Understanding and monitoring the dynamics of Arctic permafrost regions under climate change using EO & cloud computing: the contribution of EO-PERSIST project

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Abstract

Given the increasing challenges presented by climate change, understanding and monitoring the dynamics of permafrost regions in the Arctic have gained paramount importance. Permafrost, a critical component of the Arctic ecosystem, is highly susceptible to the effects of global warming, exerting profound impacts on both environmental and socioeconomic facets. In purview of it, the EO-PERSIST project is a 4 years MSCA staff exchanges project funded by EU aiming to leverage existing services, datasets, and innovative technologies to establish a consistently updated ecosystem with Earth Observation (EO)-based datasets suitable for permafrost applications. By harnessing advanced EO technologies, including innovative tools and datasets such as cloud platforms, and tapping into an extensive array of remote sensing datasets, EO-PERSIST aims to revolutionize the monitoring and assessment of permafrost dynamics. The project will promote methodological advancements in the field of permafrost by leveraging the huge volume of remote sensing (RS) datasets and providing indicators directly liked to socioeconomic effects from permafrost dynamics. EO-PERSIST will perform experimental analysis through five use cases, which will also serve as Key Performance Indicators (KPIs) of the system. As such, EO-PERSIST will establish a fertile environment for staff exchanges knowledge sharing, and know-how transfer. The present chapter aims to provide an overview of the project, introducing the project objectives in the context of the current state of the art. Furthermore, it offers an overview of the EO datasets suitable for use in permafrost studies in the Arctic region and it underlines the added value of cloud platforms and EO technology in this context. Finally, it addresses key societal challenges today linked to the study of socioeconomic impacts particularly in the European Arctic and it closes providing a vision of the expected contribution of the project to science and society.

Keywords: *EO-PERSIST*, *Cloud Platform*, *Earth Observation (EO)*, *Arctic Region, Climate Change*

1 Climate Change and Impacts

In recent times, there has been a discernible increase in both scientific and public attention towards the Arctic region, prompted by a heightened awareness of the potential impacts of climate change. According to the United Nations (2023), climate change is a pressing global issue characterized by long-term shifts in temperature patterns, precipitation levels, and other climatic parameters. It is primarily driven by human activities, such as the burning of fossil fuels (Johnsson et al., 2019; Wood & Roelich, 2019′Soeder, 2020;), deforestation (Longobardi et al., 2016; Wolff et al, 2021; Li et al., 2022) and industrial processes (Niñerola et al., 2020; Wadanambi et al., 2020; Sovacool et al., 2021), which release greenhouse gases (GHG) into the atmosphere. These gases capture heat, leading to a gradual rise in global temperatures, commonly referred to as global warming. According to the IPCC report of 2023, the GHG release has led to a rise in global surface temperature by 1.1°C above the 1850–1900 baseline during 2011–2020 (Figure 1.1). The global emissions of GHG have continued to escalate from 2010 to 2019, with disparities in historical and ongoing contributions stemming from unsustainable energy usage, land use and changes, diverse lifestyles, and consumption and production patterns. These factors exhibit variations across regions, within and between countries, and a[...] man societi[...]

