KEPLER Deliverable Report

Final report on Deliverable D3.5

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Context of deliverable within Work Package

Executive Summary of WP3. This document consists of 6 parts: Objectives of WP3, Executive Summary of Task 3.1, Executive Summary of Task 3.2, Executive Summary of Task 3.3, Executive Summary of Task 3.4 and Conclusions and Recommendations from WP3.

Objective of WP3

Work package 3 (WP3), Identification of research and capacity gaps, aims to both identify the potential for additional parameters relevant to the Polar Regions to be assimilated into models for simulations and forecasts, and also to assess different satellite missions linked to a number of in-situ and airborne observational scenarios. In particular, the effect of the Copernicus expansion in terms of its benefit for environmental monitoring, and with regard to integration/assimilation and the generation of modelling/forecast products. WP3 has two overarching objectives, these are:

Objective 1: Identify the potential for the assimilation into forecast models of additional parameters relevant to the Polar Regions.

To fulfill this objective we performed a detailed review on current assimilated marine and terrestrial parameters and identified any major limitations. The potential for assimilation of new, relevant variables has been assessed. Moreover, we present a concept on how to move forward on data assimilation.

Objective 2: To assess different satellite missions in combination with a number of in situ and airborne observational scenarios. In particular with regard to the Copernicus expansion, and in terms of the benefit of these new sensors for environmental monitoring, and their ability to integrate/assimilate into modelling/forecast products.

To fulfil this objective we prepared a comprehensive review of the current status of remotely sensed parameters acquired over Polar Regions, and compared them with the products provided by the Copernicus services. By doing so we have been able to identify current data gaps. Furthermore, an assessment of future satellite missions (in particular the HPCMs) has been performed. This has led to feasible synergies between parameters from different satellite missions being identified, which will enhance the information content considering the end-users requirements. To carry out the proposed work we divided the WP into 4 tasks, which are summarized below.

Executive Summary of task 3.1: Gaps in terms of in situ observations in order to improve Polar Regions monitoring and forecasting capabilities

The objectives of task 3.1 are two-fold: (1) Investigate what role citizen science can play in the expansion of Copernicus' In situ monitoring priorities and (2) assess how the in situ observational research community, both for marine and terrestrial, can better contribute to the aims of Copernicus with monitoring.

Rather than summarise the entire Task 3.1 we focused solely on the recommendations. For a more in-depth understanding we refer the reader to the Deliverable 3.1 report on the gaps in terms of in situ observations in order to improve Polar Regions monitoring and forecasting capabilities. In the preparation of that report there were a number of meetings of the relevant organisations that resulted in a series of recommendations for the final End-to-end Operational System Roadmap of the KEPLER project (D5.2) and the Polar Expert Group III (PEG-3) of the European Commission that highlighted an enhanced role for the Copernicus In Situ Component in the Copernicus 2.0 period (2021-28).

Recommendations on Citizen Science (CS)

The participation of non-specialists in scientific research, i.e. the public, is generally referred to as Citizen Science, Community-Based Observing, Public Participation in Scientific Research, Volunteered Geographic Information, or Crowdsourcing. In KEPLER, we use the term Citizen Science (CS), which we define as being:

"Voluntary collaborations in scientific research that is conducted, in whole or in part, by non-professional scientists, whose outcomes both advances scientific knowledge, and increases the public's understanding of science."

As one of the biggest distributors of environmental products and services in Europe we felt the Copernicus Services should play a proactive role in (a) making sure their products are accessible and useful for CS projects, (b) ensuring CS projects can improve the accuracy and usability of their products. Citizen science will continue to develop and diversify and as it does, Copernicus Services will have an opportunity to enhance its relevance and the uptake of its products by the citizens of Europe, which will increase their reputation and their role within society. For the Copernicus Services to capitalize on the broad potential of CS we suggest:

- Copernicus Services should make a greater effort to highlight and promote the number of CS projects that use their products and stimulate new ones.
- One Copernicus Service, or most likely the presently under-utilised Copernicus *In Situ Component*, is encouraged to take ownership/stewardship of CS needs and interaction for all Copernicus Services.

