Variability of soil moisture on three sites in the Northern Antarctic Peninsula in 2022/23

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Abstract
Soil moisture represents one of the crucial parameters of the terrestrial environments in Antarctica. It affects the biological abundance and also the thermal state of the soils. In this study, we present one year of volumetric water content and soil temperature measurements on James Ross Island, Nelson Island and King George Island. The volumetric water content at all sites increased with depth. The mean summer values were between 0.24 and 0.37 cm^3/cm^3 (James Ross Island), 0.30 and 0.40 cm^3/cm^3 (Nelson Island) and 0.11 and 0.36 cm^3/cm^3 (King George Island). We found that the freezing point of the soils was close to 0°C on Nelson Island and King George Island. We attributed the lower temperature of soil freezing around -0.5°C on James Ross Island to the site location close to the sea. Even though the sites are located in the distinctive climate zones and comprise of contrasting soil types, the only differences of moisture regime were observed the surficial layer of the studied sites.

Key words: soil moisture, soil thermal regime, permafrost, freeze-thaw processes

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Introduction

Antarctic terrestrial environments occupy only about 0.5% of the whole continent (Brooks et al. 2019). One of the most important parameters which can affect ecological and geomorphological processes in these areas is the availability of liquid water in the summer months.

Soil moisture is an important parameter driving the dynamics of the periglacial environment. Many of the geomorphological landforms and features are the result of frost weathering or freeze-thaw processes. Moreover, soil moisture acts as an important driver affecting soil thermal regime,

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heat transfer and active layer seasonal thawing (*e.g.* Farouki 1981, Clayton et al. 2021). Even though an increase of soil moisture usually leads to an increase in soil thermal conductivity (*e.g.* Farouki 1981, Abu-Hamdeh and Reeder 2000, Wessolek et al. 2023), it increases the amount of latent heat necessary for the phase change at the same time. As a consequence, the active layer tends to be thinner under moist conditions (*e.g.* Clayton et al. 2021).

Besides being an important land-forming parameter, soil moisture is obviously one of the most important ecological factors and one of the major drivers of the Antarctic vegetation abundance (Kennedy 1993, Ugolini and Bockheim 2008, Royles et al. 2013, Guglielmin et al. 2014). Yet, the particular limits of soil water content and seasonal dynamics favouring vegetation presence are unknown. The shortage of available liquid water can lead to a rapid worsening of vegetation condition as was observed over a 13-year period in East Antarctica (Robinson et al. 2018).

The knowledge on soil moisture in Antarctica is mostly limited to the area of McMurdo Dry Valleys where general soil research is carried out in the last few decades (*e.g.* Hrbáček et al. 2023). The vast majority of soils in the McMurdo region are very dry with water content lower than 5% (Seybold et al. 2010). The zones with a clearly distinguishable moisture regime are called water tracks and form specific ecosystems of the McMurdo region promoting also the abundance of biota or microbial diversity (Levy et al. 2011, Wlostowski et al. 2018, George et al. 2021). In the Antarctic Peninsula region, soil moisture was monitored on some sites in the South Shetlands area. Higher moisture content was observed on sites below vegetation as compared to bare ground on King George Island (Almeida et al. 2014). On Robert Island, moisture content was identified as an important factor affecting the variability of soil CO_2 flux (Thomazini et al. 2020).

A thorough examination of soil moisture variability therefore represents one of the challenges and an important step for the advance in Antarctic soil research in general (Horrocks et al. 2020, Hrbáček et al. 2023). The aim of our study is to evaluate the general patterns and variability of volumetric soil water content (VWC) measured on three sites with diverse climate conditions and lithological propertiesin the northern Antarctic Peninsula region (James Ross Island, Nelson Island and King George Island) in the period 2022-2023. Particularly we focus on:

1) Assessment of seasonal variability of soil moisture on each site;
2) Evaluation of vertical changes of soil moisture;
3) Determination of freeze-thaw behaviour of soils.

