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Spatial model of the Trooz Glacier dynamics based on meteorological data from the Akademik Vernadsky station

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Abstract. This paper models the dynamics of the Trooz Glacier, Antarctic Peninsula. To integrate remote and meteorological data, we processed ice flow velocities derived from satellite radar imagery, air temperature, and precipitation obtained from the ERA5 reanalysis, and *in situ* meteorological observations from the Ukrainian Antarctic Akademik Vernadsky station. Glacier surface velocity was estimated using the offset-tracking method applied to Sentinel-1 satellite data for the period 2015—2025, generating 286 ice flow maps. An approach is developed to calculate air temperature over the glacier surface using *in situ* measurements from the remotely located Akademik Vernadsky station, in the absence of additional data. Spatial models of temperature and glacier velocity were constructed, accounting for additional parameters such as precipitation and glacier surface elevation above sea level. Time series analysis over the past decade indicates contrasting trends: increasing air temperature at the Akademik Vernadsky station (+0.12 °C/year) and decreasing temperatures over the glacier surface (−0.07 to −0.13 °C/year). A Fourier series approximation made it possible to clarify a seasonal pattern in glacier velocity. From the mean velocities, there is a tendency toward 1—4% acceleration in ice flow. Analysis of the model showed that air temperature and surface elevation together explain approximately 54% of the spatial variation in mean velocity, with the remaining variability attributable to other factors, including glacier bed geometry, ice thickness, subglacial drainage conditions, and local ice-flow morphology. The resulting spatial models can be used to further predict climate-driven changes in the glacier system.

Keywords: ERA5, Fourier series, glacier acceleration, offset tracking, Sentinel-1

1 Introduction

Modeling glacier dynamics is an important scientific task (Zekollari et al., 2022), as it enables a better understanding of their temporal evolution and the prediction of their contribution to global sea-level change (Parkes & Marzeion, 2018; Frederikse et al., 2020). This, in turn, is essential for understanding the impacts of climate change and for developing robust scenarios of future change (Edwards et al., 2021; Hugonnet et al., 2021). Under modern conditions, this is made possible by the availability of a wide range of data sources obtained from both *in situ* measurements (Machío et al., 2017; Still et al., 2024) and Earth remote sensing methods (Gomez et al., 2019; Ciracì et al., 2020; Hu et al., 2023). The development of long-term time series based on such data enhances the reliability and accuracy of glacier dynamics models. In addition, the integration of different types of observations (Forte et al., 2024; Sanchez Lofficial et al., 2025) enables a comprehensive assessment of spatio-temporal changes in the processes under study.

The main parameters underlying glacier dynamics models include meteorological, glaciological, hydrological, and geological characteristics (T. Zhang et al., 2013). Despite significant logistical challenges, the study of mountain glaciers can be supported by direct *in situ* measurements of these parameters (Neckel et al., 2020; Yang et al., 2020). At the same time, systematic ground-based observations are extremely limited, if not nearly impossible, for Antarctic glaciers. In this context, a key source of information is Earth remote sensing data, which provide spatio-temporal coverage of the studied areas.

Such data include optical satellite imagery (Winsvold et al., 2016; Lo Vecchio et al., 2018) and, of particular importance for polar regions, radar imagery (Euillades et al., 2016; Mouginot et al., 2019; Lee et al., 2023). The use of radar technologies enables the generation of continuous time series of observations, regardless of weather conditions and illumination. This, in turn, provides stable and representative data for analysing glacier dynamics over long periods.

Owing to the continuous operation of the Sentinel-1 mission, a more than a decade-long time series of radar imagery has been established. This duration of observations provides a basis for a detailed analysis of long-term trends in glacier dynamics. In addition, the regular acquisition of imagery ensures high temporal resolution, which is critical for detecting both seasonal (Nanni et al., 2023; Otosaka et al., 2023; Charrier et al., 2025) and interannual changes (Vijay & Braun, 2017; J. Zhang et al., 2021; Cheng et al., 2022).

The detection of such patterns in glacier dynamics is based on the analysis of changes in ice flow velocity. Velocity maps are typically derived from radar imagery using the offset tracking method (Gomez et al., 2019; Jawak et al., 2019; Wen & Wang, 2025). This approach enables the assessment of the spatial distribution of velocities and their temporal variability, which is essential for interpreting dynamic processes.

Offset tracking method has proven to be a reliable tool for determining ice flow velocities from synthetic aperture radar (SAR) data. Its key advantage is the ability to capture the dynamic characteristics of fast-moving glaciers (Łukosz et al., 2022; Feng et al., 2023), particularly those common on the Antarctic Peninsula (Jawak et al., 2019). Unlike synthetic aperture radar interferometry (InSAR), which is significantly limited by coherence loss (decorrelation), OT provides stable, representative results. In addition, this approach is less sensitive to variations in ice surface properties, which further enhances its effectiveness under the harsh environmental conditions of Antarctica.

The second most important parameter in glacier dynamics models is air temperature. Glacial systems are sensitive to variations in ambient temperature, which alter their dynamics (Hall et al., 2008; Cicoira et al., 2019; Rounce et al., 2023). Meanwhile, seasonal fluctuations in ice flow velocity are directly related to the annual temperature cycle.

Increasing attention is being paid to the quantitative analysis of the relationship between climate parameters and the dynamics of West Antarctic glaciers, which are sensitive indicators of climate change on Earth (Rignot et al., 2019; Christie et al., 2022; Wallis et al., 2023). For this purpose, data from global atmospheric reanalyses are widely used to analyse temperature trends and assess climate impacts on the cryosphere (Tetzner et al., 2019; Bonshoms et al., 2022; Christie et al., 2023).

This study adopts a comprehensive approach that integrates processing of ground-based observations and remote sensing data to model glacier dynamics. Atmospheric conditions for the study area are determined based on *in-situ* measurements of meteorological parameters at the Akademik Vernadsky station located on Galindez Island (Argentine Islands, 65°15′ S, 64°16′ W). Observations from the Akademik Vernadsky station span more than half a century and constitute one of the longest climate records in Antarctica (Khrystiuk et al., 2022). Original data collected at the British Faraday Station in the 1950s have gradually been integrated with modern measurements con-

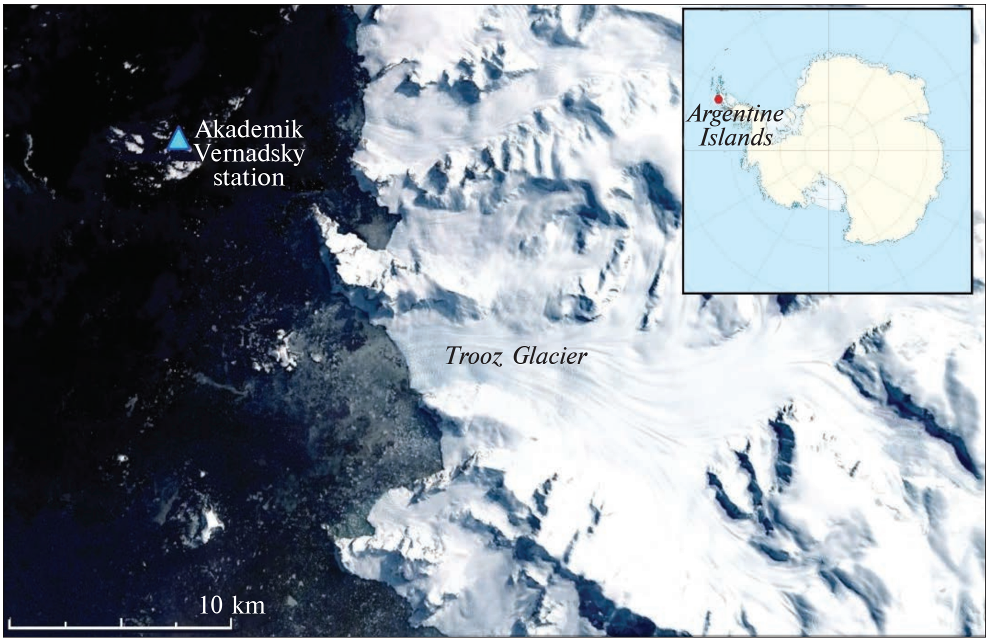

Figure 1. Akademik Vernadsky station located on Galindez Island, Argentine Islands, and the Trooz Glacier in its vicinity

ducted by the State Institution National Antarctic Scientific Center of Ukraine (SI NASC). The station systematically records key meteorological variables at synoptic intervals of 3 or 6 hours.

The object of this study is the Trooz Glacier. It is the largest glacier on the Kyiv Peninsula, separated from the Akademik Vernadsky station by the 7 km-wide Penola Strait. Therefore, meteorological observations at the station provide a reliable source of information on atmospheric changes in the region. Many glacier studies are based on relatively short time series of ice flow velocity, typically spanning only a few years. This significantly limits the ability to develop robust models of the relationship between air temperature and glacier dynamics. This study exploits the full Sentinel-1 SAR time series available for the Kyiv Peninsula for the period 2015–2025.

Meteorological parameters over the glacier surface were derived from ERA5 reanalysis data, thereby facilitating the establishment of relationships between *in situ* measurements at the weather station and different parts of the glacier.

The aim of this comprehensive approach is to develop a predictive model of the Trooz Glacier velocity in response to long-term air temperature trends in the region. In addition, it is planned to quantify the temperature component's contribution to the glacier velocity model. This will enable the assessment of temperature-driven influences on ice flow dynamics and the quantification of their contribution relative to other factors affecting flow velocity.

Study area. The study area is located in the Argentine Islands region off the western coast of the Antarctic Peninsula, near the Akademik Vernadsky station (Fig. 1). The station is situated on Galindez Island and serves as an important scientific base for long-term environmental and meteorological observations in this part of Antarctica.

The Trooz Glacier is an outlet glacier that drains into the coastal zone of the Argentine Islands. The glacier is influenced by both local climatic conditions and regional atmospheric circulation patterns typical of the maritime Antarctic environment. Due to its proximity to the Akademik Vernadsky station, it is well-suited for studies that combine remote sensing data with *in-situ* meteorological measurements.

The region is characterised by a maritime Antarctic climate, with relatively mild temperatures compared to the Antarctic continental interior, high humidity, and frequent cyclonic activity. Seasonal variability in air temperature, precipitation, and wind conditions strongly influences glacier surface processes, including accumulation, ablation, and ice flow dynamics (Kadurin & Andrieieva, 2021; S. Kadurin & V. Kadurin, 2023).

