concise overview of the WRF/Noah-MP representation of land cover, simulated processes, and associated limitations in the revised section “2.2 The WRF model and its configuration”, and (c) discuss the potentials and uncertainties of climate models to fully represent physical processes related to deforestation in the Discussion section (lines 494-502). The description of observed and imposed LULCCs is already detailed in the experiments’ description.

Flanagan, P.X., Mahmood, R., Sohl, T., Svoboda, M., Wardlow, B., Hayes, M., and Rappin, E. (2021). Simulated Atmospheric Response to Four Projected Land-Use Land-Cover Change Scenarios for 2050 in the North-Central United States. *Earth Interact.*, *25*(1), 177-194.

Lal, P., Shekhar, A., and Kumar, A. (2021). Quantifying temperature and precipitation change caused by land cover change: a case study of India using the WRF model. *Front. Environ. Sci.*, *9*, 766328.

Li, D., Bou-Zeid, E., Barlage, M., Chen, F., and Smith, J. A. (2013). Development and evaluation of a mosaic approach in the WRF-Noah framework. *J. Geophys. Res. Atmos.*, 118(21):11–918.

He, C., Valayamkunnath, P., Barlage, M., Chen, F., Gochis, D., Cabell, R., Schneider, T., Rasmussen, R., Niu, G.-Y., Yang, Z.-L., Niyogi, D., and Ek, M. (2023).nd surface model (version 5.0) with enhanced modularity, interoperability, and applicability. *Geosci. Model Dev.*, 16(17), 5131-5151.

**Comments about Data, model, and experiments:**

1) Ln 130, the authors should explain why this change is unreasonable instead of simply providing two references without elaboration.

The identification of a change as being unreasonable or illogical derives from Cai et al. (2014)'s study. In that article, a land cover transition is defined as illogical if it contradicts ecological rules and is therefore unlikely to be observed. For example, if you have bare soil, you would not expect to have a full-grown tree the following year. But sometimes satellite data can present artifacts like this, and in that case the changes are identified as unreasonable.

In our case, the statement about the changes from savanna and woody savanna to deciduous broadleaf forests in a short period (14 years) being unthinkable in the real world is based on ecological understanding. Savanna and woody savanna ecosystems typically undergo gradual transitions over extended time frames due to ecological processes. The rapid and natural conversion to deciduous broadleaf forests contradicts established ecological dynamics and is likely an artifact of the computation algorithms of land cover maps. Following the cited references (Liang and Gong, 2010; Cai et al., 2014) support our scepticism about the observed changes. Moreover, Cai et al. (2014) identify Gran Chaco as a region with a high frequency of illogic transitions. To provide a more detailed explanation, we further elaborated on the ecological implausibility of such rapid transformations (lines 132-136).

Cai, S., Liu, D., Sulla-Menashe, D., and Friedl, M.A. (2014). Enhancing MODIS land cover product with a spatial–temporal modeling algorithm, *Remote Sens. Environ.*, 147, 243-255.

Liang L, and Gong, P.: An assessment of MODIS Collection 5 global land cover product for biological conservation studies (2010). In: 2010 18th international conference on geoinformatics, Beijing, China, 18–20 June 2010, pp 1–6.

2) Ln 133, for a 1-year WRF simulation or longer simulations, nudging is often needed to constrain the simulation; however, the authors didn't discuss their choice of nudging.

A lateral boundary relaxation zone spanning ten grid-points was implemented, and spectral nudging within the domain was intentionally omitted to allow the atmosphere more freedom in responding to surface forcing (Pohl and Crétat, 2014). We recognize the significance of nudging in studies aiming to mitigate regional model drifts from the spatial scales of the forcing global reanalysis, thereby enhancing downscaled climate outcomes and constraining internal variability within the regional model (e.g., Miguez-Macho et al. 2005; Radu et al., 2008; Alexandru et al. 2009). In our case, nudging was not used, with the purpose of allowing the free evolution of variables, as impacted by surface processes. This is now clarified in lines 140-142. Despite the absence of nudging in our simulations, it is noteworthy that minimal internal variability is observed in the simulated variables, as demonstrated in the updated Figs. 5d, 6g, 7d, which now include a surrounding band illustrating the spread of ensemble members around the mean.

