Proceedings of the XVIII ECSMGE 2024
GEOTECHNICAL ENGINEERING CHALLENGES
TO MEET CURRENT AND EMERGING NEEDS OF SOCIETY

ISBN 978-1-032-54816-6
DOI 10.1201/9781003431749-622

Influence of different seasonal snow cover on thermal regime of the ground

Influence de la couverture neigeuse saisonnière sur le régime thermique du sol

Z. Motamedi*
Soil Mechanics, Mining and Geotechnical Engineering, Luleå University of Technology, Sweden

H. Mattsson, J. Laue, S. Knutsson
Soil Mechanics, Mining and Geotechnical Engineering, Luleå University of Technology, Sweden

J. Casselgren
Experimental Mechanics, Luleå University of Technology, Sweden

**Zahra.Motamedi@ltu.se*

ABSTRACT: Ground thermal regime in cold regions is influenced by seasonal snow cover, which acts as an insulating layer influencing the heat transfer between the atmosphere and the underlying soil. The thermal properties of the snow change with different environmental conditions, playing a crucial role to determine the thermal state of the sub-surface soil. Previous research in this field have faced challenges to accurately characterize thermal properties of seasonal snowpacks under varying spatial and meteorological conditions. To address this issue, two experimental field setups were constructed in Luleå, Sweden, to observe the temperature distribution of the snowpack and the ground sub-surface soil. The first experiment studied a naturally accumulated, undisturbed snowpack. The second experiment was conducted on a roadside ditch where the snowpack consists of a combination of natural accumulated snow and plowed snow from the adjacent road. In this research, heat transfer processes at both field sites were monitored over a winter season each to better understand the complex relationship between snow cover properties and sub-surface thermal regime. Furthermore, thermal conductivity of a basal layer in each snowpack was calculated over a time period, based on the field measurements. The results showed that the history of snow deposition, meteorological conditions, and changes in soil moisture impact the metamorphism process within the snowpack, thereby altering the structure of the layers of snowpack and its influence on the thermal regime of the sub-surface soil. The findings of this research have important applications in various sectors, from mining to road maintenance and agriculture.

RÉSUMÉ: Le régime thermique du sol dans les régions froides avec une couverture neigeuse saisonnière est influencé par la couche isolante de neige, qui agis sur le transfert de chaleur entre l'atmosphère et le sol sous-jacent. Les propriétés thermiques de la neige changent en fonction de différentes conditions environnementales, jouant un rôle crucial dans la détermination de l'état thermique du sous-sol. Des recherches antérieures dans ce domaine ont rencontré des défis pour caractériser de manière précise les propriétés thermiques des manteaux neigeux saisonniers dans différentes configurations spatiales et des conditions météorologiques variables. Pour résoudre ce problème, deux dispositifs expérimentaux ont été construits à Luleå, en Suède, afin d'observer la distribution de la température dans le manteau neigeux et le sol. La première expérience a étudié un manteau neigeux accumulé naturellement et non perturbé. La deuxième expérience a été menée dans un fossé en bordure de route où le manteau neigeux est constitué d'une combinaison de neige accumulée naturellement et de neige déblayée de la route adjacente. Dans cette recherche, les processus de transfert de chaleur sur chacun des sites ont été surveillés pendant une saison hivernale pour mieux comprendre la relation complexe entre les propriétés de la couverture neigeuse et le régime thermique en sous-sol. De plus, la conductivité thermique d'une couche de base dans chaque manteau neigeux a été calculée sur une période donnée, en fonction des mesures sur le terrain. Les résultats ont montré que l'historique du dépôt de neige, les conditions météorologiques et les variations de l'humidité dans le sol affectent le processus de métamorphose au sein du manteau neigeux, modifiant ainsi la structure des couches du manteau neigeux et son influence sur le régime thermique du sous-sol. Les conclusions de cette recherche sont applicables dans divers secteurs, de l'exploitation minière à l'entretien des routes et à l'agriculture.

Keywords: Ground thermal regime; thermal properties; seasonal snow cover.

