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TESTING OPTICAL SPECTRAL INDICES FOR ASSESSMENT OF SURFACE CHANGES DUE TO PERMAFROST MELTING ON LIVINGSTON ISLAND, ANTARCTICA

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Abstract

The present study aims to examine the potential of optical satellite data and spectral indices to assess surface changes induced by permafrost melting. Surface changes related to permafrost melting on Livingston Island, Antarctica, were examined using optical satellite data from Sentinel-2 sensors of the European Space Agency (ESA). The study area coincides with previous field studies by electrical resistivity tomographic profiles made to establish and visualize the presence of permafrost. Utilizing the advantages of remote sensing methods and calculation of optical indices, it was tracked whether and to what extent there was a surface change and melting of the permafrost in the study area. The observation period encompasses the astral summer seasons from 2016 to 2023.

The results show that the combination of different optical indices gives a better understanding of changes in the terrain. The combined use of the Normalized Difference Glacier Index (NDGI), Normalized Difference Snow Index (NDSI), Normalized Difference Snow and Ice Index (NDSII), Normalized Difference Water Index (NDWI), Normalized Difference Vegetation Index (NDVI), and Moisture Stress Index (MSI) indicates for a pronounced trend of melting of the active layer of the permafrost periglacial area of research in March 2016 and 2017, and from January to mid of March 2023.

Introduction

Permafrost is spread among frozen soil, rocks, or underwater sediment, which continuously remains below 0°C for two years or more. It typically exists beneath the so-called active layer, which freezes and thaws annually, and so can support plant growth, as the roots can only take hold in the soil that is thawed [1].

Permafrost is widespread in Polar Regions or high mountains and can be found in the ice-free areas of rocks and soil. It is an object of research in the periglacial areas. In addition, it has a key role in ecosystems, hydrology, and geomorphological dynamics. For example, only in the last decade, it was possible to have a more accurate overview of the thermal state of permafrost and active layer dynamics in Antarctica. This requires the installation of new GTN-P (Global Terrestrial Network for Permafrost) boreholes and Circumpolar Active Layer Monitoring sites (CALM) as part of the Scientific Committee on Antarctic Research (SCAR) expert groups' projects. However, there is still a lot to be understood about the Antarctic permafrost, the active layer, and mainly about their relationships to other environmental variables [2].

Polar Regions are among the most vulnerable territories on the planet and are very sensitive to global climate change. Remote sensing methods are very useful for studying the changes and processes that occur in these hardly reachable places. Satellites provide the ability to measure and monitor elements of the Cryosphere continuously and with better spatial coverage than field or in situ measurements. Copernicus Sentinel-2 carries an innovative wide-swath high-resolution multispectral sensor with 13 spectral bands. It is providing high-resolution optical imagery with global coverage of Earth's land surface every five days [3]. Remote sensing is used to monitor the glacier and periglacial territories. For example, permafrost cannot be directly observed from space, but different types of satellite data, along with ground measurements and modeling, allow scientists to picture permafrost ground conditions.

This research aims to test the abilities of remote sensing optical images to track the snow cover and thawing changes in the area of previously studied permafrost profiles close to the Bulgarian Antarctic Base on Livingstone Island, South Shetland Islands, Antarctica. The expectations were for lower snow coverage through the years and more wet ground because of the thawing active layer.

Study area, scientific background, and related research

The study area is situated on the South Shetland Islands, one of the Earth's regions where warming has been more significant in the last 50 years [4]. Field activities had been focused on Livingston Island, Antarctica (62º39'S, 60º21'W) (*Fig. 1*).

High mountain relief distinguishes Livingston Island. The terrain is 90% covered by glaciers. The island's geological setting provides an excellent site for studying and monitoring the relationships between permafrost, geomorphodynamics, and climate. Thermal anomalies occur at several localities and the island is a very good site for studying the interactions between volcanic eruptions near Deception Island, its ash transportation and deposition on Livingston Island, geomorphodynamics, and permafrost.

