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Deciphering Freeze–Thaw Dynamics In Rockwalls: A Novel Approach for High Accuracy Regional-Scale Modeling

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ABSTRACT

Using a large and novel array of instruments on five rockwalls in northern Gaspesia, their respective surface energy balances were calculated and their thermal regimes were measured and modeled to depths exceeding the seasonal frost penetration. A parametric analysis of the thermal properties and structural characteristics of the instrumented rockwalls was then performed. The roles of solar radiation exposure, surface thermal absorptivity, lithology, and fracture pattern on the distribution of episodic freeze–thaw cycles and on the seasonal frost distribution over a winter were quantified. The fine spatiotemporal scale of our measurements and models revealed complex thermal configurations in the first meters of rockwalls, including frozen layers sandwiched between thawed ones and vice versa. Freeze–thaw cycle frequency was primarily driven by solar radiation exposure and surface absorptivity, while seasonal frost penetration was strongly influenced by lithology and fracture pattern. The parametric analysis based on thermal and structural properties representative of the study area enabled us to extrapolate a local thermal regime model to a regional scale without needing to instrument as many sites as there is diversity in exposure, absorptivity, lithology, and fracture patterns. Other parameters, such as slope inclination, snow accumulation, and climate warming, can also be tested with this approach. This hybrid method, which combines field measurements and modeling, is intended to quantify the thermal regime of multiple rockwalls more accurately than spatial modeling and climate reanalyses, while drastically reducing the effort, cost, and risk of conventional instrumentation. It could represent a valuable tool for regional hazard management strategies.

1 | Introduction

Frost processes are recognized as key drivers of rock instabilities in permafrost regions, for example, [1, 2], as well as in environments experiencing seasonal frost (SF), for example, [3, 4] or diurnal frost [5, 6]. These processes can induce rock damage through either the volumetric expansion of freezing water [7] or ice segregation [8]. The first mechanism requires temperatures below freezing and rock water saturation exceeding 90% [7], while the second operates within specific “frost cracking windows” determined by rock strength [9, 10]

and occurs regardless of moisture content [10, 11]. In both cases, irreversible damages (microcracking) are driven by the formation of micro-ice-lenses in rock pores and discontinuities and occurs when the forces exerted by crystallization pressure exceed the rock's tensile strength [12–14]. However, since ice–rock adhesion tends to keep newly damaged rock stable, rockfalls are most frequently triggered during thaw phases [15, 16].

Transportation corridors built along rock outcrops worldwide are frequently impacted by rockfalls, for example,

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[17–24]. In the northern Gaspé Peninsula (eastern Canada), over 17,000 rockfalls hit the roads between 1987 and 2020 [25]. The region's freeze–thaw (FT) dynamics largely govern the frequency and magnitude of these events during winter mild spells and spring thaws [3]. Quantifying these dynamics is crucial for understanding frost weathering processes [26] and could help to pinpoint periods of increased tensile stress within rock pores and shear stress along discontinuities (during the cycle's freeze phase) and periods prone to instability (during the cycle's thaw phase). Additionally, measuring the depth of SF or permafrost active layer offers valuable indicators of potential rock instability triggered by frost processes [3, 4, 8, 27, 28].

Temperature sensors are commonly used to measure rockwall thermal regimes, but their deployment is typically limited to shallow depths [4, 29–35]. This limitation hinders their ability to track (1) high-amplitude FT cycles and (2) SF evolution in rock masses or the permafrost active layer. Extending measurements to greater depths is technically challenging due to high costs, accessibility issues, and rockfall hazards [3]. Modeling has offered valuable insights into the spatial distribution of permafrost as influenced by factors such as altitude [28, 36, 37], snow cover [38, 39], slope exposure [28, 36–38], rock mass anisotropy [38, 39], and climate change [40–43]. However, most studies focus on large-scale trends, leaving fine spatiotemporal variability insufficiently resolved. Climate re-analyses, such as MERRA-2 (~50 km), ERA5 (~30 km), and ERA5-Land (~9 km), similarly lack the spatial resolution to capture the thermal heterogeneity of steep and rugged terrain [44, 45]. Even high-resolution digital elevation models (e.g., ASTER-GDEM, ~30 m; RGD DEM, ~4 m) fail to fully capture the fine topographic variability typical of steep slopes, where thermal differences arise due to variations in exposure, slope angle, and snow cover, leading to temperature biases exceeding 2°C in steep slopes [46]. Despite its fine 4-m resolution, the RGD DEM tends to underestimate surface temperatures on sunlit slopes while overestimating those on shaded slopes [46]. [47] also demonstrate that the bias between simulations and observations varies with altitude. The magnitude of these biases limits our ability to model short-duration, decimetric FT cycles critical for understanding frost-induced rockfall risks. Surface rock temperature is influenced by multiple factors, including solar radiation and rock absorptivity [29, 48–51], snow cover [52–55], and vegetation [48], while heat transfer through rock is further modulated by thermal conductivity, capacity, and diffusivity, which depend on lithology and the degree of rock mass weathering [56]. Discontinuities in rock masses can enhance heat flux through air convection [57] or water advection [42, 58]; however, depending on their geometry and connectivity, cracks may also reduce conductive heat transfer by introducing poorly conductive air-filled zones [56]. Latent heat effects from water phase changes [59] further complicate thermal modeling.

Consequently, modeling the thermal regime of steep and hilly rock masses remains complex [54] and difficult to apply on a regional scale [60], especially at the fine spatiotemporal scale necessary for effective risk management. To address these challenges, we propose a novel approach that relies both on field measurements and modeling to better anticipate

frost-triggered rockfalls at a regional scale. Our strategy aims to analyze the spatiotemporal variability of FT cycles that would preclude the need for instrumenting as many sites as there are differences in exposure, absorption, lithology, and fracture configuration, without relying on down-scaled weather data and high resolution digital topographic model. To achieve this, we conduct our study on five rockwall sites, including one reference site (Manche-d'Épée [MAE]). Additionally, we introduce and discuss a refined FT cycle classification tailored to improve risk mitigation strategies and that could enhance the understanding of heat transfer processes and frost-induced rock fracturing.

2 | Study Sites

Five rockwalls on the north shore of the Gaspé Peninsula were instrumented (Figure 1). These glacially sculpted rockwalls [61] are composed of Ordovician flysch with alternating pluri-decimetric strata of sandstone, greywacke, siltstone, and pelagic shale [62, 63], along with localized Cambro–Ordovician conglomerates [64]. Haute-Gaspésie experiences a humid continental climate with short, cool summers [65]. At the Cap-Madeleine (CAM) weather station (Figure 1), the average annual temperature (1991–2020) was 3.9°C, with July and January averages of 16.3°C and −9.2°C, respectively. Annual precipitation averaged 888 mm, 33% of which fell as snow [66]. The five selected sites represent the diversity of roadside rockwalls based on structural and lithologic characteristics, solar exposure, rockfall frequency reaching the road, and year-round accessibility (Table 1).

3 | Methodology

The five rockwalls were instrumented to calculate their surface energy balance and simulate their thermal regime. From those measurements, we were able to (1) calibrate a thermodynamic model, (2) test the ability to simulate the thermal regime of sites with different characteristics from a reference site, and (3) perform a parametric analysis to test the respective roles of solar radiation exposure, surface thermal absorptivity, lithology, and fracture pattern on the freezing and thawing distribution. All parametric analysis simulations were based on the thermal properties and structural characteristics of the different instrumented sites which are transposed to the reference site (MAE).

3.1 | Rock Properties

To simulate the propagation of surface thermal signals to depth, a detailed understanding of site lithology was required. For each study site, the rock type, proportions, and average stratum thickness were quantified. Intact rock blocks, approximately 20 cm long, were sampled directly from rockwall surfaces: three blocks of conglomerate, seven of sandstone, seven of greywacke, nine of siltstone, and three of shale. Natural discontinuities in the stratified siltstone and shale facilitated sample extraction without inducing structural damage. At the LGGRM laboratory, sample volume, dry mass, and

