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# Avalanche monitoring in the ERA of climate change for mountain regions with diverse conditions

Natalya Denissova[1], Olga Petrova[2*], Maksim Pankov[3], Vitaly Zuyev[1]

*[1]Department of Information Technology, D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan.*
*[2]School of Geosciences, D. Serikbayev East Kazakhstan Technical University, Ust-Kamenogorsk, Kazakhstan.*
*[3]Avalanche prevention service, Krasnaya Polyana Resort, Sochi, Russia.*

Corresponding author: Olga Petrova (*Email: OPetrova@edu.ektu.kz*)

## Abstract

The purpose of this study is to assess the regional manifestations of climate change and to develop effective automated avalanche monitoring systems under these conditions, considering regional specifics and current climate challenges. The research methodology focuses on the analysis of climate and avalanche conditions in two contrasting mountain regions: the East Kazakhstan region and the foothills of the Main Caucasian Ridge (Krasnaya Polyana resort area). for Eastern Kazakhstan, meteorological data and records of spontaneous avalanches spanning 23 years were analyzed. For the Krasnaya Polyana resort area, meteorological data from regional weather stations covering 44 winter seasons and from the resort's own weather stations covering 17 seasons were examined. The study employs methods of mathematical statistics and modeling commonly used in modern avalanche monitoring. The results include the processing of long-term observational data, modeling of climate change trends and their relationship to avalanche activity in the studied regions, as well as research on the development and operation of avalanche monitoring systems adapted to these conditions. Conclusions based on the results show that, despite climatic and geographical differences, similar approaches can be applied to the design and operation of avalanche monitoring systems. The practical significance of the research lies in its contribution to the development of avalanche warning systems for other mountainous regions in the context of climate change.

**Keywords:** Adaptation to climate change, Automated monitoring systems, Avalanche hazard, Avalanche monitoring, Climate change.

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## 1. Introduction

Modern research provides increasingly convincing evidence of the growing impact of climate change on the dynamics of natural disasters. Numerous studies have noted an increase in the frequency, intensity, and spatial distribution of phenomena such as floods, landslides, droughts, and, to a lesser extent, avalanches.

Study [1] revealed a steady increase in the number of landslides, linking this trend to changes in precipitation and temperature on a global scale. Similar conclusions were drawn in Chapagain, et al. [2] where, using the example of Nepal, it was shown that even with a reduction in population vulnerability, the impact of climate-related disasters continues to intensify. Research conducted for the Philippines and Indonesia [3] established linear relationships between precipitation anomalies and the number of natural disasters. A review of trends in Glasser [4] shows that the number of floods has increased fourfold since 1980, while droughts, fires, and storms have doubled. A systematic analysis of historical and contemporary data for China [5, 6] confirms that climate change plays a significant role in the spatial and temporal dynamics of natural disasters, including avalanches. An analysis of 60 years of data for 176 countries in Mohanty, et al. [7] demonstrated that temperature variability has a stronger influence on the frequency of natural disasters than average temperature change.

Avalanche activity is becoming an increasingly important component of these processes. Using the example of the Western Himalayas, researchers in Ballesteros-Cánovas, et al. [8] showed that climate warming increases both the frequency and intensity of avalanches, particularly due to a rise in wet snow avalanches. Similar results are presented in Mayer, et al. [9] for the Swiss Alps: despite an overall decrease in the number of dry avalanches, an increase in wet and more severe avalanche events is projected, especially in mid-mountain areas. A study in Slovenia [10] demonstrates that rising temperatures lead to a greater number of early-season wet avalanches in winter, thereby altering the typical seasonal pattern of avalanche hazard. Researchers in Ortner, et al. [11] emphasize that avalanche-prone zones may shift upslope, while previously safe areas may fall within new risk zones. A similar conclusion was reached in Glazovskaya [12] where it was found that avalanche activity is likely to decrease in most active regions but increase in areas with historically low activity. These findings highlight the need to adapt avalanche monitoring and forecasting systems to changing climatic conditions.

Climatic changes in regions adjacent to the focus area of this study also demonstrate significant trends. In the Caucasus region, there has been a steady increase in average annual temperatures since the late 20th century, accompanied by greater variability in precipitation [13, 14]. These trends are particularly relevant for the southern slopes of the Main Caucasian Ridge, where an active avalanche hazard zone is concentrated. Study [15] also reports a reduction in snow–glacier complexes in this region by an average of 20.6%.

Similar patterns are observed in the East Kazakhstan Region. Research in Rafikov, et al. [16] revealed a decrease in the vegetation index and degradation of snow cover, which may be associated with changes in temperature and precipitation regimes. The general climatic trend in Kazakhstan, documented in Sanatova and Bektursinova [17] also confirms rising temperatures and altered precipitation patterns, including in mountainous areas.

Thus, despite differences in geographical, climatic, and altitudinal conditions, both the Caucasus and East Kazakhstan regions are vulnerable to the effects of climate change that can alter avalanche activity. However, comparative studies directly assessing the relationship between climate change and avalanche risk in these two contrasting regions remain limited. This underscores the importance of systematic analysis using modern statistical techniques and mathematical modeling, as well as the need to develop and adapt avalanche monitoring systems to a changing climate. At the same time, their ease of installation and scalability are key factors for such systems.

## 2. Materials and Methods

The analysis of avalanche activity in the regions under consideration is based on long-term meteorological data, snow depth information, and records on the frequency and magnitude of avalanches. For East Kazakhstan, meteorological data from regional weather stations for 23 years (2001–2024) [18] were analyzed. In addition, meteorological observations in avalanche-prone areas for 19 years (2005–2024) and data on spontaneous avalanches for the last 11 years (2013–2024) were provided by the State Institution Kazselezashchita. These data, obtained from snow measurement routes, include average and maximum snow depth as well as daily air temperature for each avalanche-prone site.

Data processing was performed in Microsoft Excel, with forecasts of indicators generated using second-degree polynomial trend lines. For each trend, the corresponding equation and coefficient of determination ($R^2$) are provided. It should be noted that other types of dependencies and higher-degree polynomials were considered in the study; however, they were found to produce unrealistically low or high estimates. Therefore, all forecast trends were constructed using second-degree polynomials. The dataset is presented in Table 1.

**Table 1.**
Summary of climate data for the East Kazakhstan Region, 2001–2024

| № | Data type | Data subtype | Max. | Min. | Mean | Standard deviation | Coefficient of variation, % |
|---|---|---|---|---|---|---|---|
| 1 | Air temperature, °C | Annual daily mean | 4.4 | 1.3 | 3.3 | 0.84 | 25.70 |
| 2 | | Winter daily mean | -5.2 | -12.1 | -7.8 | 1.65 | 21.20 |
| 3 | Precipitation, mm | Winter daily mean | 1.7 | 0.7 | 1.1 | 0.28 | 25.57 |
| 4 | | Annual total | 625 | 319 | 491 | 83.70 | 17.78 |
| 5 | | Winter total | 302 | 131 | 208 | 52.70 | 25.35 |
| 6 | | Summer total | 374 | 163 | 283 | 58.76 | 20.80 |
| 7 | Snow depth, cm | Seasonal daily mean | 37 | 14 | 25 | 7.26 | 29.02 |
| 8 | Wind speed, m/s | Winter daily mean | 2.4 | 1.6 | 2.1 | 0.20 | 9.52 |
| 9 | Precipitation anomaly coefficient | Cold season | 1.45 | 0.63 | 1.0 | 0.25 | 25.35 |

For the Krasnaya Polyana resort area, meteorological data from regional weather stations for 44 seasons (from the winter of 1978–1979 to the 2024–2025 season) and from the resort's weather stations for 17 seasons (2009–2024) were analyzed. The statistical data refers to the cold season, covering the period from October to the end of April. Data on spontaneous avalanches is not presented here, as the resort area is monitored by an avalanche control service and all avalanches are artificially triggered. A summary of these data is given in Table 2.

For all datasets, the standard deviation (S) and coefficient of variation (V) were calculated using equations (1) and (2), respectively, to assess the degree of variability of the parameters.

$$S = \sqrt{\frac{\sum_{i=0}^{n}(x_i - \bar{x})^2}{n-1}} \quad (1)$$

$$V = \frac{SD}{\bar{x}} 100 \quad (2)$$

where $x_i$ denotes the observed values of the variable, $\bar{x}$ is the arithmetic mean, and n is the number of observations.

**Table 2.**
Summary of climate data for Krasnaya Polyana resort area, winter seasons 2009-2010 to 2024-2025

| № | Data type | Data subtype | Max | Min | Mean | Standard deviation | Coefficient of variation, % |
|---|---|---|---|---|---|---|---|
| 1 | Air temperature, °C | Seasonal mean | 8.2 | 4.3 | 6.6 | 0.97 | 14.66 |
| 2 | | Seasonal maximum | 31.4 | 23.2 | 26.5 | 1.92 | 7.26 |
| 3 | | Seasonal minimum | -6.0 | -11.9 | -9.1 | 1.91 | 21.04 |
| 4 | Precipitation, mm | Seasonal mean | 1511 | 1000 | 1245 | 157.2 | 12.63 |
| 5 | Snow depth, cm | Seasonal mean | 55.4 | 10.8 | 23.0 | 11.60 | 50.51 |
| 6 | | Seasonal maximum | 101.0 | 24.0 | 63.3 | 24.05 | 38.03 |
| 7 | Precipitation anomaly coefficient | Cold season | 1.3 | 0.8 | 1.0 | 0.14 | 14.06 |

## 3. Study Area

### *3.1. East Kazakhstan Region*

East Kazakhstan includes a variety of natural-climatic zones, ranging from steppes and forest-steppes to the mountain systems of the Altay and Southern Altay (Figure 1), with altitudes from approximately 800 m to 4,500 m (e.g., Belukha Mountain, 4,506 m). The climate of the region is sharply continental: winters are harsh and snowy, with temperature lows reaching −57 °C. Summers are arid and hot, with maximum temperatures up to +46 °C. Precipitation distribution is highly uneven: up to 1,000–1,500 mm/year in the highlands, 400–500 mm/year in the foothills, and only 130–200 mm/year in the Zaisan Depression [19].

