CCI+ PHASE 2 – NEW ECVS
PERMAFROST

CCN4 OPTION 7
ICEINSAR: INFERRED ACTIVE LAYER WATER/ICE CONTENT AND FREEZE-THAW PROGRESSION FROM ASSIMILATING INSAR IN PERMAFROST MODEL

D5.1 CLIMATE ASSESSMENT REPORT (CAR)

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EXECUTIVE SUMMARY

Within the European Space Agency (ESA), the Climate Change Initiative (CCI) is a global monitoring program which aims to provide long-term satellite-based products to serve the climate modelling and climate user community. The two main products associated to the ECV Permafrost are Ground Temperature (GT) and Active Layer Thickness (ALT). GT and ALT are documented by the Permafrost_cci project based on thermal remote sensing and physical modelling.

The Permafrost_cci models take advantage of additional datasets, such as snow cover and land cover, to estimate the heat transfer between the surface and the underground. However, several challenges remain due to spatially variable subsurface conditions, especially in relation to unknown amounts of water/ice in the active layer that modify the effective heat capacity and the thermal conductivity of the ground. In complex terrain with large spatial heterogeneities and coarse, partly inadequate land cover categorization, the current results show discrepancies with in-situ measurements. This highlights the need to incorporate new data sources as model inputs. Although the ground stratigraphy is not directly observable from space, it impacts the dynamics of the ground surface. The seasonal thawing and refreezing induce cyclic subsidence and heave of the ground surface due to ice formation and melt in the active layer. Surface displacements can therefore be used as indirect indicator of the ground conditions.

Synthetic Aperture Radar Interferometry (InSAR) based on Sentinel-1 images can be used to measure the amplitude and seasonal progression of these displacements. The movement amplitude is related to the amount of water/ice that is affected by a phase change, whilst the timing of the displacement patterns reflects the vertical progression of the thawing/freezing front. Considering the fine to medium spatial resolution of Sentinel-1 images, InSAR time series therefore have the potential to enhance the characterisation of subsurface hydrogeologic and thermal parameters and adapt the existing Permafrost_cci models to improve their performance at the local to regional scale. The *IceInSAR* pilot project (Option 7) developed a prototype for permafrost model adjustment by assimilating Sentinel-1 InSAR surface displacement maps and time series into the model to constrain stratigraphy parameters. *IceInSAR* provided pilot results, expected to be used for adjustment of the ECV processing chain of the baseline project in a next phase.

This Climate Assessment Report (CAR) discusses the findings of the *IceInSAR* Option 7. It assesses the relevance and impact of the results, evaluate the progress in respect to the user requirements, and list the direct outcomes of the pilot project.

1 INTRODUCTION

1.1 Purpose of the document

This document assesses the results of the *IceInSAR* Option 7. It discusses the relevance and impact of the findings, evaluate the progress in respect to the user requirements, and list the direct outcomes of the pilot project. It has to be read together with the CRDP [RD-1], PVIR [RD-2] and PUG [RD-3].

1.2 Structure of the document

Section 2 outlines the study design. Section 3 assesses the relevance and impacts of Option 7 findings. Section 4 evaluates the contribution of the study to fulfil the user requirements and outlines plans for future developments. Section 5 lists the outcomes of the project (publications and conference contributions). Section 6 includes a bibliography and a list of acronyms. A glossary of the commonly accepted permafrost terminology can be found in RD-16.

1.3 Applicable Documents

[AD-1] ESA. 2022. Climate Change Initiative Extension (CCI+) Phase 2 – New Essential Climate Variables – Statement of Work. ESA-EOP-SC-AMT-2021-27.

[AD-2] GCOS. 2022. The 2022 GCOS Implementation Plan. GCOS – 244 / GOOS – 272. Global Observing Climate System (GCOS). World Meteorological Organization (WMO).

[AD-3] GCOS. 2022. The 2022 GCOS ECVs Requirements. GCOS – 245. Global Climate Observing System (GCOS). World Meteorological Organization (WMO).

1.4 Reference Documents

[RD-1] Wendt, L., Rouyet, L., Westermann, S., Bartsch, A., Strozzi, T. 2024. ESA CCI+ Permafrost Phase 2. CCN4 Option 7. IceInSAR: Inferred Active Layer Water/Ice Content and Freeze-Thaw Progression From Assimilating InSAR in Permafrost Model. D.3.2 Climate Research Data Package (CRDP). Version 1.0. European Space Agency.

[RD-2] Wendt, L., Rouyet, L., Westermann, S., Bartsch, A., Strozzi, T. 2024. ESA CCI+ Permafrost Phase 2. CCN4 Option 7. IceInSAR: Inferred Active Layer Water/Ice Content and Freeze-Thaw Progression From Assimilating InSAR in Permafrost Model. D.4.1 Product Validation and Intercomparison Report (PVIR). Version 1.0. European Space Agency.

[RD-3] Wendt, L., Rouyet, L., Westermann, S., Bartsch, A., Strozzi, T. 2024. ESA CCI+ Permafrost Phase 2. CCN4 Option 7. IceInSAR: Inferred Active Layer Water/Ice Content and Freeze-Thaw Progression From Assimilating InSAR in Permafrost Model. D.4.2 Product User Guide (PUG). Version 1.0. European Space Agency.

[RD-4] Rouyet, L., Wendt, L., Westermann, S., Bartsch, A., Strozzi, T. 2023. ESA CCI+ Permafrost Phase 2. CCN4 Option 7. IceInSAR: Inferred Active Layer Water/Ice Content and Freeze-Thaw Progression From Assimilating InSAR in Permafrost Model. D.1.1 User Requirement Document (URD). Version 1.0. European Space Agency.