The availability of long-term meteorological observations from the Akademik Vernadsky station, together with satellite-derived measurements of glacier motion, provides a valuable opportunity to investigate the relationship between climatic variability and the Trooz Glacier dynamics.

2 Data and methods

2.1 Input data

Modern satellite SAR methods allow the generation of detailed maps of glacier flow velocity and the analysis of their spatiotemporal variability. At the same time, meteorological parameters, particularly air temperature, remain key factors influencing the glacier mass balance, thermal regime, and flow velocity. However, the quantitative description of the relationship between weather-station temperature measurements and the dynamics of a specific glacier at a local scale remains insufficiently studied.

2.1.1 Ice flow velocity maps

Monitoring of changes in the glacial systems of the Antarctic Peninsula was carried out using a long-term series of SAR data from the Sentinel-1 satellite, which has provided regular observations of this region since June 2015. The resulting observational record forms the basis for analysing spatiotemporal variations in the flow velocity of the Trooz Glacier.

The offset tracking method was used to determine ice flow velocities in this study. This approach is based on the comparison of amplitude characteristics of SAR images and, unlike interferometric methods, does not require phase coherence. As a result, the method exhibits significantly higher resistance to temporal decorrelation, which is typical of Antarctic conditions.

The principle of the OT method is to perform a correlation search for displacements between pairs of consecutive SAR images. OT has several advantages: two components of the velocity vector can be derived from a single orbit – along the satellite flight direction and in the line-of-sight direction; the method remains effective even under conditions of rapid coherence loss, which is typical of regions with dynamically changing surfaces.

Despite its somewhat lower accuracy than interferometric approaches, the OT method has demonstrated high performance in areas with well-defined surface morphology. Such conditions are typical of many glaciers, where the surface contains numerous crevasses, faults, and other textural features that facilitate displacement estimation between successive images. Velocity maps derived in this way offer a consistent spatiotemporal representation of ice motion and provide a robust basis for further analysis of glacier dynamics.

The research used archival SAR data from the Sentinel-1 mission. The full set of available GRD SAR images in dual polarization (HH and HV) for the period from June 2015 to February 2025 was processed. As a result, 286 ice velocity maps were derived for the Kyiv Peninsula, in particular for the Trooz Glacier. The results obtained are in good agreement with previous multi-year studies based on the Sentinel-1 archive (Wuite et al., 2026), which confirms the effectiveness of the offset-tracking method as an important tool for monitoring glacier flow in polar regions.

The high temporal resolution of satellite acquisitions (12-day revisit cycle) enabled the formation of a consistent time series and provided a reliable basis for developing a spatial model of the Trooz Glacier flow velocity.

2.1.2 ERA5 reanalysis meteorological data

Meteorological parameters over the glacier surface were derived from the ERA5 atmospheric reanalysis available through the Climate Data Store (https://cds.climate.copernicus.eu/datasets). ERA5 is the fifth-generation global atmospheric reanalysis produced by the Copernicus Climate Change Service at the European Centre for Medium-Range Weather Forecasts. This dataset provides a consistent representation of atmospheric conditions and various meteorological parameters over recent decades. The data are distributed in NetCDF format, facilitating their use in further processing.

Data processing was performed in a Linux environment using Climate Data Operators (CDO). CDO is a collection of command-line tools for processing and analysing data in NetCDF-3, NetCDF-4, GRIB1, GRIB2, and other formats (Clmate Unboxed, 2021). Using CDO, a range of operations can be performed, including data and metadata inspection, subsetting to an area of interest, statistical analysis, interpolation using commonly used methods (*e.g.*, nearest-neighbour, bilinear, and bicubic interpolation), and extraction of model parameters at specified geographic coordinates.

Reanalysis datasets combine historical observational records with numerical models to provide consistent time series of key meteorological variables. ERA5, in particular, represents the most up-to-date and accurate reanalysis for the Antarctic region (Gossart et al., 2019). This version has been significantly improved compared to its predecessor (Gleixner et al., 2020). However, numerous studies indicate that the accuracy of temperature estimates in the model varies considerably with meteorological conditions, particularly during intense precipitation.

In the West Antarctic region, the accuracy of ERA5 temperature estimates decreases with increasing precipitation (Nicola et al., 2023). This is attributed to the limited availability of ground-based observations in the region and the difficulty of accurately representing heat and moisture exchange processes under cloudy conditions and during precipitation phase transitions (Roussel et al., 2020). For example, during periods of liquid precipitation (rain), which are increasingly observed over West Antarctic ice shelves (Wille et al., 2022), surface temperature errors can reach 2—3 °C. In contrast, during dry winter periods, temperature accuracy remains within 0.5—1.0 °C (Gossart et al., 2019).

Of particular importance are situations involving atmospheric river events. According to Wille et al. (2022), during such events, ERA5 tends to underestimate both maximum surface temperatures and rainfall, which complicates the analysis of glacier surface energy balance.

Therefore, when using ERA5 to investigate changes in the temperature regime of West Antarctica, potential errors during periods of intense precipitation should be taken into account. In particular, it is beneficial to integrate ERA5 data with *in situ* observations, GNSS data, and remote sensing results to obtain a more comprehensive understanding of climate variability (Mo et al., 2021).

Given the potential decrease in ERA5 accuracy during periods of intense precipitation, 2 m air temperature and precipitation data were used to investigate the relationship between ice flow velocity and meteorological parameters.

2.1.3 *In-situ* meteorological measurements at the Akademik Vernadsky station

For the analysis in this study, 3-hourly air temperature and precipitation data from the Akademik Vernadsky station for the period 2015—2022 were used. These records were obtained from the SI NASC archive (http://meteodata.uac.gov.ua/SYNOP_data/decoded_table_data/). The integration of these *in situ* observations with meteorological variables derived from ERA5 over the Trooz Glacier enabled the identification of relationships between temperature characteristics and other atmospheric variables influencing glacier behavior.

A characteristic feature of the study area is that meteorological measurements are conducted at sea level (0 m a.s.l.). The air temperature over the glacier surface, which extends over tens of kilo-

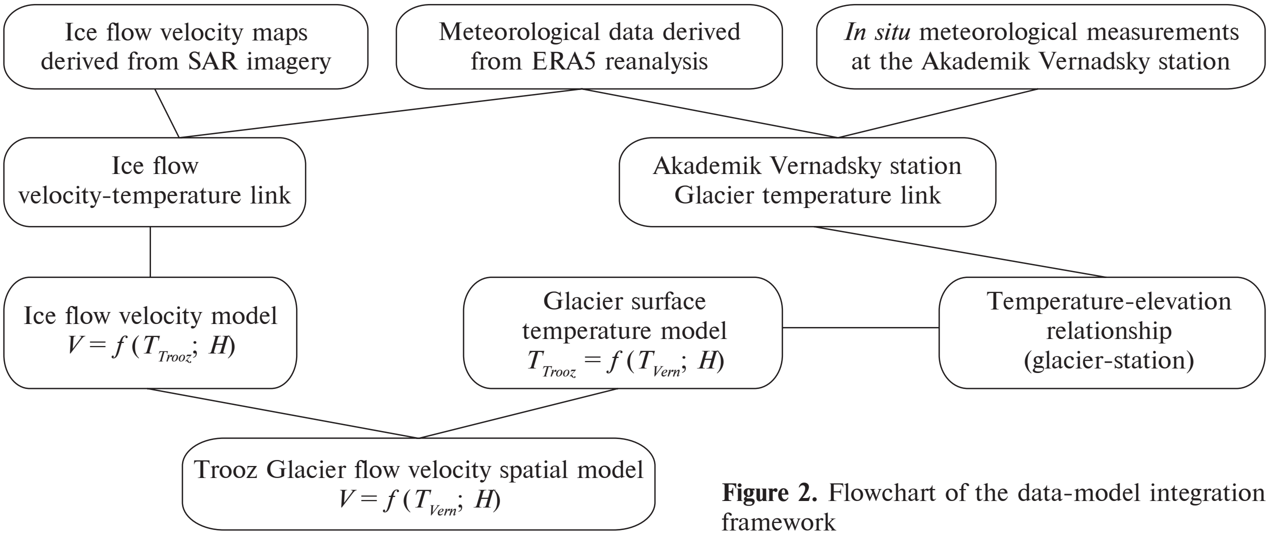

Figure 2. Flowchart of the data-model integration framework

meters, is also influenced by elevation. This necessitates accounting for the altitudinal temperature gradient and spatial heterogeneity of climatic conditions when analysing the influence of atmospheric factors on glacier dynamics.

In this context, the objective is to develop a predictive model of ice flow velocity based on meteorological observations from the Akademik Vernadsky station and atmospheric variables derived from ERA5, while accounting for glacier surface elevation above sea level.

2.2 Methods

To achieve the objective, the study developed a system of interconnected models describing: 1. The spatial distribution of air temperature over the Trooz Glacier; 2. The relationship between temperature characteristics on the glacier and both *in-situ* measurements at the Akademik Vernadsky station and the glacier's surface elevation; 3. The statistical and spatiotemporal relationships between *in-situ* temperature measurements and ice flow velocity.

The conceptual framework is reflected in the block diagram, which illustrates the relationships among input data, intermediate models, and the final predictive model for glacier velocity. Given the complexity of the processes governing glacier dynamics, the study employs a stepwise modelling approach that accounts for the hierarchy of cause-and-effect relationships between atmospheric and glaciological parameters. Formalising this structure requires a systematic representation of the interactions between input data, intermediate computational models, and final predictive relationships.

Figure 2 presents a flowchart illustrating the relationships among the studied components, reflecting the integration of meteorological observations, reanalysis data, terrain characteristics, and ice flow velocity estimates into a unified predictive model of the Trooz Glacier dynamics.

Spatial model construction was based on the analysis of input data from points along the central ice flowline (longitudinal profile P1-P12) and three transverse profiles (P4, P7, P9). The spacing of ice flow velocity values along the profiles was 100 m. Figure 3 shows a schematic representation of the profile locations on the Trooz Glacier.