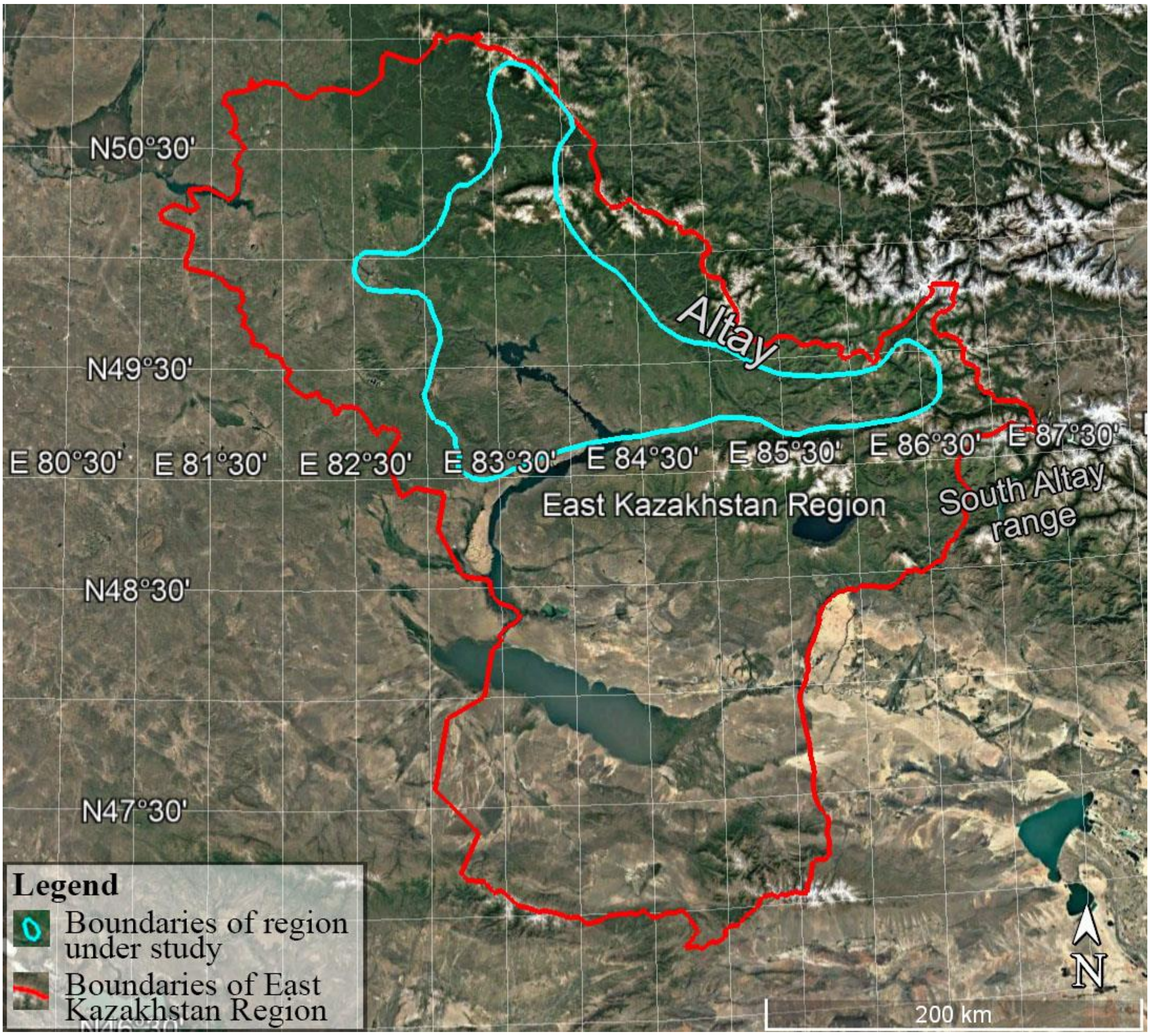


**Figure 1.**
The location of the investigated avalanche-prone areas in East Kazakhstan region.

*3.2. Foothills of the Main Caucasian Ridge (Krasnaya Polyana region).*

The study area is located at the foot of the Main Caucasian Ridge, in the southern part of the Western Caucasus, within the Krasnaya Polyana resort area (Figures 2 and 3). The climate is classified as moderately humid continental, with mild winters and warm summers. The average annual temperature is about 7–10 °C; average winter temperatures are around −2 °C, while summer temperatures reach up to +18 °C. Precipitation totals 1,400–2,000 mm/year, with a maximum in winter and spring. Heavy snowfalls on the slopes form a snow cover of up to several meters, significantly increasing avalanche hazard. The relief is represented by foothills with moderate slopes (around 800 m), transitioning into the highlands of the Main Caucasus. In winter and spring, avalanches are a common phenomenon in the region [20, 21].

Table 3 presents a comparative summary of the main climatic and geographical characteristics of the two regions.

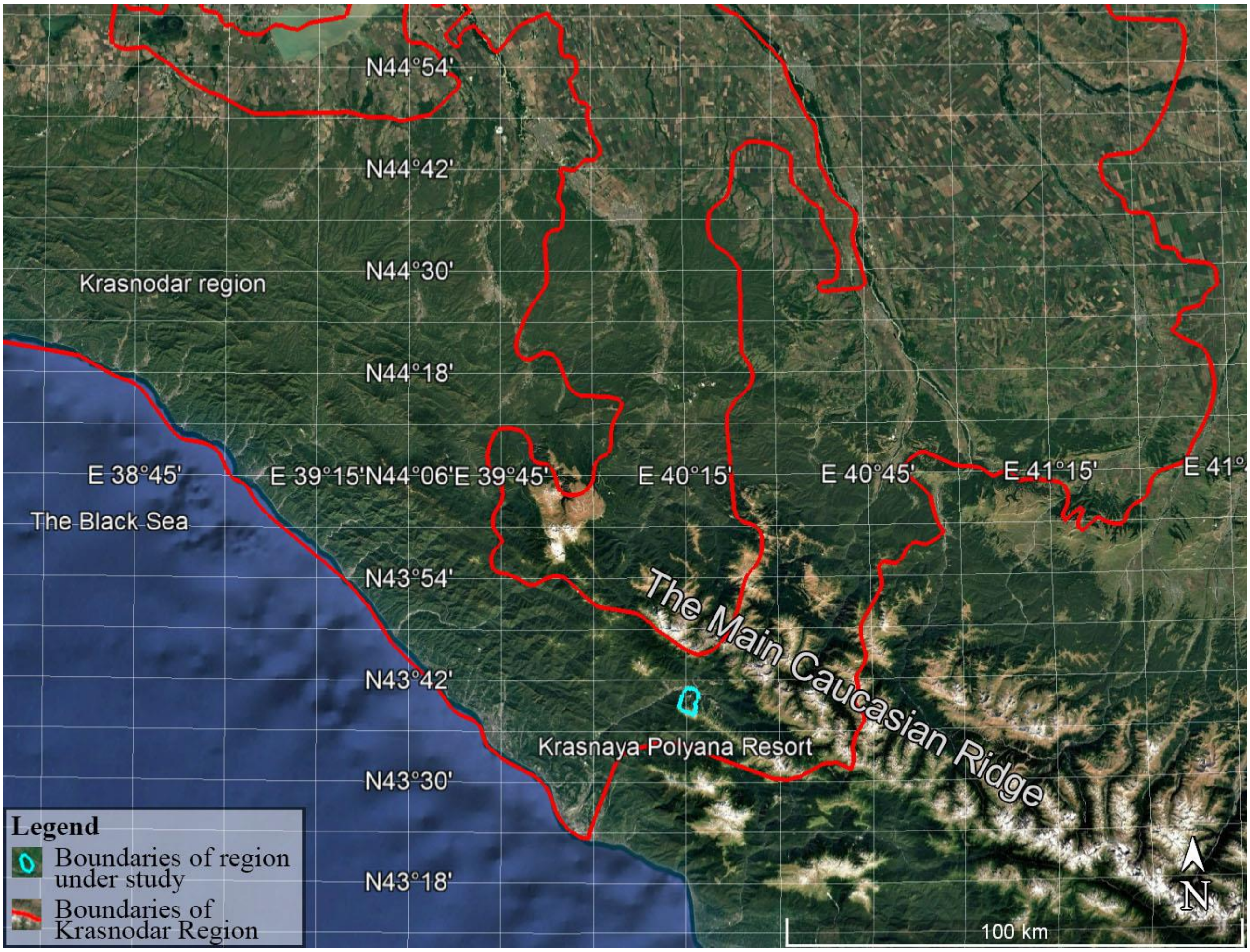


**Figure 2.**
Location of the studied area at the foot of the Main Caucasian Ridge.

**Table 3.**
Comparison of the regions studied.

| **Parameter** | **East Kazakhstan (Altay Mountains)** | **Foothills of the Caucasus (Krasnaya Polyana)** |
|---|---|---|
| Altitude range | 800–3000 m and above | foothills up to ~800 m, transition to highlands |
| Average winter temperature | −20…−30 °C (extremes down to −57 °C) | ~−2 °C, mild winters |
| Average summer temperature | +30…+40 °C (extremes up to +46 °C) | +17…+18 °C, warm summers |
| Annual precipitation | 400–500 mm (foothills), 1,000–1,500 mm (highlands) | 1,400–2,000 mm, maximum in winter/spring |
| Snow cover | Stable in highlands; depth depends on altitude and precipitation | Heavy in winter/spring; depth up to several meters |
| Climate zone | Sharply continental with strong altitude zonation | Moderately humid continental |

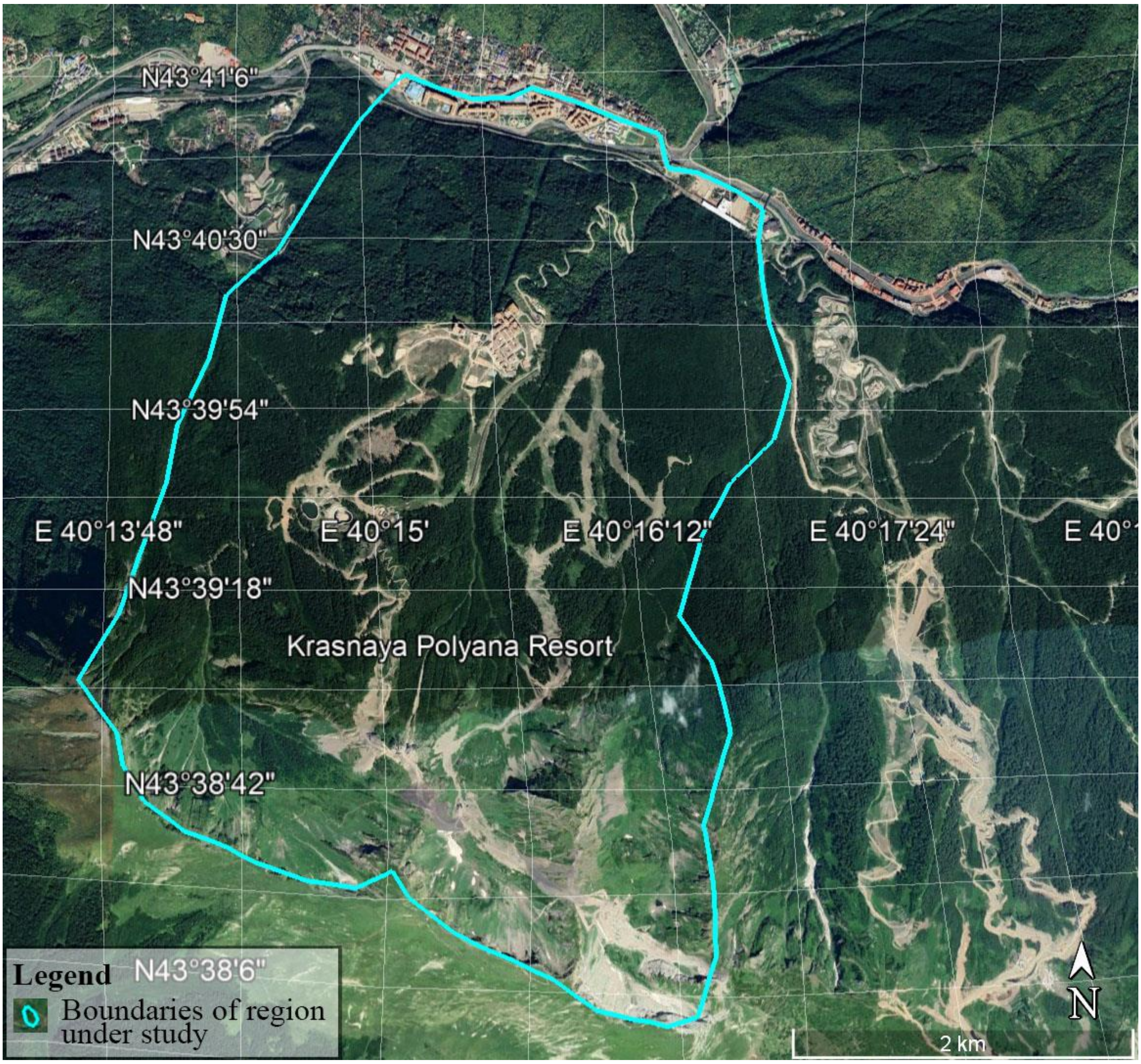


**Figure 3.**
The area under study is in the area of Krasnaya Polyana resort.

The East Kazakhstan region is characterized by a sharply continental climate with extreme temperature fluctuations and pronounced altitudinal zonation. In mountainous areas, stable snow cover creates conditions for avalanches, but its depth and stability depend strongly on elevation and annual precipitation patterns.

