INVESTIGATION OF PERMAFROST IN CHANDRATAL LAKE AREA

M.Tech Thesis

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DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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INVESTIGATION OF PERMAFROST IN CHANDRATAL LAKE AREA

A THESIS

Submitted in partial fulfillment of the
requirements for the award of the degree
of
Master of Technology
In
WATER, CLIMATE and SUSTAINABILITY

By

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DEPARTMENT OF CIVIL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY INDORE

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **INVESTIGATION OF PERMAFROST IN CHANDRATAL LAKE AREA** in the partial fulfilment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** in **WATER, CLIMATE and SUSTAINABILITY** and submitted in the **DEPARTMENT OF CIVIL ENGINEERING, INDIAN INSTITUTE OF TECHNOLOGY INDORE**, is an authentic record of my work carried out during the period from July 2023 to May 2025 under the supervision of Dr. Mohd. Farooq Azam, Associate Professor, Department of Civil Engineering, IIT Indore

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Raman!

Signature of the student with date
(Raman Yadav 29/05/2025)

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

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Date: 29/05/2025 **RAMAN YADAV (2302104017)**

ABSTRACT

This study evaluated the presence of permafrost in the Chandratal Lake region using the GEOtop model. The model was simulated using field soil temperature (10cm depth) data collected from 11 T-Loggers around the lake from September 2020 to June 2024. Furthermore, bias-corrected hourly soil temperature (Level 1 and Level 2) ERA5 data from 1991 to 2024 were used for model simulation to understand the temporal variation of soil thermal profile along the depth over three decades. The model was run using high and low thermal diffusivity for soil to get an envelope of thermal profiles of soil along the depth. The field data was used to determine the snow melt-out date for the locations of T-Loggers over three years (2021 to 2023). The study revealed an absence of permafrost in the lakes surrounding as the soil temperature stabilizes above 3.35°C in both high and low thermal diffusivity cases. This is in contrast to the previous remote sensing and air temperature-based studies that hinted at permafrost's presence in the region. These results raise the potential question of whether we are overestimating the presence of permafrost by using indirect parameters for the soil thermal profile instead of actual ground temperature.

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NOMENCLATURE

U^{ph}	:	Volumetric internal energy of soil subjected to phase change (J m^{-3})
t	:	Time (s)
G	:	The heat conduction flux (W m^{-2})
S_{en}	:	Energy sink term (W m^{-3})
S_w	:	Mass sink term (s^{-1})
L_f	:	Latent heat of fusion (J kg^{-1})
ρ_w	:	Density of liquid water (kg m^{-3})
T	:	Soil temperature (ºC)
T_{ref}	:	Reference temperature for the calculation of internal energy (ºC)
n	:	Number of observations
Q_{obs}	:	Observed (field) value
Q_{ERA5}	:	ERA5 value

ACRONYMS

GST	:	Ground Surface Temperature
MAGST	:	Mean Annual Ground Surface Temperature
MAGT	:	Mean Annual Ground Temperature
MD	:	Melt-out Date

Chapter 1. Introduction

Permafrost refers to ground that remains below 0 °C for at least two consecutive years . Figure 1 shows the cross section of a land with permafrost below the active layer along with its corresponding thermal layer. It plays a vital role in regulating surface energy balance, hydrological processes, and carbon storage. Permafrost research has gained prominence due to its sensitivity to climate change, particularly in high-altitude and high-latitude regions. Permafrost is a critical water reservoir in mountainous terrains like the Himalayas, influencing downstream hydrology. However, the region remains understudied compared to the Arctic or the Alps, where substantial advancements have been made in understanding permafrost dynamics through remote sensing and advanced modelling (Endrizzi et al., 2014).

Himalayan permafrost research has highlighted unique challenges and characteristics. Wani et al. (2021) identified the dominance of nighttime longwave radiation loss and snow insulation in maintaining permafrost stability in the cold-arid Ladakh region. Similarly, studies like Pandey et al. (2020) explored the influence of thermokarst lakes on accelerating permafrost thaw and greenhouse gas emissions, demonstrating their role as indicators of permafrost degradation. Advances in modelling, such as the GEOtop framework, have provided tools to simulate the thermal and hydrological behaviour of frozen soils, offering insights into the complex relationships of topography, snow cover, and soil dynamics in permafrost regions (Endrizzi et al., 2014). These efforts underscore the importance of integrating field observations, remote sensing, and numerical models to better understand and mitigate the impacts of permafrost thaw in the Himalayas.

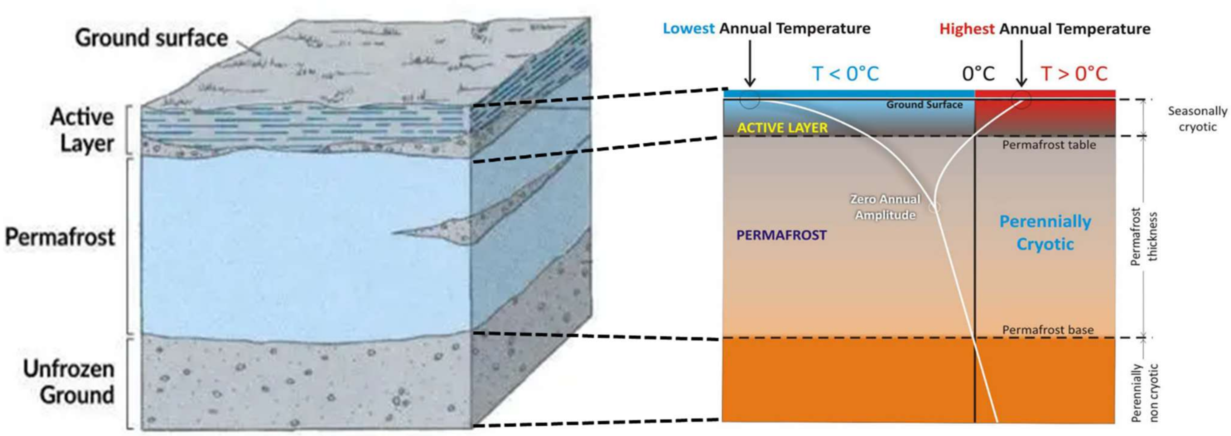


Figure 1: Cross section of a ground with permafrost (Amoghavarsha IAS Academy), and it's corresponding thermal envelope that shows the variation of maximum and minimum temperatures along the depth (Severe Weather Europe).

The Himalayas provide water to rivers through the melting of ice and snow, along with precipitation. However, the lack of knowledge and extensive research about the existence of permafrost systems in the range means no study is able to quantify how much of the discharge is due to the thawing of permafrost. Apart from its hydrological importance, the thawing of permafrost also affects the slope stability of the region (mountain range) and acts as an indicator of climate change. Additionally, the seasonal snow cover and melting also affect the runoff, ground temperature, and slope movements. The melt-out dates (MD) describe the date when complete snow cover has melted, letting the ground reach temperatures above 0^0C.

We simulate the one-dimensional heat equation at selected locations from 20 September 2020 to 7 June 2024 near the Chandratal lake (Figure 1) area. The model is driven by a time series of ground temperature data. The model outputs will provide crucial permafrost variables, such as active layer thickness, thermal offset, and mean annual ground temperature (MAGST). By combining in situ data with physically based modelling, this study will provide valuable insights into the existence of permafrost in the Chandratal region. Furthermore, understanding the state of permafrost in this area is essential for assessing its role in the regional hydrology, ecosystems, and its potential responses to climate change, and the MD of snow helps in better estimation of snowmelt runoff onset, increasing the accuracy of streamflow forecasting and reservoir planning. The dataset generated from this study will also help address data gaps related to permafrost in the region.

Chapter 2. Review of Literature

Permafrost is a critical cryosphere component that significantly affects hydrological processes, climate dynamics, and ecological stability. Understanding permafrost in unique terrains, such as the Himalayas, requires a combination of field-based studies, remote sensing, and advanced hydrological modelling. This review synthesizes findings from crucial research papers by Wani, Endrizzi, and Pandey to examine permafrost dynamics and associated processes in cold and arid environments and help us better understand permafrost in the Himalayan region.

2.1 Surface Energy Balance in Himalayan Permafrost

Wani et al. (2021) analysed the surface energy balance in Ladakh, a cold-arid Himalayas region, to understand its influence on permafrost stability. Their results showed that net radiation is the most considerable energy flux in the region, highlighting its role in governing snowmelt and permafrost thaw. Specifically, their measurements discovered longwave radiation loss as a dominant cooling factor during the night, which is critical for permafrost preservation. The authors emphasized the importance of snow cover as an insulator, reducing heat loss to the atmosphere and maintaining ground temperatures below freezing during winter. Energy flux indicated a direct relationship between snowmelt duration and permafrost thaw rates, suggesting that changes in snow dynamics due to climate change could destabilize existing permafrost (Wani et al., 2021). This work gives us a better understanding of the thermal conditions of Himalayan permafrost, particularly in regions with minimal observational data.

Further findings by Wani et al. (2018) supported the presence of permafrost at elevations of 4,500 to 5,000 meters in the Himalayas, which was concluded using long-term surface energy balance monitoring. Their study identified cold temperatures, reduced humidity, and significant nighttime radiation loss as key factors favouring permafrost formation.

Together, these studies highlighted the sensitivity of Himalayan permafrost to changes in surface energy fluxes, making it a crucial area of study.

