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# Towards improved alpine permafrost maps using the energy balance model of the CryoGrid community

Benjamin Lehmann, Florence Magnin, Maëva Cathala, Sebastien Westermann

## Introduction

The **warming of mountain permafrost** due to climate change poses significant challenges for **slope stability** and **ecosystem dynamics** in alpine regions.

Existing **permafrost mapping** methods are either developed using :

- (i) Rock surface temperatures and rock glacier inventories.
  - (ii) Statistical models linking permafrost evidence to air temperature and solar radiation
- Those current models struggle to capture **complex thermal regimes associated with variable snow accumulations** and their application is particularly challenging for **intermediately steep slopes (40°–60° inclination)**.

**Intermediately steep slopes**, a significant portion of alpine landscapes, present unique conditions :

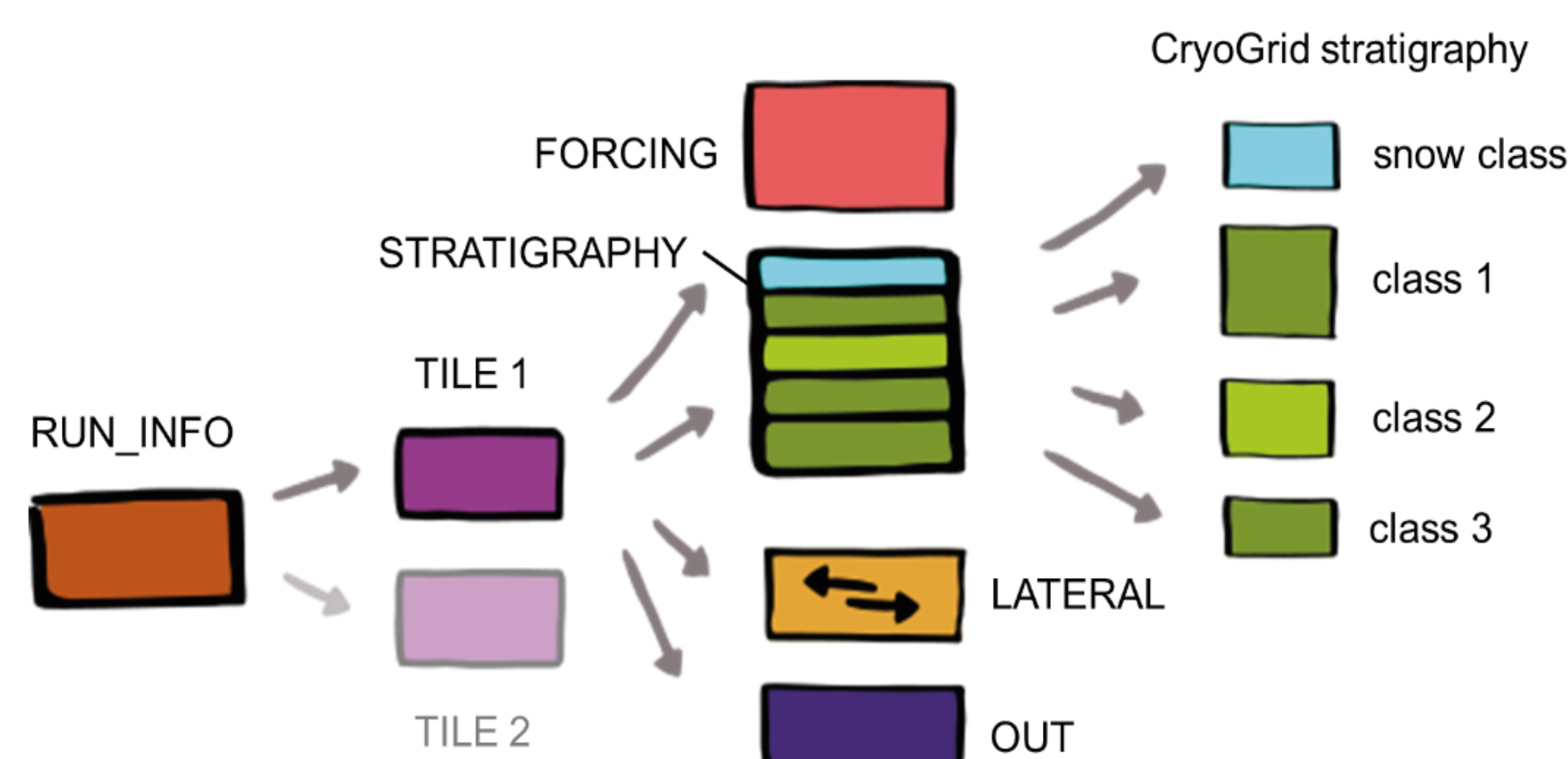
- they are strongly influenced by **snow accumulation** patterns.
- they exhibit **fractured rock**, **surface debris**, and **variable snow cover**.
- they retain **larger ice volumes** due to refreezing of **meltwater from seasonal snow**.
- they have **distinct thermal regimes** and **geomorphological behaviors**.
- their **complex micro-topography** amplifies variability in **solar radiation** and **snow distribution**.

**Intermediately steep slopes** have consequently strong implications for thermal and mechanical stability. In this project, we calibrate and applied **advanced mapping techniques** to better **capture permafrost dynamics**.