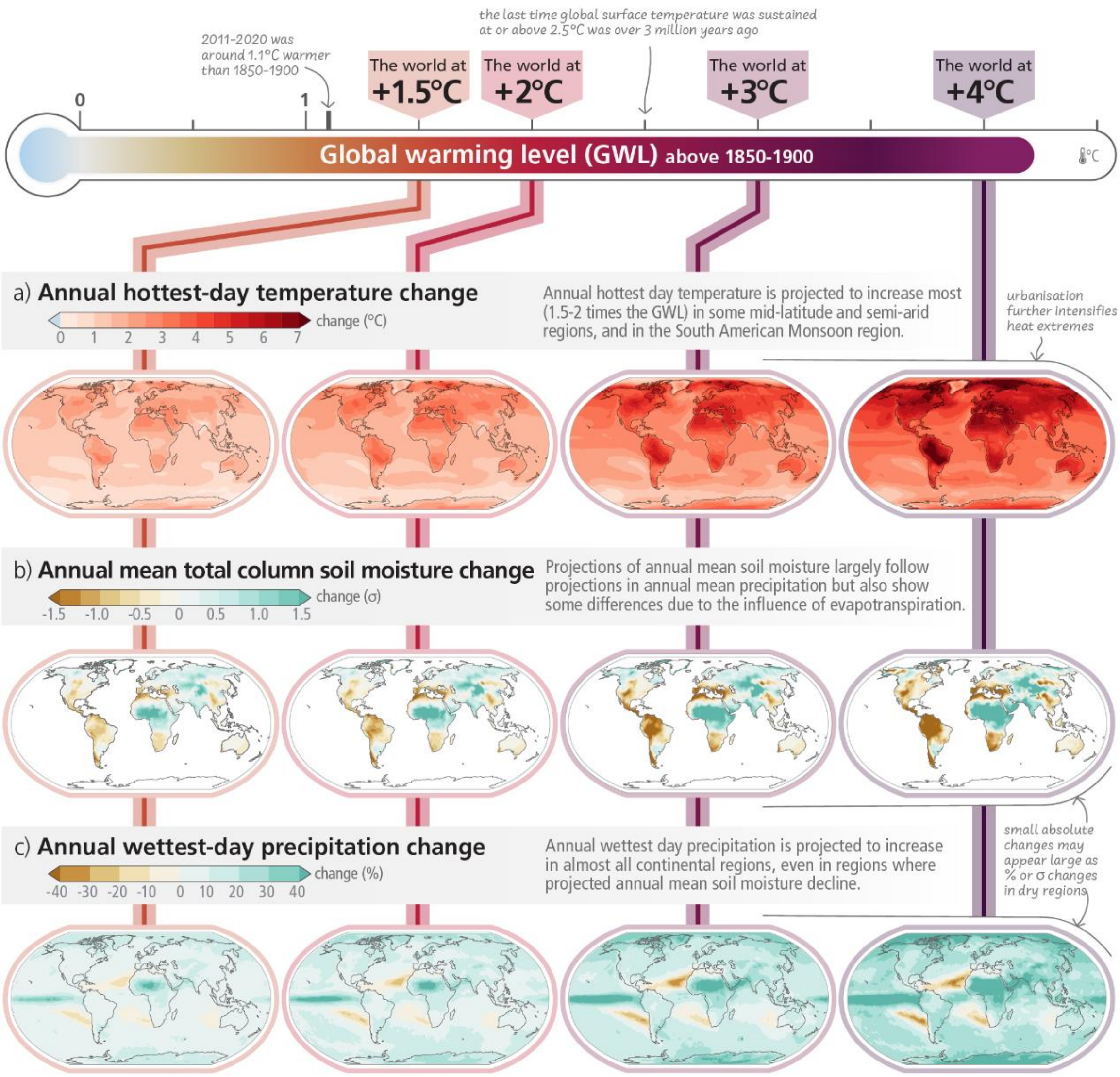

Figure 1.1. Projected changes of annual maximum daily temperature, annual mean total column soil moisture CMIP and annual maximum daily precipitation at global warming levels of 1.5°C, 2°C, 3°C, and 4°C relative to 1850–1900 (adopted from IPCC report 2023)

Such consequences include rising sea levels, which pose a threat to coastal communities, while extreme weather events like hurricanes, prolonged droughts, heatwaves, and extreme floods, which are becoming more frequent and severe (Bell et al., 2017; Srivastava et al., 2021; Tsatsaris et al., 2021). Shifts in precipitation patterns can disrupt agriculture and water resources, leading to food and water scarcity in vulnerable regions (Fitton et al., 2019; Liu et al., 2023). Additionally, the melting of polar ice caps and glaciers contributes to rising sea levels and threatens the habitats of numerous species (Khan et al., 2021; Amjad et al., 2022). The main strategies for the mitigation of climate change entail reducing human-caused emissions of greenhouse gasses (GHGs), the prominent factor of global warming. Additionally, it is crucial to adapt to the impacts of climate change, using the least number of resources to effectively address climate-related risks (Zhao et al., 2023). Both these approaches, require the discernment and quantification of substantial land changes that have occurred to enhance the comprehension of climate change and provide support to policymakers in their endeavors to effectively address and mitigate its impacts.

2 Arctic and Permafrost Regions and Climate Change

The Arctic region emerges as a hotspot of climate change, warming three times faster than the rest of the planet (Rantanen et al., 2022Hu et al., 2023). Climate change is increasingly affecting components of the terrestrial cryosphere and hydrology and its adverse impacts on the active layer freeze-thaw cycle and permafrost conditions is well-documented (Wang et al., 2021; Fox-Kemper et al., 2021). Global warming has resulted in significant effects to the local and regional Arctic natural environments, infrastructures, as well as the climate (Hjort et al., 2022). Permafrost changes have important ecological and economic impacts globally (Schuur et al., 2015; Hu et al., 2021). Given the significant concentration of the oil and gas industry, as well as pipeline infrastructure, in the Arctic today, there is a heightened concern regarding the monitoring of permafrost dynamics. Permafrost exhibits significant variability in temperature, extent, and depth. This diversity arises from distinctions in climate patterns, vegetation, and soil characteristics. Building in areas with permafrost necessitates the use of inventive construction methods specifically crafted to isolate frozen ground from the thermal influence of buildings (Suter et al., 2019). This also includes the critical assessment of socioeconomic impacts and associated costs to local communities and businesses, both in terms of preventive measures and post-disaster mitigation efforts. For instance, the collapse of a fuel tank at a power station on May 29, 2020, as documented by Rajendran et al. (2021), exemplifies the potential risks involved. Besides, as permafrost conditions retreat, microbial decomposition of soil organic carbon is accelerating, even more greenhouse gases are unleashed which exacerbating further climate change (Hugelius et al., 2014). In the northern hemisphere, permafrost regions at depths ranging from 0 to 3 meters house approximately half of the global soil carbon pool (Feng et al., 2020). Given their capacity to potentially release significant quantities of previously sequestered soil carbon into the atmosphere under warming conditions, these regions emerge as a pivotal determinant in shaping the trajectory of future climate change.

