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Research Article

Temperature distribution in the crevasse-drainage systems of the Antarctic glaciers: A case study of the Perunika Glacier

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Abstract

Discovered only about 200 years ago, Antarctica is the poorest and most isolated ecosystem on Earth. Its thinner atmosphere, due to the centrifugal forces of Earth's rotation, the ozone hole, and stronger solar radiation, creates a natural laboratory that provides information about the state and trajectory of Earth's climate condition. This study aimed to determine the depth of heat penetration from the surface of the glacier into the crevasses in the ablation zone and establish the zone of constant temperatures in the glacier. It explored the relationship between the air temperature at the glacier surface and the temperature distribution in the crevasses, including the temperature gradient at different levels and the direction of the airflow. We used autonomous data loggers for measuring and recording temperature and relative humidity. The measured depth reached 18 m in the central part of the glacier and 9 m in the periphery. An ultrasonic anemometer was installed in the deepest crevasse in to the center of the glacier to determine the size and direction of air flows. Meteorological parameters such as air temperature, humidity, atmospheric pressure, and solar radiation were measured on-site using autonomous sensors and recording devices mounted on installations on the glacier surface and at depth using alpine techniques. The results show a temperature gradient through 3-meter layers, a relatively clear boundary of the constant temperature zone, and a significant infiltration of cold air through the crevices driven by turbulent wind processes. Additionally, a weak negative correlation was found between solar activity and temperatures in the crevasses. It appears that as solar activity increases, the temperature decreases. There are also weak but consistently positive correlations with air movement both upward and downward. The temperature becomes constant with the increase of the depth until a zone of constant temperatures is determined and the temperature variance becomes insignificant. This zone varies in different crevasses, meaning it is influenced by the specific characteristics of each crevasse location. At shallow depths, temperature is influenced by external temperature, but with the depth increasing this influence decreases. On windy days, the zone of constant temperature expands. During higher solar activity, air circulation accelerates—both upward and downward. The relationship between solar activity and climatic processes in glacier drainage systems adds new insights to solar-terrestrial physics.

Key words: Antarctica, Bulgarian Antarctic base, climate change, climatology, Livingston Island, meteorology, surface atmosphere

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1. Introduction

The melting processes of glaciers are driven by a wide range of factors, with the main ones being solar radiation, where albedo or cloud cover are limiting factors (Williamson et al. 2020), and the circulation of air masses between the surface and the depths of the glacier. The difference in the morphology of mountain and continental glaciers, such as the Perunika Glacier, determines different processes through which glaciers lose or change their mass. The geographic location of the glacier is very close to the periphery of Antarctica makes that exposes it to the to higher climate change impact and the fluctuations of the solar activity. Therefore, it is an appropriate case study for the research. Worldwide research on such boundary located glaciers in the mountains has been done by Gachev (2021) and Gachev et al. (2024). However, while mountain glaciers have distinct forms determined by the relief most continental glaciers can spread over extensive areas without clear boundaries. Studies for evidence about the existence of a zone of constant temperatures within the glacier's crevasses are necessary. The stability of this zone in respect to external changes in temperature, wind, atmospheric pressure, and solar activity is the main factor for the thermal equilibrium within the glacier. So far, very few studies have been conducted on the relationship between changes in solar activity and the changes of constant temperatures in underground cavities (Stoev and Stoeva 2021). Terrestrial physics investigates the processes through which glaciers absorb and retain heat, affecting the thorough processes of glacier's melting.

The thermodynamics of crevasses in the accumulation zone of an alpine glacier in New Zealand has been studied using temperature sensors (Purdie et al. 2022). Morphological studies of crevasse-drainage glacier structures in Antarctica have been conducted using ground-penetrating radar (Schaap et al. 2020). Macro-scale modeling has been performed on internal glacier hydrological potential, subglacial melting velocities, and calculations of water flows (Willis et al. 2016). Dynamics and seismic activity of glaciers around the Spanish Antarctic base "Juan Carlos I" on Livingston Island and the Bulgarian "St. Kliment Ohridski" base have been studied by Martín et al. (2017); Georgieva et al. (2019); Letamendia et al. (2023). The temperatures of the ground surface on Livingston Island have been studied by de Pablo et al. (2024). On Livingston Island (Navarro et al. 2013) and Antarctic peninsula (Silva et al. 2019), fluctuation in glaciers mass balance and movement are done. Taking all this into account, it is necessary to formulate a concept of the microclimate of crevasses. Despite numerous and long-term studies, the process of heat exchange between the near-surface atmospheric layer and the depths of Antarctic glaciers, as well as the temperature gradient and directions of airflow are not well studied.

This study aims to investigate and present the response of microclimate of vertical air volumes into the Antarctic glacier crevasses, relative to external climatic changes and variations in surface temperatures through solving the following research tasks:

- to define the temperature gradient and determine the depth of heat penetration from the surface;
- to determine the zone of constant temperatures inside the crevasses;
- to establish the correlation between solar activity, surface meteorology, wind speed and air flow direction inside the crevasses.

The answers to these questions, combined with periodic monitoring of meteorological parameters above and within the glacier, will help us determine whether the primary factor for melting is anthropogenic or cyclical changes in solar activity.

2. Materials and methods

2.1. Case study area

Livingston Island is part of the archipelago of the South Shetland Islands (Fig. 1A) in Antarctica—a 540 km chain of four main island groups. Some of them are volcanic, including eleven major islands (Elephant and Clarence Islands; King George and Nelson Islands; Robert, Greenwich, Livingston, Snow, and Deception Islands; Smith and Low Islands) and several minor ones with many islets and rocks. It is located about 100 km north of the Antarctic Peninsula in the Southern Ocean (Bulgarian Antarctic Institute 2024).

