Thermal Behavior of Road Embankments and impact of Snow in Ditches

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Background

Road Embankment Thermal Regime

- Influenced by:
  - Frost formation
  - Snow accumulation in roadside ditches
- Uneven thermal distribution
- Local deterioration and crack formation
- Knowledge of road embankment thermal regime in winter
  - Effective management strategies
  - Structural performance and extend the service life

Snow Cover Thermal Regime-
sublimation and deposition

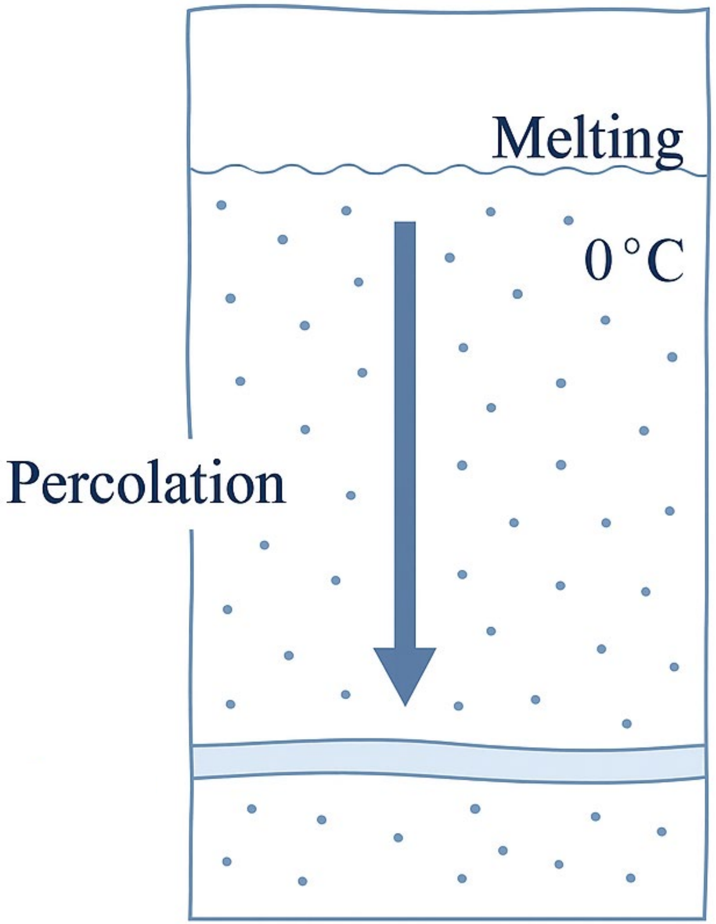
- Snow composed of:
  - Ice crystals
  - Trapped air
- Low thermal conductivity
- Temperature gradient and vapor movement
- Changes in snow microstructure

Snow Cover Thermal Regime-Melt-refreeze Processes

- Meltwater:
  - Remains
  - Percolates

- Receiving layer is below 0 °C, meltwater refreezes

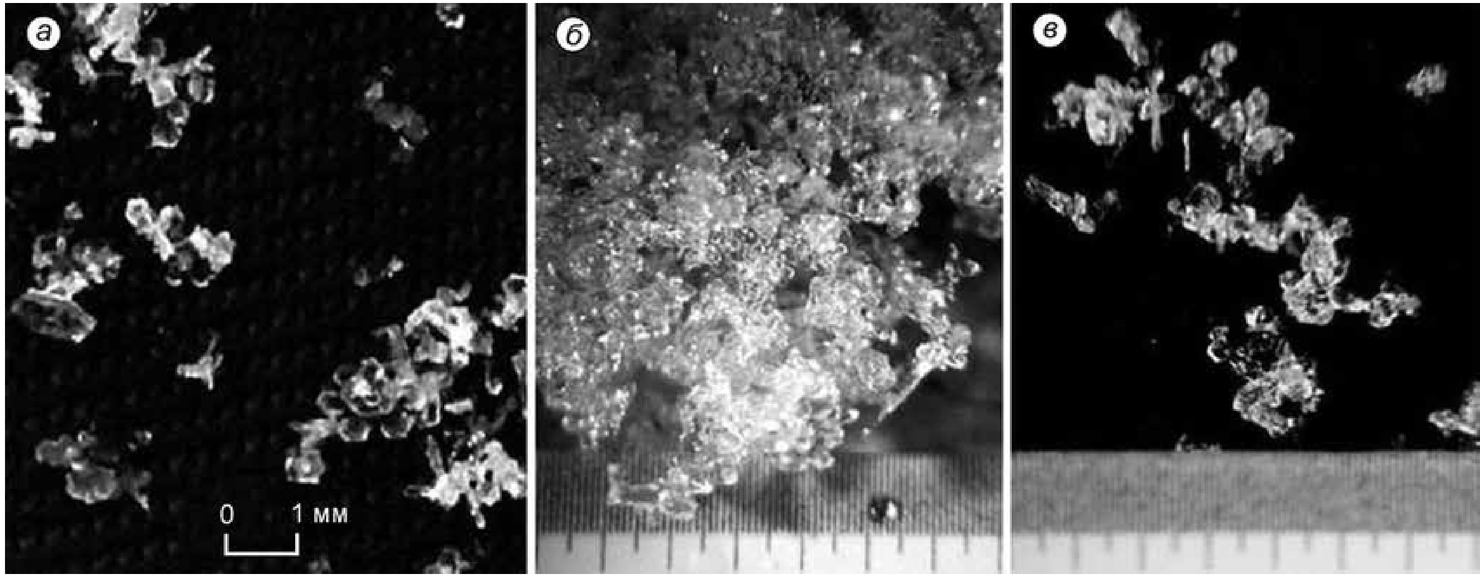
- Microstructural evolution



Snow Cover Thermal Regime

Chernov (2016)

- Key heat-transfer mechanisms:
  - Conduction
  - Vapor diffusion
  - Latent heat release/absorption



Microstructural transformations

- Snow metamorphism alters:
  - Mechanical properties
  - Thermal properties

Thermal Properties of Snow

- Snow microstructure evolves over time

Thermal conductivity measurement (needle probe):

  - single-point in time
  - up to ~30% measurement error

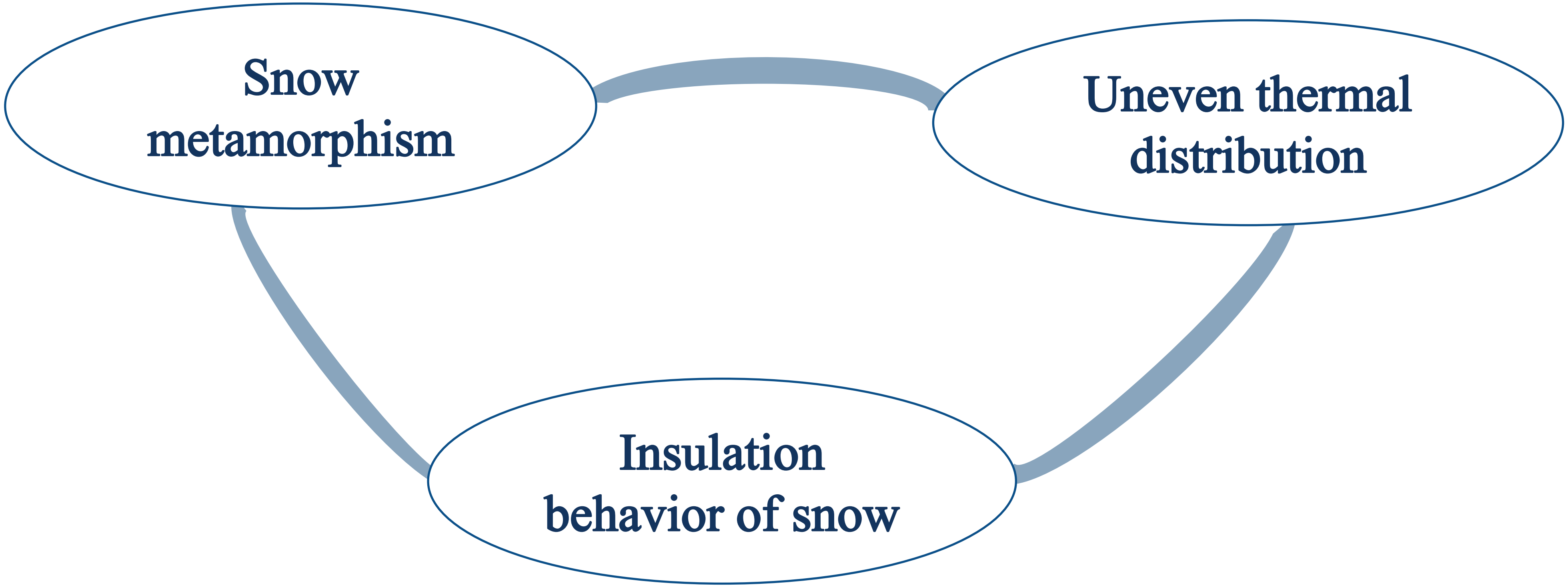
- Heat transfer in snow is complex
  - influenced by continuous phase changes

Snow Cover Thermal Regime-Roadside Contamination

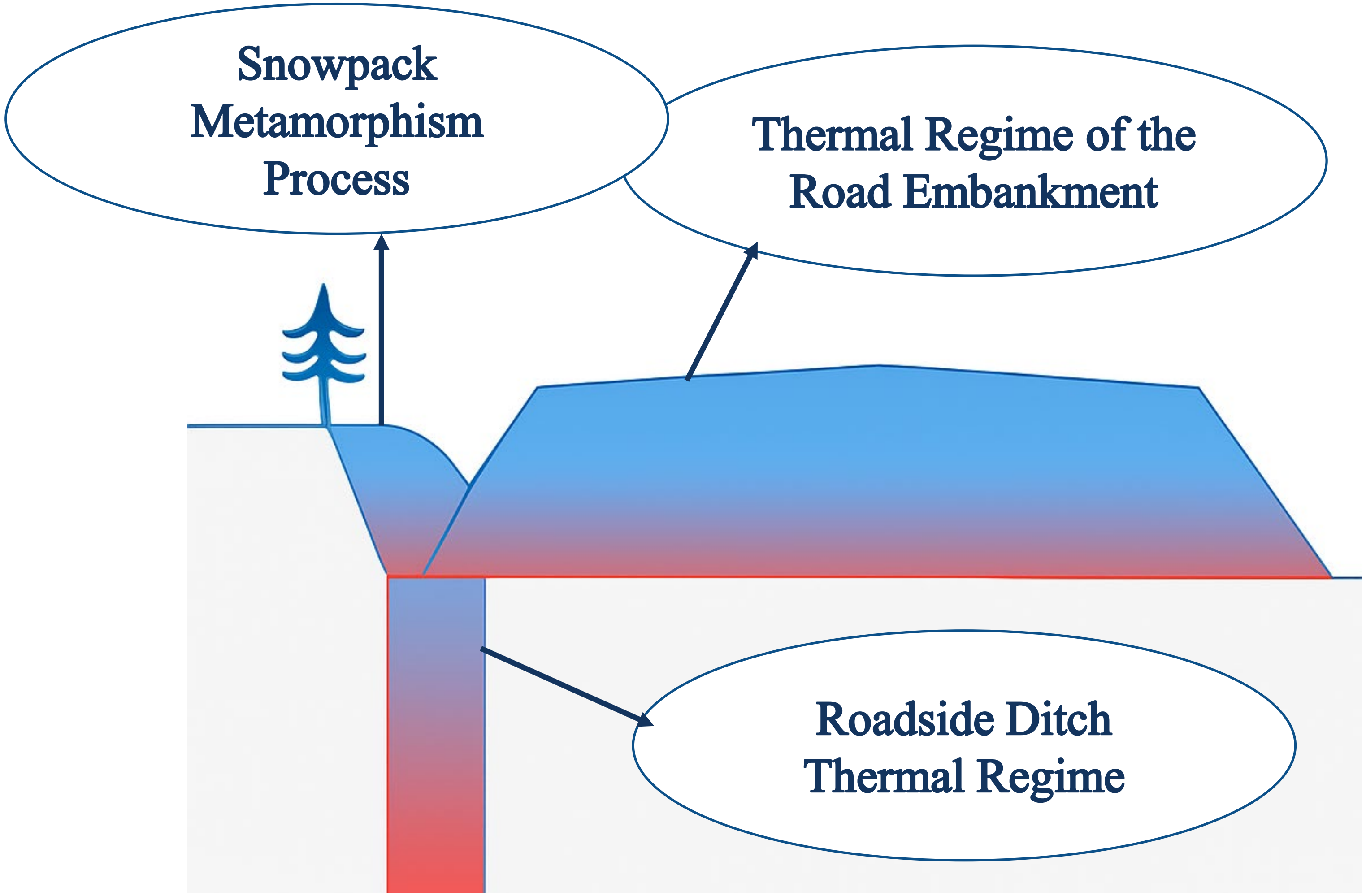
- Solid particles

- Winter maintanace
  - Sand and grit
  - Salt

Integrated Thermal Analysis



Research Objectives



Measurement Setup

Measurement Site

- **Road embankment**

  8 m-wide, two-lane section

- **Ground water level**:

