geosciences

MDPI

Article

Snowpatch Influence on Rock Weathering in the Goltsy Altitudinal Belt of South Yakutia, Russia

Andrey Melnikov [1,*], Ze Zhang [2], Tatiana Romanis [1], Leonid Gagarin [1] and Viktor Rochev [3]

[1] Melnikov Permafrost Institute, Siberian Branch, Russian Academy of Science, 677010 Yakutsk, Russia; romanis.tatyana@yandex.ru (T.R.); gagarinleo@yandex.ru (L.G.)
[2] College of Civil Engineering and Transportation, China-Russia Joint Laboratory for Cold Regions Engineering & Environment, Northeast Forestry University, Harbin 150040, China; zez@nefu.edu.cn
[3] Technical Institute (Branch), M. K. Ammosov North-Eastern Federal University, 678960 Neryungri, Russia; viktor-rochev74@mail.ru
* Correspondence: melnikowdron@mail.ru

Abstract

This research was conducted on mountain summits in South Yakutia, Russia. The findings indicate that within the *goltsy* altitudinal belt (comparable to the alpine zone), the weathering intensity of rocks above 1400 m depends on the development of snow-ice formations, particularly snowpatches. Snowpatches promote physical rock weathering along their edges by up to 1.5–4 times more intensely compared to baseline levels. The ground temperature at the edges was examined in relation to air temperatures. The conditions that facilitate rock weathering at the snowpatch edge during the summer months are characterized by diurnal air temperatures below 10–15 °C, with minimum temperatures below 5 °C. Nivation processes in the *goltsy* altitudinal belt of South Yakutia are considered as one of the dominant geomorphic agents. However, future changes are expected in the existing nival-glacial belts, as snowpatches respond rapidly to climate change, with the mean annual air temperature in South Yakutia exhibiting a rising trend.

Keywords: South Yakutia; *goltsy* altitudinal belt; snowpatch; nivation; freeze–thaw cycles

1. Introduction

The 2024 State of the Global Climate report, presented by the World Meteorological Organization [1], identifies 2024 as the hottest year in the 175-year observational record. It is also the first year in which the global average surface temperature exceeded pre-industrial levels by 1.5 °C. Over the two decades, from 2005 to 2024, the rate of ocean warming increased by more than twofold compared to the 1960–2005 period. In addition, the Report on Climate Features in the Russian Federation for 2024 [2], delivered by the Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet), indicates that the current warming trend, which began in the 1970s, has persisted across all Russian regions annually and seasonally. The mean annual temperature increase, averaged over Russia for the period 1976–2023, reached 0.50 °C per decade.

Among the most climate-sensitive objects of natural environments are glaciers. Almost all glaciers worldwide exhibit a simultaneous mass loss at increasing rates [3–8]. Snowpatches (A snowpatch is defined as a stationary (or occasionally slow-moving) accumulation of snow and ice that persists on slopes or valley bottoms through part or entire warm season after the surrounding snow cover has melted.), whether associated with glaciers or occurring independently, have also been identified as indicators of

Check for updates

Academic Editor: Danilo Godone

Received: 7 May 2026
Revised: 8 June 2026
Accepted: 9 June 2026
Published: 15 June 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

climate change. Furthermore, some researchers posit that snowpatches represent a transitional stage between seasonal snow cover and glacier formation, serving as unique precursors of the latter [9–11]. Furthermore, snowpatches actively shape topography; their persistence directly governs the intensity of nivation processes and landscape modifications, e.g., [11–16].

The geomorphic role of snowpatches was first systematically examined in the late 19th and early 20th centuries in the works of I.P. Tolmachev and F. Matthes. The process of slope landform development due to rock weathering and subsequent erosion at the edges of snowpatches was termed nivation [17,18]. While the fundamental definition of this process remains unchanged, recent research has revealed that nivation mechanisms are more complex than initially assumed [19,20]. It is well-established that continentality significantly influences nivation patterns and intensity [21,22]. However, questions persist regarding the variability of rock weathering rates across snowpatch-affected areas in different natural zones, requiring further empirical validation.

Dedicated instrumental monitoring of ground temperatures regimes in relation to snowpatch dynamics have not been conducted in Southern Yakutia to date. Nevertheless, data on nivation processes remain valuable for applied research, including engineering geology, geomorphic and landscape mapping, and permafrost studies.

This study presents the results of ground temperature monitoring within the influence zone of snow-ice formations in South Yakutia. The focus is on a typical snowpatch [57.5384, 125.1609] in the Western Yangi Range, which is located at an altitude of 1400 m above sea level and is underlain by permafrost. The mean annual ground temperature here reaches −6.5 °C, which is the lowest recorded temperature in South Yakutia based on long-term observations [23,24].

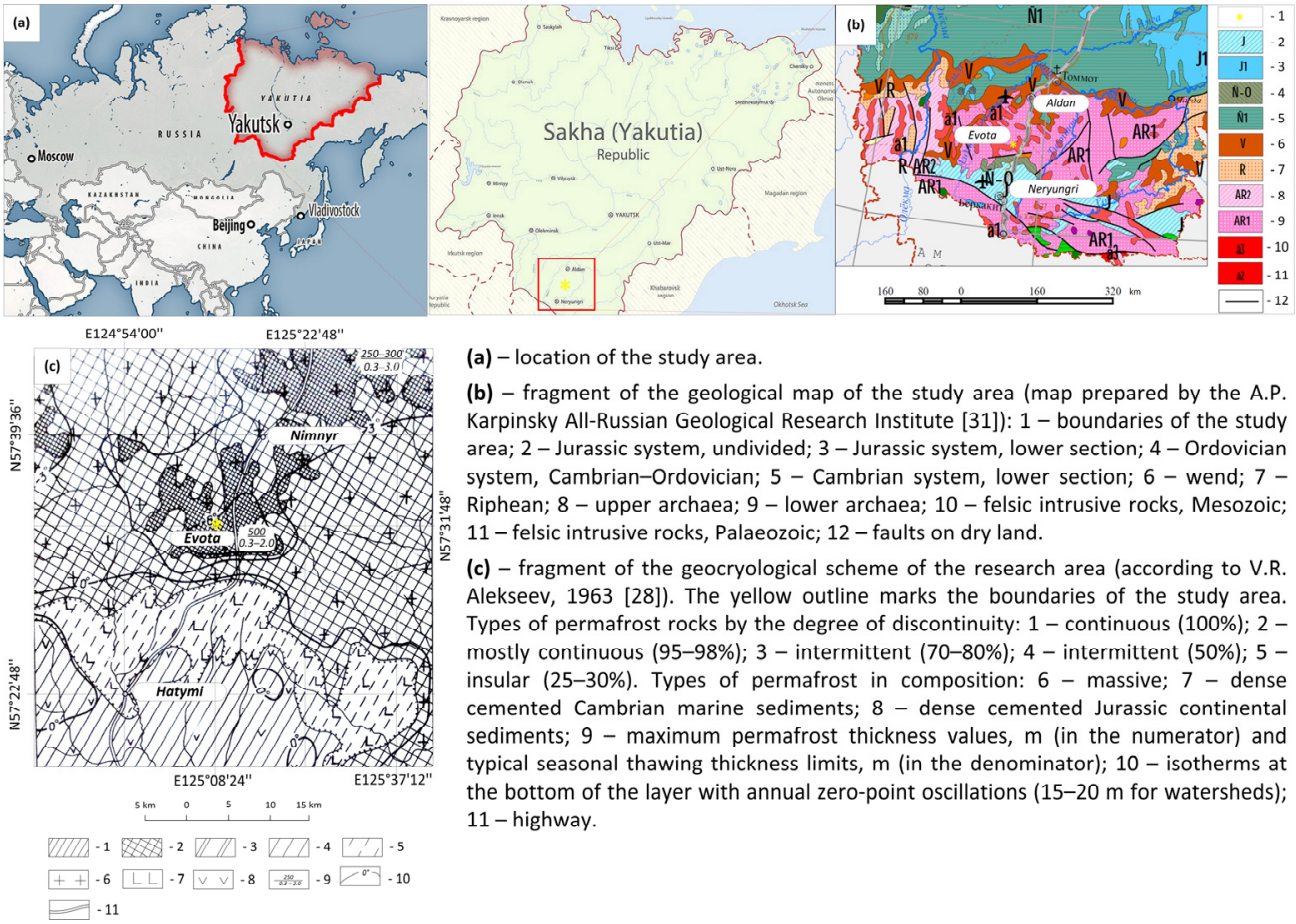
The findings of this study are expected to contribute to the understanding of the intensity of geomorphic processes, which may diminish following the disappearance of snowpatches in South Yakutia due to climate change. This finding aligns with the documented regional trend of increasing mean annual air temperatures [25–29]. For example, from 1957—approximately the start of global warming—the height of snow-ice formations (glaciers) in Yakutia had decreased by 70 percent by 2015, and their area had shrunk by nearly 40 percent [30].

