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Freeze-thaw risk in solid masonry: The difference between a climate-based and response-based analysis to study climate change.

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Freeze-thaw risk in solid masonry: The difference between a climate-based and response-based analysis to study climate change.

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Abstract. Climate change (CC) has an impact on freeze-thaw degradation in historical buildings. The changing risk is not uniform over Europe according to climate-based analyses (i.e. only using climate data). Though, degradation risks are highly affected by building parameters (e.g. wall composition, material properties…). Response-based analyses (i.e. using hygrothermal simulation results) account for building parameters, and are more detailed. Nonetheless, they are not state-of-the-art for large domains given the high computational cost. Therefore, we compared a climate-based and response-based analysis for 10 locations in Europe and the Mediterranean, focussing on the critical Freeze-Thaw Cycles (FTC) in solid masonry walls. This paper presents the CC impact for 1.780 building parameter variations at each location. The Spearman rank correlation is 0.79 between the absolute values of the climate-based frost-indices (i.e. frost decay exposure index and FTC based on air temperature (FTC_{air})), and the critical FTC in the brick masonry. The correlation of the change in freeze-thaw risk is weaker (0.33 for FTC_{air}). The error when using a climate-based analysis to represent the CC impact goes up to 100%. Alongside, the climate-based analysis cannot represent the spread of the CC impact between different parameter variations. The climate-based analysis is only suitable as an estimation.

1. Introduction

Climate change (CC) influences the durability of heritage buildings. UNESCO listed a range of CC related issues for heritage buildings, such as changes in the risk for freeze-thaw damage, biochemical degradation, salt weathering etc. [1].

The change in degradation risks in historical buildings has been mapped by several studies [2]–[5]. In two European projects, i.e. ‘Noah’s Ark’ and ‘Climate for Culture’, an atlas have been developed to illustrate the change in degradation risks over Europe, such as freeze-thaw action, decay of wooden elements, salt crystallization, biological growth etc. Moreover, Grossi et al. studied the risk for frost-related damage [4], and salt efflorescence [5] in European heritage buildings.

These studies [2]–[5] are climate-based analyses, meaning that they are based on climate data alone. However, the hygrothermal performance of the building envelope, and therefore the risk for degradation, is highly dependent on the specific combinations of building parameters (e.g. wall composition, material properties…) [6], [7]. A response-based analysis, including hygrothermal simulation results, provides a more detailed assessment of the CC impact, at a high computational cost.[1]

There are response-based analyses to assess the risk for freeze-thaw damage in historical buildings [6]–[11]. Generally, these studies only include one location, or a few locations within the same country, and focus on a very narrow set of parameter variations (e.g. one solid masonry wall with and one without interior insulation). However, the hygrothermal performance of building envelopes, as well as the change in degradation risk due to CC, is highly sensitive to parameter variations [7], [12].

It remains unclear what the specific added value of a response-based analysis is compared to a climate-based analysis, especially when studying a large domain. Therefore, we assessed the difference between both approaches over Europe and the Mediterranean.

In section 2, the climate data and simulation set-up are introduced. The climate-based analysis and response-based analysis are presented in section 3 and section 4, respectively. The difference between both approaches is discussed in section 5.

2. Methods and materials

2.1. Climate data

The climate data, which are provided by the Climate Service Center Germany, originates from the REMO Regional Climate Model (RCP) coupled to the ECHAM5 Global Climate Model (GCM) for Representative Concentration Pathway (RCP) 4.5. Two time periods of hourly climate data are studied, i.e. the historical period (1960-1989) and the projection (2070-2099), at 10 locations across Europe and the Mediterranean. The locations are situated in different climate zones according to the Köppen-Geiger classification (Figure 1) [13]. Note that the data are not bias-corrected.

2.2. Simulation set-up

Hygrothermal simulations (one-dimensional) are performed in Delphin 6. The solid masonry walls are studied at the 10 locations for the two time periods, and a range of parameter variations. The full factorial study consists of 34.560 simulations in total.