## CryoGrid community model

We apply the **CryoGrid community energy and hydrological balance model**. The **CryoGrid community model** is a flexible toolbox for **simulating the ground thermal regime and the icewater balance for permafrost**.

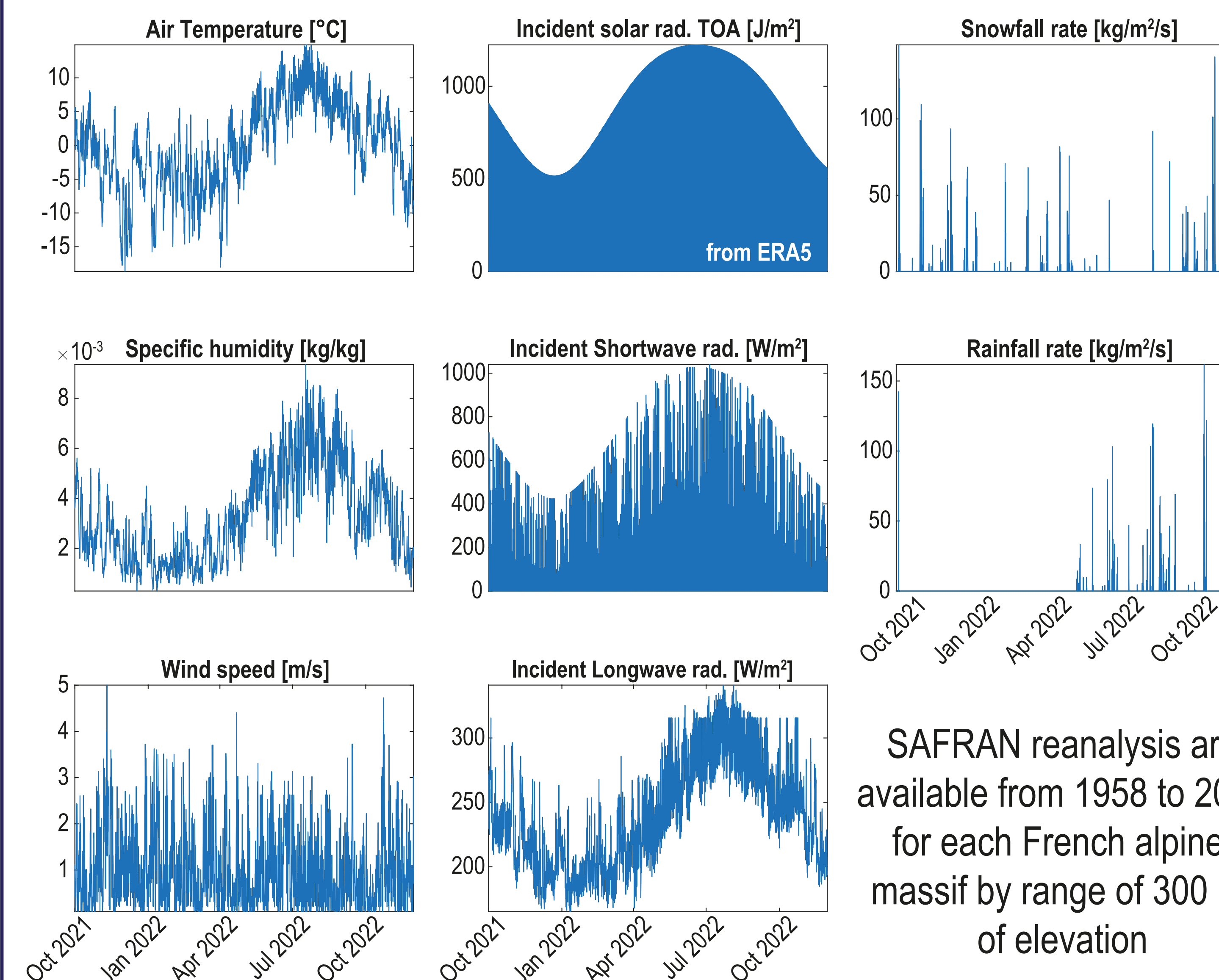
The objective is to **simulate temperature dynamics** at monitored sites in the French Alps, spanning elevations of 2500 to 3800 m a.s.l.



Hierarchy (left to right) of the different types of CryoGrid classes required for **multi-physics simulations** within the CryoGrid community model. Arrows represent pointers to classes employed in the hierarchical level (Westermann et al., 2022).