Study sites

The study sites are located on James Ross Island in the north-eastern part of Antarctic Peninsula region and on Nelson Island and King George Island in the South Shetlands (Fig. 1). There is a climate contrast between the study sites. The South Shetlands have oceanic climate with a mean annual air temperature around -2.0°C (*e.g.* Turner et al. 2020) and annual precipitation around 500-1000 mm, during summer even in the liquid form (*e.g.* Kejna et al. 2013). In contrast, the climate conditions on James Ross Island are semi-arid polar continental with mean annual temperature around -6.0°C (Kaplan Pastíriková et al. 2023) and the precipitation estimated between 300 and 700 mm, mostly in the snowy form (van Wessem et al. 2016).

James Ross Island

Located off the north-eastern coast of the Antarctic Peninsula, James Ross Island has a total area of approximately 2400 km^2, a quarter of which is currently ice-free. The largest continuous ice-free area on the island and also within the whole northern Antarctic Peninsula region is called the Ulu Peninsula and extends over 300 km^2 in the northern part of James Ross Island. The deglaciation of this part of James Ross Island dates to around 12 900 ka ago (Nývlt et al. 2014). The area is underlain by continuous permafrost, thickness of which has been estimated to 67 meters (Borzotta and Trombotto 2004).

The study site is located approximately 100 meters from the Czech Antarctic research station Johann Gregor Mendel in the northern coast of the Ulu Peninsula. It is situated on a Holocene marine terrace, overlying the Cretaceous sedimentary rocks of Whisky Bay Formation ([1]), characteristic by predominantly flat or gently sloping terrain. The soil is comprised of a loose, fine-grained sediment of prevailing sandy texture (Stachoň et al. 2014).

Nelson Island

The total area of Nelson Island is 165 km^2, of which 95% is covered by ice sheet and only around 8 km^2 is ice-free, scattered into multiple small ice-free areas along the coast. One of the ice-free areas, the Stansbury Peninsula, is located in the northern part of Nelson Island and covers approximately 2.89 km^2 (Meier et al. 2023). Nelson Island lies in the zone of sporadic permafrost (Bockheim et al. 2013), with mean annual ground temperatures around 0°C (Obu et al. 2020).

The study site is located in the central part of the Stansbury Peninsula, on a plateau with multiple lakes. The closest lake is ca. 50 m far from the study site. Geologically, the area is formed by volcanic rocks, mainly basalts, andesites and tuffs (Smellie et al. 1984). The relief of the interior part of Stansbury Peninsula forms a transition between paraglacial and periglacial domain, with moraines, lakes and patterned ground as dominant landforms. Soils in the study area are classified as clay loam to sandy loam with low organic matter content (Meier et al. 2023).

King George Island

Barton Peninsula is the second largest ice-free area of King George Island with an area of 10 km^2 and was exposed after the retreat of Collins Glacier that started at 15 ka ago (Oliva et al. 2019). The exposed surface is composed of stratified volcanic rocks (andesites) and a plutonic intrusion (Birkenmajer 1989, Hwang et al. 2011).

The study site is located approximately 20 meters away from the King Sejong Station borehole, which was installed at 127 m a.s.l. in bedrock and reaches a depth of 13 meters. It is also is situated in close proximity to the Automated Electrical Resistivity Tomography (A-ERT) setup aimed to the detection of active layer freeze–thaw dynamics using quasi-continuous electrical resistivity tomography (Farzamian et al. 2020). The ground itself is composed of a diamicton, featuring angular boulders and gravels embedded in a sandy-silty matrix. Periglacial processes occur with the formation of stone circles, solifluction lobes, and striped ground. Based on the A-ERT data (Farzamian et al. 2020), the estimated thickness of the active layer in the soils is approximately 1–1.5 meters.