  10 m below the road surface

- **Soil type in the ditch:**

  poorly graded sand

Measurement Site

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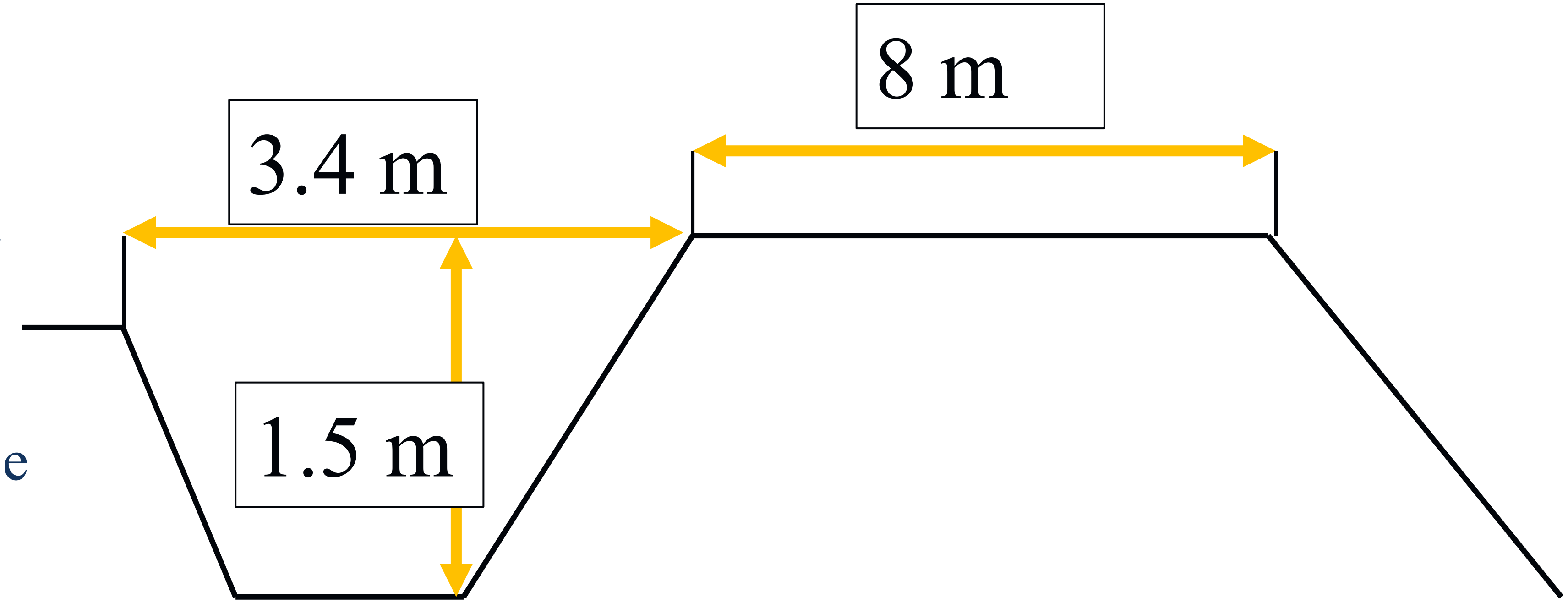
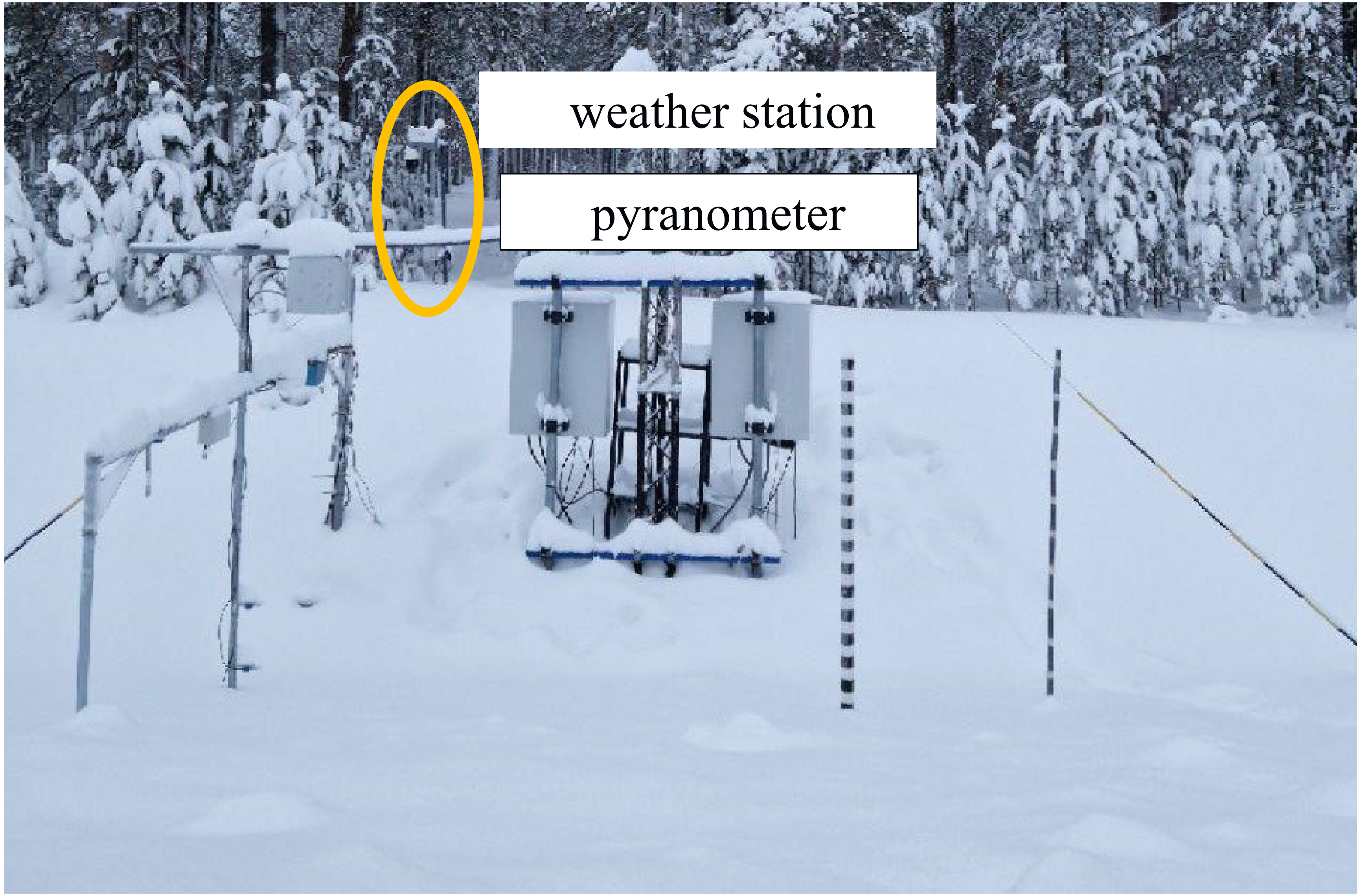


Field Measurement Setup

- Meteorological conditions
- Incoming solar radiation



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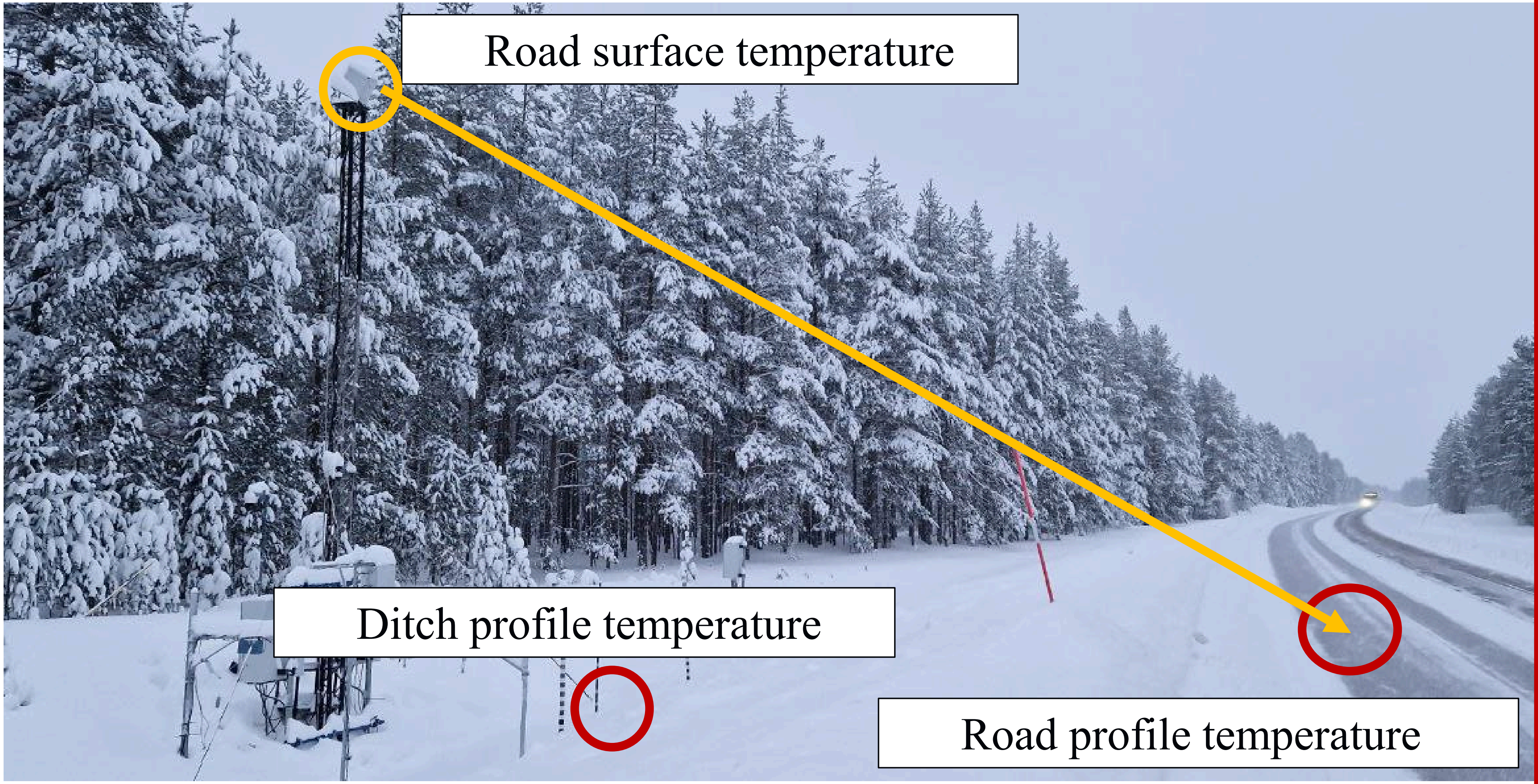
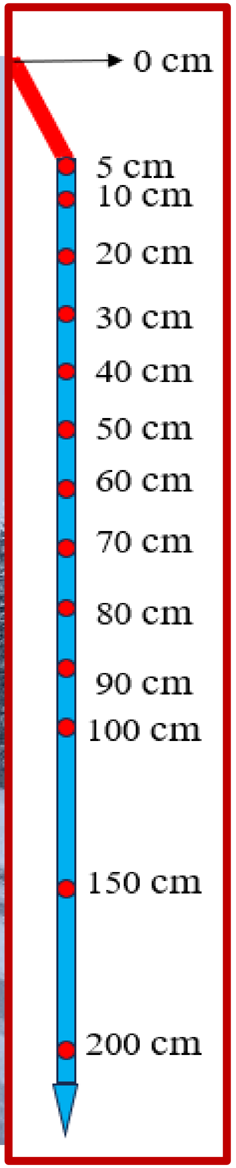
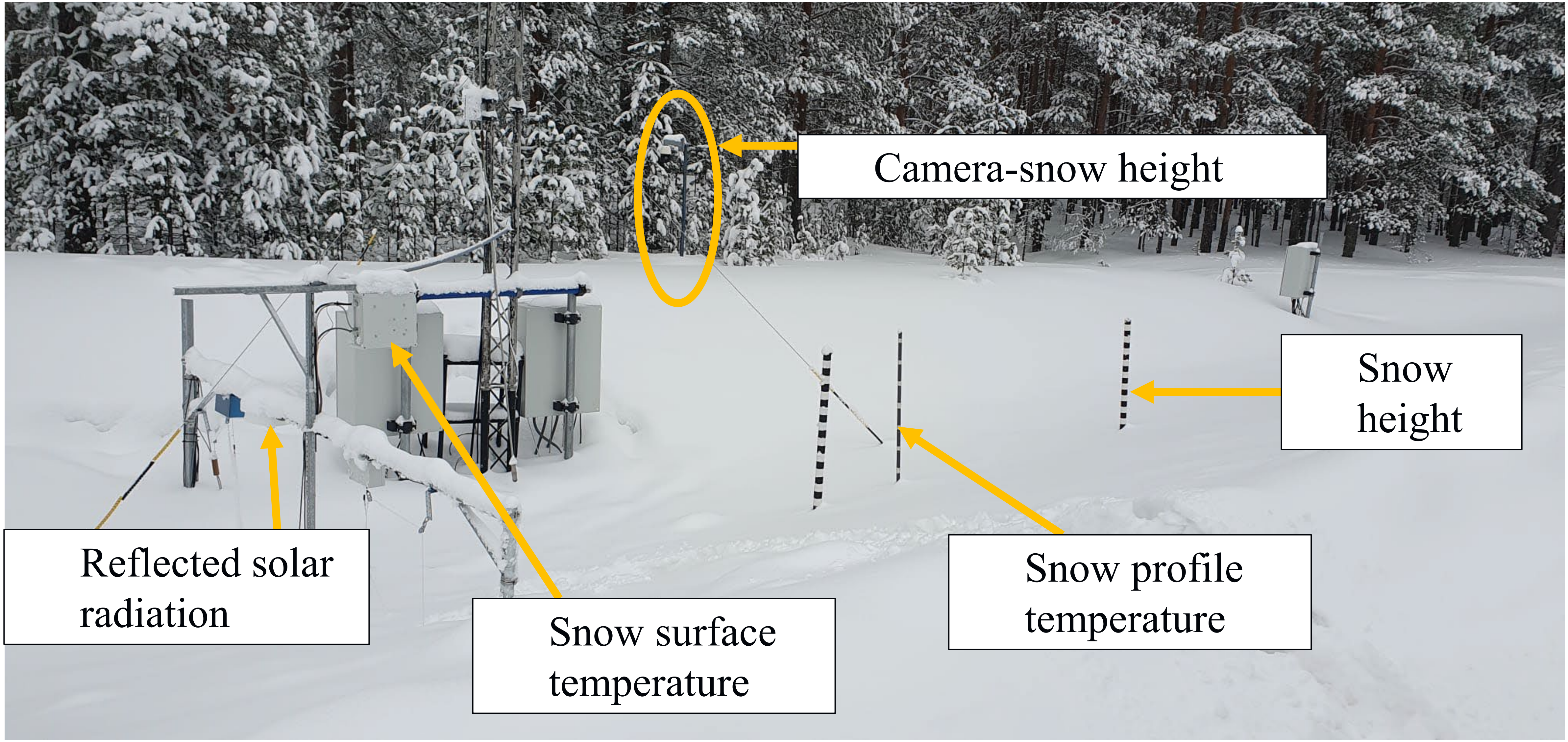




