Copernicus data utilization for polar research and monitoring purposes

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***Keywords**: Sentinel 1, Sentinel 2, Sentinel 3, Antarctica*

***Abstract:** The Polar Regions are remote and hard to reach and in the meantime they are distinguished by unique conditions, influencing in specific way processes occurring on the Earth's surface. Their study is a challenging task that needs to utilize the whole potential of the available technologies to be solved. This paper outlines Copernicus data utilization for polar research and monitoring purposes using remote sensing methods for the retrieval of additional and valuable information. In our study, we present the ability of remote sensing technology for monitoring and assessment of processes influenced by climate change and global warming combining the advantages of three of the Copernicus satellites – Sentinel 1, 2, and 3. The satellite data used and the applied methods for retrieval of information were validated through field observation of distinct objects on the Earth's surface including snow cover, wet snow, water, ice (glaciers and sea ice), vegetation (lichens and mosses), permafrost, and rocks. The monitoring of the fragile environment of the Polar Regions has extremely high ecological importance for tracking the dynamics of processes induced by climate change not only on a local but also on a global scale.*

Използване на данни от Коперник за целите на полярните изследвания и мониторинг

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***Ключови думи:** Sentinel 1, Sentinel 2, Sentinel 3, Антарктика*

***Резюме:** Полярните райони са отдалечени и труднодостъпни, като междувременно се отличават с уникални условия, влияещи по специфичен начин върху процесите, протичащи на повърхността на Земята. Тяхното изследване е предизвикателна задача, която трябва да използва целия потенциал на наличните технологии, за да бъде решена. Тази статия представя използването на данни от Коперник за целите на полярните изследвания и мониторинг. Приложени са методи на дистанционните изследвания за извличане на допълнителна и ценна информация. В нашето изследване ние представяме възможностите на дистанционните изследвания за наблюдение и оценка на процеси, повлияни от изменението на климата и глобалното затопляне, комбинирайки предимствата на три от спътниците на Коперник – Sentinel 1, 2 и 3. Използваните спътникови данни и приложените методи за извличане на информация са валидирани чрез теренни наблюдения на отделни обекти от земната повърхност, включително снежна покривка, мокър сняг, вода, лед (ледници и морски лед), растителност (лишеи и мъхове), вечна замръзналост и скали. Мониторингът на природната среда на полярните региони има изключително голямо екологично значение за проследяване на динамиката на процесите, предизвикани от изменението на климата не само в локален, но и в глобален мащаб.*

Introduction

The climate of the Polar Regions is more variable than that of mid-altitude and tropical regions [1]. The impacts of the main drivers of global warming are already evident in the Polar Regions, but the fast and continuous increase in greenhouse gases over the next century will have remarkable effects because they influence the climate and environmental systems. Although the reasonably broad estimates of how temperature, precipitation, and sea ice extent might change, and the related assessments of the possible impact on marine and terrestrial biota, it cannot be yet predicted with confidence what the area of the affected zones in the Polar Regions could be and how the affected environment would respond. However, the observed rapid changes in recent years, give us cause for concern, especially for the environmental stability of parts of West Antarctica [1].

Determining how the environment of the Arctic and Antarctic will evolve over the next century is a challenging task. Because of their remoteness and peculiarities of the climate, the climate and environment evolution in the Polar Regions can only be predicted with some degree of confidence by using models of atmosphere-ocean-ice-land interaction. Estimates from different models gave us a wide range of predictions for some aspects of the Polar climate systems, including the large scale circulation of the atmosphere, the atmospheric and land surface temperatures, the terrestrial cryosphere and sea ice extent, permafrost, terrestrial and marine environments. All listed aspects of the Polar climate systems are sensitive to changes in atmospheric, land, and oceanic conditions.

However, despite their advantages, the numerical-based biological and environmental models have not yet been able to match the relative sophistication of physical models of the climate system, but physical models have not reached the spatial scale and resolution required for application to biological and environmental systems and assessments of the biotic and ecosystem responses. While we are confident in the overall warming projections, we are less confident in the regional details, as regional results vary widely between models [1]. In such cases, satellite remote sensing gives us effective techniques and methods for monitoring, modeling, and assessment of the polar environments and the Copernicus constellation of satellites possess a powerful and complementary instrumentation for these purposes.

In the present paper, we outline Copernicus data utilization for polar research and monitoring purposes using remote sensing methods for retrieval of additional and valuable information for environmental evolution. In our study, we present the ability of remote sensing technology for monitoring and assessment of processes influenced by climate change and global warming combining the advantages of three of the Copernicus satellites – Sentinel 1, 2, and 3. The satellite data used and the applied methods for retrieval of information were validated through field observation of distinct objects on the Earth's surface including snow cover, wet snow, water, ice (glaciers and sea ice), vegetation (lichens and mosses), permafrost, and rocks. The objects and areas of observation presented in this paper are situated at Livingston Island, South Shetland Islands, in the vicinity of the Bulgarian Antarctic Base "St. Kliment Ohridski" (Figure 1). The field studies were conducted during the 31st Antarctic expedition of the Bulgarian Antarctic Institute, in December 2022. The detailed description of the field campaign and the methods for validation are presented in our previous paper [2].