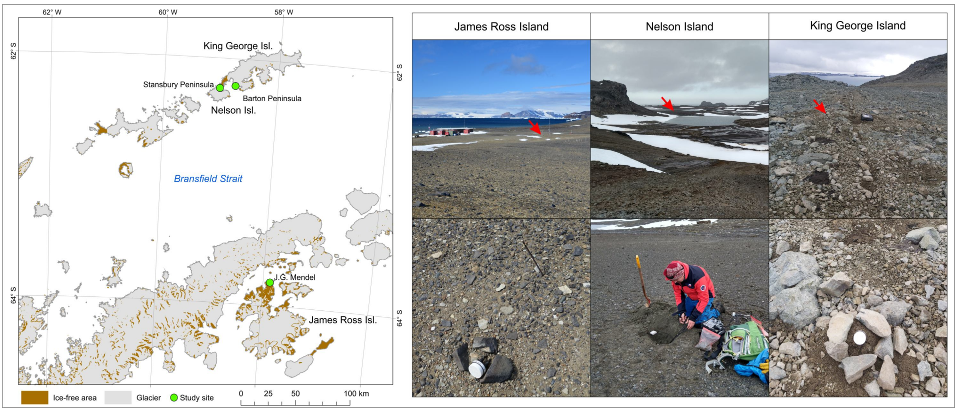

Fig. 1. Regional setting and study sites.

Methods

We used VWC data from three profiles located on James Ross Island, Nelson Island and King George Island (Fig. 1, Table 1). At all sites, VWC was measured by three time-domain reflectometry sensors CS655 (Campbell Sci.) with an accuracy of ±3% placed at different depths connected to Microlog SDI-MP datalogger (EMS Brno). The measurement and storing interval was 60 minutes. With the respect to the local conditions, the sensors were installed both in horizontal and vertical position (Table 1). Besides VWC, the CS655 sensors also provide data of soil temperature with an accuracy between ±0.1°C (range 0°C to +40°C) and ±0.5°C (full temperature range).

The daily VWC data are represented by a single measurement obtained at 16:00 UTC, which corresponds to the midday in local time of the study sites. The VWC variability was studied only for the unfrozen conditions defined by the mean daily ground temperature > 0°C. In case of frozen ground (ground temperature < 0°C), we consider VWC as approximate value of unfrozen water content (*e.g.* Zhou et al. 2014)

Finally, we used hourly data of VWC and ground temperature to construct the soil freezing curve for both phases of soil freezing and soil thawing at the bottom-most sensors.

Study site	Installation depth [cm]	Measurement period	Elevation
James Ross Island	5^h, 30^h, 50^h cm	1/1/2022–28/2/2023	10 m
Nelson Island	5^h, 20–30 ^{v}, 50-60^v cm	1/1/2022–2/2/2023	30 m
King George Island	10^h, 20–30^v, 60 ^{h} cm	23/2/2022–7/2/2023	127 m

Table 1. Description of the study sites. *Note*: ^{h} – horizontal placement of the sensor, ^{v} – vertical placement of the sensor.

Results

Variability of soil moisture and temperature

James Ross Island

Mean VWC on James Ross Island within the study period for the unfrozen soil was 0.24 cm^3/cm^3 in 5 cm depth, ranging from the minimum of 0.13 to the maximum of 0.30 cm^3/cm^3. Both the mean and the minimum and maximum values increase with depth, so that in 50 cm depth, mean VWC reached 0.33 cm^3/cm^3 and the minimum and maximum were 0.28 and 0.37 cm^3/cm^3, respectively. The amplitude between the minimum and maximum decreased with depth, from 0.17 cm^3/cm^3 in 5 cm depth to 0.09 cm^3/cm^3 in 50 cm depth (Table 2).