Acquiring a comprehensive understanding of the physical parameters influencing the Arctic climate and assessing the potential socio-economic impacts of climate change in these environments represents a paramount research priority nowadays. In this context, it is deemed a matter of critical scientific significance necessitating the indispensable development of methodologies and tools to facilitate the advancement of our comprehension in this direction. The latter has been highlighted as one of the most complex and emerging issues to be addressed today (EU Council, 2019). As it is extremely challenging to obtain long-term continuous ground-based observations due to the harsh weather conditions in the Arctic, observations from space using Earth Observation (EO) satellites are critically required to investigate the inner connections between Arctic dynamics and climate change impacts to the society and economy (Hu et al., 2012; Wang et al., 2021). The EU is firmly committed to establishing a strong link between its Arctic endeavors and overarching climate policy, exemplified by the European Green Deal and its emphasis on the blue economy dimension. By recognizing the key global role of permafrost changes in the sustainable development and climate (Chuffart and Raspotnik, 2019), has funded several EO and cloud-based platforms (e.g. Permafrost CCI, Globpermafrost, APGC) for supporting Arctic related research. However, information provided via the above-mentioned initiatives is currently dispersed through several web platforms and open datasets provided by these platforms are available in various formats, making their use difficult and in some cases impractical.

3 EO Data for Climate Change available for the Arctic

The ongoing advancement of Remote Sensing technologies, including cutting-edge satellites and innovative methods for large scale data processing, is crucial for enhancing the precision and reliability of climate change research on remote sensing data. For the Arctic region, the contribution of remote sensing data is extremely important due to its remote location and the difficulty of in situ observations.

The surface of the Arctic region can be effectively monitored using a range of optical satellites, with varying degrees of spatial resolution. These include MODIS with a 1km resolution, Landsat with a 30m resolution, and Sentinel with a 10m resolution. Additionally, very high-resolution satellites like PlanetScope (3m resolution), WorldView (0.5 – 1.5m resolution), IKONOS (1 – 4m resolution), and Pleiades (0.5m resolution) provide even more detailed observations. In the context of monitoring ice layers, Synthetic Aperture Radar (SAR) data is commonly employed, distinguished by its capability to acquire data irrespective of prevailing meteorological conditions, particularly in the presence of cloud cover. This sensor type enables us to detect changes in Land Use or Land Cover, variations of surface temperature dynamics, and quantification of changes in ice volume. Additionally, there is a plethora of global freely available geospatial datasets for the Arctic region. Those have been categorized based on the respective field to which it pertains, as described in the remainder of this section below.

3.1 Climate Weather and Atmospheric Datasets

Climate and atmospheric geospatial data are essential reservoirs for examining and observing the complex processes impacting Earth's weather patterns. Derived from satellite observations and measurements on the ground, these datasets provide critical details on atmospheric dynamics, enabling thorough investigations into climate phenomena and enhancing our understanding of atmospheric patterns and fluctuations. The *Global Land Data Assimilation System (GLDAS)* offers global coverage of key land surface conditions, including soil moisture, temperature, and precipitation. ERA-5 provides hourly estimates of numerous atmospheric, land, and oceanic climate variables, contributing to a nuanced comprehension of climate dynamics. The *Climatic Research Unit Timeseries (CRU TS)* presents monthly timeseries data encompassing precipitation, daily temperatures, and cloud cover across Earth's land areas. *WorldClim* delivers high-resolution global weather and climate data, facilitating analyses of current conditions and climate projections. *TerraClimate* provides monthly climate and water balance data globally. Satellite datasets, such as *MODIS Aqua and Terra*, *Sentinel-3*, *Sentinel-5 (TROPOMI)*, *Sentinel-6*, *SMOS*, and *SMAP*, contribute critical information on surface characteristics, ocean and land temperatures, atmospheric trace gases, and soil moisture. Additionally, datasets like *CAMS NearReal-Time Global Forecasts* offer atmospheric composition data for near-real-time global forecasting. The available datasets described above are presented in *Table 3.1*.

*Table 3.1. Available geospatial datasets for the Arctic region***, *Climate-Weather-Atmosphere*** *category.*

Dataset	**Spatial Resolution**	**Temporal Resolution**	**Link**[1]
Global Land Data Assimilation System (GLDAS)	0.25° (28 km)	3 hours	https://ldas.gsfc.nasa.gov/gldas
ERA-5	30km	1940 - Present	https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5
CRU TS (Climatic Research Unit Timeseries)	0.5° x 0.5° (~50km)	1901-2015	https://data.ceda.ac.uk/badc/cru/data
WorldClim	1km	1970-2000	https://www.worldclim.org/
TerraClimate	4km	1958-2020	https://www.climatologylab.org/terraclimate.html
MODIS Aqua And Terra	500 m	Daily, Day and Night 1999 - Present	https://modis.gsfc.nasa.gov/about/
Sentinel-3	1km	2015 - Present	https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-3
Sentinel-5 (TROPOMI)	7km x 3.5km	2017 - Present	https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-5p

[1] Last date accessed on 20/11/2023

Sentinel-6	~35 km	2020 - Present	https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-6/overview
CAMS NearReal-Time (NRT) Global Forecasts	0.4°x0.4° (~40km)	2015 - Present	https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-atmospheric-composition-forecasts?tab=overview
SMOS products	30-50 km	Daily	https://earth.esa.int/eogateway/catalog/smos-science-products
SMAP products	36km	2-3 days	https://smap.jpl.nasa.gov/data/

3.2 Land Datasets

Geospatial datasets related to land, further categorized into Terrain and Land Use / Land Cover datasets, are fundamental resources for analyzing Earth's surface characteristics. Terrain datasets like Digital Elevation Models (DEMs) provide detailed elevation information, allowing for comprehensive analyses of terrain features, slope, and landscape characteristics. Available DEMs for the Arctic Regions are presented in *Table 3.2*.