Field Measurement Setup

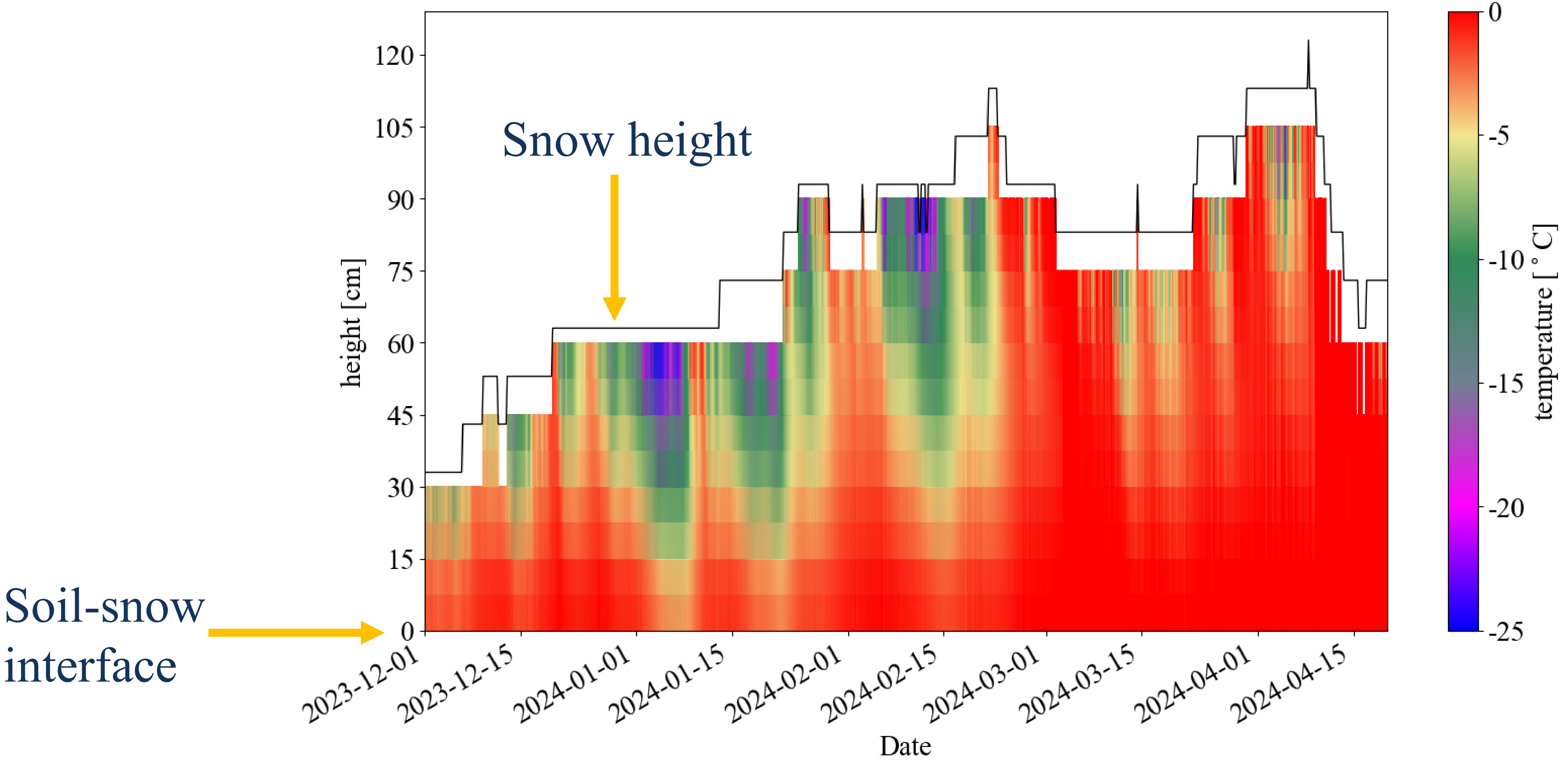


Field Measurement Setup

- Snow density

Measurements Data

Snowpack Thermal Regime

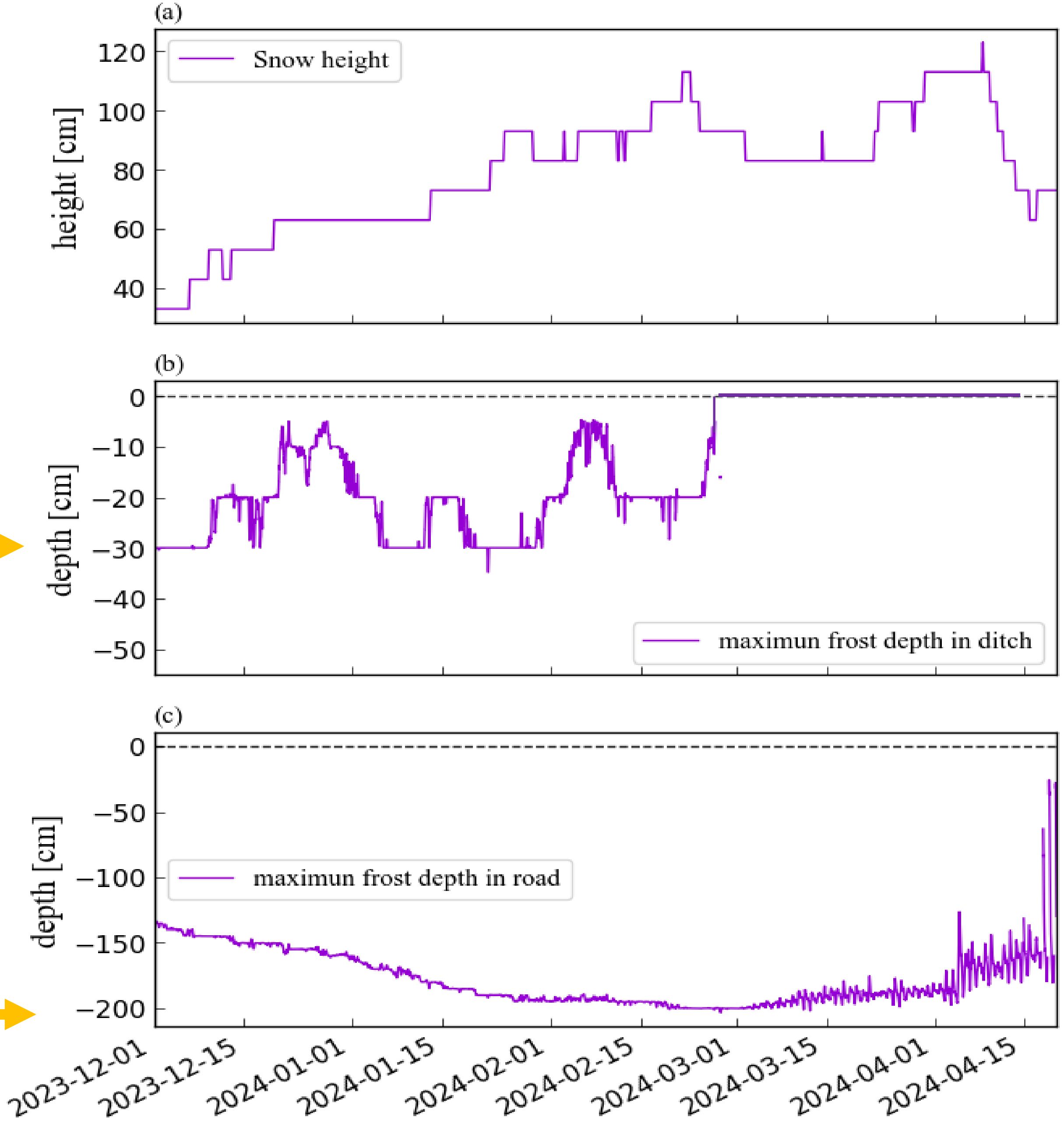


Road and Ditch

Ditch ≈ 30 cm

Maximum Frost Depth

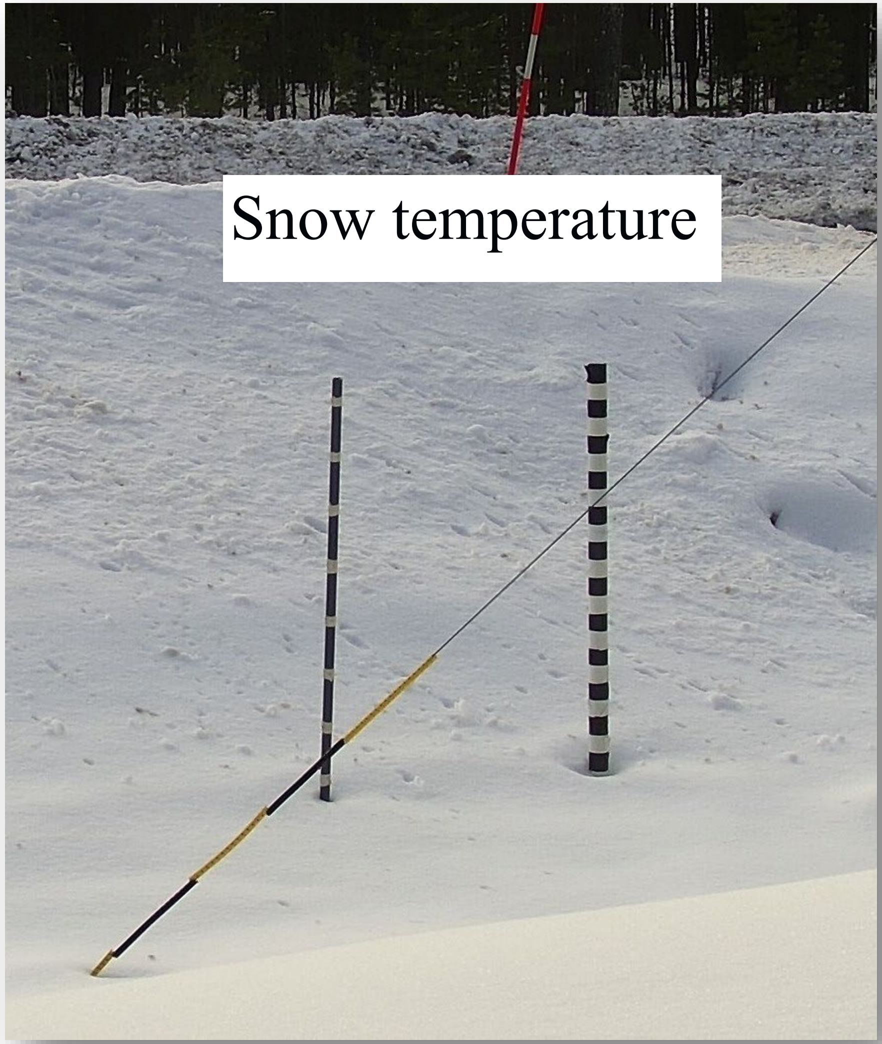
Road ≈ 200 cm



Thermal Conductivity of Snow

Input Variables for Mathematical Method

Measured variables



Estimation of Snow Thermal Conductivity

$$\underbrace{C_T \frac{\partial T}{\partial t} \Delta z}_{1} = \underbrace{Q_{net,i}}_{2} - \underbrace{\rho_w l_f \frac{\partial \theta_w}{\partial t} \Delta z}_{3}$$

1 = Heat storage

2 = Net heat into layer

3 = Energy used for melting or refreezing

$$Q_{net,i} = K_{eff} \frac{\partial T}{\partial z}$$

$$K_{eff} = K_{con} + K_{diff}$$

K_{eff} = Effective thermal conductivity ($^{W}/_{m.K}$)

K_{con} = Thermal conductivity due to conduction

K_{diff} = Thermal conductivity due to vapor diffusion

Thermal State of Snow Layers

snow layer 3

T_{top}

snow layer 2

T_{bottom}

snow layer 1

$$T_{avg} = \frac{T_{top} + T_{bottom}}{2}$$

$\boldsymbol{T_{avg}}$ = Average temperature of each snow layer

$$T_{diff} = T_{top} - T_{bottom}$$

$\boldsymbol{T_{diff}}$ = Temperature difference present in each snow layer

Thermal State of Snow Layers

$$\underbrace{C_T \frac{\partial T}{\partial t} \Delta z}_{\text{Heat storage}} = \underbrace{Q_{net,i}}_{\text{Net heat flux}} - \underbrace{\rho_w l_f \frac{\partial \theta_w}{\partial t} \Delta z}_{\text{Melting refreezing}}$$

$$T_{avg} = \frac{T_{top} + T_{bottom}}{2}$$

$$T_{diff} = T_{top} - T_{bottom}$$

1) $T_{avg} < 0$ *and* $T_{diff} \neq 0$

2) $T_{avg} < 0$ *and* $T_{diff} = 0$

3) $T_{avg} \approx 0$ *and* $T_{diff} = 0$

4) $T_{avg} \approx 0$ *and* $T_{diff} \neq 0$

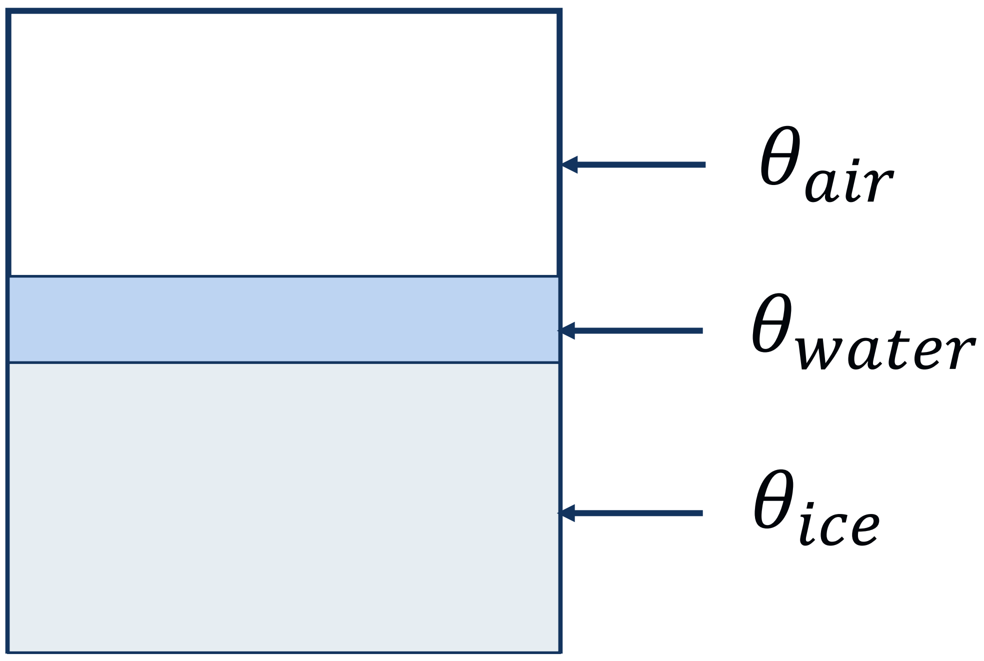
Thermal State of Snow Layers

$$\underbrace{C_T \frac{\partial T}{\partial t} \Delta z}_{\text{Heat storage}} = \underbrace{Q_{net,i}}_{\text{Net heat flux}} - \underbrace{\rho_w l_f \frac{\partial \theta_w}{\partial t} \Delta z}_{\text{Melting refreezing}}$$

1) $T_{avg} < 0$ *and* $T_{diff} \neq 0$ $\longrightarrow$ $\rho_w l_f \frac{\partial \theta_w}{\partial t} \Delta z = 0$ $\longrightarrow$ $\boxed{\text{No melting}}$

Thermal State of Snow Layers

