Editor

The authors are grateful to the editor, Mana Gharun, for her constructive comments.

Both reviewers raise important technical concerns. Particularly in terms of the parametrisation, calibration, and the validation of the model. The current responses are not convincing as referring to similar studies that have also used the model (runs under different settings) will not justify the modelling performance for this paper. The text also needs to reflect the objectives, and novelty better. Starting already with the abstract, it reads as if the authors will consider building structure parameters and based on this the motivation is phrased. However, we read later that this is not the case. The title also needs to be revised as it reflects too many topics. Please streamline it. Please also include keywords. Regarding the model performance please only refer to your own model runs (to justify the performance of the model). If you have mention you will add new results and discussion to address this, then we can evaluate how you have addressed this after seeing your full response. Regarding the motivation of the study, please make sure the motivation is clarified.

RESPONSE:

We have extensively revised the manuscript to address the reviewers' comments. We now show a comparison of soil moisture simulations with in situ observations in southwestern France during the extreme drought of 2022, using our own model runs. The Title, the Abstract and the Introduction were shortened.

The new title is: “Analysis of past and future droughts causing clay shrinkage in France”.

The new abstract is:

“Clay shrinkage-induced subsidence can cause permanent damage to buildings if the drying extends below the foundations. Clay soils and damage are widespread in France. The causes of clay shrinkage are understood at the micro scale, but the same reasoning cannot be applied at the large spatial scales that are critical for land management because the phenomenon depends on very local parameters. In this study, clay shrinkage occurrence factors are characterized and the global number of insurance claims is statistically quantified, without considering the risk of damage for each house. A drought index specifically designed for clay shrinkage is used to analyze past and future soil moisture droughts that may cause subsidence by calculating annual drought magnitudes for France. The index is based on Interactions between Soil, Biosphere, and Atmosphere (ISBA) land surface model simulations. It is calculated for several vegetation types. A comparison of the annual values of this index with the number of insurance claims for subsidence shows that the presence of trees near individual houses must be taken into account. Historical and projected simulations are performed with the main difference being the meteorological forcing provided to ISBA. The historical simulation covers the years 2000-2022 and uses the SAFRAN atmospheric reanalysis. The projected simulation covers the years 2006-2065 and uses an ensemble of climate models under Representative Concentration Pathway (RCP) 4.5 and 8.5. The historical simulation shows particularly widespread droughts in France in 2003, 2018, 2019, 2020, and 2022. In 2022, particularly high drought index values are observed throughout the country. Projections show that drought conditions are expected to worsen in the future, especially under RCP 8.5 compared to RCP 4.5. The projections diverge significantly after 2046, and both the north and south of the country are equally affected."

Keywords: clay-shrinkage, drought, climate projections

Clarification of motivation:

In response to a comment from Reviewer 1, we added the following at the end of the Introduction section: "The objective of this work is to improve the characterization of clay shrinkage occurrence factors and to statistically quantify the global number of insurance claims. The aim is not to determine the risk of damage for each house. A retrospective analysis of droughts in France since 2000 is presented. An insight into the climate warming induced trends of the YDMI is also given."

Reviewer 1

The authors thank the reviewer for their constructive comments.

We have the following answers to the reviewer's comments:

Page 1 – The causes of clay swelling/shrinkage are well established at the micro-scale and mineralogical scale. Actually defining causes at large spatial scales would not be possible since the phenomenon is impacted by very local parameters.

RESPONSE: Yes, we agree. We suggest rephrasing the original sentence as follows: **"The causes of clay shrinkage are understood at the micro scale, but the same reasoning cannot be applied at the large spatial scales that are critical for land management because the phenomenon depends on very local parameters."**

Page 3 – Damage models should also incorporate parameters related to the building structure. Mainly light-weighted constructions may be damaged by soil movements. This aspect is not taken into account while it is of major impact.

RESPONSE: Yes, we agree that the building structure is crucial for understanding clay shrinkage induced subsidence. However, this information is not widely available for France. We acknowledge that this is a limitation of the present work. This sentence was replaced by "**Clay shrinkage is well understood but depends on very local context parameter values that remains poorly understood at large spatial scales due to the building structure, the complex soil moisture dynamics and the heterogeneity of clayey soils**". We added these two sentences to Section 4.4: **"The YDMI is only a proxy for soil moisture conditions and does not integrate soil susceptibility to shrinkage and swelling or building characteristics. Therefore, the relationship between YDMI and damage is not straightforward."** We also added the following at the end of the Introduction section: "**The objective of this work is to improve the characterization of clay shrinkage occurrence factors and to statistically quantify the global number of insurance claims. The aim is not to determine the risk of damage for each house. A retrospective analysis of droughts in France since 2000 is presented. An insight into the climate warming induced trends of the YDMI is also given.**"

Page 4 – Soil shrinkage and swelling are mainly governed by flow in the unsaturated soils. Are the unsaturated soil parameters somehow considered?

