KEPLER Deliverable Report

Report on Deliverable D5.2

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Table of Contents

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Executive Summary

The **Key Environmental monitoring for Polar Latitudes and European Readiness (KEPLER)** project delivers a strategic vision for the operational integration of all relevant European capacities for monitoring and forecasting the state of the Polar Regions. This takes into account existing capabilities both from Copernicus and externally. The requirements of end-users and stakeholders living and working in or supplying Downstream Services has been central to the evaluation as this is essential for ensuring that Copernicus evolved into a monitoring programme that is relevant and delivers the necessary information to tackle the issues facing European actors in the Polar Regions, including Climate Change monitoring and prediction, waste/pollution management, safe and efficient navigation in ice-infested waters, in avoidance of environmental hazards on land, and facilitating the shift towards a low carbon economy.

Key findings are that existing, long-held, user requirements have not been addressed and that there is scope for future improvement to intensify the currently limited user uptake. This has the potential to be delivered with new satellite Earth Observing capabilities, such as the Copernicus Expansion Missions, coming online in the later half of the decade, and by greater inclusion and support for in-situ monitoring efforts, where citizens can provide significant contributions to support the overall programme through Citizen Science initiatives and thus gain a greater ownership in Copernicus. In addition, it was found that terminologies within Copernicus differ from internationally accepted practise causing confusion. Greater focus must be placed on utilising the many resources both inside and outside of Copernicus to provide stronger oversight and quality assurance of data products and information to ensure that these are relevant and fit-for-purpose to allow informed decisions and promote the accelerated uptake of new research and technological developments coming out of Horizon Europe.

The KEPLER roadmap moves us towards a comprehensive European end-to-end operational system by addressing design aspects, such as the set of required observations, and the potential inclusion of prior information to better constrain sparsely observed areas/variables. It suggests strategies to close gaps in our current forecasting capabilities, and ways to develop and sustain the observing system.

Context of deliverable within Work Package

This report is a synthesis of the work and results from Work Packages 1 to 4, and of Task 5.1 of KEPLER. Workshops and round table discussions from WP6 fed into WP 1 to 4, so therefore this deliverable is a culmination of the project work.

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Introduction

The KEPLER roadmap is intended to deliver a strategic vision for the **operational integration of all relevant European capacities** for monitoring and forecasting the state of the Polar Regions. The main focus is on land and marine capabilities delivered through the Copernicus services. The roadmap builds upon our in-depth assessment of Copernicus land and marine capabilities in the light of present and future satellite-based and in-situ data provision. It also **synthesizes into this report the linkages** between different components and programmes, and provides **guidelines to address the gaps** in overall service that have been identified by the stakeholders.

To ensure the KEPLER roadmap **covers all components** of the system, WP1[1] focused on the user needs and requirements, WP2 provided an analysis of the current (and future) Copernicus system, WP3 identified the obstacles to research and capacity gaps with respect to observations, and WP4 concentrated on sea-ice mapping and forecast capabilities. This WP (WP5) **synthesized this information** to produce the roadmap, as well as entraining knowledge on the **observing system** (both **in-situ** and **satellite**-based), **forward models/observation operators**, the **modelling/assimilation/network design** capabilities, and the **data handling** capabilities (exchange, access and interoperability) including the **dissemination** of outputs. Together this makes up a complex system that has been **designed to operate in such a way as to support** the **varied needs** of **climate change monitoring and prediction**, **waste/pollution management**, **safe and efficient navigation** in ice-infested waters, and facilitate the shift towards **a low carbon economy**. The roadmap moves us towards a European end-to-end operational system by addressing design aspects, such as the set of **required observations** (including **uncertainty estimates**, **representation scales**, **across-variable error covariances**), and the potential inclusion of **prior information** to better **constrain sparsely observed areas/variables**. It suggests strategies to **close gaps** in our current **modelling capabilities** and ways to **develop and sustain** the observing system.

To capture, in schematic form, the information flow incorporating the Copernicus Services, a pyramid diagram which consists of several layers has been developed (Fig.1). At the left of the pyramid the user needs are located, reflecting the requirement that the Services should be strongly user-driven. Note that the users are interacting in various ways (e.g., user-surveys, round-table discussions) with each layer of the pyramid indicated by arrows from the users to each layer and vice versa. The first layer of the pyramid is a layer representing the acquisition of observations; including satellite, air, ocean, ice, and land-based measurements. Boxes in the pyramid figure underlaid in dark blue are performed by the Copernicus services (Note: in-situ observations are currently not directly compiled by the Copernicus). The second layer is the data assembling layer where the raw data is processed. It includes the quality controlling and generation of (gridded) data sets used by the Copernicus Services for monitoring and forecasting but also the generation of Climate Data records (CDRs) and Essential Climate Variables (ECVs). Above that layer the Copernicus Services that KEPLER is addressing are located, including the Copernicus Land Monitoring Service (CLMS), Copernicus Marine Environment Monitoring Service (CMEMS), and Copernicus Climate Change Service (C3S). On the right of the pyramid diagram a box denoted NWP (Numerical Weather Prediction) is added to symbolize the need for atmospheric forecasts by the Copernicus Services. While the atmospheric reanalyses are

[1] KEPLER is divided into seven Work Packages (WP), which work seamlessly together to deliver an improved European capacity for monitoring and forecasting the Polar Regions.

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distributed by C3S that include globally the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5), and regionally the Copernicus Arctic Regional Reanalysis (CARRA), atmospheric short-term forecasts are not part of Copernicus but delivered (mainly) by ECMWF. In the service layer the data from the processing layer are used by models and data assimilation systems to generate reanalyses and forecasts, and these provide output products either directly to the end-users or indirectly via Downstream services. Recommendations on the further development of Copernicus Services include recommendations on future assimilation systems which a separate chapter is dedicated to. Impact assessment studies are linking all layers from 'Observation System' to 'Production' as they assist in the design of the observing system to improve forecast capabilities (marked in Figure 1 by a brace). The power of impact assessment studies is demonstrated in KEPLER by a specific method with a focus on Copernicus High Priority Candidate Mission[2] (HPCM) for marine and land assessments.

We added a 'Production' layer, layer 5, because recommendations and suggestions concerning products for sea-ice mapping, reanalysis and forecasts have been made by KEPLER. A 'Delivery' layer, the fifth layer, is divided into targeted and cross-cutting product delivery. The former is not part of Copernicus, but a cross-cutting data delivery service known as Copernicus' Data and Information Access Services (DIAS) that has been considered by KEPLER. A discussion on the current design of the five DIASes is added below with a focus on the Arctic. Ideally, all information of the different layers should be available through one data centre which would ideally, be an extension of the DIASes.

The layer above the delivery layer is given to 'Downstream Services'. It is designed for the specific needs of users, making access to data and information easier or generating specific user-driven services. Within this report we provide three exemplary user stories to demonstrate the needs of user-driven services, but also to point out the actions that have to be taken to establish these services. The user stories developed in KEPLER are (i) 'EO based decision making for cost-efficient and safe maritime navigation', (ii) 'EO based decision making for reindeer herders', and (iii) 'EO based marine emergency response'.

Different organisations might have different roles in the diagram. For instance, the national Ice Services have a primary role of supporting maritime safety through delivery of Downstream services, and this is achieved through assembling the relevant data from the observation systems and processing layers, and preparing analyses based on it.

[2] The HPCM are renamed to 'Copernicus Expansion Missions' but we will still use HPCM for consistency with the other deliverables.

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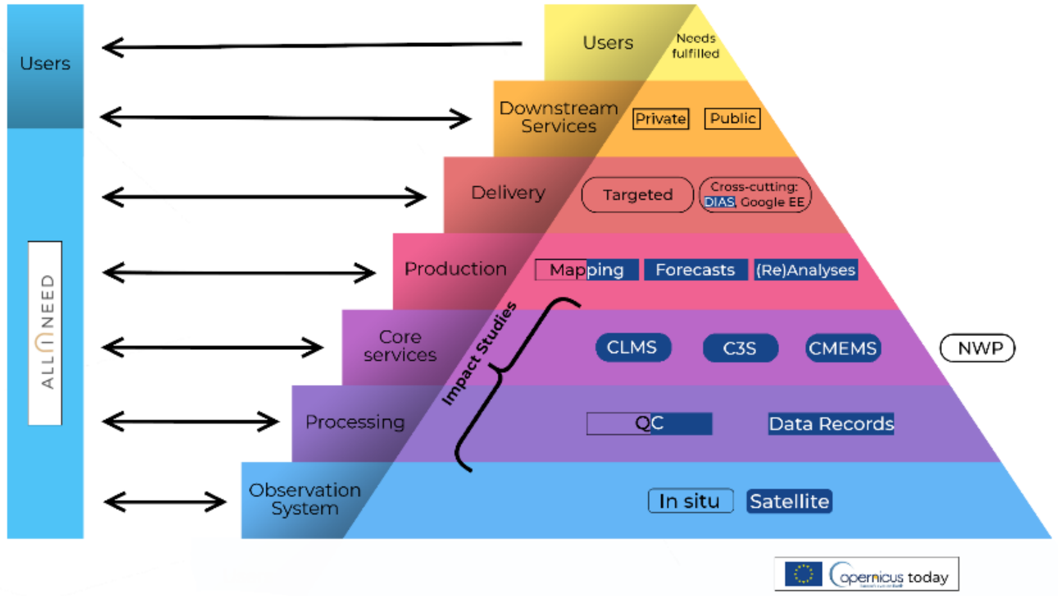

Figure 1: A schematic diagram illustrating the information flow within an end-to-end system. KEPLER has developed suggestions and recommendations for the layers that make up this schematic. Boxes with dark blue backgrounds are covered by Copernicus today. Boxes with half dark blue backgrounds are covered partially by Copernicus. QC=Quality Control.

This report first provides a general chapter about ‘Terminology’ before summarising KEPLER’s 'Overarching recommendations and suggestions’. To make it easier for the reader to follow the recommendations and suggestions they **follow the same naming scheme as the pyramid diagram. Furthermore, they start from the bottom of the pyramid and work their way up. For easy orientation we have coloured each recommendation title in the same colour as the pyramid layer it addresses.** The user stories are described thereafter. The report ends with a chapter where the pyramid diagram is expanded by traffic lights symbolizing the interactions of the different layers in and around Copernicus that are working well, could be improved, or running not well according to KEPLER’s findings.

Terminology

The KEPLER team consists of marine navigators, social scientists, in-situ and satellite observers, and experts on physical and biogeochemical modelling, data assimilation and forecasting on different spatial and temporal scales. **As the terminology used by this multi-sectoral team can have different meanings to different** organisations (and the sectors they represent) the following terms should be used with care, and ideally be explained clearly in the context they are used:

- Use of terms like ‘**near-real-time**’ (NRT) and ‘**high resolution**’: In marine navigator’s understanding this means within tens of minutes or less, and spatial scales of 300m or even less. In the understanding of satellite observers, it means within a few days and spatial scales in the order of at least 1km (except for SAR-based products). The understanding of modellers

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with respect to NRT agrees roughly with the understanding of satellite observers but in their understanding high-resolution means scales of (currently) about 1 to 5km.

