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Evaluating the freeze-thaw vulnerability of soapstone monuments and geoheritage sites in the Parco del Paradiso (Chiavenna, Italy).

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Abstract

This study investigates the vulnerability of soapstone monuments and ancient quarries in the Parco del Paradiso, Chiavenna, to freeze-thaw cycles. It employs climate-based damage functions to assess the risk of weathering-induced damage. A crucial aspect of the assessment involves the study of the homogeneity and trends in the selected climate data sources in the area of the case study. These data sources are ground-based weather stations, and in-situ installed temperature-humidity data loggers. The findings of this contribution underscore the significance of appropriately chosen reference climatic series and validation tests in ensuring the accuracy of the climate signal to analyze freeze-thaw statistics for specific cultural heritage sites. These insights are essential not only for supporting reliable assessment of the vulnerability of these invaluable heritage sites, which have played a vital role in local architecture and trade since Roman times, and for the successive development of long-term preventive conservation and maintenance strategies.

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Keywords: freeze-thaw cycles; geoheritage; damage functions; microclimate; soapstone

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Nomenclature

AWS	Automatic Weather Station
F-T	Freeze-thaw cycles
FT_{Avg}	Freeze-thaw cycles/year computed using daily average dry-bulb temperature around 0°C
FT_{eff}	Freeze-thaw cycles/year computed using daily maximum and minimum dry-bulb temperature around -3 and 1°C
FT_{Mnx}	Freeze-thaw cycles/year computed using daily maximum and minimum dry-bulb temperature around 0°C
MOP	Monitoring period (2022/02/01-2023/01/31)
MWS	Mechanical Weather Station
Prec	Precipitation in mm/day
QA	Quality Assessment tests
RCP	Recent past (2016/01/01-2023/01/31)
RRP	Distant past (1961/01/01-1990/12/31)
T_{avg}	Average daily dry-bulb temperature in °C
T_{max}	Maximum daily dry-bulb temperature in °C
T_{min}	Minimum daily dry-bulb temperature in °C
WFD	Wet frost days

1. Introduction

Heritage sites are constantly challenged by the gradual process of weathering Smith et al. (2008). Depending on their location, open-air geoheritage sites (i.e., sites which encompass intrinsically important features of geology and culture at all scales, offering information or insights into the evolution of the Earth or history) can be particularly vulnerable to damage caused by freeze-thaw cycles Deprez et al. (2020). To implement effective maintenance practices and ensure optimal conservation, it is crucial to have a thorough understanding of these geological structures' vulnerabilities. In the Parco del Paradiso, located in Valchiavenna, Northern Italy, there are soapstone monuments and ancient quarries with deep historical significance exploited since Roman times Castelletti (2018). The geological composition of the park's outcropping rock belongs to the ultramafic body of the Chiavenna Unit Arrigoni et al. (2020), characterized by a broad local lithological diversity, including peridotite, chlorite schist, calc-silicate boudins, and talc schists, historically exploited for soapstone extraction Baita et al. (2014). This study delves into the evaluation of freeze-thaw damage vulnerability on soapstone, employing climate-based damage functions as a means to quantify and manage this peril. Soapstone, as other geomaterials, is characterized by porous structures and are susceptible to multiple freeze-thaw (F-T) cycles, particularly during cold seasons in temperate regions Ruedrich et al. (2011). These cycles involve the transformation of liquid water into ice within the pores, leading to mechanical fatigue damage. This damage mechanism entails the formation of cracks in the material and structural components due to the cyclic stress induced by the expansion of the soapstone when ice forms within the pores or pre-existing cracks Bertolin and Cavazzani (2022). The likelihood of fatigue damage, akin to the effects of repetitive tensile loading on the material's surface, increases with a higher number of F-T Liu et al. (2015). The F-T process could have a noteworthy impact by intermittently serving as a high-intensity event that can either generate openings within pores and fractures or facilitate the detachment of materials. Two notable European projects, the Noah's Ark project (2004-2007) Sabbioni et al. (2006) and the Climate for Culture (CfC, 2009-2015) Leissner et al. (2015) have highlighted the importance of study F-T cycle fluctuations in past, present and future to assess their impacts on the long-term conservation of stone materials/monuments. This study is primarily focused on the comparison of diverse climate data sources for assessing the F-T vulnerability of the soapstone geoheritage of the Valchiavenna. The data sources include ground-based weather stations managed by the Regional Agency for the Protection of the Environment (ARPA Lombardia) Maranzano (2022) and in-situ temperature-humidity dataloggers installed by the Milan University for a dedicated monitoring campaign carried out over the period from 2022/02/01 to 2023/01/31. The research explores the challenges of evaluating microclimate-induced degradation processes in geoheritage sites, confronting limited local data availability, and explores solutions to address the lack of clear data correction and validation guidelines, particularly in regions with complex topography.