RESPONSE: We added the following details to section 2.1.: **"To account for surface conditions, ISBA is based on the Richards equation (Richards, 1931) for modeling water transfer in unsaturated soils. Application of this equation requires knowledge of the matric potential. This variable can be derived from soil moisture through the Soil Water Characteristic Curve (SWCC), for which several equations exist in the literature. In particular, the Campbell (1974) equation used in ISBA requires knowledge of the soil moisture at saturation and the matric potential at saturation. These two properties are derived from the soil texture based on Clapp and Hornberger (1978). Therefore, ISBA simulates water flow in unsaturated soils, but requires values of the parameters at saturation."**

Page 6 – This choice is not clear to the reviewer! What could be the impact of choosing a different soil layer?

RESPONSE: Although clay shrinkage and swelling is a relatively superficial phenomenon, it is important to focus on the deepest layer (80-100 cm) because it provides the best explanation for long-term trends, due to filtering by the superficial layers. This is consistent with the slow kinetics of the phenomenon as previously explained in Barthelemy et al. (2024). To illustrate the effect of layer depth in modeling soil moisture variations, we show below the time series corresponding to different layers for a single grid point (situated at lon=43.567, lat=1.397) close to the city of Toulouse, with a deciduous broadleaf vegetation for the year 2022.

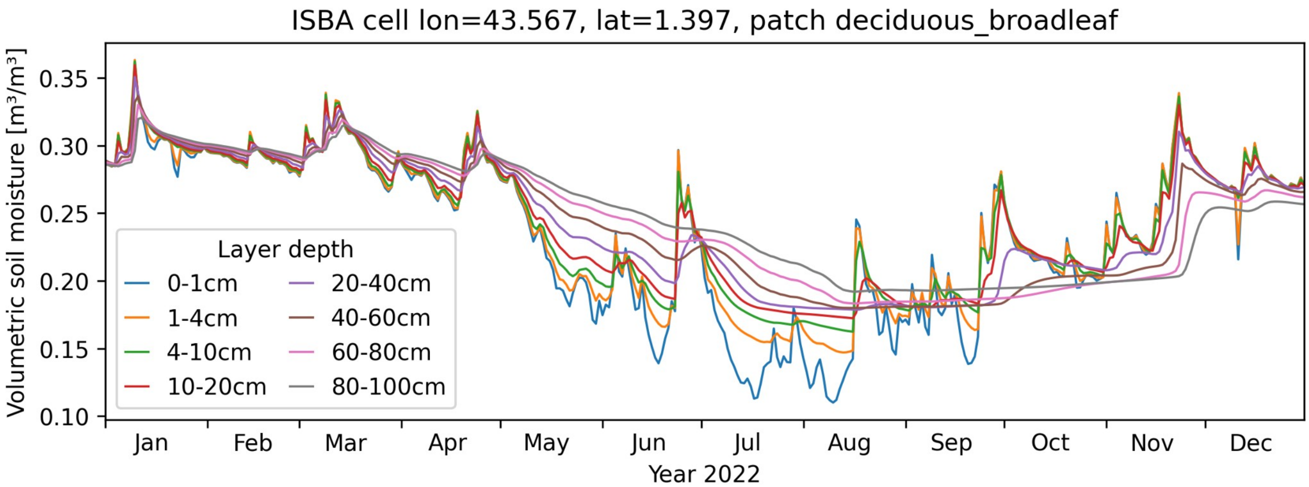

Figure 1: Variations of the volumetric soil moisture over time at the ISBA grid cell located at lon=43.567, lat=1.397, for year 2022, and a broadleaf tree vegetation type. The colors indicate different soil depths, from the soil surface to 1 m.

Figure 1 shows that the closer the layer is to the surface, the more frequently its water content fluctuates. Soil moisture begins to stabilize and shows more inertia below 20 cm. The most superficial layers dampen the fluctuations, and the time lag is explained by the slowness of the water transfer process. Choosing a more superficial layer would result in quantifying instead the short-term variations, that are not relevant to clay shrinkage and swelling. We added this explanation in Section 2.2, to the commented paragraph: "**In fact, deep soil moisture is less affected by the rapid succession of rainfall and drought experienced by surface soil moisture. The slower changes in deep soil moisture values are more consistent with the slow kinetics of clay shrinkage.** "

Page 10 – The level of damage highly depends also on the building structure (weight, stiffness, foundations...).

RESPONSE: We agree with this comment. We added the following statement to the commented sentence: **"The presence of clay mineral is necessary and the level of damage is also highly dependent on the structure of the building (weight, stiffness, foundations)."**

Page 11 (Section 4.2) – Couldn't this be checked by comparing the data?

RESPONSE: As a reminder, the projected YDMIs appear to be more pessimistic at the median and more optimistic at the extremes than the historical YDMIs. We stated in the paper that a divergence in climate forcing could explain this discrepancy. As suggested by the reviewer, we compared the precipitation and temperature fields of the SAFRAN reanalysis and the DRIAS-2020 climate models over their common period (2006-2022) to see if this could explain this discrepancy.