1 INTRODUCTION

The ground thermal regime in cold regions is strongly influenced by the presence of seasonal snow cover, which acts as an insulating layer during the cold season. Alterations in snow cover conditions have a significant influence on the correlation between meteorological conditions and the thermal state of the soil beneath the snow. Scientific research conducted in the Arctic and sub-Arctic regions has revealed that the seasonal snow cover is composed of distinct layers with varying physical and thermal characteristics (Benson & Sturm, 1993). Of particular interest in recent years is the formation of a basal layer of snowpack known as the depth hoar, which has important implications for the properties of the snowpack and interacts closely with the soil beneath the snow. Depth hoar crystals are characterized by their large size, hollow facets, and poor interconnectivity, resulting in layers of low density and low thermal conductivity. These crystals play a significant role in the thermal insulation of the snowpack.

Domine et al. (2018) emphasized that the formation of depth hoar is primarily influenced by soil moisture and wind conditions. Understanding this relationship is crucial to simulate snow properties accurately, particularly thermal conductivity, in order to effectively model the ground thermal regime.

To explore this matter, two experimental test sites were established in Luleå, located in the northern part of Sweden. The objective of the experimental configurations at the sites was to investigate and analyze how two types of seasonal snowpack, each characterized by a unique thermal conductivity in their basal layer, affect the thermal regime of the ground.

2 FIELD MEASUREMENT

Measurements were conducted at two distinct experimental field sites: Experimental Site 1 (ES1) during the winter of 2021-2022, and Experimental Site 2 (ES2) during the subsequent winter of 2022-2023, as illustrated in Figure 1 and Figure 2.

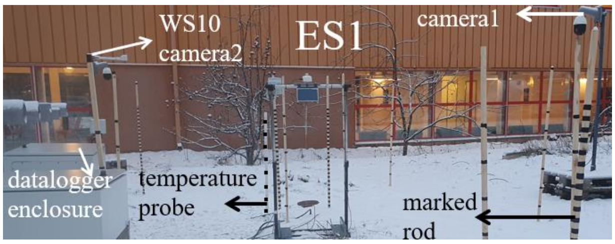

Figure 1. ES1 during the winter 2021-2022.

ES1, was situated within the premises of Luleå University of Technology. The site was specifically selected for studying a naturally accumulated and undisturbed snowpack. ES2 was located near the Luleå airport on a roadside ditch, where the snowpack consisted of a mixture of naturally accumulated snow and plowed snow from the adjacent road. At both field sites, meteorological data was collected using a WS10 weather station (Lufft Mess und Regeltechnik GmbH, 2019). To quantify snow depth, a system was implemented where two cameras were stationed at each site. The cameras captured images of rods, marked at 5 (cm) intervals, providing clear reference points for measurement. Images were taken at 4-hour intervals. Additionally, a temperature measurement probe equipped with thermocouples type T produced by Pentronic were utilized to measure the temperature of the soil sub-surface at a depth of 40 (cm), the temperature at the soil-snow interface and the temperature of 15 (cm) above the interface within the snowpack. Furthermore, thermal conductivity of the

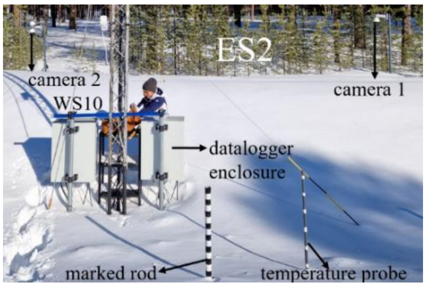

Figure 2. ES2 during the winter 2022-2023.