Based on data analysis for the period 2015–2025, consistent time series of near-surface air temperature and the flow velocity of the Trooz Glacier were constructed. To identify the underlying patterns and reduce the influence of random noise, both datasets were approximated using

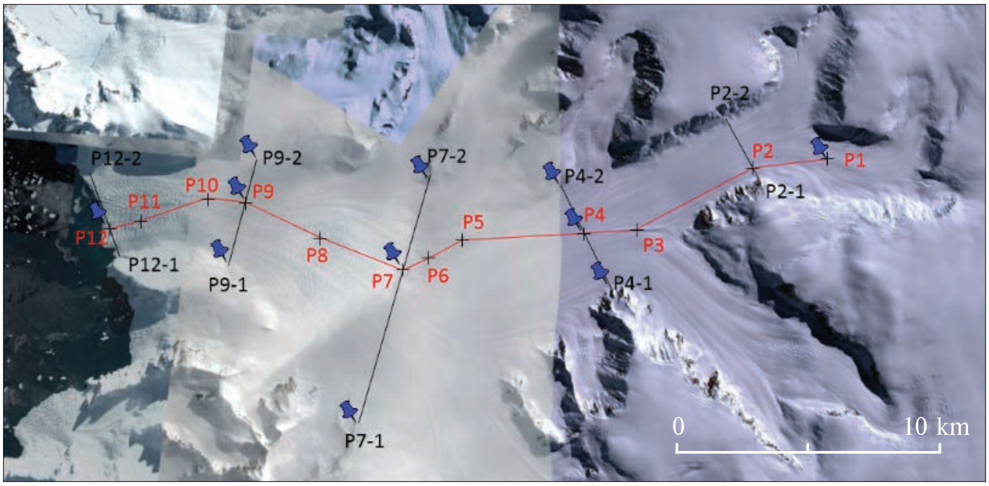

Figure 3. Control points on the Trooz Glacier used for the development of spatial models of ice flow velocity and temperature field: — central flowline; — transverse profiles; + control points

20th-order Fourier polynomials, allowing the representation of their seasonal and long-term components. The resulting smoothed relationships were used for further statistical analysis and for establishing functional relationships between the temperature regime and glacier flow dynamics, forming the basis for predictive models of glacier velocity changes.

2.2.1 Relationship between temperature variables at the "Vernadsky–Glacier" system

To establish the relationship between the ice flow velocity of the Trooz Glacier and meteorological parameters, air temperature measured at the Akademik Vernadsky station was compared with temperature data over the glacier surface derived from the ERA5 climate reanalysis. Figure 4a presents a time series of air temperature at the Akademik Vernadsky station and over the glacier surface at point P4 (the central part of the glacier) based on ERA5 data. The comparison reveals a systematic bias between the two time series. The calculated mean bias amounts to 6.1 °C. Figure 4b shows the station temperature time series after bias correction, together with the glacier surface temperature time series.

Figure 4b shows that the time series transformed from station measurements to glacier conditions exhibits deviations, particularly at the minimum temperature values. The correlation coefficient between the two time series is $r = 0.85$.

The reliability of air temperature measurements at the weather station is higher than that of temperature estimates over the glacier surface derived from reanalysis data. To improve the accuracy of transforming station-measured temperatures to glacier conditions, the two time series are represented using a Fourier series approximation:

$$t = a_0 + \sum_{i=1}^{n} \left[c_i \cdot \cos(i \cdot f) + s_i \cdot \sin(i \cdot f) \right], \qquad (1)$$

where n is the number of Fourier harmonics; a_0, c_i, and s_i are constant coefficients determined by the approximation method, $f = \Delta T / 2\pi$ (ΔT is the time interval between the first and last temperature measurements).

Figure 5 presents two time series approximated by a Fourier series. The averaging parameter was set to $n = 100$, which allows the identification of seasonal temperature patterns as well as interannual variability. The overall seasonal trend in air temperature changes at the Akademik Vernadsky station and at the glacier surface, based

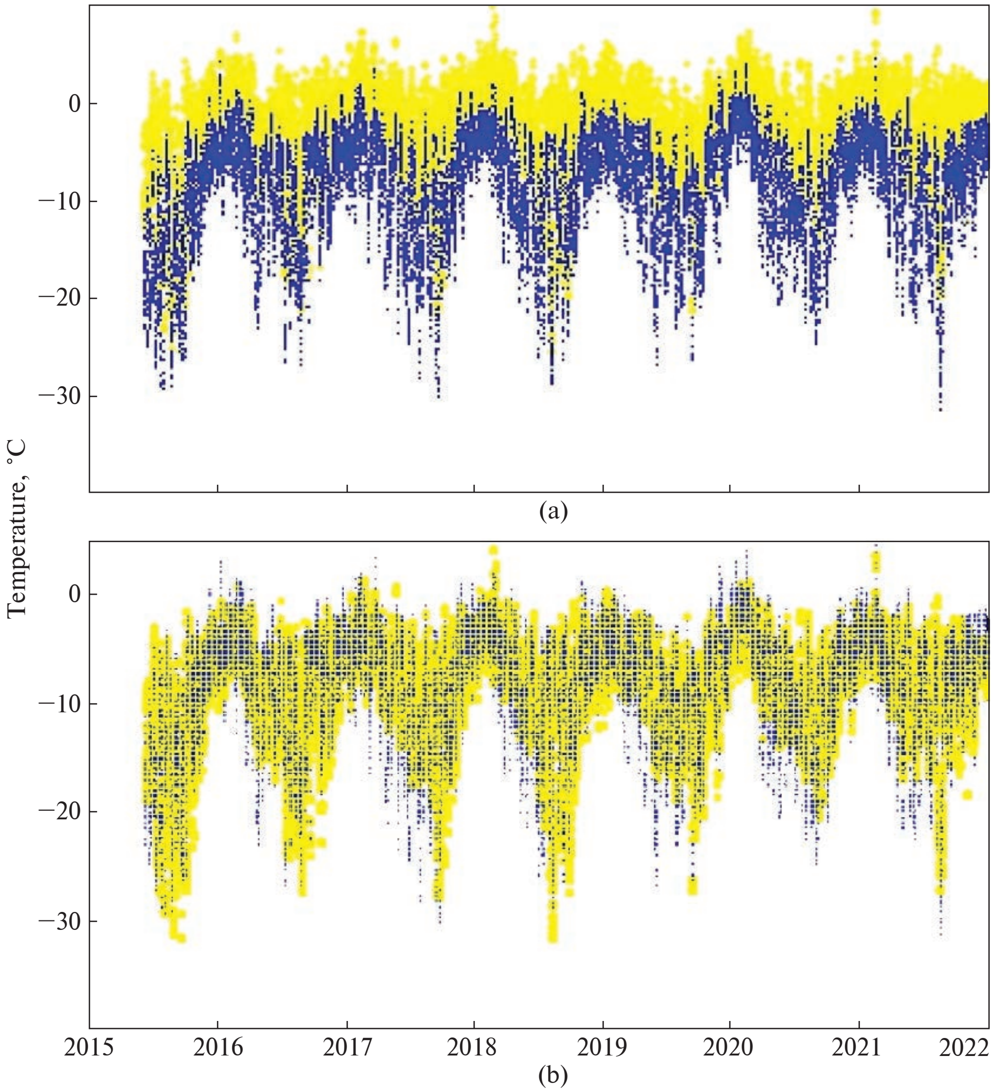

Figure 4. Time series of air temperature at the Akademik Vernadsky station (yellow dots) and over the glacier surface at point P4 based on ERA5 (blue dots): data: (a) unadjusted air temperature values; (b) station air temperature after correction for the systematic bias (6.1 °C) between station and glacier measurements

on the approximated time series, shows a strong correlation (r = 0.94).

However, the temperature difference between the glacier surface and the weather station varies with time of day. Table 1 presents the mean values of the temperature differences δ_t between the glacier surface and the weather station for different periods of the day.

The table shows that, in the first half of the day, all temperature differences are negative, whereas in the second half they are positive. This indicates that the glacier surface temperature is lower at night, resulting in a greater temperature difference in the first half of the day and a smaller difference in the second half. The magnitude of the temperature difference reaches its maximum in the first

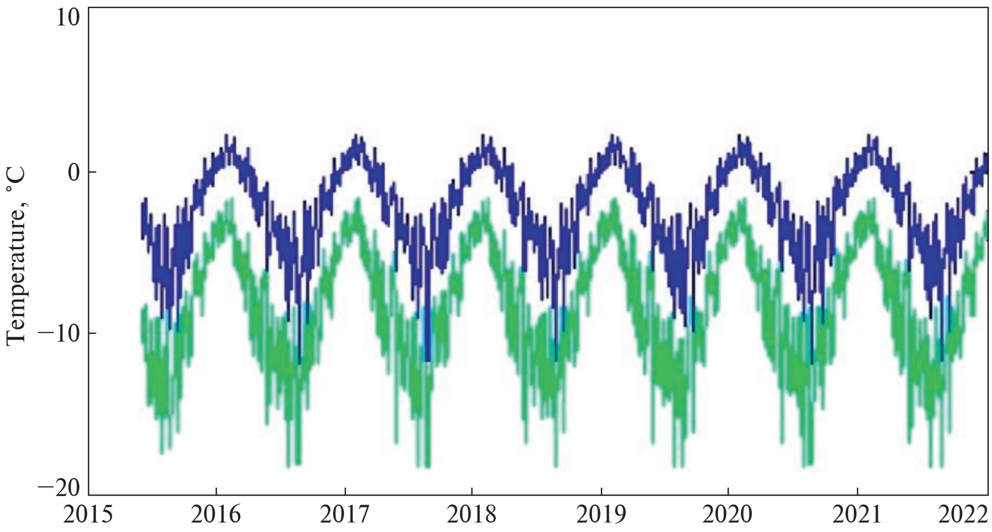

Figure 5. Time series of air temperature measurements at the Akademik Vernadsky station (blue) and at the glacier surface based on ERA5 reanalysis data (green), approximated using Fourier series

half of the day and its minimum in the second half. Accordingly, depending on the time of day, a correction δ_t from Table 1 should be applied to the predicted temperature difference.

In this study, the predictive model incorporates an additional factor – the amount of precipitation in the region. It was found that the temperature difference depends on precipitation at the time of measurement. Figure 6 shows the relationship between the measured temperature differences between the glacier surface and the weather station and precipitation amounts during the period 2015–2022.

Figure 6 shows that the amplitude of temperature differences decreases with increasing precipitation. In particular, at a precipitation of 2–3 mm, the temperature difference between the glacier surface and the Akademik Vernadsky station remains nearly constant throughout the year at approximately −4 °C. The distribution of temperature differences exhibits upper and lower bounds that vary nonlinearly with increasing precipitation.