Figure 2 below summarizes the differences in daily temperature and precipitation between SAFRAN and DRIAS-2020 simulations over the common period 2006-2022. The details for each model are also given below – they will be added to the supplementary material of the paper.

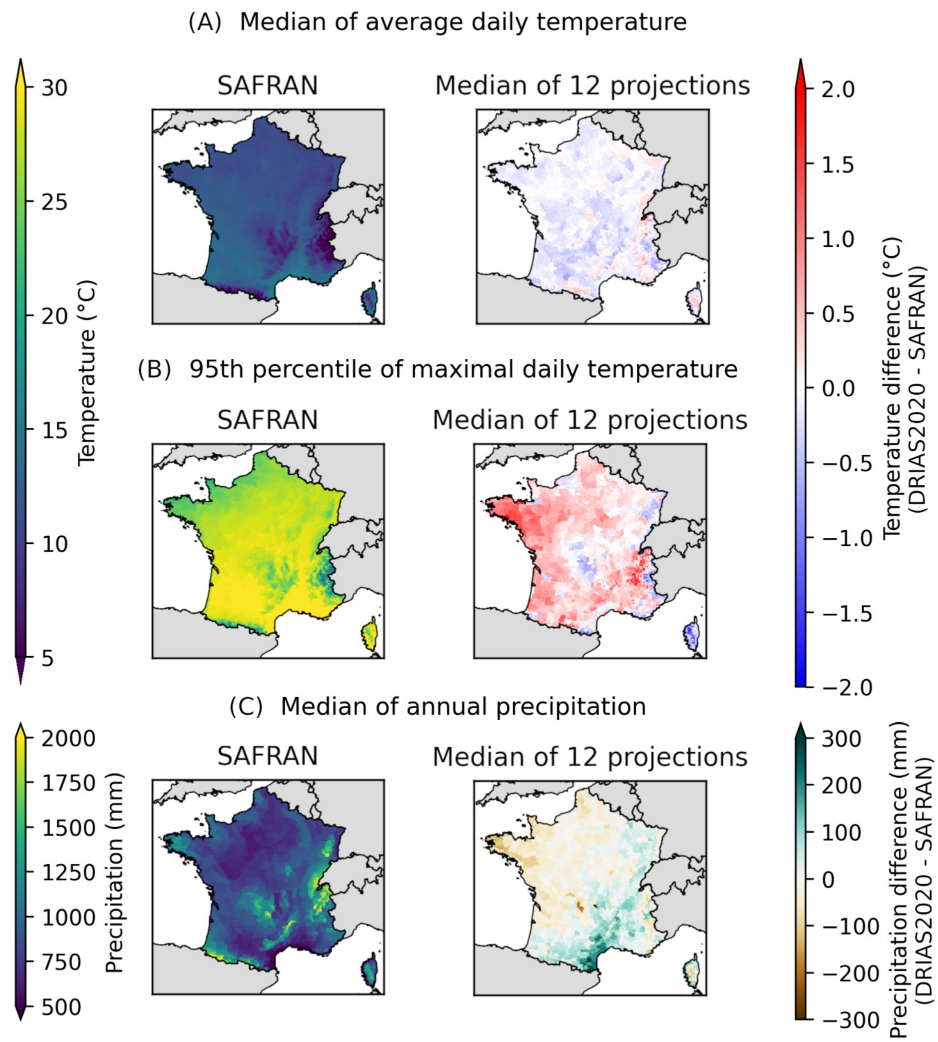

Figure 2: Climate forcing of SAFRAN (left) and projected minus historical differences over their common period 2006-2022 (right). The median of the 12 projected simulations is used. (A) Median of average daily temperature, (B) 95th percentile of maximum daily temperature and (C) median of annual precipitation.

Figures 3 and 4 shows that DRIAS simulations tend to underestimate by less than 1°C the median daily mean temperatures, and overestimate by more than 1°C the higher daily maximum temperatures, respectively. The majority of models agree on these two points. The analysis of precipitation in Figure 5 shows that annual precipitation is underestimated in the northwest and overestimated in the southeast of France. Interestingly, all models are affected by this bias.
In view of this result, differences in climate forcing could indeed contribute to the explanation of the discrepancy between historical and projected YDMI. We added the following to Section 4.2:
"**A comparison of the precipitation and temperature fields of the SAFRAN reanalysis and the climate projections over their common period (2006-2022) is presented in the Supplement (Fig. S5-S7). The climate projections tend to underestimate the median daily mean temperatures by less than 1°C and to overestimate the higher daily maximum temperatures by more than 1°C. The majority of models are in agreement on these two points. The analysis of precipitation in Fig. S5 shows that annual precipitation is underestimated in the north-west and overestimated in the south-east of France. Interestingly, all models are affected by this bias. This shows that differences in climate forcing could indeed contribute to the explanation of the discrepancy between historical and projected YDMI**"