The Copernicus lead for CS is encouraged to:

- recruit or support a small number of CS experts to develop an achievable strategy that would allow for a more integrated approach to CS by the Copernicus Services.
- perform an audit of the interaction between CS and the different Copernicus Services.
- develop mechanisms to encourage, support and facilitate more CS projects to be involved in the calibration and validation ("Cal/Val") of the present and future Copernicus products and services.
- pursue channels of communication with the European Citizen Science Association, the H2020 funded EU Citizen Science project, and other leading CS organisations within Europe. The aim is to support and advance European CS through better communication, coordination, and knowledge sharing with the focus being on strengthening the goals to and maintain the capabilities of the Copernicus Services.

The evidence suggests that CS can make a welcome contribution to enhancing the relevance of the Copernicus Services to European citizens, as well as helping to evaluate and improve the accuracy of Copernicus products themselves. Addressing the above-mentioned suggestions should provide a pathway for the data collected by citizens to become a serious and important part of Copernicus Services in the future, especially the Copernicus *In Situ Component*.

Recommendations from In situ Component for Copernicus

Unrestricted and timely access to *in situ* scientific observations and model forecasts underpins evidence-based decision making. We assessed how the observational research community, both marine and terrestrial, can better contribute to *in situ* monitoring to improve Polar Regions products of the Copernicus Services. To do this we have summarised information and recommendations from previous reports, as well as performing an in-depth consultation process with research infrastructure stakeholders.

Below we provide a series of suggestions on how the marine and terrestrial polar research community can better interact with the Copernicus Services, for the mutual benefit of both, but especially in the improvement of products and services.

We found that there was a lack of dialogue between the broader European polar research and monitoring community and the Copernicus Services (and associated Thematic Assembly Centers (TACs)). This in turn impacts the quality of Copernicus polar products and services. Recommendations and suggestions include:

- An independent scientific audit should be conducted on the CMEMS Quality Information Document (QUIDS), and equivalent quality assurance documents from CLMS and C3S, with respect to the Copernicus Services polar products.
- Prioritising the collection of *in situ* measurements in the Polar Regions for Cal/Val. This is desperately needed to reduce the identified uncertainties associated with Copernicus Services polar products.
- Developing a framework whereby Copernicus Services can better utilise European polar research assets (i.e. stations, ships, aircraft and people) to provide needed Cal/Val opportunities for Copernicus Services products.
- Enhancing opportunities for the broader European polar community to develop closer relationships with the Copernicus Services, not just with TACs.
- Ensuring independent Quality Control of services/products by establishing a continuous monitoring framework. By doing so Copernicus can independently assess improvements of their products over time, and with the onset of new satellites, and that the Copernicus Services are returning value on the investment to European society.
- Encouraging, where possible, the publishing in peer-reviewed journals of a more academic version of the QUIDS and other quality assurance documents. Independent peer-review is the bedrock of science.
- Providing recommendations from Copernicus to the European research community which clearly identify where additional research efforts need to be focused to improve the accuracy or Cal/Val data for a particular product.

Executive Summary of task 3.2: New and novel observation sensors and techniques

The objective of this task was to determine and evaluate the maturity of the different types of systems, and their practicality for Polar Regions deployments. This was achieved in consultation with the developers of observation sensor technologies and platforms.

The Copernicus programme is organised into three components, a space component, an in situ component and a service component. Whilst the majority of the focus on new technologies is with satellites and the space component, there are also developments and advances with observing systems and sensors at closer range that enhance the ability to gather additional data from in situ, airborne and underwater. Therefore, we have performed the following studies:

1. To evaluate the maturity and the practicality of different types of unmanned observing platforms for Polar Regions deployments, and
2. Determine what new sensor technologies could provide additional monitoring capability.