[RD-5] Rouyet, L., Wendt, L., Westermann, S., Bartsch, A., Strozzi, T. 2023. ESA CCI+ Permafrost Phase 2. CCN4 Option 7. IceInSAR: Inferred Active Layer Water/Ice Content and Freeze-Thaw

Progression From Assimilating InSAR in Permafrost Model. D.1.2 Product Specification Document (PSD). Version 1.0. European Space Agency.

[RD-6] Rouyet, L., Wendt, L., Westermann, S., Bartsch, A., Strozzi, T. 2023. ESA CCI+ Permafrost Phase 2. CCN4 Option 7. IceInSAR: Inferred Active Layer Water/Ice Content and Freeze-Thaw Progression From Assimilating InSAR in Permafrost Model. D.2.2 Algorithm Theoretical Basis Document (ATBD). Version 1.0. European Space Agency.

[RD-7] Rouyet, L., Wendt, L., Westermann, S., Bartsch, A., Strozzi, T. 2023. ESA CCI+ Permafrost Phase 2. CCN4 Option 7. IceInSAR: Inferred Active Layer Water/Ice Content and Freeze-Thaw Progression From Assimilating InSAR in Permafrost Model. D.2.3 End-to-End ECV Uncertainty Budget (E3UB). Version 1.0. European Space Agency.

[RD-8] Rouyet, L., Wendt, L., Westermann, S., Bartsch, A., Strozzi, T. 2023. ESA CCI+ Permafrost Phase 2. CCN4 Option 7. IceInSAR: Inferred Active Layer Water/Ice Content and Freeze-Thaw Progression From Assimilating InSAR in Permafrost Model. D.2.4 Algorithm Development Plan (ADP). Version 1.0. European Space Agency.

[RD-9] Rouyet, L., Wendt, L., Westermann, S., Bartsch, A., Strozzi, T. 2023. ESA CCI+ Permafrost Phase 2. CCN4 Option 7. IceInSAR: Inferred Active Layer Water/Ice Content and Freeze-Thaw Progression From Assimilating InSAR in Permafrost Model. D.2.5 Product Validation Plan (PVP). Version 1.0. European Space Agency.

[RD-10] Bartsch, A., Matthes, H., Westermann, S., Heim, B., Pellet, C., Onaca, A., Strozzi, T., Kroisleitner, C., Strozzi, T. 2023. ESA CCI+ Permafrost Phase 2. D1.1 User Requirement Document (URD). Version 3.0. European Space Agency.

[RD-11] Bartsch, A., Westermann, S., Strozzi, T., Wiesmann, A., Kroisleitner, C., Wieczorek, M., Heim, B. 2023. ESA CCI+ Permafrost Phase 2. D1.2 Product Specification Document (PSD). Version 3.0. European Space Agency.

[RD-12] Westermann, S., Bartsch, A., Strozzi, T. 2023. ESA CCI+ Permafrost. D.2.2 Algorithm Theoretical Basis Document (ATBD). Version 4.0. European Space Agency.

[RD-13] Westermann, S., Bartsch, A., Strozzi, T. 2023. ESA CCI+ Permafrost. D.3.2 Climate Research Data Package (CRDP). Version 4.0. European Space Agency.

[RD-14] Bartsch, A., Obu, J., Westermann, S., Strozzi, T. 2024. ESA CCI+ Permafrost. D.4.3 Product User Guide (PUG). Version 4.1. European Space Agency.

[RD-15] Heim, B., Wieczorek, M., Pellet, C., Delaloye, R., Bartsch, A., Strozzi, T. 2024. ESA CCI+ Permafrost. D.4.1 Product Validation and Intercomparison Report (PVIR). Version 4.0. European Space Agency.

[RD-16] van Everdingen, Robert, Ed. 1998 revised May 2005. Multi-language glossary of permafrost and related ground-ice terms. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology (http://nsidc.org/fgdc/glossary/; accessed 23.09.2009).

1.5 Bibliography

A complete bibliographic list that supports arguments or statements made within the current document is provided in Section 6.1.

1.6 Acronyms

A list of acronyms is provided in Section 6.2.

2 OPTION 7 STUDY DESIGN

The *IceInSAR* Option 7 was a proof-of-concept study. The primary objective was to evidence the value of Interferometric Synthetic Aperture Radar (InSAR) surface displacement to indirectly document the ground stratigraphy, and elaborate strategies for data assimilation into permafrost models.

To achieve this objective, a significant focus has been placed on comparing InSAR displacement with in-situ data acquired in Adventdalen, Svalbard (see PVIR [RD-2]) (Wendt, 2024a; Wendt et al., 2024b). An extensive field dataset on the subsurface stratigraphies and permafrost ECV variables was acquired in spring-autumn 2023 (see CRDP [RD-1]). Due to the timing of this field campaign, most InSAR analyses have been performed for the 2023 snow-free season. The CRDP is stored on Zenodo (Wendt, 2024c), and is further described in the PUG [RD-3].

In addition to the 2023 results, seasonal InSAR displacement time series were processed for all other available Sentinel-1 seasons, using both ascending and descending SAR orbits. Interannual displacement time series were also generated (see CRDP [RD-1]). These datasets are not published yet, as this part of the Option 7 is in synergy with the parallel project developing an InSAR Ground Motion Service in Svalbard (Rouyet et al., 2024). The data release is planned for end of 2025 and will be made openly available for viewing and download in a WebGIS similar to the InSAR Norway mapping service (https://insar.ngu.no/). The InSAR products served as basis for experiments to further elaborate data assimilation strategies into permafrost models (e.g. InSAR clustering) (see CRDP [RD-1] and PVIR [RD-2]).

Simulations with the CryoGrid community permafrost model (Westermann et al., 2023) were performed at selected locations where both in-situ and InSAR data were available (see CRDP [RD-1]). These simulations enabled benchmarking various model schemes and parameterizations against in-situ and remotely sensed observations, with the objective to develop processing chains capable of ingesting InSAR data into permafrost models. The code is open and accessible in GitHub repository (https://github.com/CryoGrid/CryoGridCommunity_run).