Differences for each model:

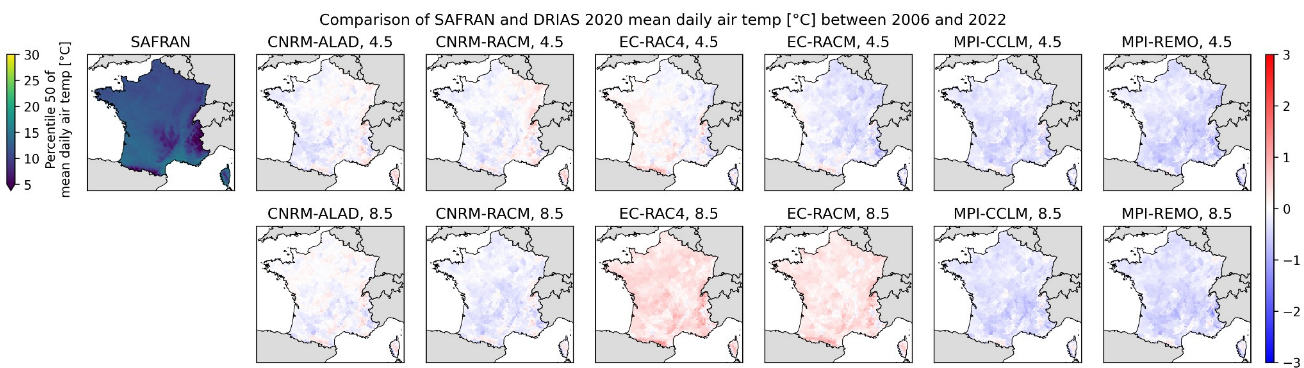

Figure 3: Comparison of the median of the average daily air temperature of SAFRAN and of the 12 projected simulations over their common period 2006-2022.

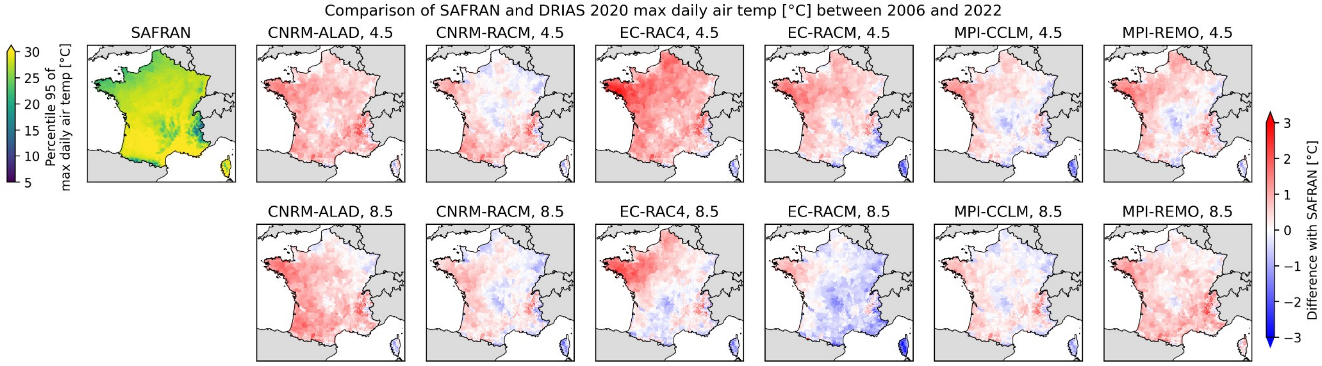

Figure 4: Comparison of the 95th percentile of the maximum daily air temperature of SAFRAN and of the 12 projected simulations over their common period 2006-2022.

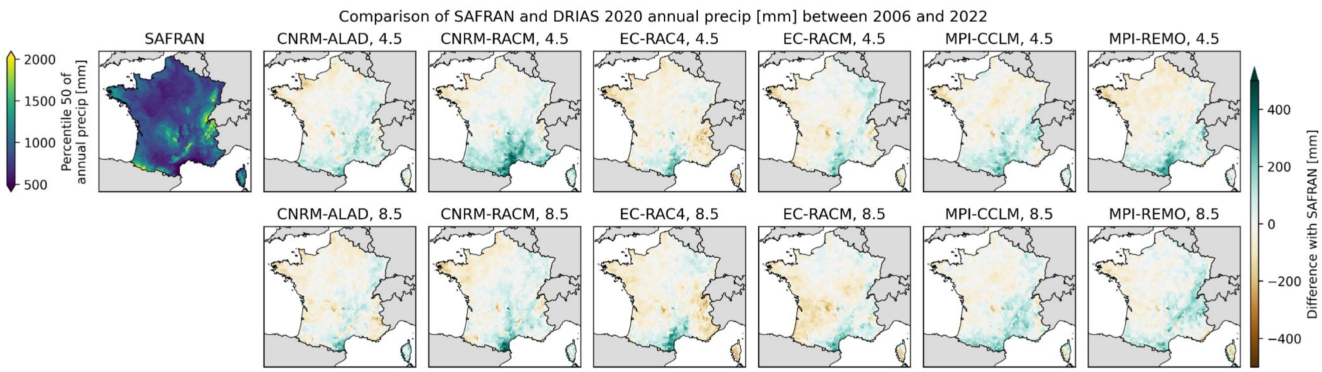

Figure 5: Comparison of the median annual precipitation of SAFRAN and of the 12 projected simulations over their common period 2006-2022.