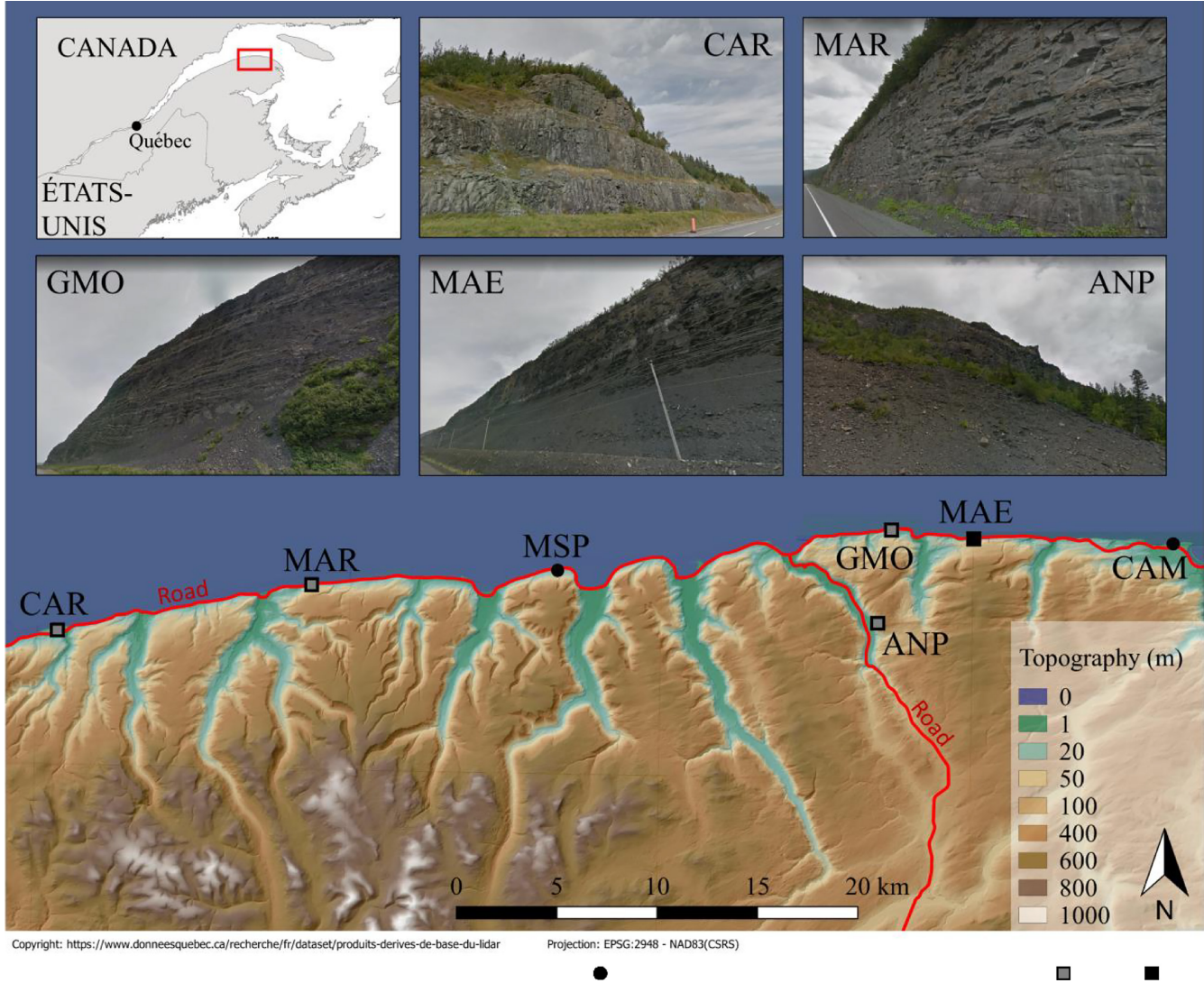


FIGURE 1 | Location map with ground-based (●) and rockwall weather stations (■ and ■ for reference site). From west to east: Cap-au-Renard (CAR), Marsoui (MAR), Mont-Saint-Pierre (MSP), Gros-Morne (GMO), Anse-Pleureuse (ANP), Manche-d'Épée (MAE), and Cap-Madeleine (CAM).

TABLE 1 | Site characteristics.

Site	Height (m)	Orientation (°)	Inclination (°)	Geological structure	Rockwall type
Manche d'Épée, MAE, reference site	90	North-facing 350	Near vertical 80	Flysch with subhorizontal bedding	Natural
Cap-au-Renard, CAR,	20	Southeast-facing 130	Vertical 90	Homogeneous conglomerate	Blasted
Marsoui, MAR	25	North-facing 0	Vertical 90	Flysch with subhorizontal bedding	Blasted
Gros-Morne, GMO	70	Northwest-facing 330	Near-vertical 80	Flysch with subhorizontal bedding	Natural
Anse-Pleureuse, ANP	35	Southwest-facing 225	Near-vertical 80	Flysch with complex folded structure	Natural

water-saturated mass were measured to determine density and porosity, following [67] standards. Thermal properties were analyzed at the Laboratoire ouvert de géothermie (LOG) at

INRS-ETE using a LGM Lippmann TCSCAN infrared scanner [68]. Detailed procedures for calculating rock properties are further elaborated in [69].

3.2 | Meteorological Data

To drive the thermodynamic model, weather microstations were installed directly on five rockwalls. These stations measured air temperature, incident and reflected solar radiation perpendicular to the rockwall surface, as well as wind speed and direction (Figure 2). Incident and reflected longwave radiation, along with atmospheric pressure, was recorded at a conventional weather station located along the coast at the center of the study area (MSP, Figure 1). Thermistor strings installed in horizontal boreholes perpendicular to the rockwall surface measured the thermal regime. Temperatures were recorded at 0.3-m intervals up to 3-m depth for the CAR, MAR, and GMO rockwalls and up to 5.5-m depth for the MAE rockwall. The thermal regime at ANP was not measured in depth due to poor accessibility, but its weather station will be used for the parametric analysis. MAE was selected as the reference site since its thermistor depth (5.5 m) exceeded the maximum SF depth. Data were recorded every 15 min throughout the study period (October 1, 2019 to May 31, 2020). Linear interpolation between thermistors provided continuous temperature profiles of the

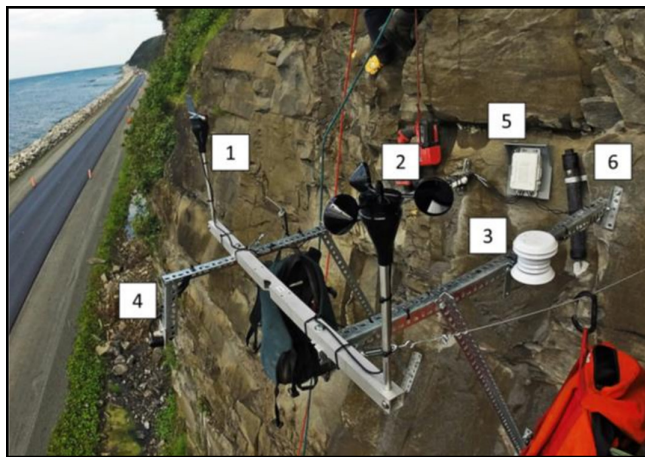


FIGURE 2 | Instrumented rockwall (MAR) including wind direction sensor (1), wind speed sensor (2), air temperature sensor (3), pyranometer (4), datalogger (5), and rock temperature thermistances (6).

TABLE 2 | Specifications of the meteorological and thermal sensors.

Data	Unit	Instrument (company)	Accuracy
Air temperature	°C	Air temperature sensor TMC6-HD + solar radiation shield M-RSA (HOBO by Onset)	± 0.25°C
Rock temperature	°C	Thermistor string 915 MHz + minilogger M-Log5W-DALLAS-US (Geoprecision)	± 0.25°C
Incident solar radiation Reflected solar radiation	W m ⁻²	Pyranometer S-LIB-M003 (HOBO by Onset)	± 10 W m ⁻²
Incident infrared radiation Reflected infrared radiation	W m ⁻²	Pyrgeometer SN-500-SS (Apogee Instruments)	± 8.5 W m ⁻²
Wind and gust speed Wind direction	m s ⁻¹	Wind speed and direction sensor S-WSET-B (HOBO by Onset)	± 1.1 m s ⁻¹ ± 5°
Air pressure	mbar	Barometric pressure sensor S-BPB-CM50 (HOBO by Onset)	± 5 mbar

rockwalls over time. Instrument specifications are detailed in Table 2.

3.3 | Rockwalls Thermodynamic Modeling

3.3.1 | From Local Weather Data

Weather conditions measured at MAE, MAR, GMO, and CAR were input into the WUFI Pro software to model surface temperatures hourly from October 1, 2019 to May 31, 2020. WUFI Pro is a user-friendly program designed for one-dimensional transient heat and moisture transfer [70]. Originally developed for evaluating the hygrothermal behavior of building materials under various climatic conditions, it has also been successfully applied to model the thermal regime and moisture in rock masses, for example, [56, 69, 71, 72]. The model is suitable for cold climates, accounting for FT mechanisms and latent heat during phase changes [70].

Once thermal conditions have been established at the rock-atmosphere boundary, the thermal regime was simulated to a depth of 20 m using a numerical grid with 1-cm resolution. At this depth, surface temperature variability is negligible, and only long-term climate changes influence the thermal regime [43]. The boundary condition at 20 m was set to a constant temperature, corresponding to the annual mean rock surface temperature recorded locally (4.6°C–6.7°C depending on site). In the absence of local measurements of saturation degree within the rock, a value of 80% was assumed for the entire modeled profiles, as suggested by Sass [72].

The simulated surface temperature was calibrated using locally measured temperatures, and the same protocol was applied for each depth where measurements allowed for the calibration of the models, by adjusting the thickness of rock layers with their specific properties. The combination of thickness and properties had to correspond to the geological units observed on the rockwall surface (Figure 1). Three statistical tests were applied: the coefficient of determination (R^2), bias (BIAS), and root mean square error (RMSE). The combination of these three statistical tests provides a comprehensive evaluation of model performance: R^2 indicates the proportion of variance explained by the model, bias reveals systematic errors, and RMSE quantifies the overall

deviation between observed and simulated values, ensuring a robust calibration of the thermal simulated regime. From a depth of 3 m for CAR, MAR, GMO and from 5.5 m for MAE, the average physical and thermal properties of shallower depths (1–3 m and 1–5.5 m, respectively) were applied down to a depth of 20 m.

3.3.2 | From Reference Site MAE

In this section, we assess the ability of the MAE-based model to reproduce the thermal regimes of the three other instrumented rockwalls (CAR, MAR, and GMO) by modifying single key parameters. The objective here is to validate the reference-site approach, demonstrating that the thermal regime of a noninstrumented site can be accurately modeled using MAE as a reference. Although some parameter choices are identical to those in the parametric analysis (Section 3.4), the goal here is model validation, not sensitivity analysis.

For MAR and GMO, which are north-facing rockwalls ($350^\circ \pm 20^\circ$), we applied the lithological configuration (thermal properties) of these sites to the MAE simulation. For CAR, which experiences distinct solar exposure due to its south-facing orientation, three sequential adjustments were tested: (i) replacing MAE's solar radiation data with CAR's, (ii) adding a modification to the 20-m baseline temperature to account for the warmer southern exposure of CAR, and (iii) incorporating CAR's lithological configuration in addition to the previous adjustments. These simulations were evaluated using R^2 , BIAS, and RMSE. This approach allowed us to quantify the model's ability to reproduce the thermal regimes of the other sites accurately, providing a robust foundation for the subsequent parametric analysis.