3 ASSESSMENT OF OPTION 7 RESULTS

3.1 InSAR products as indicator of active layer thickness

The use of InSAR seasonal time series to infer ALT is a popular research topic due to the scarce in-situ network in the Arctic and the need for large-scale monitoring strategies to widely document this ECV parameter. Liu et al. (2012) introduced a method to calculate ALT from InSAR subsidence assuming constant subsurface parameters and ice formation in sediment pores only. Since then, this method has been applied by many other authors (e.g., Schaefer et al., 2015; Jia et al., 2017; Wang et al., 2018, Peng et al., 2023, Si et al., 2024). This inversion method has shown promising results when compared to in-situ ALT measurements, but outliers have also been reported, for example in drained lake basins. In such cases, large InSAR-measured displacements lead to too large ALT estimates (Liu et al., 2014; Schaefer et al., 2015), which suggests that this model does not manage to fully represent the complexity of the subsurface conditions. However, no direct evidence could confirm/refute this hypothesis due to a lack of comprehensive studies combining in-situ subsurface observations, InSAR and modelling.

The results from *IceInSAR* Option 7 contribute to a better understanding of the previously reported discrepancies and confirm the hypothesis of a mismatch between the model parametrization and the subsurface complexity. We show that the established InSAR-ALT inversion is too simplistic for terrain with complex ground stratigraphies, including large excess ice content. ALT measured in 2023 in Adventdalen correlated poorly with both the observed InSAR subsidence and the expected subsidence from in-situ ground ice contents (see Figure 1). The correlation is better for expected subsidence calculated with pore ice content only. However, the results indicate that the contribution from excess ice dominates the expected subsidence at many sites.

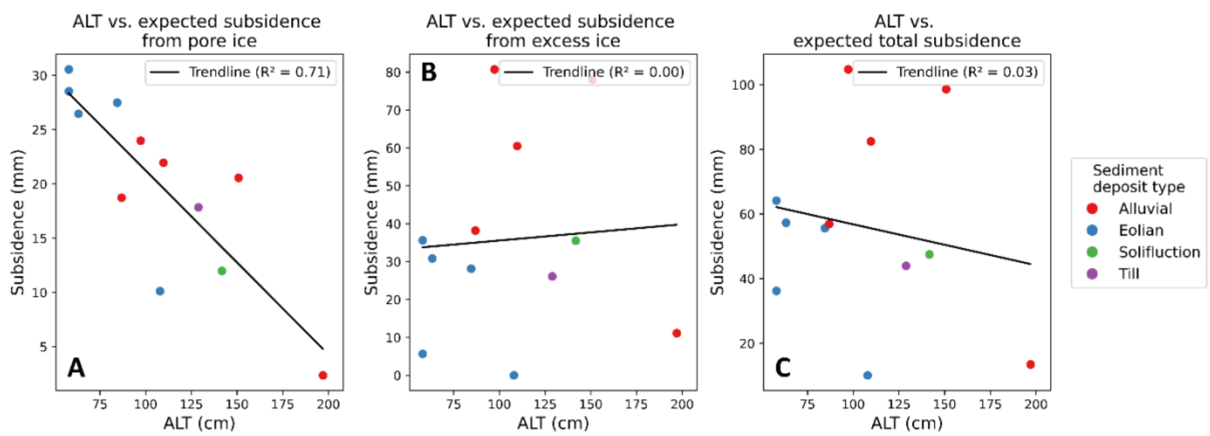

Figure 1. Relationship between the Active Layer Thickness (ALT) and the expected subsidence from pore ice and/or excess ice melt within the active layer. From Wendt (2024a), Wendt et al. (2024b). See detailed explanations in CRDP [RD-1].

The ice content is spatially variable, both horizontally between the sites and vertically along the core profiles. Generally, the excess ice is concentrated in the lower active layer and the upper permafrost (Figure 2). This shows that an InSAR-ALT inversion considering pore ice only and a constant ground ice profile is not a realistic representation of study areas like Adventdalen, especially when focusing on warm summers during which the thawing front may reach the excess-ice-rich layers. When applying

Liu et al.'s (2012) method, we recommend focusing on InSAR observations during relatively cold thawing seasons, to reduce the likelihood of excess ice melt at the base of the active layer. Outliers due to excess ice melt in the upper/middle active layer should still be accounted for. Overall, as an important conclusion of the *IceInSAR* Option 7, we recommend the development of more complex models to convert InSAR subsidence to ALT.

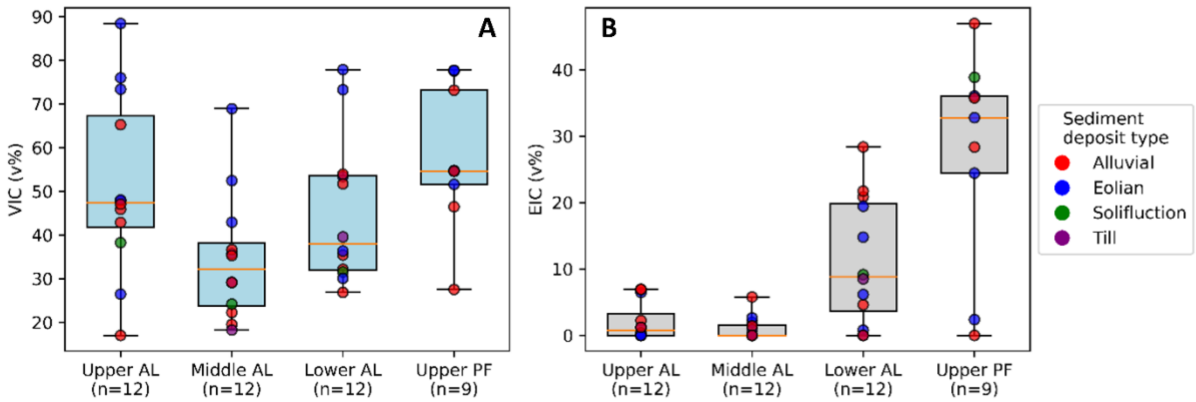

Figure 2. A. Volumetric Ice Content (VIC). B. Excess Ice Content (EIC). The results are categorized by depth locations (upper, centre and lower thirds of the active layer and the uppermost permafrost), based on the 12 coring sites. From Wendt (2024a) and Wendt et al., 2024b). See detailed explanations in CRDP [RD-1].