We evaluated the main platform types for airborne and oceanographic monitoring. We first analysed the larger Unmanned Aircraft Systems (UAS). Although smaller UAS such as off-the-shelf drones have been used with some success on Polar field campaigns, their range and length of deployment have been limited. Larger UAS systems currently suffer from a lack of experience of approved operations, and need to comply with international regulations for flight operations. Pan-Arctic missions across international Flight Information Regions (FIRs) have therefore been limited and there has yet to be any attempts to set these up routinely on a basis that can be used for repeat monitoring.

Other systems, including the High Altitude Pseudo Satellites (HAPS) being evaluated by ESA, feature extreme range and endurance at lower latitudes through solar-electric propulsion and sensors. However this is impractical for Polar deployments due to low sun angles on the, typically horizontally placed, solar panels.

There have been attempts at providing recommendations for Pan-Arctic UAS missions, such as the AMAP, 2015, and these await longer range UAS technology to become more widely available for these to be evaluated.

We have also analysed the use of smaller UAS, kites, and balloons. These are suitable in some situations such as field campaigns or stations where support personnel are available.

In situ sensors for the field of oceanography were also analysed. There has been steady advances in Autonomous Underwater Vehicle (AUV) technology in the past 20 years. Typically AUV's, similar to UAS systems, are limited in their endurance and can only cover limited areas. However, AUV systems are capable of hosting increasingly sophisticated imaging sonars that provide mapping similar to Synthetic Aperture Radar (SAR) from space or airborne platforms. Recommendations are for improved underwater navigation capability.

In the past decade, glider technology has advanced with systems either having an endurance limited by battery capacity but with the flexibility to perform underwater surveys, or having the ability to augment their requirements through wave energy but being restricted to on-surface operation. Neither have the capacity for energy-intensive sensors such as imaging sonars.

Four types of new sensor technologies have been analysed: ultra wideband radar (UWB), ground penetrating radar (GPR), and tomographic radar. UWB and GPR have been used for mapping snow cover on sea ice, and for determining internal ice layers, with the tomographic radar providing a measurement of surface height. The fourth sensor considered was bio-optical and this biogeochemical approach has potential to provide new mechanisms for detecting and monitoring various pollutants, including organophosphorus pesticides, toxic heavy metals such as mercury and uranium, phenol and phenol derivatives, perfluorooctanesulfonic acid (PFOS), antibiotics, drugs and drug metabolites, small organic molecules including toxins and endocrine-disrupting chemicals.

Although these new platforms and sensors show promising results, they have yet to be made available at a cost effective level that would mitigate the costs of widespread deployment, and potential loss, in the extreme Polar Environments. Copernicus should therefore continue to monitor these developments, and be ready to take advantage of them as technology improves and becomes more readily available.

Executive Summary of task 3.3: Research gaps of space-based Arctic monitoring

Our objective was to extract a list of knowledge and research gaps for enabling better usage of satellite data for environmental monitoring and retrieval of environmental parameters, and in data assimilation on short and midterm forecasting models for sea state, ocean physics, biogeochemistry, and ice.

First Conclusion:

First of all, a detailed review of the current status of remotely sensed parameters acquired over Polar Regions was performed. Then we compared them with the remote sensing products provided by the Copernicus service to identify current data gaps**.**