Alexandru, A., de Elía, R. Laprise, R. Separovic, L. and Biner, S. (2009). Sensitivity study of regional climate model simulations to large-scale nudging parameters. *Mon. Wea. Rev.*, 137, 1666– 1686.

Pohl, B., and Crétat, J. (2014). On the use of nudging techniques for regional climate modeling: Application for tropical convection. *Climate Dyn.*, 43, 1693–1714.

Miguez-Macho, G., Stenchikov, G.L. and Robock, A. (2005). Regional climate simulations over North America: Interaction of local processes with improved large-scale flow. *J. Climate*, 18, 1227–1246

Radu, R., Déqué, M. and Somot, S. (2008). Spectral nudging in a spectral regional climate model. *Tellus*, 60A, 898–910.

3) Ln 133, to initialize the land processes, at least six months of spin-up is needed, and the soil system usually takes longer (Jerez et al. 2019). It seems the authors did not use any spin-up periods.

Regarding the initialization of land processes, we appreciate the reviewer's concern. As clarified in our response to the general comment, a spin-up period of 11 months was employed for the evaluation of summer seasons, ensuring the attainment of equilibrium for soil variables. The validation of the CONTROL ensemble encompasses the entire simulation period, including the spin-up months. The updated Figures 5d, 6g, and 7d illustrate that simulated variables quickly stabilize within the first month of simulation, a noteworthy observation, especially for soil variables that conventionally require more time to reach equilibrium. The rapid stabilization of soil moisture can be attributed to our simulations starting during the wet season, where differences between the initial soil moisture state and the equilibrium state are minimal. A comparable approach was undertaken in a prior study (Sörensson and Berbery, 2015), specifically examining soil moisture stabilization by initializing simulations in all months of the year. The spin-up period is now clarified in lines 219-224, while the stabilization time of soil moisture is discussed in lines 291-294.

Sörensson, A.A., and Berbery, E.H. (2015). A note on soil moisture memory and interactions with surface climate for different vegetation types in the La Plata basin. *J. Hydrometeorol.*, 16(2), 716-729.

4) Ln 150, the simulation period (less than two years) is not long enough to sample the impacts of modes of variability such as MJO, thus preventing this work from getting more robust conclusions.

Note that the simulation period is 30 months long (2.5 years). This should suffice for assessing the land-atmosphere processes, which occur on shorter time scales. Conducting simulations spanning 10 years or more would provide information on large-scale modulations but would not provide new understanding of the surface processes. On the other hand, it is important to note that the Gran Chaco region, our focus of interest, exhibits minimal sensitivity to large-scale phenomena such as the Madden Julian Oscillation (MJO) and the El Niño Southern Oscillation (ENSO). Grimm (2019) demonstrates that the various MJO modes strengthen precipitation anomalies in central east and southeast South America summers, while non-significant small anomalies are found in our region of interest. Regarding ENSO, the simulation period includes an El Niño event, developed between Sep 2014 and March 2016. However, Cai et al. (2020) shows the insensitivity of Gran Chaco to ENSO phases. Moreover, Vera and Osman (2018) reported that the impact of the El Niño 2015 event has been weakened by the Southern Annular Mode (SAM).

The sensitivity of Gran Chaco to large-scale phenomena is now summarized in lines 94-98, while prevalent atmospheric conditions during the simulation period are now clarified in lines 224-228, providing a clearer context for our results.

Cai, W., McPhaden, M.J., Grimm, A.M., Rodrigues, R.R., Taschetto, A.S., Garreaud, R.D., Dewitte, B., Poveda, G., Ham, Y.-G., Santoso, A., Ng, B., Anderson, W., Wang, G., Geng, T., Jo, H.-S., Marengo, J.A., Alves, L.M., Osman, M., Li, S., Karamperidou, C., Takahashi, K., and Vera, C. (2020). Climate impacts of the El Niño–southern oscillation on South America. *Nat. Rev. Earth Environ.*, *1*(4), 215-231.

Grimm, A.M. (2019). Madden–Julian Oscillation impacts on South American summer monsoon season: precipitation anomalies, extreme events, teleconnections, and role in the MJO cycle. *Clim. Dyn.*, 53(1-2), 907-932.