3.4 | Parametric Analysis

Building on the validated MAE-based approach, we performed a parametric analysis to quantify the influence of individual parameters on the thermal regime and FT cycle indicators. Here, the

objective is sensitivity analysis, not validation. Some simulations involve the same parameter modifications as in Section 3.3.2; however, in this context, they are included solely to evaluate the impact of specific parameters on the FT dynamics. Ten simulations were performed over the period October 1, 2019 to May 31, 2020, encompassing all subfreezing events of the season. In each simulation, one parameter from the MAE simulation was replaced with a parameter from another site (MAR, GMO, CAR, and ANP). Four parameters were analyzed: two affecting the energy absorbed at the rockwall surface (solar radiation and surface absorptivity) and two controlling the propagation of the thermal signal within the rockwall (lithology and fracture pattern).

1. Solar exposure: The MAE rockwall, facing north, remains in constant shadow from mid-October to mid-March. Solar radiation measurements from MAE were replaced with data from the southeast-facing CAR rockwall (MAE-SE) and the southwest-facing ANP rockwall (MAE-SW).
2. Surface absorptivity: The absorptivity at MAE (0.7) was replaced with the lower value measured at CAR (0.5), which has a lighter colored surface (MAE-abs[⊖]), and with a higher value (0.9), representing darker basalt from McGreevy (1985) in absence of a darker local rockwall (MAE-abs[⊕]).
3. Lithology: The combination of strata used in MAE was replaced with those of CAR (MAE-k1), MAR (MAE-k2), and GMO (MAE-k3).
4. Fracture pattern: Following Schnepfleitner et al. [56], we introduced 5-mm planar fractures parallel to the rockwall surface at 35 cm (MAE-crack35), 70 cm (MAE-crack70), or both depths (MAE-crack35-70), none of which connected with the surface (Table 3). Their placement within the first meter is supported by observations using a GoPro Hero Session camera inserted into horizontal boreholes (Figure A1), showing a sharp decrease in open-crack abundance with depth. The fracture width (5 mm) was

TABLE 3 | Simulations performed in the sensitivity analysis to study the influence of solar radiation exposure, surface thermal absorptivity, lithology and fracture pattern of the rockwalls on the freeze and thaw distribution during a season.

Sensitivity parameters	# sim	Acronym	Variable modified from MAE modeled
Radiation exposure	1	MAE-SE “radiation—south east”	Solar radiation MAE → solar radiation CAR
	2	MAE-SW “radiation—south west”	Solar radiation MAE → solar radiation ANP
Surface thermal absorptivity	3	MAE-abs [⊖] “lowest absorptivity”	Absorptivity MAE → absorptivity CAR
	4	MAE-abs [⊕] “highest absorptivity”	Absorptivity MAE → absorptivity of basalt [73]
Lithology	5	MAE-k1 “highest conductivity”	Lithology MAE → lithology CAR
	6	MAE-k2 “second highest conductivity”	Lithology MAE → lithology MAR
	7	MAE-k3 “third highest conductivity”	Lithology MAE → lithology GMO
Open-crack effect	8	MAE-crack35 “crack 35-cm deep”	Lithology MAE + one crack at 35-cm depth
	9	MAE-crack70 “crack 70-cm deep”	Lithology MAE + one crack at 70-cm depth
	10	MAE-crack35-70 “crack 35- and 70-cm deep”	Lithology MAE + cracks of simulations 8 and 9

determined based on visible discontinuities observed during borehole inspections. This was intended as a simplified proxy for different levels of rock alteration, as fracture formation and widening represent a first-order manifestation of physical weathering [8, 74, 75]. We acknowledge that this approach is highly simplified and does not encompass the full range of alteration processes. Therefore, we refer to this parameter solely as “fracture pattern” or “open-crack effects” (rather than “weathering degree”), consistent with what was varied in the simulations.

These 10 simulations quantify the respective roles of solar radiation exposure, surface thermal absorptivity, lithology, and fracture pattern on 11 frost and ice segregation indicators (Figure 3). These indicators were selected for their relevance to the two primary frost processes: volumetric expansion and ice segregation. Following established studies [5, 29, 30, 36, 69, 76, 77], a threshold temperature of 0°C was used to assess freezing and thawing distributions, with the commonly used frost-cracking window of −8°C to −3°C applied to evaluate ice segregation effectiveness, for example, [78, 79].

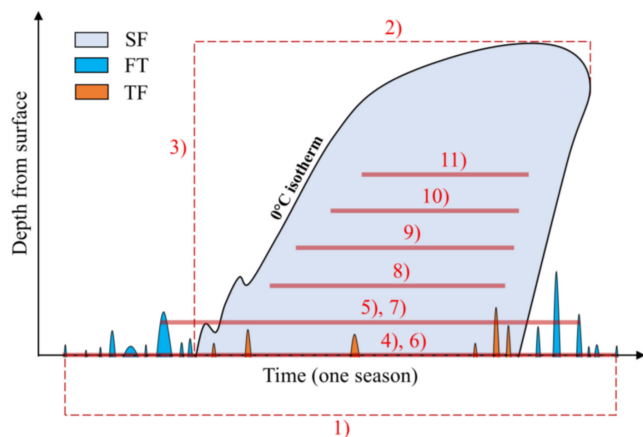


FIGURE 3 | Diagram illustrating the 11 frost process effectiveness indicators quantified for each simulation. Indicators include the following: (1) surface freezing period duration; (2) SF duration; (3) maximum SF depth, number of freeze–thaw (FT), and thaw–freeze (TF) cycles (4) at the surface and (5) at 50-cm depth; and (6–11) cumulative occurrences of ice segregation-effective temperatures (−8°C to −3°C) at depths of 0 cm (6), 50 cm (7), 100 cm (8), 150 cm (9), 200 cm (10), and 250 cm (11). Continuous black lines delineate the 0°C isotherm into the rockwall.

TABLE 4 | Bulk density, porosity, and thermal parameters measured in the laboratory for the five main types of rock characteristics of our study sites.

Rock type	Bulk density (kg/m ³)	Porosity (%)	Heat conductivity (W/mK)	Thermal diffusivity (m ² /s)	Heat capacity (J/kgK)
Shale	2467	11.32	1.76	5.89E-07	1379.24
Siltstone	2987	4.50	3.14	1.24E-06	895.04
Graywacke	2574	3.88	3.93	1.58E-06	980.06
Sandstone	3536	5.48	4.21	1.73E-06	758.22
Conglomerate	3084	4.65	4.06	1.71E-06	776.97

Note: Values of thermal parameters are for 80% water saturation.

4 | Results

4.1 | Rockwall Characteristics and Rock Thermal Properties

Laboratory-measured values for density, porosity, conductivity, diffusivity, and thermal capacity of shale, siltstone, greywacke, sandstone, and conglomerate typical of the northern Gaspé rock slopes are summarized in Table 4. The CAR rockwall consists of a single unit of fine conglomerate, while the MAR, GMO, and MAE rockwalls feature alternating strata of shale, siltstone, and greywacke or sandstone. Shale layers are typically centimeters thick, while siltstone, greywacke, and sandstone layers vary in thickness between sites. Table 5 details the percentage composition, average thermal conductivity, capacity, and diffusivity observed at the surface of each rockwall, all measured at 80% water saturation. CAR exhibits the highest thermal conductivity and diffusivity but the lowest thermal capacity. In contrast, MAE, dominated by siltstone and shale, has the lowest thermal conductivity and diffusivity and the highest thermal capacity (Table 5).

4.2 | Rockwall Modeling Performance

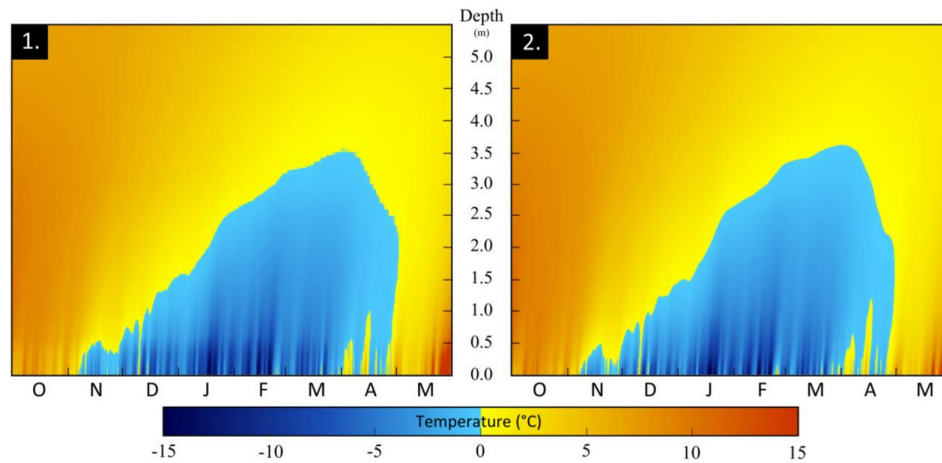
4.2.1 | Performance Using Local Weather Data

When applied to the parameters under investigation during winter 2019–2020, the modeled period of episodic FT cycle occurrence at MAE matched the measured period in duration (173 days). Both measurements and simulation indicated that the first episodic cycle at the MAE rockwall surface occurred on November 7, 2019, with the last one observed 173 days later on April 28, 2020. The modeled SF period was 2 days shorter, lasting 141 days, and the modeled maximum frost penetration depth exceeded the measured value by 7 cm (360 cm) (Figure 4). The number of episodic cycles recorded at the MAE rockwall surface was also highly consistent, with 36 measured cycles and 34 modeled cycles, as well as those reaching a depth of 50 cm (7 measured vs. 5 simulated). Near-freezing rockwall temperatures and low thermal gradients between the surface and 50-cm depth in December (+0.6°C/10 cm) and April (−0.17°C/10 cm) promote intense FT activity within the upper decimeters. In contrast, persistently subfreezing conditions from January to March minimize FT processes, even in the shallowest rock layers (Figure 4).