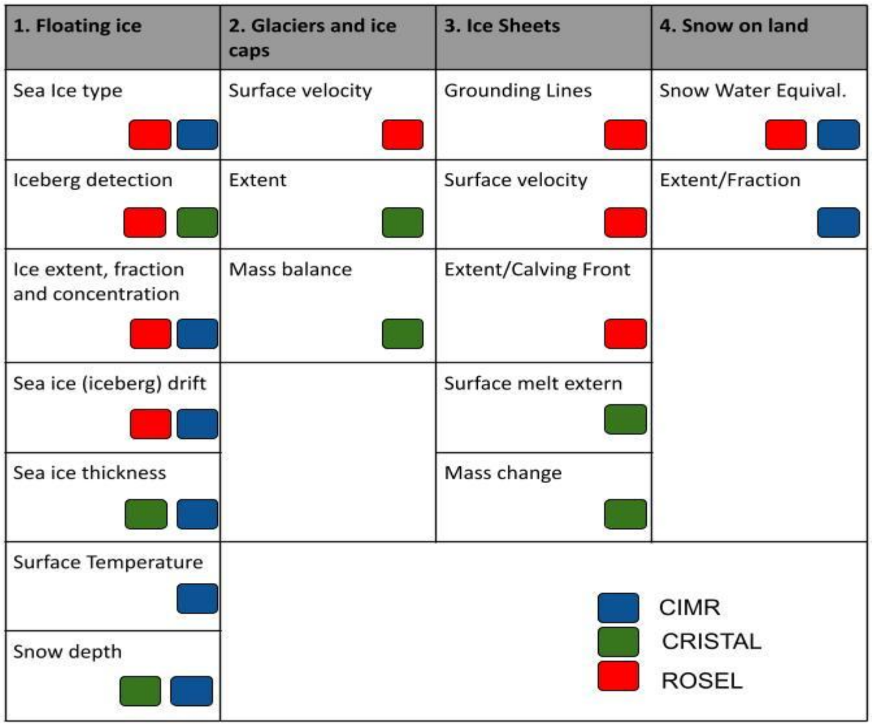
We identified several remote sensing parameters that Copernicus is not currently serving while datasets with acceptable maturity are available from different providers, such as universities and research institutes. These **parameters** are listed below (and described in page 5 from the T3.3 Deliverable) :

Remote sensing products not distributed in Copernicus nowadays	
Sea Ice	Sea Ice Age
	Melt pond fraction
	Sea ice Albedo
	Leads fraction
Land	Lake ice duration
	Lake ice thickness
	Snow melt
	Snow depth
	Snow avalanche monitoring
	Permafrost
	in land water chlorophyll and turbidity
Physical Ocean and Sea state	Surface currents
	Surf. Stress (Wind)
	Wave Spectra
	Ocean Albedo

- ➢ **Recommendation for Copernicus:** to **include the above 15 remotely sensed parameters** in the future evolution of Copernicus Services.

Second Conclusion:

We reviewed **the parameters which could be acquired/estimated with future missions** (already planned or under discussion) with special focus on the polar EU HPCM missions (CIMR, CRISTAL, ROSE-L). The Polar Expert Group (PEGIII) defined several high priority environmental parameters which should be remotely sensed in the future to improve the monitoring of the poles. Figure below shows, with color codes, which parameters can be acquired by each of the polar HPCM satellites. Blue dots are the parameters CIMR could provide, green dots are for the parameters CRISTAL could provide and RED dots are the parameters which ROSE-L could provide. More detailed information can be found in section 3, page 6, D3.3 Deliverable report.



➢ **Recommendation for Copernicus: the three polar HPCM missions are needed** to cover the identified high priority environmental parameters

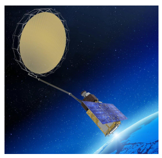
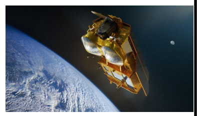
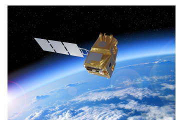
<u>Third Conclusion:</u>

We **evaluated the current and potential synergies** to improve the quality and resolution of remote sensing data products for the Polar Regions. Synergies are achievable by combining data from satellite instruments operated at different frequencies/wavelengths, in passive or/and active modes, with different spatio-temporal resolutions, different penetration depths, thus having different sensitivities to the geophysical parameters.
Some of the results are listed below:

- **18 potential synergies** of different types of sensors are presented, most of them already demonstrated in the scientific literature. From those**, only 4 will be operational in Copernicus by the end of phase 1**.

More detailed information can be found in section 4, page 14, from the D3.3 report.