In contrast, the Krasnaya Polyana resort area has a more humid and milder climate: winters are moderately cold, summers are cool. Precipitation is relatively evenly distributed, with a peak in winter and spring, forming a deep snowpack that often triggers wet avalanches. The topography facilitates frequent avalanche releases during the melting period.

These two regions represent contrasting natural and climatic conditions, enabling a comparative assessment of the influence of climate change (temperature, precipitation, snow depth) on avalanche activity. Such an analysis is particularly relevant for developing region-specific avalanche risk monitoring and prevention systems.

## 4. Results and Discussion

*4.1. Climate change analysis for East Kazakhstan Region*

The analysis of meteorological parameters for avalanche-prone areas in the East Kazakhstan region revealed changes that have occurred over an extended period. Temperature trends in the region align with global patterns, indicating a gradual increase in air temperature (Figure 4). At the same time, global warming does not preclude significant negative temperature anomalies at the regional level and may, in fact, contribute to their intensification. For example, in 2012, there was an abnormally warm summer accompanied by an extremely cold winter. The minimum point on the graph in Figure 4 corresponds to this event. Nevertheless, the overall trends remain, and the winter of 2023–2024 was the warmest in the region over the entire observation period.

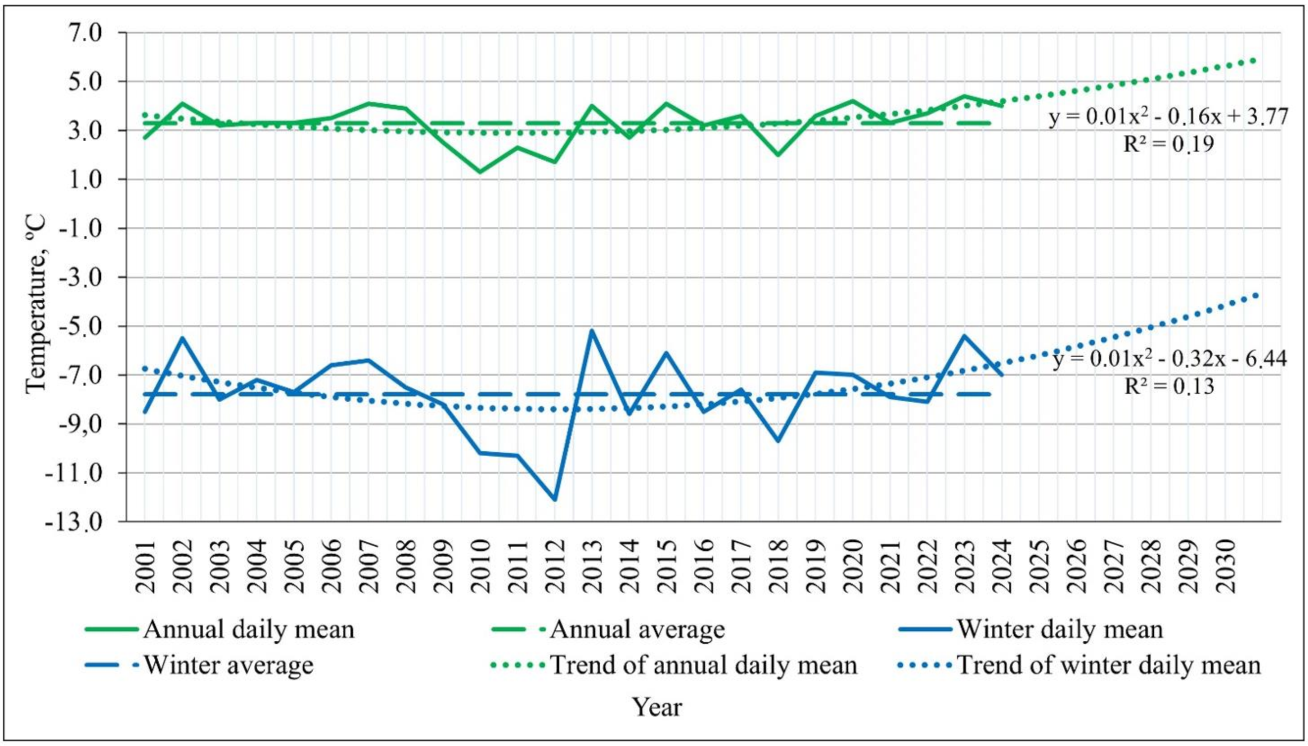


**Figure 4.**
Average air temperature data for the East Kazakhstan region and a forecast of their changes.

Figure 5 presents data on precipitation in the East Kazakhstan region. As shown in the graph, there is a gradual increase in average annual precipitation, along with a rise in winter precipitation. Since 2009, these indicators have consistently exceeded the average values for the study period. At the same time, summer precipitation has been decreasing, with seasonal totals shifting toward periods of lower air temperatures. The trend lines indicate that winters are becoming snowier, while summers are becoming drier. This tendency is clearly illustrated in Figure 6, which shows the percentage of precipitation from the annual average for summer and winter. Over the past three years, the amounts of summer and winter precipitation have been approximately equal. According to forecasts, in the future the bulk of precipitation will occur during the cold months, from October to April, and this amount is expected to increase. It should be noted that the climate of Eastern Kazakhstan has always been characterized by snowy winters. However, whereas in the past the largest share of annual precipitation fell during the warmer months, the region is now expected to experience simultaneous increases in both air temperature and winter precipitation. These trends will undoubtedly affect avalanche risk.

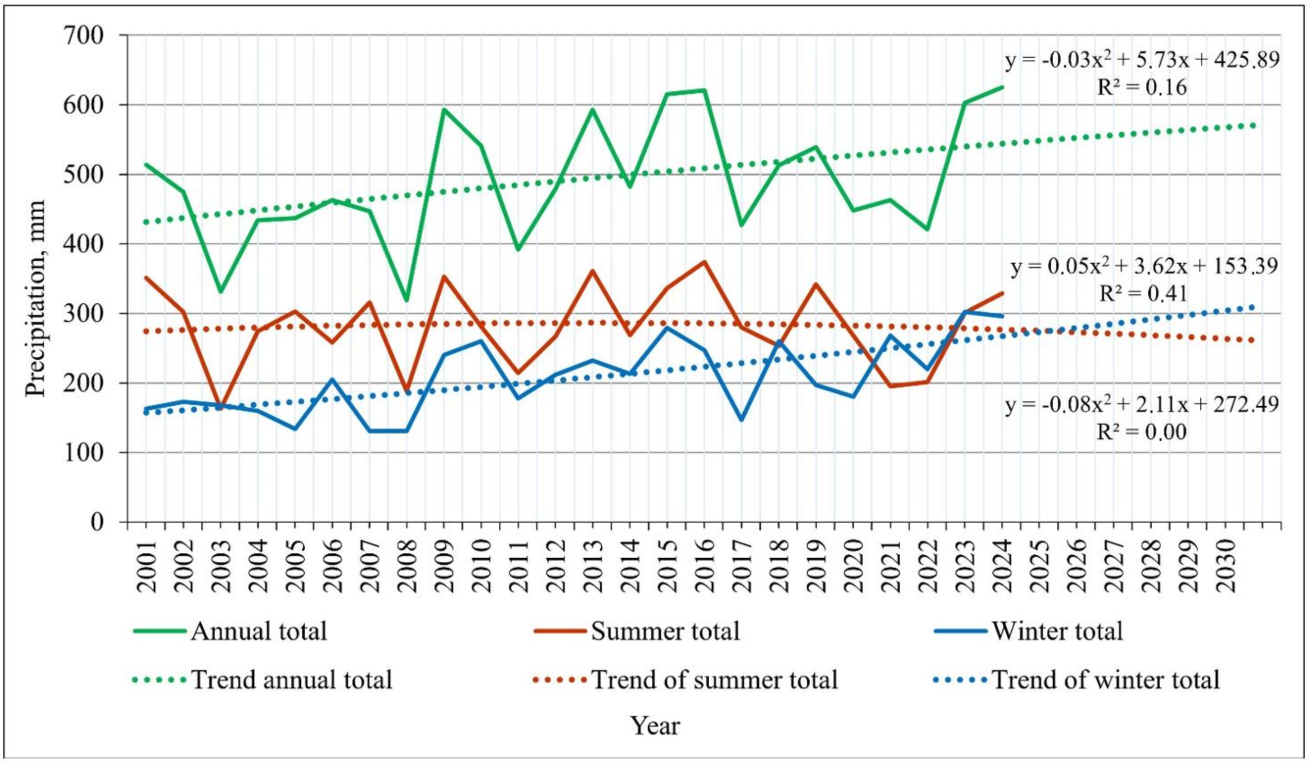


**Figure 5.**
Average annual precipitation and average winter precipitation for the East Kazakhstan Region.

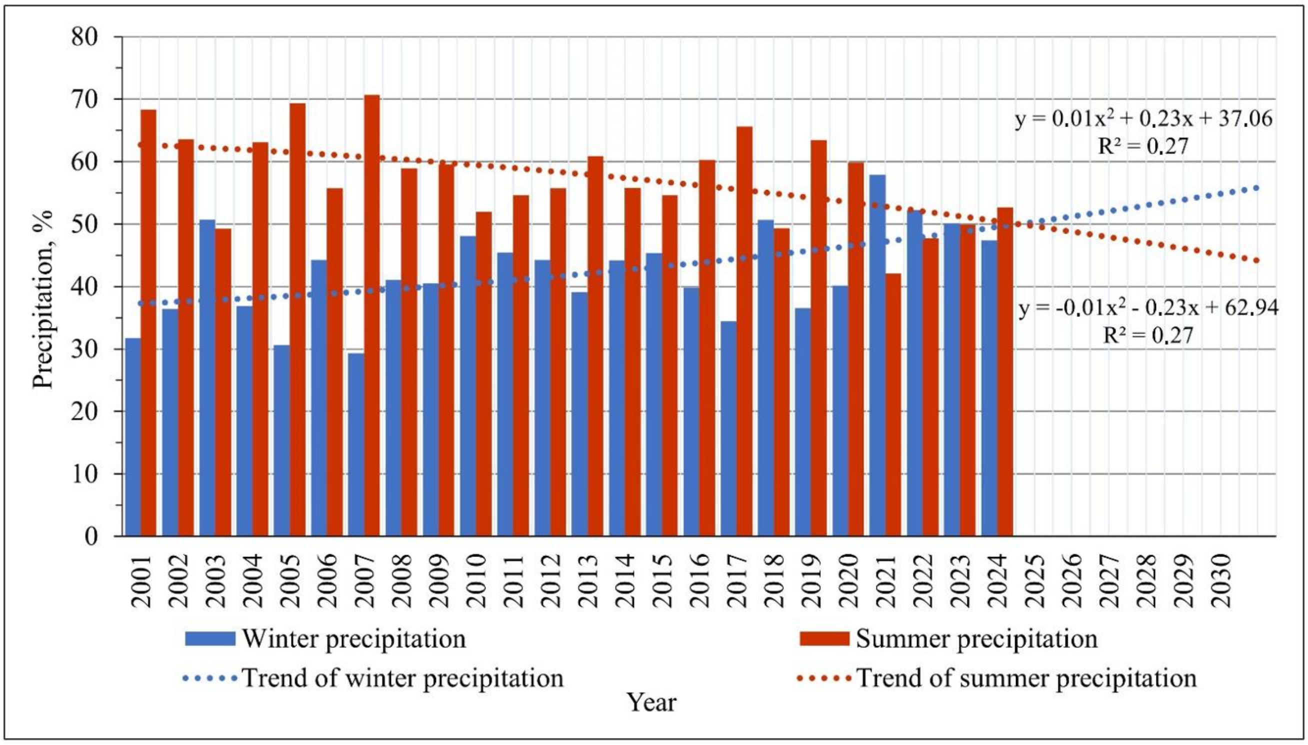


**Figure 6.**
Percentage of seasonal precipitation relative to the average annual precipitation for the East Kazakhstan Region.