2. Data and Methods

2.1. Study Area

To expand the limited observational database on microclimatic conditions of snowpatches in the *goltsy* altitudinal belt of South Yakutia, we established a monitoring site at Mount Evota, the highest point of the Western Yangi Range 1600 m a. s. l. (Figures 1 and 2). The site is underlain by exhumed post-Jurassic intrusive rocks exposed by denudation (Figure 1b).

The Western Yangi Range is characterized by severe permafrost conditions. The summer months are marked by persistent winds and humidity, with a vegetation period limited to 2–2.5 months. During the winter months, prevailing northwesterly winds remove snow cover from slopes, transporting it to valleys. The amplitude of annual air temperature exceeds 80 °C, while diurnal variations may reach 40 °C. Despite the mean snow depth remaining below 0.5 m, it shows pronounced spatial variability due to wind redistribution. Leeward slopes accumulate up to three meters of snow, with local deposits reaching 10 m. The persistent snow cover lasts from August through early June. These conditions promote deep rock freezing.



(a) – location of the study area.

(b) – fragment of the geological map of the study area (map prepared by the A.P. Karpinsky All-Russian Geological Research Institute [31]): 1 – boundaries of the study area; 2 – Jurassic system, undivided; 3 – Jurassic system, lower section; 4 – Ordovician system, Cambrian–Ordovician; 5 – Cambrian system, lower section; 6 – wend; 7 – Riphean; 8 – upper archaea; 9 – lower archaea; 10 – felsic intrusive rocks, Mesozoic; 11 – felsic intrusive rocks, Palaeozoic; 12 – faults on dry land.

(c) – fragment of the geocryological scheme of the research area (according to V.R. Alekseev, 1963 [28]). The yellow outline marks the boundaries of the study area. Types of permafrost rocks by the degree of discontinuity: 1 – continuous (100%); 2 – mostly continuous (95–98%); 3 – intermittent (70–80%); 4 – intermittent (50%); 5 – insular (25–30%). Types of permafrost in composition: 6 – massive; 7 – dense cemented Cambrian marine sediments; 8 – dense cemented Jurassic continental sediments; 9 – maximum permafrost thickness values, m (in the numerator) and typical seasonal thawing thickness limits, m (in the denominator); 10 – isotherms at the bottom of the layer with annual zero-point oscillations (15–20 m for watersheds); 11 – highway.

Figure 1. Overview map of the study area [28,31].

The permafrost thickness on Mount Evota reaches 500 m [24,28], exhibiting continuous distribution in the study area (Figure 1c). This assertion is further substantiated by the pervasive occurrence of cryogenic formations (Figure 3).

Altitudinal zonation is evident in the study area, facilitating accurate differentiation between distinct zones, such as subalpine open woodlands and Siberian dwarf pine thickets and alpine tundra. The summits of the *goltsy* groups (including Mount Evota) represent typical alpine tundra landscapes. The harsh climate affects soil formation, contributing to the formation of a contrasting soil cover structure, with complexes of stone polygons playing a leading role and with a significant distribution of Arctic saturated poorly developed soils and tundra soils.

Consequently, the monitoring site is situated in the altitudinal zone where the weathering of rock materials, their transport, and deposition are influenced by permafrost dynamics under unique thermal-moisture conditions.

2.2. Observation Management at the Monitoring Site

The snowpatch, which extends from southwest to northeast, partially persists at the monitoring site through the summer months until the subsequent winter season (Figure 4). According to the classification proposed in [32], it can be classified as a semi-perennial snowpatch—persisting for 2–8 years over a ten-year period. The length of the perennially frozen portion exhibits annual variation, reaching 400 m, with a width ranging from 30 to 70 m and a snow-ice mass thickness of 1.6 m. Since 2020, ground temperature monitoring has been carried out beneath the snowpatch and on adjacent areas without snow (Figure 5b). Temperature measurements are performed using HOBO Pro v2 data loggers [33], which

record at one-hour intervals (Figure 5c). Concurrently, the air temperature is monitored at a height of two meters above ground level (observation station No. 2).