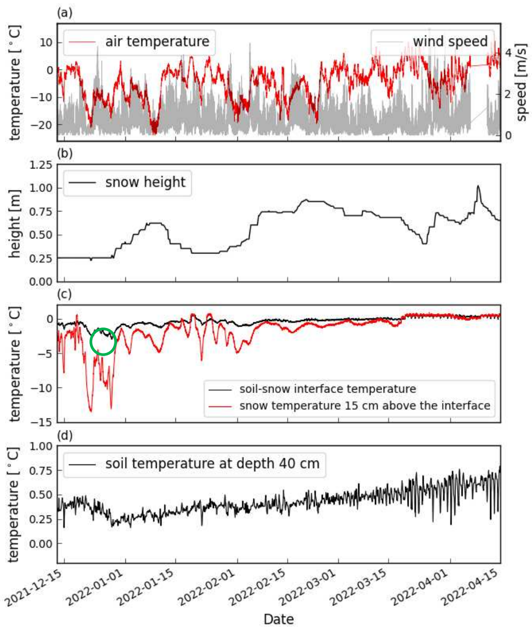

Figure 3. Recorded measurements at ES1 a) air temperature and wind speed, b) snow depth, c) temperature at the soil-snow interface and within the snowpack at a height of 15 cm above the interface, and d) soil sub-surface temperature at a depth of 40 cm.

sub-surface soil at a depth of 40 (cm) was measured using a TP01 thermal sensor. The sensors were connected to a CR1000X datalogger, manufactured by Campbell Scientific. The datalogger was housed in an enclosure equipped with additional insulation to ensure that the measured junction temperature was representative of the entire terminal block.

Figure 3 and Figure 4 present the recorded measurements at ES1 and ES2, respectively. These figures show the measurement results spanning two winter seasons, from December 13 to April 18. During the measurement period at ES1, the air temperature fluctuates between -23.7 (ºC) and 14.8 (ºC), with an average temperature of -4.5 (ºC). Similarly, at ES2, the air temperature ranges from -23.6 (ºC) to 9.9 (ºC), with an average temperature of -6.9 (ºC). However, the wind speed at ES2 is higher than at ES1.

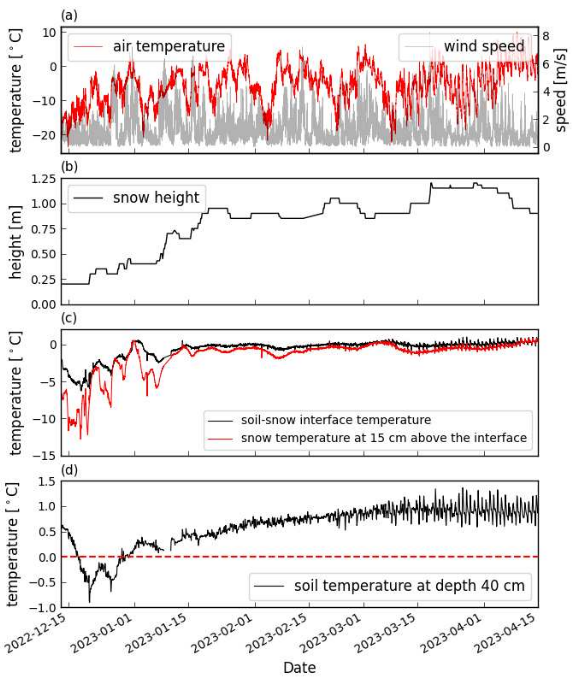

Figure 4. Recorded measurements at ES2 a) air temperature and wind speed, b) snow depth, c) temperature at the soil-snow interface and within the snowpack at a height of 15 cm above the interface, and d) soil sub-surface temperature at a depth of 40 cm.

2.1 Seasonal freeze/thaw development

The air temperature at ES1 exhibits fluctuations around the freezing point during the initial phase of the measurement period, Figure 3(a), contrasting with ES2 that initially just experiences negative air temperature, Figure 4(a). Nevertheless, within a few days, the air temperature at ES1 converges to a comparable range as that recorded at ES2. Furthermore, the data presented in Table 1, along with Figure 3(b) and Figure 4(b), highlights that the snow cover height at ES1 surpasses that at ES2 by a margin of 5 (cm) at the onset of the measurement.

Figure 3(c) and Table 1 highlight a distinct trend at the ES1 soil-snow interface in the beginning of the winter. Here, the interface temperature maintains stable just below 0 (ºC) for an extended period, characterized as the "zero-curtain" and illustrated in the figure by a green circle, before gradually dropping to -3 (ºC). This stability coincides with a phase transition from water to ice in the soil moisture, leading to the release of latent heat. Meanwhile, Figure 4(c) and Table 1 indicate a -6 (ºC) temperature decrease at the ES2 interface.