3.2 InSAR products as indicator of ground ice content

InSAR-measured subsidence and expected subsidence based on in-situ ice contents are well correlated (Figure 3), which confirms that InSAR is a good indicator of the ground ice content in permafrost terrain. The comparison between InSAR and expected subsidence shows that the observed subsidence cannot be explained without accounting for the melt and drainage of excess ice. At most sites, the excess ice melt is the main contributor to the 2023 subsidence.

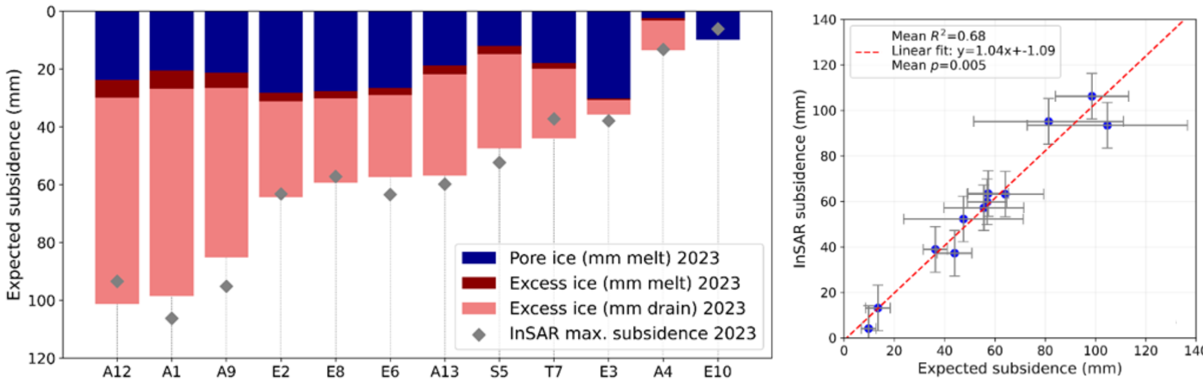

Figure 3. Left: Contribution of pore ice melt, excess ice melt and excess ice meltwater drainage to the total expected subsidence at the different coring sites. The measured InSAR subsidence at similar locations is shown with the grey diamonds. Right: Relationship between the InSAR subsidence and the total expected subsidence (pore ice melt + excess ice melt + excess ice meltwater drainage). From Wendt (2024a; 2024b). See detailed explanations in PVIR [RD-2].

The Option 7 results provide evidence that InSAR subsidence can indicate the spatial variability of ice content, both spatially (across a region) and vertically (in the active layer, and in the upper permafrost or the transient layer). Spatially, the seasonal amplitude varies between coarse-grained ice-poor landforms (e.g., alluvial fans) and fine-grained ice-rich landforms (e.g., eolian terrasses). Vertically, a combination of different InSAR products is valuable to understand the ice distribution in the active layer and upper permafrost. InSAR time series from cold seasons can be used to characterize the active layer ice content, while excess-ice content at the base of the active layer (transient layer) can be documented by late-season subsidence in warm thawing seasons (Zwieback & Meyer, 2021). Interannual time series can likely identify long-term subsidence trends, documenting ground ice loss from permafrost degradation.

3.3 Implications for assimilation of InSAR data into permafrost models

In the Permafrost_cci model, the ground stratigraphies are assigned based on landcover classes. This strategy leads to large uncertainties, since ground ice contents are difficult to parametrize due to high spatial variability, also within similar landcover classes. Over the past years, a significant effort has been placed on improving the input product (e.g., Option 6: Improved soil description through a landcover map specifically designed for the Arctic; Bartsch et al., 2024a; 2024b). Option 7 shows that InSAR time series can indirectly document the variability of ice content in the active layer and the uppermost permafrost. InSAR has therefore a clear potential for constraining the parameterization of the ground stratigraphy in future iterations of the Permafrost_cci model.

To further evaluate the potential of assimilating InSAR data into the permafrost model CryoGrid, model simulations were performed at two sites with contrasting conditions according to the in-situ data: one dry loess site with little excess ice, and one wet organic site with abundant excess ice. The performance of two model configurations was tested against in-situ observations: 1) the pore ice configuration, including only formation/melt of pore ice while neglecting formation and melt of excess ice, and 2) the segregation ice configuration, considering the formation/melt of both pore and excess ice (Aga et al., 2023). The simulated ice content changes and resulting simulated surface displacements of the CryoGrid model were compared with the InSAR displacements.

At the dry site, the pore ice model aligns well with both the in-situ data and the InSAR time series. At the wet site, the modelled ALT development generally aligns with the in-situ data. However, the pore ice model does not replicate the InSAR displacement, especially in warm seasons. This indicates that the subsidence is likely caused by the top-of-permafrost melt of excess ice, which the standard model scheme is not accounting for. Using the segregation ice model, the modelled displacement time series align better with the observed displacements. The improvement is especially visible for warm seasons, such as 2023 (Figure 4).