Figure 7 shows the upper and lower bounds of the temperature difference distribution, modeled as functions of precipitation.

The upper t_u and lower t_l boundary curves can be expressed as second-order polynomials of precipitation p:

$$t_u = 0.063p^2 - 0.801p - 1.2, \quad (2)$$

$$t_l = -0.208p^2 + 3.286p - 14.2. \quad (3)$$

Temperature difference measurements that fall below the lower bound t_l or above the upper bound t_u of the distribution are considered to have low

Table 1. Mean temperature differences δ_t between the glacier surface and the weather station for different times of day

Time of day, hour	Difference δ_t, °C
0	0
3	−0.156
6	−0.177
9	−0.118
12	0.081
15	0.310
18	0.392
21	0.252
24	0

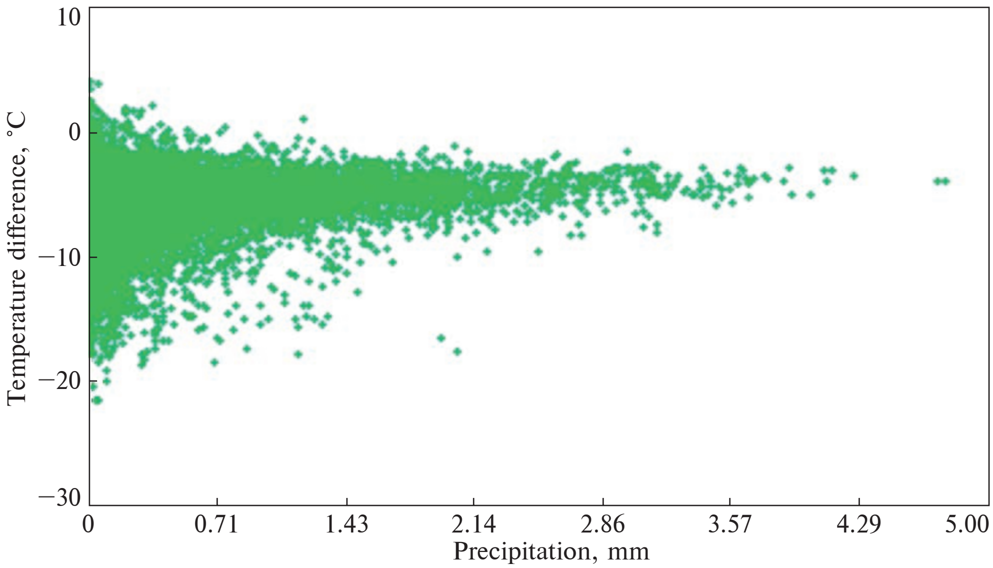

Figure 6. Distribution of temperature differences between the glacier surface and the Akademik Vernadsky station as a function of precipitation during 2015—2022

reliability. Accordingly, they should either be filtered out from the time series as erroneous values or adjusted by applying a correction δ_p to bring them within the range defined by t_u and t_l.

$$\delta_p = \begin{Bmatrix} t_u - (T_{Vern} + \delta_t) \\ t_l - (T_{Vern} + \delta_t) \end{Bmatrix} if \begin{Bmatrix} (T_{Vern} + \delta_t) > t_u \\ (T_{Vern} + \delta_t) > t_l \end{Bmatrix}. \quad (4)$$

Figure 8 shows the time series of temperature differences between the measured air temperature at the Akademik Vernadsky station and on the glacier ($T_{Vern} - T_{Trooz}$), approximated using a Fourier series. A time-of-day correction δ_t has been applied to this time series.

Figure 9 shows the time series of measured air temperature at the Akademik Vernadsky station, adjusted using the δ_t and δ_p corrections, and air temperature over the Trooz Glacier derived from ERA5 reanalysis data.

The introduction of the δ_t and δ_p corrections increased the correlation coefficient from $r = 0.85$ to $r = 0.96$. The root mean square error (RMSE) of glacier temperature estimation based on station air temperature without applying the δ_t and δ_p corrections is $m_t = \pm 2.9$ °C, whereas after applying the corrections, it decreases to $m_t = \pm 1.3$ °C.

The proposed methodology was used to develop a predictive model of the Trooz Glacier's flow velocity based on air temperature at its surface.

3 Results

3.1 Modelling of air temperature over the Trooz Glacier

3.1.1 Air temperature at the Akademik Vernadsky station

Average Temperatures at the Akademik Vernadsky station. Data from the Akademik Vernadsky meteorological station (0 m a.s.l.) were obtained from direct measurements at 3-hour intervals. To ensure a consistent determination of mean annual values, the original study period (2015—2025) was reduced to the full calendar years from 2016 to 2024. During this period, the mean annual air temperature at the station fluctuated around −2.2 °C. The coldest year was 2016 (−2.9 °C), while the warmest was 2022 (−1.3 °C), followed by slightly lower temperatures in 2023—2024. Mean monthly temperatures indicate a relatively mild maritime Antarctic climate: during summer (December—January), average temperatures reach approximately 0 to

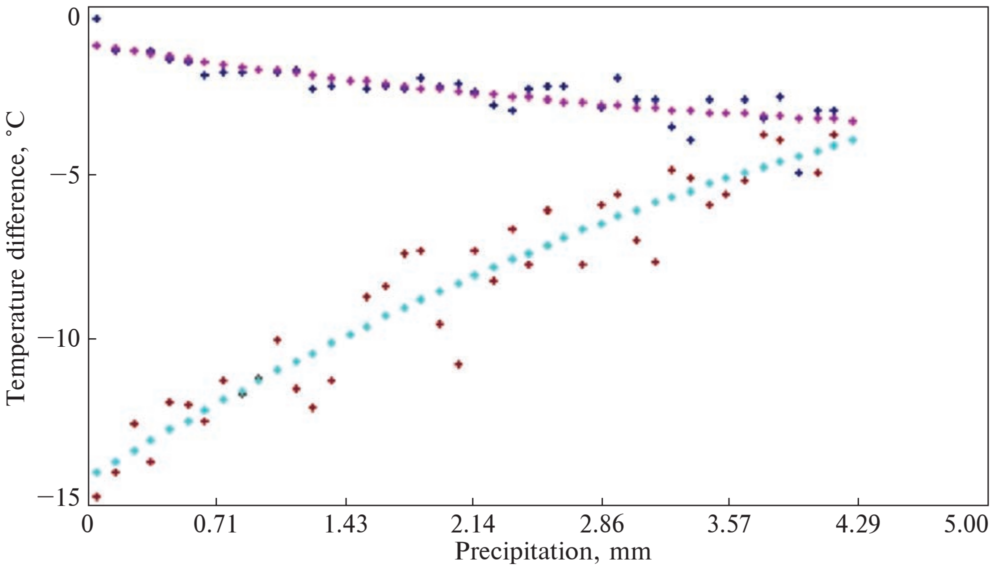

Figure 7. Extreme values of the upper and lower bounds of the temperature difference distribution between the glacier surface and the Akademik Vernadsky station and their trends: dark blue crosses — the upper bound of temperature differences; red crosses — the lower bound of temperature differences; magenta crosses — fitted trend of the upper bound; light blue crosses — fitted trend of the lower bound

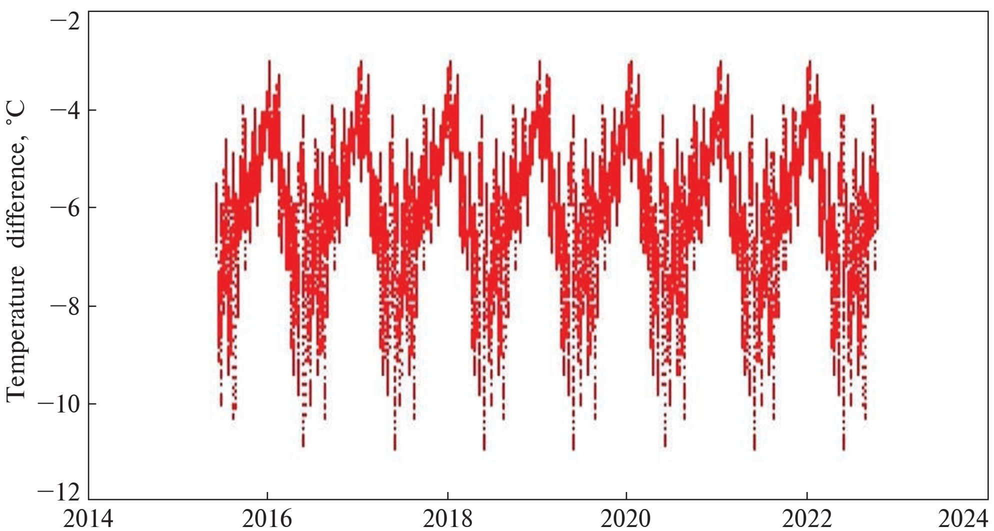

Figure 8. Time series of air temperature differences between the Akademik Vernadsky station and the surface of the Trooz Glacier, approximated using a Fourier series

+1 °C, whereas in winter (June—August) they decrease to about −8 to −9 °C.