ES1 is characterized by sandy loam soil, whereas ES2 consists of poorly graded sand. Thermal conductivity measurements conducted at the sites revealed that ES1 demonstrated an average thermal conductivity of 0.57 ($Wm^{-1}K^{-1}$), while ES2 exhibited a slightly higher value of 0.8 ($Wm^{-1}K^{-1}$). The water table beneath ES1 is situated 2 (m) below the soil surface, while the water table beneath ES2 is found at a depth of 10 (m) below the soil surface. Thus, it is expected that the soil moisture content at ES1 will be higher than that at ES2, owing to both the proximity of the water table to the soil surface and the differing soil compositions.

As shown in Table 1, the initial temperature of the sub-surface soil at ES2 is 0.4 (ºC) higher than that of ES1 at the start of the measurement period. Nevertheless, unlike ES2, the sub-surface soil at ES1 remained unfrozen throughout the entire season, as shown in Figure 3(d). Conversely, the corresponding sub-surface soil at ES2 experienced approximately 10 days of freezing after one full day of the zero-curtain phenomenon at that depth. While thawing at ES2, the sub-surface soil experienced a full-day period of zero-curtain before it fully thawed. This sequence is outlined in Table 1 and visually represented in Figure 4(d).

The air temperature at both experimental sites typically remains within a similar range, with only a brief variation noted at the onset of the measurements. Furthermore, the difference in snow depth covering the sites is merely 5 (cm) at the commencement of the study. Despite a marginal difference of 0.23 ($Wm^{-1}K^{-1}$) in the thermal conductivity of the soil between ES2 and ES1, the higher moisture content in the soil at ES1 prevents the subsurface from freezing throughout the measurement period. This can be attributed to the significant latent heat energy released during the transition of water to ice. However, the subsurface soil at ES2 experienced a short period of "zero curtain" before undergoing freezing and subsequent thawing. This phenomenon can be attributed to the low moisture content of the soil at ES2.

2.2 Snow depth

Based on the analysis by Sokratov and Barry (2002), snow depth affects the soil surface energy balance, from beginning of the active layer freezing until the snow depth reaches its maximum level. Sturm and Holmgren (Zhang, 2005) conducted field measurements on November 17, 1998 in Ivotuk, Alaska. It was observed that the influence of snow depth on soil-snow interface temperature becomes less significant when the snow depth exceeds 40 (cm).

Table 1. Variation of critical temperature with snow height during the winter season at soil-snow interface and sub-surface soil at a depth of 40 cm at ES1 and ES2.

	Temperatue (ºC)	Snow height (cm)	Date
Soil-snow interface			
ES1	-0.7	25	2021-12-13
	-2.9	25	2021-12-28
	almost stable at 0	60	2022-02-06
ES2	-1.9	20	2022-12-13
	-6.3	20	2022-12-18
	almost stable at 0	65	2023-01-13
Sub-surface soil at a depth of 40 cm			
ES1	0.3	25	2021-12-13
	0.1	25	2021-12-28
ES2	0.7	20	2022-12-13
	zero-curtain	20	2022 -12-17 2022-12-18
	-1	25	2022-12-20
	zero-curtain	40	2022-12-28- 2022-12-29

Zhang (2005) underscores the significant impact of snow thickness variations on soil-snow interface temperatures, particularly when the snow depth is below approximately 50 (cm). Nevertheless, the data from the sites ES1 and ES2 demonstrate that when the snow depth reaches 60 (cm), the soil-snow interface temperature remains consistently at 0 (ºC), as depicted in Table 1 and Figure 1(b) and (c), as well as Figure 2 (b) and (c).