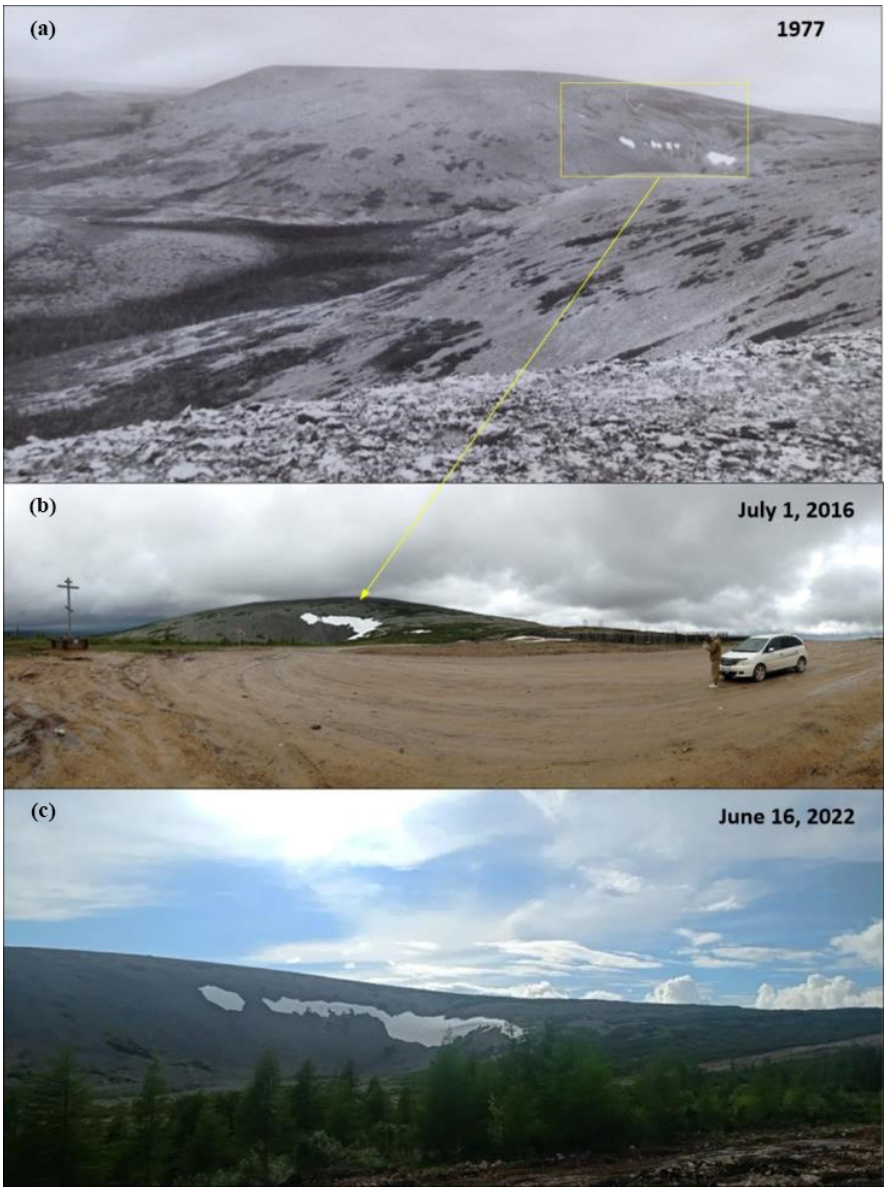


Figure 2. Mount Evota in the Western Yangi Range, South Yakutia [57.5384, 125.1609]: (**a**) photo by N.I. Novikov [34]; (**b,c**) photo by the authors.

For the selection of observation sites for ground temperature monitoring (Figure 5b), the following considerations are essential. An important component of assessing weathering intensity is the determination of the zone where a snowpatch influences the adjacent soils. In general, ground exhibits several states, each with varying degrees of weathering [35]. For a part of the year, the ground remains covered by a snowpatch. Upon snowmelt, the ground is exposed, and intense rock weathering commences. As the snowpatch undergoes further melting, the ground moves progressively away from its edges, eventually exiting the zone of influence. Therefore, it is crucial to determine the boundaries of annual snowpatch formation and the direction of its melting. At the observation station, this condition was addressed by interpreting and processing multi-temporal satellite imagery (2016–2023) and aerial photographs acquired using unmanned aerial vehicles (UAVs, 2020–2023). Vertical takeoff and landing (VTOL) UAVs Geoscan-401 [36] were

employed (Figure 5d). The same system was used to estimate mean snowpatch thickness by comparing aerial photographs taken on different dates.

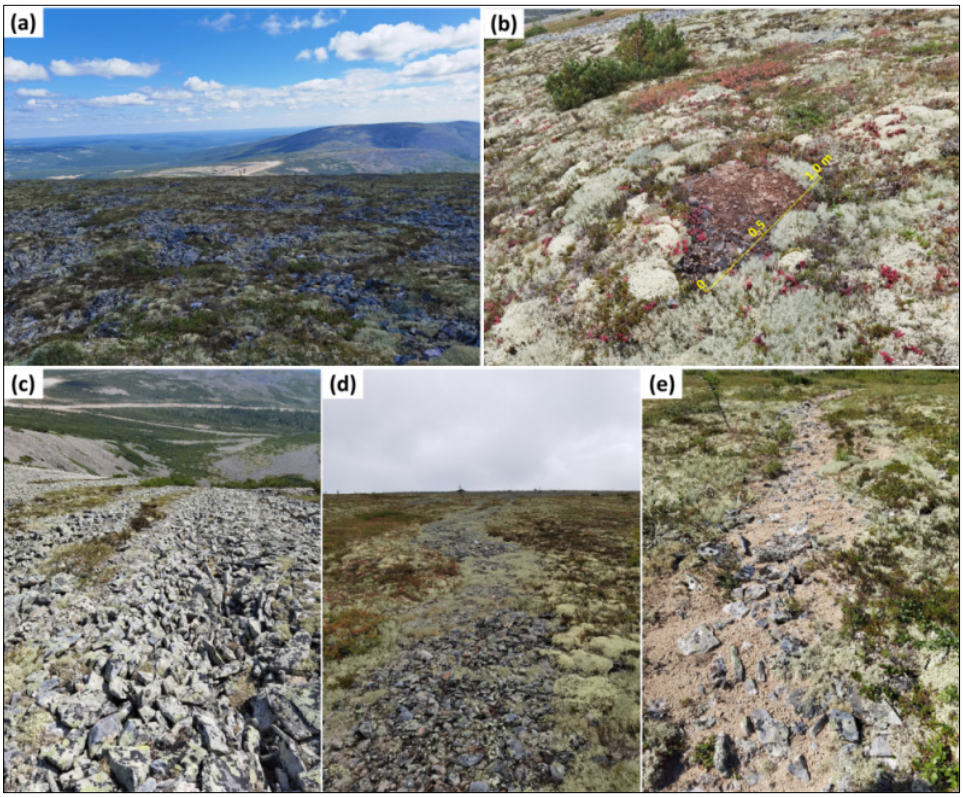


Figure 3. Cryogenic land surface processes on Mount Evota: (**a**) Stone polygons formed through frost sorting of debris in the active layer [57.5323, 125.1404]; (**b**) Frost boils resulting from small-scale polygonal cracking during uneven freezing from top and sides of enclosed volumes of thawed ground in the seasonally thawed layer [57.5323, 125.1404]; (**c**) Stone stripes [57.5357, 125.1600]; (**d**,**e**) Solifluction of soil [57.5420, 125.1618].