Two types of solid masonry walls, i.e. with/without interior insulation, are studied (Figure 2). It is varied over the masonry thickness (300, 400, and 500 mm), insulation thickness for the insulated walls (50, and 150 mm), and brick type (ZB, ZE, ZF, ZH, ZI, and ZK (Delphin material library)). Further, it is varied over the 8 main orientations (from 0° (north) to 315° (north-west), every 45°), and 4 rain exposure coefficients (0.5, 1.0, 1.5, and 2.0). The brick masonry is considered as a homogenous brick layer, a valid simplification according to Ref. [14]. The remaining parameters are kept constant.

Note that ca. 1% of the simulations did not converge. The convergence problems mostly occur in the north of Europe during wind-driven rain evens when ice is present in the pore matrix.

3. Climate-based analysis

The climate-based analysis is performed for 8 indices, as listed in Table 1. The annual climate-based indices are computed for each year in both 30-year periods (i.e. historical period and projection). For each individual climate-based index and time period, the 90th percentile of the annual values is selected, which corresponds to conditions with a 10 year return period. Please find the equation for these indices in Vandemeulebroucke et al. [15].

In the north of Europe (i.e. climate zones Cfb (Brussels), Dfb (Berlin), Dfc (Helsinki), and ET (Bodø)), the WDR_{crit} is projected to increase between +3% and +15%. The WDR_{crit} tends to decrease in the south of Europe (i.e. climate zones BSk (Valencia), Csa (Athens), Csb (Madrid), and Cfa (Milan)),

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[1] The ‘Climate for Culture’ project also includes hygrothermal whole-building simulations. However, these simulations account for the building envelope in a simplified way. The simulations are focussed on the indoor environment, and the degradation risks for indoor collections.

with -12% to -32%. For the arid desert climate zones (Cairo and Bouarfa), the WDR_{crit} tends to decrease as well, though values are generally low. Note that the WDR_{crit} is only computed during temperatures above -2°C.

The direction of the CC impact is similar for MI and CI, which are a function of wetting and drying. Both climate-based indices use the WDR_{crit} as wetting load. Yet, the magnitude of the change differs between WDR_{crit}, MI, and CI.