## Climate forcings – from SAFRAN and ERA5

To simulate ground surface temperature, we need climate forcings

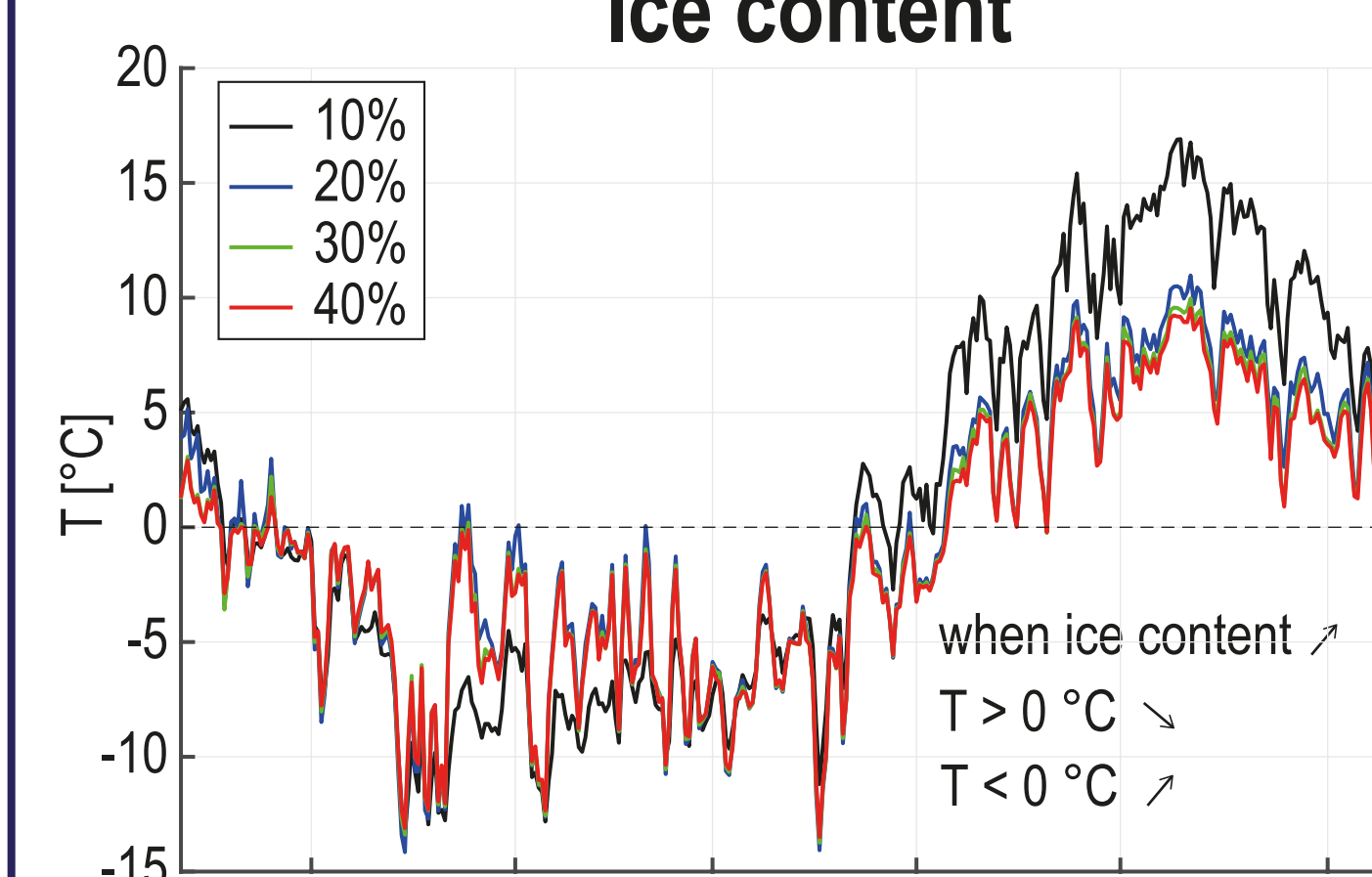