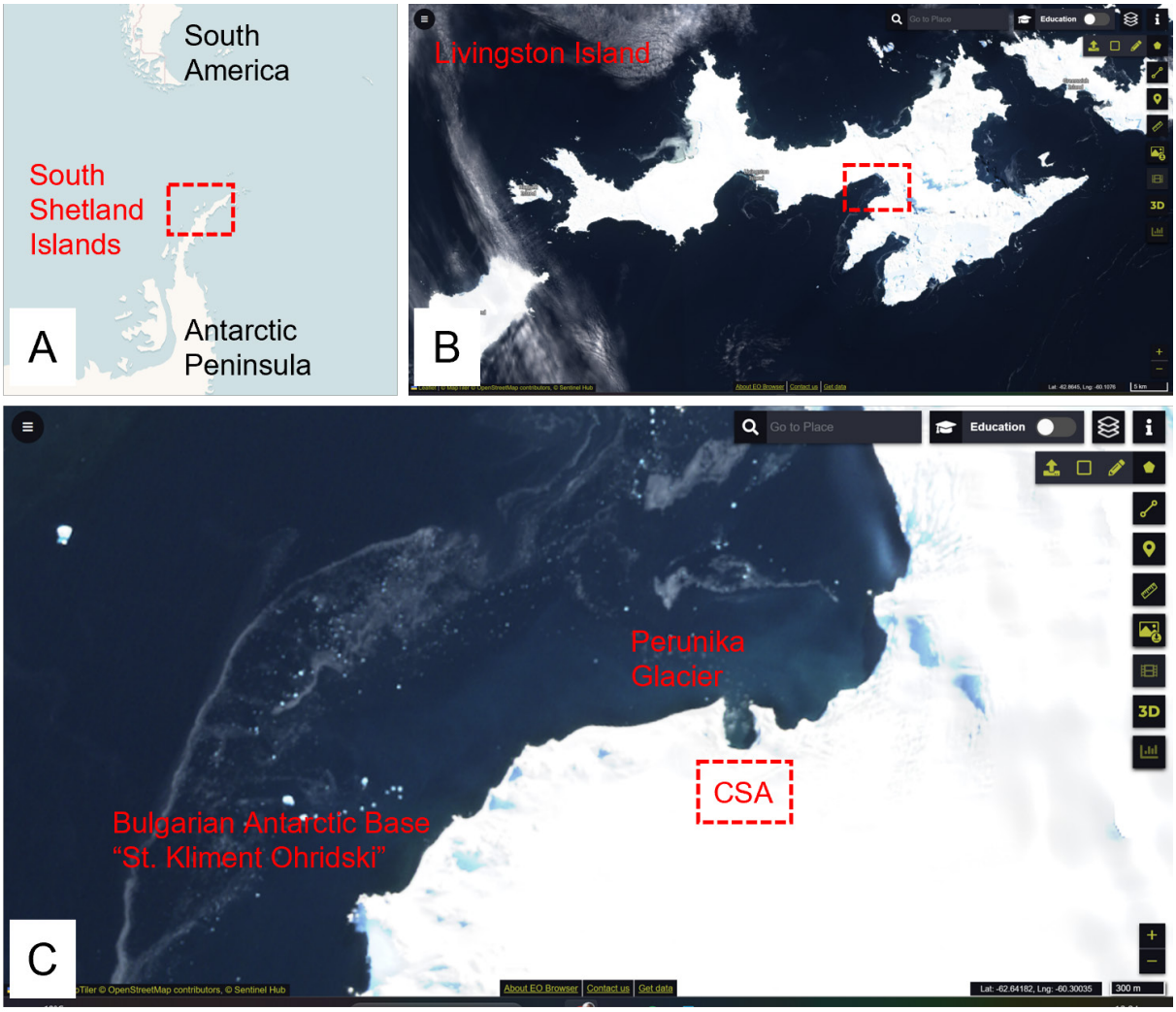

Figure 1. Location of the case study area. **A** Location of the South Shetland Islands and the surrounding territories of South America and Antarctic Peninsula **B** Location of the South Bay and the Perunika Glacier among the Livingston Island **C** Case study area. Source: Sentinel-2 Satellite platform (EO Browser 2024).

The Perunika glacier is part of the permanent ice cover of Livingston Island (Fig. 1B). With a length of about 8 km and a width of 3 km, it is located approximately 2 km north of the Bulgarian Antarctic base "St. Kliment Ohridski" (Fig. 1C).

In its lower and middle parts, where the ablation zone is most pronounced, the glacier is heavily crevassed, providing access to subglacial drainage systems formed in the sliding zone between the ice and the ground surface.

Through satellite images from the Sentinel-2 platform, it was determined that during austral summer, subglacial waters of the Perunika glacier generated a significant outflow that flows into the Southern Ocean (Fig. 1C). These factors, along with the proximity to the Bulgarian Antarctic base, influenced the choice of this glacier for the research.

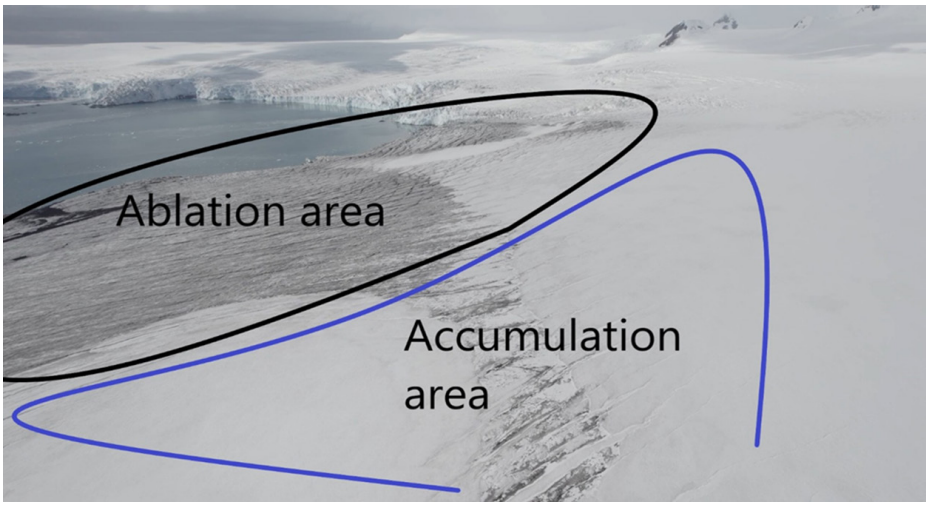

Figure 2. UAV image of ablation and accumulation areas on the Perunika Glacier.

The ablation zone of the Perunika Glacier (Fig. 2) is clearly defined in the middle and towards the end of summer due to the large number of pyroclastics (volcanic materials) scattered on the ice surface. These pyroclastics are black in color and originate from Deception Island, last erupted in 1970 and located approximately 30 km southern.

2.2. Location and mapping of measurement sites

The measurements began on January 15, 2024 when we deployed 15 sensors inside the crevasses and continue to 15.2.2024. All of the sensors are settled to measure the temperature on every 30 minutes. After a field survey, it was found that on 15.1.2024 only four crevasses (C1, C2, C3, C4) at the end of the ablation zone were open (Fig. 3A). They were located at the boundary between the accumulation zone and the ablation zone, with the main crevasse crossing the glacier width to the middle. Descending into the crevasses, it was observed that those in the central part of the glacier did not have a discernible bottom, and their depth could be comparable to the thickness of the glacier, which is around 80 meters in this area (the entrance zone is at 102 m a.s.l.).

Crevasse 1 (C1) and Crevasse 2 (C2) are located in the periphery of the glacier (Fig. 3B). They have the following characteristics:

C1—the most peripheral crevasse, located in the area of fastest glacier melting. Parallel to C2. At the beginning of the research on January 15, 2024, only a small opening about 3 meters in size was present. It had a length of about 200 m with flowing water at the bottom. We placed three sensors at the point of the crevasse opening at 3-meter intervals. Before they entered the crevasse, some of the waters flowing along the glacier were observed on the surface.