Linear Temperature Trends at the Akademik Vernadsky station. Data from the Akademik Vernadsky station indicate a positive linear trend in mean annual air temperature of approximately +0.12 °C / year, reflecting a general warming signal (Fig. 10). Over the period 2016—2024, this corresponds to an increase of about +1.0 °C (from −2.9 °C in 2016 to −2.4 °C in 2024). However, the warming

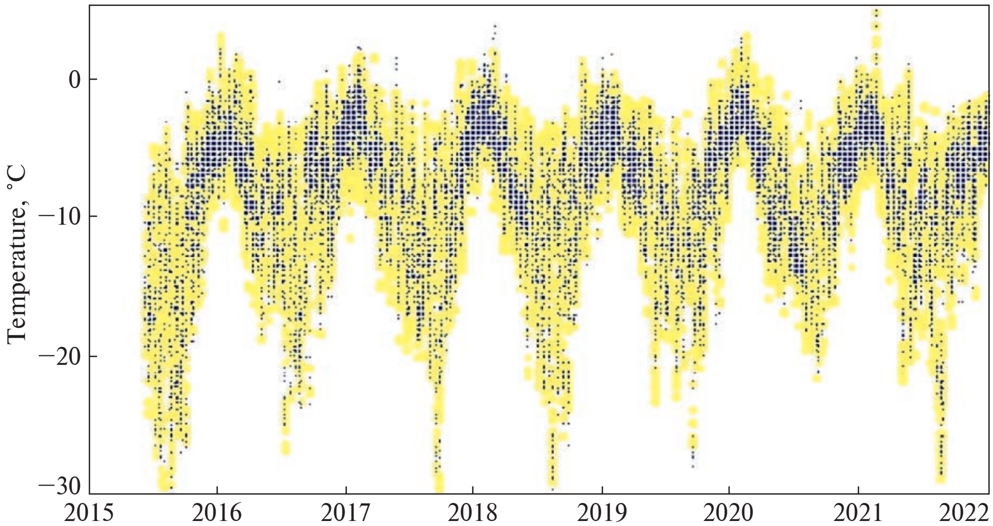

Figure 9. Time series of air temperature over the Trooz Glacier: yellow dots — air temperature from Akademik Vernadsky station, adjusted for time-of-day and precipitation corrections; blue dots — air temperature over the glacier derived from ERA5 reanalysis data

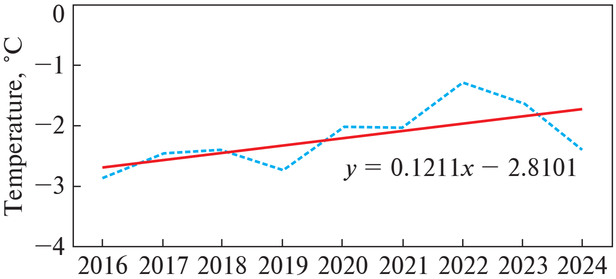

Figure 10. Mean annual air temperature at the Akademik Vernadsky station (dots) and the corresponding linear trend (line) for the period 2016—2024

signal is not uniform across seasons. The strongest temperature increase is observed during the winter months. For instance, in July the linear trend reaches approximately +0.46 °C/year, while in August it is about +0.28 °C/year. In contrast, during some summer months, the trend is weak or close to zero; in June, a slight cooling of approximately −0.08 °C/year is even observed. These results suggest that the main contribution to the observed annual warming at the station is driven by winter temperature changes.

From Figure 10, it is evident that the trend is positive, indicating a gradual warming of the air at the station. The warming rate estimated for the last decade (+0.12 °C/year) exceeds the values reported for longer-term observation periods, namely +0.048 °C/year for both 1958—2022 (Bromwich et al., 2024) and 1951—2020 (Khrystiuk et al., 2022), suggesting that air temperature increase has intensified in recent years.

3.1.2 Air temperature over the glacier

Based on ERA5 reanalysis data, a 3-hourly air temperature time series was obtained for twelve control points across the glacier for the period 2016—2024. For each point, mean monthly air temperatures were calculated over the study period, as well as mean annual values. The highest elevations of the glacier (P1 and P2, ~700 m a.s.l.) exhibit the lowest mean temperatures, approximately −8.5 °C for 2016—2024, whereas the lowest points (P11 and P12, 0 m a.s.l.) are relatively warmer, with mean temperatures of about −5.0 °C. The annual temperature cycle is typical of the Antarctic climate, with the warmest period occurring in December—January (austral summer) and the coldest in June—August (austral winter). For example, at point P1, the mean January temperature is approximately −1 °C, while in July it decreases to about −16 °C. Similarly, at the lower glacier sites (P11 and P12), temperatures approach 0 °C during summer and drop to approximately −12 to −15 °C in winter.

Average Annual Temperatures. Table 2 presents the mean annual air temperatures for each glacier point over the period 2016–2024. It can be observed that 2016 was relatively cold across most locations, while 2020–2022 were characterised by higher mean temperatures. In contrast, 2023–2024 show a return to slightly cooler conditions. In general, higher-elevation points consistently exhibit lower temperatures compared to lower-elevation sites. For example, points P1 and P2 (~700 m a.s.l.) are approximately 3 °C colder on average than points P11 and P12 (0 m a.s.l.). Interannual variability in mean temperature across the glacier is relatively modest, with differences between years typically on the order of 1–2 °C.

Linear Temperature Trends on the Glacier. To assess temporal changes in air temperature, linear trends of mean annual temperatures were calculated for each glacier point. In contrast to the Akademik Vernadsky station, all glacier points exhibit a negative trend (cooling) over the period 2016–2024. This cooling signal is primarily driven by a pronounced decrease in air temperature during 2023–2024, which significantly influenced the overall linear trend across the study period.

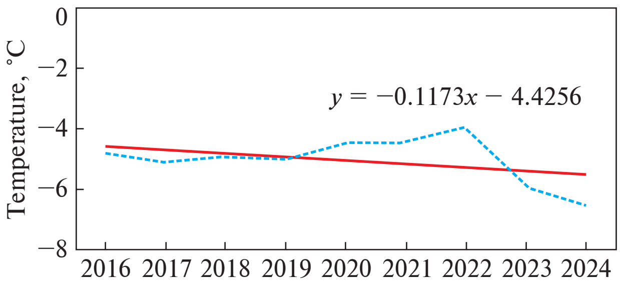

Figure 11. Mean annual air temperature (2016–2024) at point P12 (glacier front): annual mean temperature (dots); the linear trend (line)

The rate of temperature change ranges from approximately −0.13 °C/year at the lower glacier points (P8, P9, P10) to −0.07 °C/year at the highest points (P1, P2). This corresponds to a cooling of about 0.7–1.3 °C per decade. Monthly trends were also calculated for each control point on the glacier, showing variability in both magnitude and sign depending on the season. Figure 11 presents the time series of mean annual air tem-

Table 2. Mean annual air temperature (°C) at glacier control points and the Akademik Vernadsky station (2016–2024)

Point	2016	2017	2018	2019	2020	2021	2022	2023	2024	Mean temperature (2016–2024)
P1	−8.2	−9.0	−8.5	−8.7	−8.1	−8.1	−7.6	−9.1	−9.6	−8.5
P2	−8.2	−9.0	−8.5	−8.7	−8.1	−8.1	−7.6	−9.1	−9.6	−8.5
P3	−6.9	−7.7	−7.2	−7.4	−6.9	−6.9	−6.4	−8.1	−8.7	−7.4
P4	−6.9	−7.7	−7.2	−7.4	−6.9	−6.9	−6.4	−8.1	−8.7	−7.4
P5	−6.1	−6.7	−6.3	−6.5	−6.0	−5.9	−5.5	−7.4	−7.9	−6.5
P6	−6.1	−6.7	−6.3	−6.5	−6.0	−5.9	−5.5	−7.4	−7.9	−6.5
P7	−6.1	−6.7	−6.3	−6.5	−6.0	−5.9	−5.5	−7.4	−7.9	−6.5
P8	−5.2	−5.7	−5.4	−5.5	−5.0	−4.9	−4.5	−6.5	−7.1	−5.5
P9	−5.2	−5.7	−5.4	−5.5	−5.0	−4.9	−4.5	−6.5	−7.1	−5.5
P10	−5.2	−5.7	−5.4	−5.5	−5.0	−4.9	−4.5	−6.5	−7.1	−5.5
P11	−4.8	−5.1	−4.9	−5.0	−4.4	−4.4	−4.0	−5.9	−6.5	−5.0
P12	−4.8	−5.1	−4.9	−5.0	−4.4	−4.4	−4.0	−5.9	−6.5	−5.0
Vernadsky	−2.9	−2.5	−2.4	−2.7	−2.0	−2.0	−1.3	−1.6	−2.4	−2.2

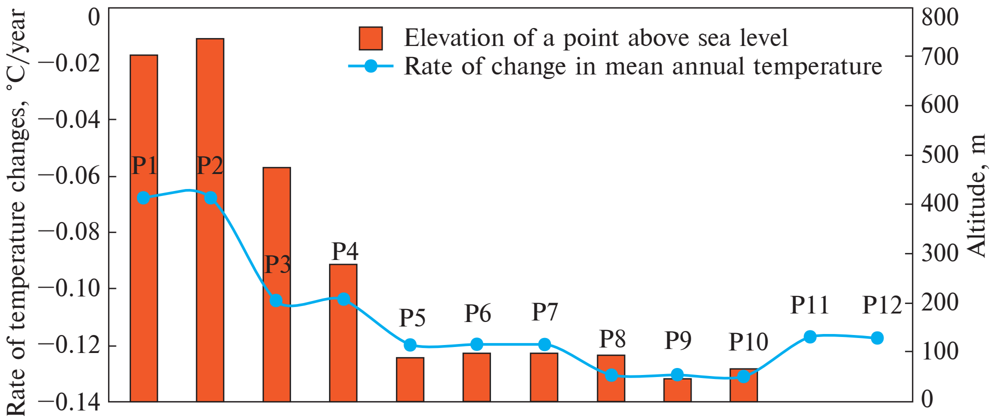

Figure 12. Spatial distribution of temperature change rates over the glacier surface at the control points

perature and the corresponding linear trend for point P12 as an example.

In general, during the warm months, temperature trends over the glacier are weak and, in some cases, indicate a slight warming. In contrast, during the cold months, a more pronounced cooling trend is observed. For instance, at point P1, the air temperature in January shows an increasing trend of +0.09 °C/year, whereas in June it decreases at a rate of −0.33 °C/year, indicating a significant cooling signal during the colder period. To summarise the rates of air temperature change across different parts of the glacier, Table 3 presents the linear trend coefficients of mean annual temperature for the period 2016—2024.

Figure 12 shows the relationship between the rate of change of mean annual air temperature and the elevation of glacier control points above sea level.

Table 3. Linear trends in mean annual air temperature over the glacier surface for the period 2016—2024

Point	Linear trend coefficient, °C/year	Point	Linear trend coefficient, °C/year
P1	−0.0678	P7	−0.1199
P2	−0.0678	P8	−0.1307
P3	−0.1039	P9	−0.1307
P4	−0.1039	P10	−0.1307
P5	−0.1199	P11	−0.1175
P6	−0.1199	P12	−0.1175

The graph indicates that all points on the glacier exhibit a decreasing trend in mean annual air temperature over the period 2016—2024. The magnitude of temperature change shows an inverse relationship with elevation above sea level as well as with distance from the coastline. Consequently, with increasing distance from the glacier terminus, more stable mean annual air temperatures are observed.

