

Response to Reviewer #2

We would like to sincerely thank the reviewer for the careful reading of our manuscript and for the constructive and insightful comments. We appreciate the positive assessment of the relevance of the study and its potential contribution to understanding how climate change may affect frost-weathering processes across Spain.

We have carefully considered all comments and have revised the manuscript accordingly. The revisions have helped us clarify the interpretation of the cryoclimatic indices, better explain the limitations of the methodology, and improve the overall presentation of the results.

Our detailed responses are provided below.

General comments

Reviewer comment: This manuscript addresses an important topic and has the potential to make a valuable contribution to the field. However, further clarification is needed on several points in order to more fully support the main conclusions. In particular, the interpretation of the data needed to be explained more clearly, including the relationship between the frost weathering index used in this study and the freeze-thaw mechanism it represents.

Response: We thank the reviewer for this positive evaluation and for highlighting the need to better describe the physical meaning and limitations of the cryoclimatic indices employed. In response, we have revised several sections of the manuscript to clarify the processes represented by each indicator, to distinguish climatic proxies from direct measures of rock damage, and to explicitly discuss the limitations associated with using air temperature as a surrogate for rock thermal conditions.

Specific comments

P6-L30. How did you reflect the aspect in the distinct geographic-climatic areas?

Response: We thank the reviewer for identifying this ambiguity. We agree that the term aspect may suggest local-scale slope exposure, whereas our classification refers to broad climatic controls operating at regional scales.

To prevent misunderstanding, we have replaced the term aspect with large-scale orientation throughout the manuscript. In this context, orientation refers to regional-scale climatic controls such as the position of the Iberian Peninsula relative to atmospheric circulation patterns, continental and maritime influences, and the arrangement of major mountain systems, rather than to local topographic slope exposure. The revised text now makes this distinction explicit.

P6-L23. It is necessary to explain more clearly which phenomena of frost weathering each indicator used in this study is intended to evaluate.

Response: We fully agree and appreciate this important observation. A new explanatory section has been incorporated into the methodology to clarify the physical meaning of each cryoclimatic indicator and its relationship to frost-weathering processes. Specifically, we now emphasize that: i) the indices used in this study should be interpreted as climatic proxies of frost-weathering potential rather than as direct measurements of rock damage; ii) FTC is conceptually related to conditions that may favour freeze-thaw activity and volumetric expansion of water, but it should not be interpreted as a direct measure of frost damage because factors such as rock properties, degree of saturation, confinement conditions, and freezing rates are not considered. iii) WFI incorporates moisture availability and therefore identifies climatic situations that are potentially favourable for frost-weathering processes, including those associated with ice segregation. iv) Air temperature and rock temperature are not equivalent. Consequently, the adopted thresholds should be regarded as indicators of regional climatic conditions favourable for freezing processes rather than direct evidence of freezing within the rock mass.

We have also explicitly stated that direct assessment of rock thermal conditions and frost-cracking processes would require site-specific observations beyond the scope of this national-scale study.

P7-L4. Regarding the definition of WFI, does it refer to precipitation without distinguishing between rainfall and snowfall?

Response: We thank the reviewer for raising this important point. The precipitation data employed in this study do not distinguish between liquid and solid precipitation. Therefore, WFI was calculated using total precipitation regardless of phase. We agree that snowfall may affect frost-weathering processes differently from rainfall. Snow cover can reduce freeze-thaw activity through its insulating effect, but it may also contribute to delayed moisture supply through snowmelt. The net influence therefore depends on local conditions and can vary considerably through space and time.

Given the national scale of our study and the very large dataset analysed, it was not feasible to incorporate detailed snow-cover dynamics. Nevertheless, we acknowledge this limitation and have added an explicit clarification in the manuscript. We also note that persistent snow cover is mainly restricted to mountain regions and represents a much smaller component of precipitation over most of Spain.

P9-L24. Why are there regions where FI is increasing?

Response: We appreciate the opportunity to clarify this point. The analysis is based on the complete 1993-2022 study period, and the reported trends are derived from statistical analyses including Mann-Kendall, Spearman correlation, and Theil-Sen estimates. Several mountain and peri-mountain stations exhibit weak but statistically significant positive FI trends. For example, stations such as Jaca and Cervera de Pisuerga show positive correlations over the study period. To help readers evaluate the magnitude of these changes, we have incorporated additional quantitative information in the revised manuscript. We agree that trend estimates are influenced by the selected analysis period and may differ if alternative starting or ending dates

are chosen. However, the objective of this study is to characterize the behaviour observed during the most recent 30-year interval using a consistent methodology applied across the entire network.

We have revised the text to better explain the magnitude and significance of these trends and to avoid overemphasizing localized increases.

P15-Table 2. Wouldn't it be better to show trends in average temperatures rather than extreme minimum temperatures?

Response: We appreciate this suggestion. The purpose of Table 2 is not to demonstrate the existence of climate warming, which is already well established, but rather to place recent frost conditions into a longer historical context by comparing recent minimum temperatures with historical records. Because the focus of this study is frost occurrence and frost-related processes, minimum temperatures are directly relevant to the objectives of the paper. Average temperatures provide valuable information regarding overall climate warming, but they are less directly linked to the occurrence of freezing conditions and frost-related indices analysed in this study.

To avoid misunderstanding, we have revised the surrounding text to clarify the specific purpose of Table 2 and its relevance within the context of frost-climate characterization.

P17-L5. What is meant by the "stochastic nature of precipitation" in the context of climate change?

Response: We thank the reviewer for this insightful comment and agree that additional clarification was necessary. The term stochastic nature of precipitation is not intended as a synonym for extreme precipitation. Rather, it refers to the inherently variable temporal behaviour of precipitation, including changes in the frequency, timing, duration and sequencing of precipitation events. For frost-weathering processes, our main interest is not the total amount of precipitation alone, but the timing of moisture availability relative to sub-zero temperatures. From this perspective, the effectiveness of wet-frost conditions depends primarily on the coincidence and sequence of precipitation and freezing events rather than on precipitation intensity by itself.

We have therefore revised the discussion to clarify this interpretation and to emphasize that WFI is intended to identify climatically effective moisture conditions associated with freezing events rather than isolated rainfall or snowfall extremes.

Technical corrections

Figure 1: Hypsometric colours should be revised.

Response: We thank the reviewer for noticing this issue. The colour scheme of the hypsometric map has been corrected so that elevation classes now follow a more intuitive progression.

Add colour bars to Figures 4 and 5.

Response: Done. Colour bars have been added to Figures 4, 5 and 6 to improve readability and interpretation.

The downward trend of IFTC is not clearly visible in Figure 4.

Response: We agree. Trend lines have been incorporated into the lower graphs of Figure 4 in order to improve the visualization of temporal tendencies and to maintain consistency with Figure 6.

Is 35.8°C a typo for -35.8°C?

Response: Yes. We thank the reviewer for catching this typographical error. The value has been corrected to -35.8°C in the revised manuscript.

Once again, we thank Reviewer #2 for the constructive comments and suggestions. We believe that the revisions have substantially improved the clarity, methodological transparency, and interpretation of the manuscript.