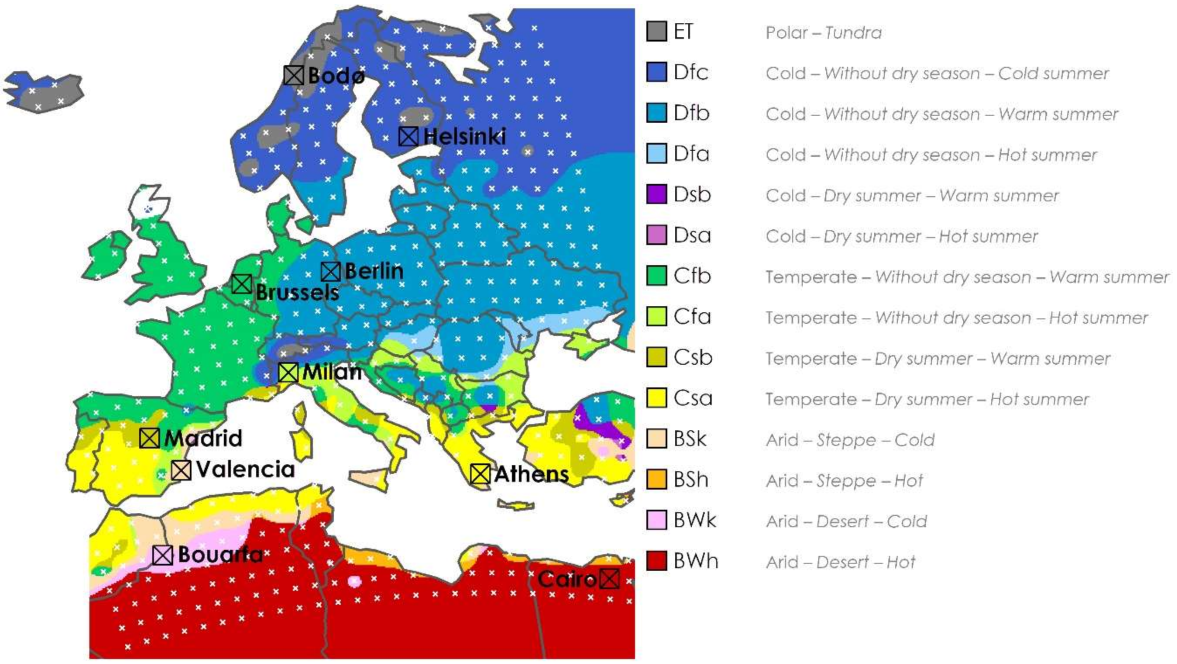


Figure 1. The 10 locations are selected from 474 grid points (white stars). The climate zones are computed based on [13] for the 474 grid points and studied GCM-RCM (Figure modified from [16]).

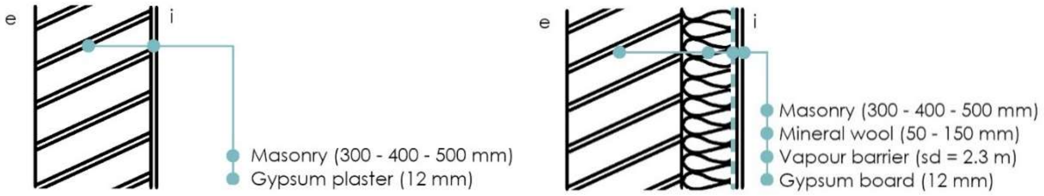


Figure 2. Next to variations in wall configuration, masonry thickness, and insulation thickness, it is also varied over brick type and rain exposure coefficient (Figure modified from [16]).

Table 1. Climate-based indices.

Name	Abbreviation	Reference
Wind-driven rain load from the critical orientation	WDR_{crit}	EN ISO 15927-3
Moisture Index	MI	[17]
Climatic Index	CI	[18]
Severity Index	I_{sev}	[19]
Mould index of the outdoor air conditions	M_{air}	[20]
Frost Decay Exposure Index	FDEI	[21]
Freeze-Thaw Cycles of the outdoor air conditions	FTC_{air}	[4]
Wet Frost	WF	[4]