3.1.3 Relationship between elevation and air temperature over the glacier

To assess the influence of elevation, a correlation analysis was conducted between the altitude of each glacier point and its mean air temperature. For each point, the mean temperature over the entire period 2016—2024 was used together with its corresponding elevation. To investigate the dependence of the rate of glacier temperature change on elevation, a correlation—regression analysis was performed between the altitude of the observation points and the linear trends in temperature change. Both annual trends and monthly trends (calculated separately for each month of the year) were considered. For the annual temperature trends, a linear regression model of the following form was constructed:

$$T_{year} = a \cdot H + b, \qquad (5)$$

where T_{year} is the rate of change in mean annual air temperature, °C/year; H is the elevation above

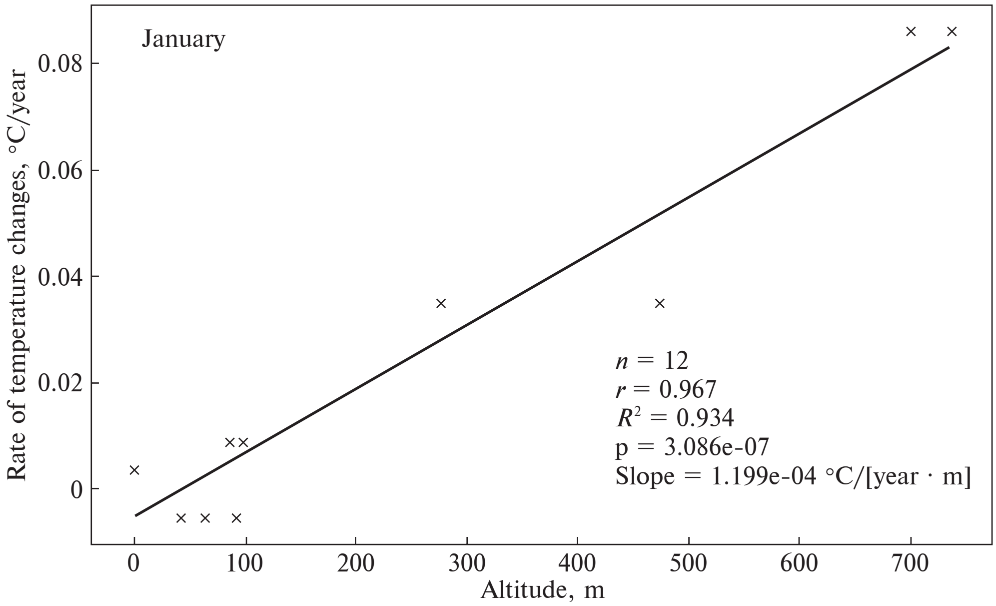

Figure 13. Dependence of the rate of mean air temperature change at a point on elevation (2016–2024)

sea level, m; a is the temperature change gradient, °C/(year · m); b is the intercept term, °C/year. The following model parameters were obtained: $a = 0.7733 \times 10^{-4}$ °C/(year·m), $b = -0.1280$ °C/year; the correlation coefficient $r = 0.939$, and the coefficient of determination $R^2 = 0.882$.

Figure 13 illustrates the relationship between the annual temperature trend at glacier control points and their elevation, with January used as an example.

In Table 4, generalised results of the dependence of temperature trends on elevation above sea level are presented for each month of the year.

A very strong inverse relationship was identified between the studied parameters (correlation coefficient r = −0.93), indicating that higher-elevation points are characterised by lower mean air temperatures. The linear regression of temperature versus altitude yields a slope of approximately −0.0043 °C/m, corresponding to a temperature decrease of about 0.43 °C per 100 m of elevation gain. The resulting lapse rate is lower than the standard atmospheric lapse rate of approximately 0.65 °C per 100 m (Rosas-Chavoya et al., 2022). This weaker temperature decrease with elevation over the glacier may be explained by maritime influence and local atmospheric conditions, including the possible occurrence of temperature inversions over the glacier surface (Gardner et al., 2009; Noad et al., 2023).

3.1.4 Model linking glacier temperature with Akademik Vernadsky station temperature and elevation

A linear model describing the relationship between temperature at the glacier points T_{Trooz} and temperature at the meteorological station T_{Vern}, considering elevation gradient, was developed using mean annual temperature data for the period 2016–2024. A multiple regression analysis of the following form was performed:

$$T_{Trooz} = a + b \cdot T_{Vern} + c \cdot H, \quad (6)$$

where H is the elevation above sea level, m. Based on the regression analysis, the following parameters were obtained: $a = -4.8$ °C, $b = 0.33$, $c = -0.00435$ °C/m. Thus, Equation (6) can be written as:

$$T_{Trooz} = -4.8 + 0.33 \cdot T_{Vern} - 0.00435 \cdot H. \quad (7)$$

The coefficient *c* corresponds to an elevation gradient of approximately −0.435 °C per 100 m, which is consistent with the previous analysis. The coefficient $b = 0.33$ indicates that interannual temperature variations at the meteorological station are transmitted to glacier points at roughly one-third of their amplitude, likely due to the thermal inertia of the ice mass and local surface effects. The intercept *a* has a relatively large negative value, indicating that even at sea level ($H = 0$), glacier temperatures are approximately 4.8 °C lower than those at the meteorological station under the same conditions. This represents a systematic offset related to the station's coastal location, whereas the glacier points are situated over an ice surface that promotes cooling of the near-surface air layer.

The model explains about 66% of the variance in glacier point temperatures (coefficient of determination $R^2 = 0.66$), confirming that elevation is the primary factor controlling temperature differences. The remaining ~34% of variability is likely associated with other environmental factors and incomplete transfer of atmospheric variability from the station to the glacier surface.

Table 4. Statistics of the monthly dependence of temperature trends on elevation

Month	Temperature rate gradient, $\times 10^{-4}$, °C/(year · m)	Correlation coefficient, r	Coefficient of determination, R^2
1	1.199	0.967	0.934
2	1.671	0.973	0.946
3	0.504	0.884	0.782
4	1.564	0.919	0.844
5	0.386	0.748	0.560
6	0.307	0.814	0.662
7	0.350	0.649	0.421
8	1.122	0.957	0.916
9	−0.103	−0.146	0.021
10	−0.320	−0.324	0.105
11	1.161	0.937	0.877
12	1.507	0.918	0.843

The resulting model (7) can be used to estimate air temperature over the glacier surface using measurements from the Akademik Vernadsky station. Continuous meteorological observations at the Antarctic station enable the reconstruction of air temperature over the Trooz Glacier surface, as well as the refinement of temperature estimates derived from ERA5 reanalysis data.

3.2 Spatial model of the Trooz Glacier's flow velocity

3.2.1 Overview of glacier dynamics

The spatial distribution of ice flow velocities for the Trooz Glacier was analysed using average velocity values obtained at control points along the central flowline for the period 2015–2025. The results enabled the identification of three characteristic dynamic zones of the glacier, which differ in flow velocity and morphometric conditions.

The lowest ice flow velocities are observed in the upper part of the glacier (points P1–P4, at elevations of approximately 700–300 m). The mean velocity is about 0.39 m/day, with minimum values at specific points reaching approximately 0.32 m/day and maximum values of about 0.47 m/day.

In the middle section of the glacier (points P5–P8, at elevations of approximately 100 m), ice flow velocities increase noticeably. The mean velocity is about 1.20 m/day, while values at specific control points range from approximately 0.63 m/day to 2.22 m/day. The highest velocities are observed in the lower part of the glacier (points P9–P12, at elevations of 0–60 m), where the mean value is about 2.18 m/day, and the velocity range varies from approximately 1.09 m/day to 3.11 m/day.

Figure 14 shows examples of ice flow velocity time series for three dynamic zones. The series were approximated using a second-order Fourier series (1).

As shown in Figure 14, the glacier velocity time series exhibits a significant amplitude dispersion. This variability is attributed to both measurement errors and possible glacier surge caused by

