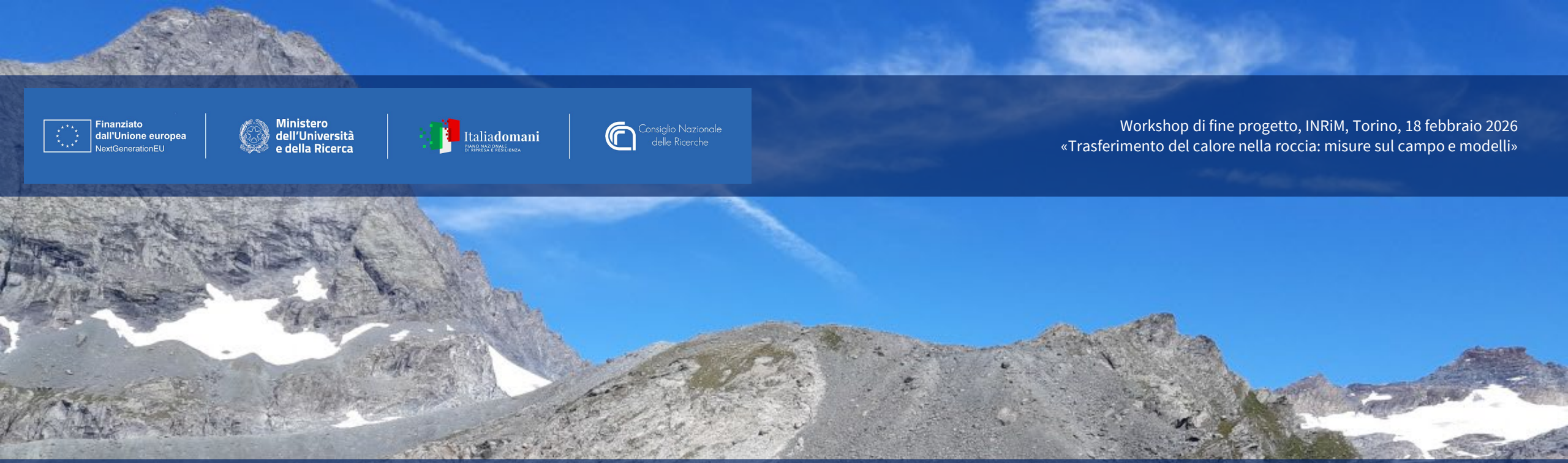

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PIANO NAZIONALE DI RIPRESA E RESILIENZA

Consiglio Nazionale delle Ricerche

Workshop di fine progetto, INRiM, Torino, 18 febbraio 2026
«Trasferimento del calore nella roccia: misure sul campo e modelli»

PRIN “Rockfall risk mitigation”: Modellazione del trasferimento di calore nelle formazioni rocciose alpine nel contesto del cambiamento climatico

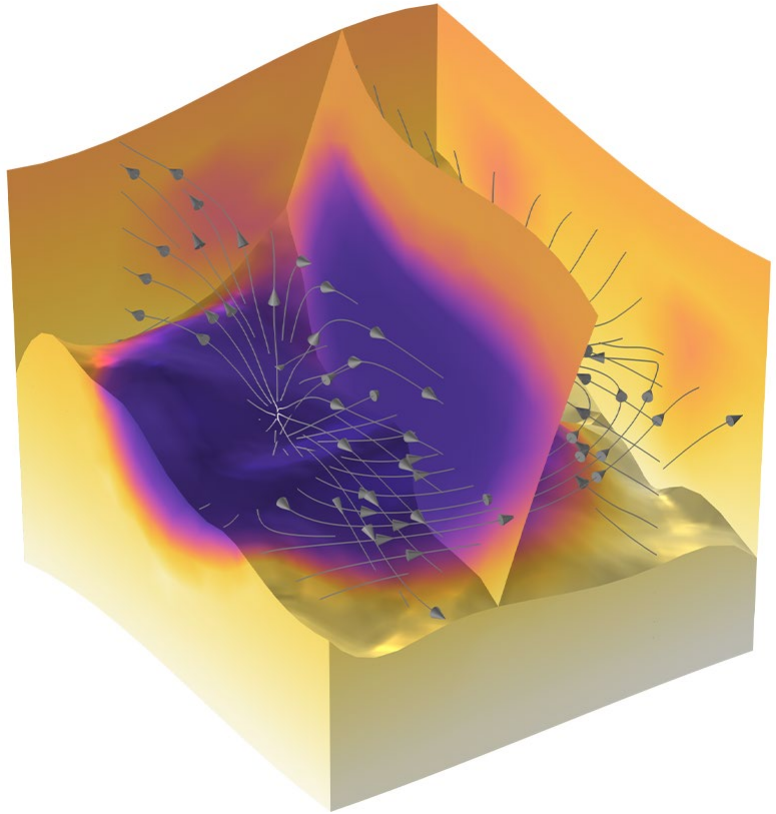
Vincenzo Corrado (Politecnico di Torino)