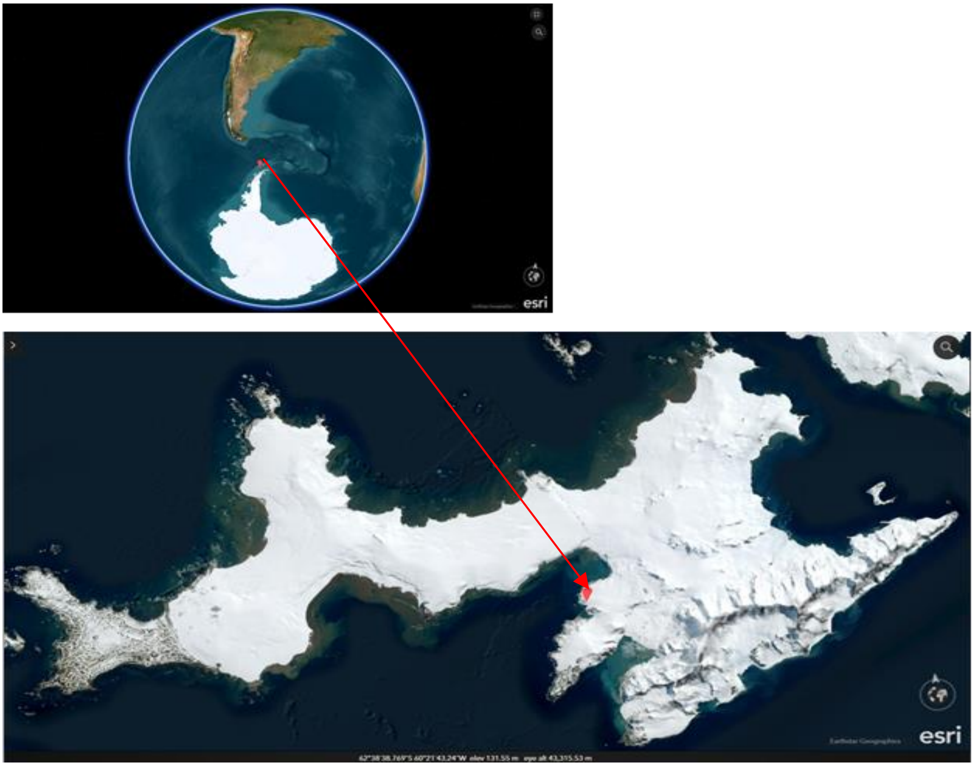


Fig. 1. Livingston Island, Sought Shetland Islands, Maritime Antarctica. ©ESA

The study area coincides with previous geophysical field studies performed by the deployment of electrical resistivity tomographic profiles to establish and visualize the changes in the active layer of the permafrost. Boreholes (deep 6 to 25 m) for permafrost temperature monitoring (GTN-P) and sites for active layer monitoring (CALM-S) were installed. The main aims were identifying permafrost characteristics and spatial distribution, identifying the climate controls on permafrost temperatures and their sensitivity to climate change, and modeling permafrost distribution and temperature in space and time to assess the potential effects of climate change [5–7].

Fig. 2. Electro-tomographic profiles A and B with their coordinates. Geographic map of the area close to Bulgarian Antarctic Base, Livingstone Island, Antarctica. M 1:2000, map sheet №4. ©Bulgarian Antarctic Institute, ©Agency for geodesy, cartography and cadaster, military geographic service. 2017.

Compared with the Arctic, very little is known about the distribution, thickness, and properties of the permafrost in Antarctica. The previous geophysical research was part of the so-called PERMANTAR project focusing on Permafrost and Climate Change in the Maritime Antarctica. The project contributes to the Global scientific effort to bridge the gap in the knowledge of Antarctic permafrost characteristics, sensitivity, and implications for climate change.

a) b)

Fig. 3. Electro-tomography profiles A and B (see Fig. 2) of the periglacial terrain, close to the Bulgarian Antarctic Base, Livingstone Island, Antarctica. 2017. ©Nadya Yanakieva

