Vegetation and snow effects on soil-atmosphere heat exchange: 2024/25 winter study

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Abstract. The paper aimed to understand soil-atmosphere heat exchange influenced by vegetation and snow cover. An observational system was implemented to monitor ground, snow, and near-surface air temperatures beginning in the 2024/25 winter season. The onset of snow cover in Moscow was on November 23-25, 2024, occurring 10 days later than the 1991-2000 average. By December 8, significant snowfall increased snow depth to 14 cm, with variations across Moscow and its regions. Observations revealed a complex snow layer structure and temperature profiles throughout December. January 2025 was marked by intermittent thaws, leading to snow cover disappearance, with January temperatures approximately 6°C above normal. The snow cover re-onset took place only in the middle of February, which was the coldest month of this winter period. The study highlights the impact of vegetation and snow on soil temperature dynamics and surface soil frost events were recorded.

1 Introduction

The Earth is undergoing climate warming (IPCC), with new temperature records being set annually, and 2024 was no exception. Warming is particularly pronounced in the Arctic, where the extent of sea ice cover is declining (NSIDC), glacier retreat and permafrost is thawing [1-17]. Investigating the influence of vegetation and snow cover on soil-atmosphere heat exchange is a critical task for understanding the specifics of atmospheric heat transfer, as well as the processes of ground freezing and thawing during winter and summer periods. To this end, the authors implemented an observation system to monitor ground, snow, and near-surface air temperatures at the Moscow State University Meteorological Observatory site. Using this system, observations were conducted to study the characteristics of soil-atmosphere heat exchange under conditions of presence or absence of snow and vegetation cover in Moscow at the 2024/25 winter season.

2 Materials and methods

For the purposes of this research, monitoring boreholes were drilled at the Moscow State University Meteorological Observatory site in areas with and without surface cover.

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Additionally, thermal sensors were installed on the soil surface and vertically within the snow column and near-surface air at 5 cm intervals in height (Figure 1).

Fig. 1. Observing system for ground, snow and near-Earth air temperature at the MSU meteorological observatory site.

Snow cover in the winter of 2024-25 in Moscow was established on November 23-24-25, and in Moscow and the Moscow Region the average daily temperature crossed 0°C towards negative values. Thus, it was possible to state the beginning of climatic winter. In 2024, this occurred 10 days later than the 1991-2000 norm. However, by the beginning of the calendar winter (December 1, 2024) in Moscow it warmed up to 0°C again, and the snow in Moscow melted. On the night of December 5, 2024, it again froze to -6°C and snowed a little, and on December 8 and 9, 2024, snow began to fall intensively in Moscow.

On the morning of December 8, 2024, the VDNKh meteorological station in Moscow recorded a snow depth of 10 cm. By the morning of December 9, the highest snow accumulation was observed in the northern Moscow region, with Klin and Dmitrov each reporting 30 cm of snow. In the eastern part of the Moscow region, snow accumulation was minimal, ranging from 2 to 5 cm, while Serpukhov recorded only 1 cm. In Moscow, the snow depth at the VDNKh meteorological station reached 14 cm, twice the normal level for this period. Subsequent snowfalls further increased the snow depth, and by the morning of December 12, the snow depth at VDNKh in Moscow had reached 19 cm. During the investigations on December 12, four distinct snow layers and a crust were identified within the snow column at the meteorological site. The results of the snow cover analysis at the Moscow State University Meteorological Observatory on December 12, 2024, are presented in Figure 2 and Table 1:

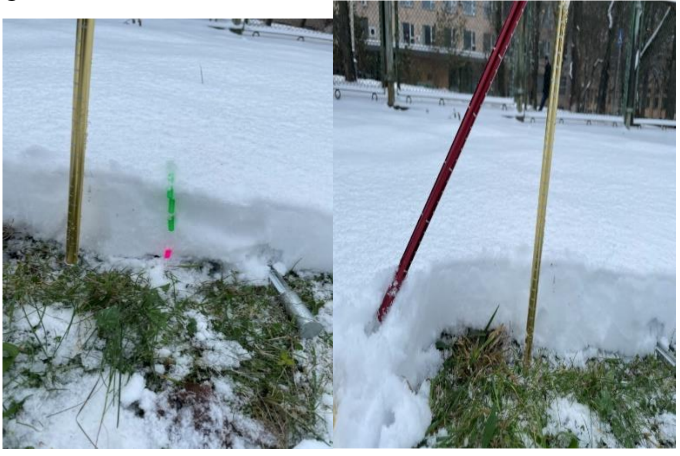

Fig. 2. Structure of the snow layer on 12.12.2024 at the meteorological site of MSU.

Table 1. Structure of the snow column at the MSU weather observatory site on December 12, 2024.

	Layer, cm	
1	9-10	A layer of fresh snow
2	8-9	Ice crust
3	6-8	Layer of loosened frozen fine and medium-grained snow with grain size up to 1 mm density together with underlying snow (207, 258, 227 cf. density 230 kg/m^3)
4	2-6	Layer of denser compacted fine-grained snow with grain size up to 1 mm density together with underlying snow (198, 204, 181 cf. density 194 kg/m^3)
5	0-2	Layer of surface loosened medium-grained snow with grain size up to 2 mm

The temperature at the time of research on December 12 in the snow column was: at the bottom (0 cm) -0°C, at the level of 10 cm (surface) -2.4°C.

Subsequent light snowfalls and frost events occurred, resulting in a snow depth of 17 cm at the VDNKh meteorological station in Moscow by the morning of December 19. During the investigations on December 19, the snow depth at the meteorological site was 21 cm, with four distinct snow layers and a crust identified within the snow column. The results of the snow cover analysis at the Moscow State University Meteorological Observatory on December 19, 2024, are presented in Figure 3 and Table 2:

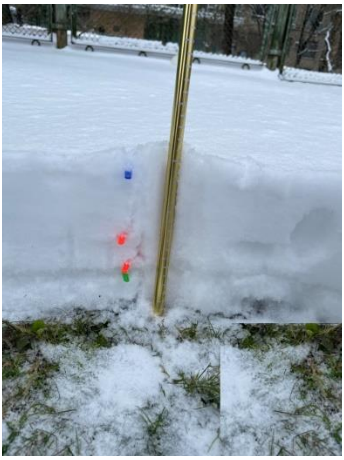

Fig. 3. Structure of the snow layer on 19.12.2024 at the meteorological site of MSU.

Table 2. Structure of the snow layer at the site of the MSU meteorological observatory on December 19, 2024.

	Layer, cm	
1	20-21	A layer of fresh snow
2	13-20	"Soft slab" – a layer of settled, non-granular, unprocessed snow (fist penetrates throughout) (152, 129, 130; average density 137 kg/m³).
3	10-13	Layer of fine-grained snow (170, 165, 173; mean density 170 kg/m³).
4	9-10	Ice crust
5	0-9	Layer of medium-grained snow with grain size up to 2 mm. This layer lacks faceting and depth hoar. It incorporates all layers from the previous

		measurement. (210, 235, 260; mean density 235 kg/m³).

During the investigations on December 19, the temperature within the snow column was recorded as follows: at the base (0 cm), -2.1°C; at 10 cm depth, -6.4°C; and at 21 cm depth (surface), -8.8°C. The air temperature was -9.0°C.

The following week saw thaws and rainfall, which caused the snowpack to become saturated and compacted. A light snowfall also occurred. By the morning of December 26, the snow depth at the VDNKh meteorological station in Moscow was 11 cm. During the investigations on December 26, the snow depth at the meteorological site was 11 cm, with one primary layer identified in the snowpack and a small amount of freshly fallen snow on top. The results of the snow cover analysis at the Moscow State University Meteorological Observatory on December 26, 2024, are presented in Figure 4 and Table 3.

Fig. 4. Structure of the snow layer 26.12.2024 at the meteorological site of MSU.