Activity of PoliTo-DENERG in the PRIN 2022 on “Rockfall risk mitigation”

1. Theoretical investigation of heat transfer in rocks, including a review of simplified and detailed numerical models, computational tools, and applications
2. Development and implementation of a COMSOL Multiphysics model using the Heat Transfer Module
3. Numerical modelling of heat transfer in the experimental zone of the Bessanese glacial basin
4. Calibration of the numerical model based on experimental data and in situ measurements
5. Sensitivity analyses to assess the thermal response of rocks under varying boundary conditions and driving forces, such as temperature, wind speed, and solar irradiance
6. Simulation of rock heat transfer scenarios under future climate projections.

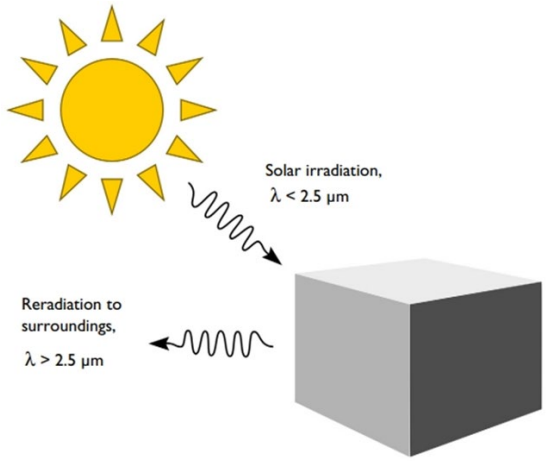
COMSOL Multiphysics for Simulating Heat Transfer in Rocks

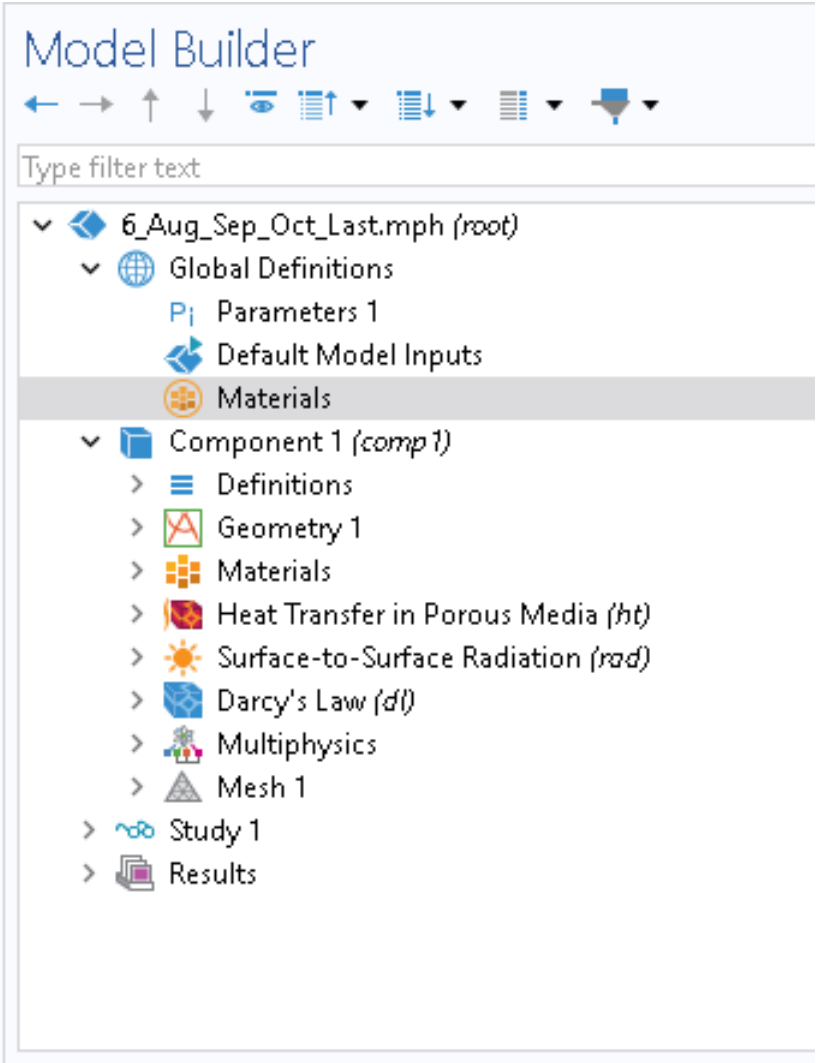
- Advanced simulation platform for transient and steady-state thermal analysis
- Heat Transfer Module: modelling conduction, convection, and radiation in rock materials
- Porous Media Submodule: simulation of heat transfer in coupled solid -fluid systems
- Multiphysics Integration: coupling heat transfer with fluid processes
- Application to alpine rock formations using site-specific meteorological forcing and lithology-dependent thermal properties