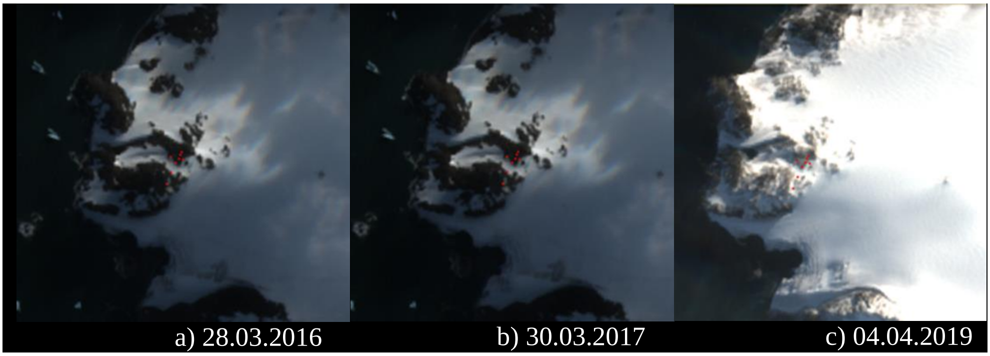
PERMANTAR involves 3 Portuguese research centers, a Spanish and Argentinean research group, and the Bulgarian Antarctic Institute, which contributes with the logistic support of its Antarctic base and scientists, who were involved in the realization of the project. The project is interdisciplinary and with multinational collaboration [8].

The last electro-tomography, as part of the PERMANTAR project, was made during the Austral summer of 2017 to repeat for the fourth time some of the profiles of permafrost research. The terrain conditions during February 2017 were without snow cover, which serves as an isolator of the ground from the direct influence of meteorological factors. The results showed that in the active layer, there is no solid permafrost, but just separate patches of frozen ground, that depleted in time [5–7].

Methods

The present research is based on the application of remote sensing methods using optical multispectral images from Copernicus satellites Sentinel-2. The Sentinel-2 images encompass the period of eight years (from 2016 until 2023) during the Austral summer (January to April). The Polar Regions, and in particular Livingstone Island in Antarctica, have been covered by clouds very often during most of the year. This is one of the obstacles to studying that part of the world using optical satellite data. Therefore, for the present research, we used only nine cloud-free images over the study area for the chosen period.

Sentinel-2 provides high-resolution images in the visible and infrared wavelengths, to monitor vegetation, soil and water cover, inland waterways, and coastal areas. Data are available globally from June 2015 onwards. The spatial resolution is 10 m, 20 m, and 60 m, depending on the wavelength and the revisit time is a maximum of 5 days to revisit the same area [9].



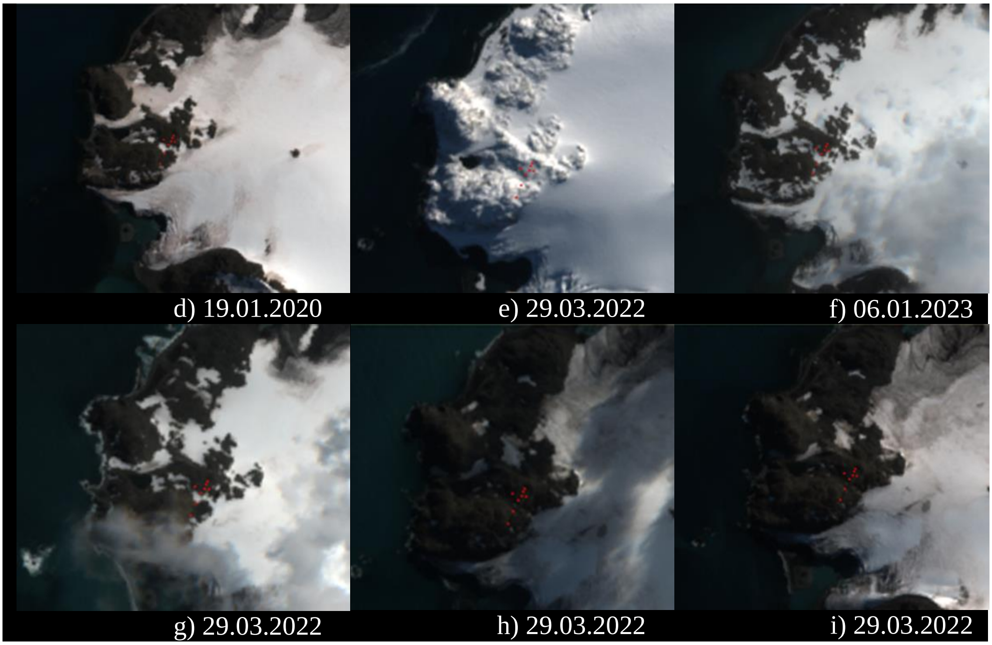


Fig. 4. Optical satellite images from Sentinel-2 of the permafrost study area, close to the Bulgarian Antarctic Base on Livingston Island, Antarctica, for six different years. ©ESA