Table 3.2. Available geospatial datasets for the Arctic region, Land category (DEMs).

Datasets (Digital Elevation Models)	Spatial Resolution	Spatial Extent	Link[2]
SRTM	90m	Global	https://www.earthdata.nasa.gov/sensors/srtm
ASTER GDEM	30m	Global	https://asterweb.jpl.nasa.gov/gdem.asp
MERIT DEM	90m	Global	https://hydro.iis.u-tokyo.ac.jp/%7Eyamadai/MERIT_DEM/
ALOS DSM	30m	Global	https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm
NASADEM	30m	Global	https://www.earthdata.nasa.gov/esds/competitive-programs/measures/nasadem

[2] Last date accessed on 20/11/2023

EUCOPERNICUS DEM	25m	EU	https://land.copernicus.eu/en/products/products-that-are-no-longer-disseminated-on-the-clms-website
TanDEM-X	12m	Global	https://data.europa.eu/data/datasets/5eecdf4c-de57-4624-99e9-60086b032aea?locale=en
Arctic DEM	2m	Global	https://www.pgc.umn.edu/data/arcticdem/

Land Use/Land Cover (LULC) datasets constitute crucial geospatial resources for discerning the spatial distribution and utilization of land resources within specific geographic regions. These datasets systematically classify and illustrate diverse land cover types and land use patterns, sourced from satellite imagery and ground-based surveys. Most of these data are available for non-commercial use and cover spatial resolution from 2.5 to 500 meters (*Table 3.3*).

Table 3.3. Available geospatial datasets for the Arctic region, Land category (Land Use / Land Cover, Surface).

Dataset	**Spatial Resolution**	**Temporal Resolution**	**Extent**	**Data Policy**	**Link[3]**
MODIS Land Cover Type (NASA)	500m	Annual	Global	Free and Open Access	https://modis.gsfc.nasa.gov/data/dataprod/mod12.php
CORINE (Copernicus)	100m	4 years, 1990 - 2018	Global	Free and Open Access	https://land.copernicus.eu/en/products/corine-land-cover
Globland30 (National Geomatics Center of China)	30m	2000-2010	Global	Free and Open Access	http://www.globeland30.org/GLC30Download/index.aspx
Dynamic World (ESA)	10m	Annual	Global	Free and Open Access for non-commercial use	https://dynamicworld.app/
World Cover (ESA)	10m	Annual	Global	Free and Open Access for non-commercial use	https://esa-worldcover.org/en
JRC Monthly Water History, Water Recurrence,	30m	1984–2022	Global	Free and Open Access for non-commercial use	https://data.jrc.ec.europa.eu/dataset/jrc-gswe-global-surface-water-explorer-v1

[3] Last date accessed on 20/11/2023

Surface Water Mapping Layers (ECD JRC/ Google)					
European Settlement Map (ECD JRC/ Google)	2.5, 10 and 100m	1984 – 2022	EU	Free and Open Access for non-commercial use	https://land.copernicus.eu/en/products/products-that-are-no-longer-disseminated-on-the-clms-website
Urban Atlas (Copernicus)	10m	2006, 2012, 2018	EU	Free and Open Access for non-commercial use	https://land.copernicus.eu/en/products/urban-atlas
Global PALSAR-2 /PALSAR Forest /Non-Forest Map (JAXA)	25m	2017-2020	Global	Free and Open Access for non-commercial use	https://www.eorc.jaxa.jp/ALOS/en/dataset/fnf_e.htm
European Impervious Surface Maps (Copernicus)	10m	2006, 2009, 2012, 2015, 2018	EU	Free and Open Access for non-commercial use	https://land.copernicus.eu/en/products/high-resolution-layer-imperviousness

From the above it becomes evident that a wealth of geospatial data is available for the Arctic region. The utilization of those datasets is contingent upon the specific requirements of individual tasks, incorporating considerations of their spatial and temporal resolution, and adherence to policies set by data providers. The spatial analysis of these datasets encompasses a range of resolutions, spanning from low to medium and high, enabling the selection of data types adapted to the needs of each research endeavor. Most of them are available on particular cloud platforms, typically requiring user subscription for data acquisition.