According to Figure 7, there is a clear tendency for the average daily precipitation in winter to increase. This indicates a growing number of days with heavy precipitation over short periods during the winter season. This trend is further supported by the analysis of the winter precipitation anomaly coefficient, shown in Figure 8. Changes in precipitation intensity have become one of the key factors contributing to the increased avalanche hazard in the region.

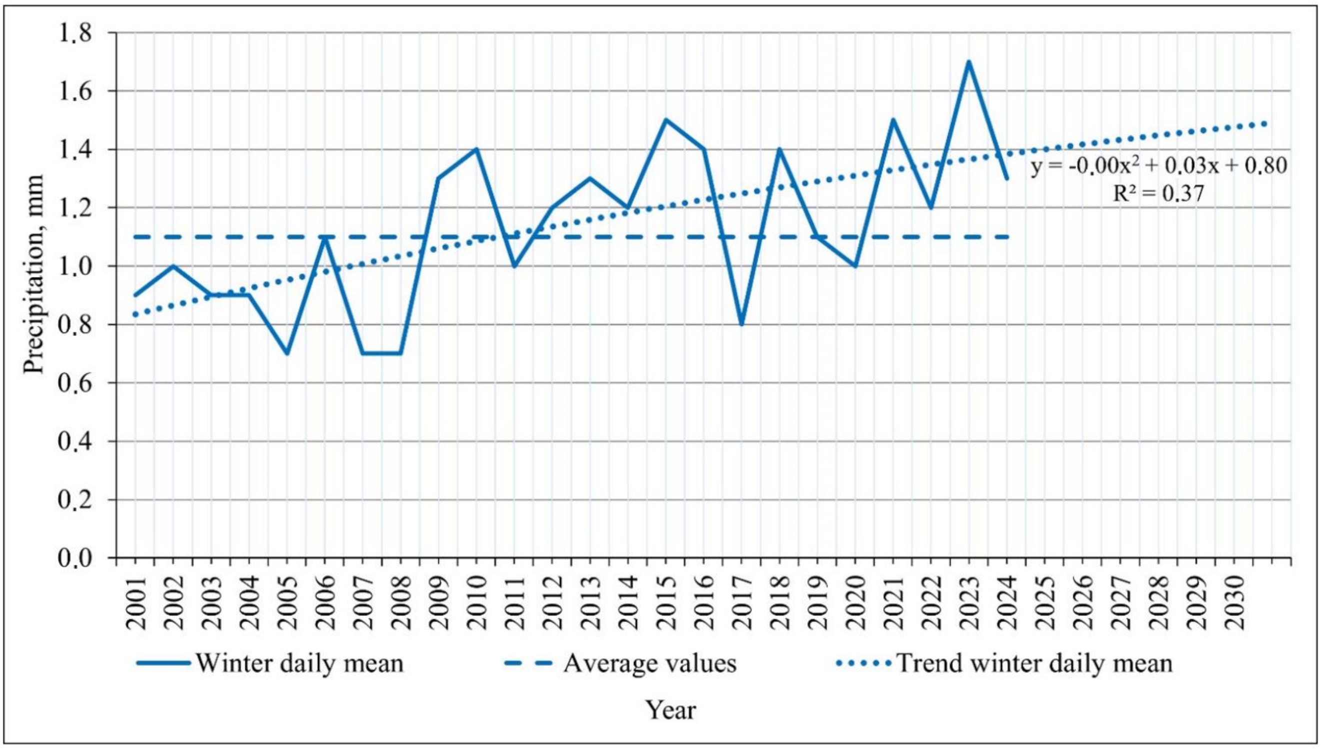


**Figure 7.**
Average daily winter precipitation for the East Kazakhstan Region.

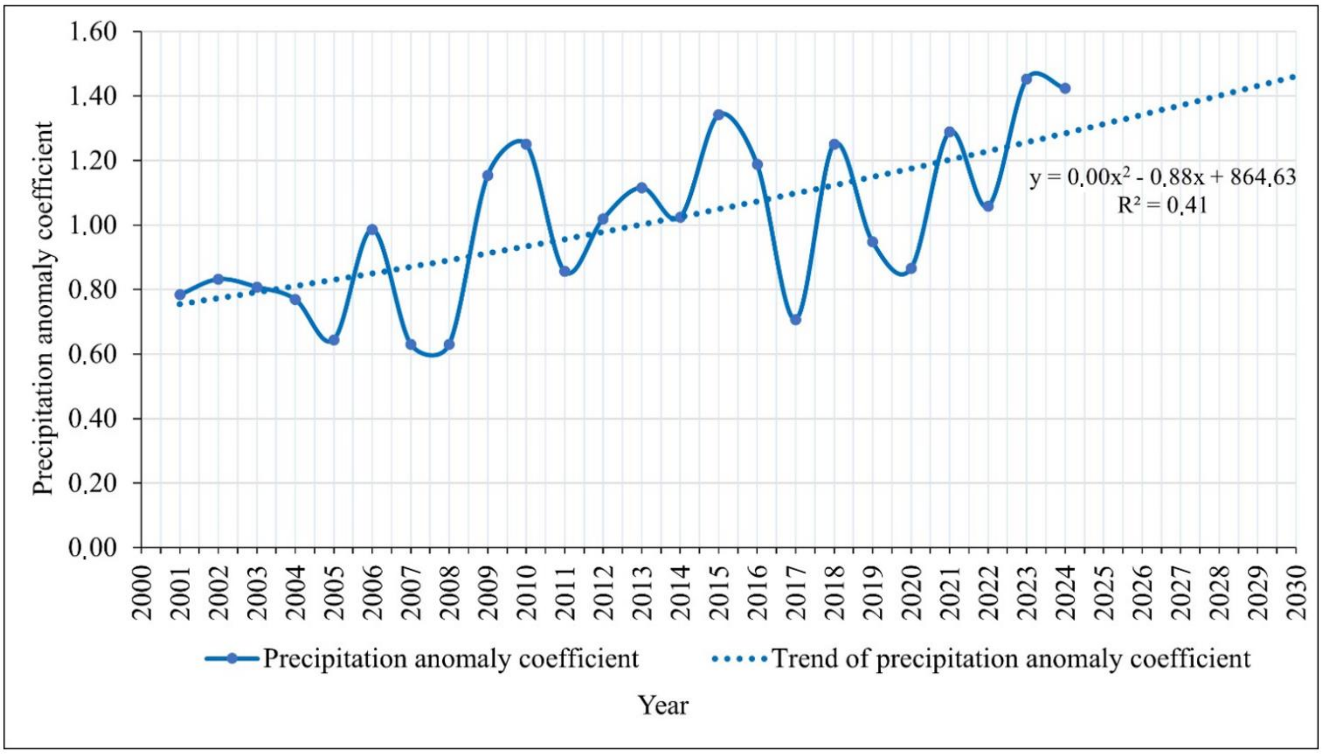


**Figure 8.**
Winter precipitation anomaly coefficient for the East Kazakhstan Region.

The graphs presented on air temperature and precipitation trends indicate ongoing changes in the region's microclimate, which are expected to persist in the coming years. The climate is becoming both warmer and more humid, inevitably influencing avalanche activity in the region.

These conditions directly affect the formation of the snow cover in the East Kazakhstan Region. The average annual snow depth is shown in Figure 9. Over the past 15 years, annual snow depth has generally exceeded the long-term average; however, the trend line reveals a gradual decline. This decrease can be attributed to rising air temperatures, including in winter, which enhance snow melting, compaction, and recrystallization processes. Such processes are additional factors contributing to elevated avalanche hazard in the region.

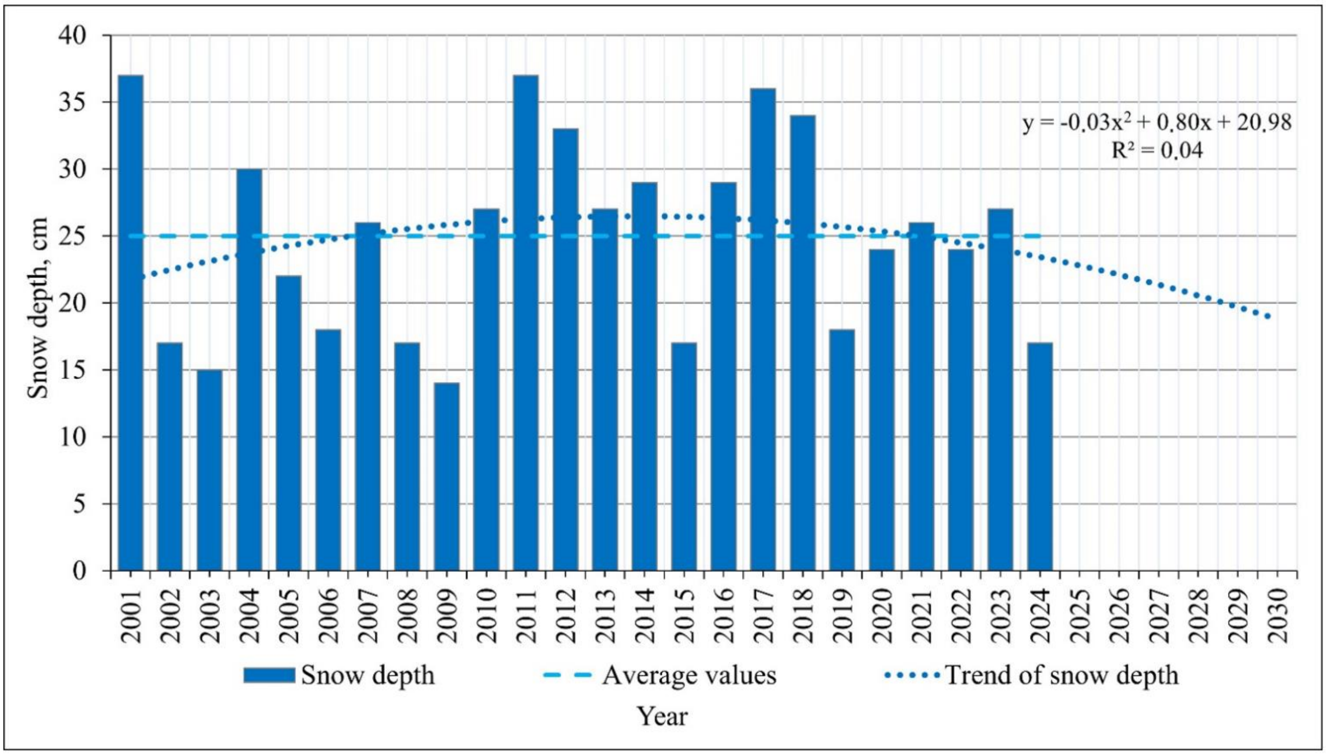


**Figure 9.**
Snow depth and its trend for the East Kazakhstan Region.

Wind regime is another critical factor affecting avalanche formation. Analysis of wind speeds for the East Kazakhstan Region (Figure 10) shows a tendency toward an increase. In mountainous terrain, wind transport of snow leads to the formation of cornices and wind slabs on slopes. The collapse of these structures often triggers avalanches. An increase in wind speed intensifies local variations in snow cover distribution, thereby raising avalanche risk.

The climate change analysis for the East Kazakhstan Region reveals the following:

- The average annual air temperature shows a steady upward trend, confirmed by a second-degree polynomial model. The winter of 2023–2024 was the warmest in the entire observation period;
- Average annual precipitation is also increasing, with the most pronounced growth in winter, leading to more frequent days of heavy snowfall and a heightened avalanche hazard;
- Wind speeds in the study area are rising, which contributes to the formation of snow cornices and wind slabs on slopes.