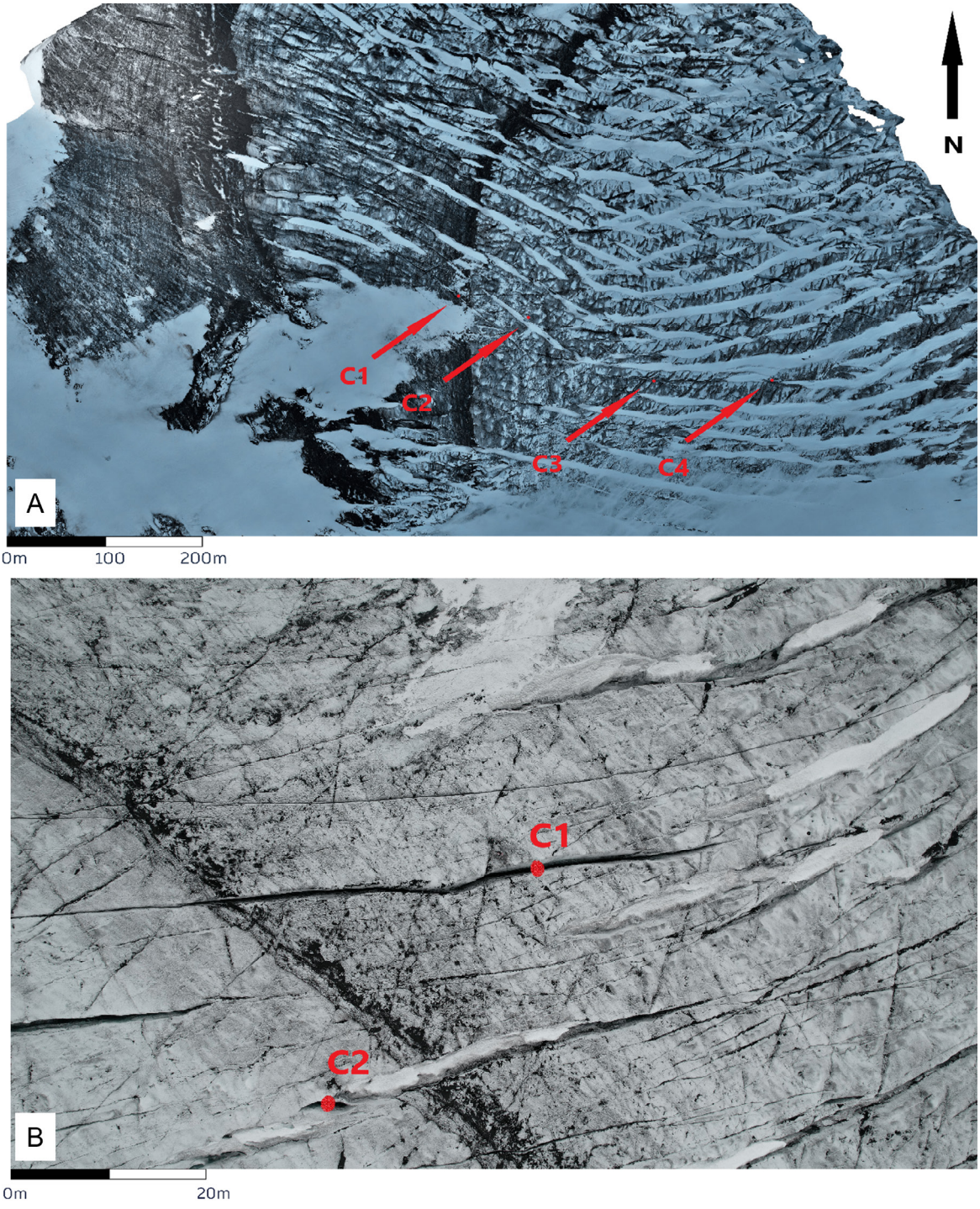

Figure 3. Location of the crevasses. **A** All crevasses with deployed sensors for temperature. UAV image generated from 1630 different images from height above the glacier surface 200 m **B** Position of sensors in Crevasses 1 and Crevasses 2. UAV image from 50 m.

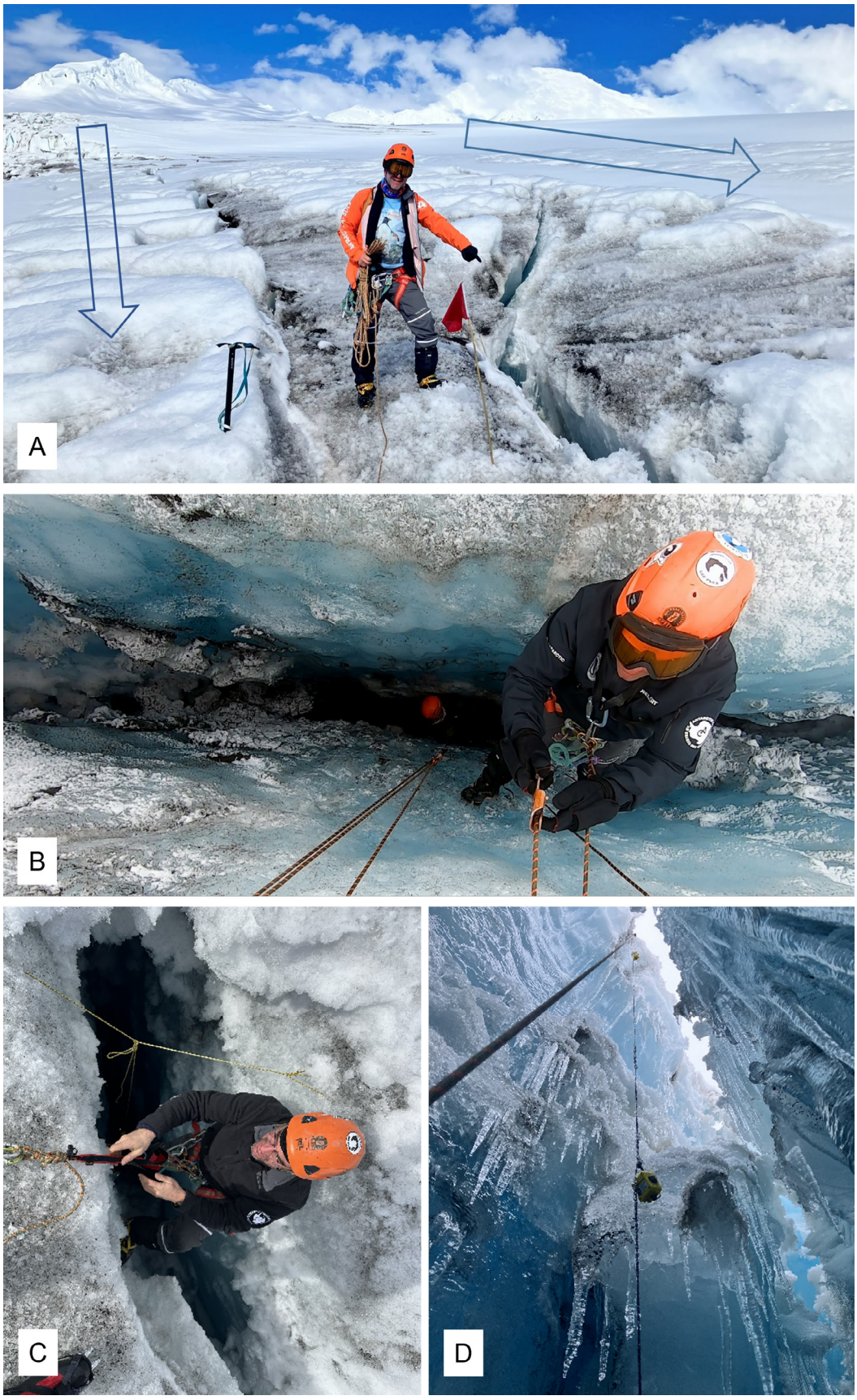

Figure 4. Locations of the measurement sites. **A** The beginning of crevasse C3, the blue arrows indicate the snow covers of two parallel and large crevasses, which, however are connected by C3 **B** Preparation for descending into the C1 **C** Preparation for descent in C4 **D** Sensors in C4.