The segregation ice model is computationally expensive. Although the results show that it is better suited to represent the observations, the current scheme cannot be realistically applied at large scales. Similarly, assimilating full InSAR time series into the model would be too computationally intensive. We therefore need to develop realistic ingestion strategies that avoid computationally demanding workflows. The InSAR clustered map generated Option 7 provides new ideas for moving in that direction (Figure 5). InSAR clustering appears to be an appropriate solution to reduce the dimensionality of the InSAR products. The mean InSAR time series of each cluster may be used for assimilation. If it is still too computationally intensive, manually defined ground stratigraphy parameters associated with each cluster could be assimilated.

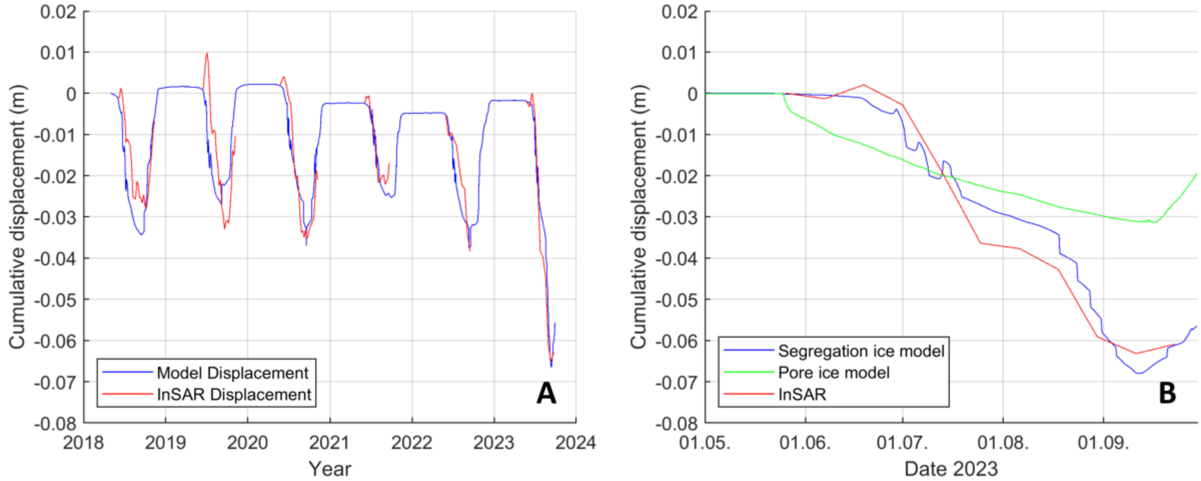

Figure 4: Simulations of segregation ice model. A. Simulated displacement time series compared to InSAR observations at the wet site (E10). B. Detailed view of the warm 2023 season, showing the difference between the two model configurations, compared to the InSAR observations. Modified from Wendt (2024a). See detailed explanations in PVIR [RD-2].

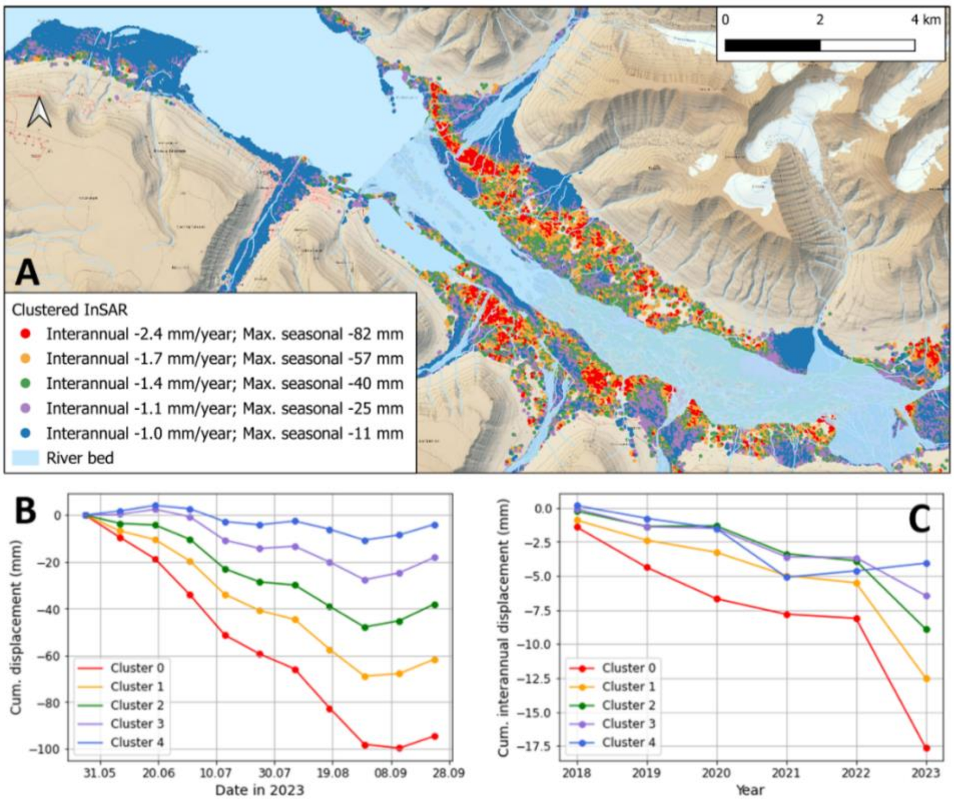

Figure 5: A. Clustered InSAR map generated using k-means clustering based on two attributes: the seasonal InSAR displacement time series and the interannual displacement trends. B. The 2023 mean seasonal InSAR time series per cluster. C. The 2018–2023 mean interannual InSAR time series per cluster. Modified from Wendt (2024a). See detailed explanations in CRDP [RD-1].

4 PROGRESS WITH REGARDS TO USER REQUIREMENTS

All Permafrost_cci user requirements from the baseline URD [RD-10] are listed in *Table* 1, but the focus is placed on those applicable for Option 7 (see URD [RD-4]). For each user requirement, the source and type of work to be addressed are identified. Some URq (shown in **grey**) are not directly applicable by the *IceInSAR* Option 7 due to the pilot nature of the project and its local–regional scale. At the end of the two-year pilot project, we have not developed operational products that directly modify the level of URq fulfilment. However, our conclusions set the necessary foundation for future work expected to enable future progress in respect to these requirements.