4 Introducing EO-PERSIST (https://eo-persist.eu/)

4.1 The Framework

The main focus of the proposed project revolves around pioneering research and innovation in the comprehensive accessibility, management, and utilization of EO data suitable for permafrost socioeconomic studies and research. This distinctive approach involves consolidating the available EO data into a unified cloud-based system/platform. The amalgamation and integration of processing workflows, data repositories, and distribution centers within a unified cloud architecture promises not only a more harmonized and resource-efficient generation and accessibility of products but also an enhanced and integrated utilization of the pertinent data and resultant products. The attainment of this objective will involve the following key strategies:

To assess the viability and effectiveness of the system, experimental analyses will be conducted through five distinct Use Cases (UC). These use cases will concurrently function as Key Performance Indicators (KPIs) for the system. Specifically, two use cases will be dedicated to the development of innovative algorithms and techniques for permafrost studies, while the remaining three will engage in Remote Sensing (RS) and Geographic Information Systems (GIS)/big data modeling. These latter use cases will lay the foundation for formulating socio-economic indicators that capture the impact of permafrost changes on various sectors, including industry and local communities. The geographical emphasis will be on European Arctic areas.

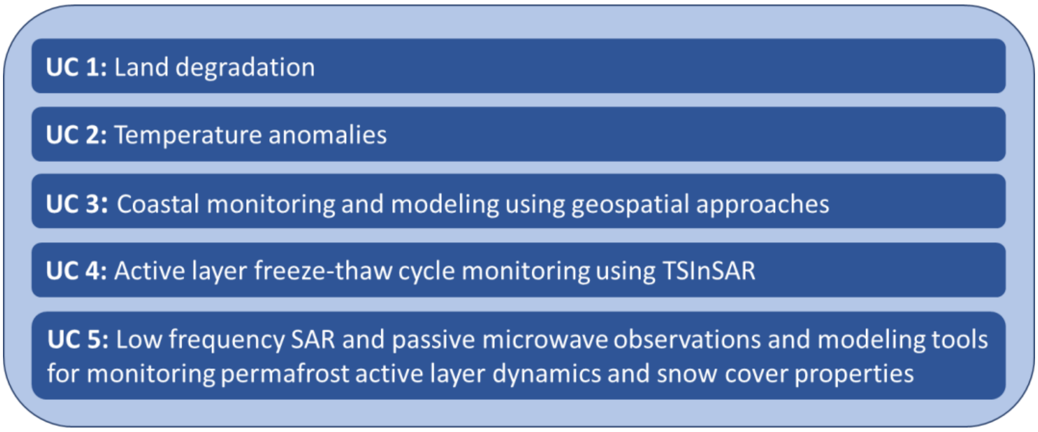

Figure 4.1. The five Use Cases which will also serve as Key Performance Indicators (KPIs) of the

4.2 Project Aims and Innovation Aspects

The aim of EO-PERSIST is to establish a dynamic collaborative research and innovation environment through staff exchanges, knowledge sharing, and know-how transfer. This initiative seeks to harness current services, datasets, and emerging technologies to achieve (a) the development of a consistently updated ecosystem featuring EO-based datasets tailored for permafrost applications, (b) methodological advancements in permafrost research by capitalizing on the vast volume of remote sensing (RS) datasets and (c) the generation of indicators directly linked to socio-economic impacts arising from permafrost dynamics.

Specifically, EO-PERSIST objectives are centered on creating a research and innovation collaboration network facilitated by staff exchanges for the purpose of:

- Exploitation of the cloud processing resources and big data EO archives to construct EO-PERSIST system.
- Design and implementation of innovative Remote Sensing (RS) algorithms (such as TSInSAR methods, Convolutional Neural Networks, and Super-Resolution methods) to facilitate the evaluation of permafrost changes.
- Application of Geographic Information Systems (GIS)-based models (such as multivariate analysis and gap filling) to large geospatial datasets for monitoring permafrost dynamics.

- Formulation and development of socioeconomic indicators for the sustainable development of the Arctic region, considering factors like land degradation, temperature anomalies, and coastal erosion resulting from permafrost dynamics and changes.
- Exchange of multidisciplinary knowledge (including Earth's processes modeling, RS, GIS, and cloud computing) among partners, fostering the integration of diverse scientific cultures to address scientific inquiries in the permafrost domain.
- Advancement of the skills and careers of staff through promotion and exchange. Reintegration of seconded staff into their respective companies/institutes with a built-in return mechanism to further leverage their newly acquired and enhanced skills and knowledge.
- Facilitation of the transition of complementary research conducted by partners to the market. This involves creating value-added products aligned with (a) a sustainable Arctic EO-based system, (b) enhanced algorithms for permafrost studies, and (c) socioeconomic indicators derived from RS outputs and GIS models, contributing positively to decision-making processes.
- Assurance of project sustainability and long-term business value.

The innovative core of the EO-PERSIST system revolves around the integration of diverse platforms into a unified hub, providing end users with access to extensive collections of EO datasets from multiple sources. This system is designed to merge a big data repository with formidable cloud processing capabilities, offering users a streamlined entry point to a comprehensive computing environment and resources. In essence, users will have the convenience of discovering, processing, and utilizing all datasets from the EO-PERSIST repository within a single, easily accessible location. Key innovative aspects of the EO-PERSIST cloud system include:

- <u>Conversion of Data Formats:</u> The system will employ a mechanism to convert traditional data formats into cloud-optimized formats, enhancing efficiency and compatibility.
- <u>Continuous Data Repository Updates:</u> The data repository will undergo continuous updates with the integration of new EO products. This entails ongoing services for data ingestion, processing, and delivery.
- <u>JupyterHub Accessibility:</u> Users will have access to JupyterHub, providing an ideal solution for those who prefer using different programming languages (such as R, Python2, Python3, Mathics Kernel, or Julia 1.0.3) for data processing. This feature adds a versatile dimension to the system's capabilities, accommodating diverse user preferences and needs.