The Sentinel-2 images (*Fig. 4 a)–i)*) were downloaded from the Copernicus data hub [10] and were transformed into composite images of 13 bands using ERDAS IMAGINE 2014. It is the software of Intergraph Corporation – an American software development and services company, which now forms part of Hexagon AB – the world's leading geospatial data authoring system [11].

The next step was to select and apply mathematical models of different indices. They provide information to define the specific characteristics of the terrain cover, such as water, snow, ice, rocks, or plants (*Table 1*) [12, 13].

The classifications of the individual indices enable comparative assessments between the individual dates in the period of observation. They are consistent with the ranges of the indices data and correspond to different land cover types – water, snow, ice, rocks, or plants (*Fig. 5*).

For the catalog of the visualization of the indices, a polygon of the study area close to the electro-tomographic profiles A and B with their GPS coordinates was drawn out. The size of the pixel is 10 m. The size of the area is around 2 square km. The different ranges of the indices' values are characterized by different colors of the visualization.

Table 1. Optical indices used in the study and description of their characteristics

Index and Range	Formula and Sentinel 2 Bands, used for its calculation	Application
MSI Moisture Stress Index 0 – 3	(1) $MSI = \frac{MidIR}{NIR}$ $MSI = \frac{B11}{B8}$	Moisture Stress Index (MSI) is used for canopy stress analysis, productivity prediction, and biophysical modeling. Interpretation of the MSI is inverted relative to other water vegetation indices; thus, higher values of the index indicate greater plant water stress and in inference, less soil moisture content. The values of this index range from 0 to more than 3 with the common range for green vegetation being 0.2 to 2 (Welikhe et al., 2017).
NDGI Normalized Difference Glacier Index -1 – 1	(2) $NDGI = \frac{Green - Red}{Green + Red}$ $NDGI = \frac{B3\ - B4}{B3 + B4}$	Normalized Difference Glacier Index (NDGI) is used to detect and monitor glaciers by application of the Green and Red spectral bands. This equation is commonly used in glacier detection and glacier monitoring applications (Bluemarblegeo, 2019).
NDSI Normalized Difference Snow Index 0 – 1	(3) $NDSI = \frac{Green - SWIR}{Green + SWIR}$ $NDSI = \frac{B3 - B11}{B3 + B11}$	The Normalized Difference Snow Index (NDSI) is a numerical indicator that shows snow cover over land areas. The Green and short wave infrared (SWIR) spectral bands are used within this formula to map the snow cover. Since snow absorbs most of the incident, radiation in the SWIR while clouds do not, this enables NDSI to distinguish snow from clouds. This formula is commonly used in snow/ice cover mapping applications as well as glacier monitoring (Bluemarblegeo, 2019).
NDSII Normalized Difference Snow and Ice Index 0 – 1	(4) $NDSII = \frac{Green - SWIR}{Green + SWIR}$ $NDSII = \frac{B3 - B11}{B3 + B11}$	The Normalized Difference Snow and Ice Index (NDSII) is a numerical indicator that shows snow cover over land areas. The Green and Short Wave Infrared (SWIR) spectral bands are used within this formula to map the snow cover. Since snow absorbs most of the incident, radiation in the SWIR while clouds do not, this enables NDSI to distinguish snow