*Table 1: Summary of user requirements, applicable at variable stages of the work: Background (BG), Production (P), and Dissemination (D). The parameters are Permafrost Extent (PE), Ground Temperature (GT), Active Layer Thickness (ALT) and Surface Displacement (SD). The Table is based on the baseline URD [RD-10] and was modified for Option 7 as outlined in the respective URD [RD-4]. In grey: not applicable for Option 7 and in **black**: applicable but not especially targeted. The filled coloured of the applicable URq indicates the current achievement status (red: not fulfilled / work not started, yellow: partly fulfilled / ongoing work, green: fulfilled / completed work).*

ID	Parameter	Requirements	Source	Type
URq_01	PE/GT/ALT	Higher spatial resolution than a map scale of 1:10,000,000	IPA Mapping group report	BG
URq_02	PE/GT/ALT	Data need to be related to a time stamp	IPA Mapping group report	P
URq_03	PE/GT/ALT	Form of delivery for maps and data need to be flexible	IPA Mapping group report	D
URq_04	PE/GT/ALT	High data quality	IPA Mapping group report	BG
URq_05	PE/GT/ALT	Benchmark dataset needs to be developed	IPA Mapping group report, GlobPermafrost/IPA mapping group workshop	P
URq_06	PE/GT/ALT	Evaluation through community	GlobPermafrost/IPA mapping group workshop	P
URq_07	PE/GT/ALT	Terminology for modelling output 'potential'	GlobPermafrost/IPA mapping group workshop	D
URq_08	GT/ALT	Depth of active layer, permafrost temperature in K and seasonal soil freeze/thaw needs to be addressed	GCOS	BG
URq_09	PE	Threshold: uncertainty 10–25 %, hor. res. 10–100 km, temp. res. 3–5 days, timeliness 5–6 days	OSCAR	BG
		Breakthrough: uncertainty 7–8.5 %, hor. res. 0.85–1 km, temp. res. 14–36 hours, timeliness 14–36 h	OSCAR	BG
URq_10	PE/GT/ALT	Distribution as NetCDF	CMUG	D

URq_11	PE/GT/ALT	Development of a new ground stratigraphy product for the permafrost domain	GlobPermafrost survey	P/D
URq_12	GT	Threshold: pan-arctic, yearly, last decade, 10 km, RMSE < 2.5 °C	Permafrost_cci survey	BG
		Target: global, monthly, 1979–present, 1 km, subgrid variability, RMSE < 0.5°C	Permafrost_cci survey	BG
URq_13	ALT	Threshold: pan-arctic, yearly, last decade, 10 km, RMSE < 25 cm	Permafrost_cci survey	BG
		Target: global, monthly, 1979–present, 1 km, subgrid variability, RMSE < 10 cm	Permafrost_cci survey	BG
URq_14	PE/GT/ALT	Monthly products	CMUG/obs4MIPs	P
URq_15	PE/GT/ALT	NetCDF format with one product per file	CMUG/Climate Data Store (CDS)	D
URq_16	PE/GT/ALT	Monthly means and daily data	CMUG/Climate Data Store (CDS)	P
URq_17	PE/GT/ALT	ERA5 spatial resolution (0.25° x 0.25°)	CMUG/Climate Data Store (CDS)	P
URq_18	PE	Threshold: global, yearly, 10 m, 85%	User Requirements for a Copernicus Polar Mission	BG
		Goal: global, yearly, 10 m, 95%	User Requirements for a Copernicus Polar Mission	BG
URq_19	ALT	Threshold: RMSE 2/15 cm (probing uncertainty / sensor uncertainty);	GCOS	BG
		Goal: RMSE 1/5 cm (probing uncertainty / sensor uncertainty)	GCOS	BG
URq_20	SD	Threshold spatial resolution: 5 m	User Requirements for a Copernicus Polar Mission	BG
		Goal spatial resolution: 1 m	User Requirements for a Copernicus Polar Mission	BG
		Threshold temporal resolution: 1 yr	User Requirements for a Copernicus Polar Mission	BG
		Goal temporal resolution: 14 days	User Requirements for a Copernicus Polar Mission	BG
		Threshold accuracy: 0.01 m/yr	User Requirements for a Copernicus Polar Mission	BG
		Goal accuracy: 0.001 m/yr	User Requirements for a Copernicus Polar Mission	BG

URq_21	SD	Threshold resolution: 100–1000 m	NRC 2014	BG
		Target resolution: 1–5 m	NRC 2014	BG
		Threshold extent: regional	NRC 2014	BG
		Target extent: circumpolar	NRC 2014	BG
URq_22	SD	Threshold resolution: 100–300 m	CryoGrid/Permafrost_cci Option 6 URD	BG
		Target resolution: 20 m	CryoGrid/Permafrost_cci Option 6 URD	BG
		Threshold period: last decade	CryoGrid/Permafrost_cci Option 6 URD	BG
		Target period: 1979 – present	CryoGrid/Permafrost_cci Option 6 URD	BG
URq_23	SD	Production of climate data records in Permafrost_cci is 1 km^2, targeting annual products based on daily input	CryoGrid/Permafrost_cci	BG

4.1 Contribution of IceInSAR Option 7

The *IceInSAR* pilot study confirms the ability of InSAR to infer information on the spatial and vertical variability of ground ice contents. While the pore-ice model set-up of the Permafrost_cci model can represent InSAR observations for dry conditions, it is not able to represent the ground surface dynamics for the selected wet site, due to the high sensitivity to excess ice. In this respect, InSAR time series can indirectly help improving the model results by documenting the variability of the ice content in the active layer and the uppermost permafrost. We conclude that InSAR has a clear potential for constraining the parameterization of the ground stratigraphy in future iterations of the Permafrost_cci model.