C2—the first explored crevasse, where three sensors were installed. It is located between the center and the periphery of the glacier at 84 m a.s.l. The width of the entrance at the beginning of the study was 80 cm. The first 9 m downwards were easily passable, and then there is a narrowing at the bottom where flowing water can be heard.

Other two crevasses—C3 and C4 are located in the central part of the glacier (Fig. 3A). Their physical characteristics (widths and lengths), and descriptions of the measurement sites are given below:

C3—a width of 0.7 m, a length of about 40 m (Fig. 4A–B). A short but deep crevasse connecting two parallel main crevasses. Open along its entire length. Five sensors (TINYTAG-4500) for recording air temperature were placed in C3. The sensors are attached to ropes at intervals of 3 m, with the first one placed 3 m from the entrance. The total depth of measurement reached is 18 m. The data recording interval is 30 minutes. An ultrasonic 2-axis anemometer WindSonic with data logger is also placed in C3 at a depth of 6 m below the surface.

C4—a width of 1.5 m, and a length of about 400 m. Closed with a snow cap along its entire length, except for a small opening with a length of 4–5 m, where the sensors were placed. Four sensors (TINYTAG-4500) are positioned every 3 m, with the closest to the surface at 6 m (due to the larger entrance width) and the deepest at 15 m. The data recording interval is also set to 30 minutes. By the culmination of the astral summer, this crevasse had expanded sufficiently for us to delve into its depths to a magnitude of approximately 40 m, affording us a view of the level and lustrous abyss of the glacier far beneath the surface.

Through the utilization of GPS, a meter and compass, a comprehensive map of the crevasses was crafted, delineating their entrances, elevations, and marking the positions of the sensors TINYTAG (yellow spots) (Fig. 6).

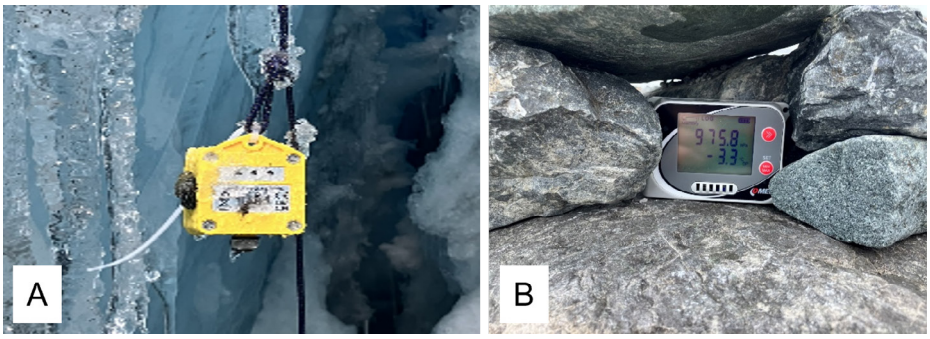

Figure 5. Sensors on site. **A** Sensor in the crevasse **B** Surface sensor on a small rock shelter.

2.3. Organization of field measurements

2.3.1. Surface meteo parameters

Apart from the sensors placed in the crevasses of the glacier, we positioned two autonomous sensors COMET U4130 around the glacier's surface to measure (Fig. 5A–B) and record external temperature, humidity, dew point and at-

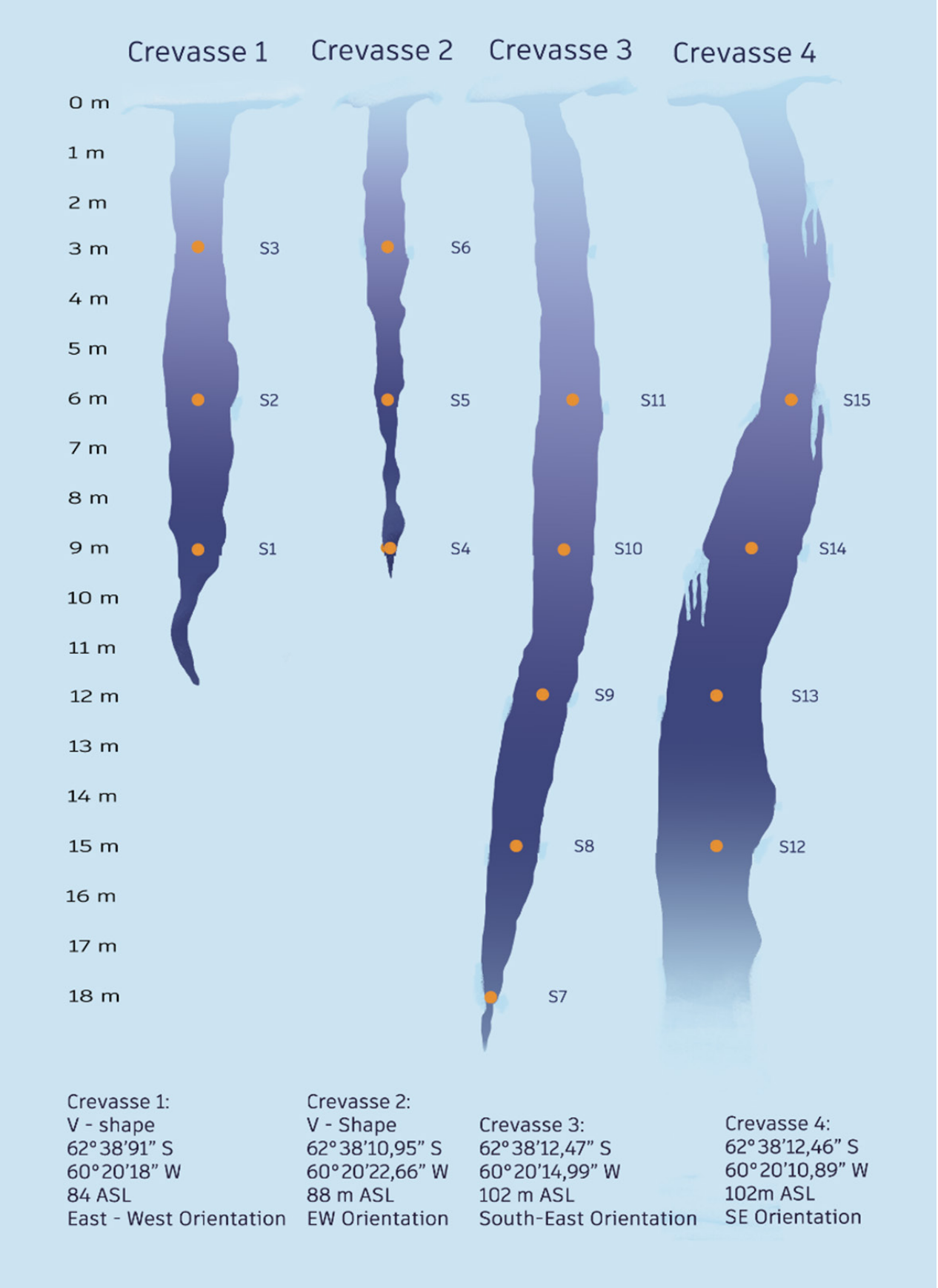

Figure 6. Scheme of the crevasses with sensors, coordinates and orientation.

mospheric pressure. The same sensors were used by the author to investigate the relationship between surface atmosphere parameters and the changes in temperature in the underground depths of the deepest karst cave in Bulgaria. Data was recorded every 30 minutes, with all sensor clocks synchronized. Additionally, each day of the measurements was supplemented with a handwritten journal, detailing the weather conditions, wind measurements, and solar radiation recordings (Table 1).