		from clouds. This formula is commonly used in snow/ice cover mapping applications as well as glacier monitoring (Bluemarblegeo, 2019).
NDWI Normalized Difference Water Index -1 – 1	(5) $NDWI = \frac{Green - NIR}{Gren + NIR}$ $NDWI = \frac{B3 - B8}{B3 + B8}$	Normalize Difference Water Index (NDWI) is used for water bodies analysis. The index uses Green and Near-Infrared (NIR) bands of remote sensing images. The NDWI can enhance water information efficiently in most cases. It is sensitive to build-up land and results in over-estimated water bodies. The NDWI products can be used in conjunction with NDVI change products to assess the context of apparent change areas (McFeeters, 1996).
NDVI Normalized Difference Vegetation Index -1 – 1	(6) $NDVI = \frac{NIR - RED}{NIR + RED}$ $NDVI = \frac{B8 - B4}{B8 + B4}$	The Normalized Difference Vegetation Index (NDVI) is a numerical indicator that uses the red and near-infrared spectral bands. NDVI is highly associated with vegetation content. High NDVI values correspond to areas that reflect more in the Near-Infrared spectrum. Higher reflectance in the Near-Infrared (NIR) corresponds to denser and healthier vegetation (GU, 2019).

Attributive tables were generated for each of the raster images and were used in diagrams to show the changes in the different points of the two electro-tomographic permafrost profiles A and B during the six years (*Fig. 6*).

Results

The optical images used for the study area are from the austral summer seasons. It is very difficult to select cloud-free optical satellite images appropriate for continuous monitoring of the same place because Livingston Island is covered mostly by clouds. For that reason, there are no images for the years 2018 and 2021.

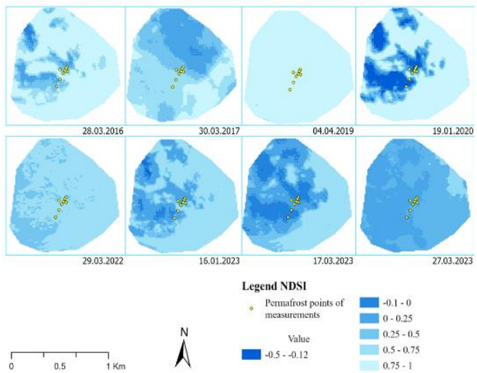
The images used for the testing of different optical indices for assessment of surface changes due to permafrost melting on Livingston Island are from 28/03/2016, 30/03/2017, 04/04/2019, 19/01/2020, 29/03/2022, 16/01/2023, 14/03/2023, 17/03/2023 and 27/03/2023.

The values of two snow and ice indices (NDSI and NDSII), one glacier index (NDGI), one moisture stress index (MSI), one water index (NDWI), and one vegetation index (NDVI) were compared to confirm the results of each of the indices, taking into consideration their typical range for a given object of observation.

The two snow-ice indices (NDSI and NDSII) show that if their values are above 0.4, usually the object of observation is snow. The range between 0.75 and 1 indicates thick snow (as it was on 04.04.2019), and thin snow is between 0.5 – 0.7 (as it was on 28.03.2016, 30.03.2017 and 29.03.2022) (*Fig. 5 a) and b)*).

When the values are between 0.2 – 0.5, it means that there is a melting snow area. That could be seen partially on 29.03.2022 in the west part of the study area, close to the shore; on 30.03.2017 in the middle of the study area, where the permafrost electro-tomographic profile A and partially profile B were situated; and on 04.04.2019, which is distinguishable only by NDSII calculation (*Fig. 5 b)*). These three days correspond mainly with thick or thin snow cover, but at the same time some parts probably are partially melted and this could be confirmed by using some of the other indices like the moisture (MSI) and water (NDWI) indices.

The other days of observation (19.01.2020, 06.01.2023, 16.01.2023, 14.03.2023, 17.03.2023, 27.03.2023) were with results below 0.2, indicating the lack of snow covering the terrain (*Fig. 5 a) and b)*). However, during these days, an increased amount of water on the terrain can be observed, which could be due to melting processes or another, meteorological factor *(Fig. 5 d) and f))*.