$$\underbrace{C_T \frac{\partial T}{\partial t} \Delta z}_{\text{Heat storage}} = \underbrace{Q_{net,i}}_{\text{Net heat flux}} - \underbrace{\rho_w l_f \frac{\partial \theta_w}{\partial t} \Delta z}_{\text{Melting refreezing}}$$



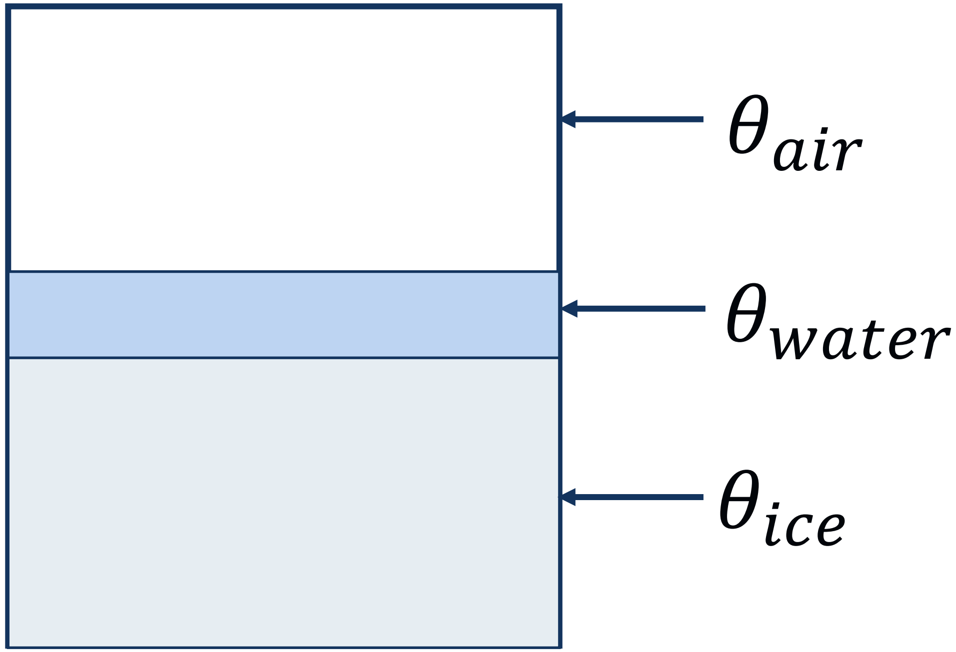
2) $T_{avg} < 0 \quad and \quad T_{diff} = 0 \longrightarrow \rho_w l_f \frac{\partial \theta_w}{\partial t} \Delta z = 0 \longrightarrow$ No melting

$$\theta_{ice} + \theta_{water} + \theta_{air} = 1$$

$$K_{eff} = K_{ice}.\theta_{ice} + K_{water}.\theta_{water} + K_{air}.\theta_{air}$$

Thermal State of Snow Layers

$$\underbrace{C_T \frac{\partial T}{\partial t} \Delta z}_{\text{Heat storage}} = \underbrace{Q_{net,i}}_{\text{Net heat flux}} - \underbrace{\rho_w l_f \frac{\partial \theta_w}{\partial t} \Delta z}_{\text{Melting refreezing}}$$



$$3\,)\; T_{avg} \approx 0 \;\; and \;\; T_{diff} = 0 \longrightarrow \boxed{\text{Just melting}} \longrightarrow Q_{net,i} = 0 \longrightarrow \theta_w$$

$$\theta_{ice} + \theta_{water} + \theta_{air} = 1$$

$$K_{eff} = K_{ice} . \theta_{ice} + K_{water} . \theta_{water} + K_{air} . \theta_{air}$$

Thermal State of Snow Layers

$$\underbrace{C_T \frac{\partial T}{\partial t} \Delta z}_{\text{Heat storage}} = \underbrace{Q_{net,i}}_{\text{Net heat flux}} - \underbrace{\rho_w l_f \frac{\partial \theta_w}{\partial t} \Delta z}_{\text{Melting refreezing}}$$

4) $T_{avg} \approx 0$ *and* $T_{diff} \neq 0$ → conduction + vapor diffusion + melting

Two unkowns in heat balance equation

Estimation of Unfrozen Water Content of Snow Layer

Fixed volume between two temperature measurement points

$$\Delta V_{layer} = \Delta V_{ice} + \Delta V_{water} + \Delta V_{air} = 0$$

Ice volume decreases 9% by melting

$$\begin{cases} \Delta V_{layer} = \Delta V_{water} - 1.09\Delta V_{water} + \Delta V_{air} = 0 \\ \Delta V_{air} = 0.09\Delta V_{water} \end{cases}$$

$$\boxed{\Delta\theta_w = \frac{\Delta V_{water}}{V_{tot}}}$$

$$\theta_{ice} + \theta_{water} + \theta_{air} = 1$$

Effective Thermal Conductivity

$$\underbrace{C_T \frac{\partial T}{\partial t} \Delta z}_{\text{Heat storage}} = \underbrace{Q_{net,i}}_{\text{Net heat flux}} - \underbrace{\rho_w l_f \frac{\partial \theta_w}{\partial t} \Delta z}_{\text{Melting refreezing}}$$