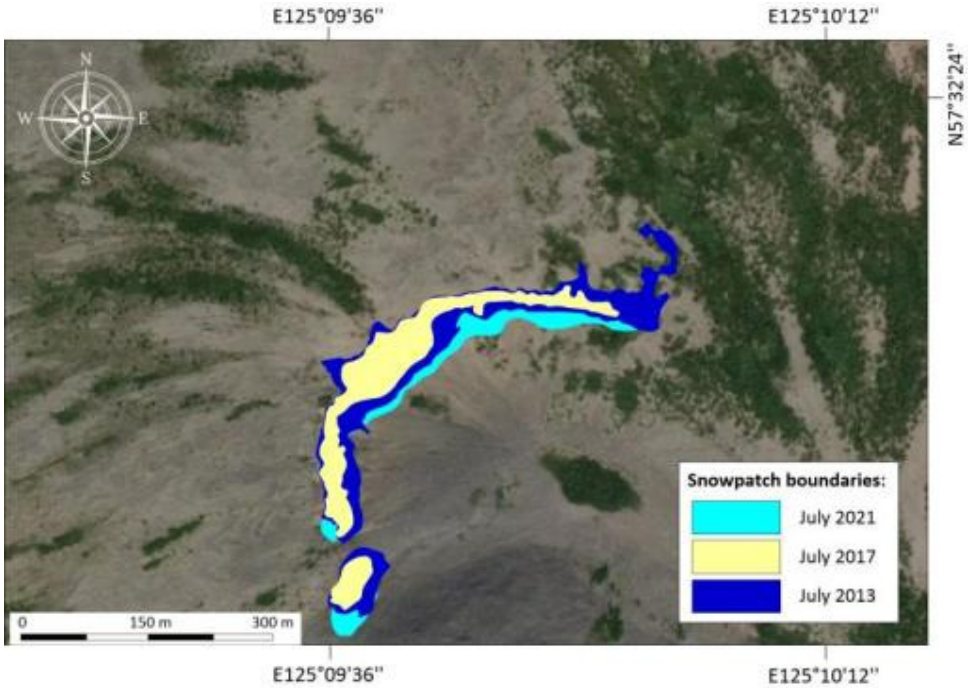


Figure 4. Snowpatch boundaries in different years.

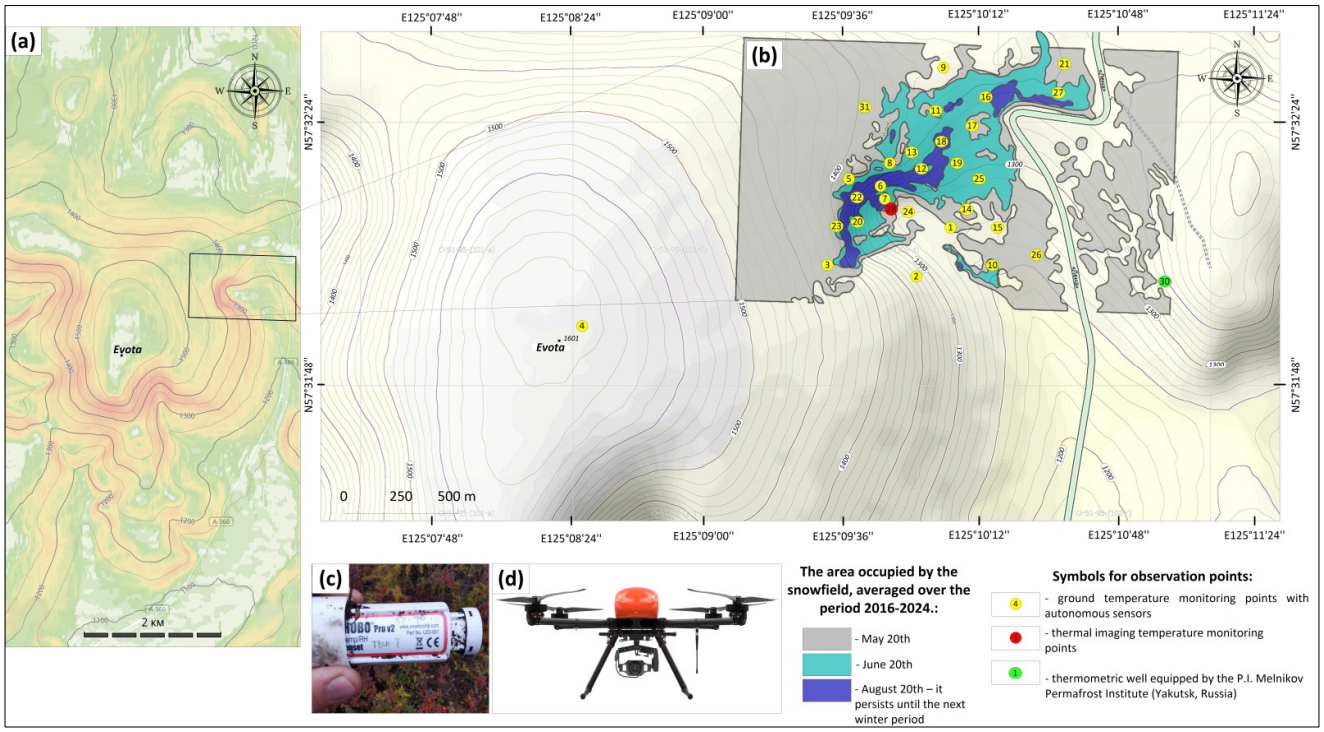


Figure 5. Observation stations located on monitoring site: (**a**) Observation station on Mount Evota; (**b**) Temperature observation stations on the ground surfaces; (**c**) HOBO Pro v2 data temperature logger; (**d**) Vertical take-off and landing (VTOL) aircraft GeoScan-401.

To determine the ground surface temperatures located within two meters from the edge of a snowpatch, we carried out hourly thermal imaging on select days at observation station No. 28.

3. Results

Observation data indicate that the mean annual ground temperature beyond the snowpatch reaches −8 °C (Figure 6a, Table 1). As one approaches the snowpatch, particularly its perennial portion with an average thickness of the snow-ice cover of 1.6 m, the temperature increases, ranging from 0 to −2.4 °C beneath the snowpatch. In contrast, the mean annual air temperature at the monitoring site was −12.6 °C. A significant discrepancy was observed in the cooling patterns between slope sections above and below the snowpatch. Temperature fluctuations were less pronounced on the lower slope.

Table 1. Number of freeze–thaw cycles and ground surface temperature beneath the snowpatch and adjacent area at the monitoring site (averaged mean values for the period 2020–2023) *.

Location of Observation Point	Observation Point Code	T_{AVG}, °C	NFTC
[57.5375, 125.1683]	1	−6.73	40
[57.5354, 125.1663]	2	−4.89	48
[57.5357, 125.1600]	3	−3.48	32
[57.5323, 125.1404]	4	−5.81	44
[57.5391, 125.1611]	5	−1.17	64
[57.5391, 125.1633]	6	−1.01	93
[57.5384, 125.1635]	7	−5.97	164
[57.5398, 125.1640]	8	−2.88	76
[57.5438, 125.1671]	9	−5.67	49

Table 1. *Cont.*

Location of Observation Point	Observation Point Code	T_{AVG}, °C	NFTC
[57.5360, 125.1714]	10	−4.01	69
[57.5421, 125.1667]	11	−3.55	73
[57.5397, 125.1660]	12	−3.18	120
[57.5403, 125.1653]	13	−4.13	69
[57.5382, 125.1694]	14	−3.90	55
[57.5376, 125.1716]	15	−5.97	62
[57.5428, 125.1701]	16	−1.98	73
[57.5416, 125.1694]	17	−2.03	70
[57.5409, 125.1673]	18	−0.99	91
[57.5400, 125.1685]	19	−2.33	83
[57.5375, 125.1619]	20	−4.05	111
[57.5442, 125.1753]	21	−6.06	39
[57.5384, 125.1618]	22	−1.55	26
[57.5372, 125.1605]	23	−2.94	75
[57.5380, 125.1653]	24	−5.02	66
[57.5395, 125.1701]	25	−4.51	59
[57.5366, 125.1744]	26	−5.62	67
[57.5431, 125.1750]	27	−3.09	70
[57.5420, 125.1618]	31	−7.05	42

* T_{AVG}—average annual temperature value; NFTC—annual number of freeze–thaw cycles (based on hourly measurements), it is calculated for each observation point based on the number of times per year the ground surface temperature crosses the 0 °C threshold.