- Use of the term **'operational'**: The concept of 'operational' varies between World Meteorological Organisation (WMO) and Copernicus documents. For the WMO, 'operational' is defined as the routines and infrastructure that produce meteorological services, mandated by national authoritative services that are responsible for providing information to support life and safety. This is determined by international agreements of different executive bodies and the services are required to provide a clear, consistent, and standardized framework based on fundamental user requirements, that can be adhered to by all wanting to contribute. Routines include explicit levels of quality management and control, compliance requirements and delivery mechanisms of the services. The WMO operational system definitions are required to be open and transparent, and they are found in various regulatory documents for the relevant domains. In contrast, in Copernicus's nomenclature, 'operational' is defined as the routine production of data by services. Levels of quality and support are determined by the individual data producers. Although Copernicus services can deliver data, they are designed for intermediate downstream users and researchers. The services provide a platform that organizes data production and dissemination and aligns with the framework setup at data centers, rather than end-user service providers. There is no requirement to provide 'operational system' definitions for Copernicus products.

- The concept of '**latency**': It means the delay between data acquisition and availability but depends on the user. It makes a large difference if available at a ground segment or at remote areas or on a ship.

- The expressions **tactical, strategic, short-term, and long-term** are also prone to misinterpretation. See Fig. 2 how the terms are understood in KEPLER for marine operations.

- **Parameter versus variable:** Parameters are by definition "a set of facts or a fixed limit that establishes or limits how something can or must happen or be done" (Cambridge dictionary). However, the term 'parameter' is often used to describe in-situ data or satellite products although they are variable in space and time. In the roadmap, we will use 'parameter' only as defined above, e.g. for values used in parameterizations.

- Starting from a well-established cross-disciplinary inventory of climate variables, we considered **Essential Climate Variables** as defined by the WMO's Global Climate Observing System (GCOS, https://gcos.wmo.int/en/essential-climate-variables/ecv-factsheets). For ocean variables, we have considered the Global Ocean Observing System (GOOS) list of Essential Ocean Variables (EOVs) www.goosocean.org/eov instead of the ECV list from GCOS. There are subtle differences in terminology between GCOS and Copernicus documents (Table 1). It would be desirable to homogenize the wording across different programmes.

GCOS	Copernicus	Example
Variable	Product	Sea ice
Product	Variable	Sea ice concentration

- **Reprocessing:** Typically this is performed to derive a temporally and spatially consistent

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observation record, and involves the use of Earth Observation (satellite or in-situ) retrieval algorithms and possibly spatial and temporal interpolation algorithms but not data assimilation per se. This type of observational product is often referred to as satellite Climate Data Records (CDRs) (Yang et al. 2016). CDRs are expected to cover as long a time period as raw satellite observations exist; the longest is currently 40 years long (the late 1970s). They should typically be longer than 20 years. CDRs can be continuously updated by Interim CDRs. CDRs require that Fundamental CDRs (FCDRs, long time series of calibrated raw satellite observations) are available. Thematic CDRs extend the climate record further for some parameters by blending the satellite record with earlier in situ or airborne observations, and sometimes reanalysis model output.

- **Reanalysis:** The application of a data assimilation procedure (including various observations into a dynamical numerical model) for a long past period of time. Examples include the ECMWF ERA-Interim and ERA5 reanalysis. A reanalysis in CMEMS has a typical duration of 25 years (starting in 1993 until the year Y-1). The C3S reanalysis ERA5 lasts from 1950 until 3 months before the present time (i.e., about 70 years). Satellite-based CDRs (aka reprocessings) are typically assimilated into these reanalyses.

- The above **distinction between reprocessing and reanalysis** motivated by the perspective of short-term forecasting and climate scenarios, which require the use of numerical models and data assimilation: a reanalysis and a data assimilative forecast will use similar machinery and have therefore been assembled in the CMEMS and CAMS inventory tables (D 5.1). However, this distinction does not apply to the CLMS which, as defined above, only provides reprocessed variables. CDRs have a value both on their own (data-driven analysis) and as input to model-based reanalyses.

- **Data users:** To understand user requirements, it is critical to be able to identify the different levels of users. By mapping the evolution of information from service providers to end-users, we can define user groups and explore what kind of services and data products are relevant to them. Fig. 3 illustrates how information is managed and utilised by the various different data users and stakeholders

- **Services**: In Copernicus, the term 'service' is not describing exclusively the delivery of a portfolio of data products but is connected to a set of commitments for the core services, e.g the guarantee that the services will be operating continuously, the implementation of help desk, and the conduction of user surveys). This contrasts with the WMO definition which includes dedicated user support to enable informed decision making with 'fit-for-purpose' information products, quality management in service information provisions, following standards for competence and qualification of personnel, accelerated uptake of advanced technology for service accessibility, and systematic evaluation of service benefits.

The implications of this lack of conceptual clarity in terminology can introduce ambiguities on all levels of interaction in an end-to-end system. The conceptual clarity in terminology has to be improved on all levels. Until this is resolved, descriptions for products developed for Copernicus are recommended to be explicit about the terminology applied.

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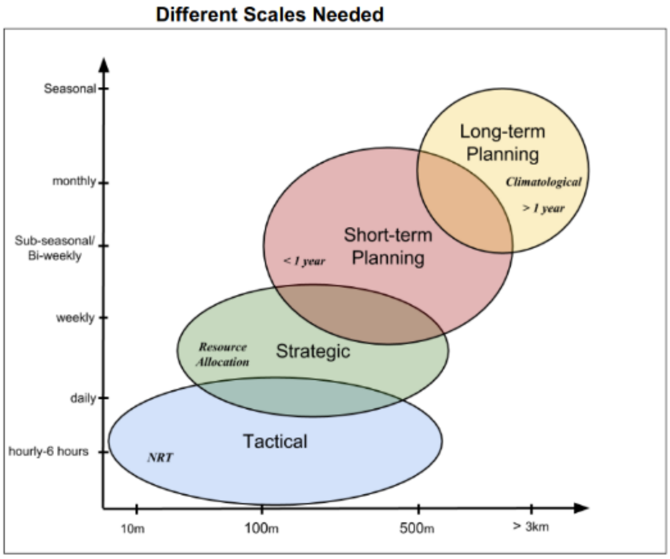

Figure 2: Definition of the terms tactical, strategic, short-term, and long-term in KEPLER with respect to marine operations.

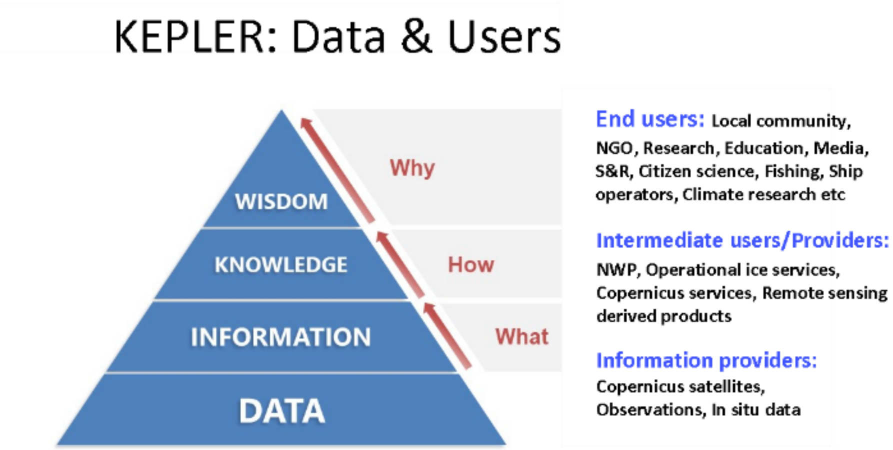

*Figure 3: The model above is based on a [DIKW pyramid] representing the structural relationships between **d**ata, **i**nformation, **k**nowledge, and **w**isdom and divides data users and stakeholders into information providers, intermediate users and end-users.*

Overarching recommendations and suggestions across all work packages

As mentioned previously the KEPLER WPs provided recommendations and suggestions to improve the end-to-end service, some of which are generic, and have been made in several work packages cross-cutting the Copernicus Services. For some, recommendations and suggestions no consensus could be reached between the wishes of the stakeholders and, e.g. the scientist performing the forecasts in the KEPLER group. In these cases the demands could be fulfilled within the next multiannual financial framework for 2022-2028, known as Copernicus 2. These recommendations and requests comprise:

- **Improved spatial and temporal resolution,** and reduced latency of model forecasts and data: The KEPLER user needs review has yielded a strong request for high spatial resolution (better than 1 kilometre) for remotely sensed observations and forecast model outputs (D1.1- Table

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13, Figure 19 and Figure 21, D1.2, D2.2, D4.1- Table 1 and 2, D4.3). **Remark:** It is unlikely that these requests could be fulfilled within Copernicus 2 but it might be possible to fulfil the demand for selected variables. We recommend **fostering new ways to fulfil the demand**s, e.g. by deep learning methods (see as well the more specific recommendations below).

- **Continuity and improved capabilities of satellite observations** are crucial. Continuous time series of European satellite-based estimates of both sea ice concentration and sea ice thickness are of utmost importance for operational users and climate research. Of the three Polar HPCMs, Copernicus Polar Ice and Snow Topography Altimeter (CRISTAL) and Copernicus Imaging Microwave Radiometer (CIMR) have the highest potential to extend the long-term climate monitoring of the changing polar sea ice. With the current timeline with launch dates at the end of the 2020s, we must expect gaps to the current missions (e.g. CryoSat-2, SMOS). The gaps between missions should be made as short as possible. The third HPCM mission, L-Band Radar Observing System for Europe (ROSE-L), has the highest potential to deliver improved capabilities for automated high-resolution sea-ice and iceberg mapping. In combination the three HPCM missions together provide the potential to deliver a further 15 variables that are not currently monitored by the existing Sentinel constellation.

  Just recently a community letter of concern regarding the imminent gap in satellite polar altimetry, which is likely to occur in the latter half of this decade, was published. Solutions for (partly) bridging the polar altimetry gap should be deployed (including fully exploiting Sentinel-3 sea-ice capabilities and/or dedicated polar airborne campaigns).

- **Co-development, co-production, and co-management** of services: The KEPLER user needs review has shown a strong interest in the co-development, co-production, and co-management of services in all investigated sectors from marine transportation to community-based monitoring, and the acceptance of these principles is increasing on all involved levels ranging from the shipowner, community members, scientists, government and other funding agencies. **We encourage all actors to engage all levels of users via Co-development, co-production, and co-management strategies.**

- The **future evolution of a Copernicus Service has to take into account all components**. The future programme should ensure the continuity of information provision by the current Copernicus Services on a pan-Arctic scale. This concerns the variables already present in the current portfolio but also the monitoring of the data quality and the data policy.

- Since the foreseen lifetime of **ESA's Climate Change Initiative (ESA-CCI)** projects is relatively short, extensions to the current Copernicus framework contracts should be considered, such that the continuity and stability of CDRs are guaranteed by Copernicus Services, preferably by C3S.

- **Better coordination and integration between Copernicus Services:** The user needs review of KEPLER noted that better coordination and integration between the individual Copernicus Services are needed. Often variables delivered by one Service are not consistent with variables delivered by another Service and users, in general, do not have the expertise to select the best-suited products from the different services.

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- **In-situ data** are extremely **scattered among several platforms,** if present at all within Copernicus. For instance, no sea ice in-situ data are available to date from Copernicus Services. It is suggested by many users to establish a "one-stop-shop" for the Polar region under the leadership of Copernicus.

- **"User-survey fatigue"** - A lot of user surveys have been undertaken in the last 15 years but the results have not been properly disseminated (e.g. in peer-reviewed journals), or available to review. As a consequence, in recent years end-users have expressed some frustration about the impact user surveys have because it is unclear if the information is used to improve services. Better dissemination and cross-organisational coordination of user surveys are recommended.