Additionally, innovative aspects of each experimental User Case (UC) and can be summarized as it follows:

UC 1: Evaluating the influence of permafrost thaw on land degradation and ecosystems.

UC 2: Employing Deep Learning techniques to model climate downscaling for enhancing image data resolution.

UC 3: Investigating novel geospatial data analysis methods for mapping changes in coastal areas and quantifying the socioeconomic impact of climate change on the Arctic region.

UC 4: Harnessing phase information from distributed scatterers to enhance spatial continuity, facilitating detailed recognition and estimation of ground deformation patterns.

UC 5: Unifying algorithms for retrieving soil Freezing/Thawing (F/T) and Snow Water Equivalent (SWE) from Synthetic Aperture Radar (SAR) data, applicable to both L- and C-bands, and develop methods for using

4.3 Project Beneficiaries

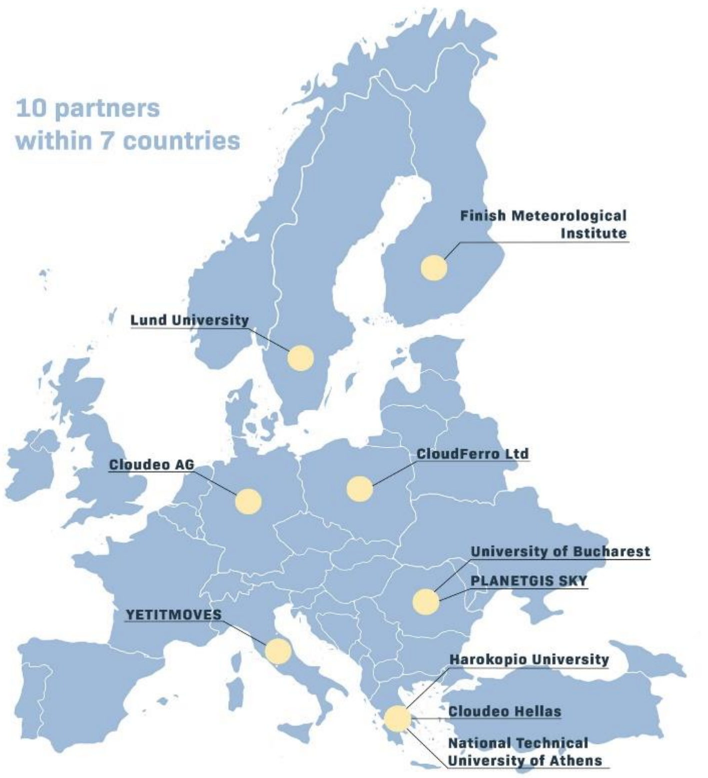

Figure 4.3. EO-PERSIST Consortium

The beneficiaries of EO-PERSIST project are research institutes, universities and companies from 7 countries located in Europe (Figure 4.1). The project necessitates the integration of various inter/multidisciplinary forms of knowledge to achieve its objectives. The primary categories of knowledge implicated in the project encompass variables, processes, and models associated with permafrost, Remote Sensing (RS), system design and cloud computing, Geographic Information Systems (GIS), geospatial socioeconomic modeling and Global Navigation Satellite System (GNSS). The synthesis of all these knowledge types is imperative for the comprehensive design, implementation, calibration, validation, and demonstration of the EO-PERSIST system. The *National and Technological University of Athens* (*https://www.ntua.gr/el/*), *University of Bucharest* (https://unibuc.ro/) and *Harokopio University of Athens* (https://www.hua.gr/index.php/en/) -the RS group- have been performing pioneering research in Remote Sensing, *YETITMOVES* (https://www.yetitmoves.it/) with expertise in GNSS, *CloudFerro* (https://cloudferro.com/) and *CloudEO* (https://www.cloudeo.group/) are key players in cloud environments, *Harokopio University of Athens* -the socioeconomic group- has considerable expertise in geospatial socioeconomics, *PlanetGIS SKY* (https://gis-sky.com/), *CloudEO* Hellas will share their expertise in GIS modeling and *Lund University* (https://www.lunduniversity.lu.se/) and *Finnish Meteorological Institute* (https://en.ilmatieteenlaitos.fi/) have considerable expertise in EPM including permafrost regions, while joint research corresponds to international mobility, based on secondments of research and innovation staff.

4.4 The structure of EO-PERSIST

The research and innovation within EO-PERSIST are structured into five key phases to ensure the quality and credibility of the conducted research and innovation endeavors across the Consortium. This framework is specifically crafted to facilitate knowledge transfer and know-how among Consortium members, fostering the transformation of inventive concepts into innovative products and services. The overarching goal is to amplify the project's impact by optimizing the entire process from idea generation to tangible outcomes.