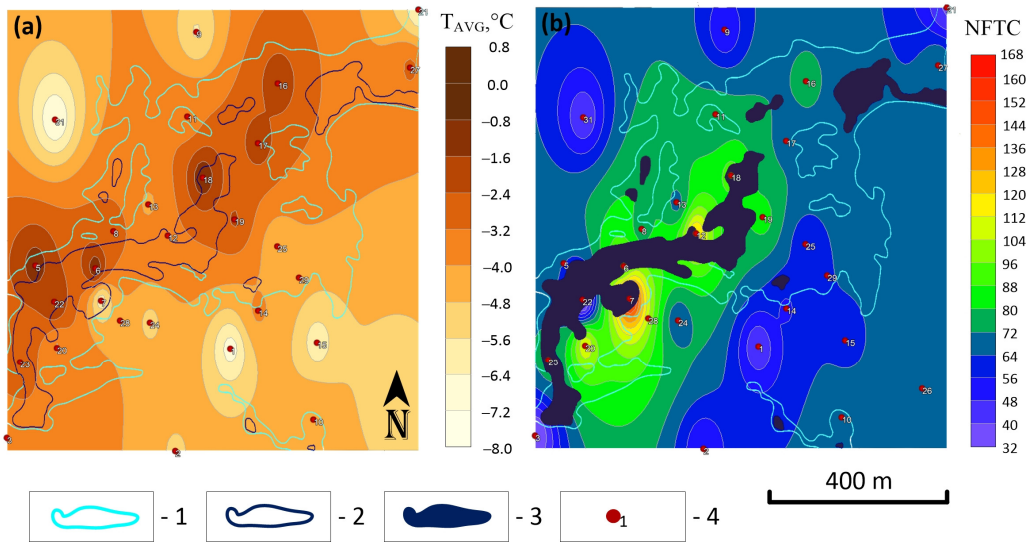


Figure 6. Distribution of temperature and NFTCs on the ground surface of the monitoring site (averaged mean values for the period 2020–2023). The schemes were constructed using the Inverse Distance to a Power method [37–39]. (**a**) Average annual surface temperature T_{AVG}; (**b**) Number of freezing–thawing cycles (NFTC) on the ground surface per year. The average snowpatch area over the period 2016–2023: 1—Snowpatch area on 20 June; 2, 3—Perennial snowpatch areas remaining until the subsequent winter season; 4—Temperature observation points.

The annual number of freeze–thaw cycles (NFTC) is a pivotal factor in the process of rock disintegration during frost weathering [40]. Near snowpatch edges, the annual NFTC was 1.5 to 4 times higher than that in other areas (Figure 6b, Table 1). For instance, observation station No. 7, located within 30 m from the snowpatch edge throughout the observation period, recorded 164 NFTC. In contrast, observation station No. 24, located 160 m away, exhibited only 66 cycles.

Sensors located in snowpatch zones characterized by slower thaw rates recorded higher number of FTCs.

The maximum number of freeze–thaw cycles occur on the surface in May and June, as well as in September and October (Table 2). Notably, the average monthly temperature at the monitoring site remained positive from May to September during the observation period.

Table 2. Number of freeze–thaw cycles on the ground surface per month for individual observation station and average monthly air temperature at the monitoring site (averaged over the period 2020–2023) *.

Month	Observation Point Code						T_m, °C
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 7	
January	0	0	0	0	0	0	–29.3
February	0	0	0	0	0	0	–26.2
March	0	0	0	0	0	0	–17.1
April	0	2	0	0	0	0	–8.9
May	3	23	1	0	3	2	1.2
June	20	0	0	9	19	125	12.7
July	0	0	0	0	0	0	16.6
August	6	2	0	10	4	0	10.6
September	11	13	21	25	19	8	4.3
October	0	8	10	0	19	29	–7.8
November	0	0	0	0	0	0	–19.4
December	0	0	0	0	0	0	–30.2
Total	40	48	32	44	64	164	–29.3

* T_m—average monthly temperature.

The climatic conditions favorable for rock weathering near the snowpatch were observed during the summer season. These included air temperatures of less than 10–15 °C during the day and the minimum values below 5 °C, which are facilitated by night cooling. For instance, on 3 June 2021, at observation station No. 8, located approximately 30 cm from the snowline with a snow cover thickness of 1.1–1.2 m, six freeze–thaw cycles were documented (Figure 7). During this period, the air temperature was below 12 °C during the day. However, on 5 June 2021, the air temperature exceeded 20 °C, with only two freeze–thaw cycles recorded.

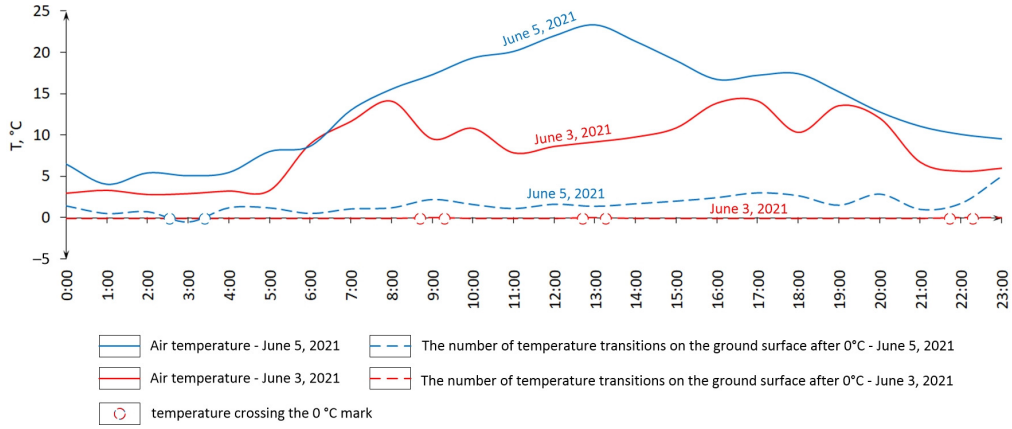


Figure 7. Correlation between diurnal air temperature (observation station No. 2) and NFTC on the ground surface near the snowpatch edge (observation station No. 8).

The thermal imaging data from observation station No. 28 indicate that the most pronounced temperature variations on the ground surface during summer occur at a distance of at least 0.3–0.5 m from the snowpatch edge. These variations can reach several degrees

compared to temperatures directly at the edge. In contrast, ground surface temperatures within 10 cm of the snowpatch edge (with a snow thickness of 1.15 m) exhibit only minor diurnal fluctuations during summer (Figure 8). Interestingly, earlier research on snowpatches in the *goltsy* regions of the Baikal and North Transbaikal areas [41] reported different findings. For these mountain zones, temperature changes at 1–10 cm from the snowpatch edges amounted to mere tenths of a degree per centimeter, while at 100–1000 cm, variations were on the order of thousandths of a degree.