- Automation of product generation that is currently generated manually: For instance, ice charts used for marine navigation are created mainly manually from raw satellite and in-situ data by human analysts. Ideally, automated product generation would reduce the subjectivity and latency of the products and give the analysts more time to spend on detailed analysis for specific users. **However, the current suite of automated products for sea ice has not yet demonstrated the capability to provide products that could be used to support operational ice services.**

On 'User needs'

A comprehensive list of recommendations from WP1 can be found at https://kepler-polar.eu/deliverables on 'Maritime and research sector needs' (D1.1), 'Community-based observing and societal needs' (D1.2), and 'Climate and weather forecasting needs' (D1.3) together with a 'Stakeholder requirements synthesis' D1.4. Here we highlight some of the recommendations and suggestions:

- **High latitude communications** do exist in remote Polar Regions, but continue to be **extremely limited**. Users operating in remote land or sea areas without a stable internet connection may find it difficult to access critical information and data for situational awareness. Although we acknowledge that this cannot be solved by Copernicus alone, actions should be taken to improve the situation. At least the awareness of the problem should be raised in the Copernicus programme to the relevant bodies, e.g. European Defence Agency (EDA) Governmental Satellite Communications (GOVSATCOM).

- **A recurring recommendation from users** is the need for information that is **easily understood and available in familiar and standard data formats**. This includes being able to easily access the information from multiple sources without having to encounter bandwidth-intensive formats and issues. The standard format usually includes Encoded Formats (ENCs), ice charts in various standard graphics formats such as JPG, GIF, and PDF, and JPEG2000 for raw satellite data when used.

- The increase of sea ice information provision should include **better dissemination, tools and training of different data products for non-specialists.** Issues with end-users' understanding of multiple products have been a **critical challenge regarding the user uptake of new products**. This training should take place in collaboration with the existing intermediate-user

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service providers.

More specific on **maritime operational needs:**

- The first mandate for **sea-ice services** is to constantly update their products with the **latest satellite observations** available in order to provide the **most accurate routine products** to support maritime safety. Operational services have the flexibility to modify their products while maintaining compliance with the WMO standards. Since the launch of the Copernicus Sentinels beginning in 2014, the information provided to the marine operational community has greatly improved due to the increase of higher spatial and temporal resolution from different sensors, as well as third-party services that develop value-added products for users. However, **end-users continue to require** essential sea ice information (i.e. sea ice type, deformation and ridging information, presence of ice at the edge and coastal zones and detection of leads) for operations in sea ice encumbered areas, as well as more accurate sea ice forecasts on shorter time scales.

More specific on **Indigenous people needs:**

- Services for Indigenous people should be available, also in **Indigenous languages**, such as the Saami, on hand-held portals and devices. The coverage and affordability of services should cover all areas of the Indigenous home areas, especially in the context of **emergency services**.

- Advancement of technological solutions should be **mindful of the "slow culture" of Indigenous communities and traditions**. Data is not always openly accessible and **intellectual property rights, Indigenous sacred engagement** with their landscapes and places, harvest locations and other cultural aspects should be followed. All stakeholders should be aware of the Ottawa Principles of Indigenous Knowledge.

More specific on **Climate and weather forecasting needs**:

- In addition to continuity, there are **high expectations toward improved (and new) sensor technology**, parameters and expected outcomes of sensors and products. For example:
    - The i**mproved capabilities of CIMR and CRISTAL**, compared to previous sensors, will help to better address intermediate user needs with respect to **resolution and accuracy** of sea-ice concentration and thickness data.
    - The inclusion of L-band SAR from ROSE-L and hybrid/compact polarimetry SAR from Sentinel-NG for operational sea ice mapping will **allow for suitable automation for operational ice services** over what is capable with only the current SAR in C-band and dual-polarisation from Sentinel-1.
    - Significant **advances are also expected** from the future availability of observations that provide information on, e.g., **wind profiles, snow on sea ice, and surface energy fluxes, and observations with reduced "polar holes"**.

- **Making more of the existing** routine (research) **observations** available for NRT applications should have **high priority**. **Aspects include more research** on **observational impacts studies** and i**ntensification of calibration/validation (Cal/Val) with appropriate in-situ data**.

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- There is still a **clear gap** between what **model-based forecast systems** can deliver and what polar (marine) **end-users need**, in particular in terms of resolution. **Continuous investments** into the development of **high-resolution forecast systems** and appropriate **data assimilation techniques** (including the development of specific Polar regions observation operators allowing for assimilation of L1/L2 satellite products) are required to generate more user-relevant services.

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Layer 1, Observation Systems: 'Identification of research and capacity gaps' with respect to observation

A comprehensive list of recommendations and analysis of gaps from WP3 can be found at https://kepler-polar.eu/deliverables/ on 'In-situ observation gaps' (D3.1), 'New and novel observation sensors and techniques' (D3.2), 'Gaps in terms of space-based capabilities' (D3.3), and 'Synthesis report on research and capacity gaps (observational network design)' (D3.4). Here some of the most urgent research and capacity gaps are highlighted:

In-situ observation gaps

The role citizen science can play in the expansion of Copernicus' in-situ monitoring priorities and how the in-situ observational marine and terrestrial research community can better contribute to Copernicus' in-situ Component in the Copernicus 2 period (2022-28) are investigated and assessed.

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. Here, we will 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 advance scientific knowledge, and increase 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 usable by CS** projects, and (b) ensuring **CS projects can enhance 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 Copernicus Services to capitalize on the broad potential of CS we suggest:

- Copernicus Services should make a greater effort to **highlight and grow the number of CS** projects using their products or validating their products.
- **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 **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 maintaining the capabilities of the Copernicus Services.

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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.

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.

Deliverable 3.1 provided recommendations for the increased use of available in situ data in validating products as this was clearly not part of the existing product development and maintenance routines that were examined (D3.1 [Table 3]). Use of ground truth should underpin any developments using EO data and allows for products to be assessed against real-world observations. It was noted that although in situ data is sparse there are a number of datasets available that could already be utilised for this purpose and will require innovative approaches to link them into the overall Copernicus services structure (i.e. following the example of how weather stations are integrated into forecasts).

This report also called for peer-reviewed journal article equivalents of quality information documents. This would provide a mechanism for independent review, but would be reliant on journal articles being put forward at one's own initiative. It would therefore be a more formalized procedure if an expert group should be set up within Copernicus that contains scientific and technical experts not connected to services or data production, that has the capability to monitor service performance and development, and can advise where linkages should be made to new technological developments coming out of the research programmes, e.g. Horizon Europe. Based on a cursory product review, such as performed in WP4, the outcomes revealed that the majority of products developed for the Arctic were demonstrably not supported by well executed quality control systems (4.1 [Table 4]).

We found that there was a significant **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** on the Quality Information Document (QUIDS) with respect to the Copernicus Services polar products should be performed.
- **Establishing an expert group, independent of Copernicus services and their data producers,** to oversee the Quality Control and Quality Assurance in Copernicus products. Persons included in this group should have a demonstrated level of competence and expertise to ensure that comprehensive audits can be provided for the full catalog of products provided in Copernicus services.

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- **Prioritising the use of *in situ* measurements for Cal/Val** in the Polar Regions. This is desperately needed to reduce the identified uncertainties associated with Copernicus Services polar products. A recommendation to establish a Fiducial Reference Measurement (FRM) system, specific for polar regions requirements.
- **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 that includes criteria and procedures for product developers. 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. Independent peer-review is the bedrock of science.
- Providing recommendations from Copernicus to the European research community, clearly identifying where **additional research efforts** need to be focused to i**mprove the accuracy or Cal/Val** data for a particular product.

New and Novel Observation Sensors and Techniques

The objective 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 close-range systems and sensors 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 uncrewed 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 Uncrewed 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 appropriate routines need to be established prior to using them for systematic 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.

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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 have 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 the 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, antibiotics, drugs and drug metabolites, small organic molecules including toxins and endocrine-disrupting chemicals.

Although these new platforms and sensors show promising results, most have yet to be made available at a cost-effective level that would mitigate the costs of widespread deployment, and potential loss, in 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.

Space-based Capabilities

The analysed variables of the Copernicus' **space-based inventory** for **land** are: snow cover fraction, snow water equivalent, snowmelt, snow depth, avalanches, snow albedo, lake ice, permafrost and soil moisture; for **sea ice**: concentration, thickness, drift and deformation, ice type, ice edge position, snow on sea ice, surface albedo, characteristics of melt pond fraction, and ice surface temperature; for the **ocean:** surface biogeochemical compounds and light, sea surface temperature, sea surface salinity, sea surface height, surface currents, and surface stress. Greenland and Antarctica **ice sheets and glaciers** are **not covered**, since they are out of the scope of this project. **Atmospheric** variables are only considered if relevant for surface fluxes.

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We have provided a summary of the Copernicus products of Polar regions that are **currently available in D3.3**. In addition, we **highlight** marine and land variables that are observable using remote sensing techniques with acceptable accuracy but **are not covered in CMEMS and CLMS** (Table 1).

It is recommended to include the 15 remotely sensed variables of Table 1 in the future evolution of Copernicus Services.

A review of **the variables which could be acquired from future missions** (already planned or under discussion) with a special focus on the polar EU HPCM missions (CIMR, CRISTAL, ROSE-L) is performed. The Polar Expert Group (PEGIII) defined several high-priority environmental variables which should be remotely sensed in the future to improve the monitoring and forecasting capabilities of the Polar Regions. Table 2 depicts the variables which can be acquired by each of the polar HPCM satellites.

Additionally, the **potential for synergies** to improve the quality and resolution of remote sensing products for the Polar Regions are evaluated for current and future satellites. Synergies are achievable by combining data from satellite instruments operating on different frequencies and wavelengths, in passive or/and active modes, with different spatio-temporal resolutions, and different penetration depths, thus having different sensitivities on the geophysical quantities. We note that exploiting multi-sensor synergies in the retrieval procedure can help to avoid typical ambiguities of single sensor retrievals.
Some of the results are listed below:

- **18 potential synergies** of different types of sensors are presented, most of them already demonstrated their value in the scientific literature. From those**, only 4 will be operational in Copernicus by the end of phase 1 (end of 2021) (Table 3)**.

It is strongly recommended that Copernicus promotes the production and distribution of the new improved products that utilize synergies, especially the ones with a high impact for intermediate and end-users.

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Sea Ice	Sea Ice Age
	Melt pond fraction
	Sea ice Albedo
	Lead fraction
Land	Lake ice duration
	Lake ice thickness
	Snowmelt
	Snow depth
	Snow avalanche monitoring
	Permafrost
	Land water chlorophyll and turbidity
Physical Ocean and Sea state	Surface currents
	Surface Stress (Wind)
	Wave Spectra
	Ocean Albedo

Table 1: Remote sensing products not distributed by Copernicus currently but recommended to be included in the evolution of Copernicus Services.

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1. Floating ice	2. Glaciers and ice caps	3. Ice Sheets	4. Snow
Sea Ice type	Surface velocity	Grounding Lines	Snow Water Equival.
Iceberg detection	Extent	Surface velocity	Extent/Fraction
Ice extent, fraction and concentration	Mass balance	Extent/Calving Front	
Sea ice (iceberg) drift		Surface melt extern	
Sea ice thickness		Mass change	
Surface Temperature			

CIMR
CRISTAL
ROSEL

Table 2: The parameters that can be acquired from 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.