COMSOL Multiphysics for Simulating Heat Transfer in Rocks

- **Heat Transfer Mechanisms**
  - Conduction
    - Fourier's law
    - Isotropic/anisotropic, linear/non-linear thermal conductivity
  - Convection
    - Natural and forced convection
    - Laminar, or turbulent flow
  - Radiation
    - Surface-to-surface
    - Participating media

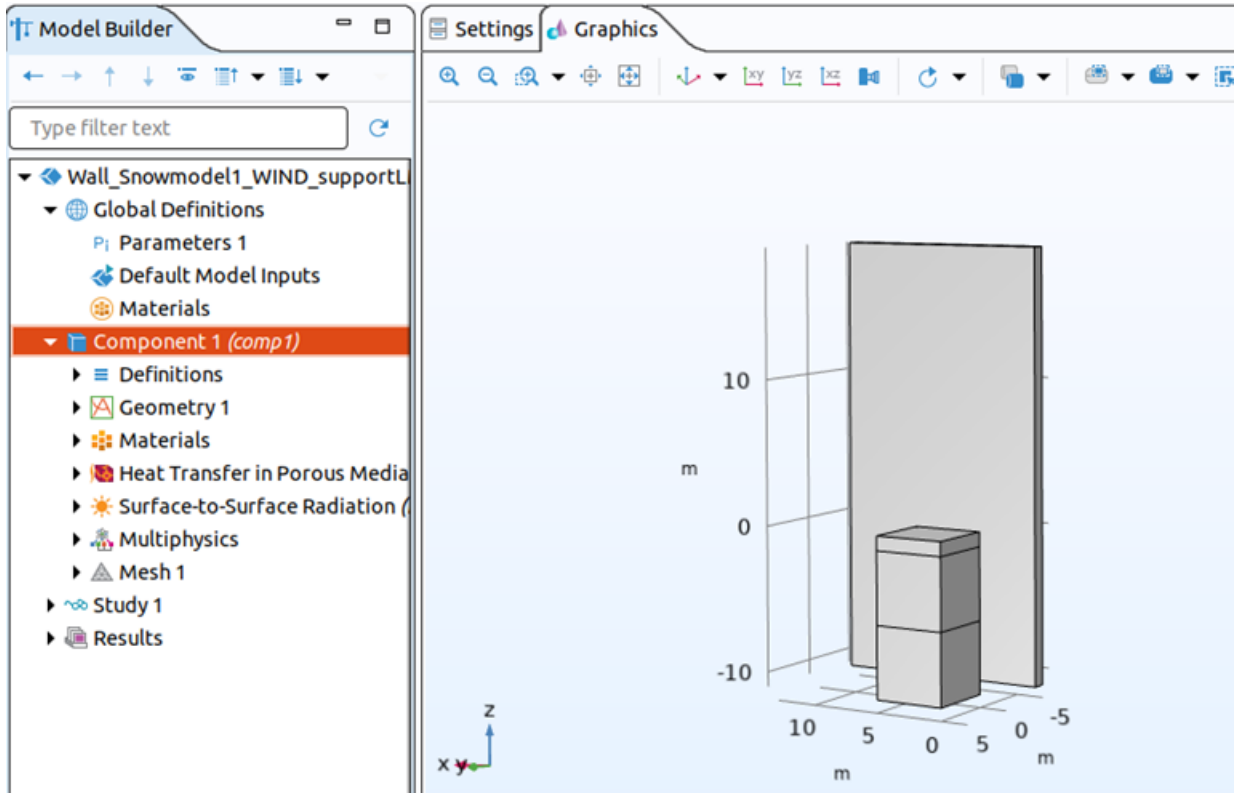




Development of a synthetic model

Purpose: to analyse heat transfer under controlled conditions in an idealised setup and establish a consistent simulation framework.