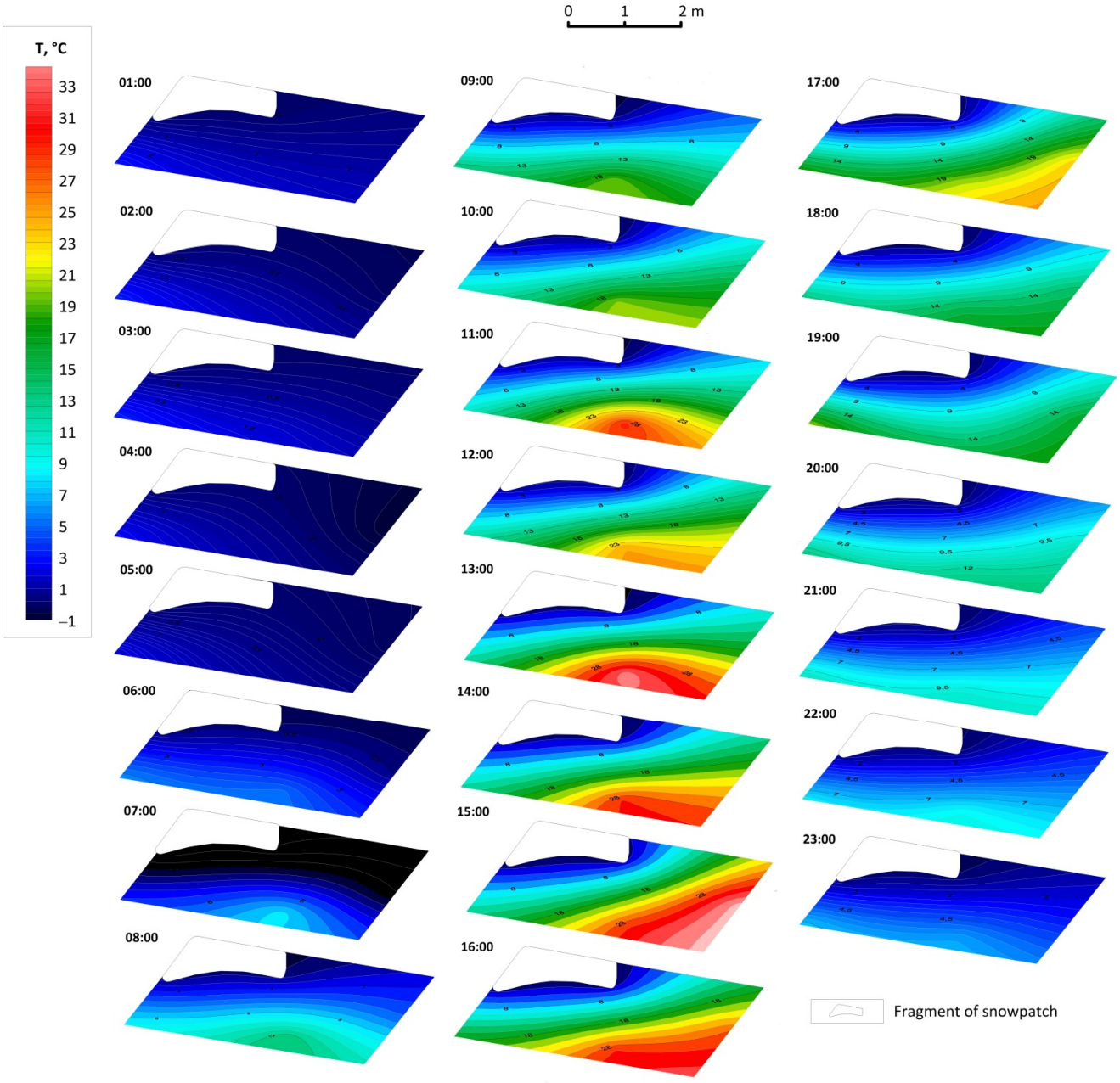


Figure 8. Diurnal variations in ground surface temperature at a snowpatch edge—thermal imaging results from observation station No. 28 on 6 June 2021 (snow depth of 1.15 m).

4. Discussion

Observations on Severnaya Zemlya (an archipelago in the Russian high Arctic) over 71 days (22 June–31 August) documented 120–140 freeze–thaw cycles in the ground at the edges of two snowpatches [42]. In contrast, areas beyond the immediate influence of the snowpatches exhibited a substantially lower number of cycles (70–80). Similarly,

data obtained by V. Vyrkin [41] from the Baikal and Transbaikal regions demonstrated that 50 freeze–thaw cycles occurred at the ground surface in the zones adjacent to snowpatches over 106 days, in contrast to a mere 15 FTC in areas without a snowpatch. These findings suggest that the intensity of cryogenic weathering in the vicinity of these formations was 3–3.5 times higher than the background level. In our study in South Yakutia, snowpatches intensified rock weathering at their edges by a factor of 1.5–4 relative to distal sites.

These and other field observations suggest that the *goltsy* altitudinal belt can be identified as a zone characterized by maximal nivation intensity, where snowpatches influence the environment. However, in such landscapes, the relationship between ground temperature at snowpatch edges and air temperatures, along with other climatic parameters, becomes complex, being mediated by the cold content in snow-ice formations. Large snowpatches, which typically retain substantial cold content, exhibit ground surface freeze–thaw cycles at comparatively higher summer air temperatures relative to the *goltsy* region and at greater distances from their edges than smaller snowpatches. When a snowpatch edge retreats slowly, the adjacent ground surface is subjected to more freeze–thaw cycles than during rapid retreats. The retreat rates are inversely proportional to snowpack depth. Consequently, the climate-dependent weathering intensity near snowpatches underscores their differential geomorphic roles across natural zones.

5. General Limitations and Assumptions

The current stage of nivation research is characterized by a departure from simplified views of it as a purely mechanical process. A growing number of studies emphasize its complex nature, in which physical and chemical weathering proceed in parallel. At the same time, an analysis of the literature and the results of our own fieldwork suggest that their relative role strongly depends on local conditions.

Traditionally, nivation was defined as a set of processes primarily associated with frost weathering and the erosive activity of meltwater. The fundamental work of Thorn and Hall [43] proposed a revision of these views, arguing that chemical weathering in snowpatch-affected areas can be significant. However, later and more recent studies indicate that the importance of chemical weathering varies greatly.

For example, a study on the massifs of the Northern Highlands of Scotland showed that nivation scarps are formed by physical weathering, whereas chemical weathering and solifluction are unimportant at that site [44]. Riggins et al. [45] emphasize that low temperatures generally limit the rates of chemical weathering; hence, bedrock is physically broken down, and chemical weathering may only precondition the rock by weakening it. Ten-year field observations of carbonate rocks in South Yakutia [46] demonstrated that physical weathering significantly predominates over chemical weathering: the proportion of chemically altered limestone did not exceed 5–7% of the volume of weathered rock. At the same time, for sandstones in the same region, under cryogenic weathering over a 25-year period, the volume of chemically altered mineral matter may reach 25–30% of the weathered rock volume [47].

On the other hand, the contribution of chemical processes to the overall landscape denudation can be substantial [48–51].