Table 1. Daily weather log.

Date	Weather conditions
14.1.2024	Clear and sunny
15.1.2024	Clear and sunny
16.1.2024	Cloudy, winds reaching up to 40 km/h
17.1.2024	Cloudy, heavy snow, winds reaching up to 60 km/h
18.1.2024	Cloudy, warm, without wind
19.1.2024	Cloudy, warm, without wind
20.1.2024	Cloudy, warm, without wind
21.1.2024	Cloudy, light wind
22.1.2024	Cloudy, wind increase in the evening
23.1.2024	Cloudy, very high wind up to 130 km/h, snow
24.1.2024	Cloudy, winds up to 50 km/h
25.1.2024	Cloudy, winds up to 40 km/h, snow
26.1.2024	Cloudy, heavy rain, moderate in afternoon
27.1.2024	Cloudy, calm, without wind
28.1.2024	Cloudy, calm weather, without wind
29.1.2024	Fog, warm, without wind
30.1.2024	Morning-high wind and snow, afternoon-clear and sunny
31.1.2024	High wind up to 70 km/h
1.2.2024	Good weather, light wind at the afternoon
2.2.2024	Warm, light rain at noon, high wind and snow at afternoon
3.2.2024	Warm, quiet, cloudy, afternoon sunshine
4.2.2024	Sunny morning, cloudy and high wind in afternoon
5.2.2024	Cloudy, high wind 60 km/h, heavy rain
6.2.2024	Cloudy, high wind 60 km/h, heavy rain
7.2.2024	Cloudy, light rain, all day
8.2.2024	Snow in the morning, cloudy but calm at the afternoon
9.2.2024	Cloudy, calm, without wind, fog
10.2.2024	Calm, sunny, light wind
12.2.2024	Calm, sunny, light wind
13.2.2024	Cloudy, fog, light rain in the morning
14.2.2024	Cloudy, strong wind 60 km/h

2.3.2. Solar activity

An essential characteristic of solar activity is the radio emission flux emitted by the Sun at a wavelength of 10.7 cm, corresponding to a frequency of 2.8 GHz. This 2.8 GHz or 10.7 cm solar radio flux has served as a key metric for monitoring solar radio activity since 1946, currently overseen by the Dominion Radio Astrophysical Observatory in Penticton, Canada (Tapping and Charrois 1994). It is a significant indicator for solar activity due to its correlation with variations in the solar ultraviolet spectrum, which influences the upper layers of Earth's atmosphere and ionosphere. Our data on solar activity is extracted from the monthly bulletin of the Royal Observatory of Belgium (SILSO 2024).

Multiple solar flares and solar filament eruptions were observed from 21–23 January 2024. The associated coronal mass ejections (CMEs) were analyzed and modeled. Results of these analysis show potential impacts on Earth as early as late in the day on 24 January, with more likely impacts on 25–26 January 2024. As a result, forecasters currently anticipate G1-Minor geomagnetic storm levels over these three days, with higher storm levels possible if more of a direct impact and/or stronger connection with Earth's magnetic field lines occurs. However, it's important to note that the direct impact of solar storms on Earth's weather and climate is still an area of ongoing research and remains complex and multifaceted. Many factors contribute to Earth's weather systems, and while solar activity can play a role, it's just one of many influences. It is worth to note that the strongest winds recorded during the measurement coincide with the geomagnetic storm caused by increased solar activity between January 21st and 23rd (NOAA 2024).

2.3.4. Sun radiation penetrating into the crevases

During measurements it was discovered that sunlight penetration within the crevasses with direct beam on the sensors may negatively impact collected data (Fig. 7). Thus all sensors were placed accordingly so that there are no extra influences on them depending on direct sunlight. Thus the solar impact was measured under equal conditions. This information helped us disregard

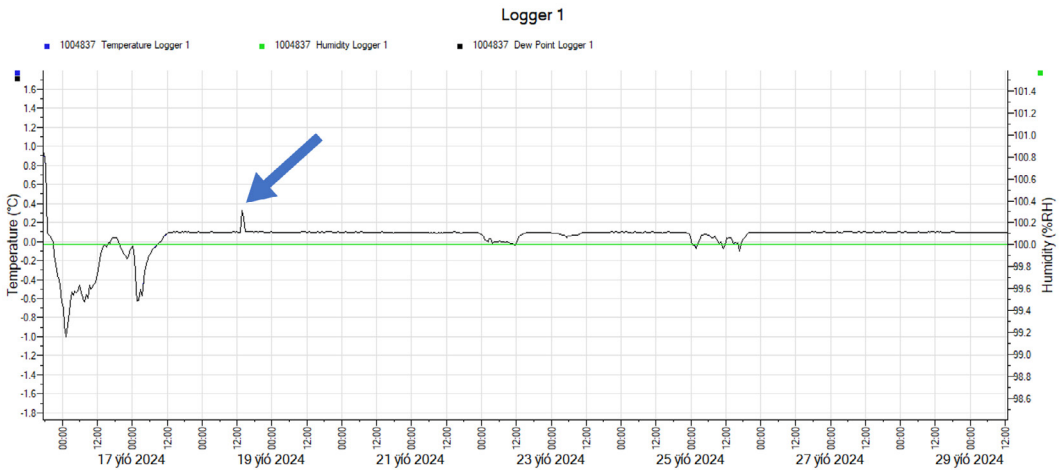

Figure 7. Blue narrow shows impact of the sunlight hit on the sensor.

Table 2. Calculated height above the horizon an azimuth of the Sun.

15 January 2024			30 January 2024		
Time	**Sun height, deg**	**Sun azimuth, deg**	**Time**	**Sun height, deg**	**Sun azimuth, deg**
6:30 AM	14	-109	6:30 AM	10	-108
7:00 AM	18	-102	7:00 AM	14	-102
7:30 AM	21	-96	7:30 AM	17	-95
8:00 AM	24	-89	8:00 AM	21	-88
8:30 AM	28	-82	8:30 AM	24	-82
9:00 AM	31	-75	9:00 AM	28	-75
9:30 AM	34	-68	9:30 AM	31	-67
10:00 AM	38	-60	10:00 AM	34	-60
10:30 AM	40	-52	10:30 AM	37	-52
11:00 AM	43	-43	11:00 AM	39	-43
11:30 AM	45	-34	11:30 AM	42	-34
12:00 PM	47	-24	12:00 PM	43	-25
12:30 PM	48	-14	12:30 PM	44	-15
1:00 PM	48	-4	1:00 PM	45	-5
1:30 PM	48	7	1:30 PM	45	5
2:00 PM	48	17	2:00 PM	44	15
2:30 PM	46	27	2:30 PM	43	25
3:00 PM	45	37	3:00 PM	41	34
3:30 PM	42	46	3:30 PM	39	43
4:00 PM	40	55	4:00 PM	37	52
4:30 PM	37	63	4:30 PM	34	60
5:00 PM	33	70	5:00 PM	31	67
5:30 PM	30	78	5:30 PM	28	75
6:00 PM	27	85	6:00 PM	24	82
6:30 PM	23	91	6:30 PM	21	89
7:00 PM	20	98	7:00 PM	17	95
7:30 PM	17	104	7:30 PM	14	102
8:00 PM	13	111	8:00 PM	11	108

deviations in temperature measurements. That's why we use licensed software PVsyst (PVsyst 2024) to determinate path of the Sun with azimuth and height around the glacier and how the path of the sun changes during the first two weeks of the measurements (Table 2).