SAFRAN reanalysis are available from 1958 to 2024 for each French alpine massif by range of 300 m of elevation

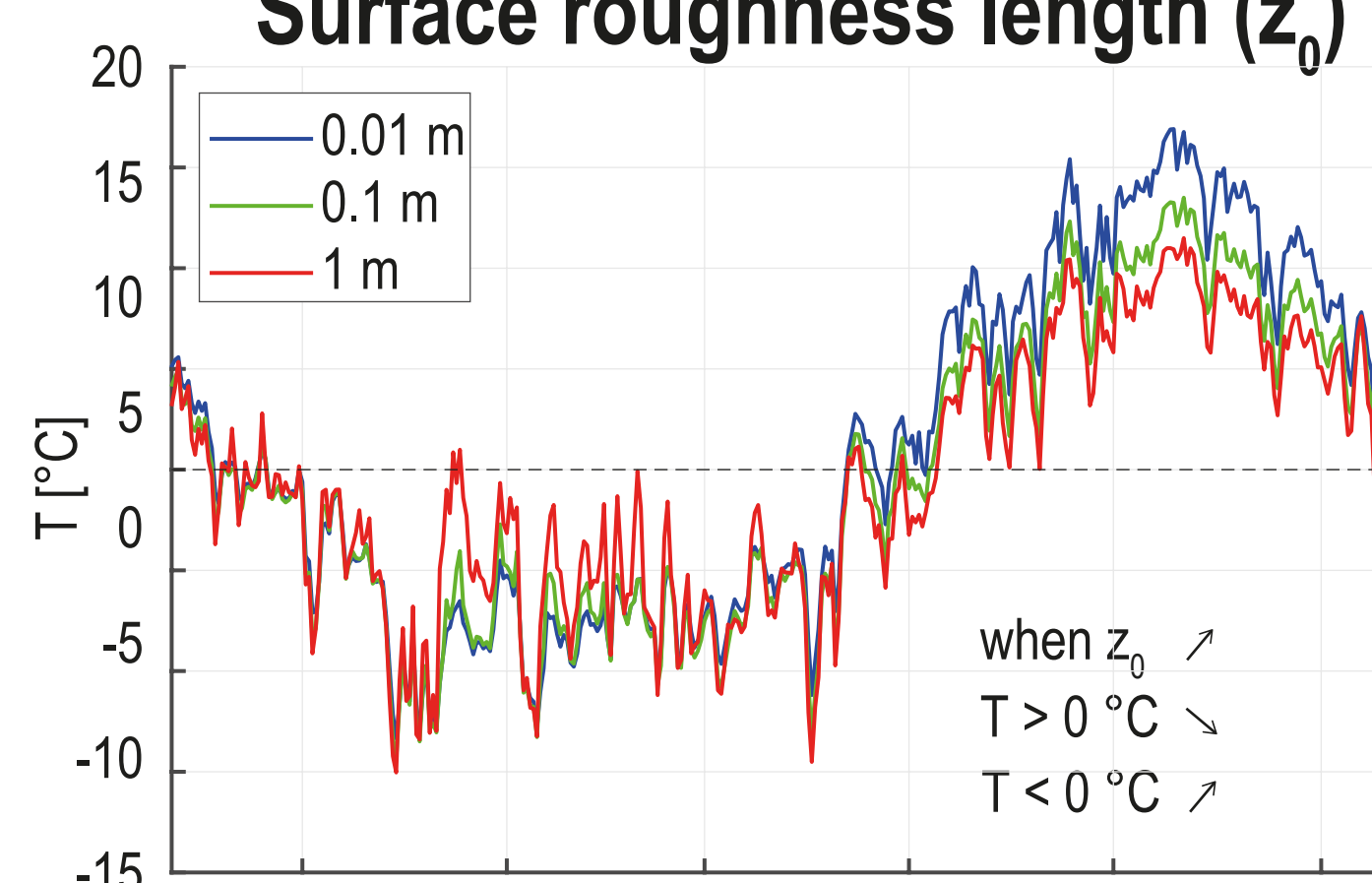
## How to calibrate ?