The first step encompasses *Communities of Practices (CoP), User Requirements and EO-PERSIST design*. During this step, a comprehensive list of user requirements and supported datasets within the platform will be established and consistently updated throughout the project's progression. Initial steps involve gathering insights from end-users, including the Advisory Board of EO-PERSIST, through various channels such as questionnaires, interviews, focus groups, workshops, and a combination of these methods. Additionally, external stakeholders, specifically invited by the project, will contribute to the establishment of a Communities of Practice group. Concurrently, a detailed analysis will be undertaken, exploring technical, regulatory, and financial aspects critical for the development of the integrated EO-PERSIST system. Based on the requirements identified through user consultations, the consortium will systematically document all available geographic and pertinent data and services, encompassing areas such as hydrology, atmosphere, and meteorology, with a focus on permafrost. A survey will be conducted for each User Case (UC), examining existing data and services by referencing analogous projects from the present or past. The inventorying process will cover data and services derived from both Remote Sensing techniques and on-site measurements, addressing historical as well as real-time data. The inventorying will be meticulous and precise, leveraging high-quality GIS applications and products, along with other database management software, to ensure accuracy and efficiency.

The second step points to the *Socioeconomic Impacts Assessment Related to Thawing Permafrost.* In this phase, socioeconomic indicators will be constructed, using Remote Sensing and geospatial models relevant to monitoring land degradation (UC1), temperature (UC2), and coastlines (UC3).

The case study on **land degradation** focuses on the environmental impact of permafrost thawing, aiming to assess the chain reaction in geomorphological processes and terrestrial ecosystems. Three specific applications will be explored:

- **Assessing the relationship between permafrost thawing and landslide occurrences:** This aspect of the study involves a comprehensive approach to understanding the interplay between permafrost thawing and landslide occurrences. The detection of landslides is a multi-step process, leveraging InSAR analysis and Sentinel-1 imagery. Furthermore, point cloud data obtained from Persistent Scatterer (PS) analyses undergoes evaluation using an Artificial Intelligence algorithm, allowing for the identification, and mapping of space-time anomalies. The integration of these anomalies with geomorphological and geological datasets contributes to the development of an advanced AI model designed specifically for landslide mapping. Additionally, a Long Short-Term Memory (LSTM) artificial recurrent neural network is being trained to estimate landslide occurrences under the influence of global climate changes, considering the latest IPCC scenarios.
- **Mapping areas with possible thermokarst induced by permafrost thawing:** In this application, which falls within the realm of geomorphology, the primary objective is to map areas that are susceptible to or already experiencing thermokarst—a phenomenon arising from permafrost thawing. The mapping process involves the use of Sentinel-2 images, applying Super Resolution algorithms to enhance resolution to 5m. Improved Sentinel-2 images are then employed to create a detailed dataset featuring collapsed pingos, sinkholes,

and pits, serving as a robust training and validation dataset for the detection model. The development of the detection model incorporates the latest Convolutional Neural Network (CNN) models, with a specific emphasis on testing object detection, object instance segmentation, and pixel classification models for accurate mapping of thermokarst in the Arctic Region.

- **Mapping the transformation of terrestrial ecosystems into aquatic ones:** This application is related to the transformation of terrestrial ecosystems into aquatic ecosystems. The methodology involves the use of Sentinel-1 and Sentinel-2 imagery, both of which prove valuable for discerning shifts from non-water to water within ecosystems. The initial stage of the application encompasses a comprehensive analysis of the advantages and disadvantages associated with these two types of imagery for mapping changes in terrestrial ecosystems. To further enhance understanding, the seasonal cycle from frozen soil/water to water undergoes scrutiny through space-time Land Cover Change Detection and Monitoring Methodologies (Zhu, 2017). This analysis aims to provide insights into the dynamic changes occurring within terrestrial ecosystems. As an outcome, a detailed map with ecosystem changes in the Arctic Region is planned to be released during the project's implementation.

The case study on **temperature anomalies** is centered on using thermal remote sensing for industrial monitoring and risk assessment, leveraging historical EO data. These applications are crucial for industry as EO data analysis enables hazard evaluation and the prevention of extensive damage. The study will specifically address two main categories within Industrial Risk Applications, utilizing a methodological approach for a comprehensive exploration.

The first category involves site *monitoring, risk assessment for chemical gases and plume detection and identification*. In this category, the focus is on monitoring and assessing sites for chemical gases in the event of a spill or accident in a chemical or oil refining plant. Emergency response authorities need to evaluate the plant and its surroundings. The second category focuses on *monitoring/risk assessment for gas, hot water, and high voltage transportation infrastructure leak detection*. In these applications, gas identification isn't necessary as the transportation infrastructure is predetermined. The focus is on two key areas: (a) natural gas transportation pipelines and (b) hot water pipelines from central heating plants.

The **coastal monitoring and modeling** case study integrates EO datasets with advanced geospatial modeling approaches, including multivariate models and raster gap-filling approaches. The primary objective is to map coastline changes in Arctic permafrost areas. Advanced algorithms, such as the ArcGIS API for Python, the ArcGIS Notebook Server, and machine learning (ML) methods will be employed to extract shorelines within a GIS environment. Long-term analysis of coastline erosion or accretion rates will be conducted using GIS techniques. A time-series analysis of EO data will reveal coastal dynamics, and the CHAOS modeling system will assess the impact of Arctic permafrost changes on atmospheric conditions.