4) $T_{avg} \approx 0$ *and* $T_{diff} \neq 0 \longrightarrow K_{eff} = (K_{ice}.\theta_{ice} + K_{water}.\theta_{water} + K_{air}.\theta_{air}) + K_{diff}$

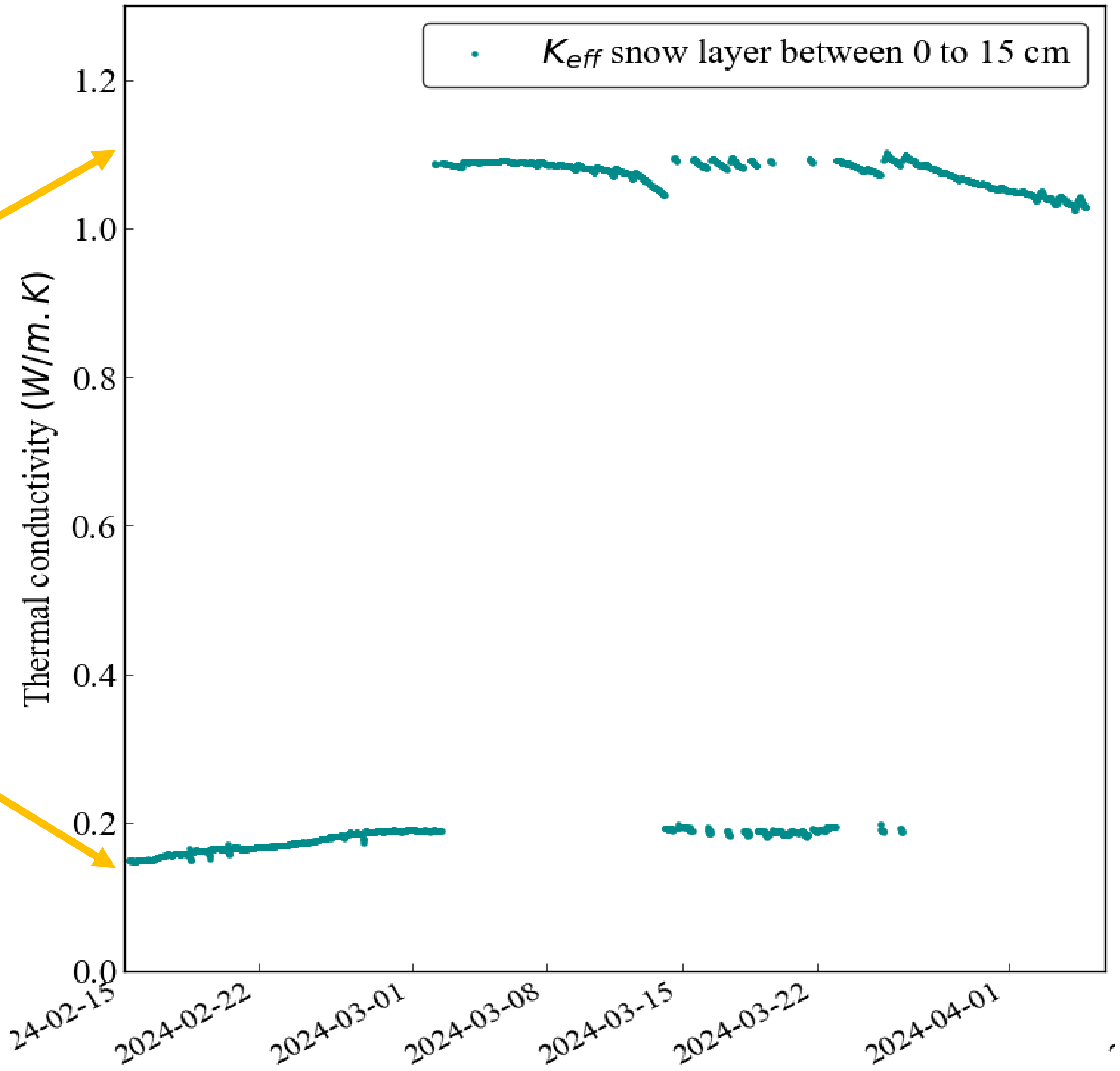
Effective thermal conductivity =

(contribution of component × components of snow) + diffusive thermal conductivity

Effective Thermal Conductivity of Snow

The soil-snow interface to 15 cm

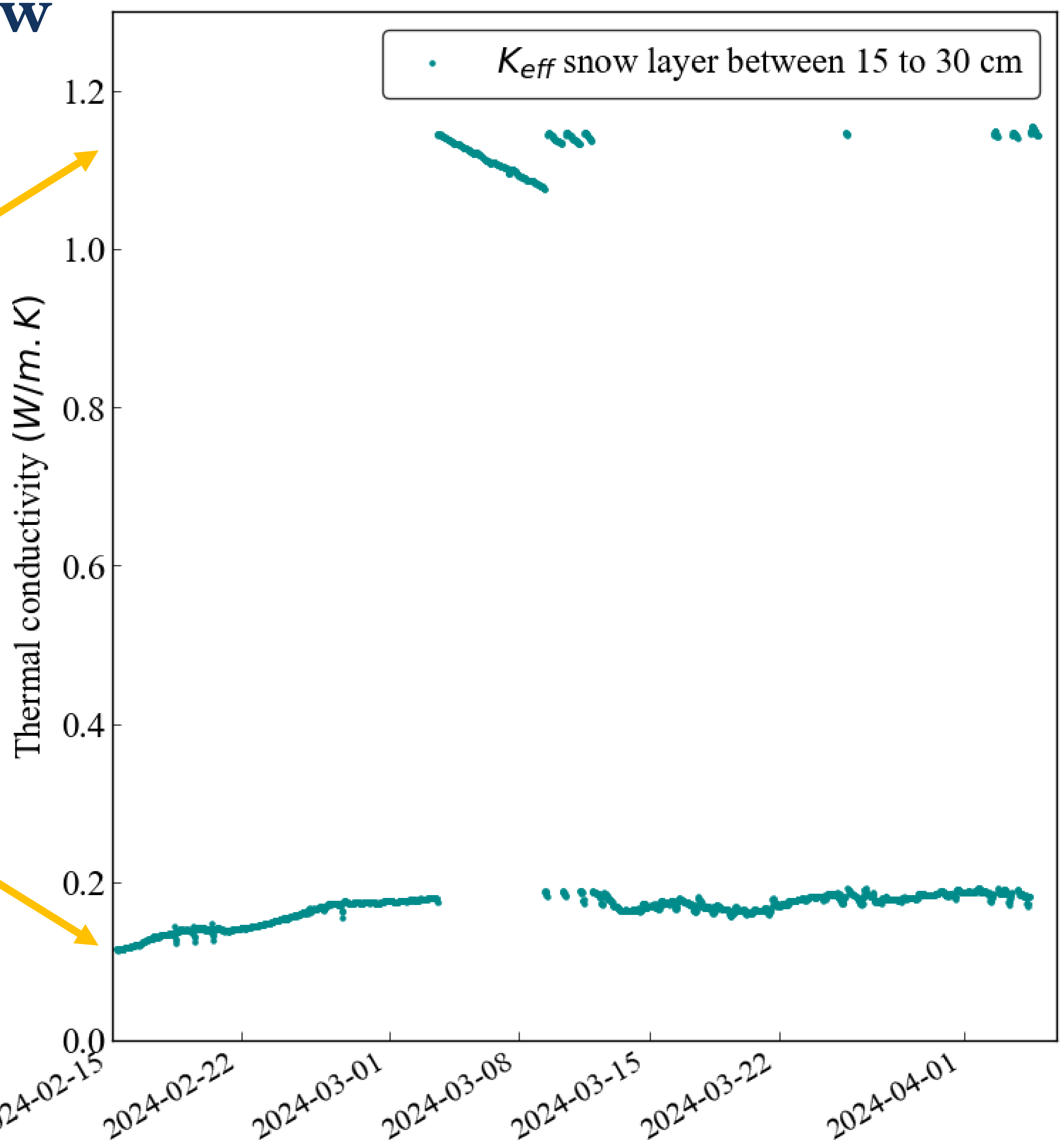
- K_{eff}:
  - $if\ \ T \approx 0\,°C,\ K_{eff}\ \approx 1.1$
  - $if\ \ T < 0\,°C,\ K_{eff}\ \approx 0.15 - 0.18$
- (Unfrozen) water content ≈ 3.5%



Effective Thermal Conductivity of Snow

The snow layer: 15 – 30 cm

- K_{eff}:
  - $if \;\; T \approx 0\,°C,\; K_{eff} \;\; \approx 1.1$
  - $if \;\; T < 0\,°C,\; K_{eff} \;\; \approx 0.12 - \; 0.18$
- (Unfrozen) water content ≈ 3.5%

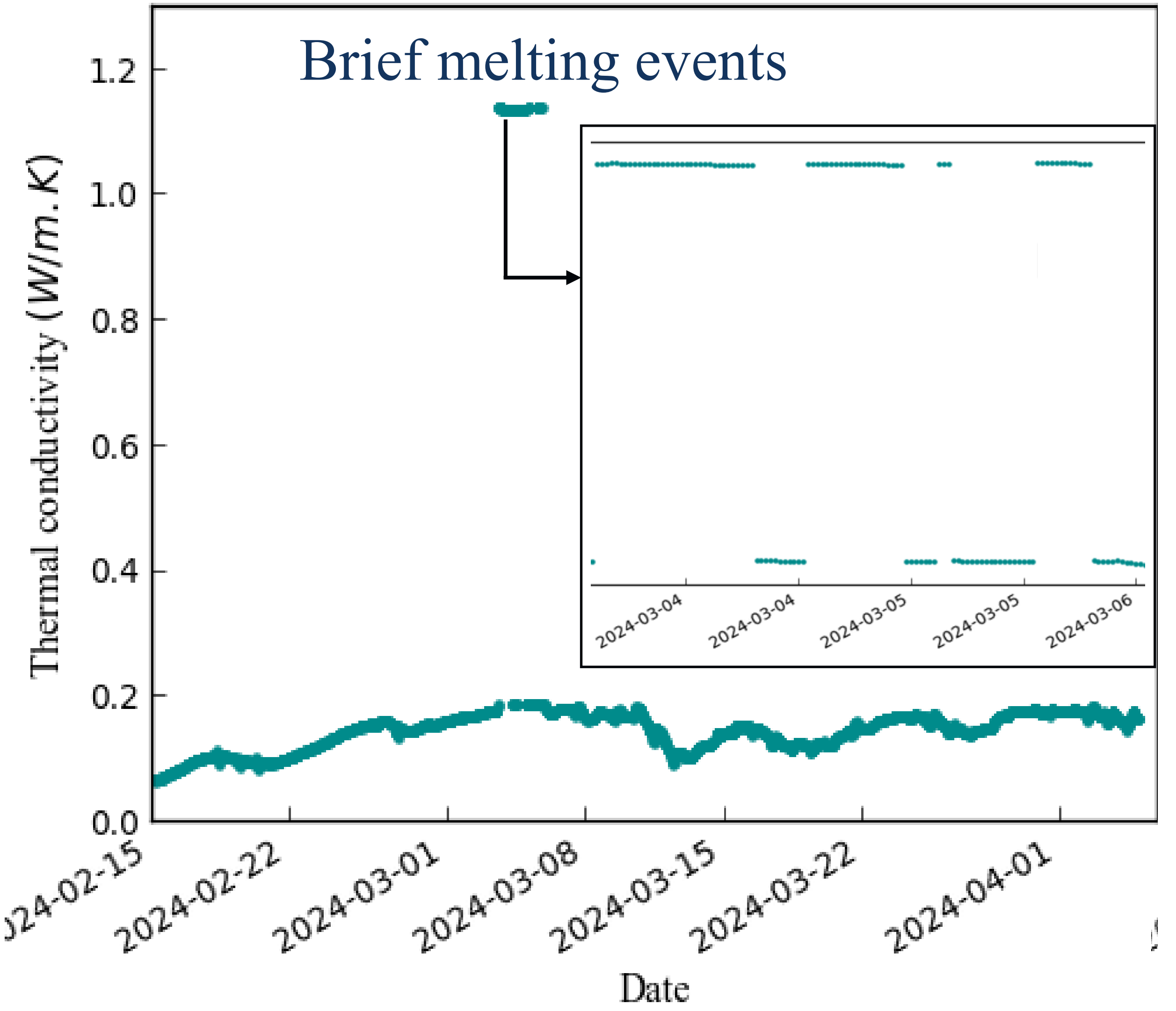


Effective Thermal Conductivity of Snow

Three snow layers from 30 – 75 cm

- K_{eff}:
  - $if \;\; T \approx 0\,°C,\; K_{eff} \;\approx 1.2$
  - $if \;\; T < 0\,°C,\; K_{eff} \;\approx 0.05 \;-\; 0.2$