Matrix of potential synergies which could be put on operation with current and future HPCM satellites. The synergies mentioned are already tested experimentally. The green boxes are synergies for land applications, light grey for ice and ocean applications. ***Text in red means operational product in Copernicus phase 1 (2021).*** ***Parameters with high impact for intermediate and end users are marked with bold fonts.***

Sensors	**PMR (e.g. CIMR)** 	**RA (e.g. CRISTAL)** 	**IR (e.g.LSTM)** 	**Optical (e.g. CHIME)** 	**SAR (e.g. ROSE-L)** 
PMR (e.g. CIMR)		lake ice thickness		**Soil moisture downscaling**	Snow Water Equivalent **Soil moisture**
RA (e.g. CRISTAL)	**SIT[1], ice type,** snow depth			Phytoplankton groups	
IR (e.g.LSTM)	**SIT, ice surface temperature, sea surface temp**	**SIT, ice type**			
Optical (e.g. CHIME)	**SIC, ice type**	**ice type** MPF		**Phytoplankton groups, phytoplankton dynamics**	snow extent snow wetness **snow avalanche** lake ice extent
SAR (e.g. ROSE-L)	**SIC, SIDrift**	sea ice deformation evolution **iceberg properties,** snow depths on sea ice	**ice type**	**SIC, ice type**	

- ➢ **Recommendation for Copernicus: to promote the production and distribution of the new improved products resulting from the synergies, specially the ones with a higher impact for the user**.
- ➢

Fourth Conclusion:

The **status quo in data assimilation was analysed and future assimilation parameters and techniques were suggested.**

The parameters **currently being assimilated into CMEMS models** and the **remotely sensed parameters recommended for data assimilation** are summarized in the table below. The specific problems faced by each parameter are explained in the report.

Remotely sensed parameters being assimilated currently in CMEMS
Sea Ice Concentration (PMR)
Sea Surface Temperature (IR)
Sea Ice Thickness (RA, LA, PMR)
Ice Drift (PMR)
Chlorophyll-a (VIS)
Sea Surface Height (RA+Grav.)
SST (from PMR)

Colour coding: Severely limited, medium level of limitation, small limitations, not sufficiently documented (white).

There is, to our knowledge, no assimilation of satellite land data as part of the Copernicus Land.

Remotely sensed parameters recommended for data assimilation		
Ocean model	**Sea ice model**	**Land Models**
sea surface salinity	sea ice surface temperature	snow cover (snow water equivalent, fractional snow covered area)
sea surface height in leads*	sea ice drift, ice type, ice deformation, roughness	land surface temperature. Freeze-thaw
Bio-Geo-Chemical	melt pond fraction, albedo	permafrost extent
ocean colour: Chlorophyll-a, phytoplankton C, phytoplankton functional-types, optical properties	**waves**	surface soil moisture
	significant wave height, swell, albedo	river level
		lake Ice Area

*: Note that the sea level in leads as proposed by Armitage et al. (2017) and SSALTO/DUACS (DOI: 10.24400/527896/a01-2020.001) were omitted from D3.3.

Additionally, we investigated the **assimilation of satellite information at lower processing levels** including exploring how services would benefit from going beyond the current status-quo (assimilation of daily/weekly/monthly averaged gridded satellite products) and start assimilating individual swaths (and/or scenes) of satellite-derived product in swath projection (Level-2), and even directly raw satellite observation (Level-1).

More detailed information can be found in section 5, page 24, from the D3.3 report.

- ➢ **Recommendation for Copernicus: to adapt the models to assimilate the mentioned parameters**, and explore the possibility to go beyond the status-quo assimilation methodologies.

The work developed in this task, led us to prepare a list of **recommendations to improve the Copernicus services for Polar monitoring**. The recommendations are summarized in a table (6.3 from the WP3.3 report), and are organized by: general, land applications, sea-ice and ocean applications recommendations. Time horizon and potential impact for the users are reported for each recommendation.

Armitage, T. W. K., Bacon, S., Ridout, A. L., Petty, A. A., Wolbach, S., & Tsamados, M. (2017). Arctic Ocean surface geostrophic circulation 2003–2014. The Cryosphere, 11(4), 1767– 1780. https://doi.org/10.5194/tc-11-1767-2017

Executive Summary of task 3.4:

Task 3.4 evaluated several observational scenarios in terms of their performance in a data assimilation system. In the construction of these observational scenarios we emphasised on the Copernicus Sentinel satellites with particular focus on the HPCMs for the expansion of the Sentinel fleet. One group of scenarios consisted of observations of the Arctic sea ice-ocean system, while another group consisted of observations of atmospheric CO2.