The present study does not reject chemical processes but focuses on some quantitative characteristics that determine the intensity of physical weathering in the *goltsy* landscape belt of the South Yakutia region. To date, there is a robust body of evidence showing that chemical weathering in snowpatch-influenced zones is a critically important, not merely a background, process. However, under the extremely low mean annual temperatures and sharply continental climate of South Yakutia, its contribution to modern surface

denudation is likely minor and requires further, more detailed investigations, including hydrogeochemical and mineralogical methods.

6. Conclusions

Research conducted in the *goltsy* altitudinal belt of South Yakutia demonstrates that snowpatches intensify physical weathering of rocks at their edges by a factor of 1.5–4 compared to background levels. The climate of the *goltsy* area in Yakutia is particularly conducive to nivation processes, which are one of the dominant geomorphic agents in this region. These findings further substantiate the established view that nivation achieves its greatest geomorphic significance in continental regions.

Author Contributions: Conceptualization, A.M.; Methodology, A.M., Z.Z., T.R., L.G. and V.R.; Investigation, A.M. and L.G.; Writing—original draft, A.M.; Writing—review & editing, A.M., Z.Z., T.R., L.G. and V.R.; Funding acquisition, T.R. and V.R. All authors have read and agreed to the published version of the manuscript.

Funding: The research was carried out within the framework of the basic project of IMZ SB RAS "Stability of engineering structures in the permafrost zone. Methods of monitoring and state prediction. Cryogenic resources" No. 126020616798-4 and National Key Research and Development Program of China (2025YFE0112500). Data visualization and schematic cartographic materials were supported by RSF Grant No. 23-77-10046.

Data Availability Statement: Data sets generated during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

NFTC	Number of freezing–thawing cycles
VTOL	Vertical takeoff and landing
UAV	Unmanned aerial vehicles

References

1. World Meteorological Organization. *State of the Global Climate 2024; WMO-No. 1368*; World Meteorological Organization: Geneva, Switzerland, 2025. Available online: https://library.wmo.int/idurl/4/69455 (accessed on 15 May 2025).
2. Russian Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet). *A Report on Climate Features on the Territory of the Russian Federation in 2024*; Roshydromet: Moscow, Russia, 2025. Available online: https://www.meteorf.gov.ru/upload/pdf_download/Доклад%20об%20особенностях%20климата%20на%20территории%20Рф%20за%202024%20год.pdf (accessed on 15 May 2025).
3. World Glacier Monitoring Service. *Fluctuations of Glaciers (FoG) Database*; World Glacier Monitoring Service (WGMS): Zurich, Switzerland, 2025. [CrossRef]
4. Meduna, V. First global comparison of glacier mass change: They're all melting, and fast. *Eos* **2025**, *106*. [CrossRef]
5. The GlaMBIE Team. Community estimate of global glacier mass changes from 2000 to 2023. *Nature* **2025**, *639*, 382–388. [CrossRef]
6. Jakob, L.; Gourmelen, N. Glacier mass loss between 2010 and 2020 dominated by atmospheric forcing. *Geophys. Res. Lett.* **2023**, *50*, e2023GL102954. [CrossRef]
7. Rounce, D.R.; Hock, R.; Maussion, F.; Hugonnet, R.; Kochtitzky, W.; Huss, M.; Berthier, E.; Brinkerhoff, D.; Compagno, L.; Copland, L.; et al. Global glacier change in the 21st century: Every increase in temperature matters. *Science* **2023**, *379*, 78–83. [CrossRef] [PubMed]
8. Zemp, M.; Frey, H.; Gärtner-Roer, I.; Nussbaumer, S.U.; Hoelzle, M.; Paul, F.; Haeberli, W.; Denzinger, F.; Ahlstrøm, A.P.; Anderson, B.; et al. Historically unprecedented global glacier decline in the early 21st century. *J. Glaciol.* **2015**, *61*, 745–762. [CrossRef]
9. Ganyushkin, D.A.; Moskalenko, I.G.; Chistyakov, K.V. Dynamics of perennial snow patches and snow-firn fields of Mongun-Taiga Mountain massif. *Vestn. St.-Peterbg. Univ. Seriia 7 Geol. Geogr.* **2012**, *4*, 164–175.
10. Kovalenko, N.V. Continuity of a genetic chain "snow patch–glacier". *Vestn. Mosk. Univ. Geogr.* **2011**, *6*, 20–25.