Ground temperature in 2022 reached an average of -3.22°C at 5 cm below surface and decreased with depth to -3.79°C at 50 cm depth. Maximum and minimum temperatures of 10.5°C and -21.1°C, respectively, were observed close to ground surface at 5 cm depth, with temperature amplitude spanning over 31°C. The absolute value of recorded temperature extremes decreased with depth as well as the amplitude between maximum and minimum (Table 3). The thawing period of 2021/2022 ended on March 13th, while the thawing period of 2022/2023 began on November 6th.

Nelson Island

Closely below ground surface at 5 cm depth, mean VWC on Nelson Island reached 0.30 cm^3/cm^3 and increased with depth, to 0.34 cm^3/cm^3 in 20–30 cm and 0.40 cm^3/cm^3 in 50 cm depth. The maximum observed in 5 and 20–30 cm depths were similar to each other, while in 50 cm depth the maximum was higher and reached 0.51 cm^3/cm^3. The amplitude of fluctuations in VWC decreased with depth, with over 0.32 cm^3/cm^3 in 5 cm to approximately 0.20 cm^3/cm^3 in 50 cm depth (Table 2).

Mean annual ground temperatures in 2022 were above 0°C throughout the whole profile, ranging from 0.3°C at 5 cm depth to 0.1°C in 50 cm depth. The absolute value of maximum and minimum observed temperature decreased with depth, same as the amplitude of temperature fluctuations, from over 15°C on top to approximately 6°C in the bottom part of the profile (Table 3). The thawing period of 2021/2022 ended on April 25th, 2022 and the thawing period of 2022/2023 began on November 18th, 2022.

King George Island

Mean VWC in 10 cm depth on King George Island site was 0.11 cm^3/cm^3 and exhibited pronounced differences between the upper and lower layers of soil, with mean VWC more than three times higher at 60 cm depth (0.36 cm^3/cm^3). The amplitude of the fluctuations was highest in 20–30 cm depth, with maximum and minimum values of 0.39 and 0.08 cm^3/cm^3, respectively. In contrast, the difference between maximum and minimum VWC in 60 cm depth reached only 0.03 cm^3/cm^3 (Table 2).

Mean ground temperature during the period from February 23rd, 2022 until February 7th, 2023 reached -0.7°C in 10 cm depth and slightly decreased with depth down to -1.0°C in the bottommost part of the profile. The temperature amplitude decreased with depth, ranging from over 10°C on the top to approximately 6°C in 60 cm depth (Table 3). Similar to the Nelson Island site, the thawing period of 2021/2022 ended on April 26th, 2022 and the thawing period of 2022/2023 began on November 18th, 2022.

	Sensor depth	VWC_{mean} [cm^3/cm^3]	VWC_{max} [cm^3/cm^3]	VWC_{min} [cm^3/cm^3]
James Ross Island	5 cm	0.24 ± 0.03	0.30	0.13
	30 cm	0.27 ± 0.06	0.37	0.20
	50 cm	0.33 ± 0.03	0.37	0.28
Nelson Island	5 cm	0.30 ± 0.07	0.47	0.15
	20–30 cm	0.34 ± 0.04	0.46	0.28
	50 cm	0.40 ± 0.04	0.51	0.30
King George Island	10 cm	0.11 ± 0.05	0.19	0.04
	20–30 cm	0.18 ± 0.06	0.39	0.08
	60 cm	0.36 ± 0.01	0.38	0.35

Table 2. Volumetric water content variability at various depths for the three study sites.

	Sensor depth	GT_{mean} [°C]	GT_{max} [°C]	GT_{min} [°C]	TP_{end}	TP_{start}
James Ross Island	5 cm	-3.2	10.5	-21.0	13/03/2022	06/11/2022
	30 cm	-3.7	4.8	-15.1		
	50 cm	-3.8	1.9	-11.8		
Nelson Island	5 cm	0.3	6.5	-8.6	25/04/2022	18/11/2022
	20–30 cm	0.2	5.0	-5.4		
	50 cm	0.1	3.4	-2.2		
King George Island	10 cm	-0.7	3.5	-6.6	26/04/2022	18/11/2022
	20–30 cm	-0.9	2.6	-5.4		
	60 cm	-1.0	1.1	-4.6		

Table 3. Ground temperature variability at various depths with the dates of the end of thawing period 2021/2022 and the beginning of thawing period 2022/2023 for the three study sites.