3 HEAT TRANSFER

3.1 Depth hoar formation

Seasonal snow cover usually consists of a coarse depth hoar layer at the base of the snowpack. This layer is characterized by its low-density and low-thermal conductivity < 0.2 (Wm^{-1}K^{-1}) (Sturm, et. al, 2002, Domine, et.al, 2016). Depth hoar typically forms through the metamorphism of snow exposed to a temperature gradient > 20 (Km^{-1}) (Marbouty, 1980).

A study conducted by Domine et al. (2018) has demonstrated the significance of wind as the primary factor influencing depth hoar formation in the polar desert. Investigations on subarctic snowpack, where wind is weak and uncompacted snow accumulates, have revealed that such snow exhibits high permeability, facilitating convection through the pore spaces (Sturm & Benson, 1997) leading to water vapor movement that encourages the growth of depth hoar crystals.

Davesne et al. (2022) have shown that snow pits in humid sites exhibit lower thermal conductivity values and less variability in the basal layer compared to dry sites. In regions characterized by higher humidity, the depth hoar crystals typically exhibit a coarser texture compared to drier locations. A lower soil moisture level leads to less latent heat released during the freezing process, speeding up the freezing of the active soil layer and consequently soil cooling. This, in turn, reduces the temperature gradient within the snowpack, resulting in decreased water vapor flux and slower snow metamorphism.

3.2 Heat transfer at soil-snow interface

As the snow accumulates and reaches a specific height, the soil-snow interface temperature stabilizes at 0 (ºC), as shown in Figure 3(c) and Figure 4(c). Therefore, the energy balance at the soil-snow interface can be expressed as

$$Q_s + Q_{sn} + I_0 = 0 \quad (1)$$

where Q_s(Wm^{-2}) represent the heat flux coming from sub-surface soil layer, Q_{sn}(Wm^{-2}) denote the heat flux within the basal layer of snowpack, and, I_0(Wm^{-2}) indicate the amount of solar radiation absorbed at the interface.

Due to the relatively small pore sizes compared to the overall volume of the soil structure, heat conduction is considered to be the dominant heat transfer mechanism within the soil.

As a result of sufficient height for the accumulated snow, the snowpack basal layer and a layer above are no longer exposed to a significant temperature gradient. Consequently, the rate of metamorphism becomes relatively slow, and the local impact of released latent heat can be disregarded. This is due to the presence of a highly conductive ice network that connects the ice volume enabling rapid heat conduction away from the layer. Furthermore, under a sufficient depth of snow cover, solar radiation at the soil-snow interface becomes insignificant.

The energy balance at the soil-snow interface when the snow reaches a sufficient height, can be depicted as follows:

$$k_s \frac{T_{1S}-T_0}{h_s} = k_{sn} \frac{T_{1Sn}-T_0}{h_{sn}} \quad (2)$$

where $k_{s/sn}$ (Wm^{-1}K^{-1}) denotes the thermal conductivity of soil/snow, $h_{s/sn}$ (m) represents the thickness of the respective soil/snow layer, T_{1S} (ºC) signifies the soil sub-surface temperature at the depth of h_s, T_0(ºC) indicates the soil-snow interface temperature, and T_{1Sn} (ºC) represents the temperature of the snow layer above the interface at the height of h_{sn}. Figure 5 provides a comprehensive view of the heat transfer mechanisms within the soil/snow layer.

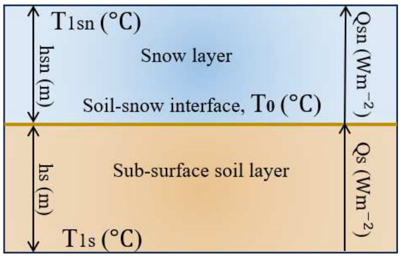

Figure 5. Heat transfer within the soil/snow layer.

3.3 Thermal conductivity of basal depth hoar layer

During the final eight days of February for the two consecutive winter seasons in ES1 and ES2, the measured temperature close to the soil-snow interface does not change very much, as shown in Figure 6(b) and (d), as well as Figure 7(b) and (d).