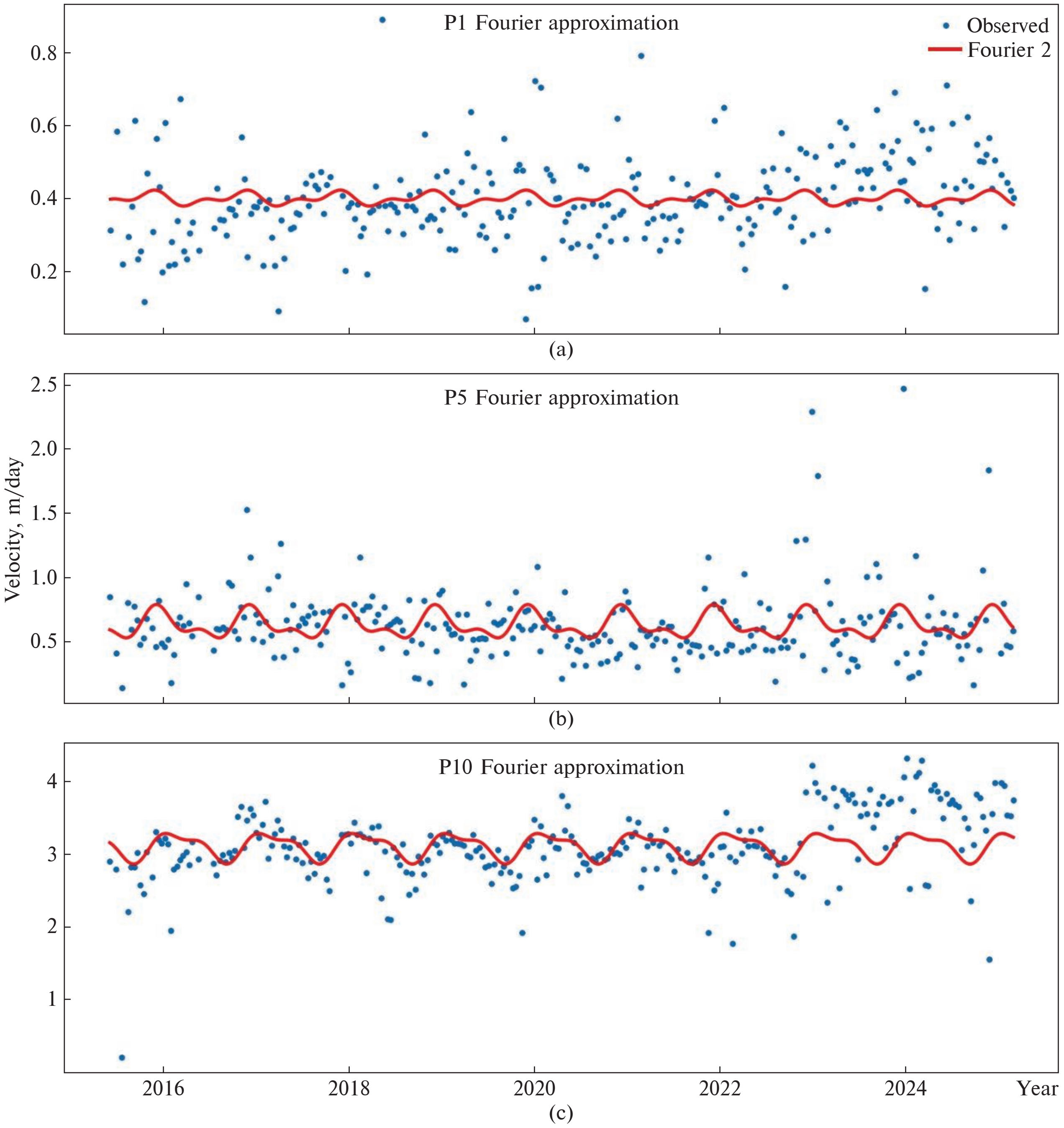

Figure 14. Seasonal variation of glacier flow velocity and its approximation using a Fourier series for three dynamic zones: (a) the upper zone represented by data from point P1; (b) the middle zone represented by data from point P5; (c) the lower zone represented by data from point P10

changes in the glacier drainage system (Wen & Wang, 2025). The analysis of such data is rather challenging. Only through data filtering (Tretyak & Kukhtar, 2023) and their approximation with a Fourier series is it possible to identify the seasonal component of glacier velocity variations.

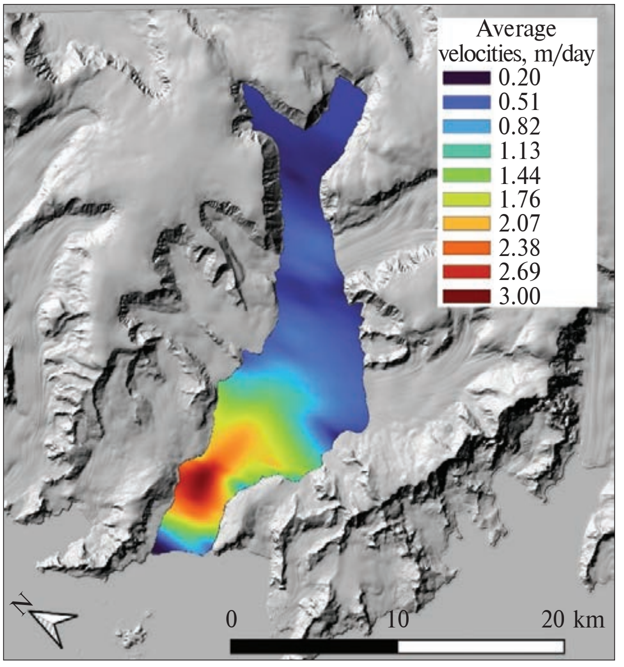

Figure 15. Spatial distribution of the mean velocities of the Trooz Glacier for the period 2015–2025

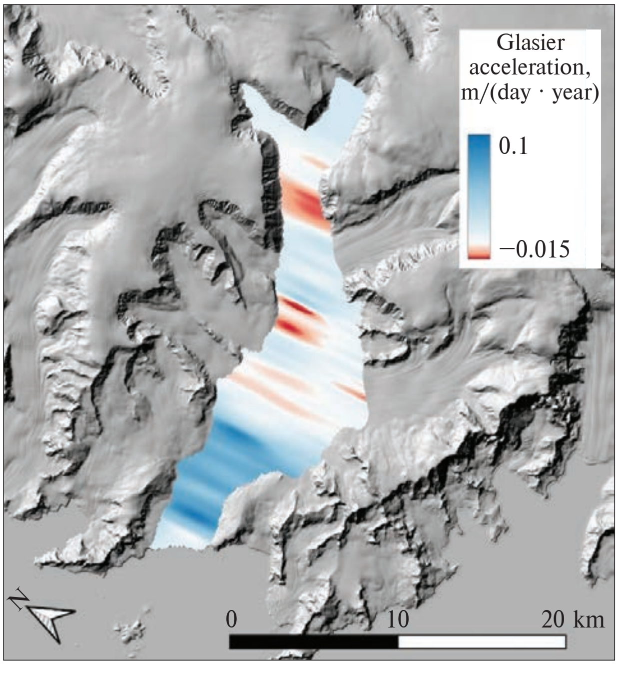

Figure 16. Spatial distribution of the Trooz Glacier acceleration over the period 2015–2025

For each of the considered control points (Fig. 14), seasonal variations in velocity are clearly observed. Maximum velocities occur at the beginning of the calendar year, corresponding to the Antarctic summer period, while minimum values are observed during the Antarctic winter. The seasonal component of velocity variations is more pronounced in the lower parts of the glacier. This is reflected in the increased amplitude of the approximation function (Fig. 14b, c) and in the improved agreement between the model and the observed data (Fig. 14c).

The mean annual ice flow velocities at selected control points are as follows: P1 – approximately 0.40 m/day, P3 – 0.47 m/day, P6 – 0.73 m/day, P8 – 2.22 m/day, P9 – 2.90 m/day, and P10 – 3.11 m/day. Overall, a systematic increase in ice flow velocity towards the lower part of the Trooz Glacier is observed. This is evidenced by correlation analysis, which indicates a negative relationship between mean velocity and terrain elevation ($r \approx -0.60$). The distribution of mean ice flow velocities over the period 2015–2025 is shown in Figure 15.

Additionally, the acceleration of the glacier at control points over the period 2015–2025 was analysed. A linear regression model was applied to each observation point. The results indicate that most points exhibit a gradual increase in ice flow velocity. In particular, for points P1, P3, P8, P9, P10, and P11, the trend coefficients are approximately +0.013, +0.018, +0.045, +0.042, +0.064, and +0.041 m/(day · year), respectively (Fig. 16). At the same time, slight deceleration is observed in some parts of the glacier. For points P2 and P4, the coefficient is about −0.012 m/(day · year), while for point P7 it is approximately −0.004 m/(day · year).

The results indicate that, overall, the ice flow tended to accelerate over the study period, with the most pronounced increase in velocity observed in its lower part. At the same time, localised zones of slight deceleration are identified in some areas, which may be associated with local morphological or dynamic features of the glacier flow.

3.2.2 Spatial model of the Trooz Glacier's velocity

As a result of the comprehensive processing, an equation for the ice flow velocity (for all points of the glacier) was obtained:

$$V \approx 7.04 + 0.96 \cdot T_{Trooz} + 0.00194 \cdot H, \quad (8)$$

where V is the mean glacier velocity at a point, m/day; T_{Trooz} is the mean adjusted temperature at the glacier surface, °C; H is the elevation of the point above sea level, m.

For the variable T_{Trooz}, the obtained model (7) is used. After transformation, an equation for the ice flow velocity based on the elevation of a point on the glacier and the measured air temperature at the Akademik Vernadsky station:

$$V \approx 2.43 + 0.32 \cdot T_{Vern} - 0.00224 \cdot H. \quad (9)$$

Based on the analysis of the obtained quantitative indicators:

1. **The influence of temperature** T_{Vern}. The derivative of equation (9) ($\partial V/\partial T_{Vern} \approx 0.32$) means that an increase in the mean temperature measured at the Akademik Vernadsky station by 1 °C leads to an average increase in velocity of approximately 0.32 m/day. This is consistent with expectations: warmer conditions result in increased meltwater production and, consequently, enhanced glacier motion.

2. **The influence of elevation** H. The derivative of equation (9) ($\partial V/\partial H \approx -0.00224$) means that an increase in elevation by 100 m leads to an approximate decrease in velocity of $\Delta V \approx -0.00224 \times 100 = -0.22$ m/day. Higher areas of the glacier are generally slower, as the driving strain gradually decreases.

3. **Model reliability.** The coefficient of determination R^2 indicates that temperature and elevation together explain approximately 54% of the variability in mean velocity between points. The other ~46% is attributed to factors such as bed geometry, ice thickness, subglacial hydrology, local morphology, and other influences.

4 Discussion

4.1 Relationship between velocity and glacier temperature (annual scale)

Estimating mean annual ice flow velocity and air temperature for the period 2016–2024 enables assessment of the contribution of the temperature regime to the dynamics of the Trooz Glacier. For each control point, the analysis included the mean annual glacier flow velocity, the local air temperature above the glacier surface, and temperature records from the Akademik Vernadsky station.

Comparison of these parameters reveals pronounced spatial variability in glacier flow dynamics. In the lower part of the glacier (approximately 0–70 m a.s.l.), significantly higher velocities are observed, ranging from about 1.82 to 2.92 m/day, which coincide with relatively warmer microclimatic conditions. In contrast, in the upper part of the glacier (approximately 700 m a.s.l.), ice velocities are markedly lower, at about 0.29–0.36 m/day, and are associated with lower air temperatures.

This pattern reflects the typical spatial structure of glacier systems, in which decreasing elevation and proximity to the glacier terminus are associated with increasing flow velocities. The obtained moderate positive correlation between air temperature and ice velocity ($r \approx +0.57$) likely reflects, to a significant extent, this spatial (altitudinal) effect rather than a purely direct causal relationship.

Considering all points and years together (a total of 108 annual observations), a positive correlation between glacier flow velocity and glacier surface temperature is also observed ($r \approx +0.57$). This result primarily reflects a spatial pattern: the lower parts of the glacier are characterised by both higher temperatures and higher flow velocities, whereas in the upper, colder areas, the ice movement is significantly slower.

At the same time, the analysis of temporal dependencies at individual control points (nine annual values per point) reveals a different pattern. For all points, the correlation between ice velocity and local glacier surface temperature is negative, with correlation coefficients ranging from approximately −0.89 to −0.28. The correlation between glacier flow velocity and air temperature measured at the Akademik Vernadsky station varies from −0.48 to +0.41. This indicates that, over shorter time scales, the relationship between temperature and glacier motion is more complex and not strictly linear or directly proportional.