11. Lyubimov, B.P. On the mechanism of nivation processes. In *Underground Ice*; MSU Press: Moscow, Russia, 1967; Volume III, pp. 158–175.
12. Bogatova, D.; Buldovich, S.; Khilimonyuk, V. Snow Patches and Their Influence on Coastal Erosion at Baydaratskaya Bay Coast, Kara Sea, Russian Arctic. *Water* **2021**, *13*, 1432. [CrossRef]
13. Grosse, G.; Schirrmeister, L.; Siegert, C.; Kunitsky, V.; Slagoda, E.; Andreev, A.; Dereviagyn, A. Geological and geomorphological evolution of a sedimentary periglacial landscape in Northeast Siberia during the Late Quaternary. *Geomorphology* **2007**, *86*, 25–51. [CrossRef]
14. Thorn, C.E.; Hall, K. Nivation and cryoplanation: The case for scrutiny and integration. *Prog. Phys. Geogr. Earth Environ.* **2002**, *26*, 533–550. [CrossRef]
15. Kunitsky, V.V.; Schirrmeister, L.; Grosse, G.; Kienast, F. Snow Patches in Nival Landscapes and Their Role for the Ice Complex Formation in the Laptev Sea Coastal Lowlands. *Polarforschung* **2002**, *70*, 53–67. Available online: http://hdl.handle.net/10013/epic.29858 (accessed on 15 April 2026).
16. Gardner, J. Snowpatches: Their Influence on Mountain Wall Temperatures and the Geomorphic Implications. *Geogr. Ann. Ser. A Phys. Geogr.* **1969**, *51*, 114–120. [CrossRef]
17. Tolmachev, I.P. On the origin of cirques. *Tr. St. Peterb. O-Va. Estestvoispyt.* **1899**, *30*, 35.
18. Matthes, F.E. Glacial sculpture of the Bighorn Mountains, Wyoming. In *Twenty-First Annual Report of the United States Geological Survey Part 2: General Geology. Economic Geology, Alaska*; U.S. Geological Survey: Reston, VA, USA, 1900; pp. 167–190. [CrossRef]
19. Nyland, K.E.; Nelson, F.E.; Higgins, D.; University, M.S. The trajectory of contemporary cryoplanation literature: A bibliometric assessment. *Permafr. Periglac. Process.* **2024**, *35*, 232. [CrossRef]
20. Mitchell, R.J.; Nelson, F.E.; Nyland, K.E. Preliminary observations of nivation processes, Cathedral Massif, Northwestern British Columbia, Canada. *Phys. Geogr.* **2021**, *42*, 513–528. [CrossRef]
21. Skrylnik, G.P. Features of morpholithogenesis in the monsoon and continental climate of the Far East. In *Higher Education: Scientific Research, Proceedings of the Interuniversity Scientific Congress, Moscow, Russia, 7 December 2019*; Infinity: Moscow, Russia, 2019; pp. 125–141. [CrossRef]
22. Vyrkin, V.B. Nivation and continentality of climate. *Mater. Glaciol. Stud.* **2008**, *105*, 173–178.
23. Zheleznyak, M.N.; Serikov, S.I.; Shatz, M.M. Ecological, geocryological, and geotechnical conditions of the Power of Siberia gas transportation system. *Pipeline Transp. Theory Pract.* **2018**, *1*, 51–55.
24. Alekseev, V.R. *Geocryological Conditions of the Southwestern Part of the Aldan Highlands and the Stanovoy Range*; Siberian Branch of the USSR Academy of Sciences: Novosibirsk, Russia, 1964.
25. Popova, L.; Avelova, S.; Gerasimova, A.; Lutz, J.; Mathiesen, S.D.; Moiakunova, A.; Petrova, A.; Pogodaev, M.; Shadrin, V.; Shishigina, A.; et al. Trends and effects of climate change on reindeer husbandry in the Republic of Sakha (Yakutia). In *Reindeer Husbandry*; Mathiesen, S.D., Eira, I.M.G., Turi, E.I., Oskal, A., Pogodaev, M., Tonkopeeva, M., Eds.; Springer: Cham, Switzerland, 2023; pp. 149–185. [CrossRef]
26. Ananicheva, M.D.; Litvinenko, T.V.; Filippova, V.V. Climate change in the republic of Sakha (Yakutia) and its impact on the population: Instrumental measurement and observations of the local population. *Geogr. Environ. Living Syst.* **2021**, *3*, 6–21. [CrossRef]
27. Gorokhov, A.N.; Fedorov, A.N. Current Trends in Climate Change in Yakutia. *Geogr. Nat. Resour.* **2018**, *39*, 153–161. [CrossRef]
28. Alekseev, V.R. *Development of a Methodology for Compiling a Geocryological Map at a Scale of 1: 500,000 Using the Example of Mountain Taiga Regions of South Yakutia*; Siberian Branch of the USSR Academy of Sciences: Novosibirsk, Russia, 1963.
29. Kirillina, K.; Tananaev, N.; Savvinova, A.; Lobanov, V.; Fedorova, A.; Borisov, A. Climate change impacts the state of winter roads connecting indigenous communities: Case study of Sakha (Yakutia) Republic. *Clim. Serv.* **2023**, *30*, 100356. [CrossRef]
30. Abramov, V. Yakutia Loses Its Mountain Glaciers. *Res. Gate* **2015**. [CrossRef]
31. Available online: https://karpinskyinstitute.ru/en/ (accessed on 15 April 2026).
32. Campbell, P.; Gachev, E.; White, D.; Dyer, F. Snowpatch nomenclature and definitions for a changing climate. *Prog. Phys. Geogr.* **2025**, *49*, 635–656. [CrossRef]
33. Available online: https://www.onsetcomp.com (accessed on 15 May 2025).
34. Novikov, N.I.; Sukhodrovsky, V.S. *Modern Cryogenic Processes of Relief Formation in the Goltsy Belt of South Yakutia (Western Yangi Range)*; Technical Report; Permafrost Institute, Siberian Branch of the USSR Academy of Sciences: Yakutsk, USSR, 1977; p. 58.
35. Vyrkin, V.B. Nivation in the mountains of the Baikal region and Northern Zabaykalye. In *Studying the Nature, Economy, and Population of Siberia, Proceedings of the 6th Scientific Conference of Young Geographers of Siberia and the Far East, Irkutsk*; Publishing House of the V.B. Sochava Institute of Geography SB RAS: Irkutsk, Russia, 1975; pp. 66–68.
36. Available online: https://www.geoscan.ru/en/products/geoscan401 (accessed on 15 May 2025).
37. Davis, J.C.; Sampson, R.J. *Statistics and Data Analysis in Geology*, 2nd ed.; Wiley: New York, NY, USA, 1986.
38. Franke, R. Scattered Data Interpolation: Test of Some Methods. *Math. Comput.* **1982**, *33*, 181–200. [PubMed]
39. Panigrahi, N. Inverse Distance Weight. In *Encyclopedia of Mathematical Geosciences*; Daya Sagar, B.S., Cheng, Q., McKinley, J., Agterberg, F., Eds.; Springer: Cham, Switzerland, 2023; pp. 666–672. [CrossRef]

40. Melnikov, A.E.; Grib, N.N. Influence of frost weathering on the recession of surfaces of technogenic landforms in Yakutia. *Res. Cold Arid Reg.* **2019**, *11*, 257–266.
41. Vyrkin, V.B. Physical weathering of rocks and microclimate near snowpatches of the Pribaikalye and Northern Transbaikalia. *Geogr. Nat. Resour.* **1980**, *4*, 101–107.
42. Chigir, V.G. On the mechanism of snowpatches' impact on their bed. *Vestn. Mosk. Univ. Geogr.* **1964**, *1*, 31–36.
43. Thorn, C.E.; Hall, K. Nivation: An Arctic-Alpine Comparison and Reappraisal. *J. Glaciol.* **1980**, *25*, 109–124. [CrossRef]
44. Ballantyne, C.K. Nivation landforms and snowpatch erosion on two massifs in the Northern Highlands of Scotland. *Scott. Geogr. Mag.* **1985**, *101*, 40–49. [CrossRef]
45. Riggins, S.G.; Anderson, S.P.; Anderson, R.S. Weathering in the cold: Granite hillslopes in Osborn Mountain, WY and Bodmin Moor, UK. In Proceedings of the American Geophysical Union, Fall Meeting 2010, San Francisco, CA, USA, 17 December 2010.
46. Melnikov, A.; Kut, A.; Zhang, Z.; Rochev, V. Carbonate Soil Cryogenesis in South Yakutia (Russia). *Minerals* **2021**, *11*, 800. [CrossRef]
47. Zabelin, A.V. Quantitative assessment of the influence of cryogenic weathering processes on the stability of slopes of coal quarry sides in South Yakutia. *Gorn. Informatsionno-Anal. Byulleten' (Nauchno-Tekhnicheskiy Zhurnal)* **2003**, *7*, 11–13.
48. Lyons, W.B.; Leslie, D.L.; Gooseff, M.N. Chemical Weathering in the McMurdo Dry Valleys, Antarctica. In *Hydrogeology, Chemical Weathering, and Soil Formation*; Hunt, A., Egli, M., Faybishenko, B., Eds.; American Geophysical Union (AGU): Washington, DC, USA, 2021. [CrossRef]
49. Hall, K. Enhanced bedrock weathering in association with late-lying snowpatches: Evidence from Livingston Island, Antarctica. *Earth Surf. Process. Landf.* **1993**, *18*, 121–129. [CrossRef]
50. Yang, Q.; Li, X.; Shangguan, D.; Han, T. Sources of hydrochemistry and chemical weathering rate at Urumqi Glacier No.1 catchment in central Asia. *J. Hydrol. Reg. Stud.* **2025**, *57*, 102107. [CrossRef]
51. Dixon, J.C. *4.14 Chemical Weathering in Cold Climates*; Shroder, J.F., Ed.; Treatise on Geomorphology; Academic Press: Cambridge, MA, USA, 2013; pp. 245–257. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.