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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, SST**	**SIT, ice type**			
Optical (e.g. CHIME)	**SIC, ice type**	**ice type,** MPF		**Phytoplankton groups, phytoplankton dynamics ***	snow extent, snow wetness. **snow avalanche risk,** 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**	

Table 3: *Matrix of potential synergies which could be put in operation with the current satellites and the future HPCM satellites (the CO2M HPCM mission is not considered in this table, however, CO2M potentially links the three Copernicus services CMEMS, CLMS and C3S, see below). The synergies mentioned are already tested experimentally. The green boxes are synergies for land applications, light grey indicates ice and sea applications. Text in red means 'in operational' in Copernicus phase 1 (until 2021). Parameters with high impact for intermediate and end-users are marked in bold. PMR= Passive Microwave Radiometer, RA= Radar Altimeter, IR= Infra-red Radiometer, SAR=Synthetic Aperture Radar. *Synergy between optical multispectral (MODIS, S3) and high spectrally resolved Ultraviolet-Visible-Near-Infrared light imaging spectrometer atmospheric sensors, like S5P, S4 or S5, or hyperspectral CHIME or PACE.*

Summary of conclusions and recommendation on 'Identification of research and capacity gaps' (D3.5)

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 make decisions. Web-based data platforms are

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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 remain 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 Europe) 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 practices 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 acquired in-situ data.

Opportunities for enhancing polar monitoring under Copernicus 2 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:

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- Community-based and local monitoring programmes offer a strong potential for linking environmental monitoring 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 to 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 polar remote sensing and model output 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.

- operating in the polar regions can be challenging, sea ice is constantly on the move in polar regions, avalanches can happen at any time, as a result search-and-rescue operations require timely access to imagery and forecasts. The requirement from the end-users for timeliness in the access to imagery, derived products and forecasts prompts the necessity for lower latency in data downlink and processing. This is an opportunity for the Copernicus Space Component and 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 uncrewed observing platforms for Polar Regions, such as Uncrewed 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 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 made on advancing on assimilating new satellite data into the Copernicus NRT forecasting and reanalysis systems. Moreover, an effort should be put into studying the viability of the assimilation of satellite information at lower processing levels (short term: Level-2 and longer-term: Level-1).

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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 indigenous 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 variables defined by the Polar Expert Group.
- The atmospheric HPCM mission CO2M monitors atmospheric greenhouse gases and is designed for quantifying surface-atmosphere exchange fluxes of carbon (i.e. the CO2M instrument is capable of measuring both atmospheric CO_2 and CH_4). Both these greenhouse gases are highly relevant for Arctic regions and the CO2M mission provides a link between the marine and land services by the integrating capacity of the atmosphere for the greenhouse gases. Both land and marine processes contribute to the atmosphere to climate change - carbon cycle feedback by e.g. thawing of permafrost (submarine and terrestrial) and subsequent releases of GhGs. Current data assimilation systems are still limited in their ability to exploit the CO2M data in such a synergistic mode.
- 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 autonomous sensors is the limited communication bandwidth 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 those dedicated to maritime transport. This necessitates sensors capable of monitoring at high spatial resolutions at or beyond this.
- Also the launch of the HPCM CHIME can fill the gap of missing land, ice (snowgrain size and its albedo) and inland water parameters. It hyperspectral data can potentially

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be used to quantify surface snow grain size distribution, physical snow properties such as albedo, topsoil organic carbon relevant for the carbon stored in Arctic peatlands and permafrost regions and to derive phytoplankton groups and sources of dissolved and organic material in polar lakes and coasts.

- 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 a twilight acquisition, and more generally polar data coverage, when designing future missions, e.g. the Sentinel-NG missions.

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Layer 2, Processing: Climate Data Record - Improved Sea Ice ECV Records

The status of the **Sea Ice Essential Climate Variable** (ECV) and its current implementation in Europe is analysed with the requirements for multi-decadal, error-characterized and time-consistent satellite-based data records. The focus is on the Copernicus Services (CMEMS and C3S) and other contributing agencies (incl. EUMETSAT OSI SAF and ESA CCI).

Recommendations:

- "**The Sea Ice ECV is more than Concentration and Thickness**": Recognize that the Sea Ice ECV is multivariate and allocate **enough funding** to its development so that all ECV products, and all EO technologies, can mature. All ECV products need repeated cycles of R&D. The current structure of the GCOS Sea Ice ECV (a unique ECV with many sub-variables) is detrimental to the development of many required Climate Data Records. It should evolve. In the meantime, the ECV products not yet recognized by GCOS (see below) should still be developed.
- Some **key missing products** (or products on which R&D is needed) are: **melt-pond fraction**, **age/type**, **snow-depth** (in particular to support thickness retrievals), **albedo**, and **lead fraction**. Climate data records of **drift** exist or are being prepared, but new R&D cycles will be needed to further mature them.
- **Coordinate the R&D and production agendas** of the main Sea Ice ECV actors (EUMETSAT, ESA CCI, C3S, and CMEMS). There is enough work for all actors but the (perceived) lack of coordination makes it difficult to get an overview of which R&D is committed by the different agencies. The teams and institutions that actually perform the R&D and production under contract for the funders should also be part of the coordination. We suggest organizing an open workshop on "monitoring the Sea Ice ECV in Europe" to gather funding agencies, the production services, and the research community at large (including key users) to prepare a roadmap.
- **Synchronize the data and service catalogues** of Sea Ice ECV observations in CMEMS and C3S. CMEMS and C3S together cover the four variables of the GCOS ECV, but the catalogues are not synchronized and it is difficult for the users to 1) find the data, and 2) trace it to the original producers.
- On Copernicus services CMEMS and C3S: gather and **make available ECV product requirements** that are specific to their use area (including assimilation in current and future analyses and downstream services) and thus **go beyond the requirements of GCOS** (e.g. higher spatial resolution, shorter latency, swath-based products). This will allow designing ECV products fulfilling the requirements of Copernicus.
- Europe **lacks a coordinated collection** of in-situ data in sea-ice-covered regions. The In-Situ TAC of CMEMS does not hold such data. For the purpose of validating ECV products, a focus of the in-situ service should be the temporal extent of the catalogue, and strict quality control. Tools should be developed and made available that can advect on-ice measurements (e.g. using model-based or satellite-based sea-ice drift products) to **allow spatio-temporal collocation** with asynchronous airborne or satellite-borne observations.
- **Satellite data rescue** should be conducted as an international endeavour to **extend ECV time-series back in time**. Recently, USA ESMR Nimbus-5 (1972-77) data were rescued and are being

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exploited as part of ESA CCI+ Sea Ice and C3S Data Rescue projects. Likewise, the archives of other heritage satellite missions should actively be unearthed, digitized, and quality controlled, because time is pressing to save such early data from being damaged or erased. For the Sea Ice ECV, satellite missions such as ESMR Nimbus-6 (USA), and SHF Meteor-Priroda (Russia), both of the mid-1970s, should be rescued. **In Europe**, retrieve and calibrate the **early Scatterometer and SAR data from the ERS missions**; such activities can be coordinated between C3S, ESA, and EUMETSAT. Internationally, the CEOS CGMS WGClimate has a role to play. **Fundamental Climate Data Records** should be prepared once the data is rescued.

- Many aspects of the sea-ice and snow **radiation emissivity and scattering are still poorly observed or modelled**. This limits our ability to progress in developing improved satellite algorithms and improve the accuracy of the Sea Ice ECV products. Continue the development of full-fledged and efficient emission and scattering models for sea-ice and snow. Community models - such as the Snow Microwave Radiative Transfer model (SMRT) - should be preferred, ideally coupled and reconciled with radiative transfer models for the atmosphere and ocean surface. These observation operators should be implemented so that they can be efficiently integrated within assimilation schemes of NWP and climate models (that predominantly use the Fortran programming language). This activity fits well the preparation for the High Priority Missions (CIMR, CRISTAL, and ROSE-L).

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Layer 2, Processing: On the status of data assimilation

The status of data assimilation (DA) was analysed and suggestions for future variables to be assimilated and their level of processing are given.

The variables currently assimilated in CMEMS forecast models and the remotely sensed variables recommended in the future to be assimilated are summarized in Table 4. The specific problems faced by each parameter are explained in report D3.3.

Remotely sensed variables currently assimilated in CMEMS
Sea Ice Concentration (PMR)
Sea Surface Temperature (IR)
Sea Ice Thickness (RA, LA, PMR)
Ice Drift (PMR)
Chl (VIS)
Sea Surface Height (RA+Grav.)
SST (from PMR)

Table 4: Remotely sensed variables currently assimilated and suggested to be assimilated in future in CMEMS. Colour coding: Severely limited, medium level of limitation, small limitations, not sufficiently documented (white).

There is currently no assimilation of remotely sensed land data in CLMS. It is recommended to promote the assimilation of remotely sensed data into CLMS models.

Table 5 lists ocean and sea ice and land variables that **should be assimilated in the expansion of Copernicus** to better serve the needs of intermediate and end-users.

It is explored how **modelling and forecasting capabilities** would benefit from going beyond the current status of data assimilation of **gridded daily/weekly/monthly averaged satellite products** by assimilating satellite-derived products on **swaths or scenes**, and even by directly assimilating **raw satellite data**.

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Three stages of increasing complexity are considered: the current status where sea-ice data are assimilated as **Level-3/Level-4 products** (gridded products), a mid-term evolution where sea-ice data are assimilated as **Level-2 products** (on individual swath or scenes), and a long-term evolution where sea-ice data are assimilated as **Level-1 products**, i.e. on the lowest level on processing.

Assimilating of **less processed products** (e.g. freeboard instead of ice thickness in case of altimetry, surface brightness temperature instead of sea-ice concentration) involves the (further) development of so-called **observation operators** which are mapping the model's state variables onto the remotely sensed observations which require a long-term effort that should be coordinated among the several institutions working on the topic (similar to the coordination performed by EUMETSAT with respect to observations operators in NWP).

The recommendations to move forward on this for sea-ice product's new approaches with respect to assimilation are resumed in Table 6.

Remotely sensed parameters recommended for data assimilation	
Ocean	sea surface salinity albedo
Ocean waves	significant wave height swell
Sea ice	sea ice surface temperature sea ice drift ice type ice deformation roughness melt pond fraction albedo
Land	snow cover (snow water equivalent, fractional snow-covered area) land surface temperature freeze-thaw surface soil moisture river level lake ice area

Table 5: Variables suggested to be assimilated in the expansion of Copernicus.

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Assimilation of Level-2 satellite products	Mid term	Towards the development of **higher resolution regional ocean/ice forecasting systems**: test, refine, and adopt Data **Assimilation of sea-ice parameters** (primarily sea-ice concentration and thickness) **at Level-2** (in swath or along track). This is a necessary preparatory step for the optimal ingestion of Level-2 data products from the HPCM CIMR, and CRISTAL. In parallel, efforts should be continued for DA of ocean and land variables at Level-2.
Co-design of Operators	Mid Term	Foster the **collaboration** and enable further dialogue between the **modelling and Earth Observation communities**, so that the Data Assimilation framework of tomorrow (including their Observation Operators) are co-designed, and benefit from the expertise in both communities.
Towards direct **assimilation of Level-1** satellite **observations**	Long Term	Continue the **development** of fully-fledged yet efficient **microwave emission and scattering models for sea-ice and snow**. Community models -such as SMRT- should be preferred, ideally coupled and reconciled with radiative transfer models for the atmosphere and ocean surface.