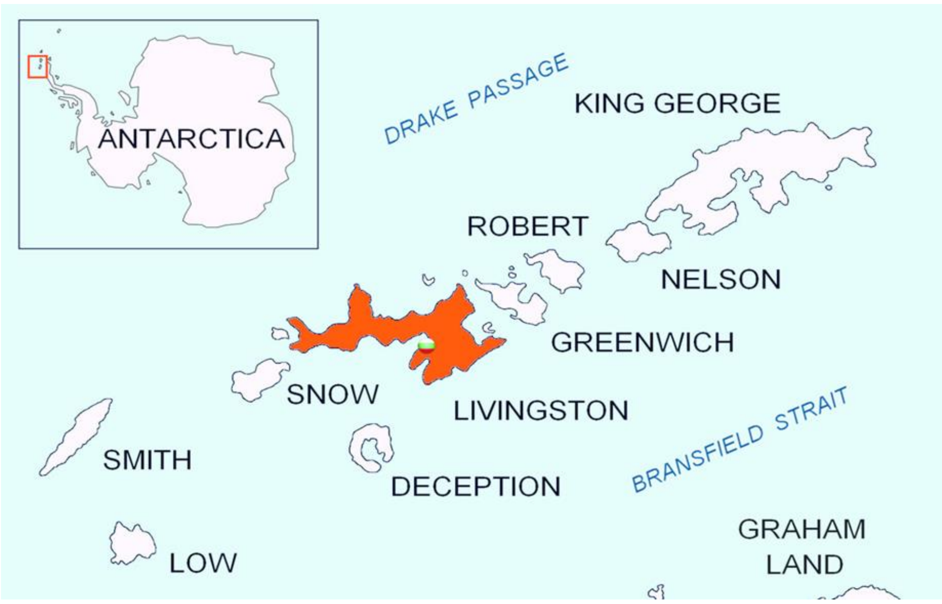


Fig. 1. Livingston Island, South Shetland Islands, Antarctica. Source: Bulgarian Antarctic Institute [3]

Copernicus satellites appropriate for Polar research and monitoring purposes

Over the past decade, the European Space Agency (ESA) has developed a constellation of satellites called Sentinels for the operational needs of the Copernicus programme. Most widely used for scientific research and monitoring purposes in the Polar Regions are Sentinel-1, Sentinel-2, and Sentinel-3 satellites.

For polar research and monitoring purposes, the Sentinel-1 mission is used for polar ice monitoring, sea ice mapping, and marine environmental monitoring. Built on the proven legacy of the

ERS, Envisat, and RADARSAT missions, Sentinel-1 carries a 12-meter Synthesized Aperture Radar (SAR) operating in the C-channel of the electromagnetic spectrum. The advantage of radar as a remote sensing tool is that it can image the Earth's surface day and night, during rain and cloud cover. This is particularly useful when monitoring areas that are prone to long periods of darkness - such as the Arctic and Antarctic. The satellite imagery from Sentinel-1 can be used for the calculation of various radar indices that enable the retrieval of additional and valuable information [4].

The Sentinel-2 MSI carries an innovative wide-spectrum, high-resolution multispectral sensor with 13 spectral channels. The combination of high resolution, new spectral capabilities, a swath width of 290 km provides an unprecedented view of the Earth. The satellite imagery from Sentinel-2 can be used for the calculation of various optical indices [5].

Carrying four instruments that operate in sync, Sentinel-3 is perhaps the most complex of all the Sentinel missions. Sea and Land Surface Temperature Radiometer (SLSTR) measures global sea and land surface temperatures every day with an accuracy of less than 0.3 K [6].

The Ocean and Land Color Instrument (OLCI) includes 21 different bands in the 0.4–1.02 μm spectral range, tuned to specific requirements for atmospheric correction and measurements of ocean, land, and vegetation color. It allows ocean ecosystems to be observed. [6]

The Sentinel-3 altimetry instruments have led to a significant change in satellite altimetry, measuring sea surface height, waves, and surface wind speed over the oceans. It also provides accurate topographic measurements on sea ice, ice sheets, rivers, and lakes. [6]

Satellite data appropriate for polar research and monitoring purposes

The proposed in this paper data and methods for polar research and monitoring purposes were verified and validated through field studies, conducted during the 31st expedition of the Bulgarian Antarctic Institute, in December 2022. The procedure includes the selection of appropriate imagery from the Copernicus program via visual interpretation, followed by revision after the field campaign. For each of the satellite images, an area of interest was precisely selected. The individual areas of interest should be identic for the optical and radar imagery. This is a mandatory step as the images should be geometrically linked and overlaid. The optical images have very high geometric accuracy, while SAR images require additional corrections and have a different resolution, which is 12/15 or 13/16 meter pixel size. Field studies of the individual areas of interest were conducted and spectral characteristics for each of the objects falling within these areas using a field spectrometer were obtained. The data obtained after the field campaign was used for verification of the satellite data and afterward for validation of the suggested methods for monitoring. A detailed description of the entire procedure can be found in our previous research paper [2].