The heat flow from the soil to the snowpack at the interface was evaluated at both research sites by analyzing the temperature measurements and the thermal conductivity of the soil. Using Eq.(2), the thermal conductivity of the snowpack basal layer situated above the soil-snow interface was estimated, relying on the recorded temperature data. The computed thermal conductivity illustrated in Figure 6(a) and Figure 7(a) indicating that the snowpack basal layer at ES2 exhibits higher thermal conductivity.

In Section 2.1, it is evident that the soil moisture at ES2 is lower than that at ES1. This lower moisture content has led to a faster freezing of the active soil layer, resulting in a reduced temperature gradient with the atmosphere. Consequently, the rate of metamorphism in the snowpack basal layer has been affected. Figure 3(c) and Figure 4(c) illustrate this phenomenon, showing that, at the beginning of the measurement period, the temperature difference between the measured temperatures is more pronounced at ES1 than at ES2.

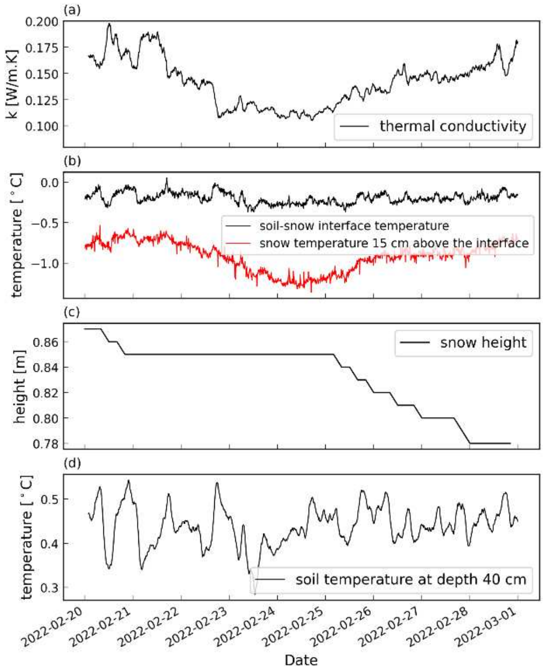

Figure 6. ES1, a) calculated thermal conductivity of snow layer above the soil-snow interface b) soil-snow interface temperature and snow temperature at 15 cm above the interface c) snow height d) soil sub-surface temperature at a depth of 40 cm.

In the ES1 area, the wind speed mostly remained below 4 (ms^{-1}), see Figure 3(a). In contrast, ES2 experiences higher wind speed up to 6 (ms^{-1}), as illustrated in Figure 4(a). The lower wind speed at ES1 compared to ES2 is expected to result in increased porosity and decreased density in the basal layer. Additionally, at ES2 the snowpack consists of a combination of naturally accumulated snow and plowed snow from the adjacent road, leading to a more compacted snowpack with reduced porosity and increased density in the basal layer.

The examination of the estimated thermal conductivity within the basal layer of the ES2 snowpack indicates that a depth hoar layer has not formed at the base of the snowpack. This is attributed to the fact that the thermal conductivity of this layer falls outside the typical range associated with depth hoar formation. This absence significantly affects the thermal regime of the ground, resulting in a diminished insulating effect, as summarized in Table 1.

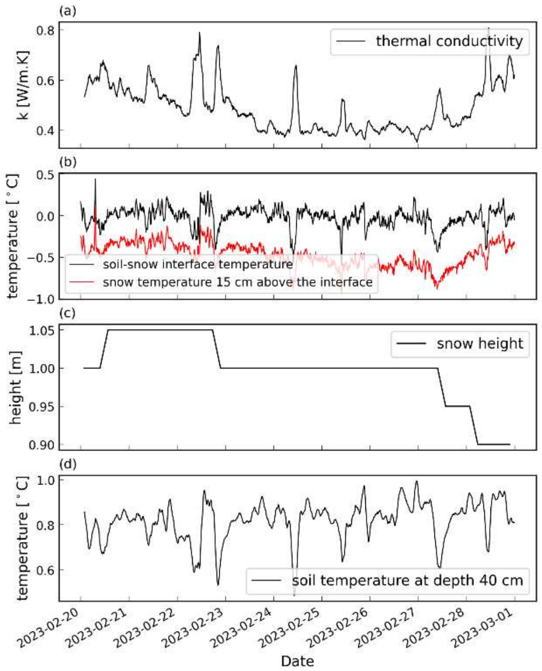

Figure 7. ES2, a) calculated thermal conductivity of snow layer above the soil-snow interface b) soil-snow interface temperature and snow temperature at 15 cm above the interface c) snow height d) soil sub-surface temperature at a depth of 40 cm.