We need to evaluate the effect of site dependent variables on ground surface  $T^{\circ}$ .

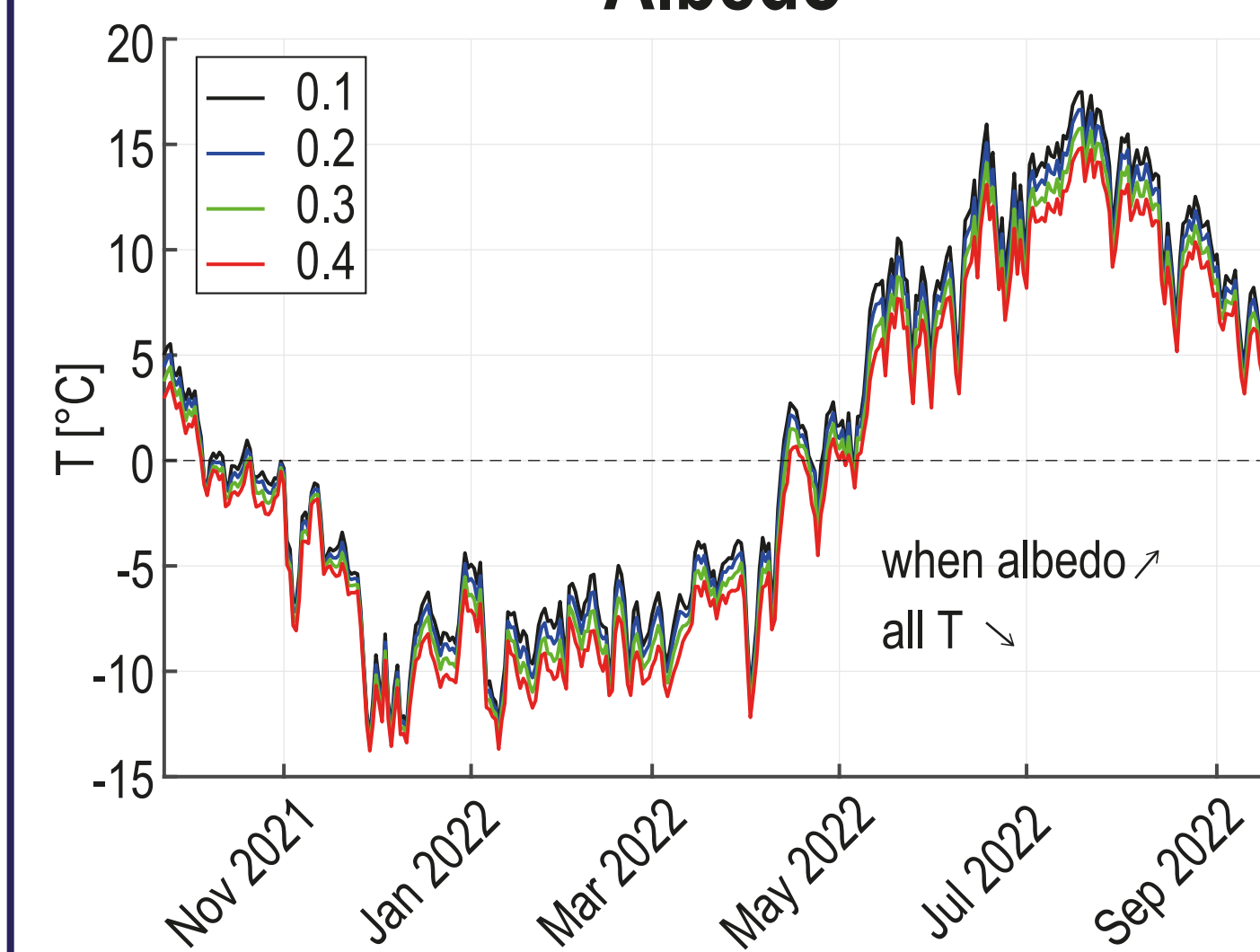
### Ice content



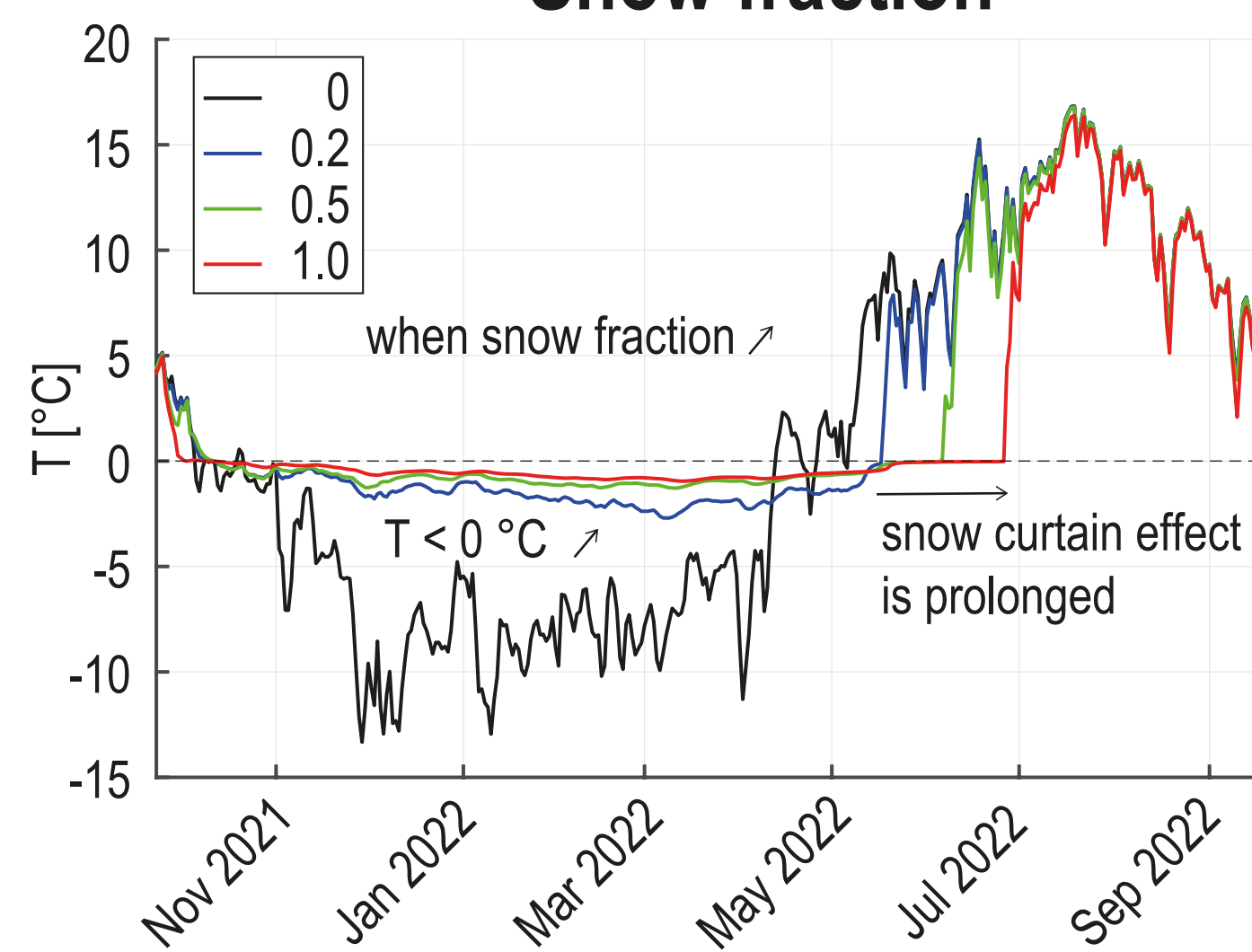
### Surface roughness length ( $z_0$ )