TABLE 5 | Lithology and average thermal properties for the first three meters depth from the surface for the CAR, MAR, GMO, and MAE sites.

Site	Shale (%)	Siltstone (%)	Graywacke (%)	Sandstone (%)	Conglomerate (%)	Heat conductivity (W/mK)	Thermal diffusivity (m ² /s)	Heat capacity (J/kgK)
CAR	0	0	0	0	100	4.06	1.71e-06	776.97
MAR	5	33	0	62	0	3.73	1.52e-06	834.88
GMO	10	38	52	0	0	3.54	1.42e-06	875.05
MAE	15	49	36	0	0	3.17	1.17e-06	933.51

Note: Values of thermal parameters are for 80% water saturation.

**FIGURE 4** | Measured (1) and simulated (2) temperatures in the first 5.5 m perpendicular to the rockwall surface between October 1, 2019 and May 31, 2020 for MAE.

The results demonstrate an excellent agreement between the simulated and measured temperatures at all depths (Figure 5). At the MAE site, the coefficient of determination (R^2) exceeds 0.98 at all depths, reaching 0.9997 at 5.5 m. The bias (BIAS) reveals a slight tendency for the simulation to overestimate temperatures near the surface, with an average value of 0.30°C. This overestimation rapidly decreases with depth, with BIAS values close to 0 (e.g., -0.03°C at 3.0 m and -0.01°C at 5.5 m). Similarly, the RMSE, which measures the average absolute deviation between simulated and measured temperatures, decreases from 0.82°C at the surface to 0.04°C at 5.5 m (Figure 5).

At the three sites with measured temperatures down to a depth of 3 m (CAR, MAR, and GMO), simulations demonstrated strong correlations with the measured data, with R^2 values exceeding 0.95 at the surface and 0.98 at 3 m. At GMO, the simulation exhibited a slight tendency to underestimate surface temperatures (-0.18°C), while slightly overestimating temperatures at depth, with a maximum BIAS of 0.42°C at 3 m (Figure 5). The BIAS was minimal overall at CAR and MAR, with mean values of 0.08°C and -0.05°C , respectively, from the surface to 3 m (Figure 5). The RMSE decreased consistently with depth, from 1.03°C at the surface to 0.40°C at 3 m at CAR, from 1.03°C to 0.29°C at MAR, and from 1.34°C to 0.43°C at GMO (Figure 5). These results underscore the model's strong accuracy and reliability in simulating temperature profiles across all three sites, both at the surface and at depth.

4.2.2 | Performance Using Reference Site MAE

The MAE-based simulation adjusted to MAR lithology reproduced MAR's thermal regime with only moderate degradation in performance. Surface R^2 decreased by ~ 0.02 to slightly below 0.95, but values reached 0.97 by 30-cm depth. Relative to the MAR-calibrated model, temperatures were systematically $\sim 0.4^\circ\text{C}$ colder across all depths, and RMSE increased by roughly 0.3°C on average. These results indicate that while performance is slightly reduced, MAR's thermal profile remains well captured.

Applying the same procedure to GMO yielded very similar results to the site-specific calibration. Surface R^2 remained at 0.95 and exceeded 0.98 from 30-cm depth downward. BIAS and RMSE were also closely comparable, with surface values of -0.47°C and 1.44°C, improving to 0.34°C and 0.35°C at 3-m depth. Overall, the MAE-based simulation reproduced GMO's thermal regime with a high level of fidelity.

The performance of the MAE-based, adjusted for MAR lithology, was evaluated by comparing the simulated temperatures to MAR's measured data. The adjusted simulation achieved R^2 values comparable to those from MAR's direct simulation, exceeding 0.98 at most depths and reaching 0.99 at 3 m (Figure 6.1). The BIAS and RMSE also closely mirrored MAR's calibrated results, with a surface BIAS of -0.73°C and RMSE of 1.36°C, decreasing to -0.45°C and 0.58°C, respectively, at 3 m (Figure 6.1). These

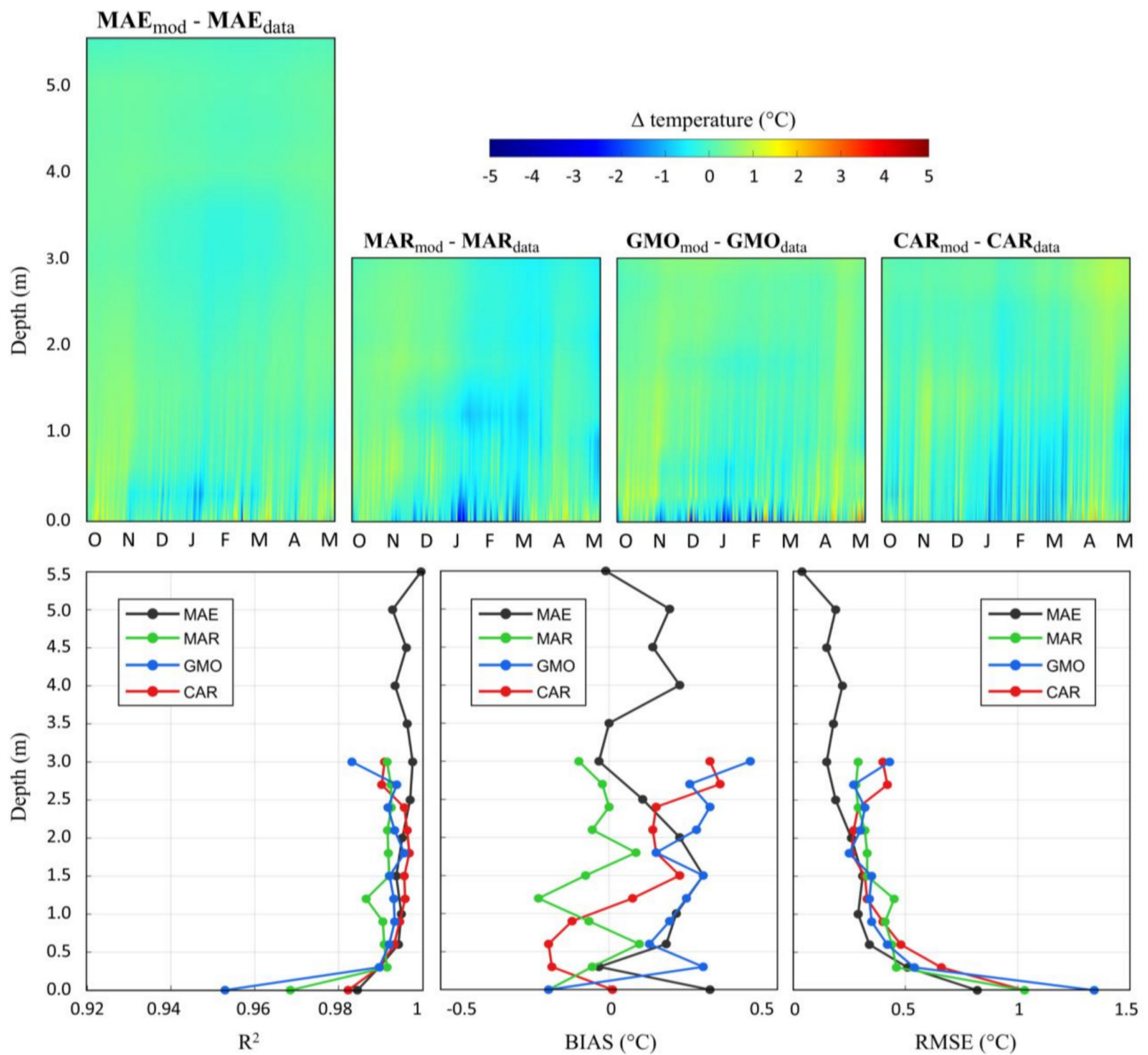


FIGURE 5 | Temperature discrepancies between simulations and measured values over time and depth and statistical performance metrics for temperature simulations from the surface to the depth of 5.5 m into the rockwall of MAE, MAR, GMO, and CAR.

findings indicate that the MAE-based simulation, with lithology adjustments, can reproduce MAR's thermal profile with nearly the same accuracy as a site-specific calibration.

The MAE simulation adjusted for GMO lithology was evaluated against GMO's measured data. The adjusted model achieved R^2 values exceeding 0.98 at depth, closely approximating the results of GMO's direct calibration. The surface R^2 was slightly lower at 0.95, and the BIAS showed minor deviations (-0.47°C at the surface, 0.34°C at 3 m) (Figure 6.2). The RMSE decreased from 1.44°C at the surface to 0.35°C at 3 m, closely aligning with the results of the GMO-calibrated model (Figure 6.2). These results underscore the capability of the MAE-based model to simulate GMO's thermal profile with a high degree of accuracy, albeit with slightly larger deviations than for MAR.

The modeling of CAR presented a greater challenge due to its distinct solar radiation and thermal regime. Solar radiation adjustments alone produced substantially lower R^2 values (0.80–0.89) compared to CAR's direct model calibration (0.97–0.99), with surface BIAS and RMSE of -2.10°C and 2.56°C , respectively. At depth, performance improved relative to the surface but still remained below the calibrated model (Figure 6.3). This demonstrates that solar radiation alone is insufficient to capture CAR's thermal regime. Including both solar-radiation and baseline temperature adjustments to reflect CAR's warmer average surface temperatures led to modest improvements. The surface R^2 increased to 0.89 (BIAS -2.08°C ; RMSE 2.55°C), and performance at 3 m reached $R^2=0.90$ (BIAS -0.30°C ; RMSE $=1.35^{\circ}\text{C}$), though differences with CAR's calibrated model remained substantial (Figure 6.4).