<u>Sentinel -1 data</u>. Polar Regions are characterized by frequent and dense cloud cover during the entire year. When it is difficult to find cloud-free optical images, it is mandatory to apply alternative evaluation methods and data such as microwave satellite data where the presence of cloud cover is not an obstacle. The advantages of microwave satellite data stem from the different wavelengths in the optical and microwave range of the electromagnetic spectrum. Different studies using satellite data for Polar research and monitoring showed that the microwave range appears to be more appropriate for these purposes [7, 8]. Radar images enable the easy detection, identification, and recognition of water, wet areas, wet snow, ice, rocks, and other objects on the Earth's surface with high ecological importance for the monitoring of the Polar Regions.

In the present paper, we present the utilization of microwave satellite data, acquired from the Sentinel-1A sensor of the Copernicus programme. The Sentinel-1A images used are from a dual-polarization C-band Synthetic Aperture Radar (SAR) instrument at 5.405GHz (C band), Level-1 Ground Range Detected (GRD) product, Interferometric Wide (IW) swath mode, which typically contains raster images in hv, vv, or hh polarization, but for the Antarctic only hh and hv polarizations are available. The spatial resolution of a pixel for the region of polar latitudes is about 14/16 meters. In addition to the standard pre-processing procedures such as georeferencing, on radar images, geometric corrections of rotation and translation [9] have been carried out, since radar images have a certain offset compared to optical ones, which is due to the principle of obtaining data from the sensor [9].

<u>*Radar indices for polar research and monitoring purposes.*</u> To monitor and assess the dynamics of various objects on the Earth's surface such as snow cover, wet snow, water, ice (and sea ice), vegetation (lichens, mosses, grasses), permafrost, and rocks, radar indices are being used [2]. In the present paper, we present two major approaches for monitoring purposes utilizing microwave satellite data.

The first approach is based on a spatial distribution of the reflectance in three-dimensional space as a dimensionless quantity. For that purpose, the Sentinel-1 imagery should be converted into decibels (dB). The classification of the individual objects in decibels enables their distinct differentiation, as for each type of object there are fixed dB values for each polarization (Figures 2 and 3) [2, 9]. For example values < 22 dB indicate for water, [U2] values between 22 and 24 dB – for wet snow, values in the range 24-27 dB show snow, and values above 27 dB – ice [8].

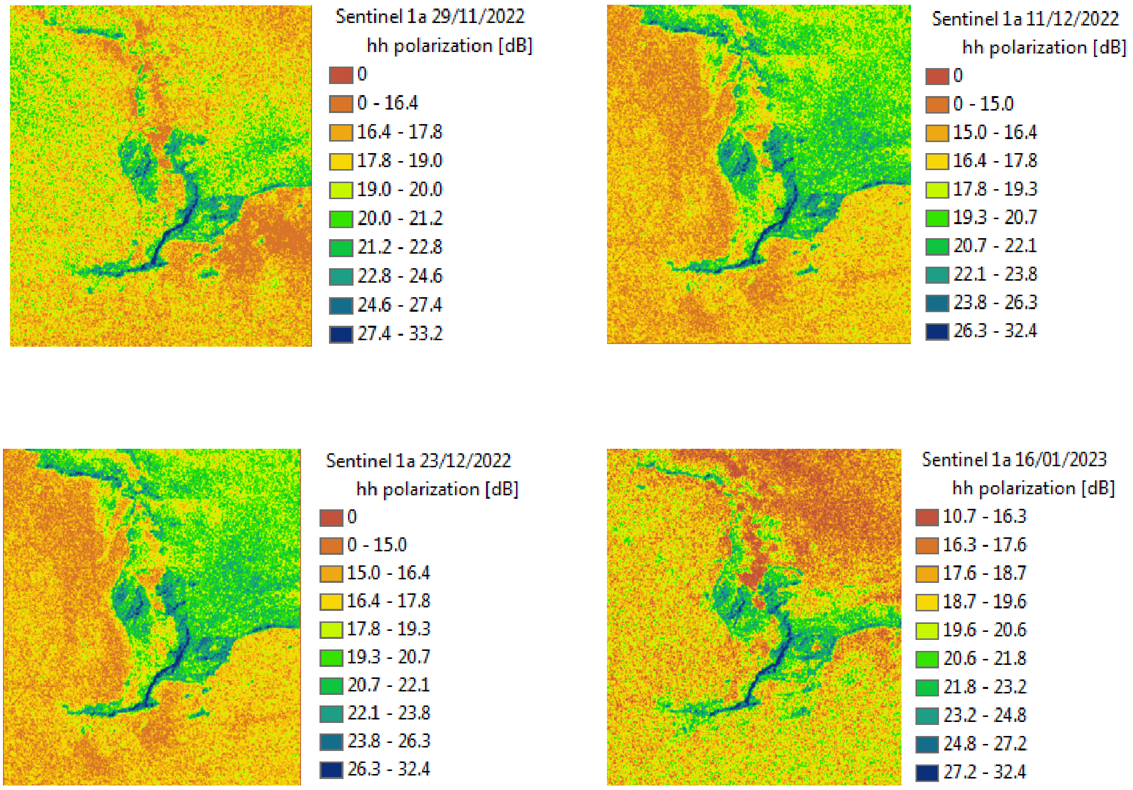
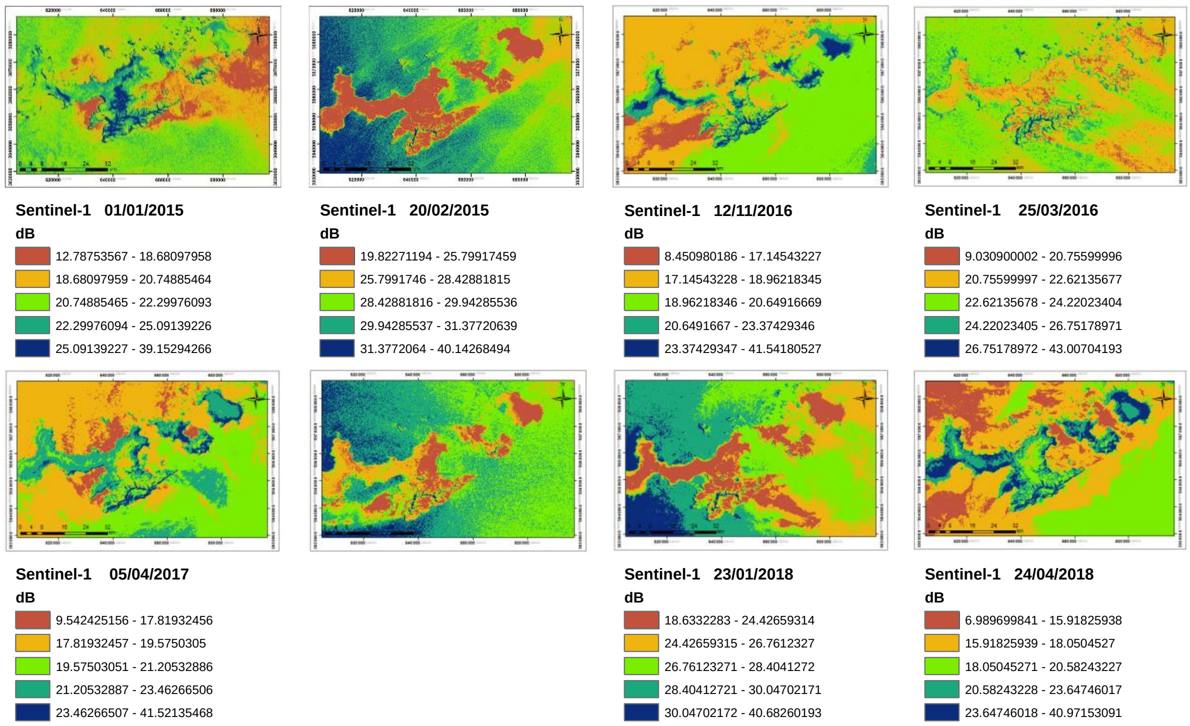