2. Materials and methods

2.1. Parco Archeologico-Botanico del Paradiso

The Archaeological-Botanic "Parco del Paradiso", located in Valchiavenna, Italy, within the "Marmitte dei Giganti" natural reserve, features Alpine terrain which is influenced by altitude, proximity to water bodies, and valley orientations. The park is notable for its ancient soapstone trench quarry dating back to the Roman period, as well as a botanical itinerary featuring rare species and exotic vegetation, anomalous in an Alpine terrain. Fig. 1 illustrates the examined geographical region situated atop a hill in the northeastern vicinity of the city of Chiavenna. The valley in this region exhibits a pronounced north-to-south orientation, while the slopes exhibit gradients ranging from 340 m to 400 m above mean sea level (m.a.m.s.l.).

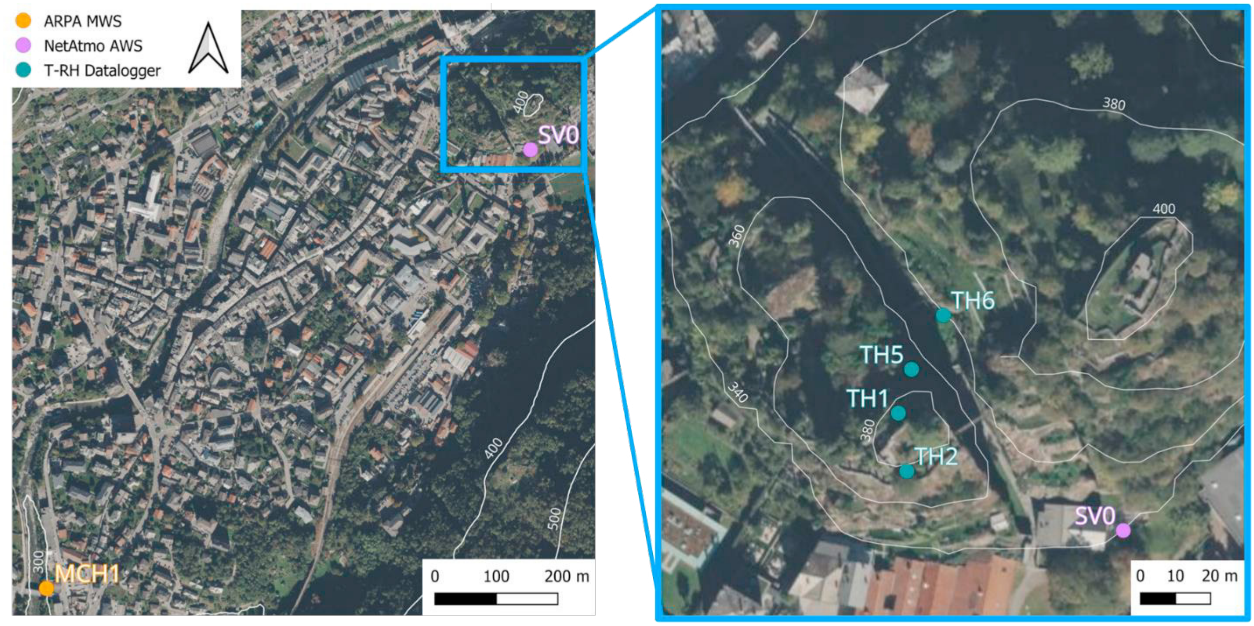

Fig. 1. The study area with a zoom window on Paradise Hill:, markers include an orange indicator for the Arpa Lombardia Mechanical Weather Station (MWS), a violet indicator for the University of Milan Automatic Weather Station (AWS), and teal markers for temperature (T) and relative humidity (RH) data loggers. The white lines are isopleths with indicated altitude in m a.m.s.l., the elevation data is sourced from a publicly available 5x5 meter DTM provided by Geoportale Lombardia. Basemap: Bing Maps Aerial (c) 2011 Microsoft Corporation and its data suppliers.

2.2. Climate datasets

Fig 1 reports, in the zoomed window, the thermo-hygrometric data loggers (i.e. TH1, TH2, TH5, TH6) installed by the Milan University to monitor the microclimate of the geoheritage gorge over a one-year period (February 2022-January 2023, later on defined as Monitoring period MOP). These dataloggers were strategically positioned approximately 10 cm from the outcropping rocks at a height of about 0.5 m above the ground. A NetAtmo automatic weather station (SV0) model NWS01-P named Valchiavenna Station of property of the Milan University that is also acquiring data in proximity