Page 11 – The RCPs are intended to indicate a kind of warming levels, so this comment is not clear to the reviewer.

RESPONSE: In order to clarify this, we replaced, in Section 4.3.1,
“The climate modeling framework adopted here involves feeding the same CO_2 evolution into a set of models and assessing their response over time. However, it is not stated that all models warm at the same rate. Other approaches exist that take this element into account. For instance, Samaniego et al. (2018) analyze drought as a function of warming instead of time. This choice enhances model consistency and reduces uncertainty.”
by
“The climate modeling framework adopted here involves feeding the same CO_2 trajectory into a set of models and assessing their response over time. RCPs consist of projections of greenhouse gas concentrations, whose increase causes the atmosphere to warm. However, models can warm at different rates depending on the modeling choices, resulting in different temperature increases for the same time horizon. For this reason, one might suggest characterizing the conditions that trigger clay shrinkage as a function of warming rather than time. This is the approach developed by Samaniego et al. (2018).”

Page 14 – The link is missing?

RESPONSE: We apologize, the link was forgotten. The data is available at:
https://figshare.com/s/61c73ec14ed0b876641e
This is a private link that is only valid for the review process. Once the paper is accepted, it will be replaced by a DOI.

References

Barthelemy, S. *et al.* (2024) 'A new approach for drought index adjustment to clay-shrinkage-induced subsidence over France: advantages of the interactive leaf area index', *Nat. Hazards Earth Syst. Sci.* [Preprint]. Available at: https://doi.org/10.5194/nhess-24-999-2024.

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Reviewer 2

The authors thank the reviewer for their valuable comments.

The manuscript analyzed droughts which may lead to clay shrinkage using a statistical method based on ISBA model and predicted future droughts according to some GCMs. This work has some significance in helping people cope with drought, but overall, it lacks innovation, and its conclusions lack strong evidence.

RESPONSE: We acknowledge that numerous papers have focused on the topic of drought and its effects. However, this study is innovative in that the assessment and comparison of historical and projected triggering conditions for clay shrinkage at a national scale has never been done before. In particular, it contributes to filling the knowledge gap on the impacts of climate change on society, which is crucial for adaptation.
We added the following sentence in the Conclusion section: "**For the first time, historical and projected triggering conditions for clay shrinkage are assessed and compared on a national scale for France using a specially developed drought index (YDMI).** ".
Also, we replaced "Unexpected differences" by "Differences".

We give the following answers to the reviewer's specific comments:

1- The introduction is overly verbose, and the main theme is unclear.

RESPONSE: We agree that the Introduction section is too long. To clarify the article's point, we shortened the introduction by deleting the first two paragraphs.

2- Has the model ISBA been calibrated ? If so, please provide details on the calibration process and the calibration results.

RESPONSE: Thanks for this comment. We propose adding this paragraph at the end of Section 2.1:
"The ISBA model does not require calibration. Instead, its concept is to adjust the values of the parameters used in the different modeling steps based on the literature. As an example, the different values of the parameters used to model photosynthesis are detailed in Table 2 of Delire et al. (2020). ISBA has been compared with other land surface models as part of the International Land Model Benchmarking (ILAMB) system (Collier *et al.*, 2018). Some results, available in Appendix B3 of Friedlingstein *et al.* (2022), indicate that the performance of ISBA is reasonable compared to other models. In particular, a higher skill is found for modeling vegetation leaf area index (LAI), which is crucial for estimating soil moisture. Peano et al. (2021) also show that ISBA is able to achieve good skill in representing plant phenology compared to other LSMs."

3- Line 150. Why choose these GCM-RCM combinations? Judging from the results, there are significant differences between these models.

RESPONSE: Thanks for this comment. As explained in the paper, the 12 couples for the DRIAS experiment were initially selected from the EURO-CORDEX ensemble (Jacob et al., 2014, 2020) based on eight criteria, including availability, realism over Europe, and dispersion (Robin et al., 2023). We added this paragraph to Section 2.2:

"The six GCM-RCM couples used in this study are a subset of the 12 couples that make up the DRIAS-2020 dataset, which is based on CMIP5 simulations (https://www.drias-climat.fr). Our motivation for further reducing the ensemble size to 6 couples is related to limited computational resources. The choice is based on the dispersion of precipitation and temperature changes during the summer season (Fig. S8, Fig. S9). The summer season is of particular importance for the phenomenon under study.."