Fig. 2. Sentinel-1 SAR image in HH polarization converted into decibels (dB).
Spatial distribution of the dB values. (Hannah Point Peninsula, Livingston Island).
Source: Spasova and Avetisyan, 2023 [2]



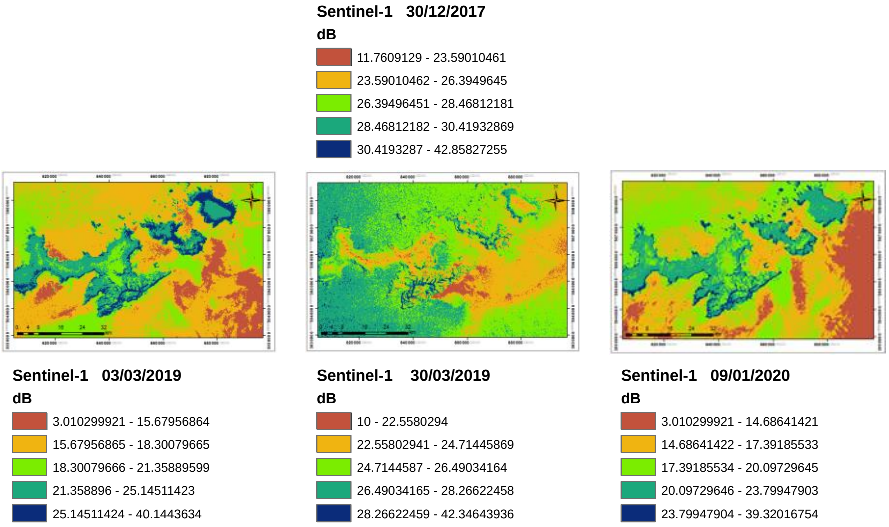


Fig. 3. Sentinel-1 SAR image in HH polarization converted into decibels (dB).
Spatial distribution of the dB values. (Bulgarian Antarctic Base area , Livingston Island).
Source: Spasova et al., 2020 [9]

The second approach for monitoring purposes utilizing microwave satellite data involves the calculation of the ratio of the spectral reflectance between two radar images, acquired in two distinct time moments (Figure 4). A value above 2 registers serious changes in the reflection of a given object (dimensionless quantity). The formula is as follows: [2, 10]

$$r_{(i,j)} = \frac{\sigma(i,j)t_1}{\sigma(i,j)t_2} \quad (1)$$

where σ is the microwave spectral reflectance coefficient for time moment t1 (an image, acquired on an earlier date) and time moment t2 (an image, acquired on a later date), and r is the relative soil/snow moisture content, estimated for the given period [2,10].

The threshold value registering significant changes is 1.7 (DWC > 1,7) and moderate changes (1 <DWC <1,7) [2].