to the monitored site since 2016 (Fig 1). Notwithstanding, a significant data gap existed for the more extended climatological period of the Distant Past (RRP) from 1961 to 1990 that could be used as reference in the environmental analysis. To overcome this data gap, historical ARPA mechanical weather station

(MCH1) data from a station located 1 km south-west, near the Lira River, within the same city, are used. This data supplementation consents to examine trends over the past, even though no data were available at the exact location during that period. The investigation examined three specific time intervals: the MOP, the Recent Past (RCP) encompassing the years 2016 to 2022, and the Distant Past (RRP). These intervals were selected, based on data accessibility and to facilitate a comprehensive temporal analysis of climate trends within the context of climate change. Data available from these sources are summarized in Table 1 with the ID of the station and dataloggers , the start-end dates and the period code, the elevation in meters above mean sea level (m.a.m.s.l.), the type of measured parameter and the continuity and completeness indices, assessing respectively gaps and observed data proportion, as calculated in Frasca et al. Frasca et al. (2017).

Table 1. Data from weather stations and dataloggers include IDs, dates, temporal period codes, elevation in meters above mean sea level, measured parameters, and continuity and completeness indices.

ID	Start-end	Period	Elevation (m.a.m.s.l.)	Data	Continuity	Completeness
MCH1	1961/01/01/-1990/12/31	RRP	301	T_{min}	1.00	0.80
				T_{max}	1.00	0.80
				Prec	1.00	0.83
SV0	2016/01/01-2023/01/31	MOP, RCP	363	T_{min}	0.98	0.93
				T_{max}	0.98	0.93
				Prec	0.97	0.84
TH1	2022/02/01-2023/01/31	MOP	376	T_{min}	0.99	0.91
				T_{max}	0.99	0.91
TH2	2022/02/01-2023/01/31	MOP	372	T_{min}	1.00	1.00
				T_{max}	1.00	1.00
TH5	2022/02/01-2023/01/31	MOP	358	T_{min}	1.00	1.00
				T_{max}	1.00	1.00
TH6	2022/02/01-2023/01/31	MOP	358	T_{min}	1.00	1.00
				T_{max}	1.00	1.00