The following was added to the Supplement:

The dispersion of temperature and precipitation changes for the DRIAS-2020 ensemble for the summer season are shown below, for RCP 4.5 and 8.5. These are available at https://www.drias-climat.fr/document/20200914_DRIAS-ScenarioRCP4.5_support_selection_modeles_v3.pdf and https://www.drias-climat.fr/document/20201214_DRIAS-ScenarioRCP8.5_support_selection_modeles_v3.pdf

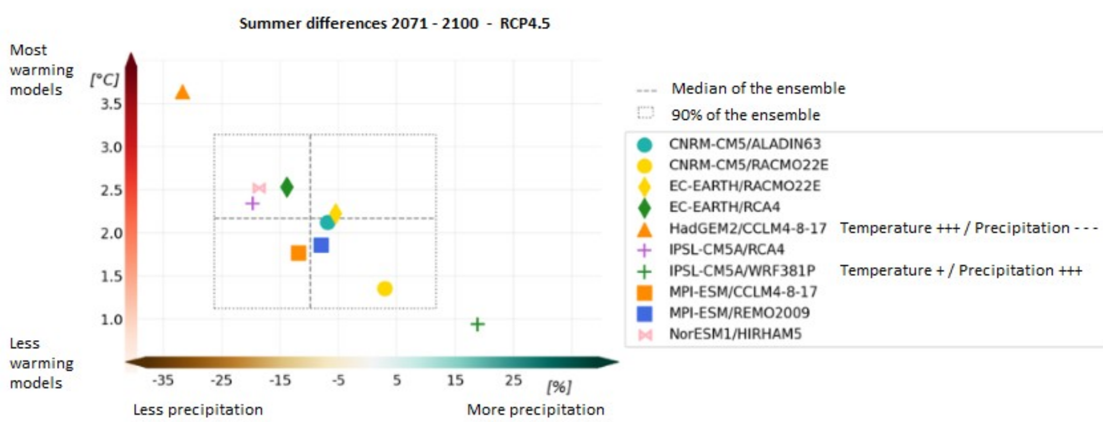

Figure 6: Dispersion of the DRIAS-2020 ensemble in temperature and precipitation changes for RCP 4.5 (adapted from DRIAS 2020).

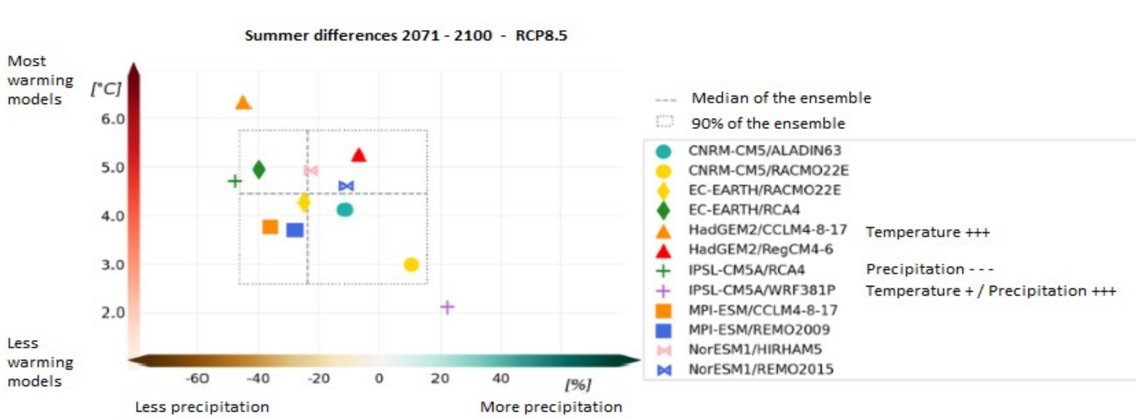

Figure 7: Dispersion of the DRIAS-2020 ensemble in temperature and precipitation changes for RCP 4.5 and 8.5 (adapted from DRIAS 2020).

The six GCM-RCM couples we selected are represented as circles, diamonds and squares of different colors in Figures 1 and 2.
For both RCPs, these six pairs:
- correspond to a duplicated GCM, with two different RCMs
- do not feature the most extreme precipitation and temperature changes of the DRIAS-2020 ensemble.
The first point is for consistency, and the second point for robustness. With only 6 different models, a single model with a very different behavior would bias results towards extremes.

4 – Section 3.1. The historical results lack a comparison with observations.

