Dear Editors,

We thank you again for the detailed analysis and valuable suggestions aimed at improving the clarity and impact of our manuscript. We understand the need to better explain the innovation of our approach and how it differs from existing works, as well as to make further improvements. A great deal of revision effort has been made by the authors, and we hope it is satisfactory for publication. If you have any further questions, please feel free to ask.

# Responses to Reviewer 1

Reviewer 1 provided a critical evaluation, questioning the scientific relevance, innovation, and practical applicability of the proposed methodology. We understand the gravity of these observations and have endeavored to address them comprehensively in the revised manuscript.

1. **General Recommendation: Rejection due to lack of clarity on scientific relevance, innovation, and practical applicability.**
    - **Response:** We appreciate the reviewer's rigorous assessment, which significantly prompted us to enhance the clarity and depth of our argumentation. We acknowledge that the previous version might not have fully articulated the distinct value of our approach. In the revised manuscript, particularly in the **Introduction (page 4, last paragraph)** and the **Discussion section (pages 12-14)**, substantial attention has been dedicated to explicitly outlining the scientific relevance and innovation. We clarify that the primary objective is not to supersede existing methodologies, but rather to offer a framework that simplifies the interpretation of complex 3D drought dynamics, rendering them more accessible and actionable for decision-makers in proactive planning. The innovation lies in translating robust scientific findings into comprehensible typologies, thereby addressing the 'complexity dilemma' that often hinders the practical application of advanced models.
2. **Simplistic view of drought (SPI only) and outdated WMO justification.**
    - **Response:** The reviewer's concern regarding the exclusive reliance on SPI and the potential limitation of a one-dimensional drought perspective is well-noted. In **Section 2.1, Step 1 (page 5)**, we have refined the justification for selecting SPI in this study. We explicitly state that, while acknowledging the importance of multi-indicator approaches and advancements in remote sensing, the choice of SPI for Northeast Brazil was strategic. This decision was based on the **superior availability of historical data and the higher density of the pluviometric monitoring network in the region** compared to other hydro-meteorological variables. The study's primary focus is to **validate a novel methodological framework for spatio-temporal drought evolution analysis**, rather than to advocate for a singular drought indicator. We emphasize that the proposed methodology is **versatile and adaptable to any gridded time-series drought index**, and future studies will incorporate additional indices. This clarification contextualizes our methodological choice within the study's scope and objectives. Furthermore, the **Discussion section (page 13)** contrasts our framework's

nature with operational systems like Brazil's Drought Monitor, which indeed utilize multiple indicators, highlighting the distinct purposes of each approach.

3. **Lack of demonstration of scientific relevance/practical applicability (generic discussions, 3D approach already done by conventional SPI, 'erratic' severity behavior not new).**
   - **Response:** We understand the imperative to demonstrate the practical utility of our framework more concretely. The **Introduction (page 4, last paragraph)** reiterates the explicit aim to provide structured and interpretable information to enhance drought evolution characterization, offering insights for proactive preparedness planning. The **Discussion section (pages 12-14)** has been significantly expanded to include a detailed comparison of our methodology with both classical approaches (e.g., SAD curves) and advanced 3D clustering algorithms. We argue that, while these methods produce rigorous scientific descriptions, our innovation lies in *translating* these complex dynamics into a simplified three-curve representation and a directly applicable typology, thereby facilitating comprehension and use by non-specialists. Regarding the 'erratic' behavior of severity, the value is not in the novelty of observing variability itself, but in the **practical conclusion derived from this observation within our framework**. As detailed in **Section 3.5, Transition Matrix Analysis of Drought Phases (page 11)**, by analyzing the transition matrix, we identified that severity exhibits a more 'erratic' behavior compared to the affected area. This finding then supports the **explicit recommendation to prioritize affected area as a more reliable indicator for decision-making**, with severity serving as a complementary metric. This transforms a known characteristic of the index into an *actionable guideline* for drought management.
4. **Drought Typologies (a posteriori, usefulness not demonstrated, generic measures, precipitation-based only).**
   - **Response:**
     - **A Posteriori Nature:** We appreciate the need for clarity regarding the *a posteriori* nature of our framework. In the **Discussion section (page 14)**, we explicitly acknowledge that 'unlike operational monitoring tools such as Brazil's Drought Monitor, the proposed framework is explicitly an *a posteriori* method: it classifies droughts only after their full occurrence.' We then justify its value not for real-time alerts, but for **drought preparedness planning**. For researchers, it offers a structured and comparable language; for decision-makers, it provides an interpretable typology that highlights recurrent patterns of drought behavior.
     - **Usefulness and Suggested Measures:** The **Introduction (page 4, last paragraph)** and **Section 3.4, Typology of Droughts Based on Evolution Dynamics (pages 10-11)** describe how these typologies enable the anticipation of behavioral patterns and proactive planning. The **Discussion section (pages 13-14)** further elaborates on their utility. For instance, by identifying the predominance of Type II droughts (rapid expansion, prolonged persistence, abrupt contraction) in Northeast Brazil, we illustrate

how this informs the need for early warning systems during the initial phase and sustained support during persistence. We argue that this moves **beyond generic disaster risk reduction advice**, as it allows response strategies to be *tailored to the specific evolutionary patterns* of events.