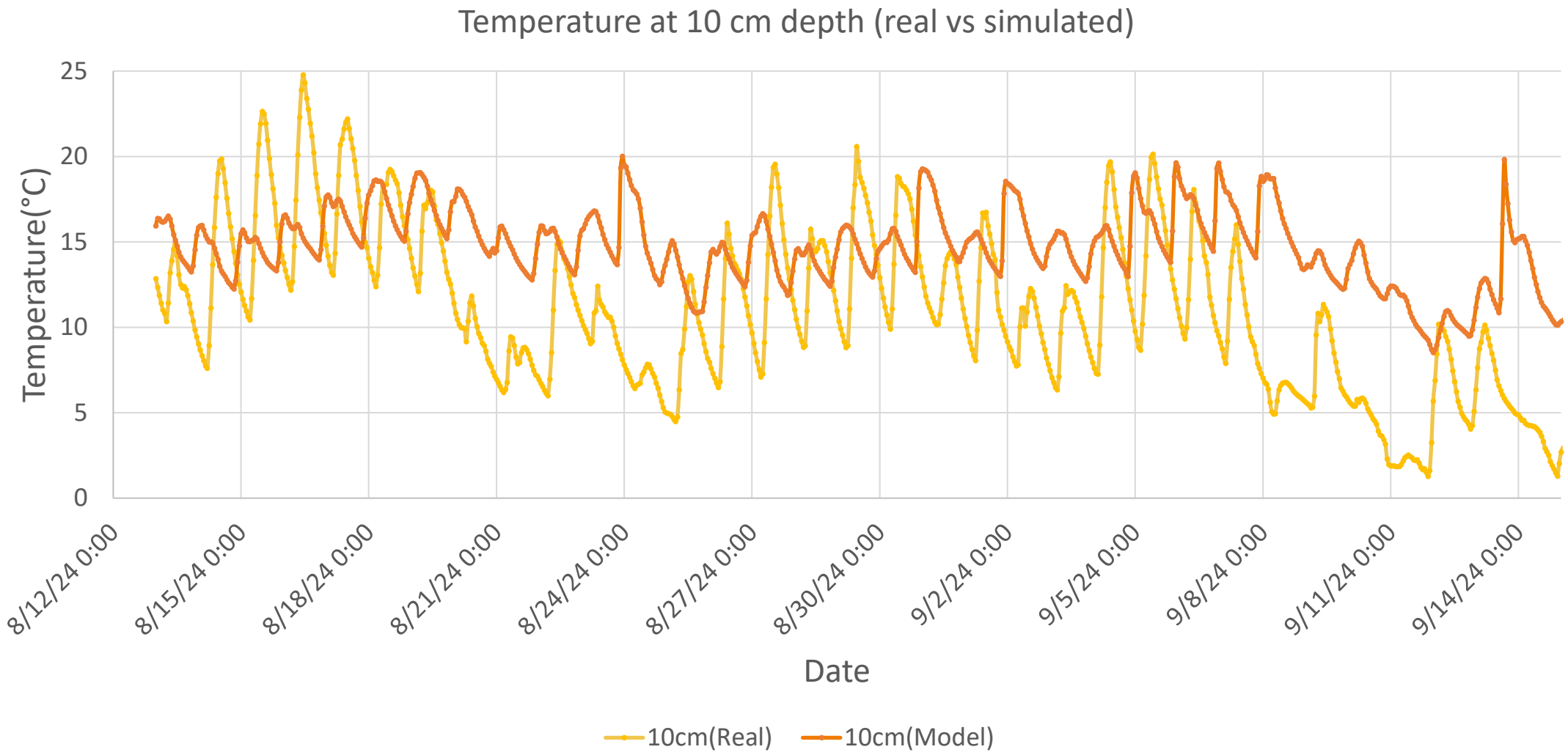
- Using default data available in the software
- Defining the geometry of the model
- Dedicating materials to the prepared geometry
- Defining the boundary condition such as climate data, thermal properties etc.
- Checking the results of the synthetic model



Development of the model with real data

- Preparation of observational data for model implementation in COMSOL
  - Site characteristics:
    - Rock surface tilted 87°, azimuth 92° from north, located at 45.30° N, 7.12° E, elevation 3473 m a.s.l.
  - Laboratory measurement of thermal properties of the investigated lithology:
    - Bulk density (ρ) = 3.13 g/cm^3,
    - Specific heat capacity (C) = 780.3 J/(kg·K).
- Surface monitoring data used as model inputs and for calibration
  - Global solar irradiance
  - Rock temperature at 10, 30, and 50 cm depth
- Model calibration through comparison between simulated and measured temperatures at corresponding depths