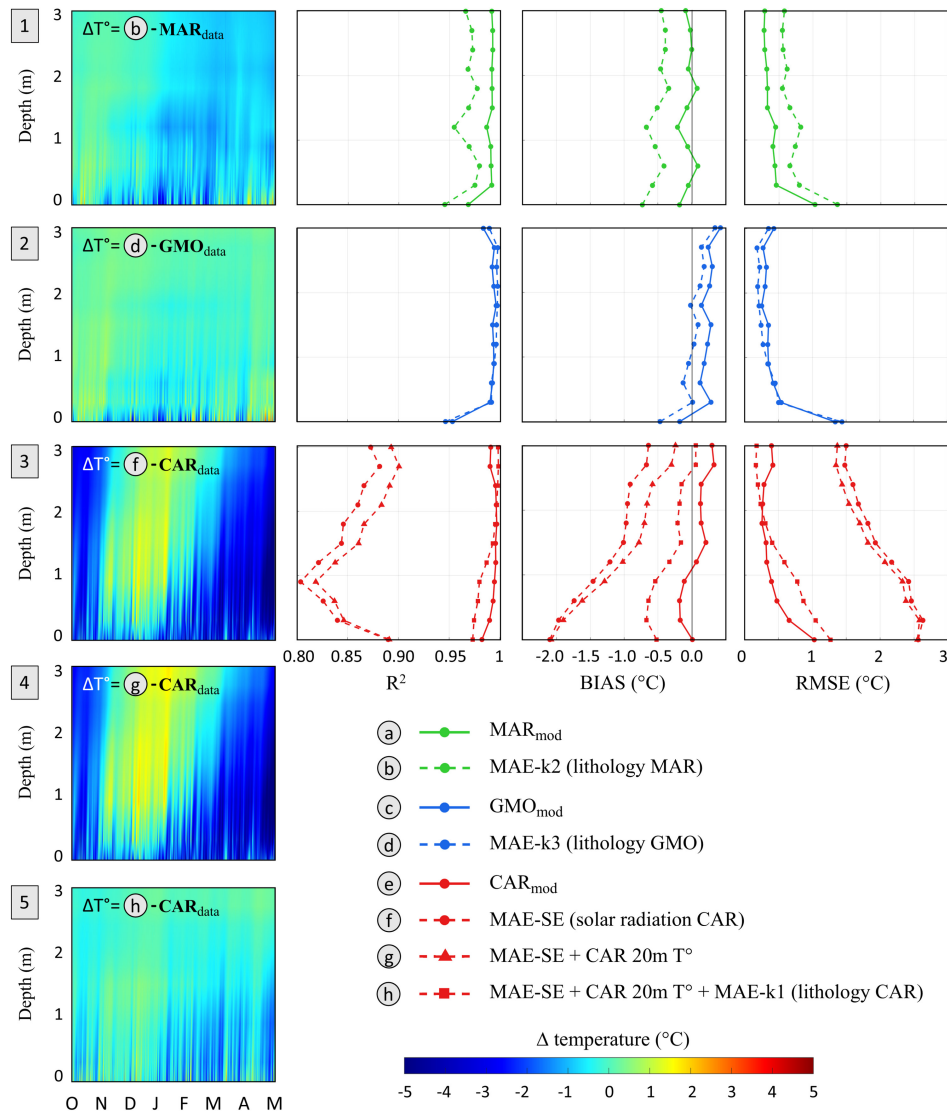


FIGURE 6 | Performance (R^2 , BIAS, RMSE) of five MAE-based simulations: (1) reconstruction of MAR using MAE's model with MAR lithology, (2) reconstruction of GMO using MAE's model with GMO lithology, and reconstruction of CAR through incremental substitution of (3) solar radiation, (4) baseline temperature, and (5) lithology. Temperature discrepancies between simulations and measurements over time and depth are also shown.

When lithology adjustments were added to the solar-radiation and baseline temperature modifications, model skill increased markedly. R^2 values exceeded 0.97 at all depths, reaching 0.99 at 3 m, and BIAS/RMSE values improved to $-0.52^\circ\text{C}/1.27^\circ\text{C}$ at the surface and $0.06^\circ\text{C}/0.18^\circ\text{C}$ at 3 m (Figure 6.5). These results demonstrate that accurately reproducing CAR's thermal regime requires combined adjustments of solar radiation, baseline temperatures, and lithology.

4.3 | Parametric Analysis

Figure 7 illustrates the temperature differences between the baseline model at MAE and the 10 simulations where individual parameters were modified. Simulations involving solar radiation (MAE-SE and MAE-SW) resulted in a notably warmer temperature regime near the surface, with differences exceeding 3°C , particularly during the spring months, while deeper

layers showed minimal yet significant differences (Figure 7). Changes to surface absorptivity (MAE-abs $^\ominus$ and MAE-abs $^\oplus$) had a less pronounced impact overall, with MAE-abs $^\oplus$ causing slight warming at the surface and MAE-abs $^\ominus$ resulting in minimal cooling. Modifications to lithology (MAE-k1, MAE-k2, and MAE-k3) revealed distinct trends: MAE-k1 (CAR lithology) induced substantial cooling throughout the profile, especially at greater depths ($>1\text{ m}$), while MAE-k2 (MAR lithology) and MAE-k3 (GMO lithology) led to smaller but consistent cooling trends, especially at depth (Figure 7). The introduction of fractures (MAE-crack35, MAE-crack70, MAE-crack35-70) altered the thermal regime of the rockwall by reducing near-surface thermal conductivity. This limits the penetration of surface temperature extremes: The rock mass warms more slowly in summer and cools more slowly in winter, resulting in more moderate temperatures at depth. Consequently, seasonal warming and cooling are dampened within the rock mass (Figure 7).

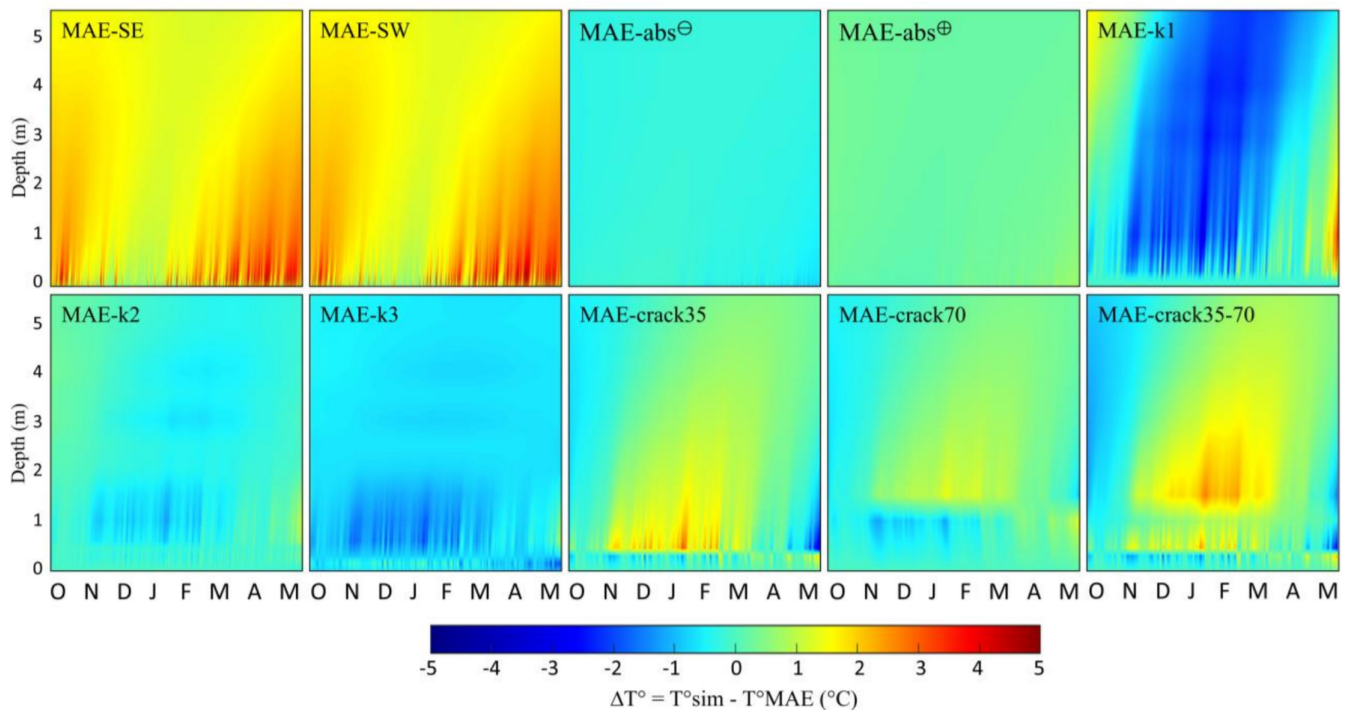


FIGURE 7 | Temperature differences between the 10 simulations where individual parameters were modified and the baseline model at MAE.