Soil freeze-thawing characteristics

James Ross Island

The period of soil freezing occurred between March 16th and April 7th, 2022 on James Ross Island. The temperature of the soil during zero-curtain period was -0.5°C. The more pronounced decrease of soil moisture to the values below 0.3 cm^3/cm^3 was visible around March 28th, 2022 (Fig. 3) which was in ca 2/3 of zero-curtain phase duration.

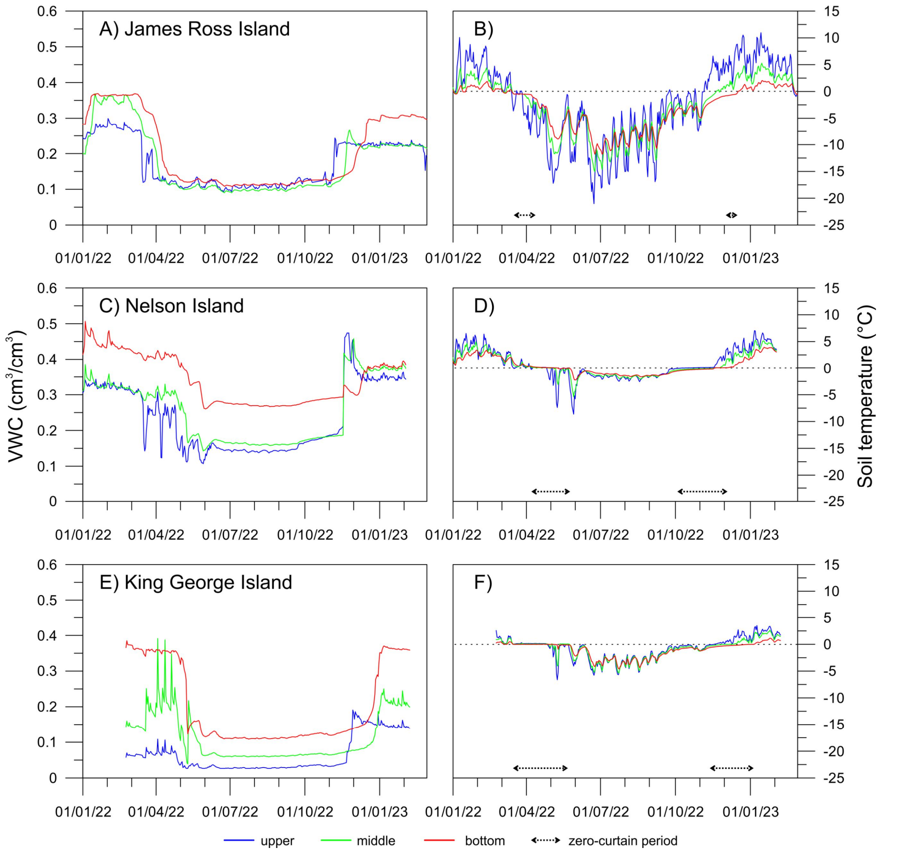

Fig. 2. Variability of studied parameters on the three sites – (A) VWC and (B) ground temperature on James Ross Island; (C) VWC and (D) ground temperature on Nelson Island; (E) VWC and (F) ground temperature on King George Island.