Vera, C.S., and Osman, M. (2018). Activity of the Southern Annular Mode during 2015–2016 El Niño event and its impact on Southern Hemisphere climate anomalies. *Int. J. of Climatol.*, *38*, e1288-e1295.

5) Ln 171, more widely used datasets such as ERA5 (precipitation, temperature, and soil moisture) and GLDAS (soil moisture) are worth using in evaluation.

We appreciate the reviewer's suggestion. For atmospheric variables (precipitation and temperature), we have chosen gridded observation datasets such as CPC and CRU, widely utilized in the literature. In response to the recommendation, we replaced WFDEI with ERA5 in the updated plots, as ERA5 is a more widely recognized reanalysis dataset. ERA5 is presented in lines 242-244 for precipitation and lines 255-256 for temperature and used in Figures 5 and 7.

Regarding soil moisture, GLDAS ingests various observational data sources into land surface models to generate its datasets, with most products focusing on meteorological fields. Notably, it lacks an assimilation of soil moisture data. Thus, the comparison between soil moisture from WRF/Noah-MP simulations and GLDAS remains limited to a comparison of two models. For this reason and considering the lack of in-situ soil moisture measurements in Gran Chaco, we consider that the use of satellite-based products, like SMOPS and HSAF, is more adequate for validation purposes.

**Comments about Experiments' results:**

We provide a specific response to each comment in this section. We would like to note that:

a) in sections 4.1 and 4.2, we focus on the description of the experiments' results, while plausible interpretation of the processes behind the changes is offered in the sections 4.3 Process-based analysis and 5 Discussion;

b) it is always a challenge to elucidate the processes that explain a specific change in a given variable due to the several factors acting together, as shown in the Fig. R2.1;

c) thus, our goal is to identify the most relevant mechanisms that explain the effects of LULCCs in Gran Chaco hydroclimate, while acknowledging that other processes may also have certain impact on our results.

Item (a) is now explained in lines 314-316, while items (b) and (c) are explained in lines 402-406. Anyway, further details of the related processes is now given throughout the entire section.

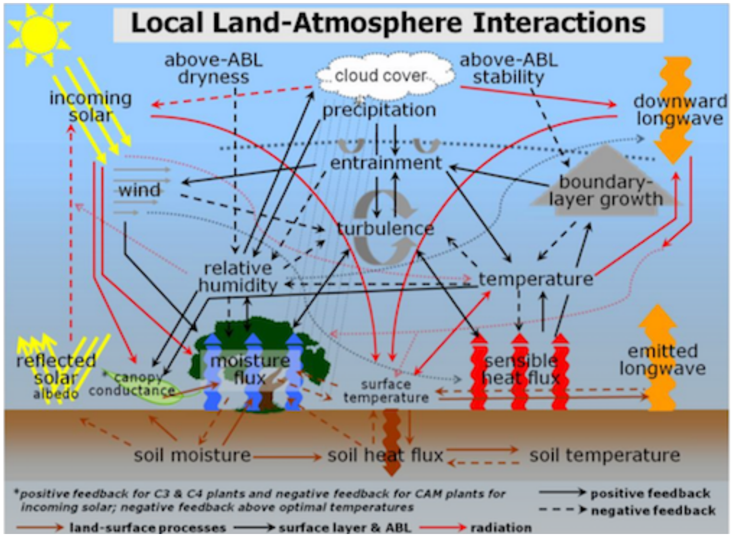


**Figure R2.1. Schematic diagram of land-atmosphere interactions (from Santanello et al. 2018).**

Santanello, J.A., Dirmeyer, P.A., Ferguson, C.R., Findell, K.L., Tawfik, A.B., Berg, A., Ek, M., Gentine, P., Guillod, B., van Heerwaarden, C., Roundy, J., and Wulfmeyer, V. (2018). Land–atmosphere interactions: The LoCo perspective. *BAMS*, 99(6), 1253-1272.

1) Ln 246, how does WRF-Noah adjust LAI and stomatal resistance responding to LULCCs?