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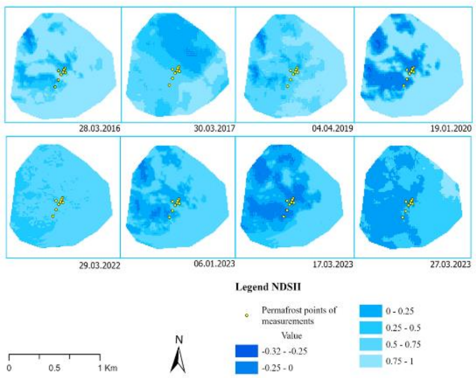

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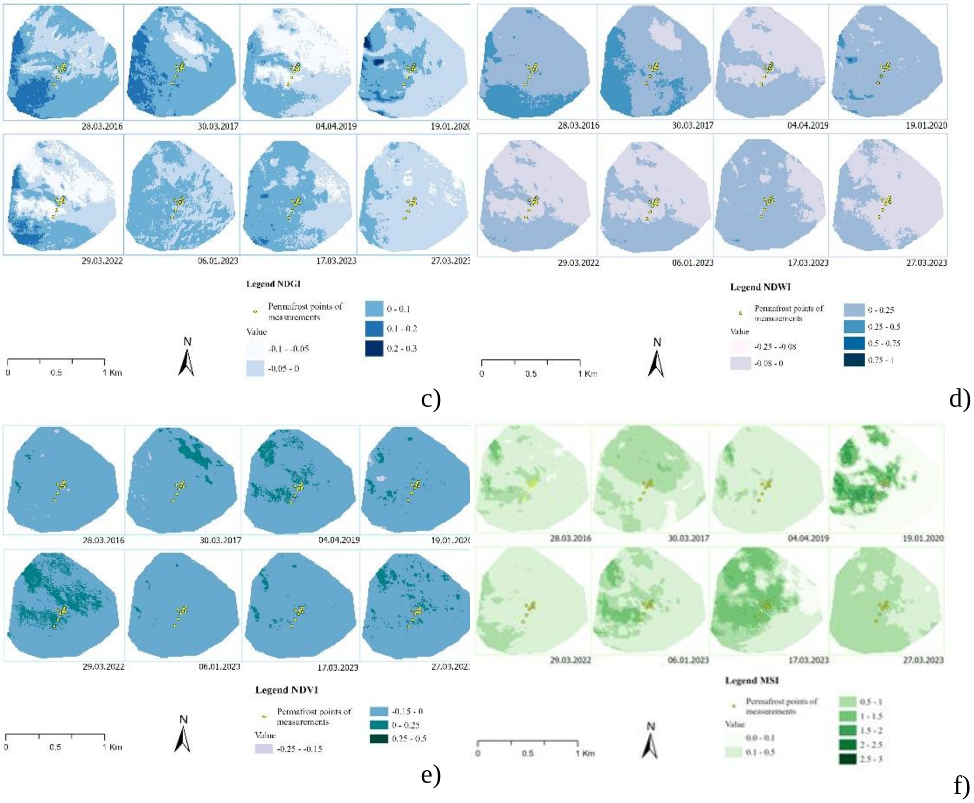


Fig. 5. Dynamics of the optical indices during the Austral summers of six different years (2016, 2017, 2019, 2020, 2022, 2023) in the permafrost study area: a) NDSI, b) NDSII, c) NDGI, d) NDWI, e) NDVI and f) MSI

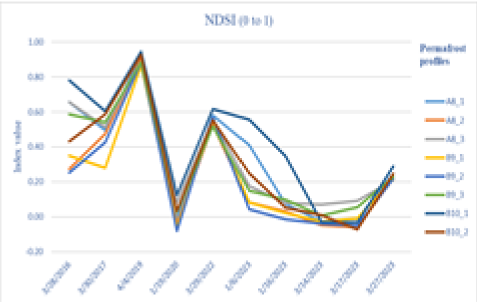
The NDGI gives information on whether the terrain was covered by snow-ice when the results are above >0.45 [14]. NDGI values below <0.45 indicate ice-mixed debris where snow is more prevalent than ice. As a result of this experiment, the NDGI values could be divided into two main groups: above 0 to 0.1, corresponding to no snow cover, and below <0 – for most snowy terrain (as it was on 04.04.2019 and 29.03.2022) (*Fig. 5 c)*). In the days of observation, there are no indications for ice to cover the terrain.