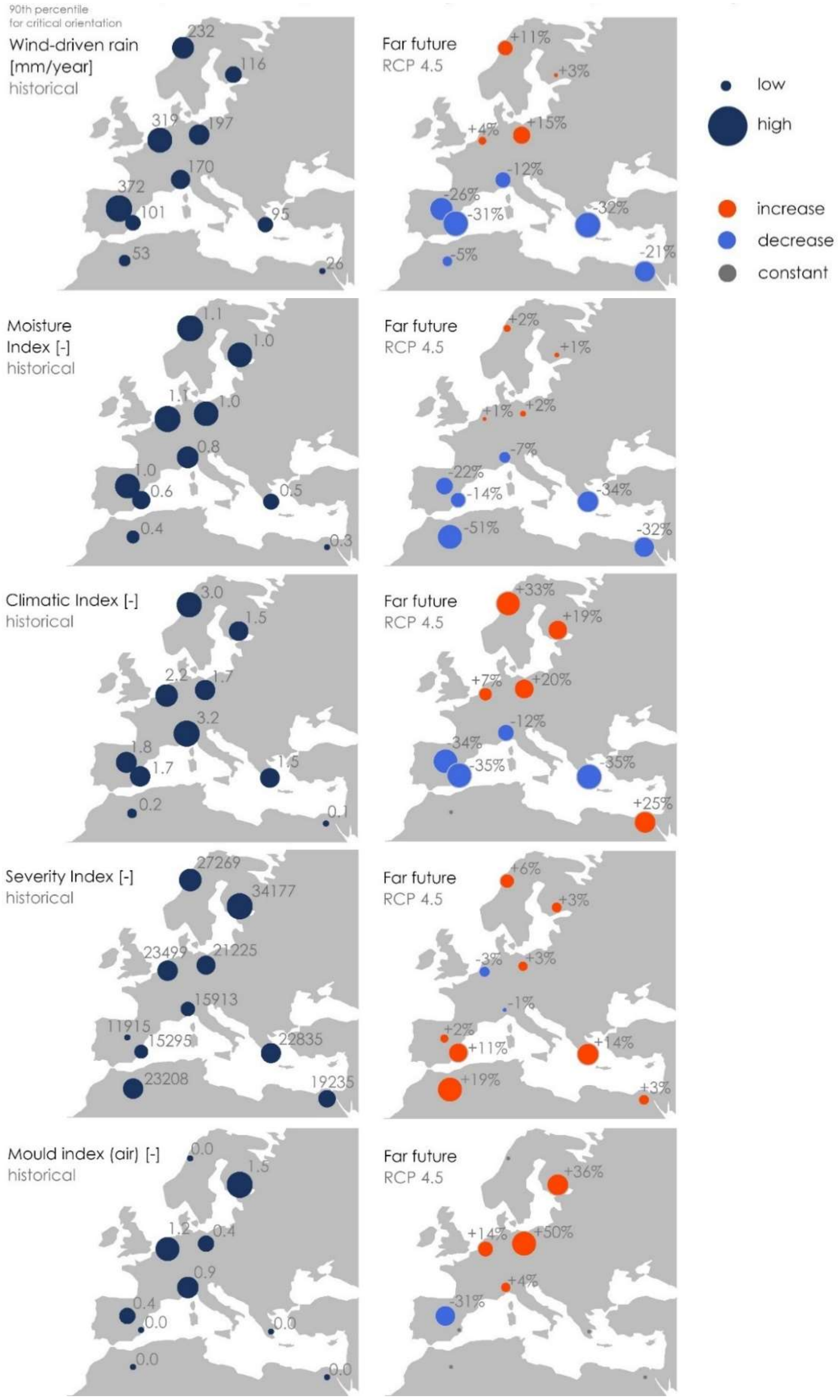
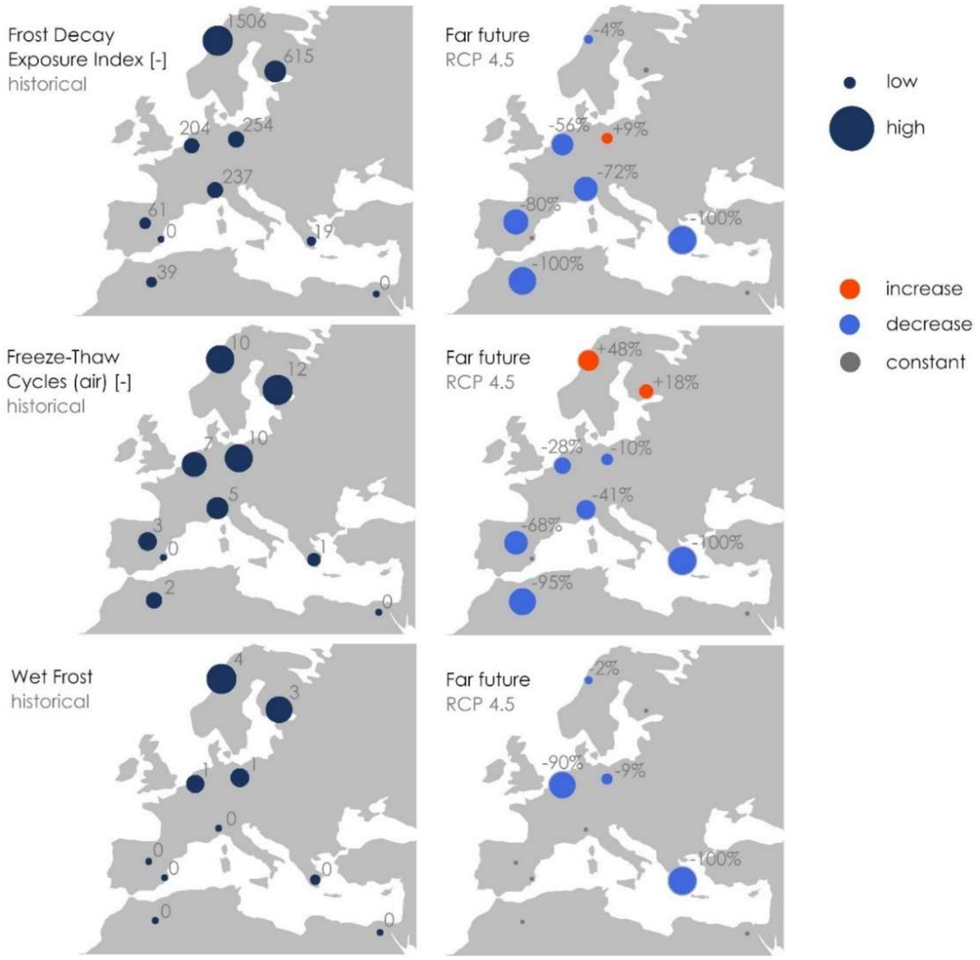