Snow layer 45 to 60 cm



Road Temperature Simulation

Predicting the Temperature Profile of a Road Embankment

1-D Finite Difference model

- From road surface to 200 cm depth
- Transient heat conduction
- Fourier's heat equation

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2}$$

ρ = density of the material
T = temperature
k = thermal conductivity of the material
t = time
z = depth within the embankment

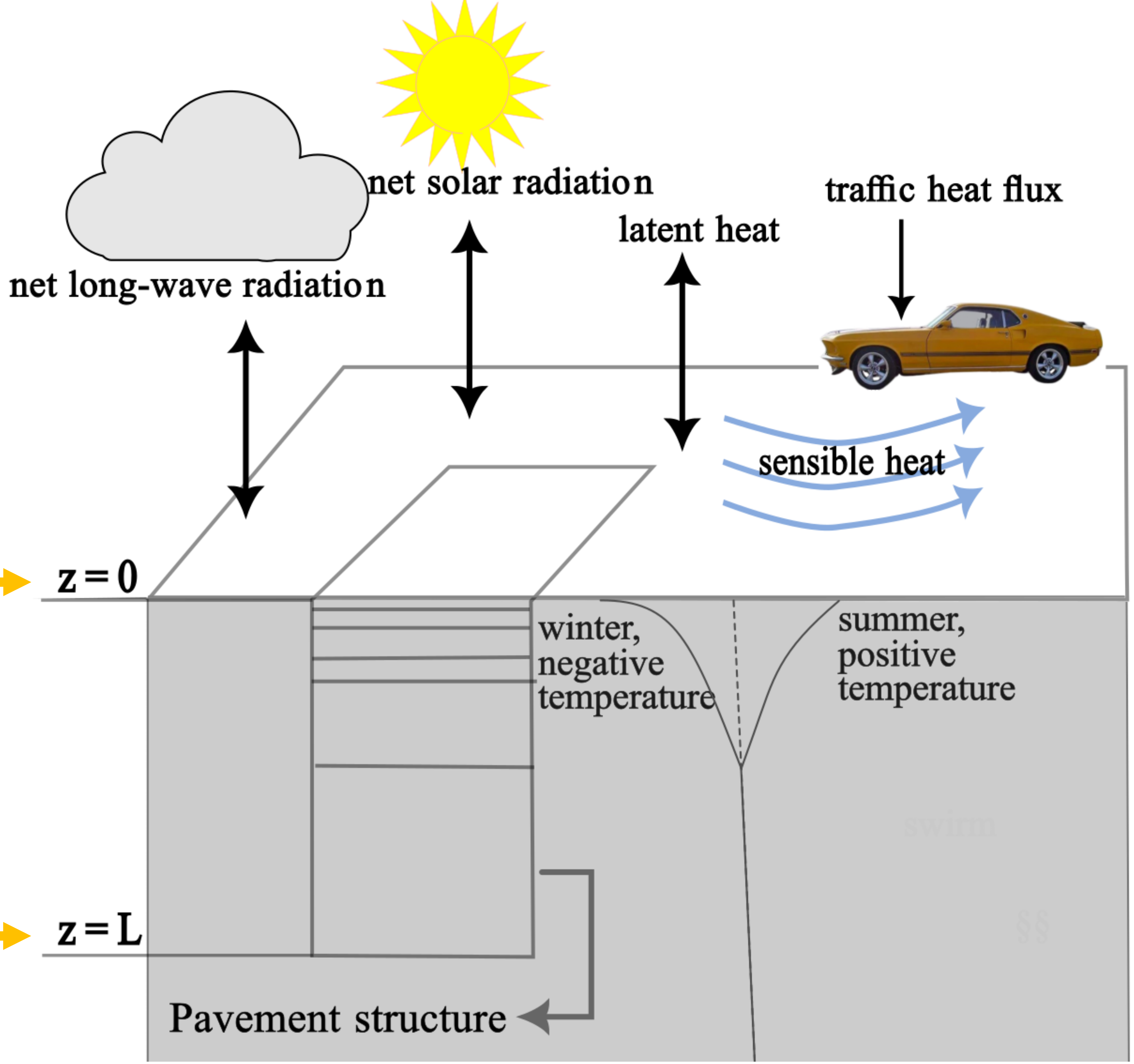
Boundary Conditions of the Heat-transfer Model

Surface Boundary Conditions:

Surface energy balance equation

Bottom Boundary Condition:

Constant-temperature



Boundary Conditions of the Heat-transfer Model

- Incoming longwave radiation estimation — Dynamic cloud cover ✓
- Latent heat flux — Aerodynamic resistances for **temperature** ✓
- Sensible heat flux — Aerodynamic resistances for **specific humidity** ✓
- Traffic heat flux — Vehicle movement ✓

Incoming Longwave Radiation Estimation

- **Dynamic cloud cover** calculation

$$K_T = 1 - \frac{I}{I_0}$$

Where:

- I_0 = extraterrestrial radiation (calculated)
- I = measured incoming solar radiation

Traffic Induced Heat Fluxes

- Improving **sensible heat flux** determination
  - Aerodynamic resistances for **temperature,** r_T

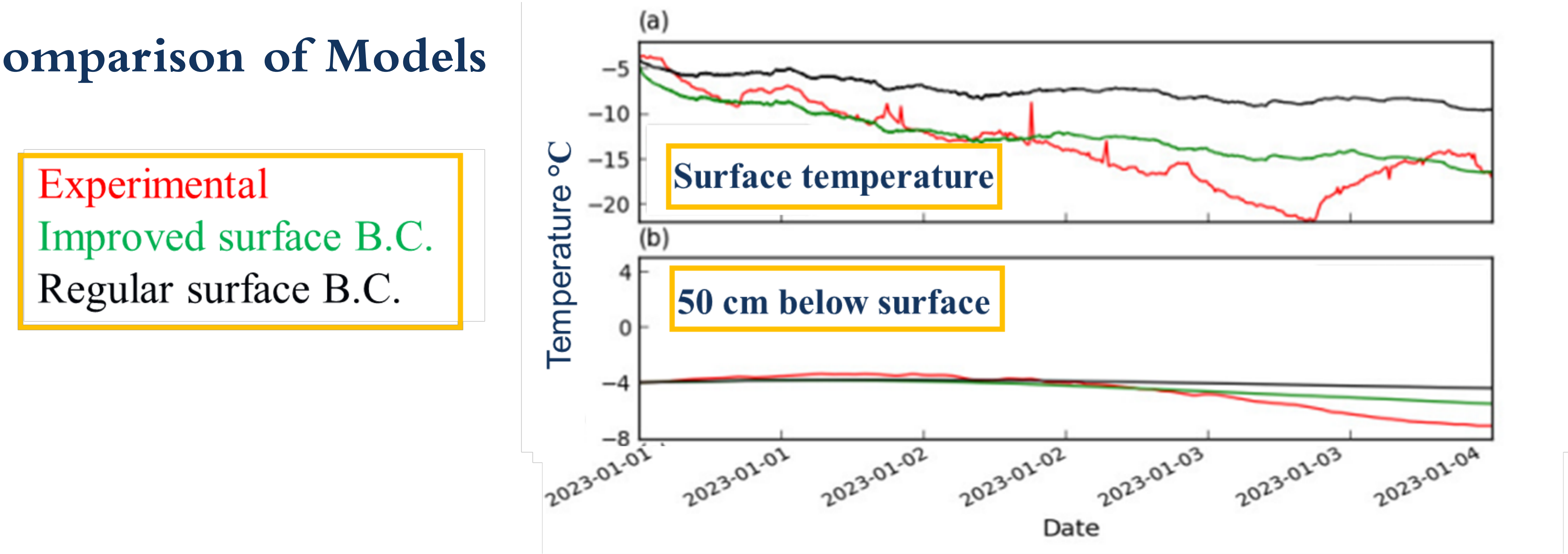
$$Q_H = -\rho_a C_p (T_a - T_s)/r_T$$

- Improving **latent heat flux** determination
  - Aerodynamic resistances for **specific humidity**, r_q

$$Q_L = -\rho_a \lambda_s (q_a - q_s)/r_q$$

- **Traffic induced heatflux** through engine effects, friction, etc.

Comparison of Models



- Validation conducted over two separate **3-day periods**
- Enhanced accuracy in predicting **road surface temperature down to ≈50 cm** depth
- **RMSE < 3°C** for surface temperature in both tested time periods

Conclusion and Future Ideas

Conclusion

Snow Thermal Properties

- Snow in ditches has thermal conductivity comparable to naturally accumulated snow in this region
- The snowpack in the ditch becomes increasingly homogeneous over time
- The proposed heat-transfer-based method shows potential as a reliable way to estimate snow thermal conductivity

Road Embankment

- Accurate road surface temperature prediction in winter needs to include dynamic surface boundary condition

Future Research

Experimental Work

- Direct measurement of thermal conductivity in the ditch snowpack

Numerical Development

- Development of a two-dimensional (2D) heat transfer model

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Estimation of thermal conductivity of snow

$$k_{eff} = \begin{cases} 0.184 + 0.016\,T_{avg}, & \text{if } T_{avg} < 0°C, \\ 0.036 + 0.003\,\rho_s, & \text{if } T_{avg} \geq 0°C. \end{cases}$$

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Thank you for your attention

Any questions?

Research Methodology Overview

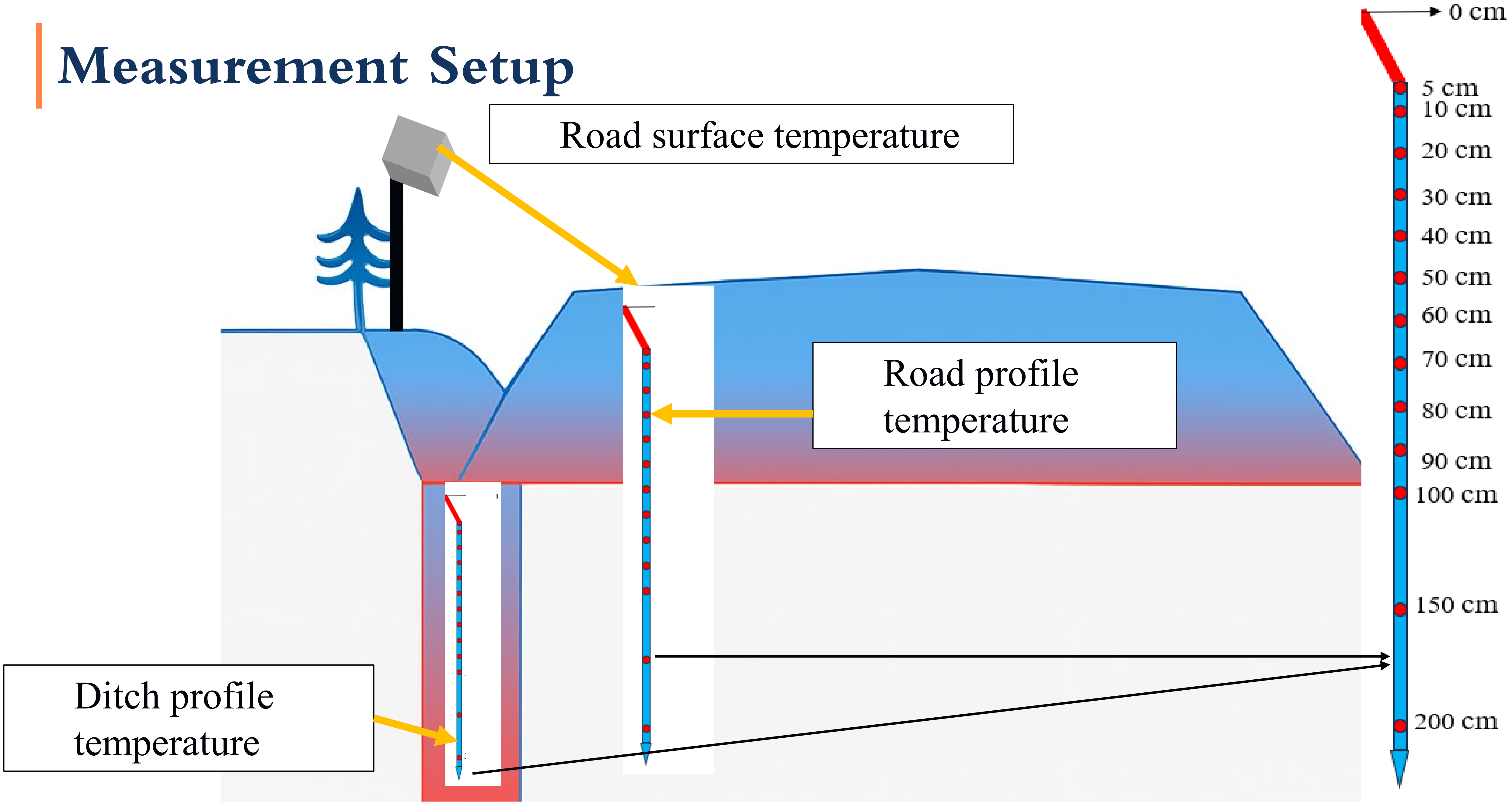
Experimental Investigation

Numerical Solution

Conclusion - Road Embankment

- Road surfa temperature prediction in winter is challanging
- A thin ice layer on the road surface undergoes continuous phase changes

