

Response to Reviewer #1

We sincerely thank the reviewer for the careful evaluation of our manuscript and for the constructive and detailed comments. We appreciate the time and effort devoted to reviewing the study. The suggestions have helped us to improve the manuscript substantially, particularly with respect to the clarification of objectives, methodological transparency, statistical description, presentation of results, and discussion of scale-related limitations.

In response to the reviewer's comments, we have revised the manuscript extensively. Major changes include:

- clarification of the scientific objectives and working hypotheses in the Introduction;
- incorporation of additional and more recent references throughout the manuscript;
- substantial revision and expansion of the data-processing and quality-control procedures;
- inclusion of new statistical information and trend analyses;
- reorganization of several sections to improve the distinction between Results and Discussion;
- addition of supplementary material and appendices containing station information and summary statistics for all analysed stations;
- clarification of the spatial scale of interpretation and the limitations associated with regional-scale climatic indicators.

Detailed responses to each comment are provided below.

General and Line-by-Line Comments

Abstract

Reviewer comment: Use acronyms consistently and clarify some terminology.

Response: We thank the reviewer for this observation. The Abstract has been revised accordingly. Acronyms are now introduced consistently, terminology has been simplified where appropriate, and references to temperature variables have been standardized throughout the manuscript.

Introduction

Reviewer comment: Several general statements were insufficiently referenced.

Response: We agree. Additional references have been incorporated in the Introduction to support previously unreferenced statements and to strengthen the scientific background of the study. Recent literature on frost weathering, frost cracking and cryoclimatic indicators has also been incorporated.

Reviewer comment: The goals and hypotheses of the study were not sufficiently clear.

Response: We thank the reviewer for highlighting this issue. The final part of the Introduction has been substantially rewritten to clearly state the objectives, research questions, and working hypothesis of the study. The revised text now explicitly explains how the different cryoclimatic indicators are used to assess frost-weathering potential and highlights our expectation that climate warming has produced a spatially heterogeneous response across Spain, including both reductions and localized persistence of conditions favourable for frost weathering.

Additional revision

During the revision process we also identified an error in Figure 1 that had not been noted by the reviewer (duplicate station numbering and omission of one station identifier). This figure has been corrected. Furthermore, the station list has been removed from the figure caption and incorporated into a new Appendix 1 containing detailed information for all stations.

Methodology

Reviewer comment: Provide more information about the meteorological stations.

Response: We agree with the reviewer. Figure 1 has been revised, and a new Appendix 1 has been incorporated containing detailed information for the complete station network, including station code, climatic classification, location, altitude, coordinates, orientation, and record length. This information provides a clearer description of the observational framework used in the study.

Reviewer comment: The data processing and quality-control procedures were not sufficiently described.

Response: We thank the reviewer for this suggestion. Section 2.2 (Data Processing and Quality Control) has been substantially rewritten. The revised text now provides a detailed description of: data screening procedures, quality-control filters, outlier detection criteria, treatment of missing observations, homogenization procedures, residual analyses, interpolation methods, and the references supporting each methodological step. Several methodological references have also been added to place our approach within established climatological quality-control frameworks.

Reviewer comment: Clarify the statistical procedures and provide references.

Response: Additional methodological information and references have been incorporated. The revised manuscript now explicitly describes the application of Mann-Kendall tests, Spearman rank correlation, Theil-Sen slope estimation, residual analysis, and the rationale for the use of generalized least-squares approaches where appropriate.

Reviewer comment: Specify ArcGIS version and geospatial procedures.

Response: This information has now been included in Section 2.3. The revised manuscript specifies the software version (ArcMap 10.8.2), interpolation procedures, grid resolution, and the geostatistical methods that were evaluated during the construction of the spatial models.

Reviewer comment: Clarify the scale of interpretation and the role of local controls.

Response: We greatly appreciate this observation. One of the major modifications introduced in the revised manuscript is a clarification of the spatial scale of analysis. A new paragraph has been added at the end of Section 2.1 explaining that the cryoclimatic indicators are derived from regional-scale daily observations and should therefore be interpreted at national and sub-regional scales. We further clarify that site-specific assessments would require higher-resolution datasets capable of resolving topoclimatic controls such as aspect, cold-air pooling, local relief, and microclimatic variability.

Results

Reviewer comment: The selection of representative stations was not sufficiently justified.

Response: We appreciate the reviewer's concern. The representative stations shown in the figures were selected to illustrate the behaviour of the variables across the main climatic and physiographic regions of Spain. Given the national scale of the study and the total number of stations analysed (84), displaying all station time series within the figures would substantially reduce clarity and readability.

To address this concern, we have incorporated a new Appendix 2 containing the values of all cryoclimatic indices for the entire station network. This allows readers to examine the complete dataset while maintaining clear and interpretable figures within the main text.

Reviewer comment: The statement regarding the impact of frost on rocks and materials was too strong.

Response: We agree. The text has been revised and the statement has been moderated. Additional explanation and supporting references have also been incorporated to better distinguish between climatic indicators and direct mechanical weathering processes.

Reviewer comment: Move the former Section 4.3 to Results.

Response: We thank the reviewer for this useful suggestion. The former Section 4.3 has been relocated and now appears in the Results section (Section 3.1), improving the separation between empirical results and process interpretation.

Reviewer comment: Clarify the meaning of "absolute minima".

Response: The text and Table 2 have been revised. The terminology has been clarified as "absolute minimum temperature", and the table now explicitly distinguishes between recent-period observations and historical absolute records.

Discussion

Reviewer comment: Local controls such as altitude and aspect should be considered.

Response: We agree. Additional text has been incorporated into Section 4.1 discussing the influence of altitude, aspect, cold-air pooling, and local topographic controls on frost occurrence. At the same time, we clarify that these factors operate primarily at local scales and therefore complement rather than replace the regional-scale patterns analysed in this study.

Reviewer comment: Certain statements should be supported by references.

Response: Additional references have been incorporated wherever the reviewer identified statements that were presented as interpretations rather than direct results of the analysis. The wording has also been revised where necessary to distinguish more clearly between observations derived from our dataset and interpretations supported by previous literature.

Reviewer comment: Clarify how the projected maps were generated.

Response: The methodology has been further clarified in Sections 2.2 and 2.3. The projected maps were generated using Empirical Bayesian Kriging (EBK) implemented through ArcGIS Geostatistical Analyst. The interpolation procedures, validation metrics, and model performance indicators have been described in greater detail in the revised manuscript.

Reviewer comment: The final paragraphs of Section 4.4 should be separated and presented as a discussion of limitations.

Response: We thank the reviewer for this recommendation. In response, we have created a new Section 4.5 entitled “Intermediate-scale downscaling as a bridge between global projections and local climate complexity.” This section now explicitly discusses scale-related limitations, the relationship between regional observations and global projections, and the implications of downscaling approaches for cryoclimatic studies.

Conclusions

Reviewer comment: Some conclusions were not sufficiently supported by the presented evidence.

Response: We agree with the reviewer and have revised the Conclusions accordingly. Several statements have been moderated and reformulated to ensure consistency with the evidence presented in the Results and Discussion sections. In particular, interpretations concerning geomorphological implications are now framed more cautiously and explicitly identified as potential consequences requiring dedicated future investigation.

Once again, we sincerely thank Reviewer #1 for the thorough and constructive review. We believe that the manuscript has been substantially improved as a result of these comments, and we hope that the revised version satisfactorily addresses all concerns raised.