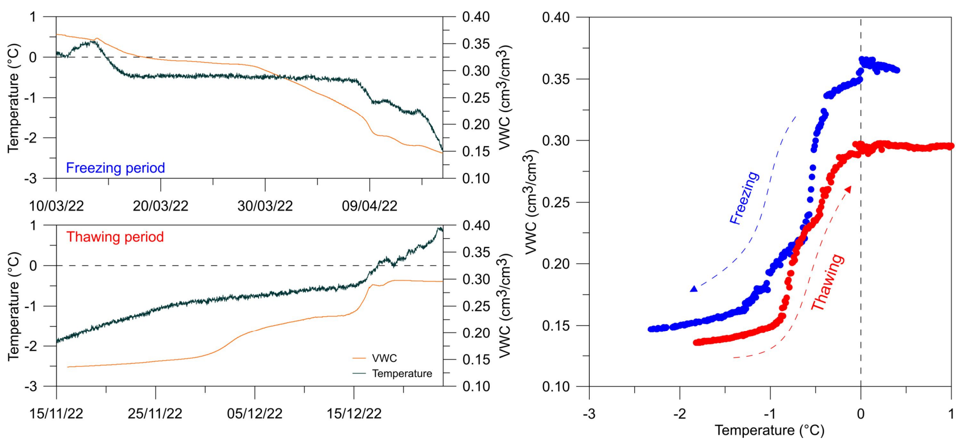

Fig. 3. The variability of VWC and soil temperature on James Ross Island during the freezing and thawing phase.

As indicated by the soil freezing curve, the inflection point representing the beginning of the soil freezing process is for the values of 0.3 cm^3/cm^3 and -0.45°C for moisture and temperature, respectively. The residual (unfrozen) water content is around 0.15 cm^3/cm^3 for the temperature -2.0°C. The soil thawing process was relatively fast. The thawing zero-curtain period occurred within a short period between December 10th and 15th, 2022 (*see* Fig. 3) when temperature was kept around -0.6°C and VWC around -0.23 cm^3/cm^3.

Nelson Island

Soil freeze-thaw curves on the Nelson Island site were distorted by the fact that the sensor at the bottommost level was and still is placed in the vertical position. Therefore, during freezing and thawing, the soil temperature sensor is above or below the freeze-thaw front. Therefore, we observed the initial patterns of soil phase change represented by a decrease of soil moisture from 0.45 to 0.37 cm^3/cm^3 under measured temperature of 0.1°C (Fig. 4). The pronounced decrease of moisture from 0.37 to 0.32 cm^3/cm^3 occurred between May 9th and 14th, 2022 when temperature dropped from 0.1 to -0.1°C. Notably, the values of unfrozen water content remain around 0.25 to 0.27 cm^3/cm^3 over the whole winter season (Fig. 2). During the thawing phase, VWC exhibited the highest increase during a short period between November 17th and 18th, 2022. We assume, that the sudden increase in temperature from -0.1 to 0.1°C might be conditioned by the sensor parameters. Yet, the change is within the accuracy of the sensor.

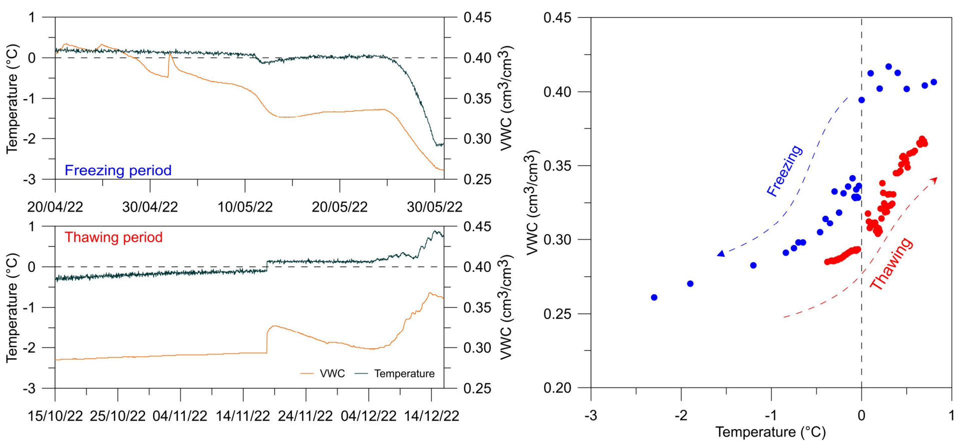

Fig. 4. The variability of VWC and soil temperature on Nelson Island during the freezing and thawing phase.