- **Precipitation-Based Only:** This point is addressed in conjunction with point 2 concerning SPI usage. We reiterate that, while the study utilizes SPI for reasons of regional data availability, the methodology is designed to be **applicable to other indices**, which will allow for a more comprehensive characterization of multifaceted droughts in future work. **Section 2.2 (page 7)** also clarifies that affected area and severity were chosen as primary characteristics for an *intra-event analysis*, focusing on the evolution of drought behavior throughout its duration, which falls within a distinct scope from a full impact analysis.

5. **Suggestion of Comparative Case Study (conventional monitoring vs. proposed methodology).**
   - **Response:** We appreciate the excellent suggestion for a comparative case study, which would undoubtedly be of significant value. While an exhaustive comparison with multiple monitoring methodologies was not the primary focus of this revision, the manuscript presents a detailed analysis of the 1990-1994 event using the three-curve model and spatio-temporal maps in **Section 3.3, Application of the Three-Curve Model (pages 9-10, Figures 5 and 6)**. This analysis illustrates how our framework reveals the expansion, persistence, and contraction phases of a specific event. The **Discussion section (page 13)**, in particular, contrasts the value of our framework with traditional monitoring systems (such as Brazil's Drought Monitor), emphasizing that while these provide real-time situational awareness, our approach **supports strategic planning by elucidating the regime of drought evolution**, enabling the anticipation of likely developments and the formulation of management measures oriented towards typical event progressions. We consider that this contextualization, while not a direct 'two-narrative' case study, effectively demonstrates the added value of the methodology.

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# Responses to Reviewer 2

Reviewer 2 provided constructive and detailed feedback, with recommendations for both major and minor revisions. We deeply value the specificity of these observations, which guided us in enhancing the methodological clarity and presentation of the manuscript.

1. **General Recommendation: Reconsider after major revisions.**
   - **Response:** We sincerely thank the reviewer for the detailed assessment and the recommendation for major revisions. The reviewer's feedback was instrumental in guiding the significant enhancements made to the

manuscript, and we believe the revised version satisfactorily addresses the principal concerns raised.

2. **Methodological Contribution (epidemiological growth curves): Not a novel concept, need to explicitly position the methodological contribution (characterize changes, enhance monitoring? How, why?).**
   - **Response:** We appreciate the request for greater clarity regarding the originality and positioning of our contribution. In **Section 2.3, The Three-Curve Model (page 7)**, we explicitly state that the model is indeed 'an adaptation of an analytical framework originally proposed by Utsunomiya et al. (2020) for monitoring the spread of COVID-19.' The innovation, therefore, does not reside in the novelty of the growth curve concept itself, but rather in the **adaptation and innovative application of this framework to the characterization of spatio-temporal drought evolution**. The **Introduction (page 4, last paragraph)** and **Discussion section (pages 12-13)** have been significantly expanded to articulate this contribution. The work aims to 'rebalance analytical robustness with practical applicability in 3D drought assessment,' providing 'more structured and interpretable information to enhance drought evolution characterization, offering insights into proactive preparedness planning.' The Discussion section directly compares our method with existing 3D clustering algorithms, such as those by Herrera-Estrada et al. (2017) and Diaz et al. (2019), demonstrating that our proposal 'translates these complex dynamics into a simplified three-curve representation and a directly applicable typology,' thereby facilitating understanding and use by non-specialists.
3. **Clarity of 3D Drought Clusters (justification of 1.6% threshold, difference from previous works, diagram).**
   - **Response:**
     - **1.6% Threshold Justification:** In **Section 2.1, Step 4 (page 6)**, the rationale for the 1.6% overlap threshold has been enhanced. We clarify that 'this specific overlap threshold of 1.6% was adopted in this study, consistent with established criteria used in previous spatio-temporal drought analyses by Li et al. (2020) and Xu et al. (2015). This choice reflects a common practice in the literature, and this filter is important for distinguishing significant spatio-temporal connections while filtering out minor, ephemeral overlaps that may not represent a continuous drought event.'
     - **Distinction from Previous Works:** In **Section 2.1, Step 4 (page 6)**, we explicitly detail the algorithm modification: 'An important consideration in the proposed algorithm is that when a cluster splits into two or more clusters, they all retain the same initial ID. This is a modification of the algorithm used by Diaz et al. (2019) and Herrera-Estrada et al. (2017), whose analysis only preserved the areas of the largest clusters.' We explain the logic behind this modification, which is to preserve events that occur simultaneously in different regions due to distinct precipitation mechanisms.
     - **Diagram:** We appreciate the suggestion for a diagram to aid in understanding the workflow of the proposed methodology. In the manuscript, **Figure 1 (page 5)** presents a schematic workflow of

the entire procedure, including the definition of spatio-temporal drought events. We consider that this visual improvement, combined with examples of drought evolution in Figure 3, provides a good understanding of the process. This remains an excellent suggestion for future visualizations.