2.2 Modelling of Frozen Soils Using the GEOtop Model

The GEOtop model, discussed by Endrizzi et al. (2014), offers a framework for understanding hydrological and thermal processes in frozen soil environments. GEOtop 2.0 incorporates detailed simulations of energy and water balances, accounting for soil freezing/thawing, snow cover dynamics, and terrain effects. Validation of the model using field data from the Alps demonstrated its ability to accurately predict soil temperature profiles and water flow under varying climatic conditions. For example, simulations revealed that soil freezing occurred at a depth of up to 1.5 meters, with subsequent thawing driven by net radiation and precipitation inputs (Endrizzi et al., 2014).

The GEOtop model has significant implications for Himalayan permafrost research. Its capability to simulate permafrost-related hydrological and thermal processes at high spatial and temporal resolutions makes it an essential tool for studying permafrost existence and stability in the Himalayas. The integration of terrain effects is particularly relevant for regions like the Himalaya, where steep slopes and altitude variations greatly influence energy fluxes and permafrost distribution.

2.3 Thermokarst Lakes and Permafrost Thaw in the Himalayas

Pandey et al. (2020) worked on the dynamics of thermokarst lakes near Chandratal in the Indian Himalayas, focusing on their role in accelerating permafrost degradation. These lakes have increased by approximately 20%, primarily due to rising temperatures and prolonged thawing periods over the last decade. The study highlighted that thermokarst lakes serve as hotspots for greenhouse gas emissions, which release methane and CO_2 as organic matter stored within permafrost decomposes upon thawing. This feedback mechanism amplifies regional warming, posing a significant threat to the stability of the Himalayan permafrost (Pandey et al., 2020).

Pandey's findings also emphasized the critical role of thermokarst lakes as indicators of permafrost degradation. The study demonstrated a strong correlation between the expansion of these lakes and subsurface warming, providing proof of linkage between climate change and permafrost dynamics in the region.

2.4 Inferring Melt-out Date from near-surface ground temperatures

Schmid et al. (2012) worked on finding out the snow melt-out dates (MD), focusing around Piz Corvatsch (south-eastern Switzerland). Forty locations were covered, using 10 miniature loggers (iButtons) to gather the near-surface ground temperature, with elevation range spanning from 2100 to 3300 m a.s.l.

Schmid et al. (2012) findings highlighted the spatial variability in the timing of snowmelting, even within smaller areas of observation, which emphasized on the importance of distributed field measurements for accurate modelling of snow dynamics.

2.5 Research Implications

The collective findings of Wani et al. (2021), Endrizzi et al. (2014), and Pandey et al. (2020) provide a near-perfect understanding of permafrost processes in cold and arid environments, particularly the Himalayas. Wani's surface energy balance studies emphasize the critical role of snow insulation and radiation loss in permafrost preservation. At the same time, Endrizzi et al. (2014), work with the GEOtop model offers a methodological framework for simulating these processes in complex terrains. Meanwhile, Pandey et al.'s (2020) investigation into thermokarst lakes highlights the cascading effects of permafrost thaw on hydrology and greenhouse gas emissions. Schmid's study explains the spatial variability of snow melting, hinting at the difference in solar radiation and other meteorological forcings within a smaller area of research.

Together, these studies highlight the fragility of Himalayan permafrost under a warming climate. Rising temperatures, changing precipitation patterns, and the expansion of thermokarst lakes could destabilize permafrost in these regions, with profound implications for downstream hydrology and carbon dynamics. Future research should prioritize the integration of in-situ observations, remote sensing data, and advanced modelling techniques like GEOtop to develop high-resolution permafrost maps and assess the broader impacts of permafrost thaw on Himalayan ecosystems.

Chapter 3. Objectives

The Chandratal lake in the Indian Himalayas is in a climatically sensitive zone, where permafrost is critical in regulating hydrological systems and maintaining ecological stability. Despite its significance, permafrost in this region remains poorly understood due to limited in situ measurements and scarce research. Rising global temperatures, joined with changing precipitation patterns, have accelerated the degradation of permafrost globally, including in high-altitude areas such as the Himalayas. This has been evidenced by the expansion of thermokarst lakes and increased greenhouse gas emissions, as highlighted in studies by Pandey et al. (2020).

A lack of high-resolution data and advanced modeling in this region inhibits the ability to predict the long-term stability of permafrost and its associated impacts on water availability and carbon cycling. Recent advancements, such as the GEOtop model (Endrizzi et al., 2014), have demonstrated the potential to simulate energy and water balances in complex terrains, but their application to the Chandratal permafrost remains unexplored. This creates an urgent need to investigate the permafrost distribution, dynamics, and vulnerability in the Chandratal lake region, integrating in situ observations, remote sensing, and numerical modeling, to address critical knowledge gaps.

Objective 1: Investigating permafrost existence in the Chandratal Lake region using in situ ground temperature data from T-Loggers

In-situ ground temperature data, measured by T-Loggers at 11 locations at a depth of 10 m, will be used to simulate the GEOtop model to get the thermal regime of the area. This will give us the presence or absence of permafrost.

Objective 2: Understanding the temporal variation of soil profile using bias-corrected Soil Temperature (Level 1 and Level 2) ERA5 data

Obtain Level 1 (3.5cm) and Level 2 (17.5cm) soil temperature from ERA5 and perform bias correction using the field data before using it to simulate the GEOtop model to understand the temporal variation of the thermal regime of the area. This will tell us if there has been a thaw of permafrost over the last three decades.

Objective 3: Inferring snow melt-out date from near-surface ground temperatures

Use the field ground temperature data (same as objective 1) to determine when the seasonal snow cover melts out, leaving the surface naked and allowing the ground surface to warm above 0^{o}C.

Chapter 4. Study Area

Himachal Pradesh is situated in the northern part of India with a greatly diversified climate due to a huge elevation range (450-6500 m). Table 1 shows climate variation with their corresponding elevations and regions. The state receives an average rainfall of 1,251mm, while snowfall of about 3m occurs at an elevation of 3000m, and it lasts from December to March. At about 4500m, snow becomes perpetual (Himachal World).

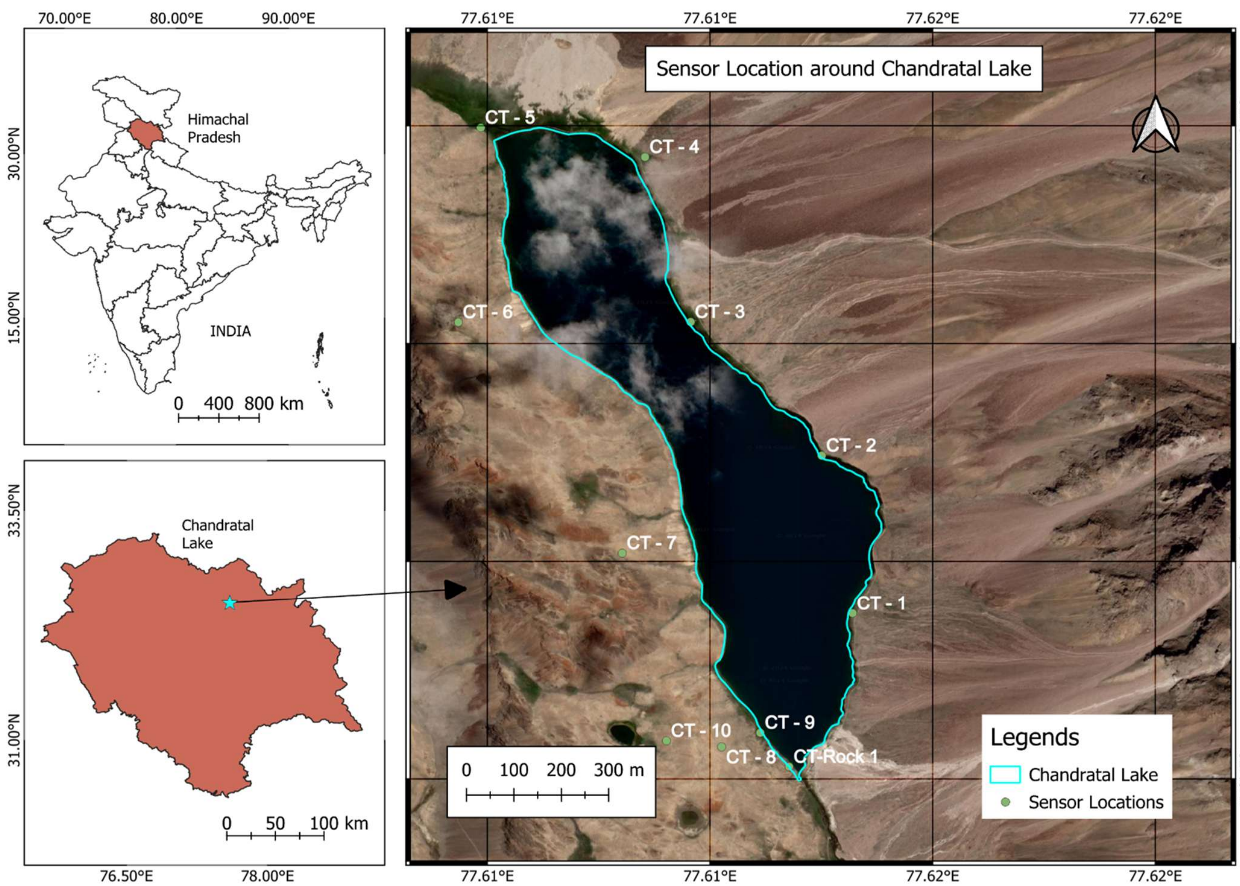


Figure 2: (Left top) Map of India showing Himachal Pradesh; (Left bottom) Map of Himachal Pradesh showing study area (Cyan star); (Right half) Experimental Chandratal lake with the distribution of T-logger sensors

The Chandratal Lake is situated in the Chandra valley of the Lahul and Spiti district of Himachal Pradesh, India (Figure 2). It is at an elevation of nearly 4300m a.s.l, having 32°28′30.65″ N, 77°37′1.42″ E coordinates (Ramsar Sites Information Service), with a surface area of 0.488 km2 and an average depth of 7.3m. The weather station at Koksar, nearest to the lake, shows that the lake receives around 1000mm of precipitation annually, mainly as winter snow (Rawat et al., 2015). The lake is mostly frozen during the period of November to March (Government of Himachal Pradesh).