The NDVI could be used not only for analyzing the state of vegetation but also for detecting snow, rocks, or water bodies. NDVI values below <-0.1 to -1 correspond to water bodies, values between -0.1 to 0 – to rocks, from 0 to 0.2 – to snow, NDVI between 0.2 to 0.5 corresponds with shrubs and grassland, and from 0.6 to 1 – with dense vegetation or rainforest [12]. The NDVI values at 04.04.2019, 29.03.2022, and 27.03.2023, for the permafrost study area on Livingston Island, are in the range between 0 and 0.2 (*Fig. 5 e)*), indicating snow conditions, which corresponds to the values of the NDGI, NDSI, and NDSII indices. For the other days of observation, the NDVI values are below 0 indicating mainly rocky terrain.

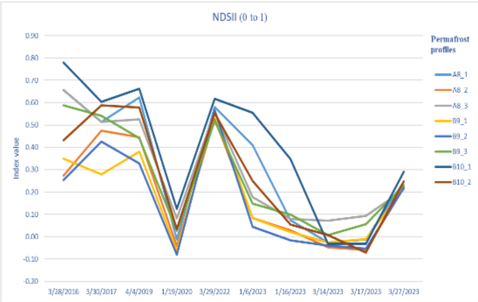
The NDWI is used mostly for detecting water bodies, but also for humid or dry surfaces. If the results are between 0.2 and 1, that corresponds with the water surface, between 0 and 0.2 – with flooding or humidity, from -0.3 to 0 – it is about moderately dry, non-aqueous surfaces, and between -1 to -0.3 – for dry, non-aqueous areas [12]. In this research, the highest NDWI values were approximately 0.25, indicating temporary water bodies that could be formed due to the melting of permafrost or recent rainfalls. Such NDVI values are typical for 28.03.2016 and 30.03.2017. Most of the other images correspond with moderate humidity between 0 to 0.2 and with moderately dry surfaces. Non-aqueous surfaces are the three mostly snowy days – 04.04.2019, 29.03.2022, and 27.03.2023 (*Fig. 5 d)*). As a main conclusion, it could be seen that the less the snow, the higher the detected humidity.

The MSI is used for canopy stress analysis. The higher values indicate greater plant water stress and, in inference, less soil moisture content. MSI and Soil Moisture Classes below <0.2 correspond to very wet conditions, values between 0.2 and 0.7 - very moist, from 0.7 to 1.2 – moist, between 1.2 and 1.7 – slightly moist, from 1.7 to 2.2 – slightly dry, and above >2.2 – dry soil [13]. The MSI values between 0.2 and 0.7 in the previous research correspond to very moist conditions. Such conditions are typical at 28.03.2016, and partially observed at 30.03.2017, 04.04.2019, 29.03.2022, and 27.03.2023 (*Fig. 5 f)*). The MSI values for 06.01.2023 and partially for 30.03.2017 and 27.03.2023 indicate moist conditions, and for the other days – slightly moist to slightly dry conditions (*Fig. 5 f)*).

The raster images in Fig. 5 give information for the whole study area. The specific differences between the two electro-tomographic profiles (A and B) could be tracked through the diagrams in Fig. 6.



a)



b)

c) d) e) f)

Fig. 6. Dynamics of the optical indices during the Austral summers of six different years (2016, 2017, 2019, 2020, 2022, 2023) in the two electro-tomographic profiles (A and B): a) NDSI, b) NDSII, c) NDGI, d) NDWI, e) NDVI and f) MSI

The diagrams confirm the main trend of the dynamics of the tested indices.

The two snow-ice indices NDSI and NDSII, and the moisture index MSI show almost the same trend of the two profiles (A and B) with deviation only in point 10_1 of profile B in January 2023, characterized by a higher presence of snow and moisture than the other parts of the profiles. The NDSI values indicate melting snow but, at the same time, there was no snow cover in that area during that period. So, that could be an indicator of the thawing process of the active layer of the permafrost area.

The water index NDWI shows the highest humidity in March 2016, 2017, and 2022 when the snow-ice indices values (NDSI and NDSII) indicate melting snow. The combined interpretation of those three indices confirms that the observed terrain was wet. However, these observations should be combined with meteo data, so it could be said for sure that the snow/permafrost in the observed area was melted during that period.