Figure 3. The impact of CC is not uniform over the studied domain. Further, the different climate-based indices result in a different direction and magnitude of the CC impact for most locations. (Figure modified from [16]).



(Figure 3 continued)

I_{sev}, which is the climate-based prediction of the RHT-index for a north-facing wall, is projected to change between -3% and +19%. There is an increase for all climate zones, except the temperate climates without dry season (Milan and Brussels). Further, M_{air} is the mould index based on the air temperature and relative humidity. The M_{air} increases for Cfa (Milan), Cfb (Brussels), Dfb (Berlin), and Dfc (Helsinki) up to +50%, and decreases for Csb (Madrid) with -31%.

The three climate-based indices using frost events as an indicator are the FDEI (i.e. based on the 4-day precipitation load followed by freezing days), FTC_{air} (i.e. number of daily temperature cycles around the freezing point), and WF (i.e. the number of days of 2 mm precipitation followed by days with temperatures below -1°C). The frost-based indices generally decrease over the studied domain up to -100%. Though, the FTC_{air} is projected to increase with +18% and +48% for Dfc (Helsinki) and ET (Bodø) respectively, and the FDEI increases with +9% for Dfb (Berlin).

Generally, the locations in the north of Europe are projected to sustain a higher risk for degradation problems for the studied GCM-RCM chain and RCP scenario. In the south of Europe and the Mediterranean, the risk for degradation tends to decrease. In the intermediate region, the direction of the CC impact is less clear. Moreover, the magnitude of the change is considerably different between the climate-based indices.

4. Response-based analysis

For the response-based analysis, the number of critical Freeze-Thaw Cycles (FTC_{crit}) is the chosen degradation indicator in this paper. The annual number of FTC_{crit} is studied at 5 mm depth within the masonry. A cycles is counted at each time that the ice mass density exceeds a critical threshold value.

The threshold value is considered to be 25% of the open porosity of the brick material. This arbitrary value is the lowest measured critical saturation degree when freeze-thaw damage occurs in historical brick stones [22]. From the 30 years in each time period, the 90th percentile value is used in this study. This corresponds to a year with a return period of 10 years in terms risk for frost damage.

The response-based analysis is performed based on different approaches. As an indicator of the overall behaviour of the different parameter variations (referred to as 'cases'), the median value per location during the historical period and the median of the change are considered (Figure 4). Alongside, the percentage of cases with an in/decrease between the historical and projected period is assessed (Figure 5). Moreover, the distribution of the results for all cases for per location is studied (Figure 6).

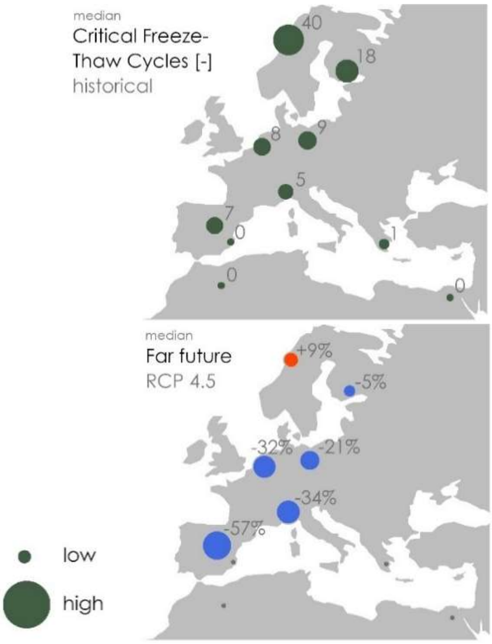


Figure 4. The median change in critical freeze-thaw cycles is generally decreasing. (Figure modified from [16]).