We employed the quantitative network design (QND) approach to assess the impact of these scenarios in a mathematically rigorous fashion through the reduction of uncertainties in a set of relevant target quantities. For the sea ice-ocean observations, our target quantities were 1-week to 4-week forecasts of sea ice volume (SIV) and snow volume (SNV) for selected regions along the Northern Sea Route and the Northwest Passage as well as for the entire Arctic. Our assessments assumed observations were assimilated in April 2015, with the respective 1-week and 4-week forecasting periods starting on May 1. For the atmospheric CO2 observations, our target quantities were the land-based fossil fuel emissions in the first week of June from several Arctic countries, namely Canada, Denmark, Finland, Iceland, Norway, and Sweden.

As our focus was on the observational scenarios and model error is an aspect that is specific to our model and difficult to specify, we deliberately excluded it from the assessments (together with biases in the observations). For example, we assumed that the penetration of radar and laser signals is treated correctly. The exclusion of model error emphasises the differences between observational scenarios and shows the upper limit for the impact that each scenario can achieve. We, however, complemented our assessments with estimates of the impact of model error on the simulated target quantities. As our reference is a prior case without any observations, the impact of a given observational data stream is also much higher than in a setup where it is added to an assimilation system that already assimilates a variety of other data sets, as it is the case for the Copernicus systems.

Our findings for the sea ice-ocean observations are:

- Sentinel 3 (S3) radar freeboard (RFB) outperforms CryoSat-2 (CS-2) RFB in the selected target regions relevant for marine transportation in the Arctic because of the higher temporal coverage. The larger pole hole of S3 is irrelevant as it is located too far away from shipping lanes, S3 outperforms CS-2 as well for the Arctic-wide assessment.

- When combined with CS-2 RFB, CIMR-like and CRISTAL-like snow depth (SND) products yield strong gain in forecast performance. The same holds for a typical product based on an atmospheric reanalysis. Although the differences for these assessments are small, for the respective accuracies that we have assumed CIMR shows the best performance among the three products.

- The combination of CS-2 RFB and ICESat-2-like laser freeboard (LFB) shows the overall best performance for both, SIV and SNV. This is because the assumed accuracy of the LFB (2 cm) was higher than the accuracy of the SND products. Furthermore, assimilation of the raw freeboard product is more beneficial than the assimilation of a derived product.

- The performance of a CIMR-like SST product is better than that of a traditional infrared-based SST product. Although the infrared product is more accurate, the better spatial coverage (owing to its capability to penetrate clouds) renders CIMR attractive for predicting SIV and SNV along the shipping routes. We note that only the combination of CIMR applied to the target region in the Baffin Bay shows a strong impact, because for other regions and with infrared the SST observations are too far away. The impact of SST is expected to be higher for summer conditions when most of the target regions are at least partially ice-free.

Assessments of several observational scenarios for atmospheric CO2 in terms of their constraint on land-based fossil fuel CO2 emissions in June show that an increase in the number of sites of a small surface network providing continuous in situ samples is more efficient than the reduction of its observational uncertainty or the addition of radiocarbon measurements. Further, combining the small surface network with a single CO2M satellite already provides a better constraint on land-based fossil fuel CO2 emissions in June than increasing the number of continuous sampling sites.

In addition the task makes the following recommendations:

- The provision of spatial and temporal uncertainty correlations with the EO products would be beneficial not only for QND assessments, but also for the assimilation of the products.

- The QND approach is ideally suited to assist the formulation of mission requirements or the development of EO products. In an end-to-end simulation it can translate product specifications in terms of spatio-temporal resolution and coverage, accuracy, and precision into a range of performance metrics. Alternatively, it can translate requirements on forecast performance into requirements on the respective observables. It can assess combinations of in situ and EO data (from multiple missions). This type of assessment can be performed for higher-level products (e.g. SIT or SIC) but also for more raw products (e.g. freeboard or brightness temperature). This approach is ideally suited to support the planning of future missions and should play a prominent role in the mission design.