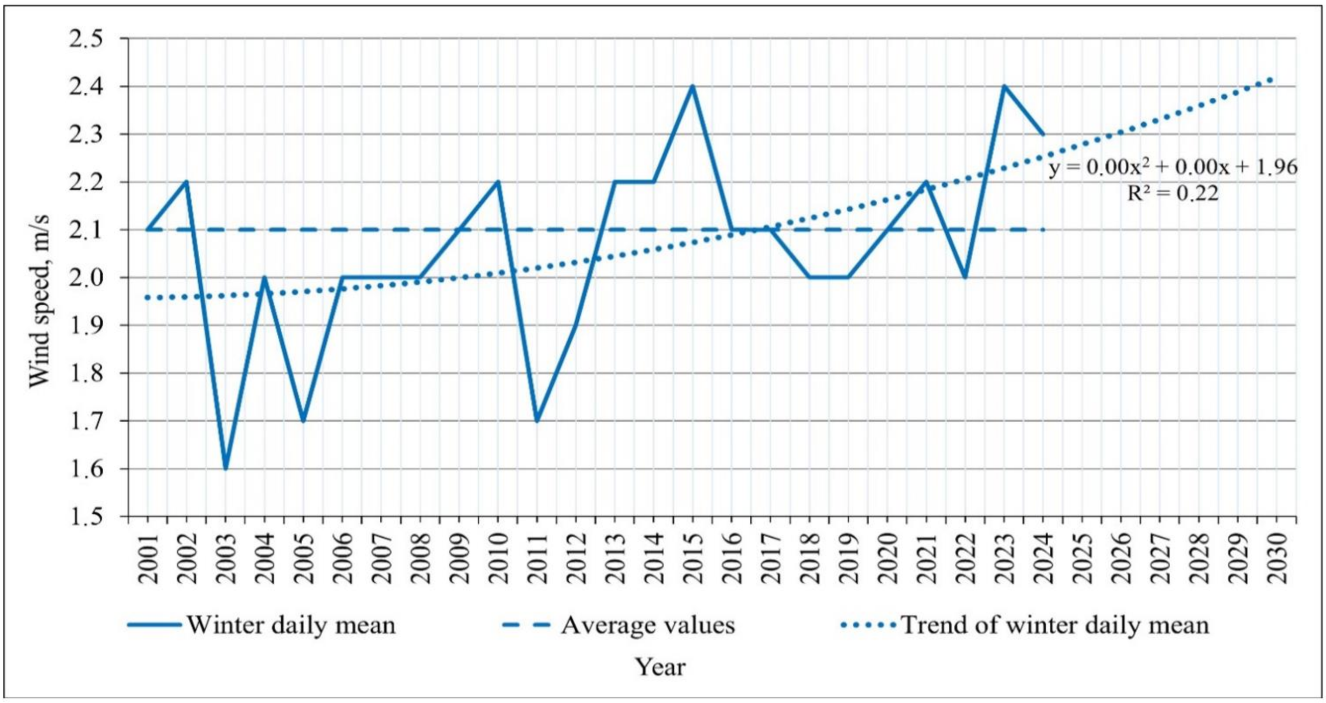


**Figure 10.**
Wind speed and its trend for the study area.

Figures 11 and 12 present aggregated statistics on the number and volume of avalanches in the East Kazakhstan Region during various winter seasons since 2013 (earlier data are unavailable). The winters of 2020–2022 were critical for the region, while the 2022–2023 and 2023–2024 seasons also exceeded the long-term average. The forecast for the upcoming winters, based on the trend lines, indicates a further increase in avalanche hazard levels. This projection aligns with the climatic changes identified in the meteorological data analysis. There is a clear correlation between rising winter air temperatures, precipitation, and wind speed, and the recent increase in both the number and volume of avalanches in the East Kazakhstan Region.

Given these trends, the need for continuous monitoring of avalanche conditions using modern methods and equipment is particularly pressing for the region.

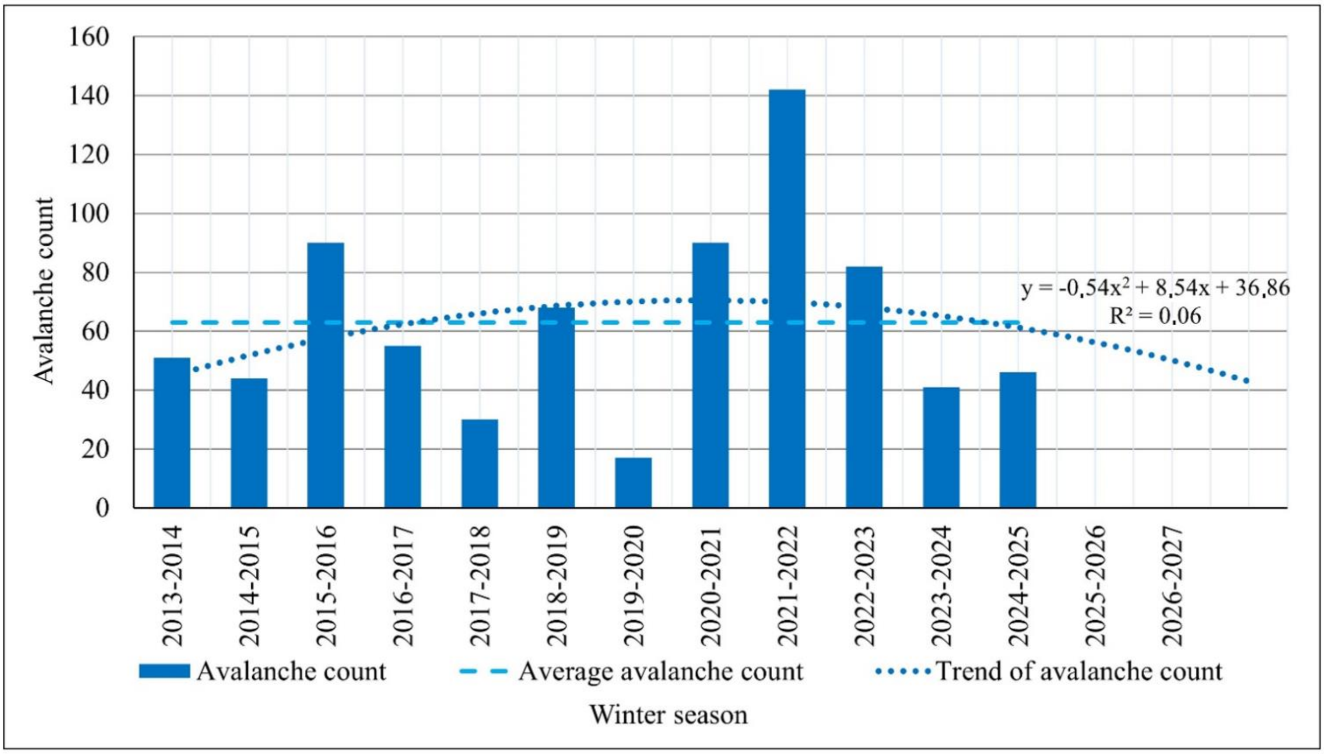


**Figure 11.**
Avalanche count in the East Kazakhstan Region during various winter seasons.

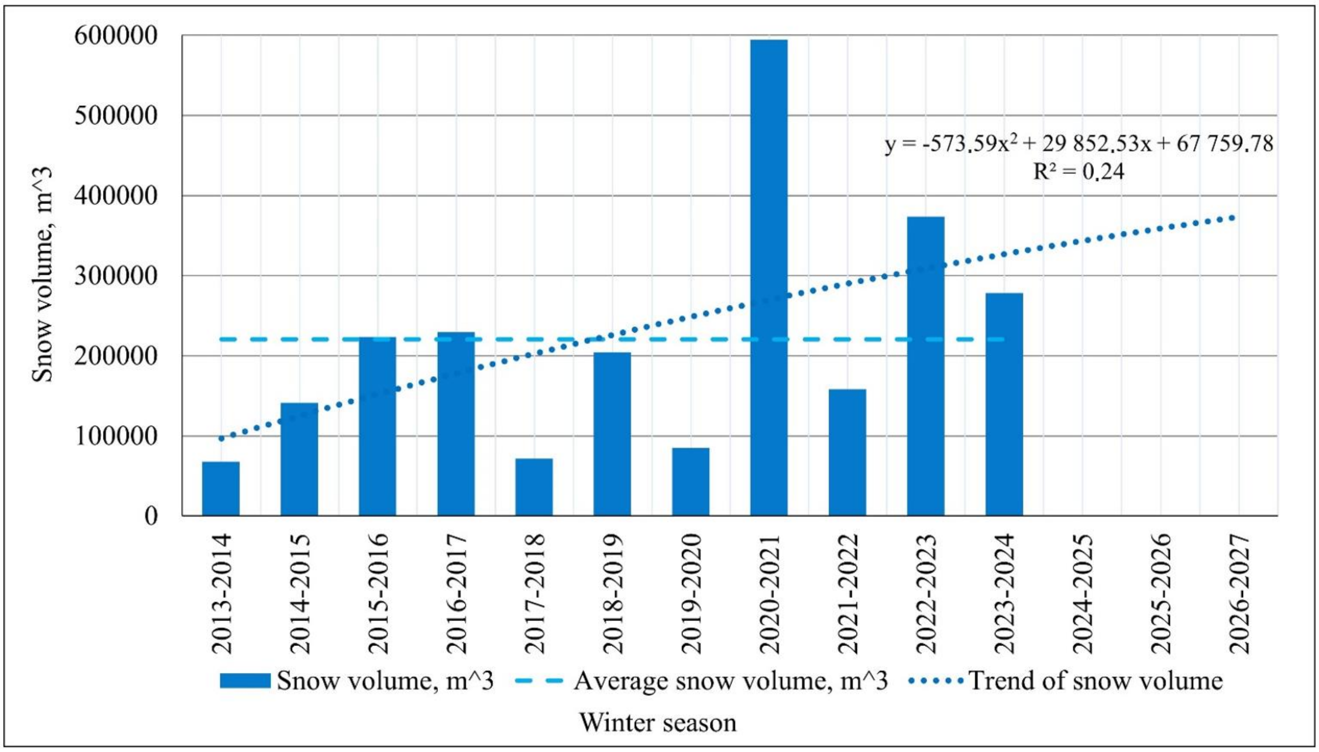


**Figure 12.**
Snow volume from avalanches in the East Kazakhstan Region during various winter seasons.

*4.2. Climate Change Analysis for the Krasnaya Polyana Region*

The analysis of climate data for the Krasnaya Polyana resort area is presented in Figures 13–16. The graphs show that temperature trends, like those in the East Kazakhstan region, correspond to global climate change patterns. However, the total precipitation during the winter season has been decreasing. In general, the average snow depth is also declining, which is consistent with the findings for other mountainous regions worldwide [22]. The precipitation anomaly coefficient demonstrates a downward trend as well.

At the same time, the maximum snow depth (Figure 15) has been increasing and remains above the average values, indicating a rise in extreme weather events in the region.

For example, during the last four winter seasons (2021–2025), an anomalous temporal distribution of precipitation was recorded. In some months, such as January 2022, there were 26 days of snowfall with a total daily accumulation of 600 cm, compared to the long-term average of 276 cm. However, during the rest of the cold season, precipitation was below normal levels.

These observations suggest that events previously considered rare, such as anomalous precipitation patterns and pronounced temperature fluctuations, are likely to occur more frequently. This indicates an expected increase in weather variability in the region.

Thus, the analysis of the Krasnaya Polyana area shows that:

- Temperature changes correspond to global climate trends, like those observed in the East Kazakhstan region;
- The region has experienced a general decrease in winter precipitation and average snow depth, consistent with patterns in other mountainous regions worldwide;
- An increase in the maximum snow depth and the frequency of anomalous precipitation events indicates greater climatic instability and extreme weather conditions.