The adjustment in LAI, stomatal resistance, and other biophysical properties, in response to land use and land cover changes (LULCCs) is governed by the association of each land cover type with specific biophysical properties in WRF/Noah-MP. Changing the land cover map implies a modification of these associated properties. Further clarification on how Noah-MP handles land cover information is now provided in the revised section 2.2 The WRF model and its configuration, as mentioned in our response to the main comment #3 of the Introduction.

2) Ln 260, it’s true that the warming in the north and cooling in the south accord with the radiation changes. However, further explanations and evidence are needed to illustrate how regional LULCCs impact radiation changes, thus altering the temperature fields.

LULCCs modify biophysical properties that are key for the radiation balance like albedo, emissivity, or leaf area index. For instance, reduced vegetation cover leads to lower latent heat flux and increased sensible heat flux. This, coupled with higher surface albedo, intensifies net shortwave radiation warming the surface, and this warmth is transferred to the adjacent air through sensible heat exchange. We elaborate on these dynamics in the section 4.3 Process-based analysis (lines 408-426) to better explain the relationship between land use changes, radiation and energy balance, and soil-atmospheric warming.

3) Ln 267 and Ln 308, what processes and mechanisms determine the decreased precipitation to LULCCs?

The processes governing decreased precipitation due to LULCCs, detailed in the section 4.3 Process-based analysis (lines 417-426), highlight the impact of agriculture intensification in the Dry Chaco. The resulting reduced LAI increases surface temperature, diminishing vegetation sheltering and enhancing outgoing longwave radiation. Simultaneously, the increased albedo reduces net shortwave radiation. These changes contribute to a reduction in net surface radiation and energy, which implies less energetic conditions in the boundary layer. This, in turn, impacts the dynamics of the planetary boundary layer, diminishing the generation of convective precipitation. This precipitation reduction contributes to declining soil moisture, creating a feedback loop as dry soil absorbs significantly less solar radiation than moist soil.

4) Ln 270 and Ln 274, the author should elaborate on the explicit processes governing the decreases in runoff and soil moisture in WRF-Noah.

Following the previous explanation, the overall reduction of precipitation is the main driver for the decreases in runoff and soil moisture. The soil moisture variations in Noah-MP are estimated with a surface water balance fed by precipitation. Thus, the reduced precipitation has a direct and immediate impact on soils, reducing their water content. The runoff in Noah-MP is constituted by surface and groundwater runoff. Surface runoff is mainly saturation-excess, while groundwater runoff mainly depends on the depth of the water table. Thus, drier soils disfavour the runoff generation in both forms. Different is the analysis for evapotranspiration, given that the removal of vegetation exposes the soil directly to sunlight, increasing the direct evaporation from bare soil. However, transpiration from plants counterbalances the changes, as it is reduced due to the lack of vegetation cover. The Noah-MP hydrology that support our interpretation is now explained in the revised section 2.2 The WRF model and its configuration.

5) Ln 294 and Ln 334, I wonder if the WRF-Noah can simulate the diminished shading associated with decreased LAI. If so, corresponding equations or mechanisms need to be provided.

Effectively, Noah-MP addresses the diminished shading associated with decreased LAI through a "semitile" subgrid scheme representing vegetation (see Fig. 1 of Niu et al. 2011 attached below). The model employs a modified two-stream radiation transfer scheme considering canopy gaps to compute fractions of sunlit and shaded leaves and their absorbed solar radiation. Additionally, it incorporates a Ball-Berry type stomatal resistance scheme relating stomatal resistance to photosynthesis of sunlit and shaded leaves, along with a short-term dynamic vegetation model.

Noah-MP's thermodynamics manages the surface energy balance by separating the canopy layer from the ground surface using the semitile subgrid scheme. Within this scheme, shortwave radiation transfer considers gap probabilities across the entire grid cell, avoiding the overlap of shadows. Longwave radiation, latent heat, sensible heat, and ground heat fluxes are independently calculated over two tiles: a fractional vegetated area ($Fveg$) and a fractional bare ground area ($1 - Fveg$), where $Fveg = 1 - e^{-0.52LAI}$.