As a result of these measurements, we found that at the beginning of the experiment, at noons, sunlight penetrate very deep in the C1 and make significant impact on the temperature (Fig. 7). Due to the lack of thermal inertia in the ice and the sensor material, there are no significant changes in the records after exposure to solar radiation.

This necessitated a slight adjustment in the positions of the upper sensors to ensure they remain unheated by the sun throughout the duration of the meausrements.

2.3.5. Wind speed and direction into the crevasse

At the beginning of the study, we deployed an ultrasonic anemometer at a depth of six meters in crevasse 4 (C4) to detect the direction and quantity of air flows (Fig. 8). The measurements were taken every minute. The position of the anemometer was tilted sideways, with the arrow, which normally points North, directed upwards in this case (Fig. 9A). This allows us to classify all airflow with an angle smaller than 90° and larger than 270° as "Downward Movement". Conversely, airflow with an angle greater than 90° and less than 270° is classified as "Upward Movement".

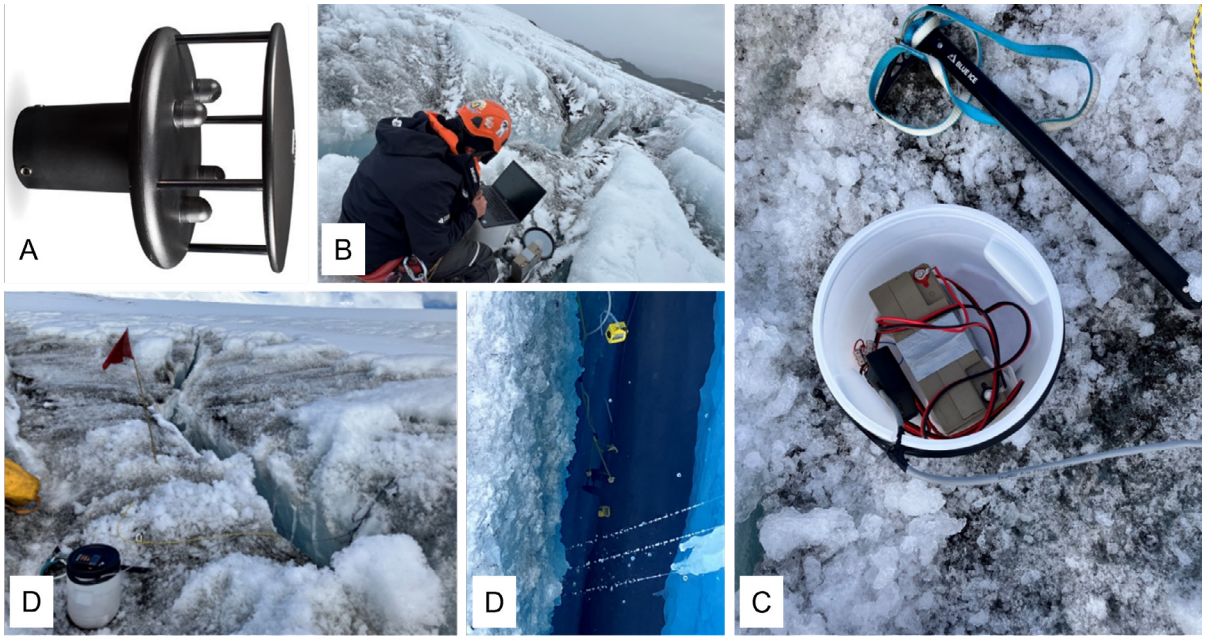

Figure 8. Field measurements with anemometer **A** Ultrasonic anemometer **B** Set the data and hour by computer **C** Box with accumulator and Data Logger **D** Position inside the crevasse **E** Position of the box with accumulator.

2.4. Data analysis

For each of the temperature sensors in the crevasses, we aggregated the data by taking the average for each hour. For example, for all data between 11:00:00 and 11:59:59 on a particular day, we took the average and compared it to the 11th hour (note: Since the data is measured every half hour, in almost all cases, it is the average of two numbers). We did the same for external data and data from the anemometer (note: for the anemometer, we aggregated 60 numbers per hour or fewer in case of missing data). In this way, for each hour, we have one number for the temperature for each of the sensors in the crevasses, for the external parameters, and the direction and speed of the wind from the anemometer. This allows us to search for correlations between different types of data. To determine how consistent the temperatures are, we calculated their variances for each of the sensors. Variance is the expected value of the squared variation of a random variable from its mean value, in probability and statistics. Informally, variance estimates how far a set of numbers (random) are spread out from their mean value.

To analyze the extensive datasets, we used Pearson correlation through the statistical software SPSS. This allowed us to investigate statistical relationships between temperatures at different depths within the crevasses and external meteorological parameters. Additionally, to determine the depth of heat penetration from the surface, we calculated the statistical variance using a procedure written in the PYTHON programming language.

3. Results

3.1. Temperature gradient and depth of heat penetration from the surface

Figure 9 shows the recorded temperatures in each of the crevasses, along with the external temperature. It is evident how the trend of internal temperatures repeating decreases with depth, and the temperatures become more constant. The blue line indicates external temperature for the period from three weeks and the other line indicates internal temperatures through 3 m. It is evident that Crevasse 1, being shallower and located on the periphery of the glacier, responds more deeply to external changes.

3.2. Determination of the zone of constant temperatures

In each of the crevasses, the variance decreases with the increase of the depth, meaning that temperatures become more consistent at greater depths. Table 3 shows the temperature variances for each of the sensors.

Results prove that at depths deeper than 9 m, in the central crevasses, the variance tends to zero and therefore we have stability in temperatures.

Table 3. Temperature variance for each of the sensors.