The Option 7 conclusions pave the way for upcoming model adjustments, which are targeting the following objectives aligned with the user requirements:

- To take advantage of high-resolution Sentinel-1 SAR satellite data (initial resolution: 20x5 m; final multi-looked resolution between 40 and 100 m) to constrain the model and provide downscaled products in specific regions (contribution to URq_09, URq_12, URq_13, URq_18).
- To develop a prototype for permafrost model adjustment by assimilating InSAR-based surface displacement to indirectly document subground properties, better assess the product accuracy at the regional scale and further improve model performance (contribution to URq_4, URq_9, URq_12, URq_13, URq_19).
- To enhance the characterisation of subsurface hydrogeologic and thermal parameters based on complementary input data and contribute to a new representation of the model subgrid variability (contribution to URq_11, URq_12, URq_13, URq_21, URq_22).
- To provide a new product type (surface displacement) at the regional scale valuable for different user communities, both for operational applications in Svalbard and for model validation and development purposes (contribution to URq_3, URq_18, URq_20).

4.2 Plan for future developments

The Option 7 results show a high sensitivity to the excess ice content of the ground, which highlights the need for a better representation of ice segregation processes in the model. However, implementing a more advanced Permafrost_cci model scheme with detailed ground ice dynamics is too computationally demanding for global application at 1-km resolution. Nevertheless, InSAR time series can indirectly help to improve the model results by documenting the variability of the ice content in the active layer and the uppermost permafrost. The main challenge is to develop products which provide key information to the model, while avoiding too computationally demanding ingestion strategies. Assimilation of the full-resolution InSAR time series is currently unrealistic, at least for large-scale applications. Instead, the use of clustered products should be investigated. One solution is to assimilate the mean InSAR time series of each cluster. However, even this simplified workflow is still computationally demanding especially for the excess ice model, so the first step forward is to associate manually defined ground stratigraphy parameters (ice-poor vs. ice-rich conditions) to each cluster based on user knowledge.

Another solution is to combine the information provided by InSAR with the landcover products currently used in the model, or those under development in the Permafrost_cci project (Option 6). We expect that the landcover and InSAR products are both correlated and complementary. The landcover captures the spatial variability of the surface types that indirectly relate to the geological and hydrothermal conditions, while InSAR more directly documents the subsurface ice content. The information contained in InSAR can therefore be used to refine the landcover categorization or develop new composite products. In Figure 6, we show a first comparison between the Option 6 Permafrost_cci landcover products (Bartsch et al., 2024a; b) and InSAR displacement in Adventdalen (see CRDP, [RD-1]), Svalbard. The proportion of landcover classes within each InSAR cluster varies. As expected, the fraction of classes associated with moist conditions are more represented in clusters 0–3, corresponding to high subsidence rates (i.e. ice-rich conditions), while classes associated with dry conditions are more represented in clusters 3–4, corresponding to low subsidence rate (i.e. ice-poor conditions) (Figure 6). However, the wide range of classes included in each cluster also shows that the ground conditions are spatially variable within each landcover class. In this respect, InSAR may be able to refine the subsurface parameterization of each landcover class. In the future, we see significant potential in developing composite InSAR-landcover products and testing their impact on the model performance in selected regions. A natural first step in that direction is to systematically compare InSAR and landcover in several Arctic regions.

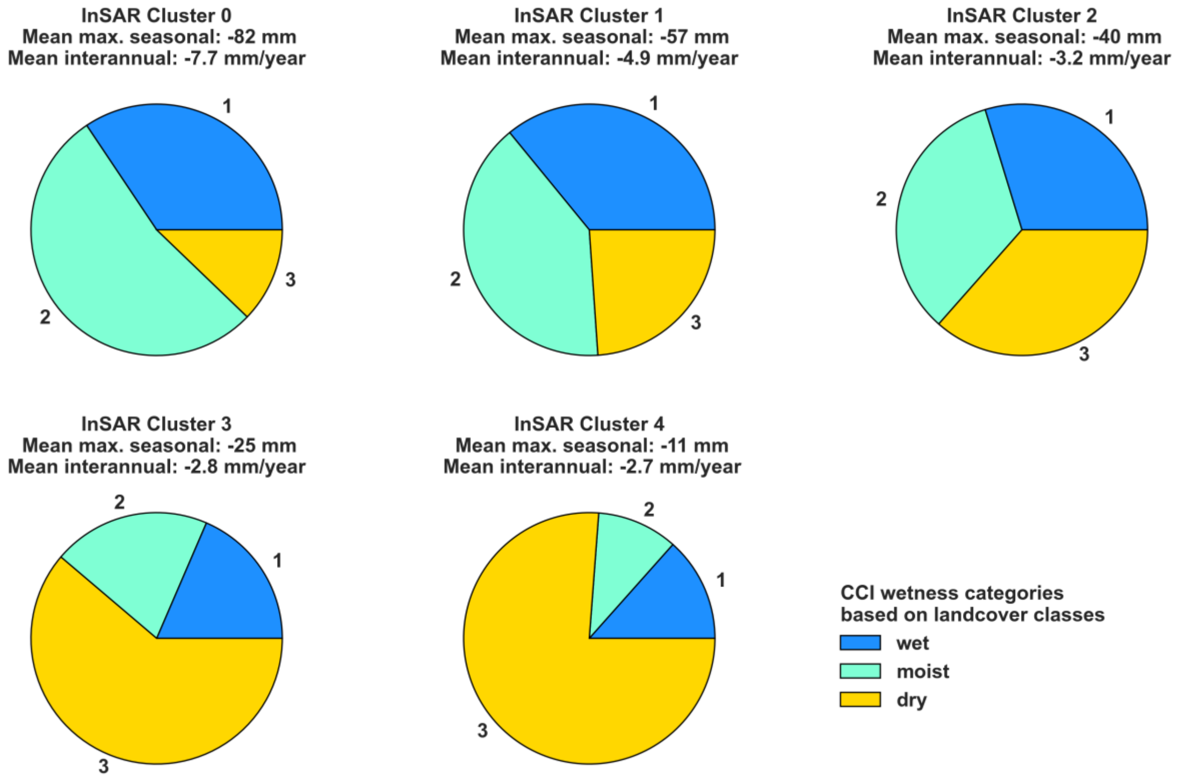

Figure 6: Comparison between InSAR clusters and landcover classes, grouped by wetness categories (according to Table 2 in Bartsch et al., 2024b).