Conclusions and Recommendations from WP3

The marine environment in the Polar Regions is changing, with this comes both challenges and opportunities. Earth Observation (EO) has a key role to play in the sustainable development of the region, and information services must be flexible in order to respond to the changing needs and conditions. Importantly they must provide much more information for the Arctic peoples and the wider society, science, private sector and decision makers.

Arctic monitoring programmes are very diverse, with many successful interdisciplinary approaches. By providing actionable information to management authorities and community members, the programmes can be used by the stakeholders, to take decisions. Web-based data platforms are increasingly used for data storage and communication.

Some of the Arctic monitoring programmes have made their data publicly available through global repositories. This type of data has been one of the major contributions to the global environmental monitoring of the Arctic in relation to the UN Sustainable Development Goals. In the end-user and stakeholder engagement of KEPLER, see deliverables D1.4, D2.2, and D2.3, and deliverables D3.1, D3.2 and D3.3 of this Work Package, a number of issues with current Copernicus information provision were identified. These include:

- It was found that there was a lack of dialogue between the broader European research community and the Copernicus Services (and Thematic Data Assembly Centers - TACs). This in turn impacts the quality of Copernicus polar products and services.
    - We highlight the TACs because as the name implies, these are the structures within the services that are responsible for assembling the data relevant to a theme. The task of assembling the data is not the role of the Marine Forecasting Centres (MFCs) as these are the users of the data being assembled by the TACs.

- Although there is a high level of in situ, airborne and oceanographic observational activity in the Arctic, projects and programmes are disconnected and there is no clear path for this data to be ingested into operational monitoring, either for WMO or Copernicus. The inability to use this data for calibration/validation again impacts the quality of Copernicus polar products and services.

- There remains significant roadblocks in terms of Copernicus' ability to deliver information near-real time (NRT) to support critical operations such as disaster management and search-and-rescue. These include data processing latencies and communications bandwidth limitations.

- There is a lack of synergy in the use of data products coming from different satellite missions. As a result there are a number of potential parameters that are not provided using existing capabilities.

- Investment into new observational technologies is being conducted at a national or international (Horizon 2020) level. However there is no clear mechanism for utilising these in the polar regions, or bringing these into Copernicus monitoring.

Suggestions for immediate enhancement of Copernicus Polar Services

These suggestions include recommendations of goals easy to achieve based on best practises that can be implemented with minimal funding required from Copernicus and its services.

- Improving communications between stakeholders and end-users is essential to better identify the end-users needs.

- Citizen science enables local stakeholders to collect data and communicate findings with greater certainty than ever before. Copernicus should promote Citizen Science to enhance and increase the number of the acquired in situ data.

Opportunities (1-5 years) for enhancing polar monitoring under Copernicus activities

Opportunities have been identified to be solved in the near future (between 1 and 5 years). They could be stated following directions or with new activities in Horizon Europe. The opportunities for Copernicus and EU identified are:

- **Community-based and local monitoring programmes** offer a strong potential for linking environmental to awareness raising and enhanced decision making at all levels of management. However, community-based programmes could provide important information, feedback and in situ data that potentially could fill the gaps and contribute in climate modelling and in research within such areas as risk management, safety, food- and water security. Community-based programmes can also be **a way to fulfill the rights of the citizens to take part in decisions** that are related to their regional and local areas and to be able to take part in knowledge sharing in order to develop and safeguard their environment.

- **To prioritise in-situ measurements for calibration and validation of the remote sensing data in the Polar Regions.** There is a desperate need to reduce the identified uncertainties associated with Copernicus remote sensing and models output polar products. By developing a framework whereby Copernicus services can better utilize European polar research assets (ie. stations, ships, aircrafts, and people) to provide needed calibration and validation opportunities for Copernicus Services products.