Crevasse number and sensor	Variance of the sensors
crevasse1_9m	0.016464
crevasse1_6m	0.067207
crevasse1_3m	0.179162
crevasse2_9m	0.000065
crevasse2_6m	0.009135
crevasse2_3m	0.095654
crevasse3_18m	0.002996
crevasse3_15m	0.010283
crevasse3_12m	0.036019
crevasse3_9m	0.072153
crevasse3_6m	0.090527
crevasse4_15m	0.000586
crevasse4_12m	0.003642
crevasse4_9m	0.003087
crevasse4_6m	0.042197

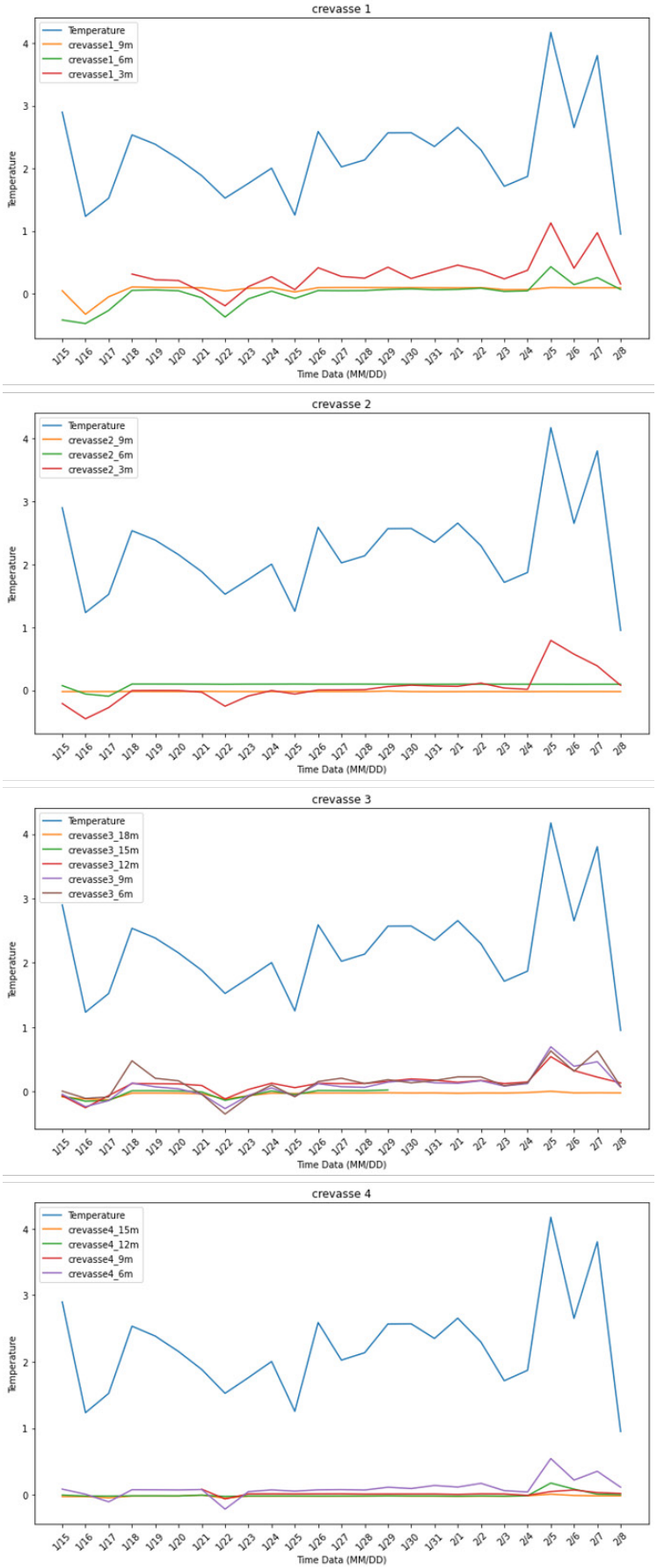

Figure 9. Temperature gradients in the crevasses.

In addition to this, we established the average values in the zone of constant temperatures (Table 4). Proven by the data, the constant temperature zone at the periphery of the glacier differs from the temperature at its center. Moreover, this point varies in different crevasses with a variance threshold of approx. 10 m in crevasse 1; around 8–9 m in crevasse 2; about 15 m in crevasse 3; about 12 m in crevasse 4.

Table 4. Calculated average temperature for each sensor inside the crevasses and surface sensors.

Crevasse number and sensor	Average temperature in crevasses, °C
crevasse1_9m	0.063
crevasse1_6m	0.008
crevasse1_3m	0.325
crevasse2_9m	-0.020
crevasse2_6m	0.081
crevasse2_3m	0.042
crevasse3_18m	-0.035
crevasse3_15m	-0.032
crevasse3_12m	0.123
crevasse3_9m	0.098
crevasse3_6m	0.148
crevasse4_15m	-0.020
crevasse4_12m	-0.003
crevasse4_9m	0.015
crevasse4_6m	0.097
Outside sensors:	
Temperature	2.225
RH	79.591
DewPoints	-1.022
Pressure	983.837

3.3. Correlations between outside meteo parameters and temperature inside the crevasses

The correlation with external temperature decreases with increasing depth for each of the crevasses (Table 5). For depths above the selected conditional points of constant temperature (with variance less than 0.01), correlations with external temperature are less than 0.4. Crevasse 3 is an exception. The correlations there are quite high even at greater depths. As mentioned earlier, we also found that the zone of constant temperature extends quite deeply in this crevasse.

Table 5. Correlations between external atmospheric parameters and the data from the sensors in crevasses.

Crevasse number and sensor	Correlation: T °C outside/ crevasse T °C	Relative humidity	DewPoints	Atmospheric pressure
crevasse1_9m	0.320	0.296	0.424	-0.208
crevasse1_6m	0.639	0.446	0.728	-0.385
crevasse1_3m	0.832	0.183	0.649	-0.375
crevasse2_9m	0.064	-0.013	0.023	-0.011
crevasse2_6m	0.274	0.188	0.307	-0.110
crevasse2_3m	0.625	0.409	0.683	-0.488
crevasse3_18m	0.466	0.402	0.594	-0.245
crevasse3_15m	0.533	0.460	0.662	-0.369
crevasse3_12m	0.623	0.403	0.683	-0.469
crevasse3_9m	0.709	0.403	0.727	-0.478
crevasse3_6m	0.790	0.373	0.744	-0.482
crevasse4_15m	0.385	0.161	0.344	-0.240
crevasse4_12m	0.393	0.130	0.322	-0.478
crevasse4_9m	0.303	0.173	0.315	-0.214
crevasse4_6m	0.697	0.273	0.607	-0.434

3.4. The role of external wind in changing the point of constant temperature

For the precise definition of the role of external wind and its impact on the temperature within the crevasses, eight representative measurements were conducted. All of them were ran out during days with significant wind (of more than 40 km/h)—16th, 17th, 23rd, 24th, 25th, and 31st January and 5th and 6th February. We grouped and correlated the extracted data into one set (with wind), and into another set (without wind) (Table 6). We repeated the up mentioned analyses separately in two groups.

All collected results proved that whenever there is an absence of a surface wind (of more than 40 km/h) there is a stable temperature gradient within the crevasses. In the contrary—if there is a strong surface wind the zone of constant temperatures is shifting towards the surface.

Table 7 shows correlation coefficients between temperatures from the sensors in the crevasses and the external temperature, calculated separately for windy days (first column) and calm days (second column). It is clearly visible how all correlations are larger during windy days, indicating that the external temperature plays a greater role. Additionally, correlations above 0.4 are at shallower depths during windy days.

3.5. Analysis of air movements up and down within the crevasses

For the recent analyses, we took data from the anemometer (averaged hourly), data from crevasse 3 (sensors 7, 8, 9, 10, and 11), and surface temperature.