Table 1: Climate variation w.r.t elevation

Elevation (m)	Climate	Area
450-900	Hot and Sub-humid	Southern Low Tracts
900-1800	Warm and Temperate	
1900-2400	Cool and Temperate	
2400-4800	Cold Alpine and Glacial	Northern and Eastern Mountain Range

To reach Chandra Tal, which is 110 km from Manali, we followed the Manali-Kaza route, crossing the Atal tunnel, till Batal, which is the last mobile network zone for this route. From Batal, we rode along a 15km stretch of unpaved road to reach the Chandratal lake (Figure 3). Chandratal was selected as a site for this study as it has been shown as a location with presence of permafrost in previous studies (Pandey et al., 2020) and given the touristic nature of the area, the accessibility and stability of the area are much greater compared to other hilly regions.

Figure 3: Chandratal Lake, the site for my study captured during the field visit of 2024

Chapter 5. Data Collection and Modelling

5.1 Near-surface ground temperature measurements

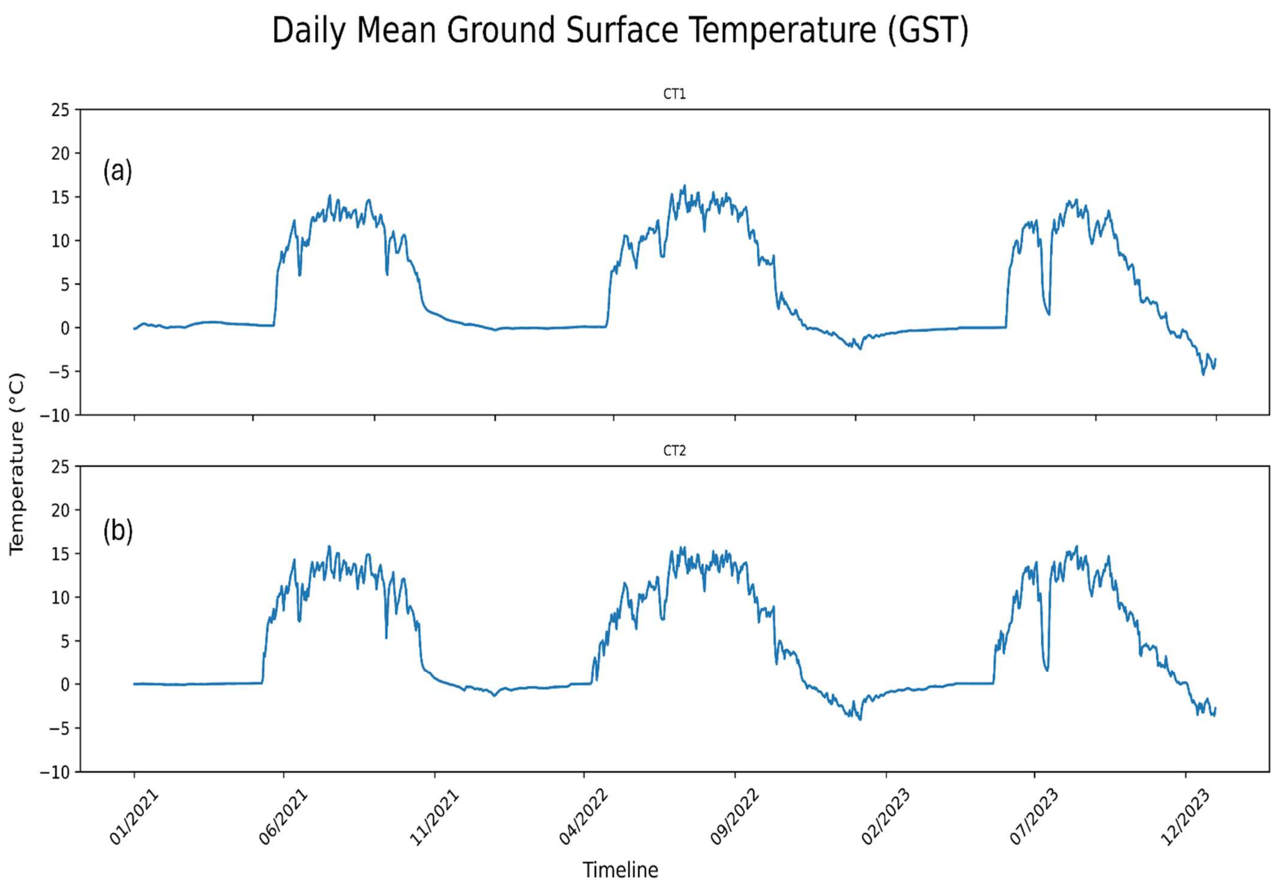
The ground temperature measurement was done at 0.1m depth using GEOprecision T-loggers, which have a lest count of 0.1ºC and resolution of 0.01ºC. They have a working range from -40ºC to 85ºC and run 4 to 5 years on a single battery life. During the field visit of September 2020, 11 loggers were installed near the periphery of the lake. All loggers are M-Log 5W – Simple (GEOprecision). The data from these loggers was collected in the recent expedition of June 2024, as shown in figure 3. This data can be used to either validate the model if we use the meteorological data or directly for simulation if we use the soil section of the model. For this M.Tech project, we will use this as the input data for the model. At the time of logger insertion, the soil was simply filled back, not compacted. There is a possibility of erosion due to the looseness of soil as well as due to natural factors such as wind and rainfall, given the instability of the terrain.

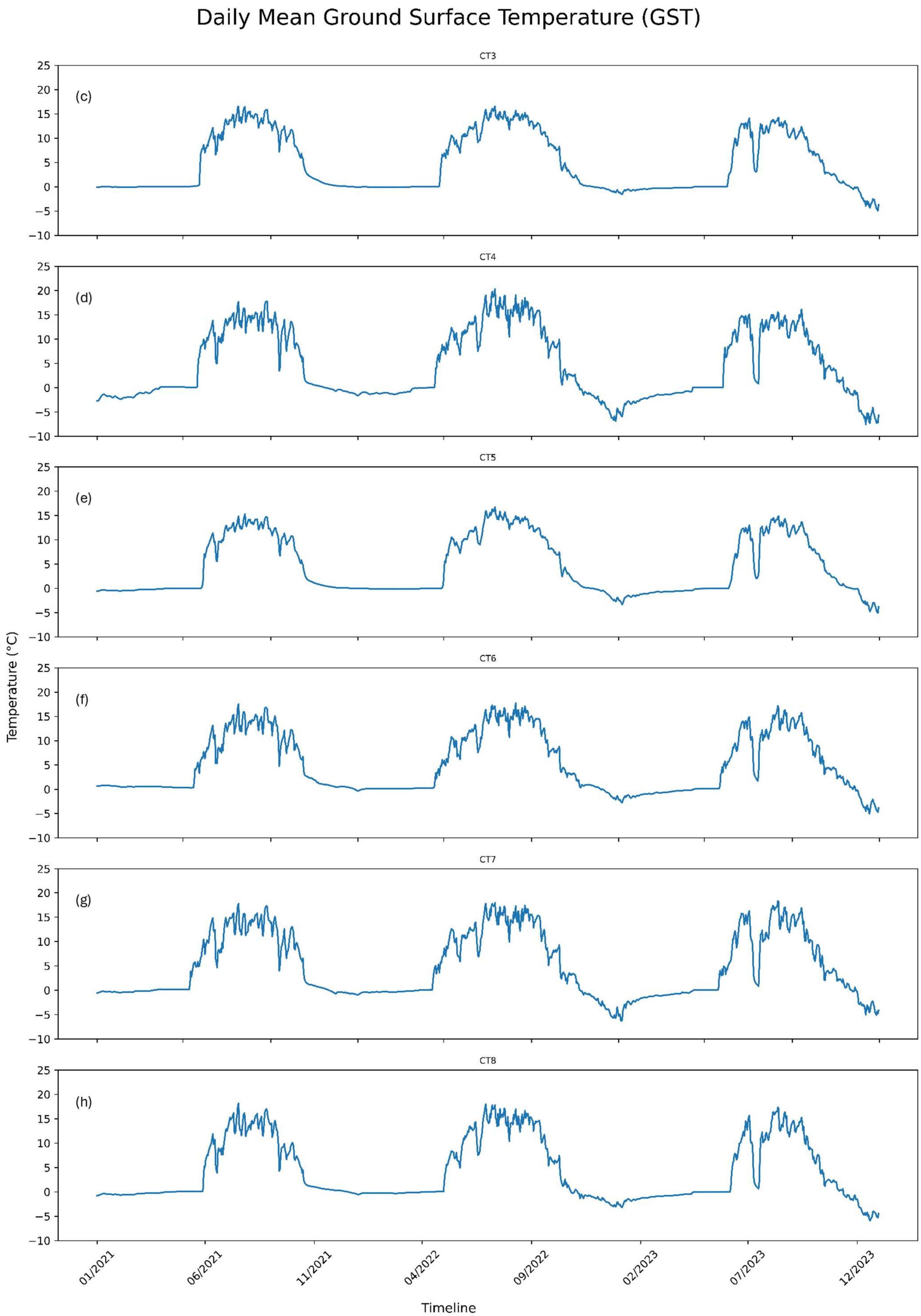
Figure 4: Data collection from T-loggers by the team at Chandratal lake

Logger at CTRock-1 location could not be located in the 2024 expedition, so the location has data till June 2022, the date of the last expedition.