The key flux equations for net longwave radiation ($La$), latent heat ($LE$), sensible heat ($H$), and ground heat ($G$) fluxes over a model grid cell are as follows:

$$La = (1 - Fveg)Lag,b + Fveg(Lav + Lag,v)$$
$$LE = (1 - Fveg)LEg,b + Fveg(LEv + LEg,v)$$
$$H = (1 - Fveg)Hg,b + Fveg(Hv + Hg,v)$$
$$G = (1 - Fveg)Gg,b + Fveg(Gv + Gg,v)$$

Finally, the surface energy balance equation over a grid cell is:

$Sav + Sag = La + LE + H + G.$

The Noah-MP thermodynamics is now summarized in the revised section 2.2 The WRF model and its configuration. For additional details, please refer to Niu et al. (2011), sections 3.1 and 3.5.

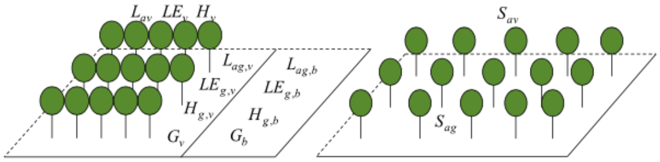


**Figure 1.** Schematic diagram for the "semitile" subgrid scheme. (left) Net longwave ($L_a$), latent heat ($LE$), sensible heat ($H$), and ground heat ($G$) fluxes are computed separately for bare soil (subscript "b") and vegetated (subscript "v") tiles following the "tile" approach, while (right) short-wave radiation fluxes ($S_{av}$ and $S_{ag}$) are computed over the entire grid cell considering gap probabilities.

Niu, G.Y., Yang, Z.L., Mitchell, K. E., Chen, F., Ek, M.B., Barlage, M., Kumar, A., Manning, K., Niyogi, D., Rosero, E., Tewari, M., and Xia, Y. (2011). The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. *J. Geophys. Res. Atmos.*, 116(D12).

6) Ln 297, considering the regional average signals are limited, how could you conclude that the temperature change extremes (0.6 degreeC here) is not a result of model uncertainties?

Temperature changes of 0.6 °C in magnitude are only observed at grid cell level, where the radiation and energy budget components present large differences (>10%). Additionally, the analysis of the model dispersion among members indicates negligible internal variability. These points support our assertion that the magnitude of warming or cooling is a consequence of the the observed land cover changes.

7) Ln 301 and Ln 315, the land grids in WRF-Noah are isolated and thus cannot impact surrounding grids. Explicit mechanisms are needed to confirm that WRF- Noah can resolve the remote effects of LULCC.

**Uncoupled** land surface models (LSMs) operate on isolated grid cells and **cannot directly alter surrounding grids**. However, when a LSM is **coupled** to a climate model, as in our case with WRF/Noah-MP, they **inevitably impact surrounding grids** since (a) grid volumes in the atmosphere are fully connected, and (b) the land interacts with the atmosphere in each time-step. This interaction involves setting the forcings for each other.

As a proof of concept, consider two adjacent grid points where all surface parameters are the same. Then, you modify the parameters for one of the grid points. As a result, you would have a change in surface fluxes and other variables at one point but not at the other. A change in the surface fluxes implies a change in the surface temperature, evapotranspiration, and atmospheric variables. The resulting horizontal gradients give rise to advective processes, effectively facilitating nonlocal effects of the LULCCs. In other words, LULCCs exert a direct and immediate local impact on the soil, modifying the surface fluxes, which, in turn, alter the local and non-local atmospheric conditions, influenced by atmospheric dynamics such as moisture and heat transport. Therefore, we emphasize that climate models uniquely serve as the ideal tool to unravel the intricate chain of processes affected by changes in initial and boundary conditions. This analytical capability cannot be replicated using observed data or reanalysis.

The interaction between WRF and Noah-MP is now explained in lines 184-188. The advantages of using climate models for this kind of studies is now highlighted in lines 494-503.

8) Ln 341, MSE is not only determined by local processes but also by large-scale circulations; thus, the changes in MSE cannot be solely explained by LULCCs.

We acknowledge the reviewer's point that MSE is influenced by both local and large-scale circulations. The proposed experiments exclusively modify the land cover map while maintaining the same lateral boundary conditions, meaning that the large-scale circulation remains unchanged among simulations. Consequently, any observed changes in variables can be solely attributed to the proposed LULCCs.