Table 6. Correlation between variance in days with wind of more than 40 km/h and less than 40 km/h

Crevasse number and sensor	Days with wind of more than 40 km/h	Days with wind of less than 40 km/h
crevasse1_9m	0.035717	0.004948
crevasse1_6m	0.121373	0.038901
crevasse1_3m	0.204139	0.167434
crevasse2_9m	0.000004	0.000096
crevasse2_6m	0.026022	0.000025
crevasse2_3m	0.221753	0.031819
crevasse3_18m	0.006056	0.001311
crevasse3_15m	0.015968	0.005292
crevasse3_12m	0.074712	0.016559
crevasse3_9m	0.117571	0.049395
crevasse3_6m	0.098375	0.085661
crevasse4_15m	0.000555	0.000603
crevasse4_12m	0.009272	0.000422
crevasse4_9m	0.000824	0.004103
crevasse4_6m	0.056004	0.034821

Table 7. Correlation between surface temperature and the temperature detected by sensors within the crevasses.

Crevasse number and sensor	Days with wind of more than 40 km/h	Days with wind of less than 40 km/h
crevasse1_9m	0.455	0.179
crevasse1_6m	0.781	0.530
crevasse1_3m	0.910	0.795
crevasse2_9m	0.024	0.077
crevasse2_6m	0.424	0.134
crevasse2_3m	0.751	0.599
crevasse3_18m	0.586	0.368
crevasse3_15m	0.602	0.416
crevasse3_12m	0.799	0.486
crevasse3_9m	0.833	0.623
crevasse3_6m	0.892	0.727
crevasse4_15m	0.674	0.233
crevasse4_12m	0.618	0.260
crevasse4_9m	0.359	0.312
crevasse4_6m	0.833	0.621

For the anemometer data, we counted the difference between the number of times the air moved up and down within an hour, as well as the sum of the corresponding speeds for upward and downward movements. The first variable indicates whether the air movement is predominantly downward (positive values) or upward (negative values), while the second variable represents the quantity of air moving downward (negative values indicate upward movement).

We found that there are no correlations between the direction of airflow and the amount of airflow with the temperatures of the sensors and external temperature. There are also no correlations between these variables and the different temperature differentials, i.e., the difference between the external temperature and that at 6 m, and 9 m. Additionally, there are no correlations with other external parameters—RH, DewPoint, Pressure. Finally, we divided the data based on wind conditions—windy days and non-windy days. Predominantly, the air moves downwards.

On windy days, the average number of downward movements is 3.91, while on non-calm days, it is 5.47. The difference is not statistically significant: $t(570) = 0.858$, $p = 0.39$.

On windy days, the average amount of air during downward movement is 0.49, while on calm days, it is 1.76. The difference is close to the statistical significance: $t(570) = 1.821$, $p = 0.07$.

4. Discussion

We successfully defined and measured meteorological parameters within the crevasses, including the temperature gradient, temperature stability at depth, and average temperature. This research provides a reference point against which we can compare future changes in the glacier. The discovery of a negative correlation between solar activity and crevasse temperatures establishes a direct link between ionospheric disturbances and the ground-level atmospheric layer.

The identification of a zone of constant temperatures within the glacier and the determination of the depth of this zone contribute to the scientific research of the meteorology of glacier drainage systems. Such a study has not been conducted in Antarctica before, and there is no information on whether these parameters change in response to solar activity, seasonal variations, anthropogenic activity, etc. The air movements in the crevasses indicate that the glacier has a “breathing” pattern independent of external changes. To understand the mechanisms of this process, additional anemometers should be installed in the future, and parameters not yet studied should be included (e.g., tides of the Southern Ocean and temperature fluctuations of ocean water).

Thanks to Bulgaria’s new research vessel “Sv. Sv. Kiril i Metodii”, we can repeat the study over a larger area and on neighboring islands. It would be useful to determine the distance from the studied glacier where temperatures above the zone of constant temperatures become strictly negative and the glaciers are stable.

Compared to other similar studies (Purdie et al. 2023), we believe our sensor mounting systems are much more stable. The ropes to which the sensors were attached were secured to the ice using an “Abalakov” knot (Kopeckova

2024) and ice screws buried in ice to reduce melting around the screws due to shortwave solar radiation. Despite the lack of budget for radiation shields for the sensors, we managed to predict light penetration into the crevasses and its impact on the study. Unfortunately, we started the study with two ultrasonic anemometers, but due to a severed cable, only one remained operational, which was insufficient to describe the entire air circulation. In the future, sensors should reach the bottom of the glacier, which we visually determined to be about 50 m below the lowest sensor at site C4, thus providing a complete temperature gradient from the bottom to the surface.

Although glaciers in Antarctica and around the world are relatively well-studied, the question of heat exchange between the external surface atmosphere and the internal glacier air volumes remains unresolved. The findings from the experiment, such as the constant temperature, its value, and the correlation between solar activity and temperatures in the glacier, provide a basis for long-term monitoring of these parameters, which could provide forecasts for glacier melting. The applied basic methodology for the study is directly linked to the development of sensors, equipment, and software that we install in the glaciers. The methods for securing the measuring instruments in conditions of intense solar radiation and winds reaching up to 140 km/h are the same as those used by high-altitude climbers during ascents in the Himalayas but were found inadequate for our needs in Antarctica. In the future, sensors that do not require frequent servicing may be deployed, as well as the use of a greater number of anemometers for more precise determination of air currents.

5. Conclusion

With this study, we initiated a multi-year monitoring of the temperature equilibrium in the glaciers, which can be developed by other researchers on different glaciers, thus providing a new climatic map on the state of subglacial temperature fluctuations. The experience we've accumulated over the past two years during the investigation of thermodynamic fluctuations in deep and vertical caves has been very beneficial for launching the current project (Parov 2023). Whether it pertains to glacial karst formation or that occurring in easily soluble limestone rocks, the process of formation is one and the same.

With increasing depth of the crevasses, the temperature becomes more constant. We can conditionally consider the point where the temperature variance becomes insignificant as the zone of constant temperature. In different crevasses, this zone is at different depths, meaning it is influenced by the specific characteristics of each crevasse location. At shallow depths, temperature is influenced by external temperature, but as depth increases, this influence decreases. On windy days, the zone of constant temperature expands. The air movement in the crevasses is turbulent in nature. Air moves predominantly downwards than upwards. No correlations are found between the direction of airflow and the temperatures recorded by the crevice sensors. No correlations are found between the direction of airflow and the external parameters. There is a tendency, but it lacks statistical significance ($p = 0.07$), for the amount of air moving downwards to be lower on windy days than on calm days.

The relationship between changes in solar radiation intensity and temperatures in glaciers is an important aspect of studying climate change. Studies indicate that variations in solar activity can influence Earth's climate, including glaciers. While solar activity is an important factor, there is a consensus in the scientific community that human activities, particularly emissions of greenhouse gases such as CO_2, have a significant impact on the climate. Therefore, to clarify the relationship between changes in solar radiation intensity and the reduction of temperatures in glaciers, it is necessary to consider multiple factors and conduct multifactorial analyses, including studies on solar activity, atmospheric conditions, and anhropogenic impact.

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Additional information

Conflict of interest

No conflict of interest was declared.

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No ethical statement was reported.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.