Baseline simulation results



Calibration process

1. Correction of missing or duplicated data in the observational dataset
2. Adjustment of model geometry and boundary conditions (back boundary temperature)
3. Calibration of intrinsic rock thermal properties to minimise the temporal lag between real and simulated subsurface temperatures at different depths
   - Thermal diffusivity
4. Refinement of climate forcing inputs to further reduce model-data discrepancies in subsurface temperatures
   - Convective heat transfer coefficient
   - Solar irradiance

Calibration of rock thermal properties

Purpose: to minimise the temporal lag between real and simulated subsurface temperatures at different depths.

a = thermal diffusivity

δ = thermal penetration depth = $\sqrt{\frac{2 \cdot T \cdot a}{\pi}}$

t = time lag in heat propagation = $\frac{x}{2}\sqrt{\frac{T}{\pi \cdot a}}$

Calibration of climate forcing inputs

Purpose: to further reduce model-data discrepancies in subsurface temperatures.

I = solar irradiance

$$T_{\mathrm{e,eff}} = T_{\mathrm{ea}} + \frac{\boldsymbol{I} \cdot \alpha - 4 \cdot F_{\mathrm{sk}} . \varepsilon \cdot \sigma \cdot \left(\frac{T_{\mathrm{ea}} + T_{\mathrm{sk}}}{2} \right)^3 \cdot (T_{\mathrm{ea}} - T_{\mathrm{sk}})}{\boldsymbol{h_c} + h_{\mathrm{r}}}$$

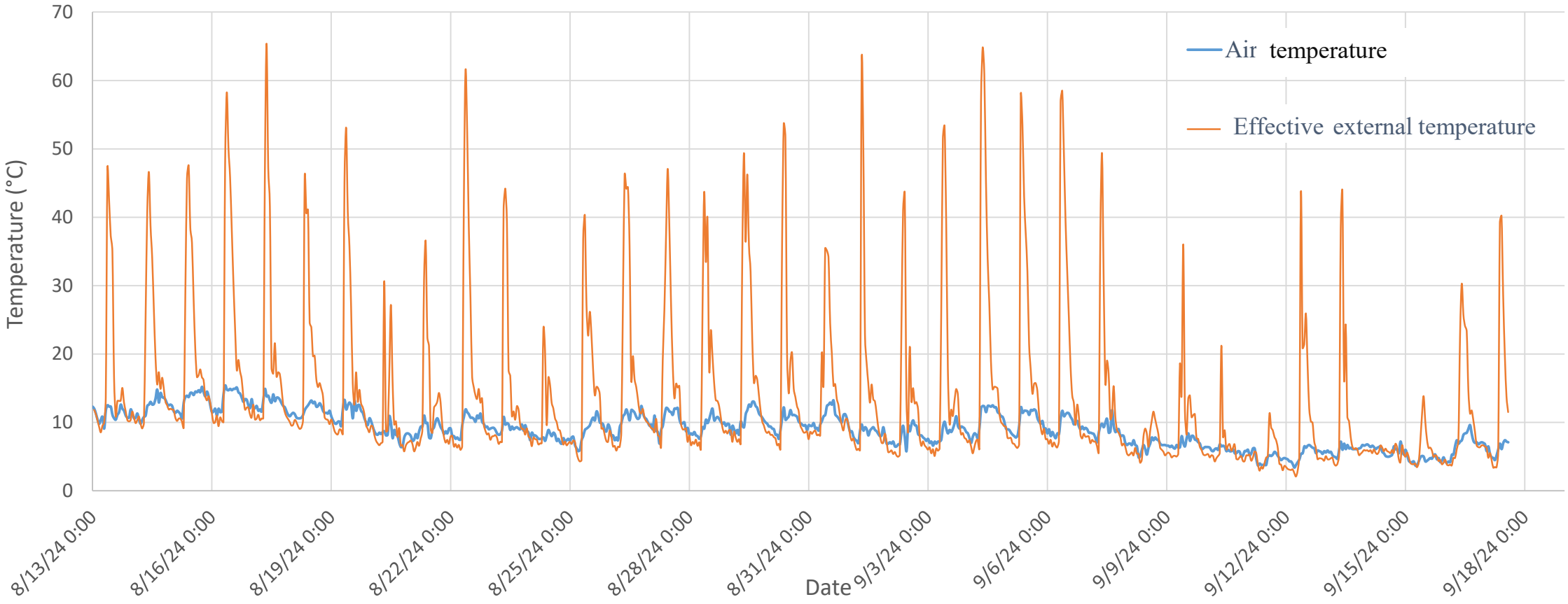
$\boldsymbol{h_c}$ = convective heat transfer coefficient:

$$h_c = \begin{cases} \dfrac{2 \cdot k \cdot 0.3387 \cdot Pr^{1/3} Re_L^{1/2}}{L\left(1 + \left(\frac{0.0468}{Pr}\right)^{2/3}\right)^{1/4}} & , \quad Re_L < 5 \cdot 10^5 \\ 2\dfrac{k}{L} Pr^{1/3}\left(0.037 \cdot Re_L^{4/5} - 871\right) & , \quad Re_L \geq 5 \cdot 10^5 \end{cases}$$