Increasing climatic instability and the occurrence of extreme snowfall events raise the likelihood of avalanche-prone situations, making continuous and comprehensive avalanche monitoring a key element in ensuring safety in the region.

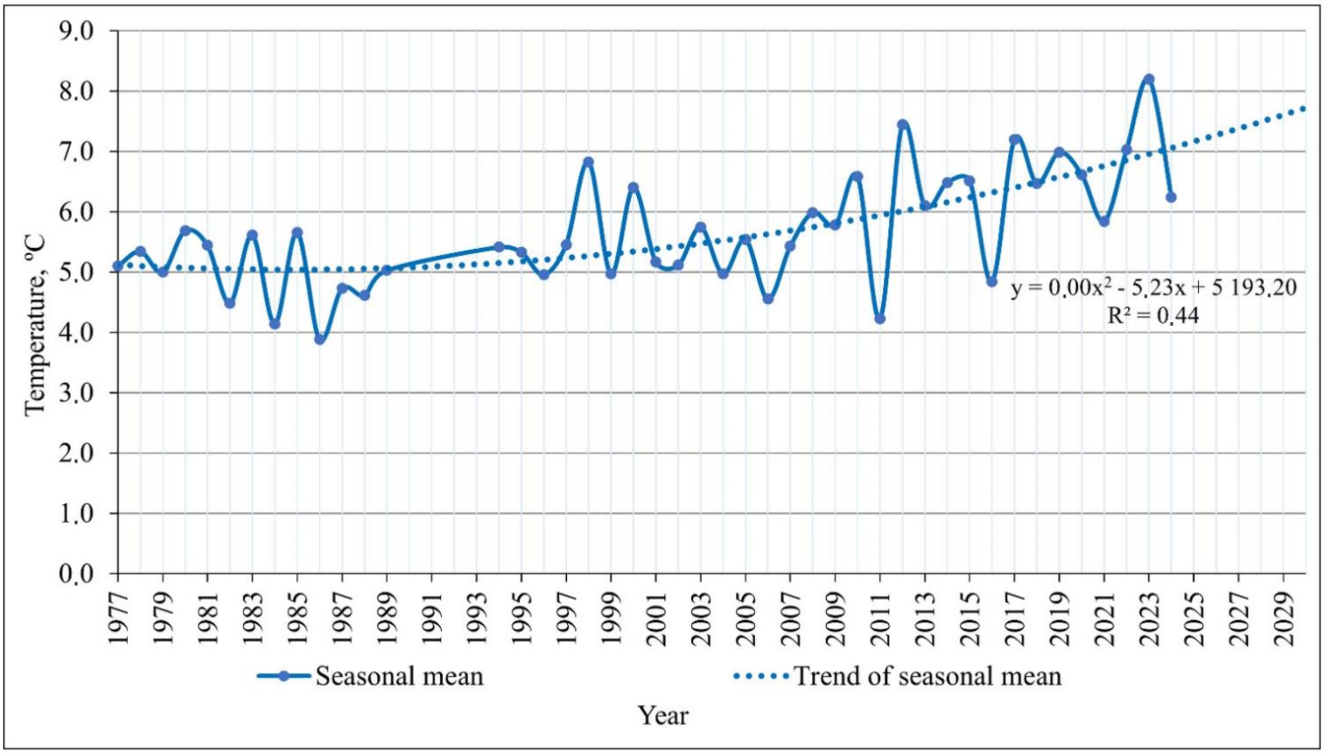


**Figure 13.**
Average air temperature data for the Krasnaya Polyana resort area and the forecast of their changes.

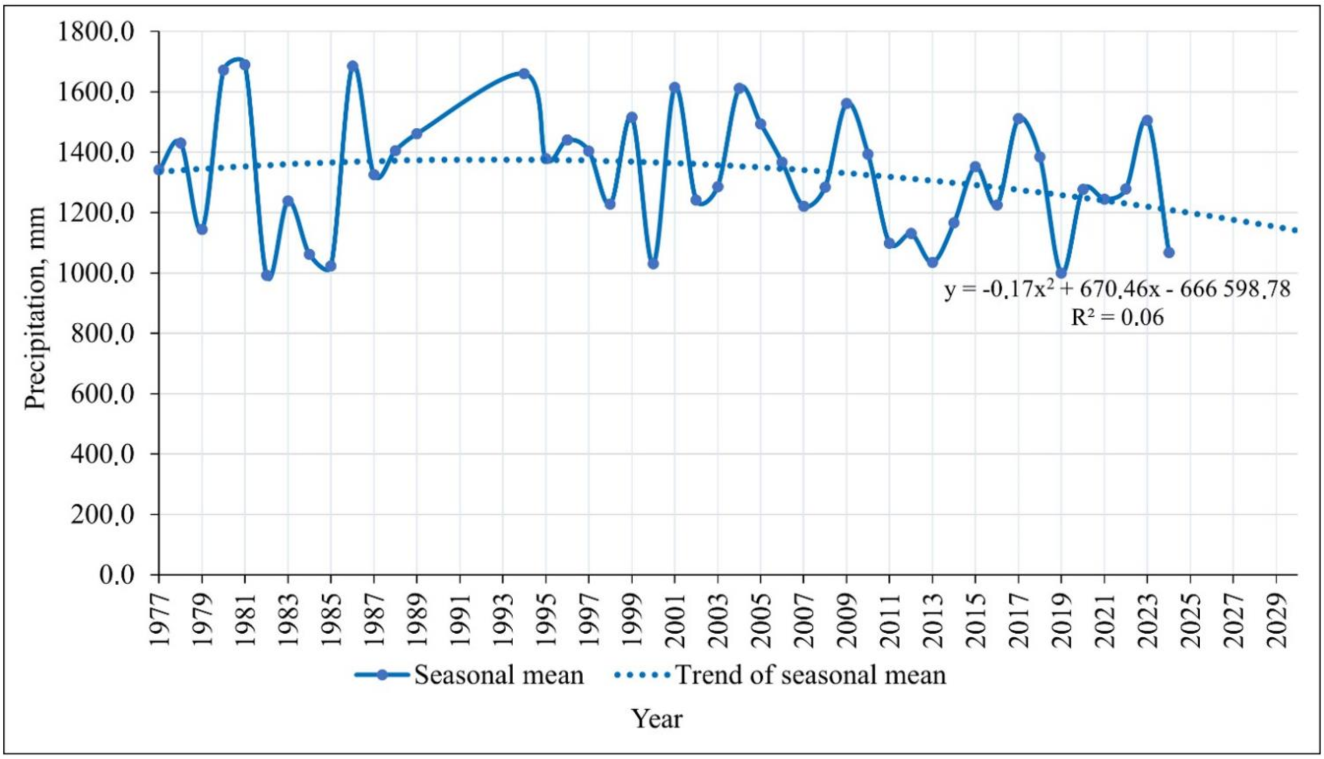


**Figure 14.**
Average precipitation data for the Krasnaya Polyana resort area and the forecast of their changes.

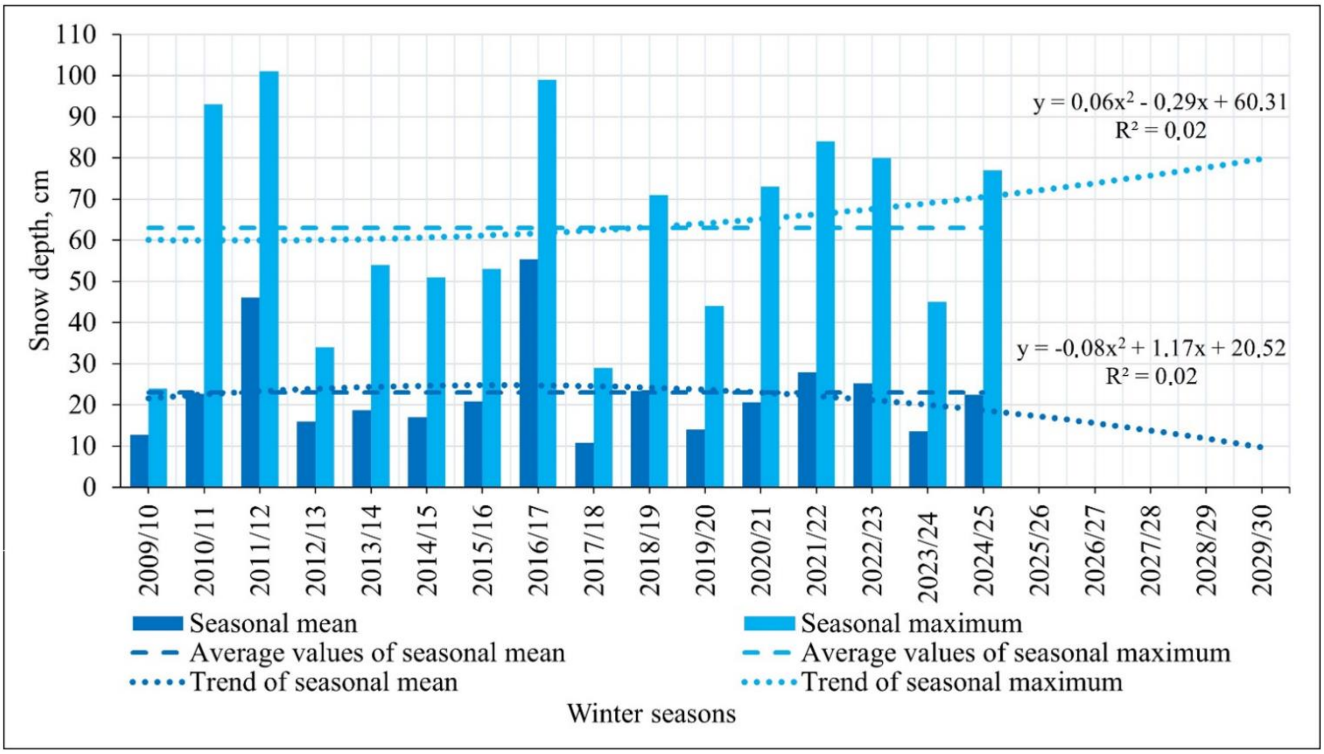


**Figure 15.**
Statistical data on the snow depth for the Krasnaya Polyana resort area and the forecast of their changes.