The moisture index MSI directly corresponds with the two snow-ice indices (NDSI and NDSII). The lower the MSI is, the lower the snow indices' values, but it does not correspond with NDWI, which gives more information about the humidity of the terrain, and also does not correspond with the NDSI data for melting snow.

The vegetation index NDVI could not detect any presence of vegetation across the study area, but showed the presence of some temporary water bodies with values between -0.1 and -0.23 in 2016 and 2017. The highest NDVI values were observed in the area of point 8_1 from profile A and also in point 10_3 from profile B in January 2023. That trend is another confirmation of the probable melting process on the surface of the study area.

Conclusions

The periglacial areas have higher dynamics in the conditions and changes of the ground than the glacial areas. Snow is the main isolator of the permafrost and its complete absence would be a reason for the thawing of the active layer of permafrost. In addition, the rocky terrain facilitates the snow and ice melting and, for that reason, they are very short-lived.

The results showed that the combination of different spectral indices gives a better understanding of the dynamics in the condition of the terrain. The combined use of the indices serves as some kind of verification of the results obtained. The values of NDSI, NDSII, NDWI, NDVI, and MSI indices show a trend of intense melting of the active layer of the permafrost periglacial area in March 2016 and 2017, and in the period between January and mid-March 2023. The observed trend for the latter period could be seen mostly in point 10_1 from profile B of the electro-tomographic profiles.

For a better understanding of the processes, it is necessary to conduct frequent observations in February, because this is the month with the highest temperatures during the austral summer in Antarctica. The main disadvantage of the study is the lack of cloud-free optical images from February during all of the six studied years, and most of all from February 2017 when the electro-tomographic profiles A and B were installed. This disadvantage could be overcome by adding Synthetic Aperture radar (SAR) data from the Sentinel-1 sensor in the research [15]. In addition, to better distinguish the possible factors for the observed high amount of water content on the terrain of the studied area we need daily meteorological data. One possible factor is the melting process of the snow cover or permafrost, but this water could be a result of recent rainfalls.

The integration of SAR and daily meteorological data is a required asset in our future research.

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ИЗПИТВАНЕ НА ОПТИЧНИ СПЕКТРАЛНИ ИНДЕКСИ ЗА ОЦЕНКА НА ПОВЪРХНОСТНИ ПРОМЕНИ, ПОРОДЕНИ ОТ ТОПЕНЕТО НА ПЕРМАФРОСТА НА ОСТРОВ ЛИВИНГСТЪН, АНТАРКТИДА

Н. Янакиева, Д. Аветисян

Резюме

Целта на настоящото изследване е да проучи потенциала на оптичните сателитни данни и спектралните индекси за оценка на промените на земната повърхност, предизвикани от топенето на пермафроста. Повърхностните промени, свързани с топенето на пермафроста на остров Ливингстън, Антарктика,

бяха изследвани с помощта на оптични сателитни данни от сензори Sentinel–2 на Европейската космическа агенция (ESA). Районът на изследването съвпада с предишни теренни проучвания чрез томографски профили на електрическо съпротивление, направени за установяване и визуализиране на наличието на пермафрост. Използвайки предимствата на методите за дистанционно наблюдение и изчисляване на оптични индекси, беше проследено дали и в каква степен се наблюдават изменения на повърхността и има ли топене на пермафроста в района на изследване. Периодът на наблюдение обхваща астралния летен сезон от 2016 до 2023 г.

Резултатите показаха, че комбинацията от различни спектрални индекси дава по-добро разбиране на промените в терена и се валидират един друг като вид проверка на информацията. Според комбинацията от индекси – нормализиран разликов индекс за сняг (NDSI), нормализиран разликов индекс за сняг и лед (NDSII), нормализиран разликов воден индекс (NDWI), нормализиран разликов вегетационен индекс (NDVI) и индекс на стрес от влага (MSI) – се вижда, че има висока тенденция за вероятно топене на активния слой на перигладиалната зона на изследване на пермафроста през март 2016 и 2017 г. и от януари до средата на март 2023 г.