To address missing data and erroneous readings in both SV0 and MCH1 climate series, a quality assessment and homogenization procedure was performed. In this process, nearby stations, specifically ARPA Automatic Weather Stations (AWS) and Mechanical Weather Stations (MWS) Maranzano (2022), were used as references to ensure the reliability and consistency of data for the target stations SV0 and MCH1. AWS data can be accessed on the following page: https://www.arpalombardia.it/temi-ambientali/meteo-e-clima/form-richiesta-dati/ (Last access on 30/06/2023) . Historical network data of MWS can be downloaded from the following portal: https://idro.arpalombardia.it/it/map/sidro (Last access on 30/06/2023). For SV0 data validation, 14 ARPA automatic stations from the ARPA Sondrio database were employed. All stations were selected within a 30 km radius from the target. Similarly, 11 mechanical stations were used for MCH1 data quality assessment and homogenization. Quality Assessment (QA) tests, including range, step, consistency, and persistence checks, were conducted before and after each homogenization step according to the thresholds reported in Estévez et al. (2011). The homogenization process comprised distinct phases: potential reference homogenization, reference selection, and target homogenization using the selected reference for each data series. Initially, data were gathered from ARPA Lombardia Automatic Weather Stations (AWS) and Mechanical Weather Stations (MWS) located within a distance of 30 km from Chiavenna. For MWS, daily maximum temperature (T_{max}), minimum temperature (T_{min}), and precipitation (Prec) were collected, while AWS data consisted of sub-hourly temperature and precipitation, subsequently aggregated into daily mean temperature (T_{avg}), T_{max}, T_{min}, and Prec. The data underwent an initial Quality Assessment test (QA-1), wherein individual parameter observations failing the test were eliminated and treated as missing values. The Climatol R package was employed for the homogenization of the potential reference series for each parameter, encompassing

T_{max}, T_{min}, and Prec Guijarro (2018). Subsequently, a second Quality Assessment test (QA-2) was applied to the homogenized series. Hierarchical clustering analysis, considering the correlation between time series derivatives for each parameter of MCH1 and SV0, was employed to identify suitable reference series for the target stations. The final homogenization of the target stations climate series, MCH1 and SV0, was performed again using the Climatol R package Guijarro (2018), followed by a concluding Quality Assessment test (QA-3). This comprehensive procedure was undertaken to ensure data reliability and consistency, enabling accurate computation of F-T cylces and facilitating meaningful comparisons in the analysis of climatic trends.

2.3. Freeze-thaw indexes

In literature, a straightforward index involves counting freeze-thaw cycles when the temperature crosses 0°C within a specified time frame Brimblecombe et al. (2011). In this study four different risk indexes have been used as follows. The annual freeze-thaw cycle (FT_{avg}) count was determined using daily average temperature data, with a cycle starting when the temperature fell below 0°C one day and rose above 0°C the day after. Furthermore, an index (FT_{Mnx}) was computed based on daily maximum and minimum temperatures, with cycles identified when the minimum temperature was below 0°C and the maximum temperature was above 0°C on the same day. The concept of effective freeze-thaw cycles (FT_{eff}) was also applied, utilizing a criterion of a minimum temperature below -3°C and a maximum temperature above 1°C on the same day Brimblecombe et al. (2011). Wet frost days (WFD) are calculated by counting the number of days when rainfall exceeds 1 mm/day and maximum temperatures is above 0°C, followed immediately by a day where the minimum temperature falls below 0°C within a specific year as adapted for this study from Grossi and Brimblecombe (2007). A different threshold is applied with respect to the aforementioned paper since the objective is to understand the worst-case scenarios.

3. Results and discussion

In Figure 2, the plot illustrates certain parameters of the climate data series after undergoing a validation and homogenization process. In particular, Figure 2a shows data from the MCH1 and SV0 weather stations, highlighting generally high validity values, exceeding 80% for the original data (grey bar in Figure 2a). The remaining percentage has been successfully imputed during the homogenization process (cyan bar in Figure 2a). Notably, there is an exception observed for the minimum temperature data at the MCH1 station, which required correction for the most recent data due to the identification of a breakpoint on 1979/02/01 (violet bar in Figure 2a). Figure 2b, on the other hand, displays the root mean square error (RMSE) between raw and validated data.