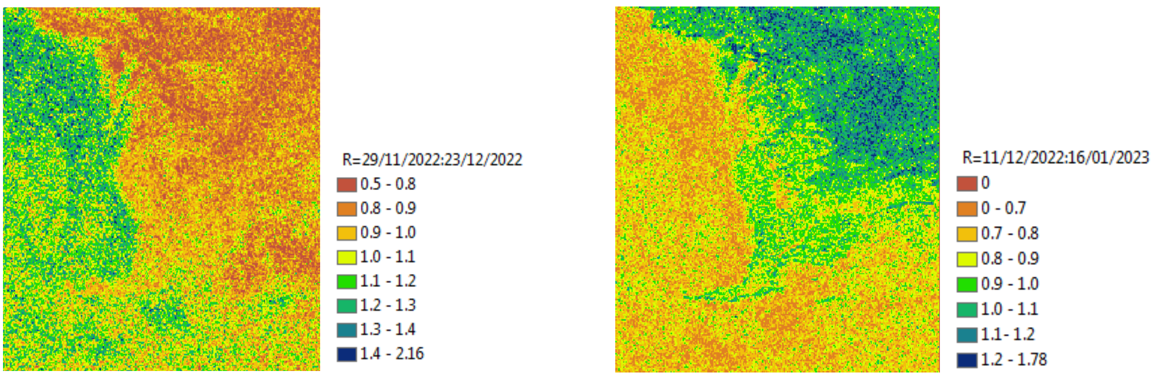


Fig. 4. Spatial distribution of the radar index for estimation of the relative soil/snow moisture content (Hannah Point Peninsula, Livingston Island). Source: Spasova and Avetisyan, 2023 [2]

<u>Sentinel-2 data.</u> Sentinel-2 data used in the present paper to present approaches for monitoring Polar Regions are from the S2MSI1C product, containing 13 spectral bands covering the electromagnetic spectrum in the range between 0. 44 and 2.19 μm. The spatial resolution of the various spectral bands ranges between 10 to 60 m and was used for the calculation of optical indices.

<u>Optical indices for polar research and monitoring purposes.</u> The dynamics of the objects on the Earth's surface such as snow cover, wet snow, water, ice (and sea ice), vegetation (lichens, mosses, grasses), permafrost, and rocks can be tracked also by the application of spectral indices calculated on

optical images [2]. Unlike radar imagery, cloud-free imagery is a prerequisite for monitoring purposes using optical data.

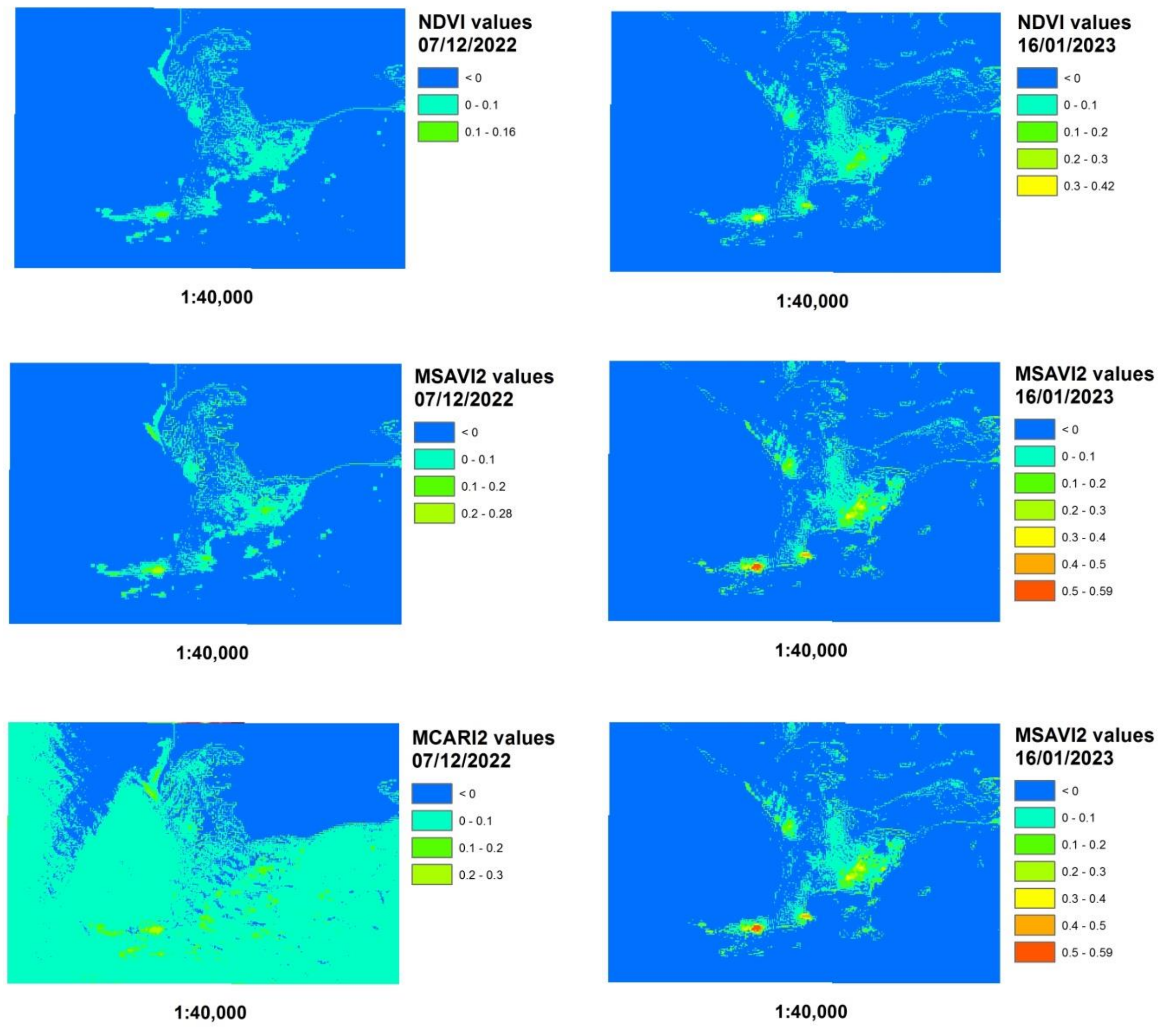
Observing spectral changes before and after a given event or process (snow accumulation, wet snow melting, ice cover change, vegetation change, etc.), which are often very dynamic, in polar latitudes necessitates the use of different spectral bands and wavelengths. With the help of the spectral indices, a quantitative evaluation of the changes can be made (Figure 5). Table 1 presents some of the basic indices used for monitoring the processes in the Polar Regions.