Measurement Setup

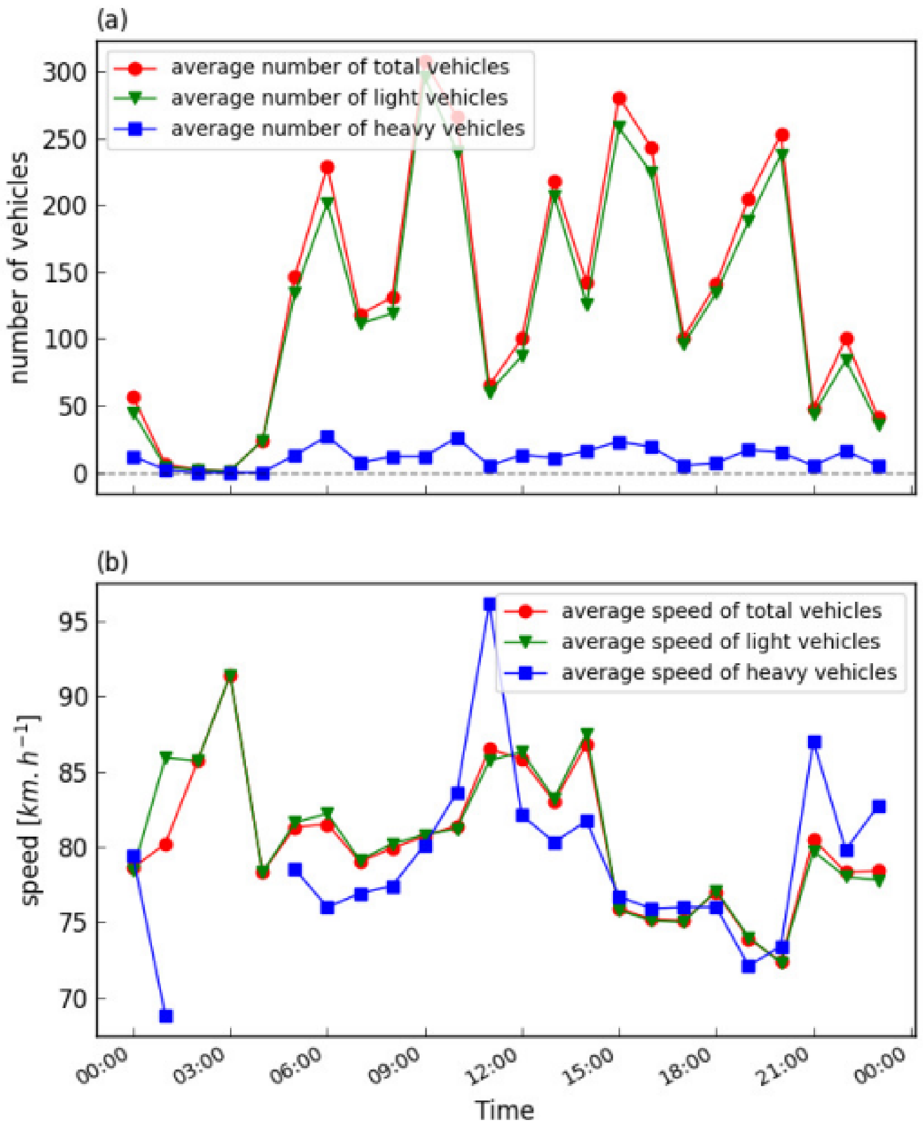


Traffic-Induced Heat Fluxes

Traffic heat flux due to vehicle movements

- Measurements were performed for 2 weeks

- symbolic representation day
  - Traffic density
  - Traffic speed



Results: Model Performance with Enhanced Surface Boundary Conditions

- In winter, **longwave radiation** under cloudy conditions strongly influences road surface temperature.
- **Traffic-induced heat fluxes** (sensible, latent, and tire–road friction) also modify near-surface heat exchange.

Role of Dynamic Cloud Factor

- Captures **real-time variations in cloudiness** during daylight hours.
- Provides more realistic incoming longwave radiation.

Thermal State of Snow Layers

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$$T_{avg} = \frac{T_{top} + T_{bottom}}{2}$$

$$T_{diff} = T_{top} - T_{bottom}$$

1) $T_{avg} < 0 \quad and \quad T_{diff} \neq 0 \Rightarrow$
2) $T_{avg} < 0 \quad and \quad T_{diff} = 0 \Rightarrow$

$$\left.\rho_w l_f \frac{\partial \theta_w}{\partial t}\Delta z = 0 \right\} \text{No Melting}$$

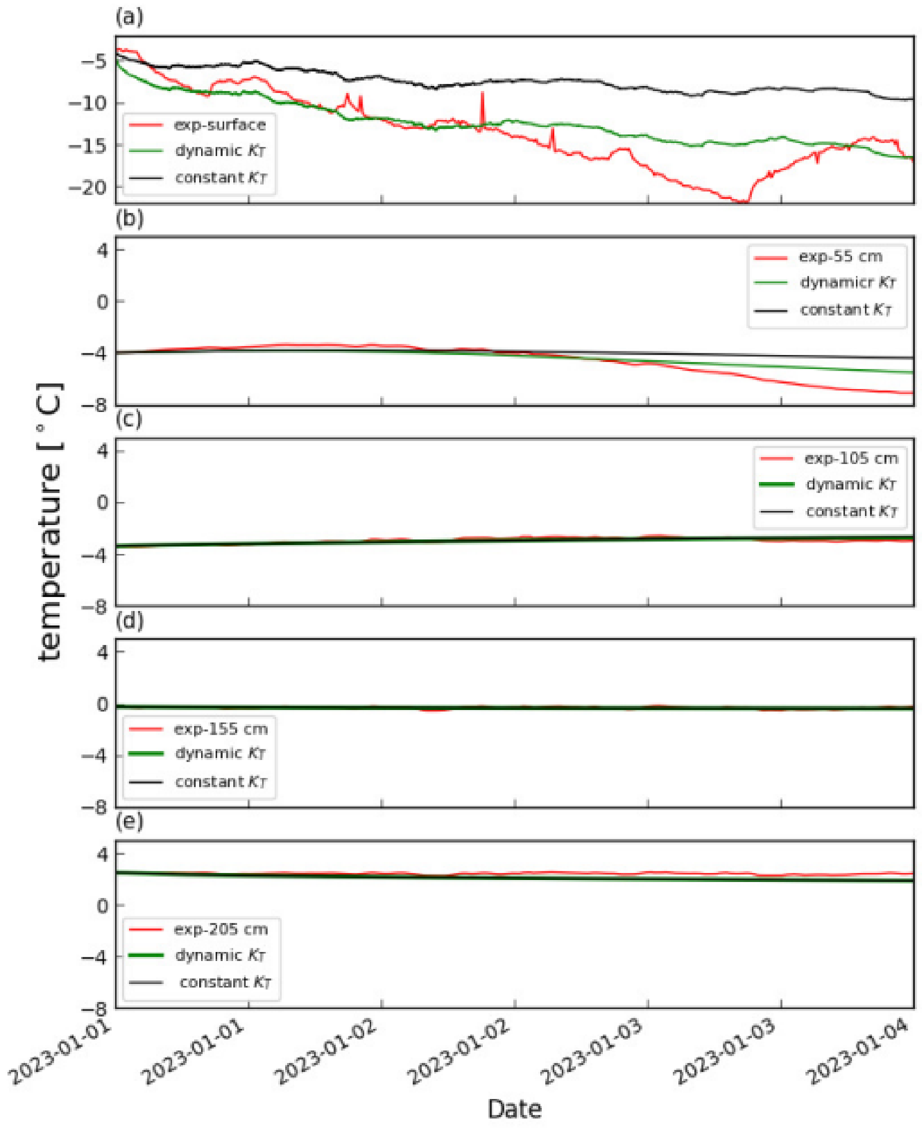
3) $T_{avg} \geq 0 \quad and \quad T_{diff} \neq 0 \Rightarrow$ All heat fluxes present
4) $T_{avg} \geq 0 \quad and \quad T_{diff} = 0 \Rightarrow$ Just melting is present

Unfrozen liquid water is present

Finite Difference Model – Results Using Dynamic Cloud Factor

Time Period and Approach

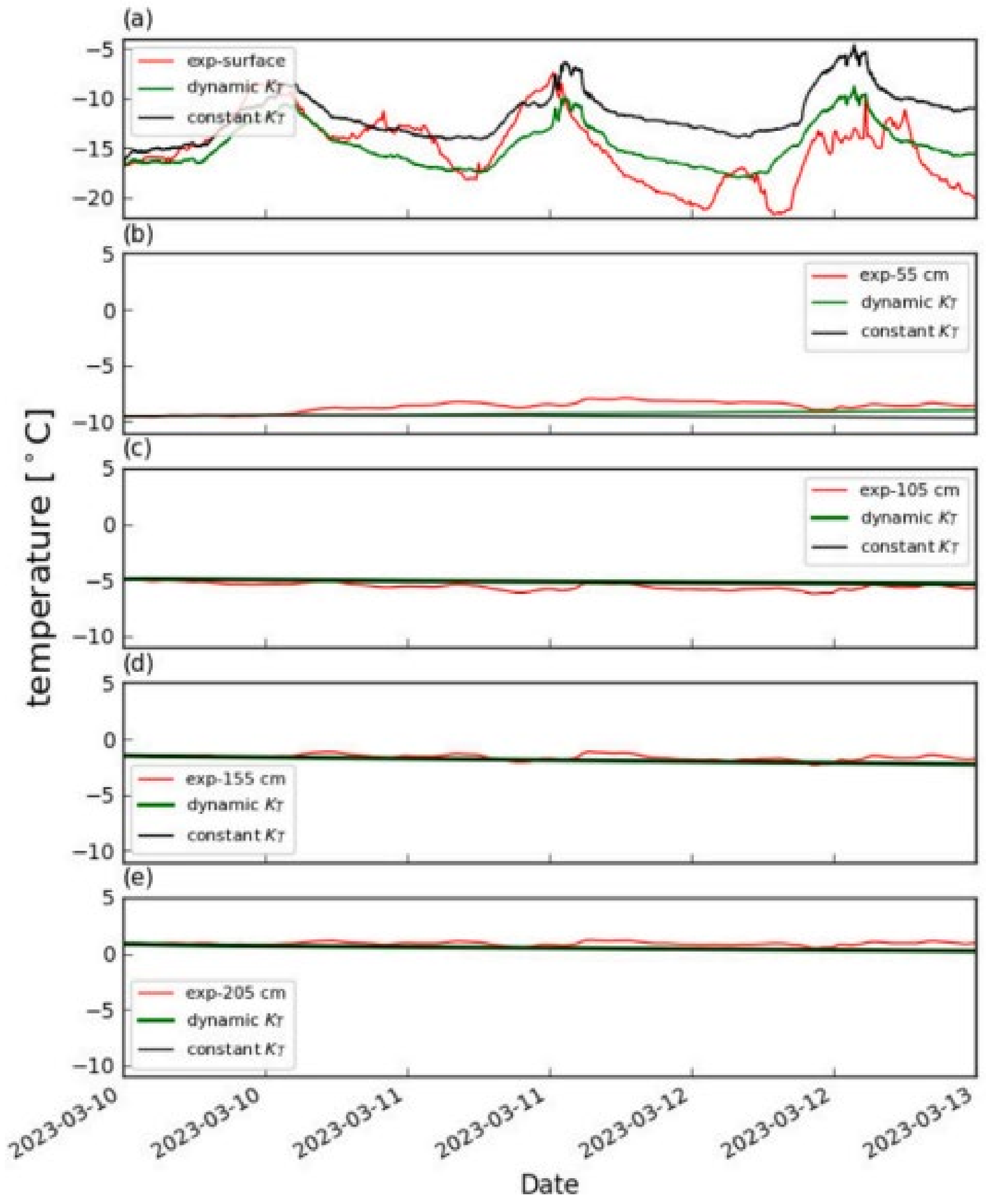
- Model performance assessed during **1–4 January 2023**
- Temperature outputs validated against field measurements at **surface, 55 cm, 105 cm, 155 cm, and 205 cm** depths
- Both dynamic and constant cloud cover (K_T) formulations were tested