King George Island

The zero-curtain period ended on May 9th, 2022 when a clear and rapid decrease of soil temperature and moisture started (Fig. 5). Soil freezing process starts at the temperature closely below 0°C. The stable frozen soil is around temperature -0.5°C with a residual water content of 0.14 cm^3/cm^3. The soil thawing process begun on December 15th, 2022 when soil moisture started to increase considerably and ended on December 27th, 2022 when the moisture values have stabilized. The temperature during the thawing process was between -0.2 and -0.05°C (Fig. 5).

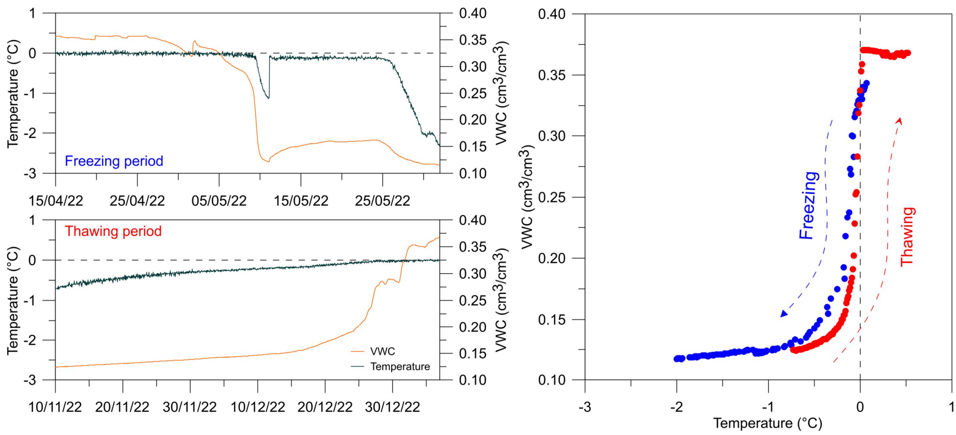

Fig. 5. The variability of VWC and soil temperature on King George Island during the freezing and thawing phase.

Discussion

The study sites are located in the parts of Antarctic Peninsula with distinctive air temperature average (*e.g.* Oliva et al. 2017, Turner et al. 2020), precipitation rates (*e.g.* van Wessem et al. 2017, Palerme et al. 2017) and the overall soil thermal conditions (*e.g.* Hrbáček et al. 2023). Yet, the VWC variability on the study sites exhibited a relatively similar pattern. The highest VWC was observed on Nelson Island, on the side of the Antarctic Peninsula with higher annual precipitation rates and the soils with relatively find matrix favouring the soil retention. The lowest VWCs were observed on Barton Peninsula, which we mostly associated with the gravelly matrix of the study site (Fig. 1; Farzamian, personal communication).

Notably, the site on James Ross Island, which is often classified as semi-arid polar-continental climate zone (Martin and Peel 1978), had also relatively high VWCs reaching up to 0.37 cm^3/cm^3. However, when compared to the hyper-arid climate conditions typical for McMurdo Dry Valleys where soil moisture is very often lower than 0.05 cm^3/cm^3 (Seybold et al. 2010, Levy et al. 2011), VWC data from AWS-JGM site indicate relatively humid soils. Indeed, the analysis of gravimetric water content on other sites on James Ross Island showed that the moisture content can be 7 to 12% than on AWS-JGM (Hrbáček et al. 2019).