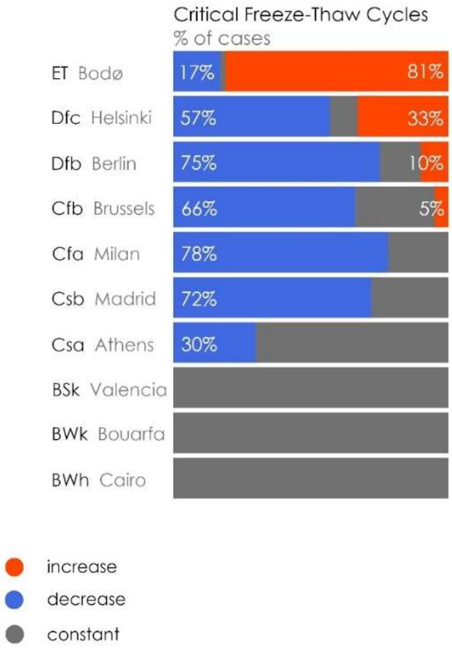


Figure 5. The percentage of cases (i.e. parameter variations) with an in/decrease is not uniform over Europe. (Figure modified from [16]).

The median FTC_{crit} is the highest in the north of Europe, i.e. 18 and 40 cycles in Dfc (Helsinki) and ET (Bodø), respectively (Figure 4). In the Mediterranean, there is no risk for freeze-thaw damage (i.e. arid climate zones). In the intermediate region, the median FTC_{crit} ranges between 5 and 9 cycles.

For the majority of the locations, the risk for freeze-thaw damage decreases (Figure 4). The median changes ranges between -5% and -57% in Dfc (Helsinki) and Csb (Madrid), respectively. On the other hand, there is a median increase in FTC_{crit} of +9% in ET (Bodø). Note that the using the median value of the distribution leads to similar issues as with the climate-based indices. Though, the median has only been considered in Figure 4 as a first estimation of the degradation risk.

Further, the percentage of cases with a decreasing FTC_{crit} is between 66% and 78% in Csb (Madrid), Cfa (Milan), Cfb (Brussels), and Dfb (Berlin) (Figure 5). The share of cases with decreasing values is lower in Dfc (Helsinki), i.e. 57% of the cases, and significantly lower in ET (Bodø), i.e. 17% of the cases. Though, the percentage of cases with an increasing risk for freeze-thaw damage increases towards the north: 5% in Cfb (Brussels), 10% in Dfb (Berlin), 33% in Dfc (Helsinki), and 81% in ET (Bodø).

The spread of the CC impact can be large, as is illustrated in Figure 6. The decrease in FTC_{crit} goes up to -100%, and is strictly negative for the locations in the south of Europe. For Cfb (Brussels), Dfb (Berlin), Dfc (Helsinki), there are individual cases with a very large relative increase. The distribution of the change can be both positive and negative, indicating an increase or decrease, respectively.

In general, the risk for freeze-thaw damage is higher in the north of Europe, whereas there is no freeze-thaw risk in the Mediterranean. Furthermore, the change in FTC_{crit} is strictly negative in the south of the domain, whereas almost all cases show increasing values in the north. The change is less uniform in the intermediate region.