### Albedo

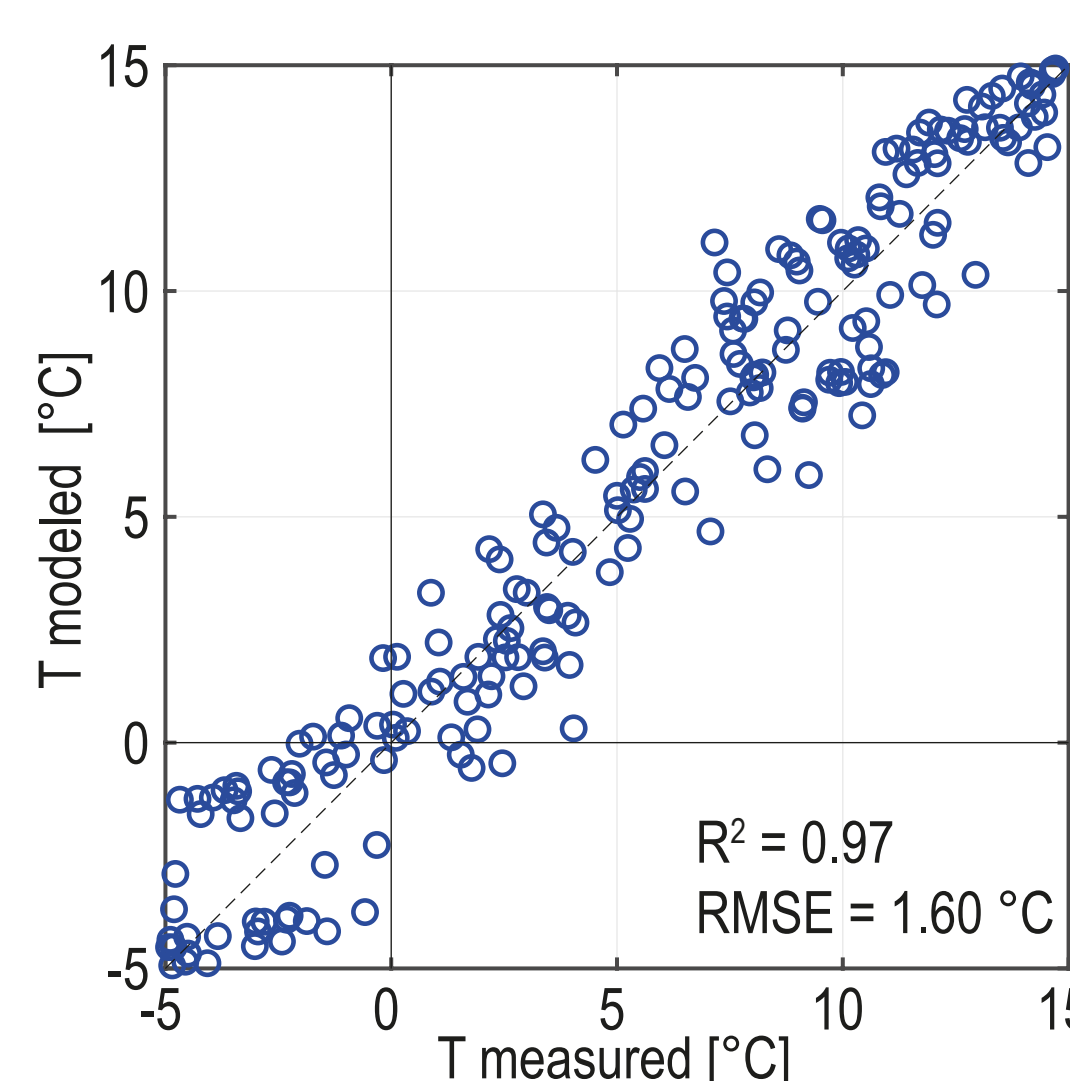
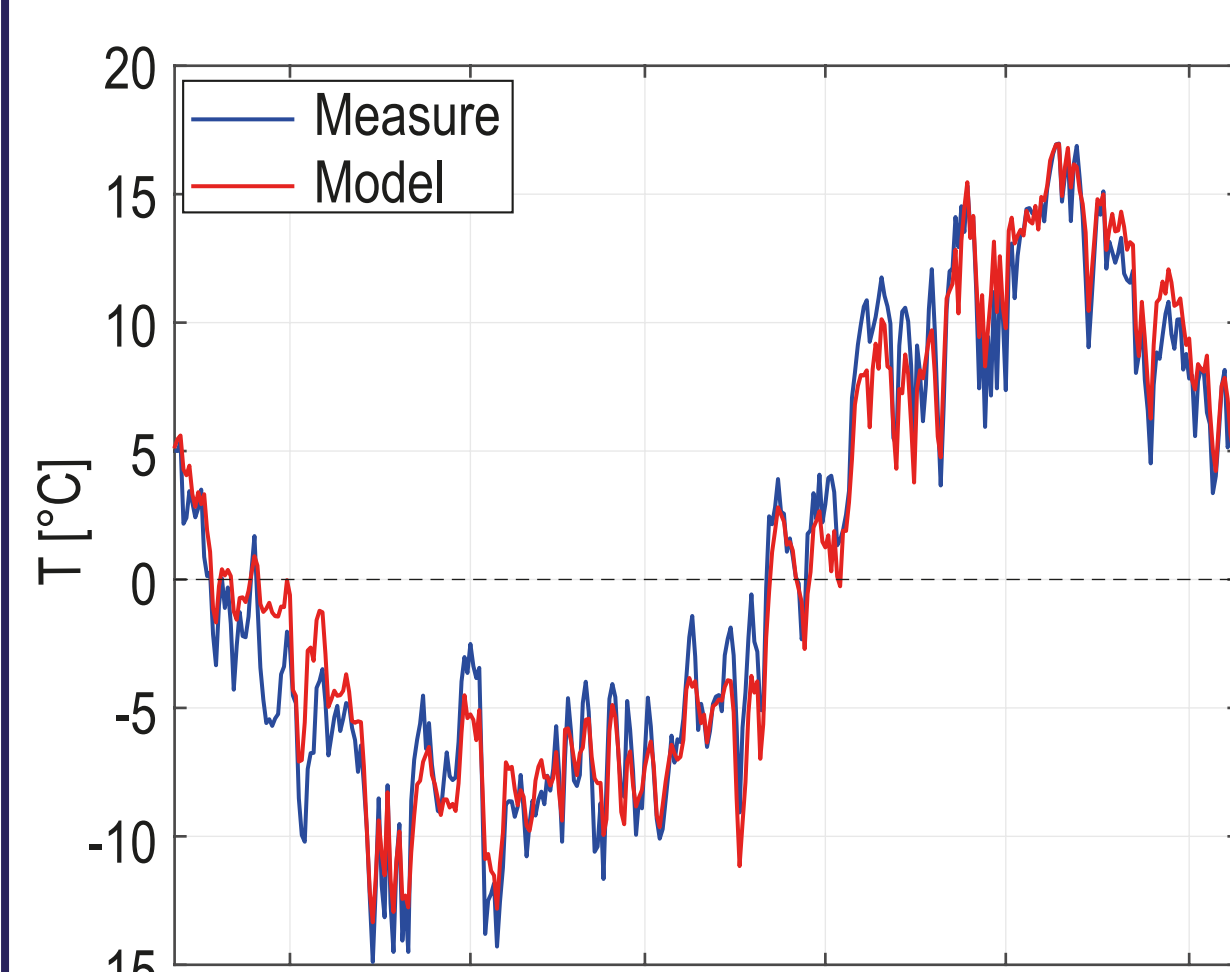