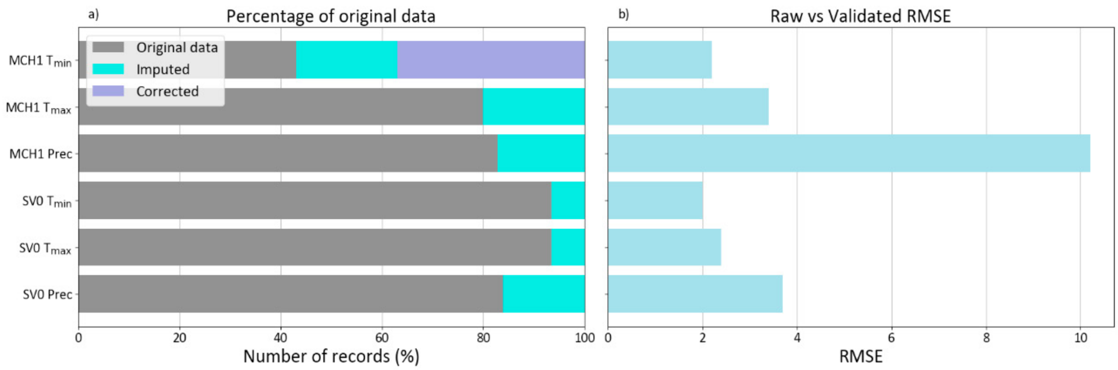

Fig. 2. The dataset obtained after the homogenization process. a) Percentage of original (grey), imputed (light blue), and corrected (violet) data for each variable at the target station MCH1 and SV0. b) Root-mean-squared error between raw data series and corrected data.

In MOP (TH1, TH2, TH5, TH6 and SV0), the count of freeze-thaw (F-T) cycles is notably low, with FT_{Avg}, FTeff, and WFD all registering at 0 events (Fig. 3a). Intriguingly, FT_{Mnx} indicates the potential for freeze-thaw events to occur in the vicinity of the geosite under study, but this phenomenon is observed only in specific locations. Specifically, these events are more likely to occur in the north-facing area of TH1 (green cell in Fig. 3a) at the hill's summit, as well as in TH6 (blue cell) and TH5 (violet cell) within the trench quarry. Figure 3b displays the typical thermal years for MCH1 (black thick line, averaged over a 30 year climatic reference period) and SV0 (blue thick line, averaged over 7 years), with overlaid values of monthly average, maximum, and minimum temperatures for each monitoring month retrieved by dataloggers. It is noteworthy that, in the vicinity of exposed rocks, summer temperatures exceed the historical yearly averages from recent and remote reference periods. A comparable, though attenuated, effect is observed in winter months for minimum temperatures. This disparity in temperature profiles accounts for variations in monitoring cycles among different thermos-hygrometers, attributed to their differing exposure and proximity to exposed rock formations.