Table 1. Optical indices for polar research and monitoring purposes using Sentinel-2 data of the Copernicus Programme

Index	Formula	Description
Normalized Difference Vegetation Index (NDVI), [11]	NDVI = $(\rho_{783} - \rho_{665})/(\rho_{783} + \rho_{665})$ (2)	NDVI is the most commonly used spectral index for monitoring vegetation and assessing photosynthetic activity. NDVI is highly correlated with climate change and serves as an effective measure of climate-related vegetation changes.
Modified Soil-Adjusted Vegetation Index (MSAVI2), [12]	$MSAVI_2 = \frac{2\rho_{783}+1\sqrt{(2\rho_{783}+1)^2-8(\rho_{783}-\rho_{665})}}{2}$ (3)	MSAVI2 is an adapted version of the Soil Adjusted Vegetation Index (SAVI) designed to reduce the inaccuracies of NDVI in areas with exposed soil surfaces [12].
Modified Chlorophyll Absorption Ratio Index (MCARI2), [13]	$MCARI_2 = \frac{1.5[2.5(\rho_{783}-\rho_{665})-1.3(\rho_{783}-\rho_{559})]}{\sqrt{(2\rho_{783}+1)^2-(6\rho_{783}-5\sqrt{\rho_{665}})}-0.5}$ (4)	MCARI2 is a modified version of the Chlorophyll Absorption Index (CARI) designed to estimate chlorophyll variation. The derived MCARI2 index is less sensitive to variations in chlorophyll concentration, but has a significant linear relationship with green LAI (leaf area index) [13].
Normalized Difference Water Index (NDWI), [14]	NDWI = $(\rho_{865} - \rho_{1375})/(\rho_{865} + \rho_{1375})$ (5)	NDWI exploits the differential response of the NIR (Near-infrared wavelength) and SWIR (Short-wavelength infrared) reflectance in healthy vegetation, increasing the accuracy of assessing vegetation water content.
Moisture Stress Index (MSI), [15]	MSI = ρ_{1610}/ρ_{833} (6)	MSI is used for water stress analysis of vegetation. A higher value of the index indicates greater water stress in the plant, resulting in lower water content [15].
Disturbance Index (DI), [16]	nTCW = (TCW − E{TCW})/(St.Dev(TCW)) (7) nTCB = (TCB − E{TCB})/(St.Dev(TCB)) (8) nTCG = (TCG − E{TCG})/(St.Dev(TCG)) (9) DI = $nTCB - (nTCG + nTCW)$ (10)	DI has proven to be an effective approach for detecting vegetation disturbances and monitoring their changes in terrestrial ecosystems.

Normalized Differential Greenness Index (NDGI), [17]	$NDGI = \frac{TCG(t_2)-TCG(t_1)}{\lvert TCG(t_2)\rvert+\lvert TCG(t_1)\rvert}$ (11) $TCGn(t)=TCG(t)-E\{TCG(t)\}St.Dev.[TCG(t)]$ (12)	NDGI estimates small positive and negative changes in the green mass of vegetation over a period of time. NDGI ranges from +1 to −1, as NDGI < 0 indicates a negative change, and NDGI > 0 indicates a positive change [17].
Normalized Difference Snow Index (NDSI), [18,19]	$NSDI = \frac{\rho_{490}-\rho_{1610}}{\rho_{490}+\rho_{1610}}$ (13)	NDSI is useful for studying snow cover. Its value ranges from 0 to 1. The most appropriate bands are 2 and 11 on the Sentinel-2 MSI.

Unlike standard indices that use simple arithmetic equations for their calculation, DI and NDGI are based on Tasseled Cap Transform (TCT), applied on stacked images, containing all 13 bands of the Sentinel-2 images. The outputs from this procedure are TCT multi-band images containing three layers—TCB (Tasseled Cap Brightness), TCG (Tasseled Cap Greenness), and TCW (Tasseled Cap Wetness). Depending on the target index for calculation (DI or NDGI), the obtained output layers are used for decomposition, calculation of the normalized values of the TC components, calculation of the averages and standard deviations for each of the Tasseled Cap components, and finally for calculation of the indices [16,17].