- Sea ice is constantly on the move in polar regions, avalanches can happen at any time, search-and-rescue operations require timely sea ice imagery and forecasts. The requirement from the end-users for a timeliness in the access to imagery, derived products and forecasts prompt the necessity for lower latency in data downlink and processing. This is **an opportunity for Copernicus Services to ensure near-real-time data (<1h) for better and critical operations in the Arctic.**

- Several remotely sensed parameters distributed by research institutions were identified which are not being served into Copernicus (15 in total). We recommend considering **those identified parameters to be distributed in the future evolution of Copernicus Services.**

- **Synergistic use of satellite missions** can enhance the accuracy of several remote sensing parameters. Yet, synergy products are typically processed by ground segments at the space agencies. Therefore, **there is the need to promote the research on satellite data synergies and distribute** the new variables through Copernicus Services. Moreover, data assimilation is the ideal approach for merging such data sets because it intrinsically ensures consistency.

- In-situ data are too sparse for validation and could be further supplemented by new technologies. The implementation and **further development on different types of unmanned observing platforms** for Polar Regions, such as Unmanned Aircraft Systems, High Altitude Pseudo Satellites, Autonomous Underwater Vehicles, need to be promoted. New sensor technology should also be further developed. Although some new platforms and sensors show promising results, they have yet to be **made available at a cost effective level** that would mitigate the costs of widespread deployment, and potential loss, in the extreme Polar Environments. **Copernicus should therefore continue to monitor and promote these developments**, and be ready to take advantage of them as technology improves and becomes more readily available.

- More effort should be done on advancing on **assimilating new satellite data** into the Copernicus NRT forecasting and reanalysis systems. Moreover, an effort should be put on studying the viability of the assimilation of satellite information at lower processing levels (short term: Level-2 and longer-term: Level-1).

Challenges to overcome in next 5-15 years

The challenges we have observed during the WP3 work package development are summarized below. We consider challenges, as the activities/goals which require more long term work, between 5 and 15 years.

- To **maximise the potential of community-based monitoring for decision making.** There is the perception that information from local people is both subjective, informal and is sometimes seen as unscientific approaches. A growing literature, and through the KEPLER project, demonstrates that data collected systematically by indeginous and community members are comparable to those obtained from professional scientists. Management authorities are sometimes slow at operationalizing or acting upon local observations in their decision making. Regardless of this, involving people who face the daily challenges and consequences of environmental challenges in monitoring can help in adapting decision making on the natural resource management to local realities in a rapidly changing Arctic environment.

- The **three polar HPCM missions** (CIMR, CRISTAL and ROSE-L) are necessary to cover the identified **high priority** environmental parameters defined by the **Polar Expert Group.**

- The **lack of temporal and spatial in-situ data in the Polar Regions is causing real problems in assessing the quality of Copernicus products** for the polar regions. The quality assurance, calibration and validation are severely limited. Acquisition and archiving of a more extensive in situ dataset, with a more active role in managing it played by the Copernicus In Situ Component is required. The increase of in situ data will grant a more robust quality assessment of satellite products and improve the geophysical retrieval algorithms.

- One of the limitations for acquiring data with unmanned sensors is the limited communications between the central Arctic and the continent. **Data communications are limited and expensive.**

- An enhanced spatial resolution of sea ice and iceberg data, with a target of 300 meters or better, is a requirement of the end users, especially from those dedicated to maritime transport. This necessitates sensors capable of monitoring at high spatial resolutions at or beyond this.

- New polar missions should **consider the extent of their polar observation hole** in the design phase, and thoroughly evaluate the trade-offs required for reducing its extent within the constraints of the mission's objectives. This is important for visible/infrared imagers, for which twilight acquisition mode should be part of the core mission requirements, and with SAR where the choice of right or left-looking configuration should be evaluated. There is the need to carefully consider twilight acquisition, and more generally polar data coverage, when designing future missions, e.g. the Sentinel-NG missions.

- Observing system simulation experiments and (computationally more efficient) **quantitative network design studies** should be routinely applied in the design of new space missions, the specification of mission requirements and the development of new types of products.