Figure 5: GEOprecision T-Logger

As the loggers are inserted at a depth of 0.1m (10cm), they are affected by the environmental changes over the surface of the ground, so we treat these temperatures as the ground surface temperature (GST). Figure 7 shows the mean daily GST for the 11 locations.




Daily Mean Ground Surface Temperature (GST)
CT3
(c)
CT4
(d)
CT5
(e)
CT6
(f)
CT7
(g)
CT8
(h)
Temperature (°C)
01/2021
06/2021
11/2021
04/2022
09/2022
02/2023
07/2023
12/2023
Timeline

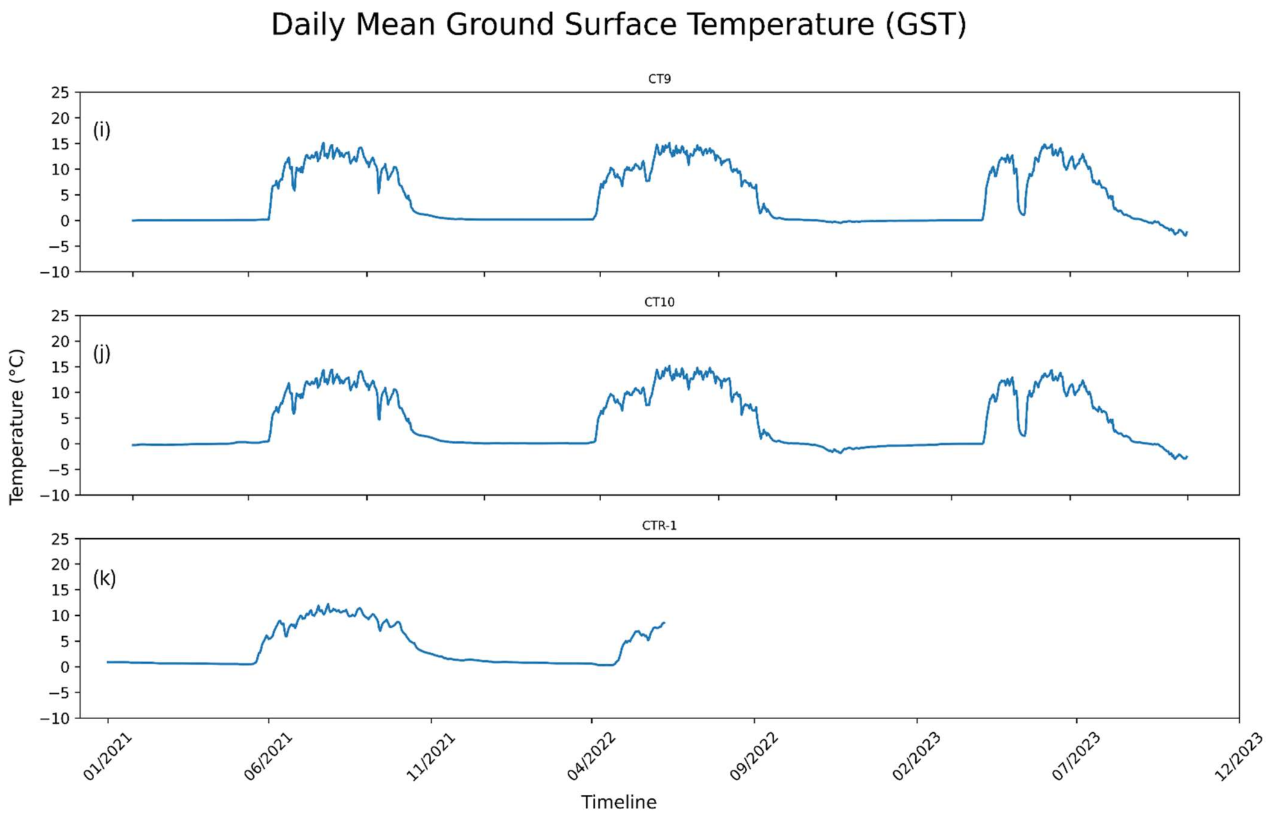


Figure 6 (a to k) : Mean daily GST for CT1 to CT10 an CTR-1 from January 2021 to December 2023

5.2 Reanalysis Data

Hourly soil temperature of two levels (STL1 and STL2) was downloaded from ERA5 from 1991 to 2024. Two levels were taken as the temperature is at the middle of each layer, an STL1 covers 0-7 cm depth, and STL2 covers 7 to 28 cm, making their centres 3.5 cm and 17.5 cm. With our field loggers stationed at 10 cm depth, we interpolated the temperature of two layers to get the ERA5 soil temperature at 10 cm depth.

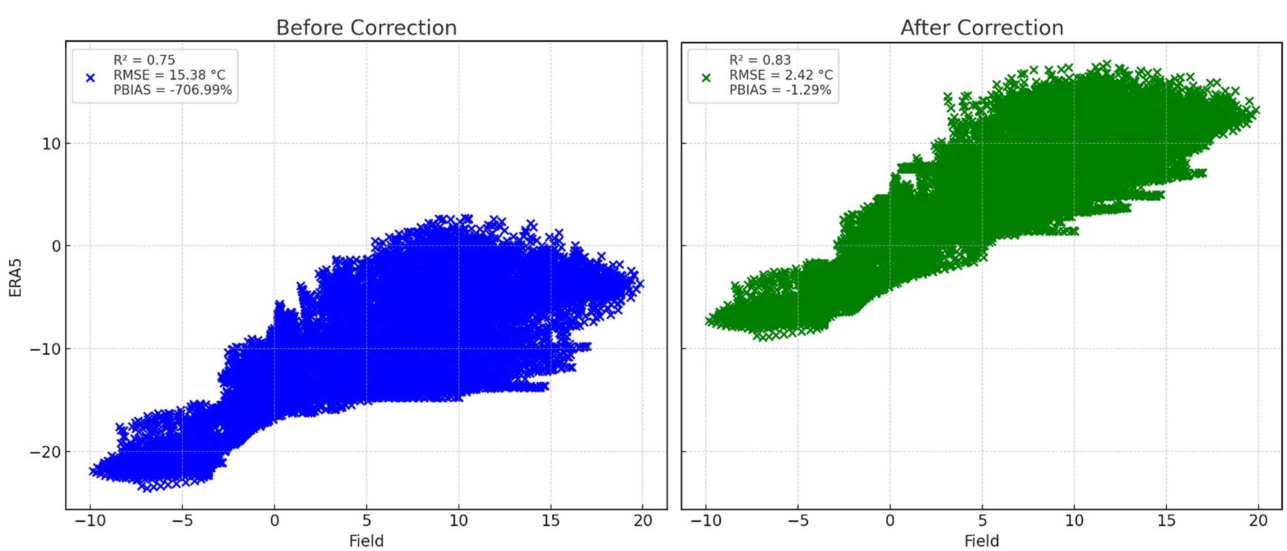


Figure 7: Before and after statistics of ERA5 vs Fiel data

The ERA5 data has a systematic bias, as it showed an R^2 of 0.75 but with an RMSE of 15.38 °C, with ERA5 data being less than the field data (Figure 5). For bias correction, we found the monthly average of field data and the ERA5 data from September 2020 to May 2024 to find the additive correction factor (Table 2) and performed additive bias correction on the complete ERA5 data.