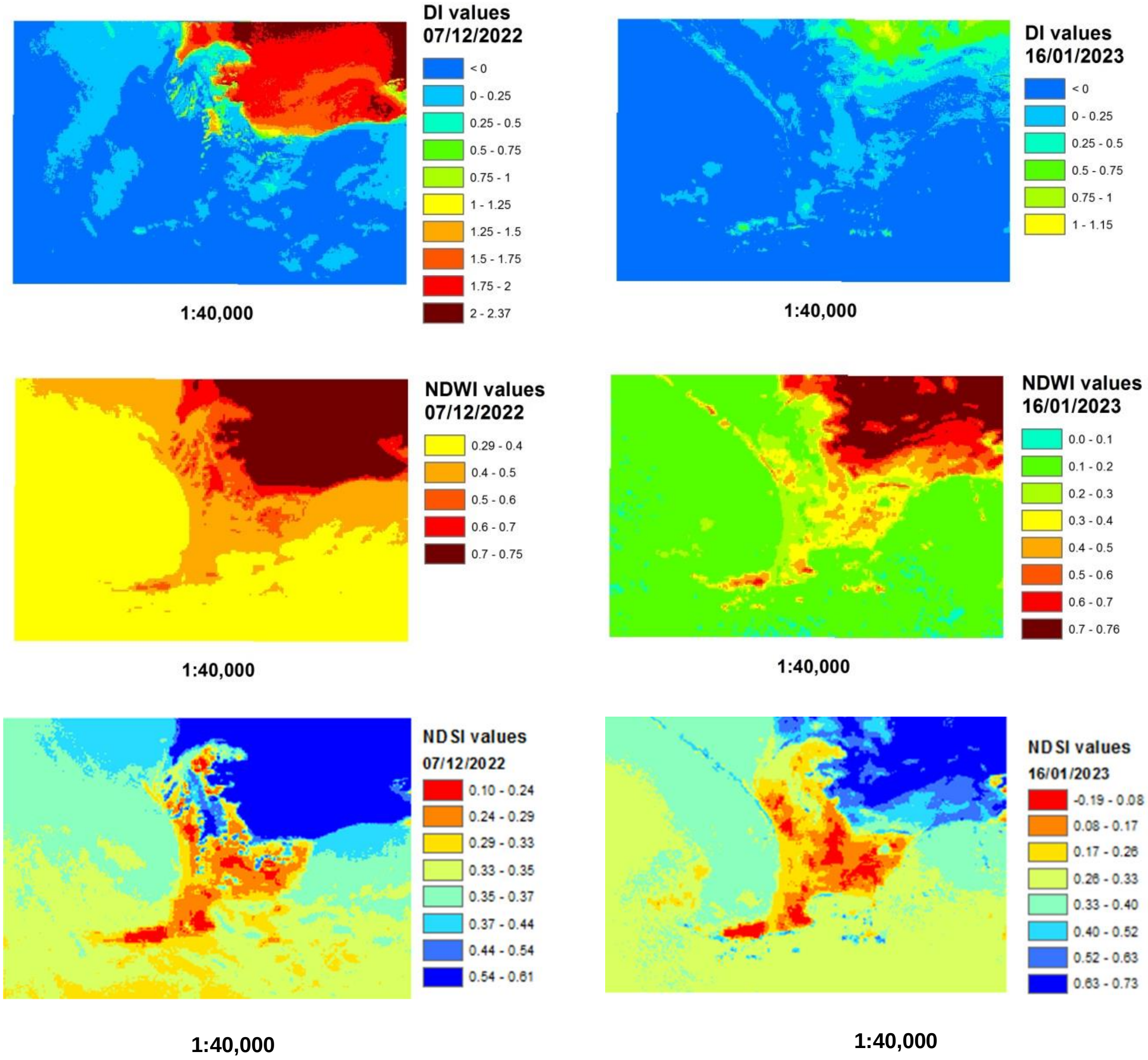


Fig. 5. Spatial distribution of the Sentinel-2 based optical indices (Hannah Point Peninsula, Livingston Island). Source: Spasova and Avetisyan, 2023 [2]

Sentinel-3 data

Measuring the land surface temperature. Sentinel-3 data are from the Sea and Land Surface Temperature Radiometer (SLSTR) dual-view scanning temperature radiometer. SLSTR provides data in 9 bands ranging from 0,55 to 12 μm of the electromagnetic spectrum. The spatial resolution is 500 m for the VIS and SWIR bands and 1 km for the MWIR and TIR bands. In the present paper, we used Level 2 Land Surface Temperature (LST) to demonstrate spatial differentiation of the land surface temperatures on Livingston Island, Antarctica (Figure 6). The Land Surface Temperature is the radiation temperature, derived from infrared radiation. A simplified definition would be: "How hot would the surface of the Earth feel when touched at a certain location." From the satellite's perspective, the "surface" is all it sees when it looks through the atmosphere at Earth. It can be snow and ice, grass, the roof of a building, or the leaves in the crown of a forest [6].