RESPONSE: We modified the end of Section 4.3.2 and added an new Figure, as follows:
"Although ISBA has been extensively validated against field data from several study sites, measured for example by Frequency Domain Reflectometry (FDR) probes (Decharme et al., 2011) or lysimeters (Sobaga et al., 2023), it relies on simplifying assumptions that introduce bias. These assumptions are specific to each model and result from choices made during the design phase. To compensate for individual biases, it would be appropriate to base drought assessments on simulations from multiple land surface models, as done by Samaniego et al. (2018). Also, observations of soil moisture at a depth of 0.8-1.0 m are scarce, and such comparisons are therefore not applicable on a national scale. Because the 2022 drought was exceptional, it is particularly important to validate the historical simulations for that particular year. Figure 8 shows a comparison of ISBA soil moisture profile simulations with in situ observations at the edge of the city of Toulouse, using data from the grassland FR-Tou ICOS site (Calvet et al., 2024). Across all individual soil layers, the Pearson correlation coefficient (R) is larger than 0.92 and the unbiased root mean square deviation (ubRMSD) is smaller than 0.063 m3m-3. The best results are obtained for deep soil layers. For the 0.8-1.0 soil layer, R = 0.95 and ubRMSD = 0.015 m3m-3. Figure 8 also illustrates the difference between local volumetric soil moisture values and the large-scale simulations. These differences are due to the fact that vertical heterogeneities of soil properties are not described in the model and that local soil properties are highly variable. Therefore, the YDMI calculation is based on a unitless soil moisture index (Barthelemy et al. 2024). Finally, Fig. 8 shows that the soil moisture simulations are significantly affected by the type of vegetation considered. For deciduous broadleaf trees, deep soil moisture changes are smoother than for grasses, in relation to the thicker root zone layer and the contrasting responses to soil water stress."

A comparison of YDMI and subsidence insurance claim data has already been done and commented for a subset of 20 municipalities in Barthelemy et al. (2024). It showed that the annual number of claims is positively correlated with the YDMI, although the former is not trivial to interpret as it is affected by several sources of uncertainty. Because of this last point, it is not relevant to perform the same analysis at the national level. We nevertheless made a comparison of YDMI with annual numbers of requests for recognition of the state of natural disaster issued by municipalities in section 4.1 of the article, both of which are in agreement.