All of the study sites followed a similar pattern of increasing moisture with increasing depth. Such a pattern is typical for the moisture profiles in permafrost affected areas where the frozen soil creates an impermeable layer and the moisture is accumulated at the base of the active layer (*e.g.* Shur et al. 2005, Andresen et al. 2020). We attribute the differences between the maximum seasonal water content values mostly to the differences in soil texture. The sites on Nelson Island and

James Ross Island are comprised of soils with relatively high content of fine material (Stachoň et al. 2014, Meier et al. 2023) which creates favourable conditions to keep a relatively high amount of soil water even in the surficial part of the profile. The gravelly matrix in the topmost part of soil on King George Island has a low capability to keep the water (*e.g.* Scheinost et al. 1997) which is transported downwards through the soil profile and accumulated above the permafrost table (*e.g.* Andresen et al. 2020).

The beginning of the thawing season showed different patterns of VWC when all three sites are compared. A VWC regime with a pronounced short-term maximum peak was observed on Nelson Island and was very likely caused by the infiltration of snowmelt water which very often lead to full water saturation (*e.g.* Mohammed et al. 2019). We assume that some meltwater infiltration occurred also on King George Island, as the VWC values at top and middle sensors were twice higher than at the end of the thawing season 2022 (Fig. 2). The overall occurrence of snow on Nelson and King George Islands is also suggested by the isothermal ground thermal regime prior to the zero-curtain period, which is one of the indicators of snow presence (*e.g.* Zhang 2005, Oliva et al. 2017). In contrast, the initial thawing on James Ross Island does not show any signs of possible snowmelt infiltration. The VWC values in the beginning of thawing season 2022/23 are even lower than they were at the end of the thawing season 2021/22. The moisture loss during winter was ca. 0.02 to 0.05 cm^3/cm^3

The soil freezing curves reveal that the freezing temperature is very close to 0°C on the sites on Nelson and King George Island, whereas the freezing temperature on James Ross Island was around -0.5°C. We suppose that the major reason is the close proximity to the sea and the fact, that the site is located on the marine terrace presumably exhibiting some level of salinity. A laboratory experiment found that salt content lower than 0.5% is sufficient to decrease the freezing point to -1.0°C in sandy soils (Bing and Ma 2011). The soil freeze-thawing hysteresis exhibited typical loop with higher VWC values in freezing phase than thawing at all sites (Devoie et al. 2022).

We also detected noticeable values of unfrozen water content especially on Nelson Island, where the VWC during winter did not dropped below 0.25 cm^3/cm^3 at the depth of 50 cm. Even though the TDR are considered to slightly overestimate the amount unfrozen water content (*e.g.* Watanabe and Wake 2009), the absolute value of overestimation of non-calibrated sensors was found lower than 0.05 cm^3/cm^3 in many studies (*e.g.* Watanabe and Wake 2009, Zhang et al. 2011, Zhou et al. 2014). High amount of unfrozen water content in the frozen ground can increase the heat transport and generally promote the permafrost thawing (*e.g.* Romanovsky and Osterkamp 2000, Oldenborger and LeBlanc 2018).

Conclusion

This study brings the first results from a newly established network for soil moisture monitoring in the northern Antarctic Peninsula region. Even though the distinctive conditions between oceanic climate on South Shetlands and semi-arid climate on James Ross Island create a prerequisite for distinctive soil moisture regime, the observation shows rather small differences between study sites. In absolute values, the moistest site was Nelson Island where soil moisture exceeded 0.50 cm^3/cm^3, which can be related to the overall moist climate and fines soil matrix favouring water retention. The moisture values on King George Island and James Ross Island were comparable in the bottommost zone. We assume that the lowest moisture in the top layer on King George Island was attributed to coarse and highly permeable soils.

Importantly, we observed a noticeable amount of unfrozen water content at all of the sites. High amount of unfrozen water can significantly promote heat transfer to the ground and favour the active layer thickening. Therefore, mainly in the border conditions of permafrost presence on the South Shetlands, the variability of soil moisture can be one of the crucial parameters affecting the distribution of active layer thickness and permafrost.

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