4 CONCLUDING REMARKS

The present study underscores the vital role of snow metamorphism in shaping the structure of the layers of the snow cover. This metamorphic process, influenced by factors such as snow deposition history, meteorological conditions, and soil moisture content, results in alterations of the thermal properties of snow, particularly its thermal conductivity. Consequently, the varying thermal conductivity of different types of snow cover leads to diverse heat transfer effects on the thermal regime of the ground. However, accurately measuring snow thermal conductivity poses challenges due to the variability in snow properties across different spatial and environmental conditions. Consequently, physical models of snow struggle to adequately simulate snow properties and in particular thermal conductivity.

These findings hold implications for various maintenance sectors, for instance road maintenance, in planning both cost-effective and environmentally friendly operations. Nevertheless, it is essential to recognize that the existing body of research on the influence of different types of seasonal snow cover on seasonally frozen ground remains limited.

ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by the Swedish Transport Administration (Trafikverket) within the research program “Make Way for the Future” (Bana Väg För Framtiden – BVFF).

REFERENCES

Benson, C., & Sturm, M. (1993). Structure and wind transport of seasonal snow on the Arctic slope of Alaska. *Annals of Glaciology*, 18, 261-267. https://doi.org/10.3189/S0260305500011629.

Davesne, G., Domine, F., & Fortier, D. (2022). Effects of meteorology and soil moisture on the spatio-temporal evolution of the depth hoar layer in the polar desert snowpack. *Journal of Glaciology*, 68(269), 457-472. https://doi.org/10.1017/jog.202021.105.

Domine, F., Barrere, M., & Sarrazin, D. (2016). Seasonal evolution of the effective thermal conductivity of the snow and the soil in high Arctic herb tundra at Bylot Island, Canada. *The Cryosphere*, 10(6), 2573-2588. https://doi.org/10.520194/tc-10-2573-2016.

Domine, F., Belke-Brea, M., Sarrazin, D., Arnaud, L., Barrere, M., & Poirier, M. (2018). Soil moisture, wind speed and depth hoar formation in the Arctic snowpack. *Journal of Glaciology*, 64(248), 990-1002. https://doi.org/10.1017/jog.2018.89.

Lufft Mess und Regeltechnik GmbH. (2019, 09 23). Manual weather station WS10. Retrieved 05 23, 2023, from : www.lufft.com/fileadmin/lufft.com/ 07_downloads/1_manuals/Manual_WS_10_EN_V1-5_01.pdf.

Marbouty, D. (1980). An experimental study of temperature-gradient metamorphism. *Journal of Glaciology*, 26(94), 303-312. https://doi.org/10.31 89/S0022143000010844.

Sokratov, S. A., & Barry, R. G. (2002). Intraseasonal variation in the thermoinsulation effect of snow cover on soil temperatures and energy balance. *Journal of geophysical research*, 107(D10), ACL-13. https://doi.org/10.1029/2001JD000489.

Sturm, M., & Benson, C. (1997). Vapor transport, grain growth and depth-hoar development in the subarctic snow. *Journal of Glaciology*, 43(143), 42-59. doi.org/10.3189/S0022143000002793.

Sturm, M., Perovich, D. K., & Holmgren, J. (2002). Thermal conductivity and heat transfer through the snow on the ice of the Beaufort Sea. *Journal of Geophysical Research: Oceans*, 107(C10), SHE-19. https://doi.org/10.1029/2000JC000409.

Zhang, T. (2005). Influence of the seasonal snow cover on the ground thermal regime: An overview. *Reviews of Geophysics*, 43(4). https://doi.org/2010.1029/2004RG000157.