The statistical analysis, such as the coefficient of determination (R^2), root mean square error (RMSE), and Percent Bias (PBIAS), is used to evaluate the performance of the model. These indicators were computed using the following equations.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Q_{ERA5}-Q_{obs})^2}{n}} \quad (1)$$

$$R^2 = \left(\frac{\sum_{i=1}^{n}(Q_{obs}-\bar{Q}_{obs}).(Q_{ERA5}-\bar{Q}_{ERA5})}{\sqrt{\sum_{i=1}^{n}(Q_{obs}-\bar{Q}_{obs})^2.\sum_{i=1}^{n}(Q_{ERA5}-\bar{Q}_{ERA5})^2}}\right)^2 \quad (2)$$

$$PBIAS = \frac{\sum_{i=1}^{n}(Q_{ERA5}-Q_{obs})}{\sum_{i=1}^{n}Q_{obs}} \times 100 \quad (3)$$

Table 2: Monthly correction factor

Month	ERA5	Field	Correction Factor
January	-17.6829	-3.03044	14.65248
February	-17.7126	-2.33466	15.3779
March	-17.4389	-1.87857	15.56037
April	-16.6548	-1.24101	15.41381
May	-14.8338	1.355901	16.18966
June	-11.8456	6.775128	18.62073
July	-6.18014	10.70968	16.88982
August	-3.48173	12.24826	15.73
September	-3.81057	9.656724	13.46729
October	-9.04018	3.411987	12.45216
November	-13.7494	-0.85888	12.8905
December	-16.2786	-2.51376	13.76482

5.3 About GEOtop

GEOtop version 3.0 (GEOtop) is an open-source model that simulates complex and combined heat and water budgets along with the energy exchange with the atmosphere to estimate the characteristics of permafrost or frozen soil. The model has been effectively employed in a number of studies in high-elevation areas (Bertoldi et al., 2010; Dall'Amico et al., 2011a, b, 2018; Fiddes and Gruber, 2012; Gubler et al., 2013; Endrizzi et al., 2014; Fiddes et al., 2015; Engel et al., 2017; Wani et al., 2020). The model does heat conduction in 1-D and can solve Richard's equation for water transportation in both 1-D and 3-D, describing freezing and thawing processes as well as the infiltration of water in the ground. The model assumes a rigid soil scheme, meaning that no volumetric change occurs during freezing and thawing. For this work, we are solving the heat equation (Equation 4) at the 11 pre-decided sites using the GST as forcing.

$$\frac{\partial U^{ph}}{\partial t} + \nabla \cdot G + S_{en} - \rho_w \left(L_f + c_w (T - T_{ref}) \right) S_w = 0 \tag{4}$$

The model is simulated by first initializing it (Figure 6) at a constant temperature, so that the model attains thermal equilibrium. This is done to make the model forget about the initial meteorological conditions that are given and simulated only based on external forcings that we provide.

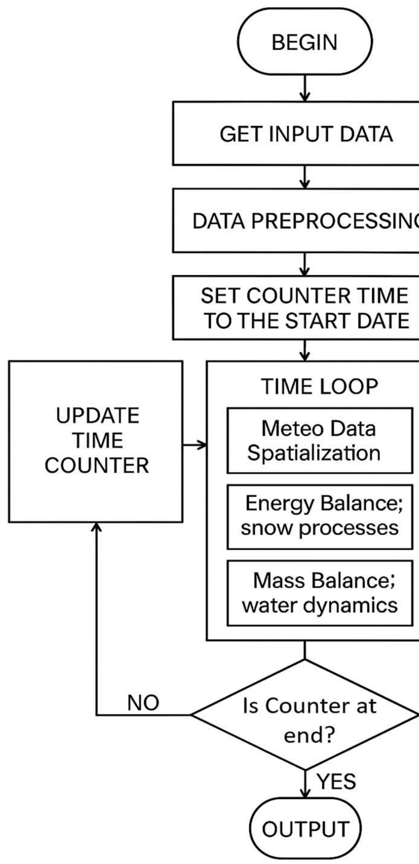


Figure 8: Structure of GEOtop model

5.4 Setup of GEOtop model

GEOtop was driven by giving input of GST as the upper boundary and a zero-flux constraint as a bottom boundary, using soil parameters (Table 3) available in the literature (Gubler et al., 2013). The soil in the surroundings of Chandratal is 50% to 70% clay and 30% to 45% silt (Shamurailatpam et al., 2021). The parameters are taken with the soil composition in mind.

Table 3: Parameters for GEOtop model

Parameter	Value	Range	Unit
Thermal capacity of soil solids	2.25×10^6	2.25×10^6	$J\ m^{-3}\ K^{-1}$
Soil porosity	0.43	0.374 - 0.487	$m^3\ m^{-3}$
Thermal conductivity (high)	4.0		$W\ m^{-1}\ K^{-1}$
Freezable water content (high)	0.03		$m^3\ m^{-3}$
Thermal conductivity (low)	2.5		$W\ m^{-1}\ K^{-1}$
Freezable water content (low)	0.40		$m^3\ m^{-3}$
Water content saturated	0.43	0.374 - 0.487	$m^3\ m^{-3}$
Water content residual	0.059	0.055 – 0.072	$m^3\ m^{-3}$
van Genuchten (α)	0.001	0.001 – 0.003	mm^{-1}
van Genuchten (*n)*	1.52	1.4 – 3.2	
Hydraulic conductivity	0.0032	0.0019 – 0.0825	$mm\ s^{-1}$

5.5 Input Data and Initialization of Model

We use the GST as input for the model. As there is a certain degree of ambiguity in the input data, simulations are done 200 times at each location (Figure 6), so that they lose the memory of initially given values and attain values in equilibrium with the meteorological forcings and the soil (ground) properties. For better initialization, we do repeated modelling of GEOtop at 1 m depth, then we use the modelled GEOtop as the initial condition for running it at 5 m depth, and repeat the same for 10 m depth, and this creates the most stable condition of the group. To counter the effect of different types of soil solids, we vary the thermal conductivity (high and low) and the relative saturation of pores in the soil space.

5.6 Determining Snow Melt-Out Date

The Melt-Out Date (MD) represents the end of seasonal snow cover and is determined by analysing daily ground temperature fluctuations. Snow presence is inferred when the standard deviation of daily ground temperatures is low, indicating thermal insulation by snow. However, to ensure the reliability of this snow detection, a validation metric called MDr (Minimum Daily Range) (Equation 5) is used. MDr is calculated as the difference between a threshold value (0.2°C) and the average daily standard deviation (Equation 6) of ground temperatures between January 1 and March 31. A positive MDr indicates low temperature variability, suggesting a stable and insulating snow cover, and thus, the computed MD is considered reliable. Conversely, a negative MDr reflects higher ground temperature fluctuations, which may result from inconsistent or absent snowpack; in such cases, the MD is deemed unreliable and is discarded. This check ensures that MD is only reported when the snow detection method is supported by consistent thermal conditions.

$$\mathrm{MDr} = 0.2 - \sigma_{\text{Jan–Mar}} \tag{5}$$

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{6}$$

Let: σ_d = standard deviation of temperature on day d; $T_{\max,d}$ = maximum temperature on day d. Then the snow presence indicator S_d is defined as:

- If $T_{\max,d} \geq 0$ and $\sigma_d < v_1$, then S_d=1
- $T_{\max,d} < 0$ and $\sigma_d < v_2$, then S_d=1
- Otherwise, S_d=0
- Where: v_1=0.1ºC ; v_2=0.3ºC
- Days with $GST_{max} > 3$ºC are considered snow free

Using the above condition, we analyse if the snow cover is reliable or not, and if it is detected that the reliability is good, we put in place the remaining conditions to find the MD.

Chapter 6. Results and Discussion

6.1 Investigation of permafrost

Figures 8 and 9 represent the ground thermal envelopes with low and high diffusivity cases, respectively, using the field data for simulating the GEOtop model. These results show the thermal envelope when the model was simulated using the T-Logger data from 01st November 2020 to 07th June 2024. Our investigation with the field data and the available parameters shows an absence of permafrost in the region, as at zero amplitude depth, the mean annual ground temperature (MAGT) is greater than zero (Table 4), and for the existence of permafrost, it should be less than zero for two or more consecutive years. The same observation is made for high as well as low diffusivity cases, with the temperature remaining on the positive side

Table 4: MAGT of sites at zero-amplitude depth in high and low thermal diffusivity cases

Location	**MAGT (°C) (High Diffusivity)**	**MAGT (°C) (Low Diffusivity)**
CT1	3.50282	3.44912
CT2	3.50220	3.44850
CT3	3.50275	3.44904
CT4	3.50234	3.44864
CT5	3.50029	3.44660
CT6	3.50197	3.44827
CT7	3.50273	3.44903
CT8	3.50261	3.44891
CT9	3.50164	3.44794
CT10	3.50218	3.44848
CTR-1	3.50253	3.44883

From the above results, we infer that with the given availability of soil parameters and model forcing, there is an absence of permafrost in the Chandratal Lake region. However, there is a genuine lack of studies on soil parameters in the Indian Himalayan region, which may potentially provide a different result. Additionally, remote sensing-based studies (Pandey et al., 2020) had vouched for the presence of permafrost in the Chandra Basin, might have overestimated the presence, especially at the elevation of Chandratal lake.