4.3.1 | Exposure to Solar Radiation

The MAE rockwall, initially north-facing, was compared to southeast (CAR) and southwest (ANP) exposures through MAE-SE and MAE-SW simulations. Switching to southeast or southwest orientations reduced the SF duration by 32 and 37 days, respectively, with the latter dissipating about a month earlier in spring and its maximum depth decreasing by 109–116 cm (Figure 8.1 and 8.2). However, exposure to southeast and southwest exposure only shortened the total period of freezing occurrence by 4 days (Figure 8.3). On south-facing rockwalls, the last episodic cycle occurred on April 24, 2020, while two low-magnitude FT cycles were recorded on April 27 and 28, 2020 in the north-facing model (Figure 4). Direct solar exposure significantly increased episodic cycles at the surface (SE: +47, SW: +50), including +21 FT and +26–29 TF cycles. This sharp increase in surface occurrences (SE: +238%, SW: +247%) contrasts with the reduced occurrence of these cycles at a depth of 50 cm (SE: –40%, SW: –20%), indicating that these cycles remain very superficial (Figure 8.4, 8.5 and 8.6). Additionally, southeast and southwest exposures reduced frost cracking temperatures (–8°C to –3°C): the cumulative annual exposure to this range of temperature dropped by 13%–15% at surface, by 13%–15%, at 50 cm by 50%–55%, at 100 cm by 91%–94%, and disappeared below that depth (Figure 9).

4.3.2 | Surface Absorptivity

A decrease in absorptivity to 0.5 (MAE-abs[⊖]) extended the SF duration by 4 days and increased its maximum depth by 18 cm compared to the MAE model. This change also resulted in fewer FT (–4) and TF (–1) cycles at the rockwall surface (Figure 8). Conversely, increasing absorptivity to 0.9 (MAE-abs[⊕]) shortened the SF duration by 13 days and reduced its

maximum depth by 7 cm. High absorptivity led to an increase in surface episodic cycles (+7) and at 50-cm depth (+2), with a more pronounced increase in FT cycles (+5) than TF cycles (+2). Reducing surface absorptivity to 0.5 resulted in a slight increase in the occurrence of temperatures between –8°C and –3°C at the surface and up to 1 m depth (+1–6%), but a substantial increase at greater depths, particularly at 150 cm (+145%) (Figure 9). Increasing absorptivity to 0.9 led to a slight increase in the occurrence of temperatures in the frost cracking window at all depths, with a maximum increase of 14% at 1 m (Figure 9).

4.3.3 | Lithology

Simulations MAE-k1, MAE-k2, and MAE-k3 exhibited thermal properties that enhanced thermal energy propagation within the rockwalls compared to the MAE model (Table 3). With higher thermal conductivity, these simulations showed increases in the maximum SF depth of 166, 37, and 56 cm, respectively (Figure 8). In simulation MAE-k3, the major thaw on December 10, 2019 (Figure 4) did not fully thaw the rockwall, causing the SF to start earlier, on November 7, instead of December 10 as in the other simulations. Consequently, SF durations were slightly longer in MAE-k1 (+3 days) and MAE-k2 (+2 days) but notably longer in MAE-k3 (+41 days). Simulation MAE-k3, which has a more persistent SF, also featured a larger number of TF cycles at the expense of FT cycles (Figure 8). The enhanced thermal energy propagation in simulations MAE-k1, MAE-k2, and MAE-k3 allowed temperatures between –8°C and –3°C to reach greater depths. In MAE-k1, the cumulative annual duration of this temperature range increased by 22% at 1-m depth, 554% at 1.5 m, and appeared at 2.0 m (64 days) and 2.5 m depth (11 days) (Figure 9).

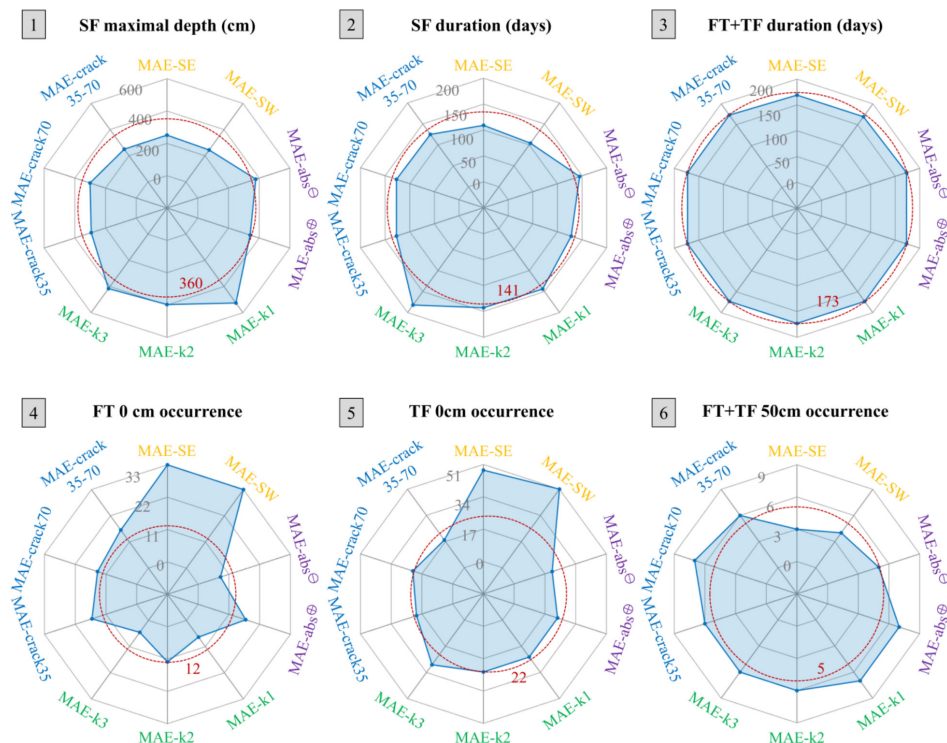


FIGURE 8 | Radar charts of all simulations (winter 2019–2020) compared to the reference model (red dashed line). Panels show (1) maximum SF depth, (2) SF duration, (3) duration of FT and TF cycles, (4) occurrence of surface FT cycles, (5) occurrence of surface TF cycles, (6) occurrence of FT + TF cycles at 50-cm depth. Colors indicate parameter type: yellow = solar radiation, purple = surface absorptivity, green = lithology, blue = open-crack effects.

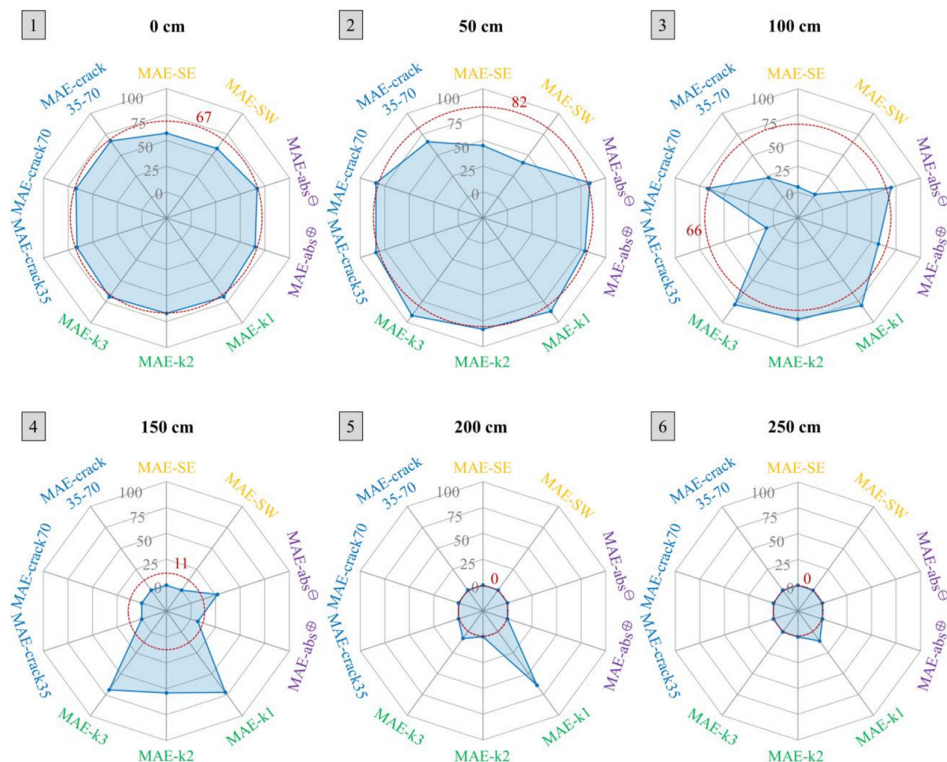


FIGURE 9 | Radar charts showing the cumulative number of days with temperatures between -8°C and -3°C at different depths for all simulations during winter 2019–2020, compared to the reference model (red dashed line). Each panel represents a specific depth: (1) surface, (2) 50 cm, (3) 100 cm, (4) 150 cm, (5) 200 cm, and (6) 250 cm. The acronym colors correspond to the type of parameter modified in each simulation: yellow for solar radiation exposure, purple for surface absorptivity, green for lithology, and blue for open-crack effect.

4.3.4 | Effects of Fractures

The addition of 5 mm surface-parallel cracks within the first meter of the MAE models (MAE-crack35, MAE-crack70, and MAE-crack35-70) increased weathering and shortened SF duration by 14 to 16 days (Figure 8). Cracks at 35 or 70 cm reduced the maximum SF depth by about 60 cm, while both cracks combined decreased it by 110 cm. While surface cycle frequency remained largely unaffected, more cycles occurred at 50-cm depth. Overall, an increase in surface FT cycles and a decrease in TF cycles were observed (Figure 8). Crack-induced weathering had no effect on surface temperatures between -8°C and -3°C but reduced the depth of this temperature range occurrence from 1.5 to 1 m (Figure 9).

5 | Discussion

5.1 | FT Cycles Definition and Characteristics

The literature has traditionally defined three types of FT cycles: diurnal, seasonal, and millennial or perennial [80, 81]. Diurnal cycles are short-duration events (e.g., 24 h) that penetrate only the first decimeters of rock masses [8]. Seasonal cycles persist for several consecutive months each year, typically reaching depths of 3–7 m [3, 82]. While these cycles do not penetrate to depths beyond 10 m [81], millennial cycles persist long enough to reach much greater depths [83]. In periglacial environments, diurnal, seasonal, and millennial cycles can occur simultaneously.