9) Ln 348, changes in CAPE should be illustrated in your simulations to draw the conclusion here.

We appreciate the reviewer's feedback. Unfortunately, due to computational constraints, we did not store all WRF output variables for the 12 simulations, including the 3d variables required to estimate CAPE. We hope that the alternative offered here will be of the reviewer's satisfaction. We relied on interpreting changes in energy variables and precipitation, supporting our analysis with the precipitable water field (see Fig. R2.2). While we recognize that precipitable water does not replace CAPE, they both contribute to our understanding of atmospheric conditions. The reduced precipitable water in the FUTURE experiment would suggest less moisture available for convection to develop. In the revised version (lines 417-426), the processes are explained in terms of precipitable water instead of CAPE.

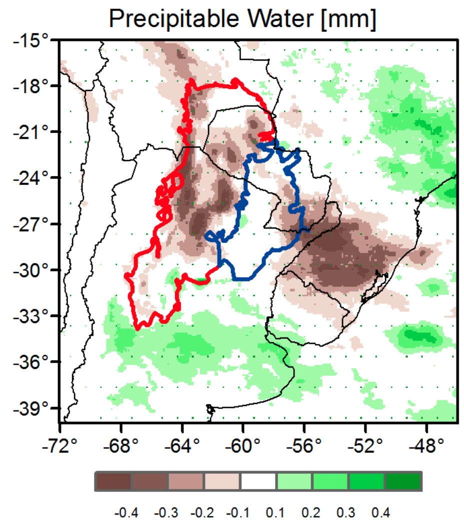


**Figure R2.2. Differences in the summer precipitable water in the AG_INT scenario (FUTURE-CONTROL).**

10) The main text or the supplement should provide mechanisms in WRF-Noah governing the processes in the land-atmosphere feedback pathway illustrated in Fig. 14. For example, temperature changes seem to result from changes in radiation budget instead of the driver of radiation changes.

As explained along all the previous responses, the revised manuscript incorporates additional details elucidating the mechanisms governing the series of processes depicted in the land-atmosphere feedback pathway illustrated in Fig. 14. We appreciate the comment on temperature clarity, acknowledging that the variable refers to surface temperature, which determines the outgoing terrestrial radiation term in the radiation balance. The increased surface temperature is transferred to the adjacent air through sensible heat exchange. Representing this intricate interaction in a schematic diagram poses a challenge, but the purpose of our plot is to synthesize the dominant process pathways (as explained in lines 402-406).

Lastly, note that due to the HESS journal's guidelines, supplementary material cannot be used to provide additional scientific interpretations or findings beyond the manuscript's contents (see section Supplements in https://www.hydrology-and-earth-system-sciences.net/submission.html). Thus, in the revised manuscript, we have endeavoured to enhance clarity without excessively extending the length of the paper.

**Comments about Discussion and conclusions:**

1) Corresponding content should be modified and adjusted based on the comments above.

In the revised manuscript, we have restructured the initial “Discussion and Conclusions” section in two distinct sections: “5 Discussions” and “6 Concluding Remarks.” Section 5 is now more extensive, offering a thorough discussion that addresses the reviewer's raised concerns comprehensively. We specifically explore the strengths and limitations of climate models, delve into topics such as model validation and internal variability, and draw comparisons between our results and relevant findings from other studies. This enriches our research outcomes with added depth and perspective.

2) Some conclusions should be examined (e.g., the remote effect and the mechanisms of decreasing precipitation). The author needs to address whether WRF-Noah can resolve these processes.

In our responses to comments about "Experiments’ results," we provide an expanded explanation addressing all the reviewer's concerns about the processes triggered by LULCCs in Gran Chaco and the capability of WRF/Noah-MP as a tool to uncover such processes. The concluding remarks in the revised version succinctly summarize the main findings resulting from the in-depth analysis of the experiments’ results and their discussion.

**Technical Comments:**

1. The color bars in Fig. 5 to Fig. 12 should be adjusted for more scales. For example, only seven color scales in Fig. 6 make it hard to distinguish the changes. In Fig. 12, lots of areas are saturated.

Thank you for your feedback. We have reviewed the colour scales in all figures, including adding more scales to enhance clarity and address saturation issues.