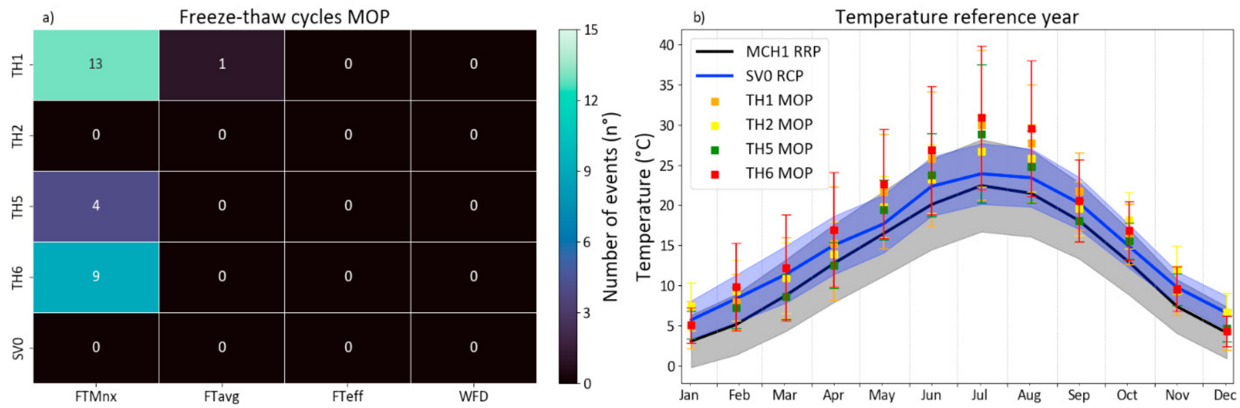

Fig. 3. a) Heatmap illustrating the number of Freeze-Thaw (F-T) cycles using various counting methods for dataloggers (TH1, TH2, TH5, TH6) and the AWS SV0 during the MOP monitoring period. b) Typical thermal years for MCH1 (black thick line, averaged over a 30-year climatic reference period) and SV0 (blue thick line, averaged over 7 years), with superimposed monthly average, maximum, and minimum temperatures as recorded by the dataloggers for each monitoring month.

The choice of methodology for counting cycles, whether utilizing average temperature (FT_{Avg}) or maximum and minimum temperatures (FT_{Mnx}), exerts a significant influence on the computed annual cycle counts when analyzing ground-based climate data (Fig. 4). When employing FT_{Mnx}, for the RRP dataset, the analysis revealed a total of 1116 cycles over 30-year-long period (mean=37.2 cycles per year, maximum=61 cycles, Figure 4a). Conversely the utilization of FT_{Avg} yielded a total of 93 cycles over a 30-year-long span (mean=3.23 cycles per year, maximum=8 cycles per year, Figure 4b). Employing the FT_{Mnx} methodology for the same station identified a total of 23 cycles within the RRP dataset, with an annual average of 3.28 cycles (see Figure 4c) and a maximum of 13 cycles observed in the year 2016. When average daily temperature data was input into the FT_{Avg} framework, the analysis yielded a total of 3 cycles over a seven-year-long period in the RCP dataset, with a maximum of 1 cycle occurring in any given year, resulting in an annual average of 0.43 cycles (see Fig. 4d). The process of homogenization and validation of climate data has therefore been proven to be invaluable in addressing the underestimation of freeze-thaw cycles, which can reach levels as high as 15.7% for MCH1 and 17.5% for SV0, primarily due to missing data.

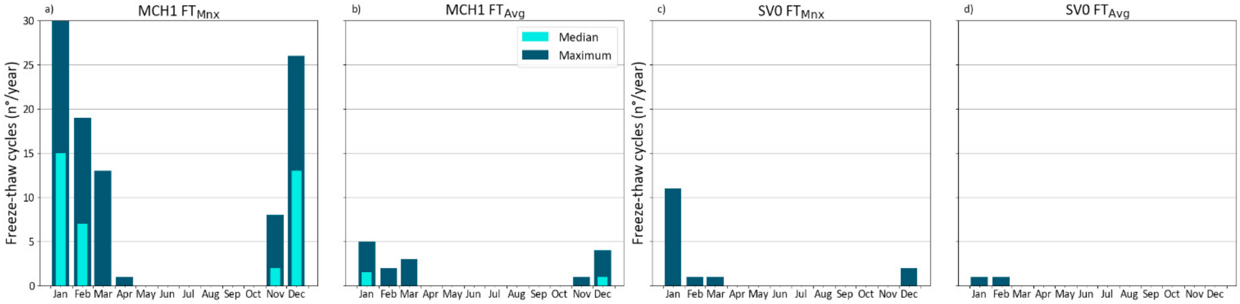

Fig. 4. Monthly bar plots indicating the count of Freeze-Thaw (F-T) events. Dark blue bars represent the monthly maximum values, while light blue bars represent the medians for: a) MCH1 Station - FT_{Mnx}, b) MVCH1 - FT_{Avg}, c) SV0 - FT_{Mnx}, d) SV0 - FT_{Avg}. MCH1 counts are relative to the 30-year period RRP, while SV0 counts are relative to the 7-year RCP.