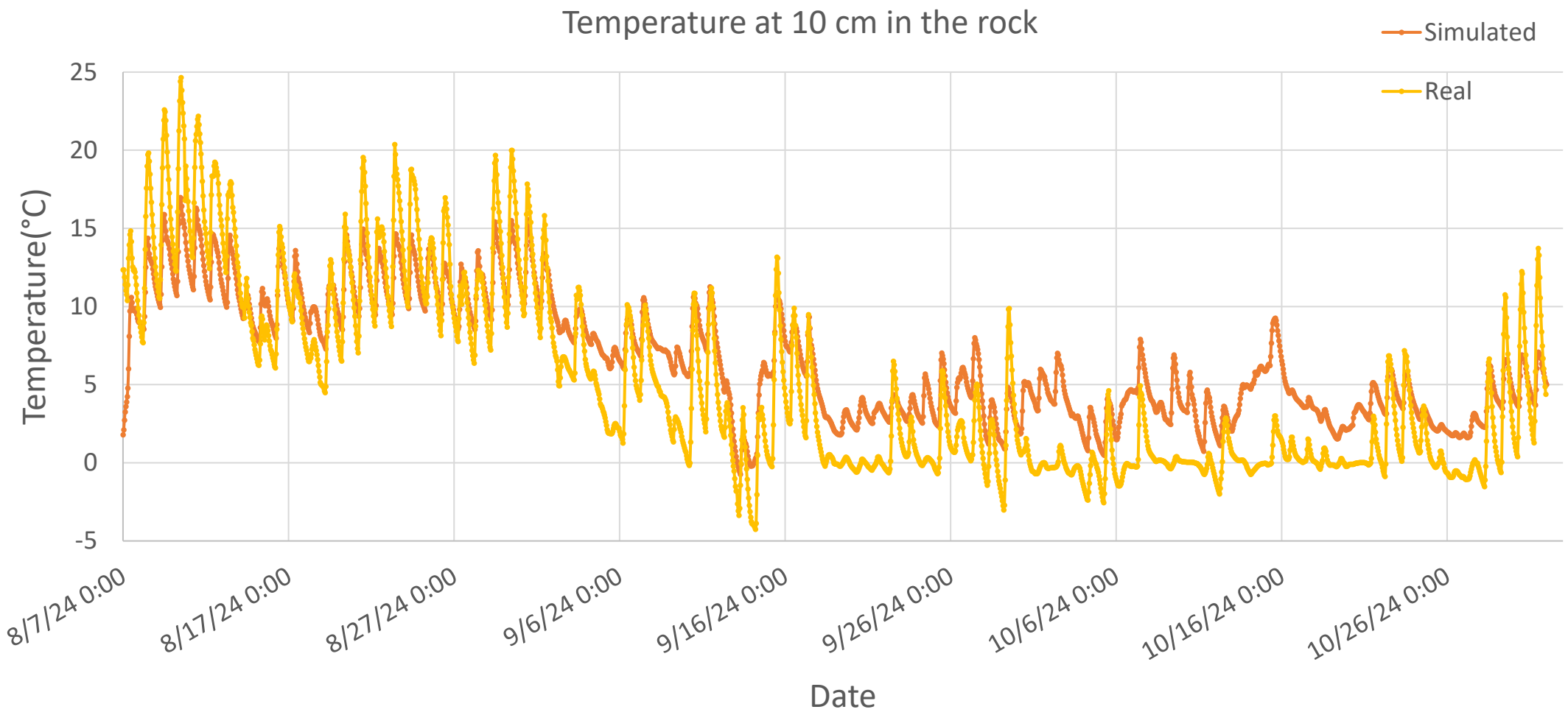
vs

$$h_c = 5.7 + 3.8 \cdot v_z$$

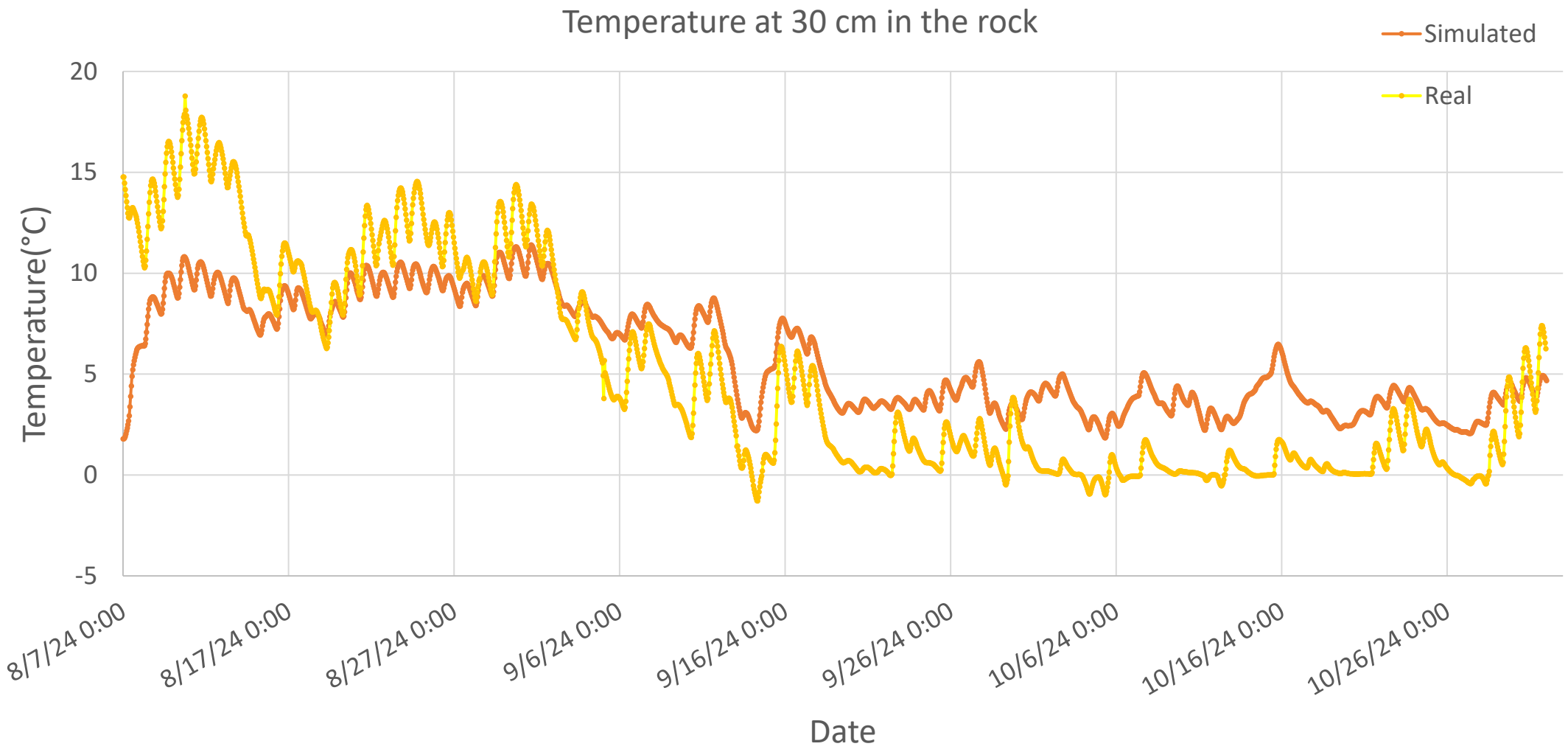
Calibration of climate forcing inputs



Simulation results after calibration



Simulation results after calibration



Simulation results after calibration

$$STD = \sqrt{\frac{\sum_{i=1}^{N}\left(T_{\text{real},i} - T_{\text{Ave}}\right)^2}{N}}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(T_{\text{real},i} - T_{\text{Simulated},i}\right)^2}{N}}$$

- Correlation and coefficient of determination (***R^2***)
- Normalized Root Mean Square Error (***NRMSE***) relative to data range = $\frac{RMSE}{T_{\text{real}}^{\max} - T_{\text{real}}^{\min}}$
- *RMSE* standard deviation ratio (***RSR***) = $\frac{RMSE}{STD}$

Method Depth	R^2	*NRMSE*	*RSR*
10 cm	0.87	0.10	0.50
30 cm	0.89	0.13	0.50
50 cm	0.80	0.17	0.66

Simulation results after calibration

Calibration Outcomes

- Improved agreement between measured and simulated temperatures
- Reduced temperature bias and temporal lag after calibration
- Enhanced reproduction of observed temperature variability