Finite Difference Model – Results Using Dynamic Cloud Factor

Time Period & Setup

- Evaluation period: 10–13 March 2023
- Higher temperature variation due to solar radiation



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- **Road embankment**

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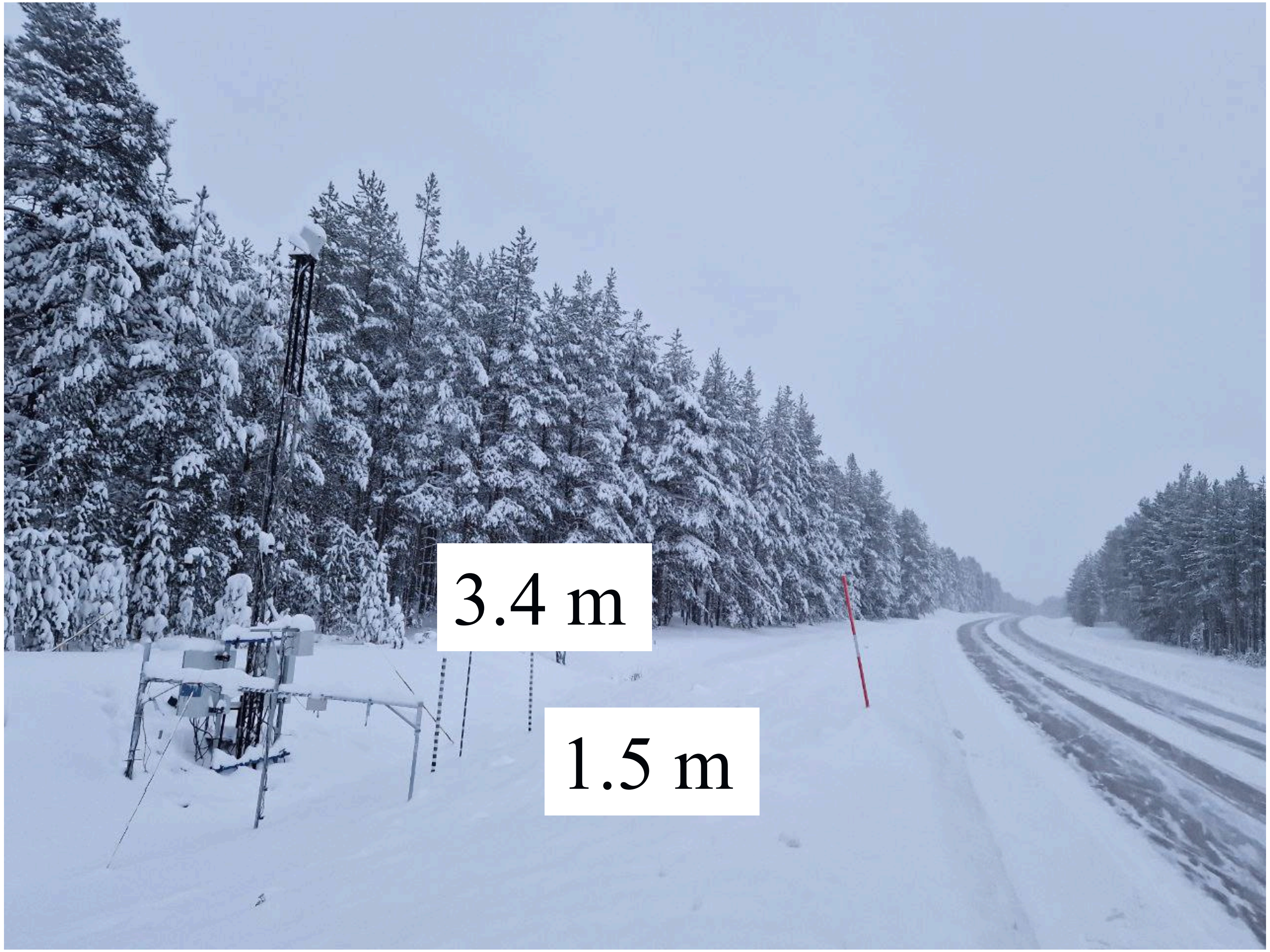
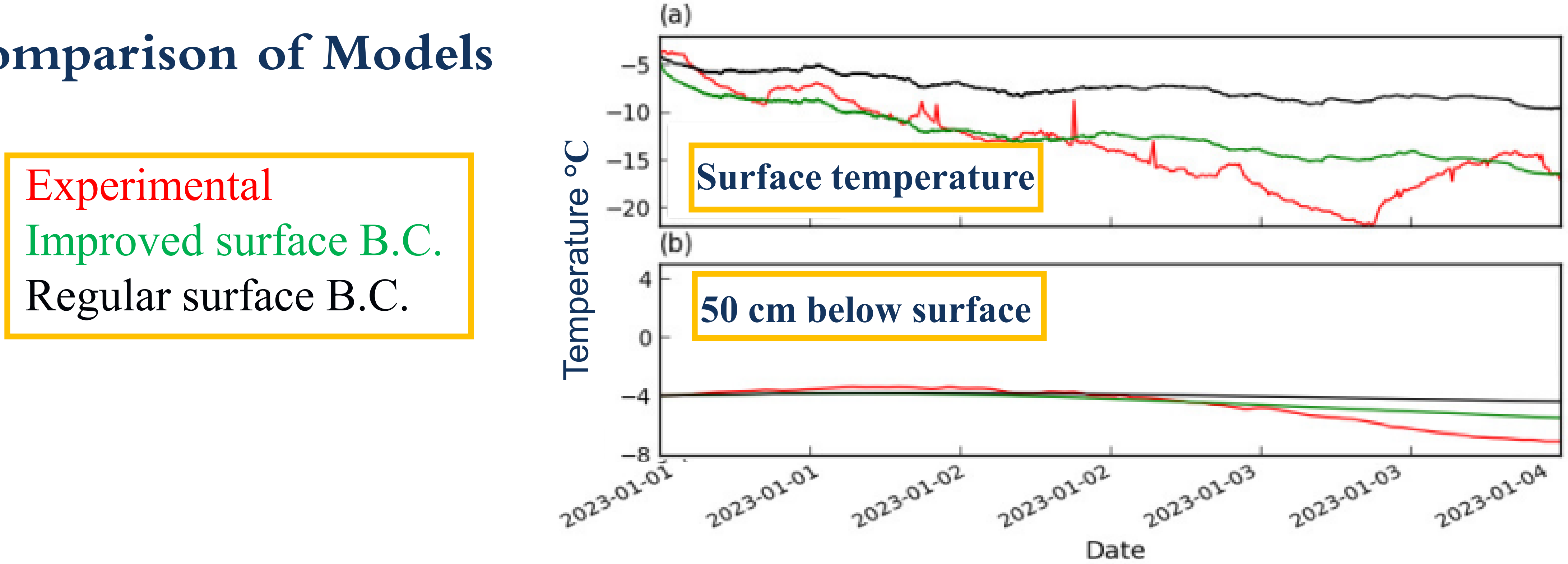
- Ground water level: 10 m below the road surface



Comparison of Models



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- Tested both **dynamic and constant cloud-cover**
- Enhanced accuracy in predicting **road surface temperature down to ≈50 cm** depth
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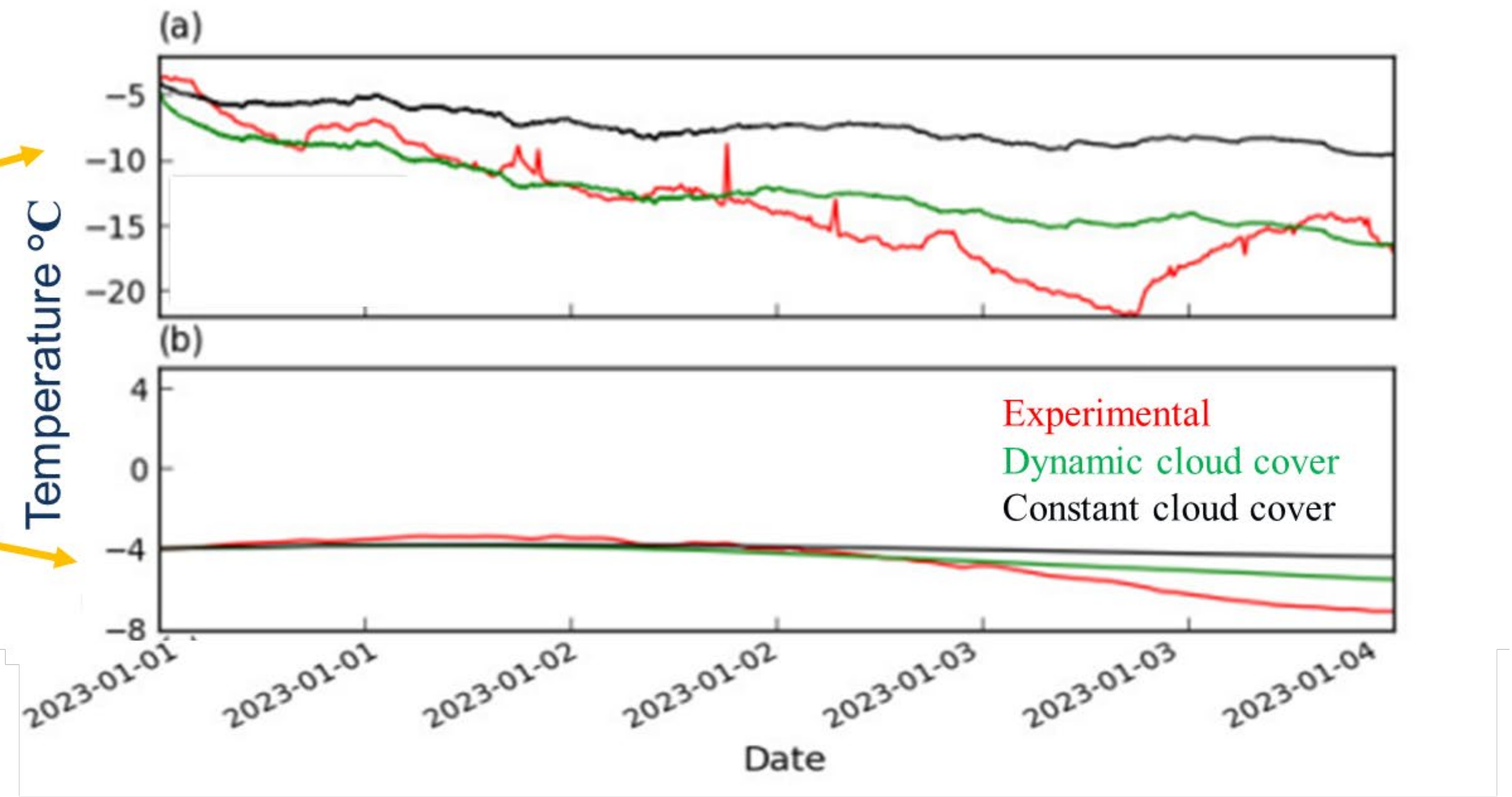
Surface temperature

50 cm below surface



Experimental
Improved surface B.C.
Regular surface B.C.