4. **Lack of Detailed Descriptive Statistics/Maps on Drought Evolution.**
    - **Response:** We recognize the importance of descriptive statistics for a comprehensive understanding. In **Section 3.4, Typology of Droughts Based on Evolution Dynamics (pages 10-11)**, we present detailed statistics on the **prevalence of the four drought typologies** in the studied region, both for affected area and severity. This illustrates how areas and durations vary in terms of evolutionary patterns. Furthermore, **Figures 3, 5, and 6 (pages 9-10)** clearly depict the **spatial evolution of the drought footprint** and clustering maps for representative events. While we have not included exhaustive tables of statistics for *all* events to maintain focus on the methodology, the provided information, including the dominance of Type II droughts and their characterization, offers insights into variability and spatial patterns.
5. **No Comparison with Classic Techniques or Benchmarking.**
    - **Response:** This point has been thoroughly addressed and incorporated into the **Discussion section (pages 12-13)** of the revised manuscript. We conduct an in-depth comparison of our framework with classical techniques, such as the Severity-Area-Duration (SAD) curves by Andreadis et al. (2005), and with more recent 3D clustering approaches, including the works of Herrera-Estrada et al. (2017), Diaz et al. (2019), Cammalleri and Toreti (2023), and Banfi et al. (2024). This section clarifies how our methodology **complements and extends** these existing approaches by offering a 'process-oriented view' and by translating complex results into a 'simplified and actionable typology,' thereby highlighting the added value of the proposed method for proactive planning.
6. **CRU Dataset (0.5° resolution) is Coarse, Comment on Representativeness and Limitations.**
    - **Response:** The concern regarding the resolution of the CRU TS v4.05 dataset is valid and has been explicitly addressed in the **Discussion section (page 14).** We acknowledge that 'the use of the CRU TS v4.05 dataset, with its 0.5° resolution, while providing a long historical record crucial for drought climatology, is acknowledged to be quite coarse for a region characterized by high spatial rainfall variability such as Northeast Brazil.' We discuss the implications, such as the limitation in capturing fine-scale meteorological phenomena, and suggest that future applications would benefit from higher-resolution precipitation data.
7. **Lack of a Stand-Alone Discussion Section.**
    - **Response:** We appreciate this important observation. The revised manuscript now includes a **dedicated 'Discussions' section (pages 12-14)**, clearly separated from the results. This section facilitates a thorough critical reflection on comparisons with prior studies, the limitations of the current work, the transferability of the methodology, and directions for future research, directly addressing the reviewer's point.
8. **Minor Comments:**

- **Flexibility for Other Indices (validity of area threshold).**
    - **Response:** In **Section 2.1, Step 1 (page 5)** and the **Discussion section (page 14)**, we assert the methodology's versatility for application to any gridded drought index. While the universal validity of the 1.6% threshold for other indices has not been explicitly tested in this study (which might require a sensitivity analysis depending on the index), the flexibility of the framework allows for such adjustments in future applications. The methodology is inherently adaptable to different drought indicators, representing a key strength.
- **Typology Assignment (automated or visual/manual, who labels).**
    - **Response:** We appreciate the request for clarity. In the **Discussion section (page 14)**, we directly address this point: 'Furthermore, the assignment of drought events to typologies was performed visually, which, while guided by theoretical models, introduces a subjective element. Although effective for this initial methodological demonstration, an automated classification method for typology assignment would enhance objectivity and scalability for large datasets.' This is identified as an important direction for future work.
- **"Growth curve" and "dynamic curve" potentially confusing, suggestion of schematic diagram.**
    - **Response:** We thank the reviewer for the suggestion to enhance terminological clarity. In **Section 2.3, The Three-Curve Model (page 7)**, we detail the definitions of 'Growth Curve,' 'State Curve,' and 'Dynamic Curve,' and explain the terminological modification relative to the original work by Utsunomiya et al. (2020) to avoid confusion in the context of droughts. **Figures 6 and 8 (pages 10 and 11)** provide explicit visualizations of these curves applied to drought events, aiding comprehension. While **Figure 1** presented the whole workflow with the conceptual model of the three curves.
- **References (Utsunomiya et al. 2020 missing, Diaz et al. 2019 vs 2020).**
    - **Response:** We confirm that the complete reference for Utsunomiya et al. (2020) has been added to the reference list (page 16) and correctly cited in the text. Regarding Diaz et al., Diaz et al. (2019) and Diaz et al. (2020) were actually Diaz et al. (2018) and Diaz et al. (2019), and they do refer to distinct publications.

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We thank the reviewers once again for their time and valuable contributions, which have unquestionably elevated the quality of the manuscript. We believe that the revised version satisfactorily addresses the points raised, presenting the methodology in a clearer, more robust manner, with enhanced contextualization of its relevance and applicability.

We remain available for any further clarification.

Sincerely,

João Dehon de Araújo Pontes Filho