However, surface cycles affecting rockwalls do not fit neatly into the diurnal category due to their high temporal variability, ranging from minutes to days. In midlatitude environments, the shortest surface cycles penetrate only a few centimeters, while longer cycles can exceed 1 m in depth (Figures 4 and 10). Unlike seasonal cycles, surface cycles occur irregularly rather than in a predictable pattern (Figures 4 and 10). We propose the term “episodic cycles” to better describe these processes. Episodic

cycles encompass both FT and thaw-freeze (TF) transitions, commonly referred to as “winter thaws.” While both involve alternating above- and below-freezing temperatures, the direction of temperature change is crucial, as the thawing phase is often the primary trigger for rock instabilities [15, 16, 84, 85].

Our analysis of the northern Gaspé Peninsula indicates that episodic cycles interact closely with SF. For example, during winter 2019–2020, a thaw event on December 10, 2019, lasting 35 h and reaching a maximum temperature of 11°C , temporarily interrupted a 34-day-old frost layer in the MAE (Figure 4), CAR, and MAR rockwalls. Since 2017, thermal regime monitoring has revealed that early-winter thaws penetrating beyond 1 m, and disrupting existing SF layers are a recurrent phenomenon (unpublished data). These thaws typically occur when the upper meter of rockwalls is below but near the freezing point (Figure 4). Given their capacity to interrupt SF, episodic cycles cannot be considered in isolation. We thus propose defining “SF” as the longest period during which subfreezing temperatures persist within the rock mass, regardless of transient near-surface thawing (Figure 3).

Various freezing and thawing configurations can develop in rockwalls. Frozen rock at depth may become trapped between two thawed layers (Situation 1, Figure 10), or the inverse may occur, with a thawed layer embedded within a frozen mass (Situation 2, Figure 10). In more complex cases, a surface thawed layer can overlie a frozen layer, which in turn overlies a thawed pocket within the SF layer (Situation 3, Figure 10). Situation 3 underscores the fact that, at fine spatiotemporal scales, multiple freezing and thawing fronts can coexist within the upper meters of a rockwall (Figure 10). Our study highlights the complexity of freezing and thawing distributions in rockwalls, which exhibit a wide range of configurations (Figure 10). Notably, surface FT and TF cycles do not dissipate uniformly with depth, leading to asynchronous thawing events at different levels (Figure 10). These conditions

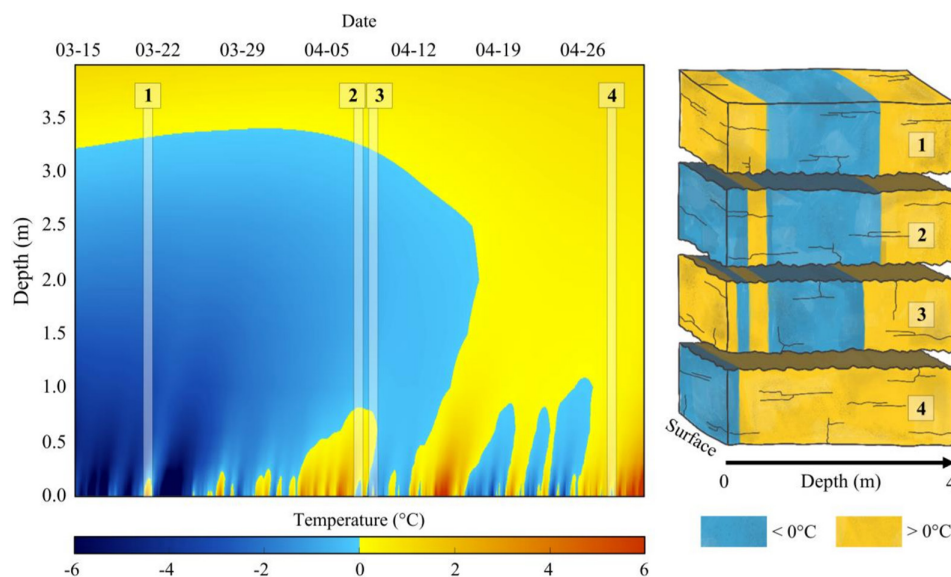


FIGURE 10 | Potential freeze and thaw combinations occurring in a rockwall between March 15, 2020 and April 30, 2020. Situations (1) and (3) correspond to thaw-freeze cycles at surface; situations (2) and (4) correspond to FT cycles at surface.

generally occur within narrow temperature ranges near 0°C and probably do not cross the “frost cracking window” associated with ice segregation. However, frost weathering can still occur through the volumetric expansion of freezing water even near the freezing point, especially in highly saturated rocks during spring snowmelt [31, 32, 49]. This spatial and temporal variability helps explain why thawing may occur asynchronously at different depths, occasionally promoting instabilities of varying magnitudes [3, 4]. Understanding these dynamics is essential for accurately assessing rockfall hazards in periglacial environments.

5.2 | Controlling Factors of Freeze and Thaw Distribution

5.2.1 | Fall, Winter, and Spring Rockwall Thermal Gradient

Rockwall surface temperature plays a significant role in the occurrence of episodic cycles while the thermal gradient in the rock mass controlled the amplitude of these cycles. Surface temperature variations of similar intensity and duration in fall, winter, and spring have differing effects due to seasonal differences in thermal gradients. In fall, heat stored during summer creates a steep temperature gradient between the surface and the first few meters of rock. This limits the penetration of early episodic cycles (Figure 4). Matsuoka [4] mentions that, even when temperature fluctuations around the freezing point penetrate to depths of up to 40 cm, the high thermal capacity of the rock mass can prevent the complete freezing of water within pores and discontinuities.

During early winter, SF deepens while frozen rock temperatures remain close to 0°C. TF cycles during this period can penetrate deeper and temporarily cause the rockwall to completely thaw for a short time (Figure 4). By deep winter, the cold temperatures at the surface and within the rock mass are no longer conducive to any further TF cycles from propagating to depth (Figure 4). In spring, the first meters of the rock mass are colder than its surface, but this transitional period is characterized by a very small temperature gradient. This made it conducive to high amplitude TF cycles until the SF dissipated and to high amplitude FT cycles after this dissipation (Figures 4 and 10). The shallow thermal gradient of this period, combined with near-freezing temperatures in the first meters of the rockwall, favored complex combinations of episodic cycles. Our data show that in spring, at least three thawing fronts can simultaneously coexist and evolve at depths of 10 cm, 1 m, and 3 m (Figure 10, Situation 3). Since any rock instabilities that develop during the freezing phase of FT cycles are triggered in the thawing phase [3, 15, 16, 85], the complex combinations within the rockwall can have serious repercussions on springtime rock instabilities, especially regarding their magnitude. The propagation of surface cycles into deeper rock layers is thus highly dependent on the thermal gradient within the rockwall.

5.2.2 | Control of Tested Factors

Rock surface temperature cannot be reliably inferred from air temperature [60, 86, 87] due to other influencing factors.

Topography controls rockwall exposure to solar radiation while rock characteristics, including color, determine absorptivity [28, 38, 56, 88]. The propagation of the thermal signal absorbed at the surface depends on the thermal conductivity, capacity, and diffusivity of the rock mass, which are governed by lithology and weathering degree (porosity, cracks) [56]. Variations in exposure, surface absorptivity, lithology, or fracture pattern could significantly affect episodic cycle amplitudes, FT and TF cycle distributions, SF depth, and spring dissipation rates.

Draebing and Mayer [60] showed that north-facing rockwalls have daily temperature variations on the order of 4°C, compared to 16.5°C on south-facing rockwalls. This characteristic, also put forward by Schnepfleitner et al. [56], favors a high frequency of episodic TF cycles affecting south-facing rockwalls in winter (Figure 8). However, these many cycles are very superficial and never reach 50 cm in depth until the end of March (Figure 8). The modest amplitude of these cycles during winter is due to the combination of low solar radiation intensity and cold temperatures within the rock mass. However, absorbed solar energy reduces SF depth by approximately 1 m and decreases the occurrence of temperatures conducive to the ice segregation process starting at the depth of 50 cm (Figure 9). In spring, solar radiation impacts south-facing slopes at the most direct angle [49], accelerating SF dissipation by over a month (Figure 9). This rapid dissipation strongly favors episodic FT cycles over TF cycles in April.

Increased rockwall surface absorptivity amplifies the proportion of incident solar radiation absorbed, resulting in more frequent episodic cycles at the surface and at 50-cm depth (Figure 8). This effect is more pronounced at the surface due to short-term energy storage corresponding to daylight hours. High absorptivity increases TF cycle frequency while shortening their duration, as SF dissipates more rapidly. Conversely, lower absorptivity reduces TF cycle frequency but extends their occurrence period due to prolonged SF persistence. Changes in absorptivity of ± 0.2 have minimal impact on SF depth (Figure 8) or ice segregation-conductive temperatures (Figure 9). This same surface absorptivity variation applied on a southern exposure rockwall should have more repercussions.

Thermal signal propagation depends heavily on the thermal properties of the rock. Higher thermal conductivity allows seasonal and episodic cycles to penetrate deeper. Thus, in a conglomerate rockwall with high conductivity (Table 5), the SF reaches 5.3 m compared to 3.5 m for a rockwall composed of 85% siltstone and greywacke (Figure 8). While the SF maximum depth is substantially greater (+166 cm), dissipation occurs only 3 days later, as stronger winter cooling is offset by more efficient spring warming. This higher thermal flow minimally affects ice segregation-conductive temperatures within the first meter but significantly increases their occurrence at 1.5 m and introduces occurrences at depths up to 2.5 m (Figure 9). Lithology has limited influence on surface episodic cycle frequency but significantly affects cycle amplitude due to variations in energy propagation. While the major thaw on December 10, 2019 caused SF interruptions in the MAE model (Figure 4) and simulations MAE-k1 and MAE-k2, it did not lead to a full thaw of the rockwall in simulation MAE-k3.