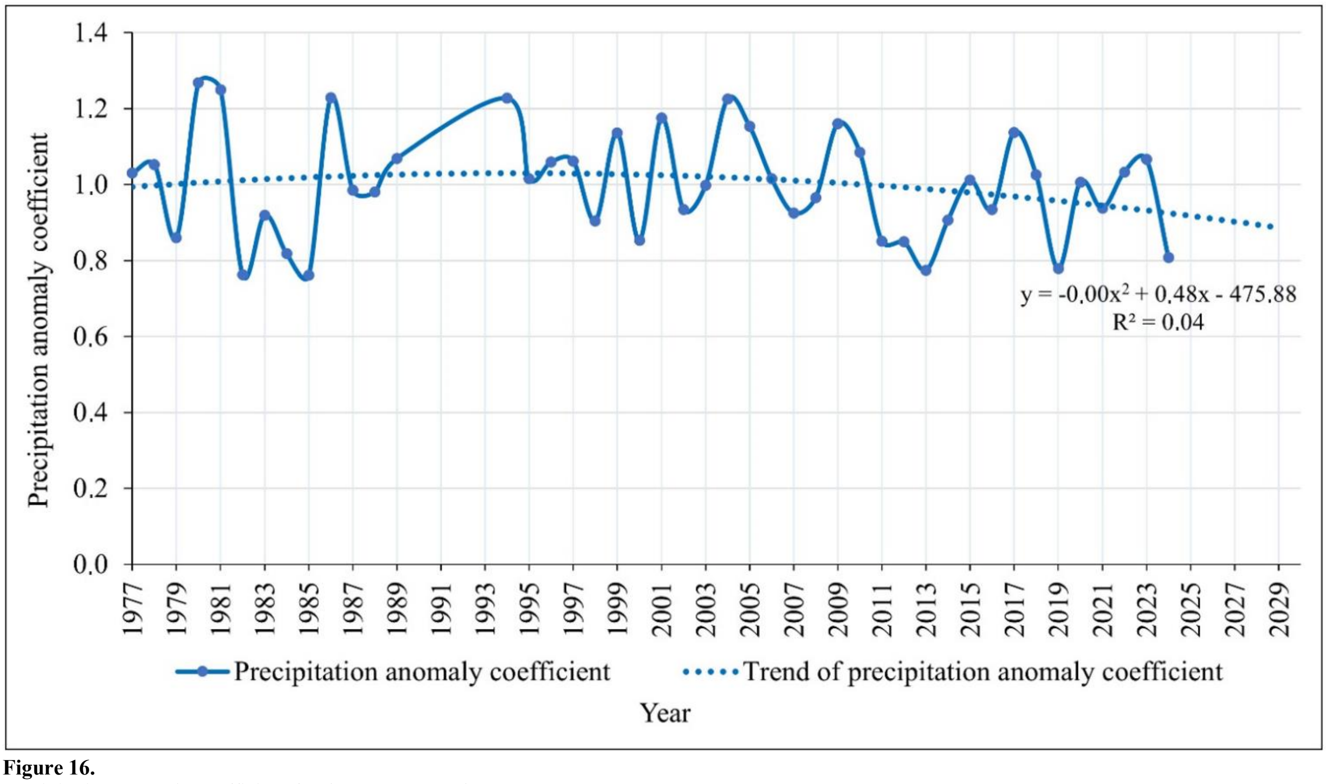


**Figure 16.**
Precipitation anomaly coefficient for the Krasnaya Polyana resort area.

*4.3. The Concept of an Automated Avalanche Hazard Monitoring System*

At present, interest in developing automated monitoring systems for natural hazards, including avalanches, is growing worldwide. Such systems can be based on the analysis of various factors, the use of modern equipment, software solutions, and neural networks. For example, acoustic sounding or infrasound signal recording has been applied in previous studies [23, 24]. In the Swiss Alps, a monitoring system based on LiDAR and optical sensors is used to measure fluctuations in snow depth within avalanche zones [25]. Snow cover monitoring is also conducted using a microwave radar system with two receivers [26]. Automatic real-time avalanche detection is performed through optical visualization of satellite images [27].

Despite the diversity of methods and the possibilities offered by remote sensing, a key requirement is the ease of installation of monitoring systems in mountainous areas, along with simplicity and cost-effectiveness of sensor design. These factors ensure the feasibility of widespread deployment and improve the accuracy of the collected data.

The climate changes discussed above, along with the increasing avalanche risk, stimulate the development of avalanche hazard monitoring systems in the study regions.

At the Krasnaya Polyana resort, the Snowburst hardware and software complex is successfully used for monitoring [28]. The complex consists of a weather station and software for analyzing avalanche conditions. It is installed on a spur of the Aibga Ridge at an altitude of 2,150 m. The primary purpose of the weather station (Figure 17) is to collect and transmit snow and meteorological data from an avalanche-prone slope section threatening the ski resort.

**Figure 17.**
The weather station of the Snowburst hardware and software complex.

The weather station includes a multi-parameter sensor that measures standard meteorological variables: air temperature, wind direction and speed, atmospheric pressure, and relative humidity. Additionally, it is equipped with a remote rod containing 15 temperature sensors (spaced every 10 cm) for measuring the snowpack temperature profile (Figure 18a) and a laser sensor for snow depth measurement.

In addition to the main weather station, the resort operates six remote snow-temperature rods installed in avalanche zones. These are powered by lithium-polymer batteries charged via mini solar panels. Data from the rods are transmitted to the microcontroller via radio frequency communication (Figure 18b).


**Figure 18.**
External snow-temperature rod.

All data collected from the weather station and snow-temperature rods are stored on dedicated servers. Weather data for any required period can be retrieved when necessary. The information from the weather stations is also transmitted to an information board in the avalanche prevention service office, where it is displayed in a clear visual format (Figure 19). Based on the data collected, the avalanche prevention service issued an avalanche bulletin. Furthermore, seasonal statistical analysis is conducted to predict future trends (Figure 20).


**Figure 19.**
Display of information on the board in the avalanche prevention service office.

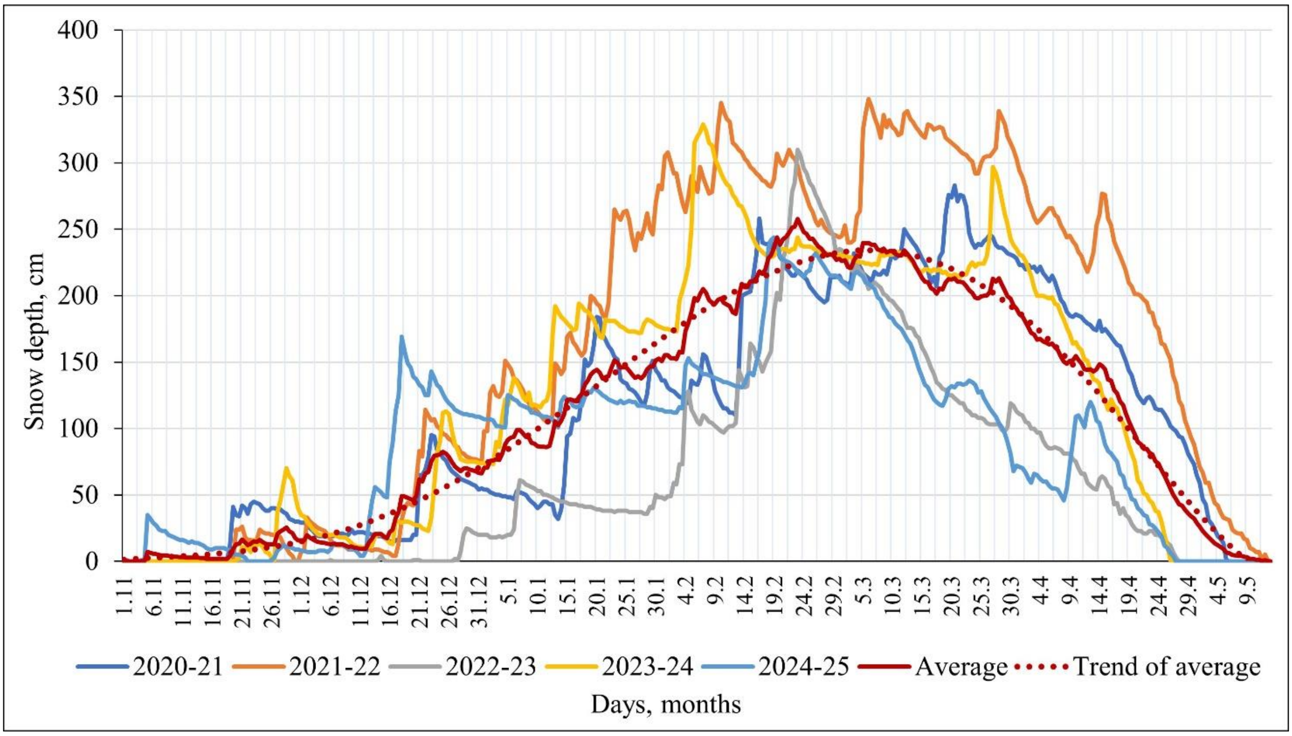


**Figure 20**.
Registration of changes in the height of snow with a snow-temperature rod on the slope.

A similar system is being developed for the East Kazakhstan Region. The avalanche monitoring system designed in this study consists of a base monitoring station operating in conjunction with snow-temperature rods. Unlike the system used at the Krasnaya Polyana resort, the base station in this case is installed not above a hazardous avalanche accumulation area, but below the slope in a location safe from avalanches.

The avalanche hazard monitoring system developed for the East Kazakhstan Region (Figure 21) is a hardware–software complex comprising sensors and equipment that collect key meteorological and climatic parameters to ensure effective monitoring and real-time data transmission.

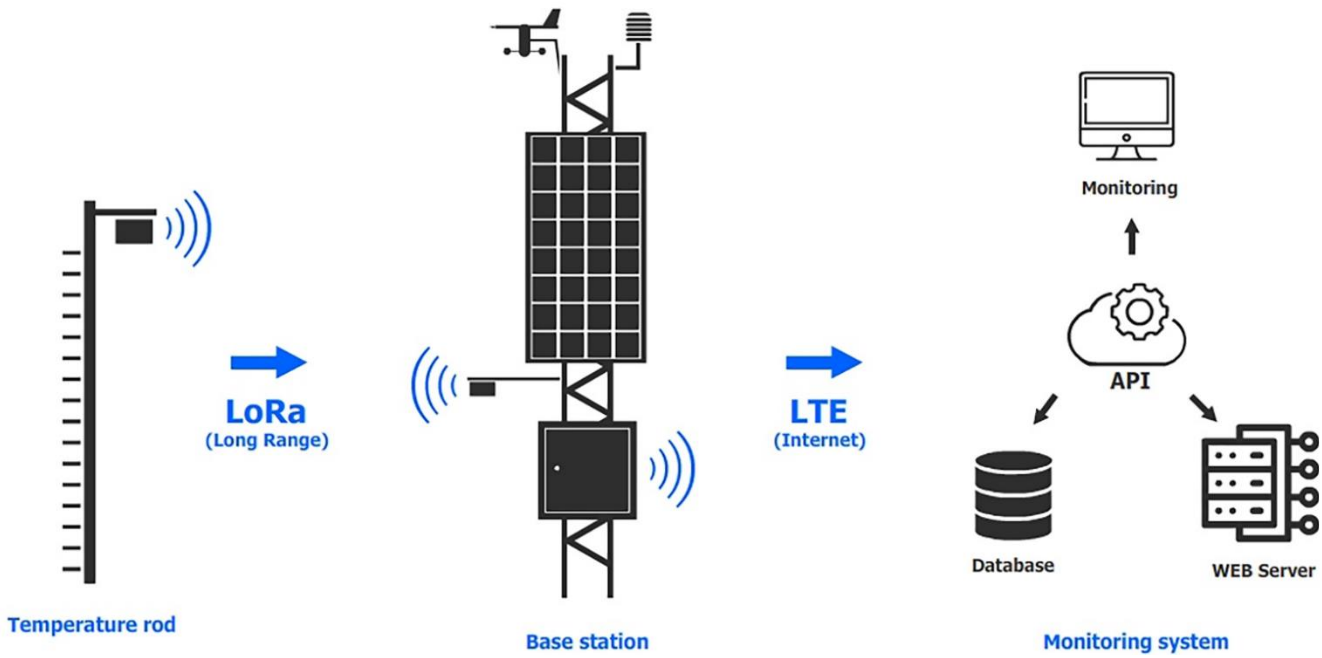


**Figure 21.**
Avalanche hazard monitoring system diagram.

The monitored parameters include wind speed, wind direction, air temperature, relative humidity, atmospheric pressure, snow depth, and the snow cover temperature gradient. All equipment, including the mast structure, can be easily installed manually and does not require heavy machinery or aircraft support (Figure 22).

**Figure 22.**
Base station and snow-temperature rod in an avalanche-prone area of the East Kazakhstan Region.

The station was tested during the 2024–2025 winter season in an avalanche-prone area of the East Kazakhstan Region. Real-time data received from the station allows the identification of critical moments for avalanche formation (Figure 23). The system’s algorithms process the data to assess the likelihood of avalanche occurrence. For example, Figure 23 illustrates periods of elevated avalanche risk during heavy precipitation events, accompanied by an increase in snow depth, simultaneous or subsequent rises in wind speed, and sharp increases in air temperature.