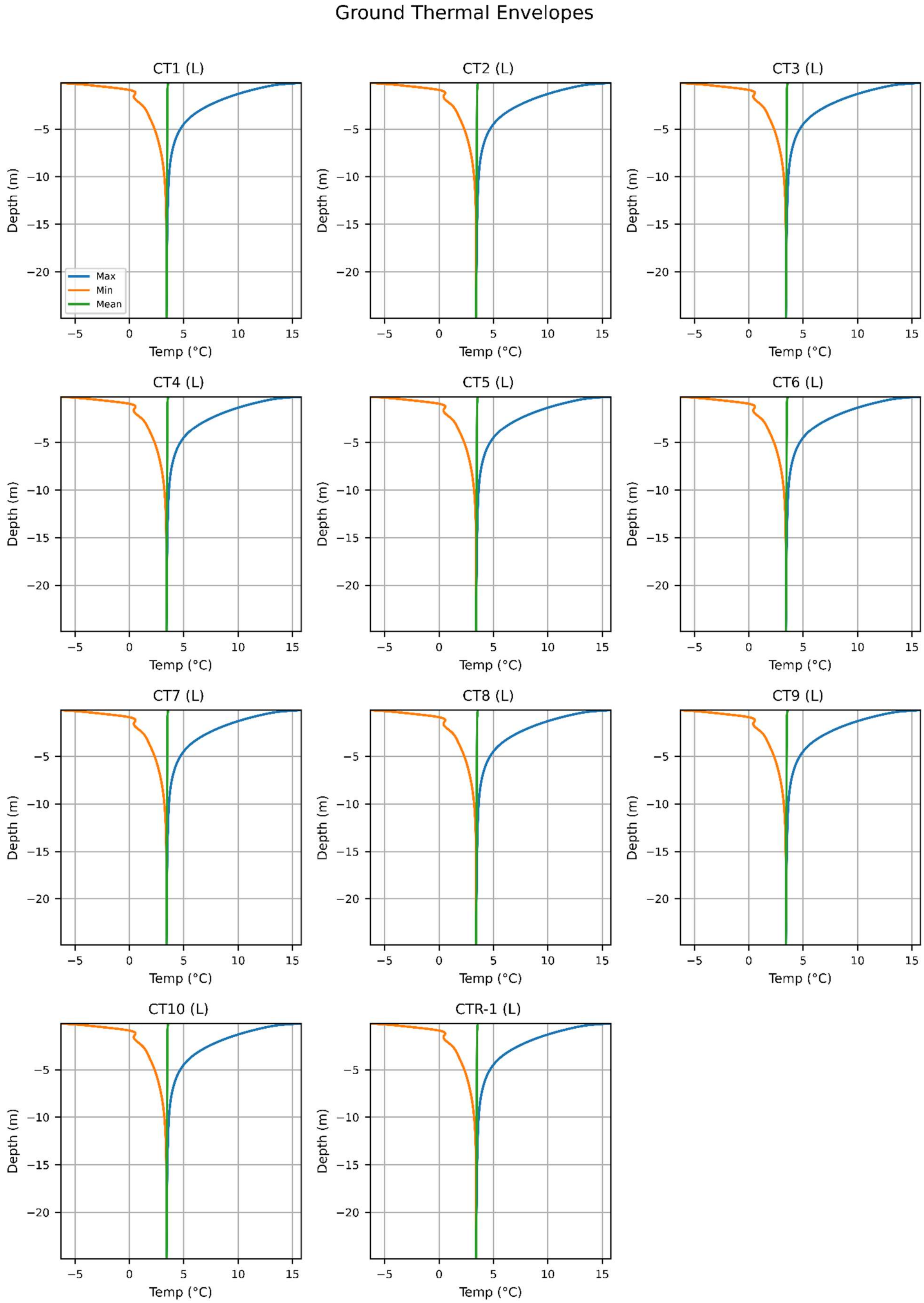


Figure 9: Ground thermal envelopes for CT1 to CT10 and CTR-1 for low (L) diffusivity simulation using field data

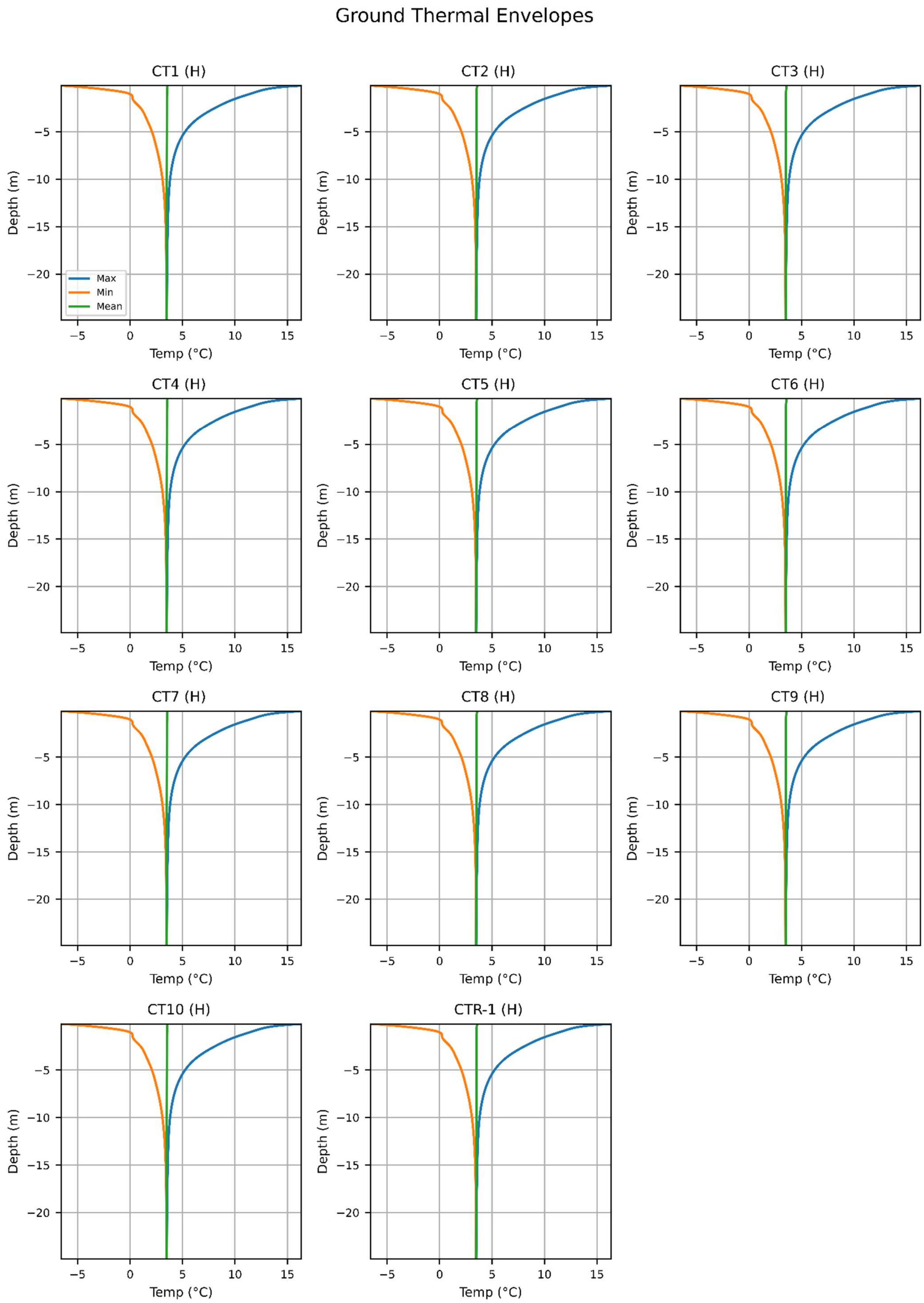


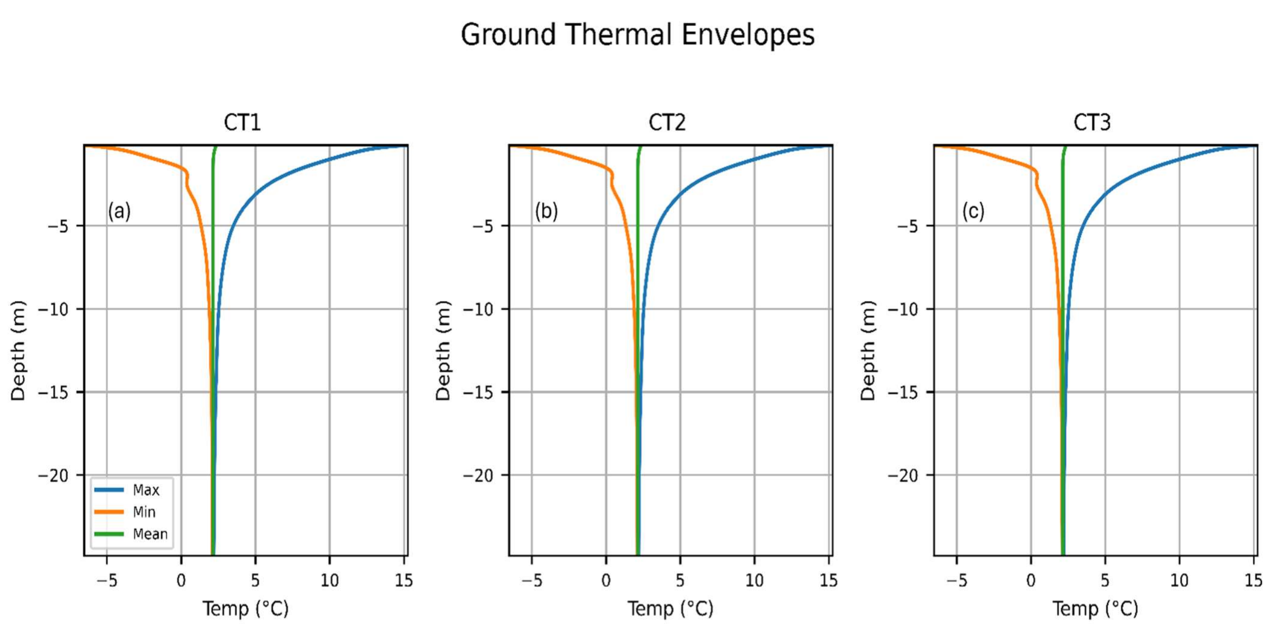
Figure 10: Ground thermal envelopes for CT1 to CT10 and CTR-1 for high (H) diffusivity simulation using field data

6.2 Temporal variation of ground thermal scheme

Figure 10 shows the thermal envelope when the bias-corrected ERA5 GST was used to simulate the model from 01st January 1991 to 31st December 2024. For the long-term data, only the low diffusivity case was simulated, as that gives us a lower zero-amplitude depth temperature with the same parameters, as proved in objective one. Here, too, like the field data, the model simulations show that the temperature at zero amplitude depth is greater than 0 °C (Table 5), which means that there has been an absence of permafrost in the region from 1991 to date, and it is not a case of thawing of permafrost in the area.