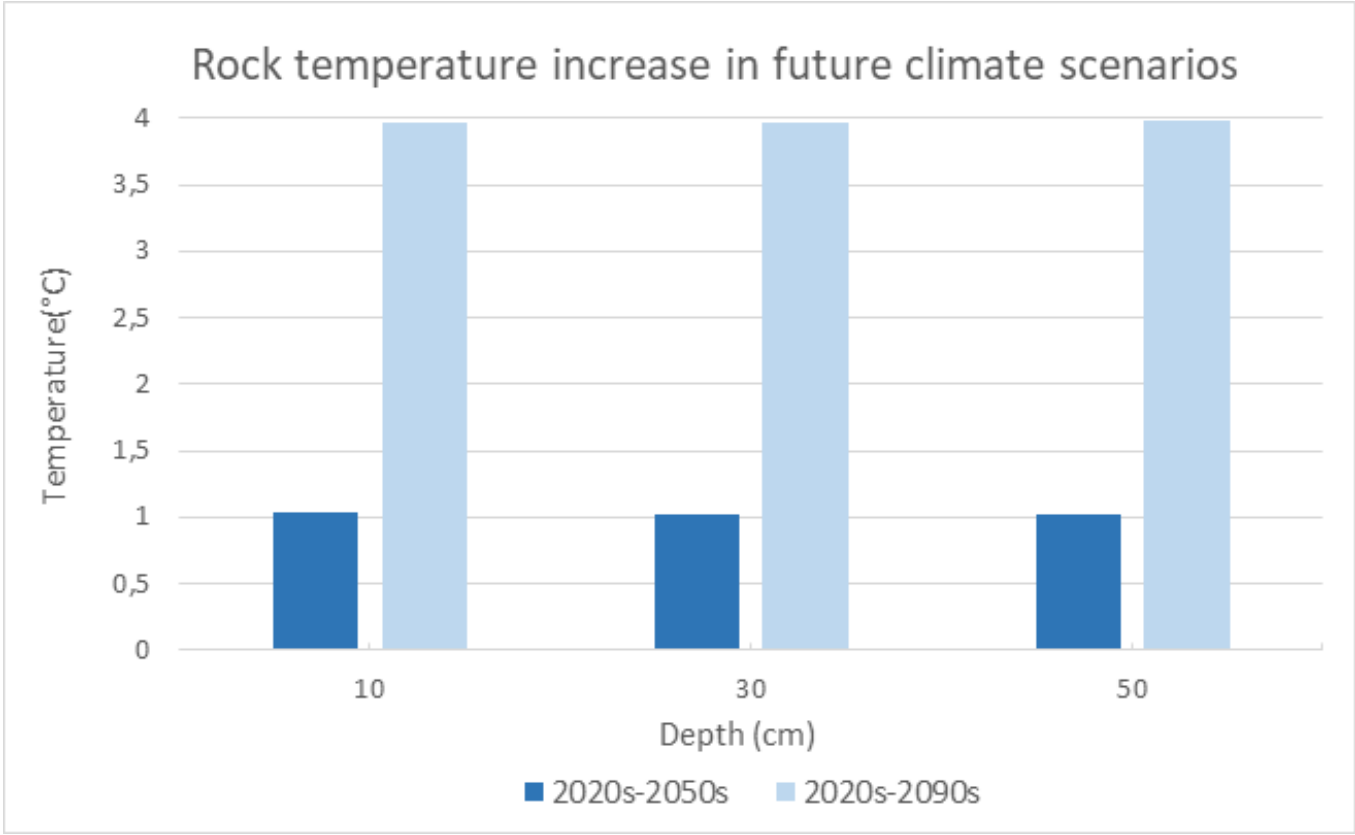
Limitations:

- Requirement for high-quality monitoring data (air temperature, wind speed, and solar irradiance)

Simulation results under future climate scenarios

Yearly mean subsurface temperature [°C]

Depth	2020s	2050s	2090s
10 cm	-1.99	-0.97	1.96
30 cm	-2.09	-1.06	1.87
50 cm	-2.18	-1.17	1.78



Conclusion

- Validated numerical model for simulating heat transfer in alpine rock formations
- High agreement with field data ($R^2 > 0.8$; *NRMSE* within acceptable limits) across lithotypes and depths
- Robust tool for analysing subsurface thermal dynamics in complex alpine environments
- Quantification of future near-surface warming (2020s–2090s), supporting thermo-mechanical and rockfall risk assessments under climate change

Grazie per l’attenzione!

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