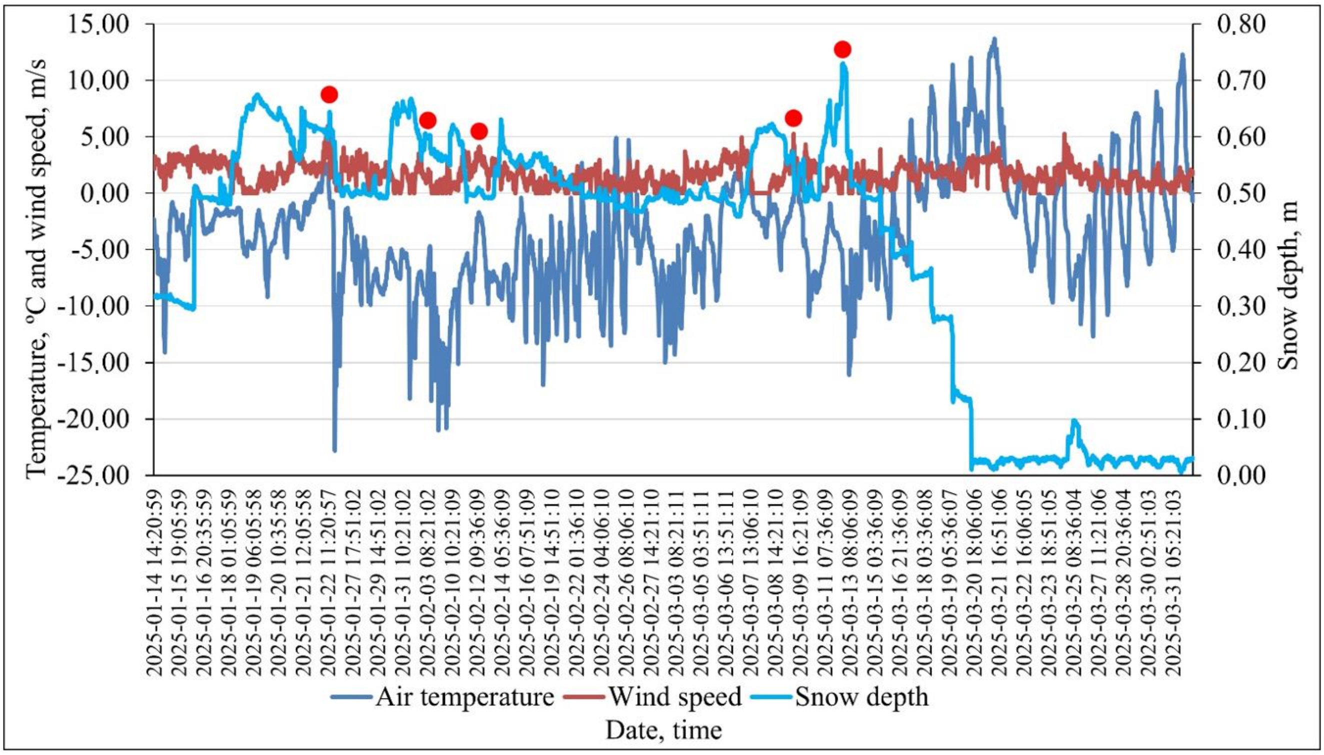


**Figure 23.**
Detection of critical periods of increased avalanche risk based on monitoring data.

The system also provides insights into the microclimate of each avalanche-prone area, including the wind rose, prevailing wind directions and speeds, temperature ranges, relative humidity, and snow accumulation on the slope. Figure 24 shows the wind characteristics of such an area, which help determine the likely formation directions of snow cornices and wind slabs.

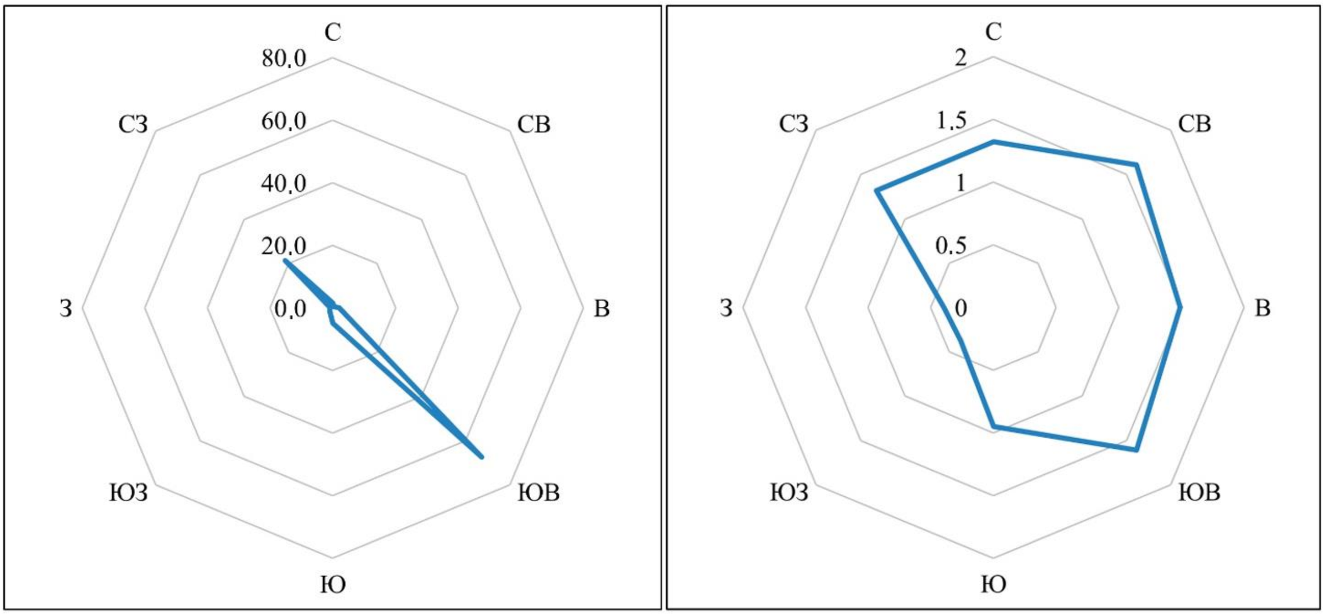


**Figure 24.**
Wind rose and wind speed distribution in an avalanche-prone area.

Data from the snow-temperature rod additionally enables the detection of temperature gradients within the snowpack. Different types of snow metamorphism occur under varying temperature and gradient conditions, influencing the strength and stability of snow layers. Certain types of metamorphism, such as that caused by depth hoar formation, can create weak layers that may trigger avalanches. The temperature profile makes it possible to anticipate such processes. The system's algorithms visualize the temperature profile as a heat map, improving data interpretation (Figure 25).

All monitoring data are made available to the relevant units of the Emergency Department of the East Kazakhstan Region and the state institution Kazlezashchita for informed decision-making on avalanche risk prevention.

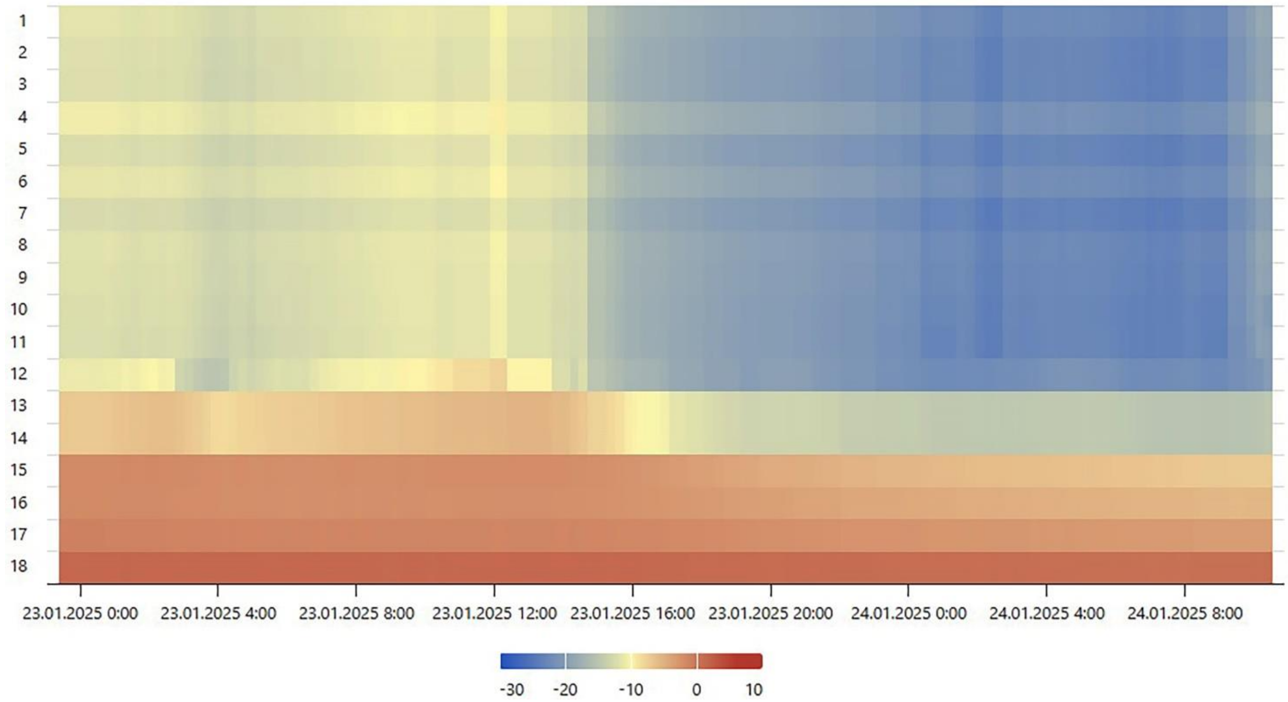


**Figure 25.**
Visualization of snow-temperature rod data as a heat map.

## 5. Conclusion

The material presented in the discussion provides insight into the regional manifestations of climate change in two contrasting regions with increased avalanche activity, as well as demonstrates the capabilities of modern monitoring systems. The analysis revealed that both in the East Kazakhstan Region and in the Krasnaya Polyana area, climatic trends consistent with global warming are observed: an increase in average annual temperature, changes in precipitation patterns, and an increase in the frequency of extreme weather events.

The East Kazakhstan Region is characterized by an increase in winter precipitation and the number of days with heavy snowfall, a rise in wind speed, and a decrease in the average snow depth, while avalanche activity increases. In Krasnaya Polyana, there is a decrease in the total amount of winter precipitation and in the average snow depth, but an increase in maximum snow height and in the frequency of abnormal precipitation events, indicating growing climatic instability. In both regions, climate change is driving the transformation of avalanche activity, the displacement of avalanche-prone zones, and increased avalanche hazards.

The monitoring systems in both regions are software–hardware complexes comprising weather stations and remote snow-temperature rods, which collect key parameters such as air temperature, relative humidity, atmospheric pressure, wind direction and speed, snow depth, and the snow temperature profile. These stations are safe to install and maintain, easy to deploy, autonomous (solar panels, batteries), transmit real-time data, and contain algorithms to detect critical avalanche conditions. The systems used in the study also provide data visualization to support decision-making.

Further development of the monitoring system should focus on expanding the station network to cover a greater number of avalanche-prone areas, thereby increasing the spatial resolution of monitoring. Integration with remote sensing technologies (satellite and unmanned aerial systems) would enable the observation of avalanche events and snow conditions in hard-to-reach locations. The application of neural network models and machine learning algorithms could automate avalanche risk forecasting through the comprehensive analysis of long-term and real-time data. In the context of climate change and the intensification of extreme precipitation, it is advisable to develop early warning systems capable of notifying emergency services and the public in real time. Simplifying sensor designs and reducing their cost would facilitate large-scale deployment, including in remote mountainous areas.

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