### Snow fraction

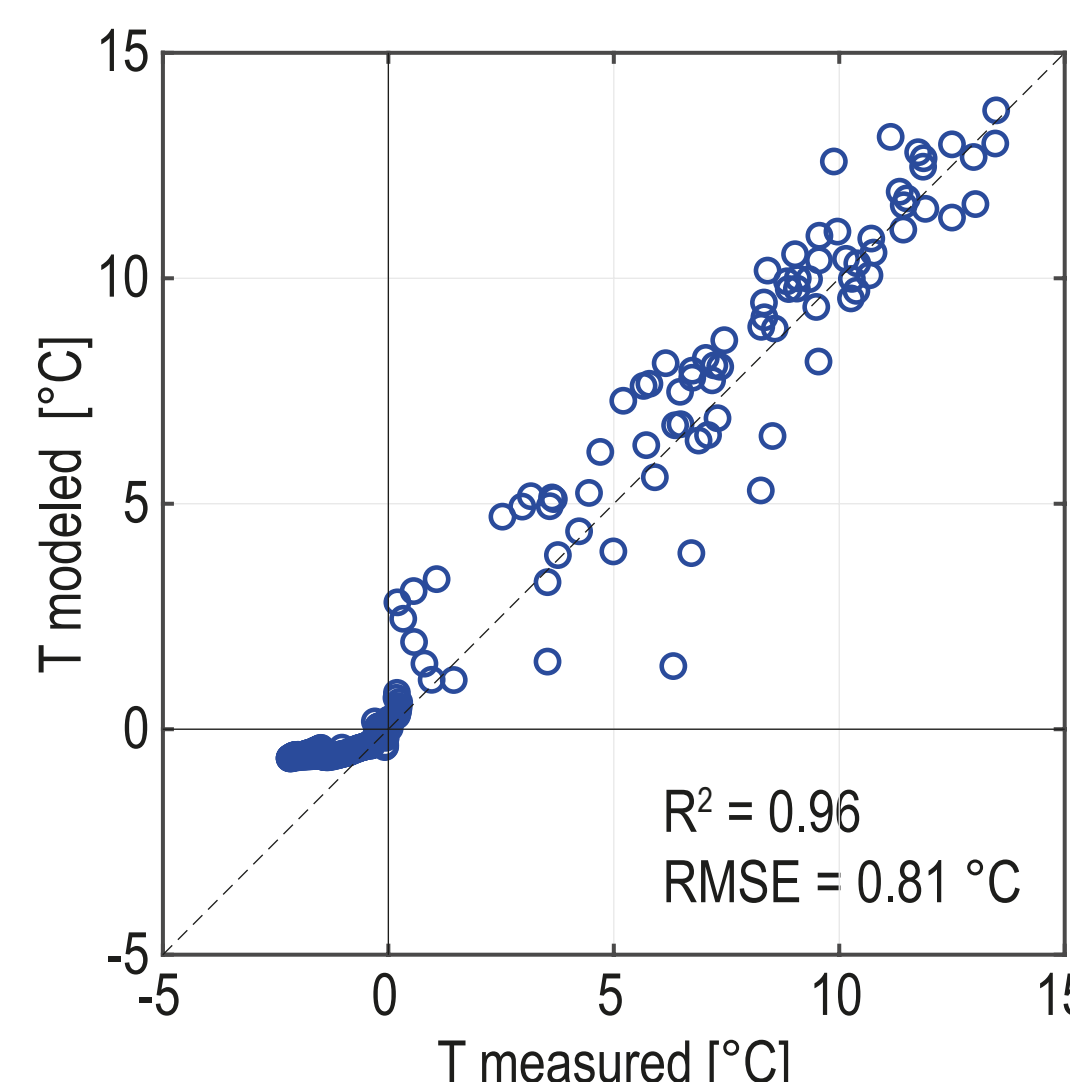
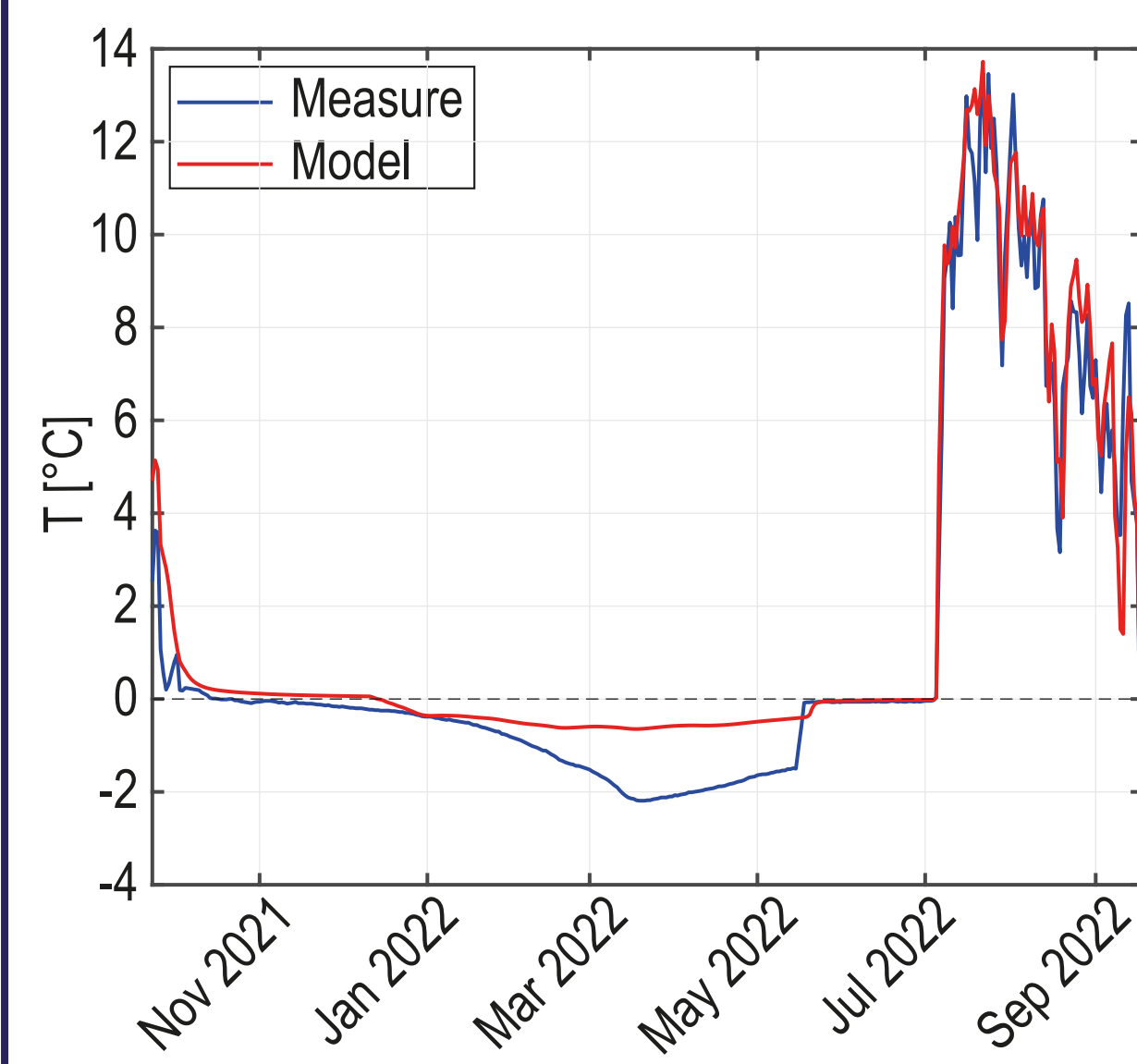


## Calibration with GST measurements

### Snow-free rockwall



### Snow-affected rock surface



	Snow-free rockwall	Snow-affected rock surface
Site specific variable		
latitude [°]	45	45
longitude [°]	6	6
elevation [m a.s.l.]	3245	3157
slope angle [°]	80	20
aspect [°]	60	60
sky view factor [-]	0.55	0.85
Surface specific variable		
albedo [-]	0.18	0.18
roughness length [m]	0.01	0.2
Climatic variable		
snow fraction [-]	0	2
ice conc. in ground [-]	0.1	0.1
initial temp. profil [°C]	-0.6	-0.6
Results 1991 - 2020		
MAGST [°C]	-0.36	-0.89
Median [°C]	-0.9	-0.01
1σ [°C]	7.18	2.78

Once calibrated, **the model will be generalized** to account for variable slope angles, sun exposures, surface roughness, ground characteristics, and precipitation regimes.



## Perspectives

These calibration steps will enable **spatial application of the model on digital elevation models** to generate **improved permafrost maps** for alpine settings, encompassing steep rock walls, creeping debris slopes, and intermediately steep slopes. Additionally, the model outputs will provide insights into **permafrost evolution in diverse mountain slopes** and **support stakeholders in developing effective risk mitigation strategies**.