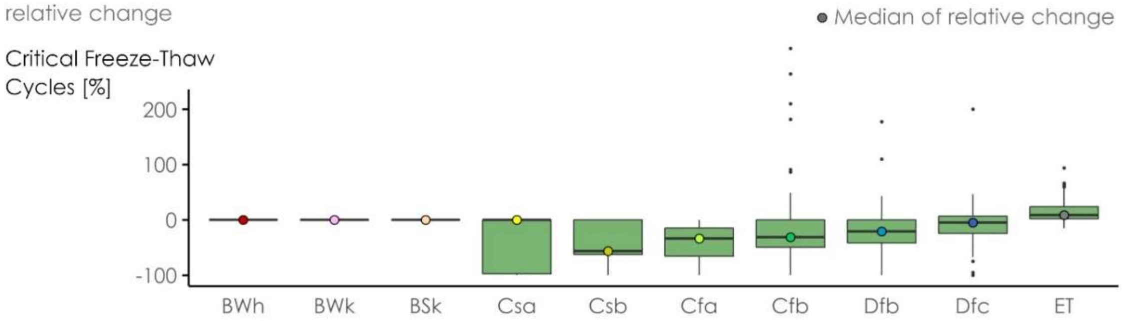


Figure 6. The range of the relative change in critical freeze-thaw cycles for the different cases (i.e. simulated parameter variations) is quite large. (Figure modified from [16]).

5. Discussion and conclusions

There is a link between the climate-based analysis and response-based analysis, as they both result in a similar general conclusion. Though, the magnitude of the change differs between the climate-based indices and FTC_{crit}, and even in between the individual climate-based indices.

Further, there is a correlation between climate-based indices and the response-based index (i.e. FTC_{crit}) when considering the absolute values of the indices. The spearman rank correlation coefficient is the largest for FDEI and FTC_{air} with a value of 0.79. WDR_{crit}, MI, CI, and WF also result in values higher than 0.60. The correlation is low for I_{sev}.

The correlation is weaker for the change in climate-based indices compared to the change in FTC_{crit}. The highest spearman rank correlation coefficient is obtained for I_{sev} (0.44), which is unexpected since there is no apparent reason why it would perform best. FTC_{air} is ranked in the second place (0.33).

The range of the error between the change in climate-based indices and change in FTC_{crit} is the smallest for MI (4 – 57%), followed by WDR_{crit} (5 – 61%). For the frost-related indices, the range of the error goes from 0% to (nearly) 100%.

Moreover, the climate-based analysis results in a single value per location and per index. The change is either positive, negative or zero. The response-based analysis, on the other hand, produces a distribution including many parameter variations. The change can be positive for some parameter combinations, and negative for others. The spread in CC signal is quite high at certain locations. To illustrate, the FTC_{crit} changes between -62% and +1% (10th and 90th percentile of the change) in Dfb (Berlin), whereas the change in the climate-based FTC_{air} is the single value -10%. The climate-based analysis is unable to represent the spread of the CC impact over a range of parameter variations.

The added value of a response-based analysis is most apparent in regions with large variations between the parameter combinations. Especially in Cfb (Brussels), Dfb (Berlin), and Dfc (Helsinki), the CC signal varies between the parameter combinations.

Furthermore, this study is performed using 1 GCM-RCM chain and 1 RCP scenario, as it focusses on the difference between a climate-based and response-based analysis. The spread of the change in risk for freeze-thaw damage is completely attributed to the parameter variations. Though, climate models have to deal with uncertainties due to physical parameterizations, numerical approaches, emission uncertainties, climate variability etc. For a complete study of the CC impact on degradation risks, an ensemble of models and RCP scenarios should be accounted for.

In future research, the climate vulnerability should also be monitored in existing buildings. To facilitate this (e.g. decide on monitoring locations, degradation criteria…), the degradation risks should be mapped on building envelopes by means of hygrothermal modelling, and validated with observations.

Table 2. Correlation and error between climate-based indices and the FTC_{crit}.

	Spearman rank correlation coefficient with FTC_{crit}[a]		*Range of error with* FTC_{crit}[a,b]
	Absolute values	Relative change	Relative change
WDR_{crit}	0.61	0.05	5 – 61%
MI	0.73	0.00	4 – 57%
CI	0.63	0.25	0 – 64%
I_{sev}	0.27	0.44	3 – 67%
M_{air}	0.55	-0.14	0 – 83%
FDEI	0.79	0.11	0 – 100%
FTC_{air}	0.79	0.33	0 – 95%
WF	0.66	0.08	0 – 90%

[a] based on complete distribution of results; [b] 10th percentile of error – 90th percentile of error %

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