The LST accuracy is approximately 1 K, especially at night when there is no differential surface heating [20]. The area of Livingston Island was studied in the summer when the Sun does not set. For that reason, no significant differences in temperature were observed between the measurements performed in the morning and at noon.

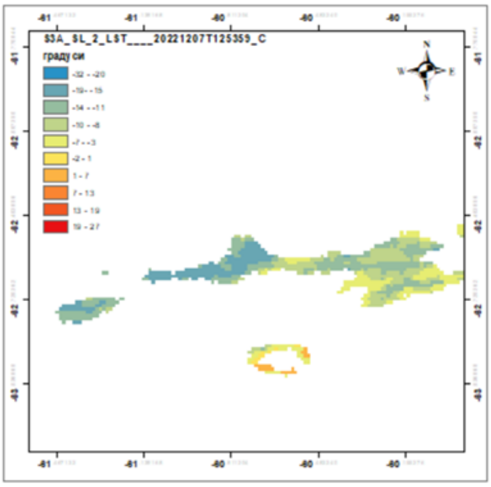


Fig. 6. Spatial distribution of the LST, derived from Sentinel-3 SLSTR sensor on Livingston Island, Antarctica at 07.12.2022, 12:53 local time

<u>Measuring the elevation of the Earth's surface.</u> The Synthetic Aperture Radar Altimeter (SRAL) instrument of the Sentinel-3 satellite is used for measurements of the elevation of the Earth's surface. Altimetry satellites are designed to measure the distance between the satellite and the Earth's surface. The mechanism of this process consists of transmitting a radar signal to the Earth and receiving the reflected signal. The time elapsed between transmission and reception of the radar signal is used for calculating the distance between the satellite and the ground surface. In Sentinel-3, the SRAL instrument measures this elapsed time [21].

The scientific community is usually concerned with the height of a surface relative to a reference surface (ellipsoid or the geoid). The surface height can be estimated using the difference between the range and altitude. The range is the distance between the satellite and the Earth's surface. However, all corrections due to environmental conditions should be taken into consideration in this process. Such corrections are atmospheric propagation corrections (ionosphere and troposphere) and geophysical corrections (tides and atmospheric pressure loading) [21].

Figure 7 shows an elevation model of Livingston Island, Antarctica, derived through the Sentinel-3 SRAL instrument.

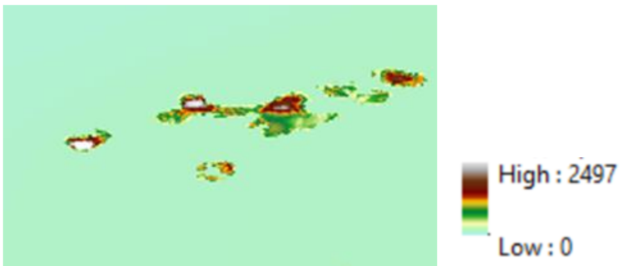


Fig. 7. Elevation Model of the Livingston Island, Antarctica, derived through Sentinel-3 SRAL instrument. Source: Spasova, 2023 [22]

<u>Measuring snow properties.</u> The sea and Land Surface Temperature Radiometer (SLSTR) instrument on board Sentinel-3 enables also the derivation of various snow properties with significant importance for tracing the climate and environmental processes in the Polar Regions. Examples of such snow features are snow grain size, snow particle shape [23], and snow depth. Figure 8 presents the spatial distribution of snow cover depth on the territory of Livingston Island, Antarctica. The Sentinel-3 LST image was acquired on 07/12/2023 and was involved in the validation process using data from the field observations.

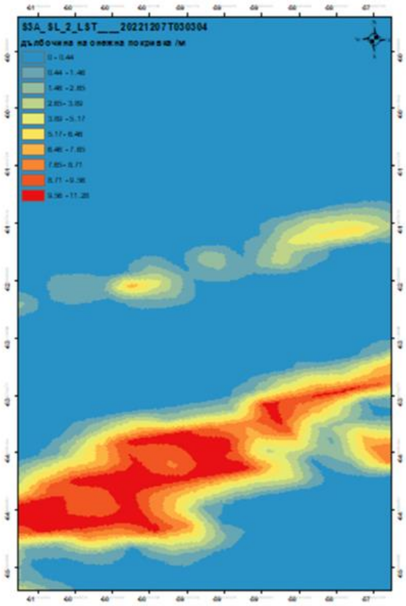


Fig. 8. Spatial distribution of snow cover depth on the territory of Livingston Island, South Shetlands Islands, Antarctica. Source: Spasova, 2023 [22]

Conclusion

The present paper presents only basic applications of the Copernicus data for Polar research and monitoring purposes. However, the article points to the wide range of potential applications for which the satellites presented can be used. Moreover, all presented data are freely available in the Open Access portal of the Copernicus Programme. It can be used for weekly or monthly analyses of the Polar Regions and to generate a database with long enough statistical series to allow the use of already ready-made models for research and monitoring.

Acknowledgements

This study was supported by „Polar scientific research for young scientists", 2022 Bulgaria and Bulgarian Antarctic Institute (BAI) , contract No. 70-25-59/10.08.2022, Project: DESTINATION EARTH ANTARCTICA – DIGITAL DATA SPACE, PILOT PROJECT.

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