Table 5: MAGT of sites at zero-amplitude depth

Location	MAGT (ºC)
CT1	2.1434
CT2	2.1415
CT3	2.1434
CT4	2.1420
CT5	2.1435
CT6	2.1407
CT7	2.1434
CT8	2.1430
CT9	2.1396
CT10	2.1415
CTR-1	2.1427



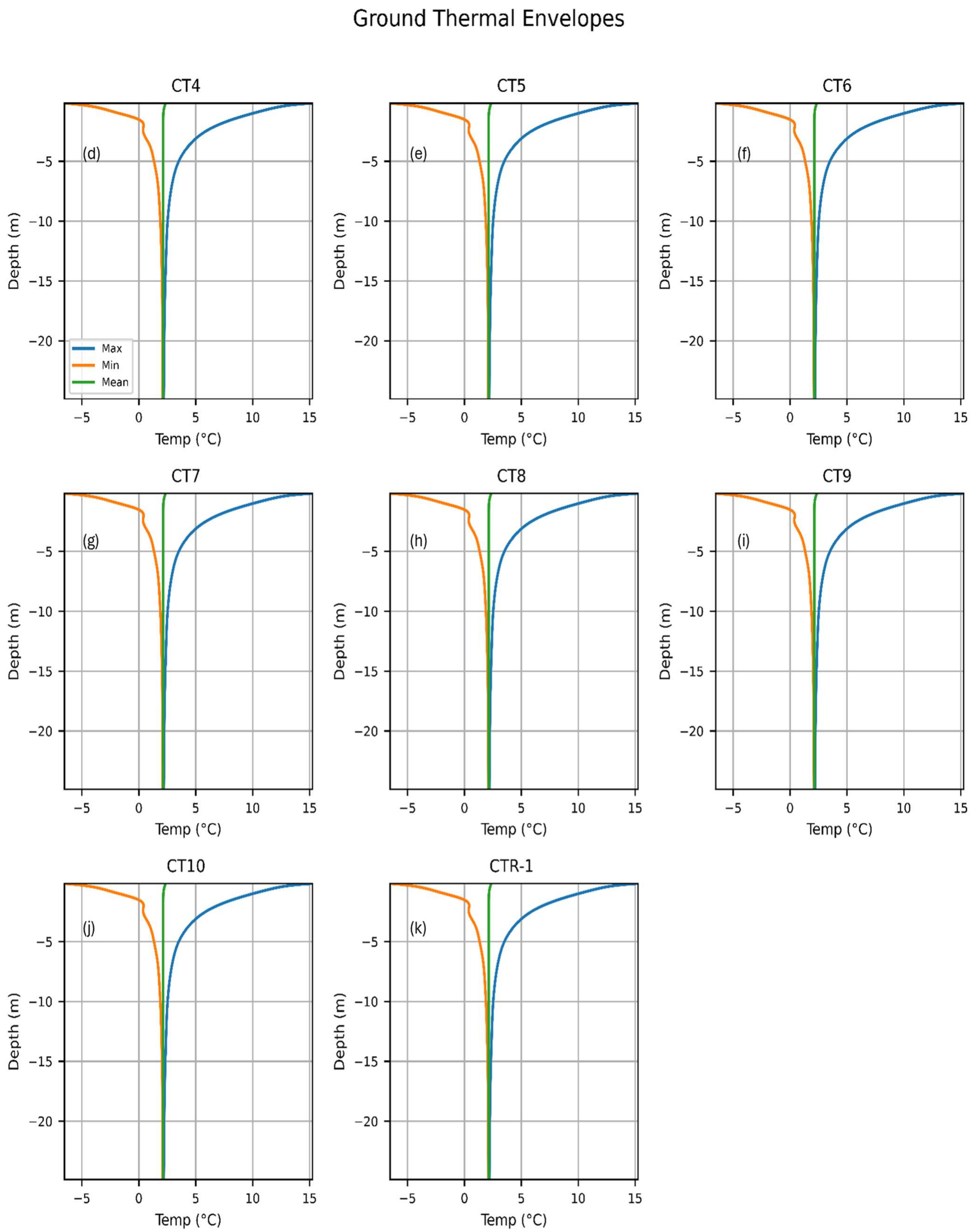


Figure 11 (a to k): Ground thermal envelope for CT1 to CT10 and CTR-1 for model simulation from 1991 to 2024 using ERA5 data

The second objective showed that there is minimal temporal variation in the thermal regime of the ground surface over a span of 34 years, which is aided by the fact that the MAGST has not varied too much over the same period (Figure 15). Because of the lack of homogeneous variability, the long-time simulation results, done using ERA5 data, align with the model simulation using field data.