Table 6: Steps that have to be taken to elaborate the data assimilation in CMEMS (from D3.3).

Layer 3, Core Services: On 'Polar Regions provision in Copernicus Services'

A comprehensive list of recommendations and analysis of gaps from WP2 on 'Polar Regions provision in Copernicus Services' can be found at https://kepler-polar.eu/deliverables/ on 'CLMS

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improvements' (D2.1) and 'CMEMS improvements' (D2.2).

CLMS

Land variables are currently scattered among the portals of various services and projects (e.g. CLMS, CMEMS, C3S, ESA-CCI). The provision of these variables should be **streamlined to be accessible via one single cloud-type repository**, preferably via the DIAS platforms. Ideally, an Arctic service could be added to Copernicus and made available by the **DIAS platforms**, where **all the relevant land and marine variables** would be accessible within one **unified framework.**

Currently, no land forecasts are performed. Efforts should be taken to deliver forecasts.

Recommendations in detail for the future description of the Polar Regions' land part:

- Include the existing CLMS variables, with the exception of surface soil moisture, lake ice extent, and land surface temperature, which shall be replaced with their equivalents from the **respective ESA-CCI projects**.
- Include additional products from the following **ESA-CCI projects**, when available: permafrost, Glaciers, Biomass, Snow, Land cover, Fire (the latter three are already included in CLMS, hence the recommendation is to harmonize with the existing products).
- Include from **C3S:** snow cover extent, land cover, surface soil moisture, and surface albedo.
- Include the products from the **GlobPermafrost** project until the products of **ESA-CCI permafrost** have been evaluated sufficiently.
- Include products from the **Global Wildfire Information System** (GWIS – collaboration Copernicus/GEO/NASA) in particular **active fires, burnt areas, and fire danger forecasts**. This would also be relevant for the **Copernicus Emergency Management Service (EMS)**.
- The foreseen **European Ground Motion Service (EGMS)** could be extended to the Circumpolar Arctic Region, providing data **products on-ground dynamics** related to the ongoing **thawing of permafrost**. These products would be very valuable to **local communities and government organizations** to evaluate the safety of existing and planned constructions and contribute to the Copernicus EMS.
- Avalanche monitoring in Polar regions by Sentinel-1 could be included as a CLMS polar service or in a wider global/pan-European service, however due to the short time-series of S1 data (since 2014) it makes more sense at the present stage to include it as an EMS service.

CMEMS

The future **CMEMS service** should intend to close gaps in the **current portfolio**:

- A **more complete portfolio** of **sea ice variables** has to be foreseen in the future service. Important sea ice quantities are **missing** within the current catalog (both from models and from observations). However, large efforts have to be made for the **evaluation and validation** of such quantities.

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- ◦ The lack of comprehensive in-situ sea ice (thickness) data set for evaluation and/or assimilation is clearly a **gap for model development**.

- ◦ **In-situ sea ice variables** should be included in Copernicus's portfolio. Currently, no in-situ sea ice variables are included.

- Important gaps in the description of the **biogeochemical state** of the polar oceans are present. A lack of observations hampers model **development**.

- No **icebergs forecasts** are provided, at least not by core services. An important development in iceberg drifting models is needed (link to EMS).

- A **river hydrological service** should link the **Land and Marine Services**, including **nutrient loads.**

- Having similar services for **Antarctica** is rather challenging, as **no proper regional MFC** exists. Services in the Southern Ocean are part of the GLO MFC system.
- Even if **CMEMS services** will evolve towards **resolution less than 5km**, very high resolution (less than 100m) **required by end-users** is not reachable on a pan-Arctic scale in **Copernicus' phase 2 perspective** for many reasons (computing and storage capacities, model evaluation, assimilation system...). In order to better meet the end-users requirements, a **new interface with intermediate users** where Copernicus services could play the role of the background information has to be defined.
- HPCM priorities wrt **CMEMS**: the **CIMR mission** remains the mission that best meets **the CMEMS commitments** (core service) for Polar Regions with high feasibility in the implementation. To a lesser degree, the **CRISTAL mission fulfills CMEMS commitments** together with an important degree of feasibility in the implementation. CRISTAL will allow better monitoring of the **sea ice volume**. Together with the measurement of the SLA (complementing Sentinel-3) the ongoing developments in the assimilation of thick SIT will make CRISTAL of high interest for the core service. The **ROSE-L mission**, focused on high spatial resolution, **fulfills partly the role of the core service** for reliable **automated** sea-ice-chart-like products concentrating on sea ice types and deformation. Having these **three missions in synergy** brings **tremendous opportunities** for CMEMS commitments in terms of spatial and temporal coverage and continuity of the service with **potentially important improved capacities**.
- Sea level, sea ice and waves should be tailored and combined to contribute to the **monitoring of coastal erosion along the Arctic under Climate Change**.

Synthesis on the visions of the evolution of the Copernicus services

The synthesis on the visions of the evolution of the Copernicus service (D5.1) reports on ways to improve the description of the changing Arctic Regions in all existing and planned marine Copernicus Services capability. It is based on an inventory of polar-relevant variables (including Essential Climate Variables) that will be available in 2021 from Copernicus Services and related European databases. **The report attempts to draw priorities for improved completeness and internal consistency of Copernicus services for the Arctic**.

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Prioritized list of problems identified and recommendations given:

- The diversity of international data providers is **prone to confusion and hampers the uptake of the most recent update of a given product**. Users have to deal with the complexity of the data landscape and **should be guided transparently to the best available data**. We recommend thus the establishment of a one-stop-shop for all Copernicus Arctic/Polar data (across all services). It could be powered for example by a DIAS cloud solution and accesses all nominal products at their sources. Such a cross-Copernicus window should allow services as
    - Dataset discovery
    - Subsetting
    - Visualisation
    - Easy handling of polar projections.
    - Cloud computing (including the 'invoke' service from INSPIRE)
    - Comparisons between different products
    - Overlays with external validation data

- Lack of information about the quality of atmospheric input data. This hampers the interpretation of sea ice forecasts as well as ocean forecasts and land parameters as well as international cooperation on both scientific and operational matters. Uncertainties can be estimated from atmospheric Ensemble Prediction Systems (EPS), available in C3S, but these have no counterparts in CMEMS nor in CLMS.

- Closing the Arctic water cycle: Hydrological models are a missing link between land and the ocean components. In the Arctic, the rivers are very important for the freshwater fluxes, but also the heat fluxes and nutrient loads for the marine ecosystem and the carbon cycle. At present, the river inputs to ocean models are not connected to precipitations from the atmosphere. The Arctic rivers have several specificities that require dedicated attention.

- Icebergs are a major threat to navigation. These are monitored in CMEMS and EMS but their forecasting is left for downstream services. The consistency between CMEMS and EMS could be improved if icebergs were forecasted as a Copernicus service.

- Seasonal predictions are not considering biogeochemical nor wave parameters.

We suggest a few ways to improve the description of the changing Polar Regions in Copernicus Services capability:

- Adding Permafrost variables to the CLMS and C3S data servers.
- Adding evaporation to the CLMS data server.
- Adding river nutrient fluxes to the ocean.
- Adding observations of avalanches to CLMS.
- Include regional seasonal predictions of Arctic biogeochemical variables to complement CMEMS, CLMS and C3S in the ocean as well as on land.
- Address the ECVs that were too complex to be treated as a conventional database: biodiversity (both land and ocean) and human pressure.
- With lower priority, include regional seasonal predictions of ocean wave variables.

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- Set up a meta-browser that can harvest polar ECV data from CMEMS, CLMS, C3S, CAMS data stores and other international sources consistently, following the example of the THORPEX Interactive Grand Global Ensemble project (TIGGE) for weather data.
- Support international intercomparison and validation activities for ocean products (such as OceanPredict), sea ice products (such as the Sea Ice Drift Forecast Experiment (SIDFEx) and atmospheric products (such as an Arctic focus of the SPARC Reanalysis Intercomparison working group S-RIP[3])
- Ease the transfer and/or distributed access to climate data products across programmes (C3S/CMEMS, CCI/CMEMS/C3S/, CCI/C3S/CLMS, SAFs/Copernicus) to avoid duplication, or double-branding, and merge those. Both technological and ownership aspects will need to be addressed.
- For Climate Data Records, clarify the set of requirements yielding in the various programmes. E.g. CCI will target GCOS requirements, while SAFs and C3S will target needs of the reanalyses (that may or may not be similar to those of GCOS). Formalize the process of exchanging requirements between the CDR initiatives (See KEPLER D4.2 for more details on the latter).

[3] https://s-rip.ees.hokudai.ac.jp/

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Layer 4, Production: On (re) analyses

The sea ice/ocean and land surfaces are extremely sensitive to changes in the atmosphere, which has a very large impact on forecast quality, but CMEMS is missing an orderly protocol to **evaluate new Arctic atmospheric reanalysis when they become available**. This evaluation should be done as a comparative exercise involving state-of-the-art atmospheric reanalyses and should not only concentrate on global atmospheric reanalyses, but should take regional reanalyses, as for instance CARRA, a regional Arctic reanalysis with 2.5 km horizontal resolution, into account. CARRA is currently produced under the umbrella of C3S and led by the Norwegian Meteorological Institute with five partner institutes. (CARRA is not pan-Arctic, but an updated reanalysis with pan-Arctic coverage is on the agenda for possible production in the next phase of C3S.) First results from CARRA indicate that this very high-resolution reanalysis is able to capture Polar Lows and other extreme events much better compared, for instance, to ERA5. It also applies new satellite data sets for surface properties as well as additional meteorological observations from national archives not used in ERA5. This will contribute immensely to better simulations and understanding of extreme events in the sea-ice and ocean and on land. **The comparative exercise should focus on the critical topics: surface winds, surface air temperature, heat and radiation fluxes, precipitation among others.** At the very least, **the biases should be quantified.** Another urgent knowledge gap that has to be addressed by atmospheric models is the fact that large amounts of data assimilated regularly in the atmospheric reanalyses in mid-latitudes are not taken into account in Polar regions (e.g. a large proportion of microwave sounder derived near-surface profiles are not considered by many DA systems because the radiances are not known well enough). On a less urgent note, the deposition of Nitrogen and Phosphorus nutrients to the ocean is calculated in the EMEP model, but not distributed by CAMS.

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Layer 4, Production: On improved sea-ice mapping

CMEMS is analysed with respect to the **maritime sector needs** on a 5 to 10 years time horizon.

Recommendations - User needs

- **Harmonize the different Arctic ice charts** according to the WMO standards. Ice services should be supported with the necessary data products to enable a seamless transition. Different Arctic ice charts should be **merged into a combined ice chart product**. It should contain ice edge, extent, concentration, age, type (stage of development) and thickness. This product might also include analysis on polynyas and leads.
- CMEMS is recommended to offer **SIGRID-3 Shapefile format** for transferring and archiving ice information. SIGRID-3 file format is in place and in use in all major ice services, and at in-situ data providers **including Ice Watch**. It is scalable, supported by all GIS software and portable into the Electronic Navigation Chart (ENC) format. CMEMS is using the Shapefile format for the product *SAR Sea Ice Berg Concentration and Individual Icebergs Observed with Sentinel-1*. This should be applied to ice charts as well.
- For several products, spatial resolution can already be **increased within limitations of SAR data** (10-100m) and manual ice analysis spatial resolution. Through the use of vector Shapefiles, resolution in the focus areas can be retained without excess bandwidth use.
- Products should include **levels of certainty** taking into consideration inherent seasonal and regional characteristics and limitations in order to be more useful for maritime users.
- Iceberg products that can display **individual icebergs with higher resolution** need to be developed,and introduced to CMEMS. Ideally with all false targets filtered out. Satellite update frequency in certain regions needs to be analyzed and eventually combined with Copernicus Contributing Missions. SAR satellite surface detection hit rate/confidence needs to be parameterized.