The third step encompasses the *Scientific Advances for Permafrost Monitoring.* In this phase, the Consortium will develop innovative algorithmic approaches within the permafrost domain. The first endeavor involves the development of an innovative approach based on big SAR data to provide information related to the active layer freeze-thaw cycle (UC4). The primary goal of this Use Case is to design a TSInSAR algorithm specifically for permafrost regions, with the capability to effectively utilize interferometric measurements of distributed scatterers and leverage spatiotemporal information during the unwrapping procedure.

The second entails developing methodologies that harness low-frequency SAR observations to monitor permafrost active layer dynamics and facilitate snow modeling (UC5). The objective of this Use Case is to develop and assess the capabilities of L-band SAR imagery for retrieving both soil Freeze/Thaw (F/T) state and Snow Water Equivalent (SWE) with the eventual aim of exploiting the impact of these retrievals on permafrost active layer dynamics. The primary sources of remote sensing data will be ALOS2 and Sentinel-1 observations. A time series of ALOS2 imagery is accessible for various test sites through an ESA-JAXA collaboration involving FMI, and all Sentinel-1 data are publicly distributed.

The fourth step is the *Implementation of EO-PERSIST System.* This phase includes all necessary procedures for designing and implementing the proposed structure of the platform. The EO-PERSIST system will be built upon the existing CloudFerro public cloud infrastructure - CREODIAS. This involves leveraging its EO data repository and utilizing cloud resources, including computing power and storage. CREODIAS stands out as a highly scalable processing cloud, equipped with a local storage capacity exceeding 26 PetaBytes, housing diverse Copernicus data, such as imagery from Sentinel satellite missions, Landsat satellites, Copernicus services, and various datasets. In this step, all partners will closely collaborate and exchange knowledge and expertise to transition the designed system into an operational state.

The fifth and final step focuses on the *Validation of the EO-PERSIST System*. The developed algorithmic approaches will be calibrated and validated exploiting EO-PERSIST cloud-based resources. This process will specifically target regions where high-quality information, such as in-situ measurements, is readily available. Complementary knowledge of the socioeconomic activities will be incorporated for enhanced accuracy. Subsequently, utilizing the calibrated and validated EO-PERSIST approaches, an uncertainty assessment will be conducted over permafrost regions in Europe. For each socio-economic indicator within EO-PERSIST, an uncertainty layer, leveraging all available multisource datasets, will be generated. The engagement of other identified users and stakeholders will be a key component, facilitating platform utilization and collecting valuable feedback on the added value of the service.

5 Conclusions and Future Outlook

EO-PERSIST assembles a consortium comprising distinguished academic and industry experts across diverse disciplines to address the imperative of monitoring permafrost conditions in the Arctic region. Through the introduction of novel methodologies and innovative tools, leveraging contemporary geoinformation technologies, the project will have a broad applicability and influence on scientific, societal, and economic realms. The avant-garde EO-PERSIST web platform, characterized by technological advancements, including state-of-the-art cloud computing, and access to a spectrum of EO datasets from advanced sensors. The integration of cloud computing is pivotal in providing scalable resources for the efficient processing of the vast EO datasets from. This technological synergy promises to yield unprecedented insights into permafrost studies in the Arctic.

The comprehensive EO dataset made available through EO-PERSIST presents unique opportunities for the exploration of geoinformation technologies in permafrost studies and related applications and also underscores the importance of a cloud-based platform in enhancing accessibility and scalability. The cloud infrastructure ensures the seamless availability of data, fostering collaboration and facilitating real-time processing. Notably, this involves investigating the interplay between climate dynamics and anthropogenic activities and their historical implications for permafrost areas across varying geographical scales.

The embedded case scenarios within EO-PERSIST serve as exemplars, illustrating the platform's efficacy in addressing research inquiries and evaluating socio-economic impacts associated with permafrost studies. The outcomes from these inquiries have the potential to influence policies and decision-making in permafrost regions, contributing to the refinement of mitigation strategies. The system will be flexible and facilitate communication to improve Situational Awareness relevant to permafrost. As such, it will provide timely information relevant to permafrost to local and government authorities as well as stakeholders.

The potential influence of comprehending the application of geoinformation technology in permafrost studies in the Arctic extends beyond the realm of science, intersecting with various fields to which EO-PERSIST also makes substantive contributions. As big data is overwhelming all scientific disciplines, the imperative arises for tools capable of collecting, analyzing, and responding to this data in real-time. Noteworthy applications encompass domains such as advanced security cameras, smart-city infrastructure, and autonomous vehicles among others. The cloud-based platform and methodologies envisioned within EO-PERSIST, particularly those related to data processing and modeling, possess significant adaptability for application across diverse disciplines. This adaptability extends to scenarios where combining complementary information from various environmental parameters derived from EO data can enhance output outcomes. In the era of "Big Data", such a conceptual framework is essential, and our project aligns with this imperative. EO-PERSIST holds significant potential for a distinctive contribution by fusing EO data, opening avenues for innovative approaches and capabilities development in various fields, including the cryosphere, ecology, and the study of natural hazards and climate change impacts. For instance, an improved understanding of permafrost processes could lead to a better understanding of the general observation of an acceleration of the water cycle under climate change. The importance of this lies in the substantial and diverse potential impact of climate change on society. Addressing the study of climate impacts on society is considered as a topic of key priority to be addressed today.

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