To assess the trend in the past and recent periods, linear interpolation was performed using FT_{Mnx} (Figure 5a-c) and WFD data (Figure 5d). By examining the slope of the interpolating line, one can infer whether the number of F-T has increased, decreased, or does not exhibit a trend. This analysis was extended to all AWS and MWS stations utilized during the homogenization phase, and the slope was plotted as a function of the station's elevation for comprehensive analysis (Figure 5c-d). The analysis of freeze-thaw cycles over time reveals a decreasing trend for both target stations (Figure 5c). Notably, SV0 has limited available data years. Examining the slope of the interpolating line, it becomes evident that the trend is less clear for the AWS stations but consistently decreasing for the MWS (Figure 5c-d). This suggests a decreasing number of freeze-thaw cycles over the years, with a more pronounced decrease at higher elevations. Additionally, there is a more observable decrease in WFD (Figure 5d).

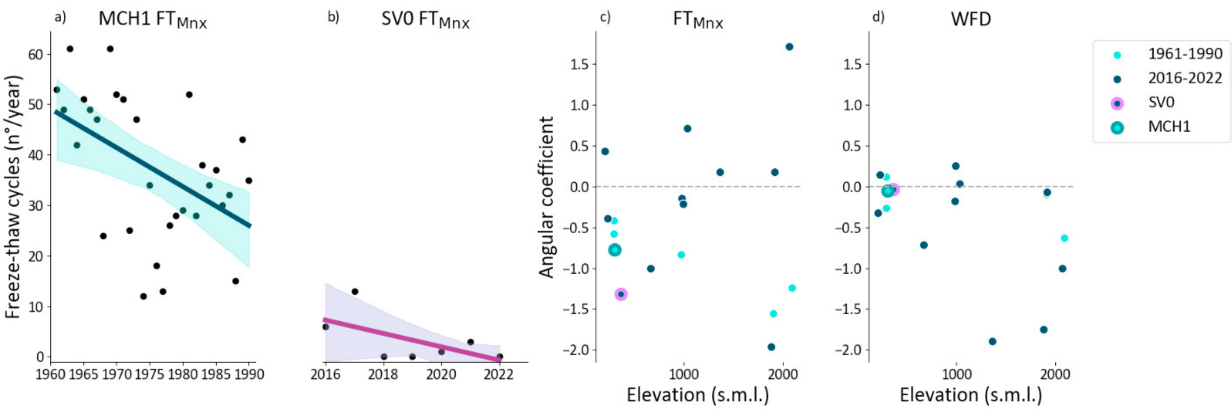

Fig. 5. a) Number of freeze-thaw cycles per year for station MCH1 calculated with FT_{Mnx}, with a trendline obtained through linear interpolation. b) "Number of freeze-thaw cycles per year for station SV0 calculated with FT_{Mnx}, with a trendline obtained through linear interpolation. c) Slope of the trendlines for each station used in the homogenization process as a function of elevation for cycles counted using FT_{Mnx}. d) Slope of the trendlines for each station used in the homogenization process as a function of elevation for cycles counted using WFD.

4. Conclusions

Studying F-T effects on stone heritage is crucial for material preservation and visitor safety. In this work, there is a difference in the count of annual F-T occurrences depending on the freezing and thawing thresholds and the initial dataset, considering whether it includes T_{avg}, T_{max}, or T_{min}. The rocks in the Parco del Paradiso, specifically those from the old soapstone quarry, experience limited freeze-thaw cycles, predominantly in the north and northwest-facing areas. The imputing and homogenization processes of temperature data have proven valuable for estimating F-T occurrences and studying the impact of climate change on both the geoheritage and its surroundings. In fact, there is an observed trend in the number of freeze-thaw cycles in Valchiavenna, influenced by the elevation. Over the years, the number of cycles has decreased, particularly at elevations above 1500 m. In future studies, the thermo-hygrometric datasets processed in this study will be utilized to assess additional damage functions in a multi-risk scenario.

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