Recommendations - Future challenges

- Encourage and **establish a framework that facilitates dialogue** and discussions with information providers, operational ice service providers, third-party services and users. This can also assist in coordinating: user needs, mariner training requirements, science priorities and product development for optimization of the product portfolio and support the development of more relevant products to be used by operational maritime users. The available product catalogue should be continued to be frequently updated based on user needs.
- Introduce new **multisensor products for risk assessment**. Develop a system that can provide overlapping information for users to choose from, for decision-making in near real-time activities.

Recommendations for Copernicus in general

- The **national ice services** (i.e. European Ice Services) are recommended to have a clearer and more well-defined role in Copernicus REACT for their direct support of Search and Rescue missions at ice-covered seas.

Recommendations concerning satellite missions

- More satellite data is required than what the Sentinel-1 constellation is able to provide at

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subarctic latitudes (50-70°N) and at the North Pole region (88-90°N).

- High spatial resolution (on the meter scale) satellite coverage in multiple frequencies (i.e. C, L and X band) in different combinations is needed. The proposed ROSE-L mission is anticipated to respond to these requirements, but also to identify icebergs in sea ice. In support, more ground-truth data is needed.
- Keep in mind that a **stable and long-term** SAR satellite acquisition scenario has the highest priority for operational navigational needs. Improved routine monitoring and increase of images and data over specific areas are secondary.

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Layer 4, Production: On more user-relevant sea-ice forecasts

Recommendations on **more user-relevant sea-ice forecasts are grouped** into **several streams** of research and development work that can be addressed with relative independence and at different speeds. The **time frame** for which results can be expected **varies considerably**. Some improvements (e.g. better forecast communication) should be easily attainable in the near future with a little bit of effort and additional funding, whereas other improvements (e.g. new class of physics-based sea-ice forecast models) still require basic research and have many developmental milestones ahead of them before being potentially usable for user-relevant forecasting.

Stream 1: Improved understanding and utilization of existing forecasts

This stream of work can be carried out by the core Copernicus Services with the aid of the forecast producers and end-users. Improvements should be easily obtained in the short- to medium-term by better-exploiting synergies of expertise and tools that already exist across the different stakeholders of sea-ice forecasts.

- Copernicus should further foster **the collaboration** between forecast producers, intermediate users and end-users, in order to build a mutual understanding of requirements and constraints and develop **more useful representation and communication** of sea-ice forecasts. **Training activities** for intermediate and end-users on how to use and interpret the forecasts are an important tool to do that.
- **Skill and uncertainty of already provided** variables (e.g. SIC, SIT, drift) against relevant targets (e.g. ice charts) needs to be assessed **more systematically** and be provided as part of the forecast. The provision of forecast uncertainty is essential for the user to make more informed decisions on whether a particular forecast provides any **added value** for a particular decision that needs to be made. Developing useful and reliable sea-ice forecast products requires **sustained interaction** between forecast users and producers to scope potentially useful products and then co-develop them.
- It should be investigated which additional sea-ice parameters that are required but currently not provided could be easily provided with some confidence, without further evolution of the forecasting systems.

Stream 2: Evolution of existing forecasting systems

This stream of work will mainly be carried out by the forecast producers. The role of the Copernicus Services would be to (i) provide the technical framework to allow the provision of ever larger and more complex data sets and (ii) stimulate and support research and development of user-relevant improvements to the forecasting systems. Progress will be gradual and continuous over the short to long term.

- The use of sea-ice observations for forecast initialization needs to be improved, e.g. the necessary research needs to be conducted to **assimilate Level-2** (orbit-based) sea-ice products. This is especially relevant to the Copernicus HPCMs but requires much **more sophisticated observation operators** to map the observations to the model equivalent.
- The **spatial resolution** of current sea-ice forecasts should be increased as far as possible. Since sea ice, the atmosphere and the liquid ocean are strongly interdependent, any resolution increase in the sea-ice component needs to be accompanied by resolution increases in the atmosphere and the ocean.

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- It is important to acknowledge that **current sea-ice models** are **not appropriate** for modelling sea ice at scales below a few kilometers, so the **potential for resolution increases is limited**.
- It is essential to further **reduce forecast biases** in the coupled atmosphere-ocean-sea-ice forecast system. These are often limiting the usefulness of current sea-ice forecasts. At longer lead times, most bias improvements might come from improving the model quality, while at shorter lead times, improvements in data assimilations methodology might be most promising.
- The widespread provision of **ensembles and retrospective forecasts** is essential to calibrate forecasts and robustly assess their skill. Having a large archive of forecasts is also essential as **training data for machine-learning approaches**.
- Attempts should be made to **close the spatial resolution gap** by providing **probabilistic information** about decameter-scale features on a coarser grid (e.g. lead or ridge density in a given area of 10 x 10 km). This can be done from forecast ensemble information, or from subgrid-scale parameterizations. The linkage from continuum sea ice models to discrete elements models that resolve individual ice floes should also be established. Research into the skill and usefulness of these potential products is needed.
- More user-relevant sea-ice properties can be provided by **constructing proxies from available model variables**, for instance, ice convergence as a proxy for difficult ice conditions where a ship could expect to become beset. It should also be investigated how far improved or new physical parameterizations are able to provide some of these parameters; some examples would be a floe-size distribution, an ice-thickness distribution, or providing an area fraction of ridged ice.

Stream 3: Improve provision of observations to allow robust forecast assessment and calibration

This stream of work on improving the provision of freely available earth observations is at the very heart of the Copernicus Services. A better provision of already existing observations can be achieved over **the short term** with well-manageable additional resources. New types of in-situ and satellite observations, e.g. the Copernicus HPCMs, can be integrated into the Copernicus Services as and when they become available.

- The **availability of relevant sea-ice observations** needs to be improved, in order to facilitate forecast **evaluation and calibration**.
- For advanced sea-ice variables (e.g. floe size distribution), it is **often difficult to obtain high-quality large-scale** observations **to verify the model**. Likewise, the lack of suitable observations also prevents forecast models from initializing these parameters.

Stream 4: Nowcasting and short-range forecasting using sub-kilometre scale sea-ice observations

This stream of work should be carried out by **intermediate users** of the Copernicus Core Services who develop **downstream applications**. The landscape of these intermediate users will likely be diverse and may comprise commercial entities, national weather services, and publicly funded research groups. Activities in this stream are expected to be diverse as well - they will be initiated by and focused on specific user needs and can take place at any point in time.

- **Hybrid forecasting methods** are a promising approach to achieve sub-kilometre resolutions for short-range forecasts. This class of methods **combines** the ice properties derived from

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high-resolution satellite observations like SAR with the predicted ice drift derived from **lower resolution model fields**. However, this approach is dependent on further improvements to the lower resolution model fields, which currently might not have sufficient quality.
- The use of **machine learning tools** should also be considered for calibrating or downscaling low-resolution forecasts at short lead times, or for filling in observational gaps in a short-range forecast.

Stream 5: Develop a new class of physics-based sea-ice forecast models

This stream of work is most likely still the remit of **basic research** and is hence reliant on the **availability of sufficient and sustained public funding**. Research groups at universities, weather and climate modelling centres, and possible commercial actors are expected to participate. Considerable resources over the long term will be required to make progress with this stream of work, and the chances of the efforts eventually leading to user-relevant operational forecasting systems are still uncertain. Copernicus Services can play a role to guide this research and will provide the lower-resolution boundary conditions that these models will rely on.

- For an explicit and realistic simulation of sea-ice physics with a **sub-kilometre resolution**, a new class of sea-ice models needs to be developed. **Prototypes for such models exist**, but to our knowledge they are currently only used for basic research in an **idealized context**. Long-term research with substantial resources and uncertain outcomes is needed to establish if and how these models can be used for **operational forecasting**.

Layer 1, 2, 3, 4 Observation Processing Core services Production - linking observational strategies and forecast quality

Observation impact assessment studies are linking the Observation System with the forecasting system as they assist in the design of the observing system to improve forecast capabilities with respect to the needed data coverage, resolution, accuracy and can even take into account cross-error-covariances - they are cross-cutting activities.

Within KEPLER several **observational scenarios** were evaluated in terms of their performance in a data assimilation system. In the construction of these observational scenarios the **Copernicus Sentinel** satellites were emphasized with particular focus on the **HPCMs** for the expansion of the Sentinel fleet. One group of **scenarios** consists of observations of the **Arctic sea ice-ocean system**, while another group consists of **observations of atmospheric CO2**.

The quantitative network design (QND) approach is used to assess the **impact of these scenarios** through the reduction of uncertainties in a set of relevant target quantities. For the **sea ice-ocean observations**, our target quantities are 1-week to 4-week forecasts of **sea ice volume** and **snow volume** for selected regions along the **Northern Sea Route and the Northwest Passage** as well as for the **entire Arctic**. For the atmospheric **CO2 observations**, our target quantities are the **land-based fossil fuel emissions** in the first week of June from several Arctic countries, namely Canada, Denmark, Finland, Island, Norway, and Sweden.

Some **selected** results (D3.4 provides more detail on a part of the results):

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- **A hypothetical Sentinel 3 (S3) radar freeboard** outperforms CryoSat-2 (CS-2) Radar freeboard 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**. While this is trivial for the selected target regions relevant for shipping (too far away), S3 outperforms CS-2 as well for the **Arctic-wide assessment which is important for the sea-ice mass balance**.
- Combined assimilation of the CS-2 radar freeboard product with a satellite product of snow depth yields a **strong gain** in forecast performance compared to assimilation of the CS-2 radar freeboard product alone. The performance is much weaker, if the CS-2 radar freeboard product is assimilated together with snow depth observations from a hypothetical Arctic-wide network of up to 123 buoys instead of a satellite product. Leaving out the boys in the Russian economic zone clearly degrades the performance along the Russian coast.
- 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 Copernicus Anthropogenic Carbon Dioxide Monitoring (CO2M) satellite** already provides a **better constraint on land-based fossil fuel CO2 emissions** in June than **increasing the number of continuous sampling sites**. We further evaluated constellations of 2 and 3 CO2M satellites. Our assessments clearly show that each additional CO2M satellite contributes a further reduction in posterior uncertainty of the fossil fuel emissions.

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**. It can assess **combinations of in-situ and EO data** (from multiple missions – see slides on 'Synergies'). This type of assessment can be performed for **higher-level** (e.g. gridded SIT or SIC) but also for **lower-level products** (e.g. freeboard or brightness temperature – see slides on 'Assimilation').

The QND approach is only one method among others (e.g. Observing System Simulation Experiments (OSSEs) and Bayesian Hierarchical Modelling) allowing observation impact studies. It is recommended to take more advantage of these methods for planning of satellite missions but also in-situ networks.

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Layer 5, Delivery: Data delivery - targeted and public

Developing private Downstream services in the Arctic is handicapped due to the **non-free of cost** deliverance of atmospheric forecast products. Additionally the cross-cutting delivery of data via DIAS and Google Earth Explorer (Google EE), although cost-free at the moment, are intended (or probably intended in the case of Google EE) to be no free-of-charge services. Because a very low to be expected return-of-investment for most Arctic Downstream services, especially if indigenous people (see below the user story on reindeer herders) or local communities are beneficiaries, non-free of cost delivery of data add another handicap.