For global InSAR products over permafrost regions, efficient workflows for upscaling need to be developed. Further research is needed before InSAR technology reaches maturity for systematic global coverage, but the development of large-scale InSAR operational services, such as the European Ground Motion Services (EGMS, https://egms.land.copernicus.eu/), show that advances in this field are fast. InSAR GMS extensions in Arctic regions are foreseen in the future. In the recent report of the Copernicus Polar Task Force (Duchossois et al., 2024), it is stated that “it is necessary to expand the EGMS over Arctic regions” (p.36). The development project of the InSAR Svalbard GMS is featured as an example (p.37–38), and the task force recommends to “follow these regional efforts to expand the EGMS across the polar regions” (p.38). For constraining permafrost modelling, large-scale InSAR processing could initially focus on only two thawing seasons: one that is exceptionally cold and one that is exceptionally warm. This approach would allow to understand spatial patterns of ice content in the active layer (cold thawing season) and in the uppermost permafrost (warm thawing season). These patterns could, through spatial clustering, be assimilated into permafrost models like CryoGrid for improved model simulations.

5 PUBLICATION AND OUTREACH

5.1 Publications

The results are published as preprint in *The Cryosphere Discussion*:

- Wendt, L., Rouyet, L., Christiansen, H. H., Lauknes, T. R., and Westermann, S. (2024). InSAR sensitivity to active layer ground ice content in Adventdalen, Svalbard. EGUsphere [preprint]. https://doi.org/10.5194/egusphere-2024-2972.

In-situ and InSAR data from 2023 season are available in the Zenodo repository (data properties also described in the PUG [RD-3]):

- Wendt, L. (2024). Ground ice contents and InSAR displacements from Adventdalen, Svalbard. [Data set]. Zenodo. https://doi.org/10.5281/zenodo.11187360.

5.2 Presentations

Two contributions related to the *IceInSAR* Option have been presented at scientific conferences:

- Wendt, L., Rouyet, L., Christiansen, H. H. and Westermann, S. Assessing the relationship between ground ice content and InSAR surface displacements in Adventdalen. Poster. Svalbard Science Conference, 30–31. October 2023, Oslo.
- Wendt, L., Rouyet, L., Christiansen, H. H. and Westermann, S. Evaluating InSAR sensitivity to in-situ ground ice contents across different landforms. Oral. 12th International Conference on Permafrost (ICOP), 16–20 June 2024, Whitehorse, Canada.

5.3 Student teaching and supervision

The results of the *IceInSAR* Option 7 are related to the M.Sc. work of Lotte Wendt:

- Wendt, L. (2024). Assessing ground ice changes in Svalbard from SAR interferometry and modelling. M.Sc. thesis. Department of Geoscience, Faculty of Mathematics and Natural Sciences, University of Oslo (UiO), Norway. Available at: http://hdl.handle.net/10852/112526. Main supervisor: Prof. Sebastian Westermann. Co-supervisors: Dr. Line Rouyet, Prof. Hanne H. Christiansen.

Theory and use of InSAR for permafrost applications in Svalbard, incl. findings from Option 7, have been taught and discussed in a course at UNIS:

- One-day lecture and practical exercise on Remote Sensing of Permafrost Regions as part of the MSc/PhD AG-330/830 course on Permafrost and Periglacial Environments (spring semester 2024), University Centre in Svalbard (UNIS). Teacher: Line Rouyet.

5.4 User outreach

Advances in permafrost modelling, incl. Option 7 findings, have been discussed during the last CryoGrid community workshop:

- CryoGrid community workshop ITCH and ESA Permafrost_cci User workshop: one week workshop on using and developing the CryoGrid permafrost model further, including Option 7 work. Oct. 21-25, Drøbak, Norway, 30 participants.

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6.2 Acronyms

AD	Applicable Document
ADP	Algorithm Development Plan
ALT	Active Layer Thickness
ATBD	Algorithm Theoretical Basis Document
B.GEOS	B.Geos GmbH
CAR	Climate Assessment Report
CCI	Climate Change Initiative
CRDP	Climate Research Data Package
ECV	Essential Climate Variable
EO	Earth Observation
ESA	European Space Agency
E3UB	End-To-End ECV Uncertainty Budget
GAMMA	Gamma Remote Sensing AG
GCOS	Global Climate Observing System
GT	Ground Temperature
GTN-P	Global Terrestrial Network for Permafrost
UIO	University of Oslo

INSAR	Synthetic Aperture Radar Interferometry
IPA	International Permafrost Association
NORCE	Norwegian Research Centre AS
PE	Permafrost Extent
PF	Permafrost Fraction
PSD	Product Specification Document
PUG	Product User Guide
PVASR	Product Validation and Algorithm Selection Report
PVIR	Product Validation and Intercomparison Report
PVP	Product Validation Plan
RD	Reference Document
RMSE	Root Mean Square Error
SAR	Synthetic Aperture Radar
SD	Surface Displacement
SSD	System Specification Document
URD	Users Requirement Document
URq	User Requirement
WMO	World Meteorological Organisation