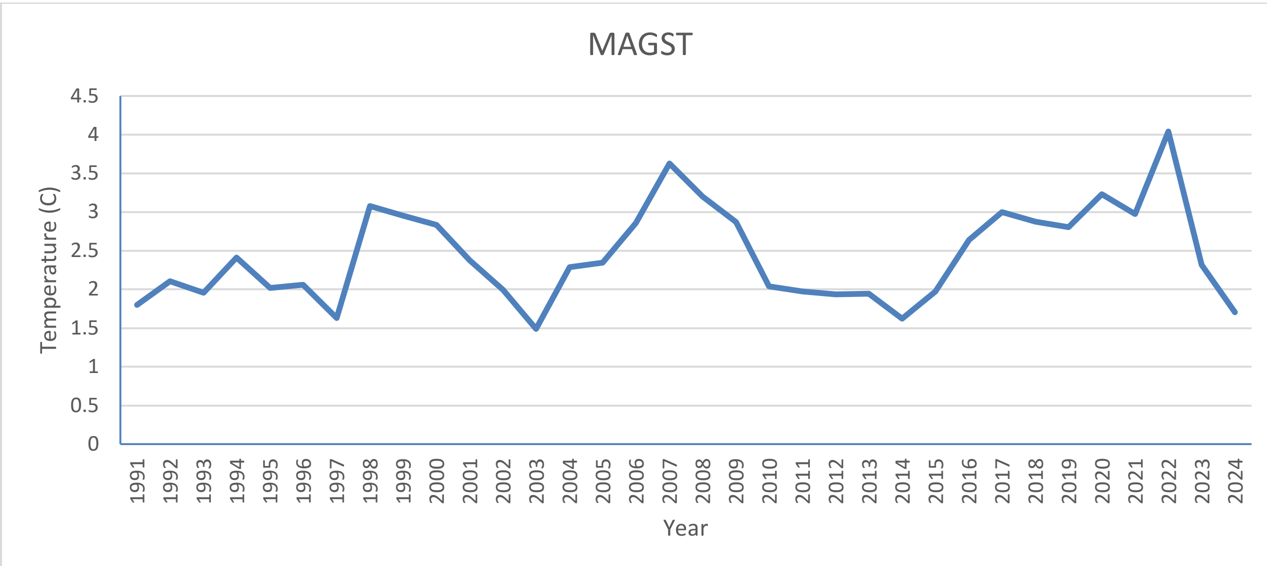


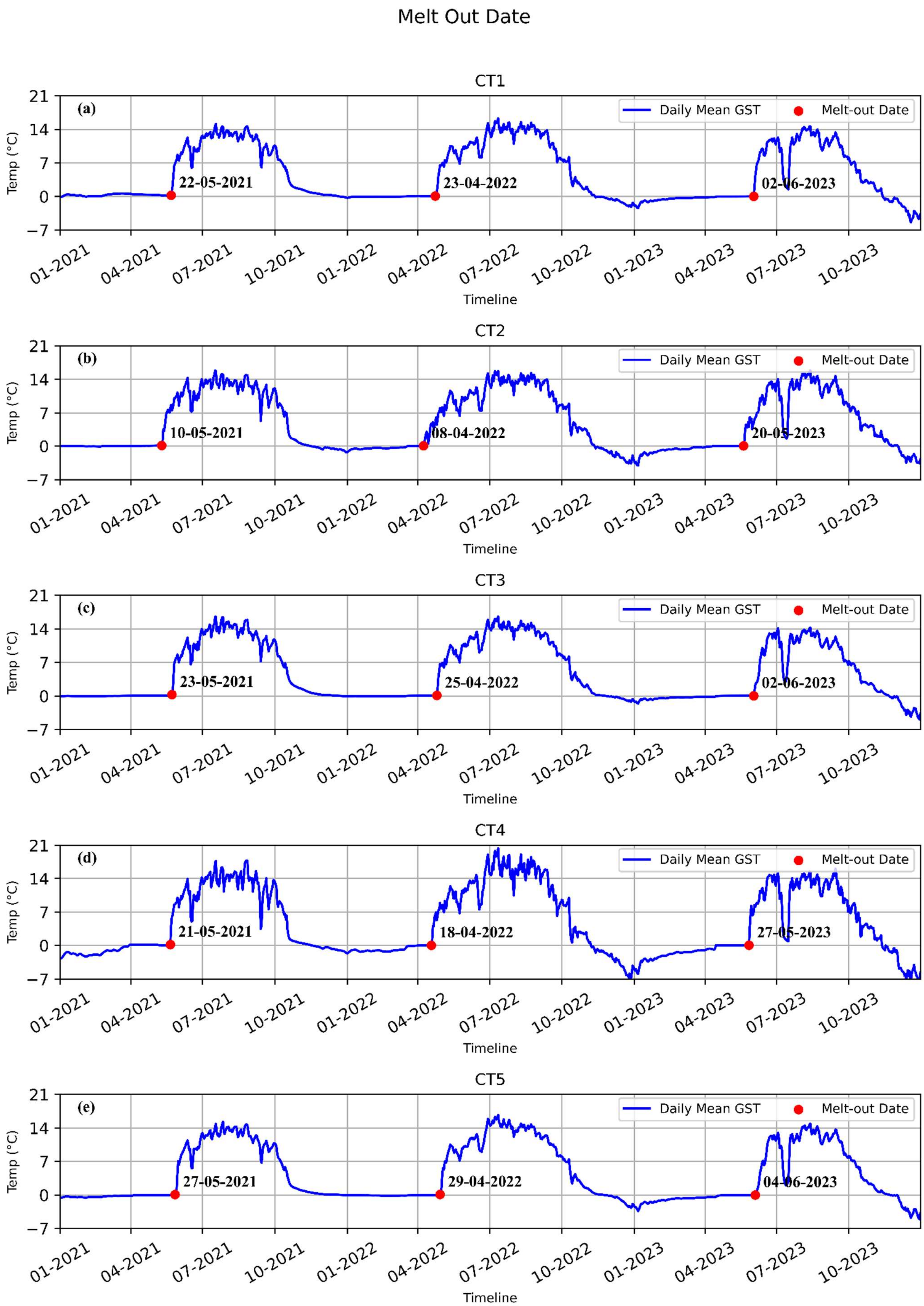
Figure 12: MAGST from 1991 to 2024

6.3 Melt-out Date Determination

Figure 12 shows the inferred snow MD from the field GST. As mentioned in (Schmid et al., 2012), there is variability in the small area of study, with there being different dates of snow MD in location in very close proximity of each other. Year 2022 experienced the melting sooner than 2021 and 2023, whereas year 2023 experienced the longest period of snow cover, which is also supported by the MAGST of the three years (Table 6). Year 2022 saw an increase of 0.65 °C compared to 2021, which resulted in the early melting of snow in the area.

Table 6: Year-wise MAGST for the Chandratal lake area

Year	MAGST (°C)
2021	4.66
2022	5.31
2023	3.44


Melt Out Date
CT1
(a)
CT2
(b)
CT3
(c)
CT4
(d)
CT5
(e)
Daily Mean GST
Melt-out Date
Temp (°C)
Timeline
22-05-2021
23-04-2022
02-06-2023
10-05-2021
08-04-2022
20-05-2023
23-05-2021
25-04-2022
02-06-2023
21-05-2021
18-04-2022
27-05-2023
27-05-2021
29-04-2022
04-06-2023
01-2021
04-2021
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10-2023

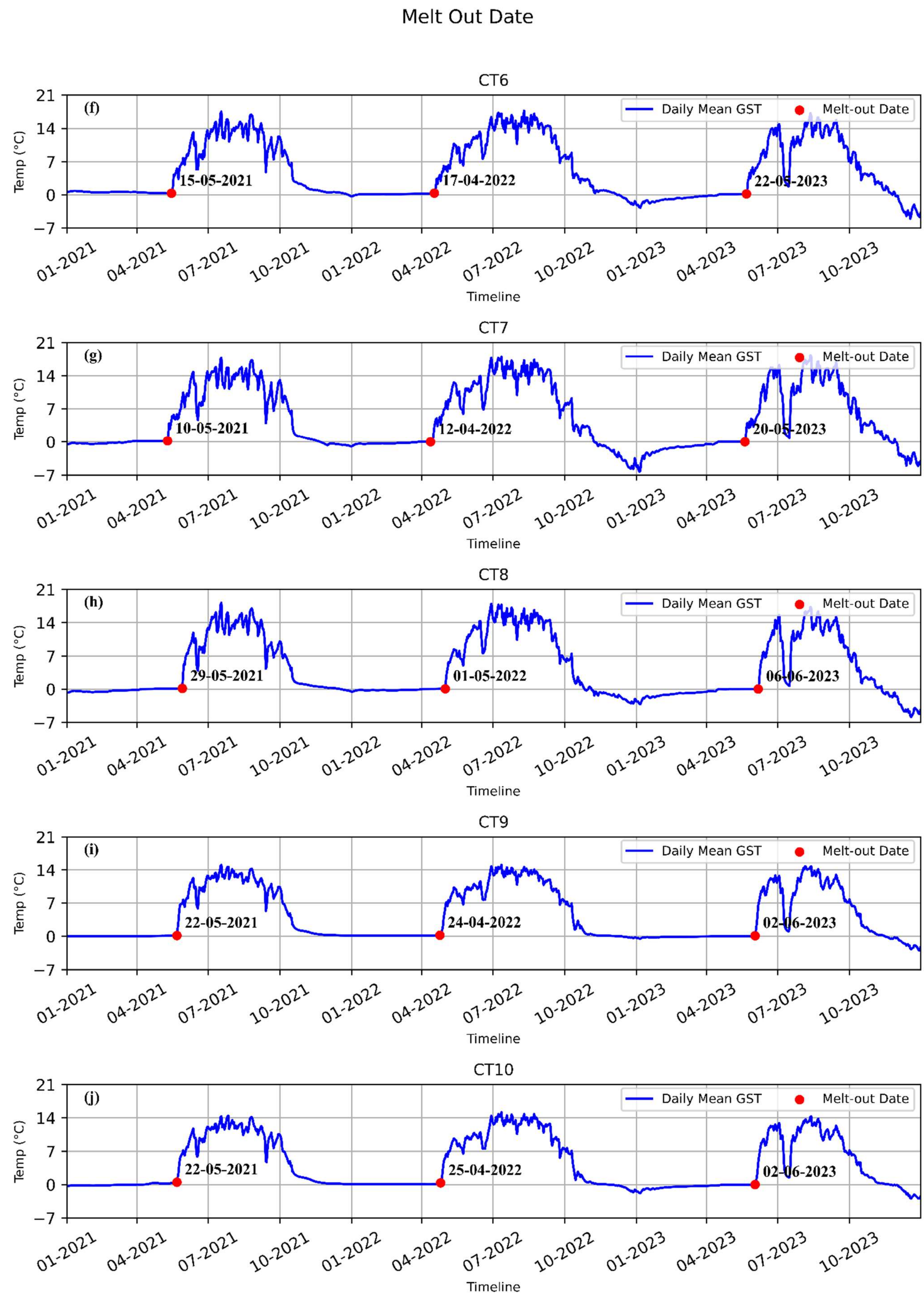

Figure 13 (a to k): Snow MD with temperature profile for CT1 to CT10

Chapter 7. Conclusion

This study investigates the presence of permafrost in the Chandratal Lake region of the Western Himalayas using both short-term field data and long-term reanalysis data through the GEOtop model simulations. Three primary objectives were addressed: assessing permafrost presence, evaluating the temporal ground thermal regime, and determining snow melt-out dates.

7.1 Absence of Permafrost in the Chandratal Region

Simulation results based on field temperature logger data (from November 2020 to June 2024) show that the Mean Annual Ground Surface Temperature (MAGST) at the zero-amplitude depth is consistently above 0 °C across all observation sites. This condition fails the essential criterion for permafrost existence, which requires the MAGST to remain below 0 °C for at least two consecutive years.

Both high and low thermal diffusivity scenarios, simulated with identical soil parameters and forcing data, produced consistent results. The MAGST ranged between 3.44 °C and 3.50 °C, confirming that permafrost is absent in the area under current thermal conditions. This directly contrasts some remote sensing-based studies (Pandey et al., 2020), which might have overestimated permafrost presence at this elevation in the Chandra Basin.

7.2 Long-Term Thermal Regime Analysis

Further model simulations were conducted using bias-corrected ERA5 ground surface temperature data from 1991 to 2024, simulating a 34-year period. These long-term simulations also confirmed the absence of permafrost, with the zero-amplitude MAGST consistently above 2 °C.

Moreover, the temporal variation in the thermal regime was found to be minimal over these three decades, with Figure 15 showing stable MAGST trends. This indicates that the region has not experienced permafrost degradation, but rather, it likely never supported permafrost during the study period.

7.3 Snow Melt-Out Date (MD) Variability

The third aspect of the study focused on identifying snow melt-out dates based on near-surface ground temperature signals. Significant spatial and interannual variability in melt-out timing was observed even within this small study area.

The year 2022 saw the earliest snowmelt, coinciding with the highest MAGST (5.31 °C), whereas 2023 experienced prolonged snow cover, corresponding to the lowest MAGST (3.44 °C).

This finding reinforces the relationship between ground thermal regime and snow dynamics and shows how small-scale spatial heterogeneity plays a role in snow retention and melt timing.

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