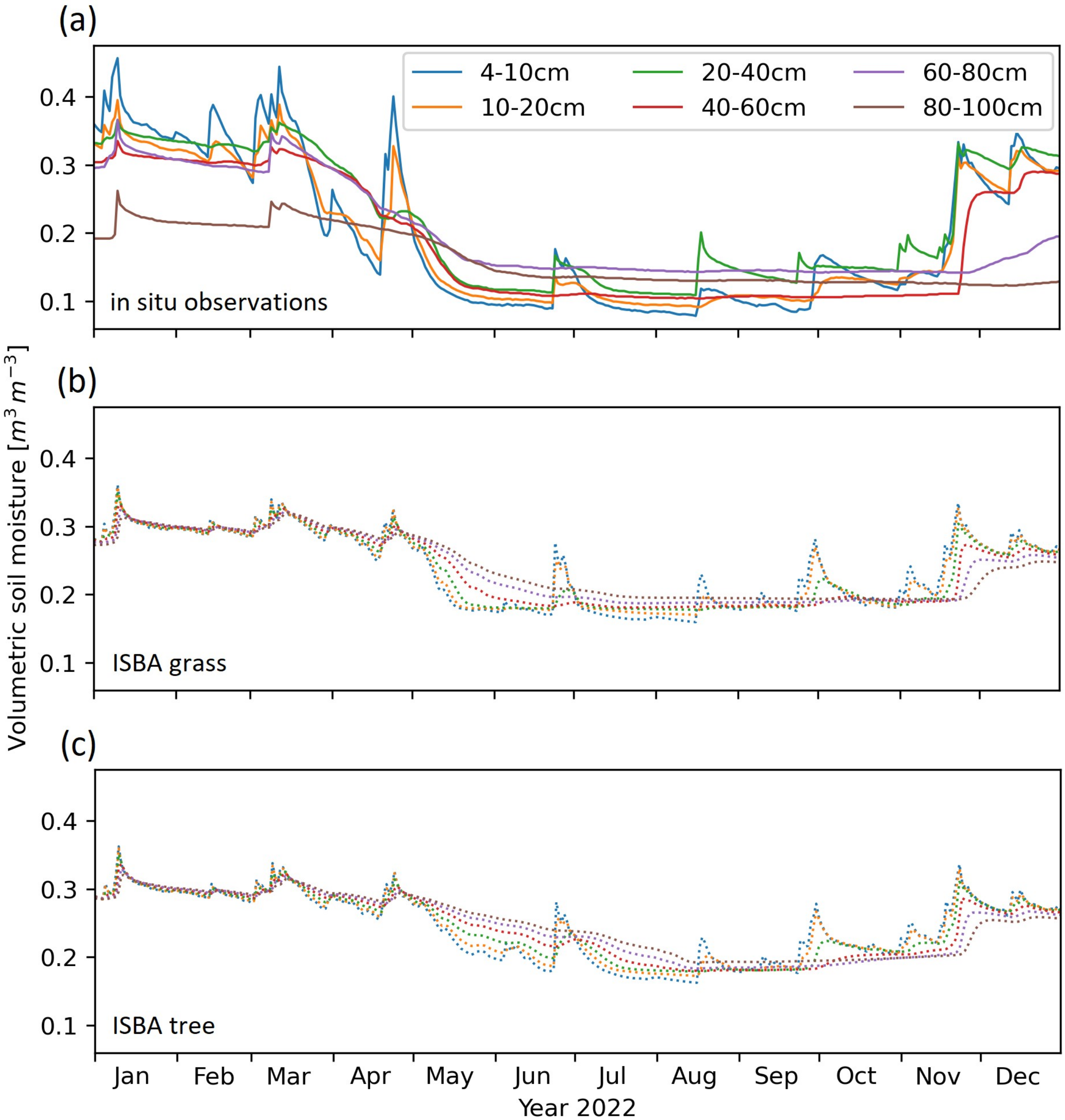

Figure 8 - Comparison of ISBA soil moisture profile simulations with in situ observations in the city of Toulouse, using data from the grassland FR-Tou ICOS site (Calvet et al., 2024) for six soil layers (0.04-0.1, 0.1-0.2, 0.2-0.4, 0.4-0.6, 0.6-0.8, 0.8-1.0 m): (a) in situ observations for grass, (b) simulation for grass, (c) simulation for deciduous broadleaf trees.

5 – Line 215. Why only choose third quartile of YDMI as an indicator. Does it have special significance? Generally, 50th percentile is more commonly used.

RESPONSE: The following sentence was added to Section 2.4: "**The third quartile was chosen as an indicator because it allows characterizing upper trends and it is more robust than the maximum.**" Similar trends of increasing YDMI over time are noticeable considering the 50th percentile, as shown in the picture below:

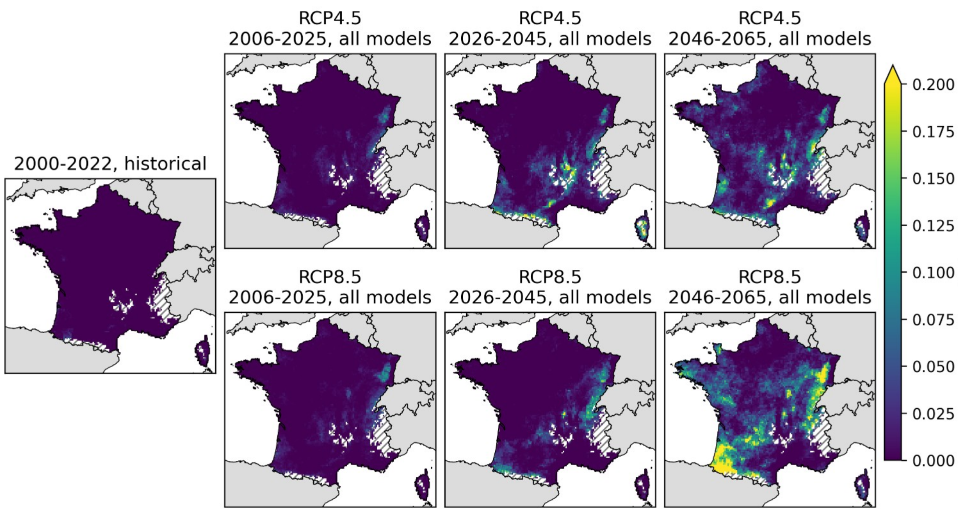

Figure 8: Median of YDMI, separating time horizon and RCP. Areas ith gray hatching correspond to filtered moutain area (average altitude > 1100 meters).

6- Figure 3-Figure 6. From the figure, the trend of the different model are inconsistent. What has caused the significant differences between the different models? Can we draw meaningful conclusions from results with such significant results?

RESPONSE: Climate models are numerical programs that simulate the various components of the climate system, such as the atmosphere, ocean, and continental surfaces. Climate models are used to assess the consequences of climate change by inputting increasing CO_2 concentrations and observing how this affects system variables. Their horizontal resolution ranges from 100 km for global climate models to 10 km for regional climate models. The physical processes involved are extremely complex and sometimes occur at spatial scales below the resolution of the model. For example, small clouds, which have a significant impact on climate, can measure only several hundred meters and therefore cannot be represented individually in climate models. This requires simplifying assumptions and parameterizations. The assumptions chosen vary from one modeling group to another, leading to contrasting predictions. This is explained (in French) in Risi and Bony (2019). It is therefore perfectly normal for the different climate models to predict contrasting results. This characteristic is the main motivation for basing conclusions on an ensemble rather than a single climate model. Moreover, the fact that the majority of simulations point to increasing drought characteristics indicates that this is a meaningful conclusion of the study.

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Robin, Y. *et al.* (2023) *Projections climatiques régionalisées: correction de biais et changements futurs*. Available at: https://entrepot.recherche.data.gouv.fr/file.xhtml?persistentId=doi:10.57745/99X4CD.

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