- It is recommended to **find solutions for free-of-cost delivery of Copernicus and NWP Arctic-related data if Downstream services intended for local communities and local and indigenous people via the DIASes.**

- **The potential role of the DIASes as a cloud solution including cloud computations, as had been under consideration earlier, should be reinforced**. It could be powered for example by a DIAS cloud for assessment of all nominal products (as well as on their source level) across all Copernicus services. Such a cross-Copernicus window should allow cloud computations e.g. dataset discovery, subsetting, visualisation, comparisons between different products, overlays with external validation data.

- In 2016, the 'FAIR Guiding Principles for scientific data management and stewardship' were published. The authors intended to provide guidelines to improve the **F**indability, **A**ccessibility, **I**nteroperability, and **R**euse of digital assets. The principles emphasise machine-actionability (i.e., the capacity of computational systems to find, access, interoperate, and reuse data with none or minimal human intervention). Metadata and data should be easy to **find** for both humans and computers. Machine-readable metadata is essential for the automatic discovery of datasets and services. This includes assigning a globally unique and persistent identifier and registering the data in a searchable resource. The data should be **accessible** by their identifier using a standardised open, free, and universally implementable communications protocol. Because the data most likely needs to be integrated with other data, in addition, **interoperability** with applications or workflows for analysis, storage, and processing is essential. The ultimate goal of FAIR is to optimise the reuse of data. To achieve this, metadata and data should be well-described so that they can be replicated and/or combined in different settings. (Meta)data are richly described with a plurality of accurate and relevant attributes and are released with a clear and accessible data usage license. **The European Commission and Copernicus are prompted to request to follow the FAIR principles in all funded projects to facilitate the exchange of data.**

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Layer 6, Downstream services: User stories – Examples of User-driven Downstream Services

User stories are provided to demonstrate the need for the development of user-driven downstream services. The three examples given in detail are

1) EO-based decision making for cost-efficient and safe maritime navigation

2) EO-based decision making of Reindeer herders and

3) EO-based emergency response.

These user stories will be accompanied by short films for web, presentations, educational use, and social media channels that are currently in production (see WP6 of KEPLER). It has been agreed at the first meeting on the roadmap in January 2020 that the roadmap would include example user stories, and describe specific R&D that is recommended to address these user requirements in future services. Two additional user stories of high relevance for end-users are outlined briefly at the end of this chapter (Permafrost/landslide and fjord ice).

1) EO based decision making for cost-efficient and safe maritime navigation

The challenges for cost-effective and safe navigation in ice-infested waters differ for instantaneous information on the ice conditions needed and for planning activities over some time horizon.

A Cruise ship wanting sea ice mapping around Svalbard

Downstream contact would be the National Ice Services. The ice service would provide sea ice maps (ice chart). Ice charts are created mainly from raw satellite and in-situ data. This case would bypass the modelling and analysis level.

Current status of downstream services: These ice charts are analysed and drawn manually by an expert Ice Analyst, i.e. due to varying levels of human experience and skill these are to some extent subjective and will come with some latency. However due to multiple analysts' involvement in ice chart production over some days there is potential for self-correction.

Actions that have to be taken to improve the service: Automatically-generated sea ice and iceberg maps have the potential to provide routine, accurate sea ice maps with improved spatial detail and reduced latency. A number of these are at the experimental stage, yet none have so far demonstrated year-around robust and accurate results such that they could be incorporated into the value chain of the national Ice Services or used independently without compromising maritime safety. In particular there are issues to overcome with an accurate representation of the sea ice in the marginal ice zone, coastal areas and at the ice edge, particularly during the summer melt period, and with detection of hazardous multi-year sea ice and iceberg inclusions within the ice pack. This is critical for the reason that the highest volume of maritime activities operate during the Spring and Summer seasons, particularly in the region between Greenland and Russia.

Recommendation: Continuing fostering the R&D activity for the generation of automatically generated ice mapping through Horizon Europe activities. This includes the development of machine learning algorithms (Artificial Intelligence), which might be a promising way to merge remotely sensed

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observations from different sources and sensors including in-situ and aerial reconnaissance data. There should be a more joined-up definition of the research requirements from the respective EC DG's and Copernicus Services.

Recommendation: There should be better and more formal integration of the national Ice Services (European Ice Services and others) into Copernicus services to ensure that their requirements are addressed. Currently, this is not the case, resulting in competition by Copernicus services with internationally mandated (WMO, IMO and IHO) monitoring activities.

Recommendation: Support the development by small and medium-sized enterprises of enhanced information visualisation and analysis tools like for instance (Example: IcySea app Figure 4).

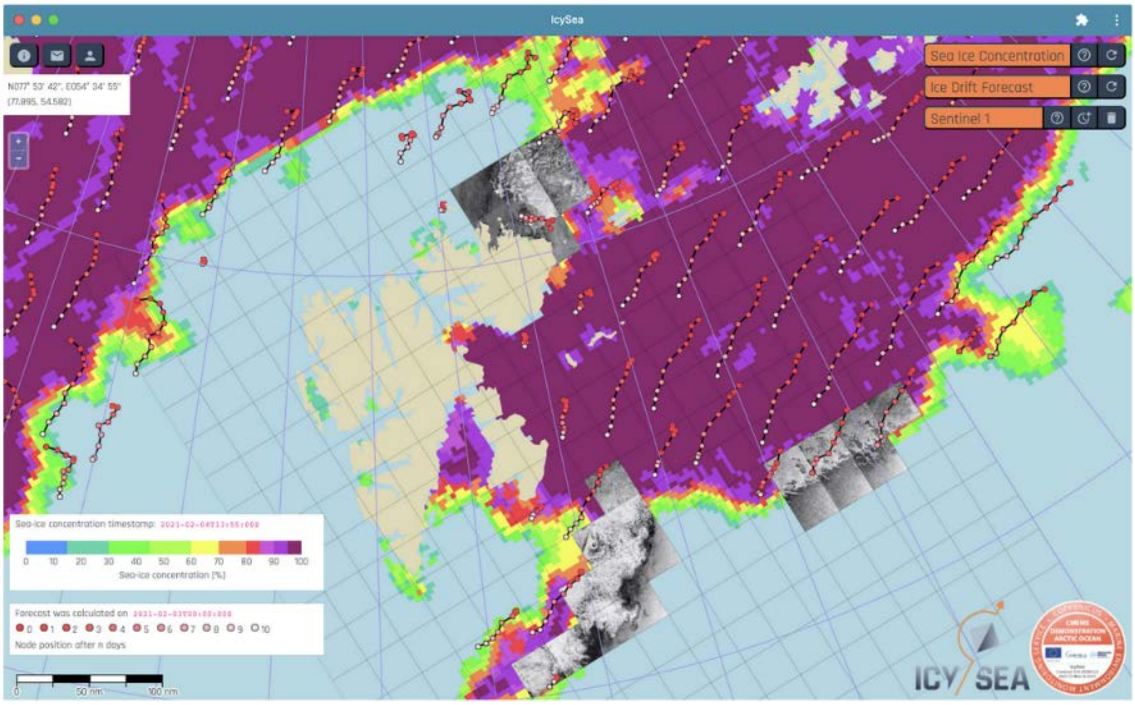

*Figure 4: Screenshot of the IcySea app. The coloured background shows AMSR2 sea-ice concentration, grey images are Sentinel-1 radar satellite scenes and the red dots are improved sea-ice drift forecast trajectories. The forecasts range **10 days** into the future and cover the area around the Svalbard archipelago with a **spatial resolution of 12.5 km** . In the IcySea app the forecasts will be visualized with points anticipating the future location of ice patches. The IcySea sea-ice forecasts are improved by means of machine learning techniques developed at the Norwegian Meteorological Institute.*

A Ship wants to plan activities over the next 48 hours

The ship needs 100m resolution ice information (ice concentration, ice thickness, ice pressure, lead fraction, ridge density, ice drift, and snow depth).

Current status of downstream services: Downstream contact could or would be a commercial entity. In the demanded resolution only a now-cast based on a SAR image would be available that would only partly fulfil the request. Other sea ice variables such as ice concentration and ice drift (10km, e.g.

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OSISAF), and ice thickness from SMOS and CryoSat2 (25km, e.g. AWI) are available, however, they will not reliably cover the ice in the areas of coastal zones, marginal ice zones and the ice edges. Critical parameters such as ice pressure, lead fraction, ridge density and snow depth would also be not available from these observations, due to the low spatial resolution. Though, low-resolution model forecasts and analyses in about 3km could be gained from the ArcMFC. Currently, a Downstream Service is set up that merges high-resolution satellite imagery and optimized bias-corrected forecasted modelled ice drift data (from ArcMFC) in an automated fashion (https://driftnoise.com/svalnav.html). Data transmission to a frontend client software occurs in near real-time and is optimized for low bandwidth connections.

Actions that have to be taken to improve the service: The actions that have to be taken are numerous. Ideally, a forecast would be generated with a 100m resolution for all desired ice variables. To achieve that

- Sea ice observations on the desired resolution are necessary but will probably not be available within a time horizon of Copernicus phase 2 (2022-2029). SAR imagery offers possibilities for high-resolution ice concentration, ice drift and deformation (leads, pressure ridges, ice pressure), but for ice and snow thickness the desired resolution will probably not be reachable within the time horizon. More has to be done to improve coverage of (mainly sea ice thickness) observations into the summer melt period.

- The resolution of numerical forecasting models has to be increased. However, there is currently only limited experience with ice models on these spatial scales Currently operating forecasting systems are using sea ice rheologies which might be not applicable for the demanded spatial scale. Models utilizing sea ice rheologies better suited for these spatial scales are in development and have started to be provided by CMEMS since July 2020 in a downgraded, gridded form but have yet to be evaluated for their performance at the sea ice edge or during summer conditions.

- The data assimilation systems have to be extended and verified for the demanded spatial scales.

- The resolution of the atmospheric forecasts has to be increased to capture, e.g. Polar lows, with better accuracy. During the Year of Polar Prediction (https://www.polarprediction.net/) a lot of progress has been made to increase the reliability and fidelity of atmospheric forecasts.

Recommendations: Foster the R&D activities on all the above-described levels. Additionally the potential of merging satellite products from different sensors (e.g. radar and optical) has to be exploited much more than it is currently.

A ship wants to plan a route over the next 14 days.

Current status of downstream services: In the German-funded project Ice Forecast and Routing Optimization (IRO2) an ice forecast based on a coupled atmospheric – sea ice-ocean model was combined with a navigation program in order to optimize shipping routes through ice infested waters (https://www.hsva.de/our-research/research-arctic-technology.html#iro2). Low-resolution remote sensing sea ice data had been used to provide initialization for the ice forecast with a spatial resolution

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because it delivered information on the risks traveling into the area.

Actions to be taken to improve service: The actions that have to be taken are similar to those of the example for navigation for 48 hours if spatial scales of about 100m should be resolved. However, due to inherent limits to atmospheric predictability, uncertainty 14 days ahead is much higher. Also the initialization of the sea ice model for 14 days forecasts needs a lot of attention: at these longer lead times, poorly observed properties like the ice thickness and type play a larger role than well-observed properties like sea-ice concentration. More attention should be paid to the post-analysis of forecast quality and providing information on how a range of forecast models are performing, not just the select few delivered by Copernicus services. This would also provide a benefit in improving trust in the forecast results.