The latter's lithology is sufficiently conductive for the winter SF to be located at the depth of 1.2 m on December 10 but not conductive enough for the surface thaw to reach that depth. Lithologies favoring persistent SF are more affected by TF cycles than FT cycles (Figure 8).

Adding cracks to simulations increases rock weathering, reducing thermal conductivity, capacity, and diffusivity at crack locations (Figure 8; [56]). Increased crack density in the first meter slows surface cooling propagation, retaining higher winter rockwall temperatures. This context favors higher amplitude TF cycles despite the presence of cracks (Figure 8) while reducing the occurrence of frost-cracking window temperatures (Figure 9). Spring surface warming is also slowed by fractures, but heat flux from depth remains unaffected. Crack placement constrains unilateral winter cooling more than bilateral spring warming, leading to SF dissipation approximately 15 days earlier than in the reference model (Figure 8). This earlier dissipation favors FT cycles over TF cycles (Figure 8). Our findings are consistent with those of Schnepfleitner et al., who demonstrated that a 1-mm crack parallel to the surface at 20-cm depth reduced annual temperature amplitude from 21°C to 16.5°C and to 10.6°C for a 1-cm crack opening. Similar impacts are observed at 50 cm and 1-m depth [56]. When cracks communicate with the surface, heat flux increases through air convection [57, 89, 90] and water advection [42, 58, 91], amplifying thermal signal propagation to depth and increasing temperature variation amplitude. Surface-connected cracks also enhance rock permeability and water availability [42, 92] and critical factors for frost weathering effectiveness [31, 32, 35, 49, 93]. During temperature oscillations around freezing, open water-saturated cracks alter both the thermal signal propagation speed and the latent heat exchange associated with phase changes [59]. Our methodology enables quantification of the respective influence of these factors on freezing and thawing distributions in rockwalls.

5.3 | Relevance and Assessment of the Proposed Method

The method we proposed to quantify the thermal regime of rockwalls serves as an intermediary between field measurements and regional-scale modeling, drawing on the respective strengths of these approaches. It enabled us to quantify the thermal regime of 10 different rockwalls from a single borehole (Table 3). Numerous other combinations could also have been simulated by modifying several variables simultaneously (e.g., lithology and solar exposure) and testing additional parameters such as slope inclination, snow accumulation, or climate warming.

Slope inclination significantly influences solar radiation absorption and, consequently, the thermal regime of rockwalls. In midlatitude environments, vertical slopes (90°) absorb more energy in winter than gentler slopes (45°), while the reverse occurs in summer, except for west-facing slopes where vertical steepness absorbs more energy year-round [49]. In cold temperate climates, snow accumulation must also be considered for gentler slopes due to its insulating effect [26, 38, 52, 53, 55]. Our study focuses specifically on rockwalls, which are vertical or

near-vertical. The model simulations used an 80° slope inclination to match the MAE rockwall, consistent with field observations showing that, irrespective of wind intensity and direction, snow does not accumulate on slopes exceeding 70° in the northern Gaspé Peninsula. Nevertheless, the effects of slope and snow on thermal regimes could easily be tested using the proposed method. This approach has already been applied by Birien et al., who substituted surface air temperature time series instead of radiation or absorptivity parameters to assess the long-term influence of climate warming on freezing–thawing dynamics and frost damage potential [69].

This hybrid method, which combines field measurements and modeling, addresses some of the limitations inherent to each classic approach while capturing the spatial heterogeneity of conditions on a regional scale. Directly measuring the thermal regime within rockwalls provides the most accurate data but not necessarily the most representative. The logistical challenges of drilling boreholes, including the heavy and bulky equipment required, often limit instrumented sites to more accessible locations, which may not reflect the most unstable or problematic rockwalls. Similarly, for the most unstable (and problematic) rockwalls, less dangerous and potentially less representative sites could logically be prioritized. The cost and effort involved could also limit the number of instrumented sites without covering the whole spatial heterogeneity of rockwalls on a regional scale [86]. In addition to these issues of representativeness, field measurements are prone to data gaps (e.g., instrument failure and battery or memory depletion) and can generate environmental impacts (e.g., residual anchors and battery disposal). This approach could also be relevant to study processes that require long-term weather time series (e.g., permafrost degradation) or to perform projection into the future to anticipate evolution of natural hazards (e.g., rockfalls), which is crucial in a risk management context [69].

Regional climate models (RCMs) and climate reanalyses, while increasingly powerful, struggle to accurately model the thermal regime of steep, complex terrain at a regional scale [54, 60]. Their relatively fine spatial resolution often smooths out topographic variability, especially in mountainous regions, leading to errors in altitude estimates and, consequently, air temperature approximations [44, 46, 47]. Consequently, the near-surface air temperature, which drops linearly with increasing elevation because of the phase shift rate effect as well as complex phenomena such as temperature inversions, can also be misrepresented [94], further complicating accurate near-surface air temperature estimation. Moreover, surface temperature is influenced not only by air temperature but also by incoming solar radiation, which depends on slope, aspect, shading, and other parameters that are challenging to model at fine scales [49, 95]. Snow cover distribution and albedo also play critical roles in surface temperature modeling, yet these factors remain inadequately represented in RCMs [96].

Our method strikes a balance between precision and scalability. While it cannot capture the entire spatial heterogeneity of a region, it provides more accurate quantification of thermal regimes across multiple rockwalls than traditional approaches, while significantly reducing the effort, cost, and risks associated with field instrumentation. For example, by relying on a

single borehole and simulations, we were able to model decimetric thaw processes that are critical for understanding rock-fall hazards [3]. Unlike RCMs and climate reanalyses, which lack the resolution to capture episodic cycles and other fine-scale phenomena, this method could provide the most adapted spatiotemporal accuracy to evaluate these decimetric changes at a regional scale and be a major asset in a risk management strategy.

6 | Conclusions

Using a comprehensive and innovative array of instruments across five rockwalls, their thermal regime was measured and modeled. Early winter conditions revealed weak temperature gradients between the rockwall surface and the first meters of depth, with temperatures hovering near freezing. This context facilitates large-amplitude thaws, some reaching the SF at depth. As a result, the “SF” is defined as the longest continuous period of subfreezing temperatures in a rockwall over a winter. The fine spatiotemporal resolution of our data highlighted significant variability in the frequency, duration, and depth of what are typically referred to as “diurnal cycles,” which we argue are more aptly termed “episodic cycles.”

Results reveal complex thermal configurations in the first meters of rockwalls: Frozen layers at depth can be encased between thawed layers, and vice versa. In some cases, two freezing fronts and two thawing fronts can coexist simultaneously, particularly in late winter when the SF is established at depth and the temperature gradient weakens and rises close to the freezing point. Since rock instabilities triggered by FT processes often occur during thawing phases, these complex thermal patterns can significantly influence instability magnitude.

A parametric analysis of the thermal and structural properties of the instrumented rockwalls quantified the roles of solar radiation exposure, surface thermal absorptivity, lithology, and fracture pattern on the distribution of episodic cycles and SF throughout the winter. Episodic cycle frequency is predominantly controlled by solar radiation exposure and surface absorptivity, while lithology and fracture density strongly influence the depth penetration of SF. These parameters also affect the dissipation rate of SF in spring, shaping the distribution of FT and TF cycles.

By incorporating thermal and structural parameters representative of the study area, a local thermal regime model was extrapolated to a regional scale without requiring instrumenting as many sites as there is diversity in exposure, absorptivity, lithology, and fracture configuration. The method also allows for testing additional parameters, such as slope inclination, snow accumulation, or climate warming. This hybrid approach—combining field measurements and modeling—provides a more precise means of quantifying the thermal regimes of multiple rockwalls compared to spatial modeling alone, while significantly reducing the effort, cost, and risk associated with traditional instrumentation. It represents a powerful tool for quantifying decametric episodic cycles on a regional scale and offers valuable support for rockfall hazard management strategies.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Deciphering Freeze–Thaw Dynamics in Rockwalls: A Novel Approach for high accuracy Regional-scale Modelling (<https://doi.org/10.5281/zenodo.14991461>).

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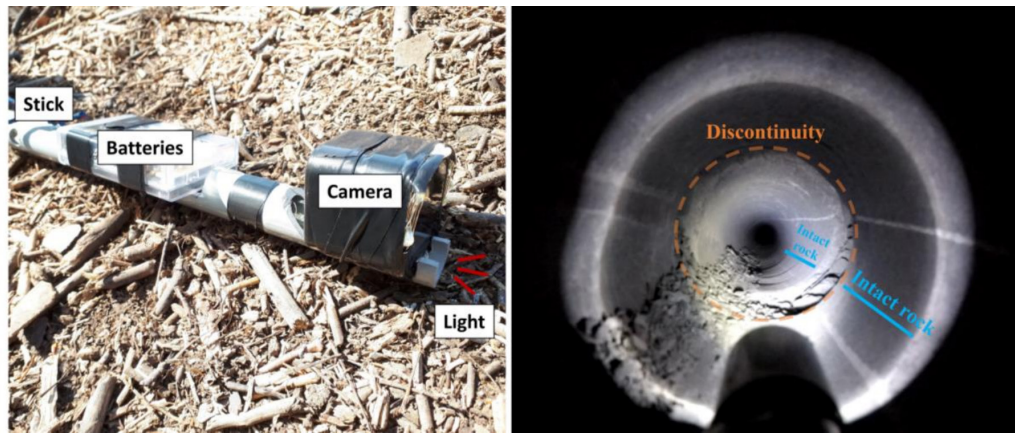


FIGURE A1 | GoPro setup and borehole observations prior to installing the thermistor string. [Colour figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/ppp.70040)]