Table 3. Structure of the snow layer at the site of the MSU weather observatory on December 26, 2024.

	Layer, cm	
1	10-11	A layer of fresh snow
2	0-10	Layer of compacted icy snow with aggregates and ice grains (penetrable by one finger) (272, 330, 275; mean density 292 kg/m³).

Temperatures at the moment of research on December 26 in the snow column were: at the bottom (0 cm) 0°C, at the 11 cm level (surface) 0°C. The air temperature was 0°C.

3 Results and discussion

The snow accumulation patterns at the beginning of the winter of 2024 resembled those observed at the start of the winter of 2023, when December snowfall initially led to significant snow accumulation and the development of processes within the snowpack. However, by the New Year, nearly all the snow had melted due to rain and thaw events.

The beginning of 2025 in Moscow was characterized by light snowfall and intermittent thaws, followed by the complete disappearance of the snow cover (Figure 5). This phenomenon was not uncommon, as historical data from the VDNKh meteorological station indicate that Moscow experienced snow-free periods from January 3–20, 2007;

January 11, 2014; January 1–4, 2018; and January 5, 17–22, 2020. The average monthly temperature in January 2025 was approximately 0°C, about 6°C above the norm. Daytime temperatures reached 7°C on January 30, 2025, setting new records, with earlier record highs also recorded on January 27, 28, and 29, 2025 (5.6°C, 5.4°C, and 5.1°C, respectively). However, the snows cover in Moscow re-onset by February 15–16, 2025 since February 2025 turned out to be only a little warmer than usual in terms of temperature, with significantly less than normal precipitation. According to the observations of the VDNKh weather station, the average monthly air temperature was -4.8°C, which is only 1.1°C higher than normal. February was also the coldest month of the 2024/25 winter.

Fig. 5. The disappearance of the snow cover in Moscow in January 2025 (photo taken on January 30, 2025).

To investigate the influence of vegetation and snow cover on soil-atmosphere heat exchange in Moscow during the early winter of 2024/25, a temperature monitoring system was installed at the Moscow State University Meteorological Observatory site. The system consists of a vertical probe equipped with 20 sensors spaced at 5 cm intervals and a horizontally laid, partially buried thermocouple array on the soil surface. Observation data from the system were recorded twice daily and stored in logger memory. Changes in temperature, precipitation, snow depth, and the results of soil surface and near-ground air temperature observations were processed and are presented in Figure 6.

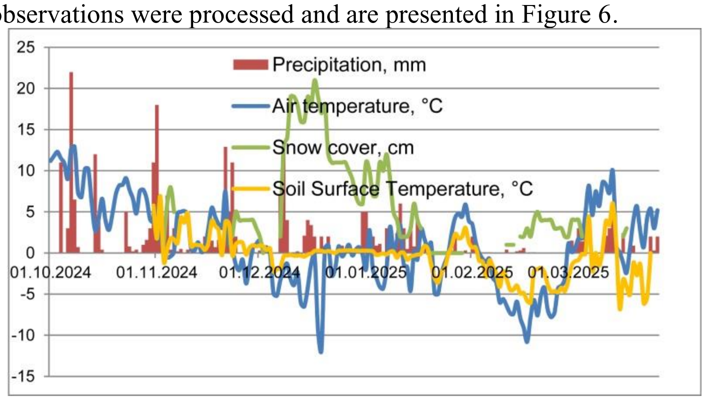

Fig. 6. Change in temperature, precipitation, snow cover thickness and soil surface temperature in Moscow in winter season of 2024/25.

4 Conclusions

The graph (Figure 6) demonstrates that, during cooling events when air temperatures dropped below freezing, the soil did not cool sufficiently. However, on November 3, 2024, frost occurred on the soil surface in Moscow, and by November 4, snow fell on slightly frozen ground. Additional soil frost events were recorded on November 19, 22, 26, and December 4. The essential soil freezing was in February, when the most cold wether was dominant.

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