Response to Reviewer #2

Manuscript Title: Hourly-Scale Modeling of Storm Transitions in Southern Brazil with Markov Chains

We sincerely thank the reviewer for their careful evaluation and constructive comments, which have helped improve the quality and clarity of the manuscript. Below, we provide a detailed response to each comment.

Comments of the reviewer #2

The study investigates the sub-daily dynamics of storms in southern Brazil (Rio Grande do Sul – Drainage Area of the Lagoons, DAL), modeling transitions between storm intensity states using seasonal first-order Markov chains based on hourly precipitation data from 15 INMET stations (2007–2024).

The manuscript presents several strengths. First, the hourly scale of analysis represents a relevant contribution for the region, where most previous studies have focused on daily or monthly scales. Second, the seasonal separation of the modeling framework improves the physical consistency of the results, acknowledging the strong seasonal modulation of rainfall dynamics. In addition, the dataset is reasonably robust, comprising 15 stations and recent observations. Nevertheless, the temporal coverage (17 years) could ideally be extended to better represent long-term climatological variability. The study also offers practical applicability, providing useful insights for hydrological modeling, flood risk management, and infrastructure planning in the study region.

However, the reviewer identifies several aspects that should be strengthened before the manuscript can be considered for publication:

1. Although the title refers to Variable Length Markov Chains (VLMC), the implemented framework is essentially a first-order Markov chain with seasonal segmentation. There is no comparison with second-order chains, non-homogeneous Markov models, or integration with atmospheric covariates.

R/ We sincerely thank the reviewer for this insightful and constructive comment, which helped us improve the clarity and positioning of the manuscript.

First, we have revised the manuscript to clarify the methodological framework and avoid potential ambiguity regarding the use of Variable Length Markov Chains (VLMC). The approach is now consistently described as a Markov chain framework with seasonal segmentation, which more accurately reflects the implemented methodology.

Second, temporal variability was explicitly addressed through chi-square tests of temporal homogeneity for each station and season. The results ($p > 0.05$) indicate

that transition probabilities remain stable within each seasonal subset, supporting the assumption of time-homogeneous Markov chains and addressing potential concerns related to non-stationarity.

Third, higher-order Markov models were considered; however, statistical tests consistently supported a first-order structure. Adopting higher-order models would increase complexity without clear gains and would limit the spatial interpretability of transition probabilities, which in this study is achieved through a 3×3 matrix representation that enables direct climatic and topographic interpretation.

Finally, the study focuses on the intrinsic transition dynamics derived from precipitation data. For this reason, atmospheric covariates were not incorporated, as the objective was to provide a parsimonious and physically interpretable framework. The inclusion of external drivers represents a valuable direction for future research.

2. The model lacks out-of-sample validation and does not include comparisons with alternative modeling approaches, which limits the assessment of predictive skill and robustness.

R/ We sincerely thank the reviewer for this important comment. In the revised manuscript, we have explicitly clarified and delimited the objective of the study—particularly at the beginning of the Abstract and in the Introduction—to emphasize that the work focuses on the probabilistic characterization of storm-state transitions rather than on predictive forecasting.

We agree that out-of-sample validation and comparisons with alternative models are essential in predictive modeling frameworks. However, given the defined scope of this study, the emphasis is placed on understanding the temporal structure and persistence of rainfall events, rather than on evaluating predictive skill. For this reason, out-of-sample validation and model comparison were not included. These aspects are recognized as valuable directions for future research.

3. The physical discussion remains relatively superficial. The connections with the Low-Level Jet (LLJ), Mesoscale Convective Complexes (MCCs), and regional circulation patterns are predominantly qualitative and would benefit from a more quantitative analysis.

R/ We sincerely thank the reviewer for this valuable comment. We have carefully considered this suggestion and, in the revised manuscript, we have expanded the discussion of the physical mechanisms associated with storm dynamics throughout the document. In particular, the roles of the Low-Level Jet (LLJ), Mesoscale

Convective Complexes (MCCs), frontal systems, migrating anticyclones, and downslope (katabatic) flow from the Andes have been further developed and better integrated into the interpretation of the results.

4. The connection with climate change is still limited. Although CMIP6 projections are mentioned in the discussion, there is no temporal analysis of trends in transition probabilities, nor an evaluation of non-stationarity in the Markov matrices.

R/ We sincerely thank the reviewer for this important comment. We have expanded the discussion on climate change in Section 4.4 (Discussion of Results), strengthening the interpretation of our findings in the context of recent observations and CMIP6 projections.

In addition, the stationarity of the transition probabilities was formally evaluated through temporal homogeneity tests, which supported the assumption of stable behavior within the analyzed period. This aspect has been clarified in the manuscript. Furthermore, we have extended the discussion to acknowledge that, under projected climate change scenarios, storm dynamics may exhibit non-stationary behavior in the future, particularly in terms of increasing probabilities of more intense states.

Therefore, prior to acceptance, the following improvements are recommended:

a) Include comparisons with Hidden Markov Models and second-order Markov chains;

R/ We thank the reviewer for this suggestion. As addressed in a previous comment, higher-order Markov models were evaluated, and results supported a first-order structure. The use of Hidden Markov Models was not considered necessary, as the storm states are directly observed. These aspects have been clarified in the revised manuscript.

b) Incorporate predictive validation (e.g., out-of-sample testing or cross-validation);

R/ We thank the reviewer for this suggestion. As addressed in a previous comment, the objective of this study was explicitly delimited to focus on probabilistic characterization rather than predictive performance; therefore, out-of-sample validation was not included. This has been clarified in the revised manuscript.

c) Test for temporal trends in the transition matrices;

R/ We thank the reviewer for this suggestion. Temporal variability in the transition matrices was assessed through chi-square tests of temporal homogeneity, which did not indicate significant changes over time. Therefore, no clear temporal trends were identified. This has been clarified in the revised manuscript.

d) Explore potential non-stationarity in the time series.

R/ We thank the reviewer for this suggestion. Potential non-stationarity was addressed by dividing the data into seasonal subsets, allowing the transition dynamics to vary between seasons. Within each subset, temporal homogeneity tests indicated stable transition probabilities over time. Therefore, no significant non-stationary behavior was detected within the analyzed period. This has been clarified in the revised manuscript.

Overall, while the study presents relevant regional contributions, the inclusion of the above methodological and diagnostic enhancements would substantially strengthen its scientific robustness and suitability for publication in an international journal.