The physical interpretation of the results indicates that the spatial increase in glacier flow velocity arises from a combination of factors, including rising air temperature, increasing ice thickness, and proximity to the glacier terminus, where basal sliding and internal ice deformation are typically enhanced.

On a temporal scale, the velocity at a given point is controlled not only by temperature conditions but also by a range of additional processes, such as variations in ice thickness, changes in flow geometry, the opening and closure of crevasses, and the evolution of the subglacial drainage system. Over relatively short observation periods (approximately 9 years), the influence of these dynamic processes may exceed the direct temperature signal, thereby explaining the observed differences between spatial and temporal correlation patterns.

4.2 Relationship between velocity and glacier temperature (monthly scale)

Analysis of monthly glacier velocity and temperature data helps to clarify their relationship at shorter time scales. A generalisation of data from all control points and the entire observation period (2016–2024) shows that, for most calendar months, there is a moderate positive correlation between mean glacier flow velocity and mean glacier surface temperature. The correlation coefficients range from approximately $r \approx 0.23$ in September to $r \approx 0.57$ in April and July, while for most months they lie in the range of $r \approx 0.40$–0.55.

The obtained relationships indicate that, over short time intervals, increases in glacier surface temperature are generally accompanied by a corresponding increase in ice flow velocity. This behaviour may be associated with thermodynamic changes in ice properties and an increased availability of meltwater, which enhances basal sliding. At the same time, the relatively moderate values of the correlation coefficients suggest that temperature is not the sole controlling factor governing variations in glacier flow velocity.

4.3 Models of the relationship between temperature and glacier velocity

The study also analyses the results of approximating time series of temperature and glacier flow velocity at 12 control points. The parameters of the second-order polynomial model (coefficients b_0, b_1, b_2), together with the estimated linear trends, were used to investigate the features of temporal variability of these parameters.

Based on the obtained characteristics, a correlation matrix was constructed, regression relationships were established, and observation points were clustered to assess the influence of temperature factors on glacier dynamics.

The derived regression equations, along with the corresponding coefficients of determination (R^2), reflect the nature and strength of the relationship between temperature conditions and glacier flow velocity:

1. Maximum glacier velocity ($V_{\max\_b0}$) as a function of the rate of change of mean temperature (T_{mean_b1}):

$$V_{\max\_b0} = 13.040 \cdot T_{mean\_b1} - 8.458, \; R^2 = 0.825; \quad (10)$$

2. Maximum glacier velocity ($V_{\max\_b0}$) as a function of the acceleration of mean temperature (T_{mean_b2}):

$$V_{\max\_b0} = -95.356 \cdot T_{mean\_b2} - 3.507, \; R^2 = 0.782; \quad (11)$$

3. Maximum glacier velocity ($V_{\max\_b0}$) as a function of the acceleration of minimal temperature (T_{min_b2}):

$$V_{\max\_b0} = -36.050 \cdot T_{\min\_b2} + 3.092, \; R^2 = 0.829; \quad (12)$$

4. Mean glacier velocity (V_{mean_b0}) as a function of the acceleration of mean temperature (T_{mean_b2}):

$$V_{mean\_b0} = -79.789 \cdot T_{mean\_b2} - 3.271,\ R^2 = 0.603. \quad (13)$$

The regression models show that temperature parameters significantly influence both the mean and the maximum glacier velocities. For most models, the coefficient of determination R^2 exceeds 0.6–0.8, indicating a high level of linear dependence.

Positive regression coefficients in the models with the T_{mean_b1} parameter (linear trend of mean temperature) indicate that a systematic long-term increase in mean temperature leads to an increase in the maximum glacier velocity. This is consistent with the expected physical behaviour: rising temperatures enhance ice melt, reduce ice viscosity, and promote an increase in ice flow velocity.

At the same time, models with temperature acceleration parameters (T_{mean_b2}, T_{min_b2}) exhibit negative coefficients at high R^2 values. This suggests that excessively rapid warming (*i.e.*, increased temperature acceleration) leads to decreases in the maximum and the mean glacier velocities.

Over the 2016–2024 period, most points show a gradual acceleration of glacier motion (0.02–0.06 m/(day · year)) accompanied by a simultaneous decrease in the glacier surface temperature (≈ −0.1 to −0.15 °C/year). This indicates that glacier kinematics are controlled not only by thermal factors but also by geometric and mechanical influences.

5 Conclusions

This study employs a comprehensive multi-level approach to investigate the dynamics of the Trooz Glacier, integrating Sentinel-1 SAR satellite data, ERA5 meteorological reanalysis, and long-term *in situ* observations from the Ukrainian Antarctic Akademik Vernadsky station. The use of consistent time series spanning the period 2015–2025 enabled a comprehensive analysis of the spatio-temporal variability of both the temperature regime and ice flow velocity.

The temperature regime of the study area shows a complex pattern of variability. A positive temperature trend (+0.12 °C/year) was identified at the Akademik Vernadsky station, whereas a general cooling tendency is observed over the glacier surface (−0.07 to −0.13 °C/year), primarily associated with recent colder years. A distinct altitudinal temperature dependence was established, with a gradient of approximately −0.43 °C per 100 m, which is lower than the standard atmospheric lapse rate and can be attributed to marine influence and local temperature inversions.

A systematic temperature offset was identified between *in situ* observations at the station and glacier surface temperatures derived from the ERA5 reanalysis. The proposed correction scheme, which accounts for the diurnal temperature variation (δt) and the influence of precipitation (δp), substantially improved the consistency between the time series. In particular, the correlation coefficient increased to $r = 0.96$, while the root mean square error decreased by more than half. These results demonstrate the high effectiveness of the proposed approach for transforming station-based temperature data to glacier conditions. The developed regression model further enabled the establishment of a quantitative relationship between air temperature at the station and both temperature and elevation on the glacier.

Analysis of glacier flow velocity revealed a pronounced spatial differentiation in dynamics, ranging from approximately 0.4 m/day in the upper reaches to over 3 m/day in the lower part of the glacier. An overall acceleration of ice flow was observed, particularly in the terminus zone, indicating enhanced dynamic activity. At the same time, a negative correlation between ice velocity and elevation ($r \approx -0.60$) was identified, reflecting the increasing contribution of basal sliding and internal deformation processes toward the lower parts of the glacier.

The developed generalised model of glacier velocity indicates that temperature and elevation jointly explain approximately 54% of the observed variability in ice flow velocity. In particular, a 1 °C increase in temperature corresponds to an increase in velocity of about 0.32 m/day, whereas a 100 m increase in elevation leads to a decrease in velocity. These findings confirm the physical role of temperature as a key factor controlling ice melt and enhancing basal sliding.

A positive spatial correlation between temperature and ice velocity is observed; however, at the temporal scale for individual points, this relationship is often weak or even negative. This highlights the complex nature of glacier dynamics, in which, in addition to temperature, factors such as bed geometry, ice thickness, subglacial hydrology, and internal deformation processes play significant roles.

Analysis of seasonal variability indicates that maximum ice flow velocities occur during the summer, consistent with higher temperatures and enhanced melt processes. At the same time, the correlation between temperature and velocity at the monthly scale remains moderate ($r \approx 0.4-0.55$), further supporting the multifactorial nature of glacier dynamics.

The regression models describing the dependence of ice velocity on temperature indicate that thermal parameters significantly influence both the mean and maximum glacier flow velocities. For most models, the coefficient of determination (R^2) exceeds 0.6–0.8, indicating a strong linear relationship.

Overall, the results confirm that air temperature is an important but not the sole factor controlling the dynamics of the Trooz Glacier. The proposed approach enables a quantitative assessment of its contribution and provides a basis for developing predictive models of glacier behaviour under conditions of climate change. Future research should focus on the integration of GNSS, InSAR, and geophysical data to establish comprehensive multi-sensor cryosphere monitoring systems.

Data availability. The meteorological observations used in this study were obtained from the open-access database of the State Institution National Antarctic Scientific Center (89063 Akademik Vernadsky Station), available at http://meteodata.uac.gov.ua/SYNOP_data/decoded_table_data/. The SAR imagery analysed in this research was acquired from the Alaska Satellite Facility (ASF) data archive (https://search.asf.alaska.edu/), which provides access to NASA-supported synthetic aperture radar datasets from multiple satellite missions.

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Прогнозна модель динаміки льодовика Труз на основі метеорологічних спостережень на станції «Академік Вернадський»

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Реферат. У роботі виконано моделювання динаміки льодовика Труз (Антарктичний півострів) на основі інтеграції дистанційних і метеорологічних даних. Основою дослідження є сумісне опрацювання швидкостей льодового потоку, визначених за даними супутникового радіолокаційного знімання, температури повітря та кількості опадів, отриманих із реаналізу ERA5, а також результатів безпосередніх метеорологічних спостережень на Українській антарктичній станції «Академік Вернадський». Для оцінювання швидкості руху льодовика використано метод offset tracking за даними супутника Sentinel-1 за період 2015–2025 рр., у результаті чого сформовано 286 карт льодового потоку. Розроблено підхід до розрахунку температури повітря над поверхнею льодовика на основі даних безпосередніх вимірювань на віддалено розташованій станції «Академік Вернадський» за відсутності додаткових даних. На основі розробленої методики побудовано просторові моделі температури та швидкості льодовика з урахуванням додаткових параметрів: кількості опадів і висоти поверхні льодовика над рівнем моря. За результатами аналізу часових рядів встановлено наявність протилежних трендів:

до підвищення температури на антарктичній станції «Академік Вернадський» (+0.12 °C/рік) та до її зниження над поверхнею льодовика (−0.07...−0.13 °C/рік) протягом останнього десятиліття. Використання апроксимації рядами Фур'є дало змогу виявити виражену сезонність у зміні швидкості руху льодовика. За середніми значеннями швидкостей спостерігається тенденція до прискорення льодового потоку на рівні 1−4%. Аналіз моделі показав, що температура повітря та висота поверхні разом пояснюють близько 54 % просторової варіації середньої швидкості, тоді як решта змін зумовлена впливом інших факторів, зокрема геометрії ложа льодовика, товщини льоду, особливостей підльодовикового дренажу та локальної морфології льодовикового потоку. Отримані просторові моделі можуть бути використані для подальшого прогнозування кліматично зумовлених змін льодовикової системи.

Ключові слова: ERA5, Sentinel-1, відстеження зміщення, прискорення льодовика, ряд Фур'є