Recommendations: Also the recommendations are similar to the 48-hour forecast. R & D should aim to improve the input data for the initialization of sea ice models to gain insight into the achievable lead time. Set up routine analysis of forecast quality and performance, and disseminate in a user digestible format.

2) EO based decision making for Reindeer herders

The herder and herd are using pasture lands out in the mountains based on Indigenous knowledge of the quality and quantity in traditional land use. EO confirms a traditional forecast that a Rain-on-Snow event is approaching with the freezing rain low front from the sea and the herder moves the herd to a safer pasture as the current pasture will be frozen over and the animals cannot eat the lichen. In transit the herder will review the EO mobile app to check the avalanche danger and the safety of river ice to move the herd along a safe route. The herd and herders are happily in a safe location, away from the Rain-on-Snow events.

Current status of downstream services: No such service is available or planned to our knowledge. Parts and pieces of the service could be found elsewhere (e.g. the Norwegian Water and Hydrology Authority provides a service for avalanche monitoring based on Sentinel-1 https://satskred.nve.no/). Wet snow mapping based on S-1 will probably be provided as a pan-European Copernicus service soon, but little is known about near-real-time aspects. Integration of sub-components of such a service could be a foreseeable path forward. Further integration and adaptation to a service that can be easily used on a cell phone in the field are also required. Such a service should also be set up using the Sami language in addition to English.

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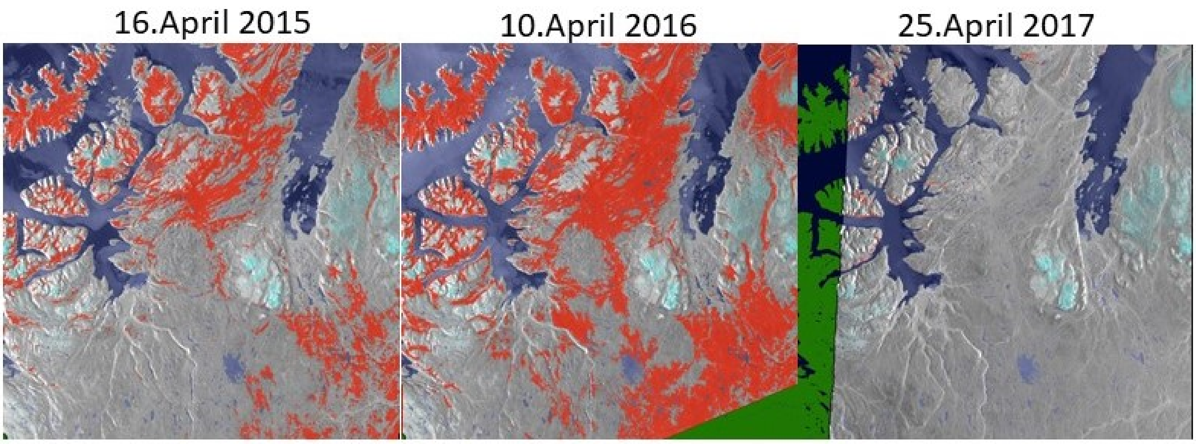

Figure 5: Examples of wet snow maps over Finnmarksvidda, Norway for April 2015-2017. Melting snow (red) started to develop in coastal regions before the continental religions. The reindeer herders need distributed knowledge about the transitions from dry snow, via wet snow to bare ground for the summer pastures along the coast before they can start the migration of the herd. The migration is coincident with the reindeer calving, and this adds uncertainty to the already vulnerable animals.

Actions that have to be taken to set up a service: An integrated down-stream service could provide valuable information to the reindeer herder to make crucial decisions on the timing of the movement based on 1) snow cover & wetness status, 2) avalanche activity, 3) lake & river ice status on the migration route. 4) regional weather forecast. An integrated service that assembles information from CLMS and other open sources may provide information that facilitates better decisions. The end product might also need adaptation (compression) to allow low bandwidth download, adaptation to the language of the indigenous people (Sami) language and close interaction with users (co-productivity). The service should be provided as a cell phone app.

Recommendations: TBD [D2.1 "Community-based observing and societal needs"]. A downstream service for the reindeer herders is challenging to fund solely based on commercial terms, and should have a transnational dimension as it covers northern parts of Norway, Sweden, Finland and Russia. European funding from an EU project or a Copernicus downstream service would be ideal.

Other land-related user stories of high relevance for end-users

Permafrost/landslide

Interferometric SAR can provide danger maps at local scales that are valuable for local communities. The Norwegian Geological Survey (NGU) provides deformation maps for Norway in https://insar.ngu.no/, but the service has so far not been implemented for Svalbard. A Pan European service will also become available shortly (REF). Downstream services based on these maps could clearly be envisaged for downstream users. For example, farmers operating nearby dangerous slopes, construction companies or local/regional authorities as well as house owners may well use the deformation maps in addition to other EO-based information layers like soil moisture maps or surface thaw/freeze maps to extract valuable information for their daily life.

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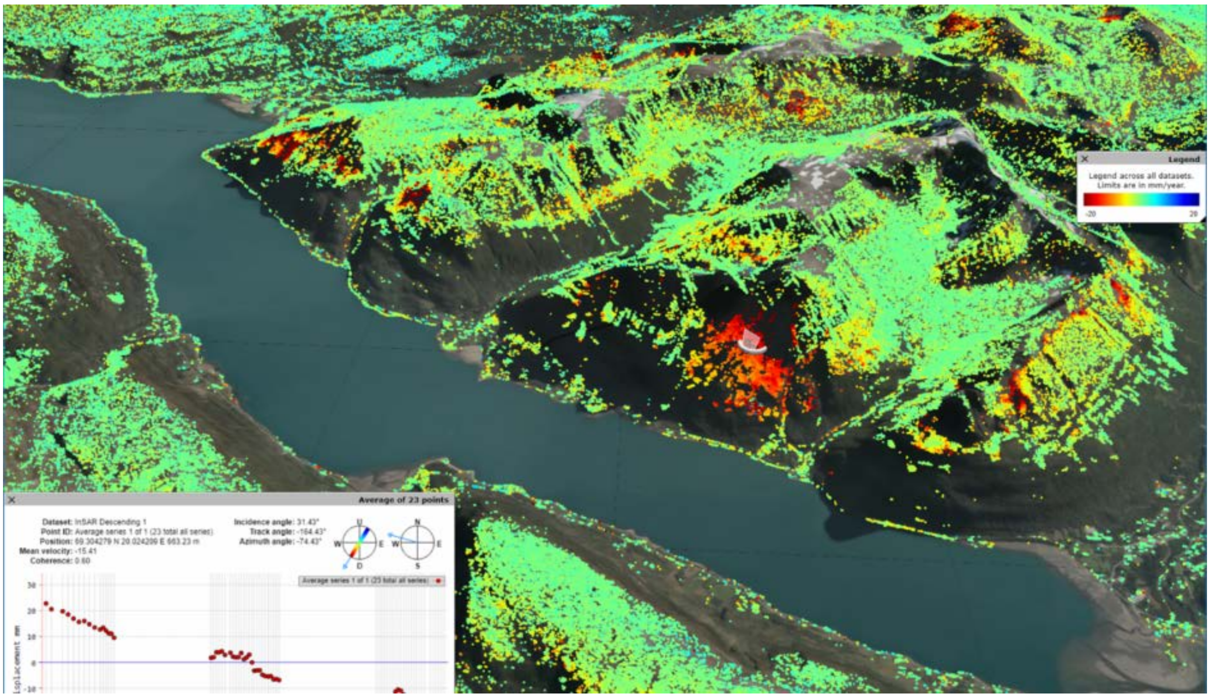

Figure 6. Example from insar.ngu.no where unstable mountain regions are displayed in 3D together with time series of the displacements. Several unstable regions have been detected, and some of these are close to roads or habited areas.

Current situation: A new Copernicus service based on InSAR (EGMS) will be launched in 2022 https://land.copernicus.eu/pan-european/european-ground-motion-service. Several studies have demonstrated the usefulness of interferometric SAR for the detection of landslides in e.g. southern Italy (Refice at a., 2019) and Syria (Hammad et al., 2019) but also for permafrost regions in China (Wang et al., 2019), discontinuous permafrost (Eckerstorfer et al., 2018), and for Svalbard (Rouyet et al., 2019). Permafrost regions are particularly susceptible to sudden changes as the active layers start melting.

Actions that have to be taken to set up a service: Several downstream services should be fostered based on the availability of displacement maps. Permafrost regions are in general more sparsely populated and less monitored by traditional methods, so satellite-based displacement maps could play a crucial role in detecting changes and related hazards caused by permafrost melting.

Recommendations: Stimulate R&D on the usability of interferometric SAR for the generation of danger maps for local communities.

<u>**Fjord ice**</u>

Fjord ice is a general problem in many fjords in the Arctic leading to challenges for ship navigation or security for people who walk on the ice. The fjords are often (but not always) covered by the larger scaled ice charts, but frequently there is a need for more high-resolution maps and downstream services that offer warnings to people, or safe navigation leads through the ice.

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Figure 7. Leisure on the sea ice near Sandvika, Norway in January 2021. The ice was mainly safe, but close to a river outlet the ice was thin, and several people ended up in the water (copyrights: Aftenposten.no). Downstream services directed to the general public could have alleviated the problem.

Current situation: A pre-study merging satellite observations (marine sea ice and land river run-off) and in-situ observation (e.g. web-cam) and airborne drone measurements had been carried out by NORCE in the RESICE project for Kongsfjorden, Svalbard (Johansson et al., 2020). Climate Change has significantly reduced the amount of sea ice in the fjords, and a climatology study by O'Sadnick et al. (2020) provides a time series of this for the Norwegian mainland at https://ndat.no/fjords/. This also shows that many fjords are still frozen for large parts of the winter season every year, partly due to freshwater release from rivers.

Actions that have to be taken to set up service: Downstream services related to fjord ice in the Arctic should be supported. The services could be directed to the general public and/or to companies that require up-to-date info on fjord ice. Traditional ship navigation in fjords is seriously hampered by ice, but also new industries like tourism might utilize the information for security purposes as well as for planning. Historical information on fjord ice could also play an important role in the transportation sector.

Recommendations: Stimulate R&D and services related to fjord ice monitoring.

3) EO based marine Emergency response

A fishing vessel sends out a distress call-engine problem in the mid-winter rough seas. The search-and-rescue SaR helicopter deploys and needs support from the meteorologists and the sea-ice experts to

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direct the crew rescue operation. When the sea calms down, the Coast Guard takes immediate action to prevent the oil spill, again with the support of the meteorologist sea ice experts. 18 months later a wreck salvage operation commences with the support of meteorologists and sea-ice experts that provides a spectrum of info (meteorology, sea ice extent, iceberg tracking). Will involve SAR imagery

Current status of downstream services: Copernicus does not provide access to meteorological information, so the Joint Rescue Coordination Centre (JRCC) organising the SaR response contacts the relevant National Weather Agency (NWA). The NWA provides weather forecast information to support the immediate evacuation of the fishing vessel crew by helicopter. The next Copernicus satellite images acquired by Sentinel-1 SAR is processed for the European Maritime Safety Agency (EMSA), and shows that there has not been any ice spill connected with the incident. Nevertheless, a Coast Guard vessel makes a route plan to the site using the latest ice chart from the NWA ice service and its ice experts to conduct a recovery of hazardous materials onboard the wreck. During the trip to the site, it was found that sea ice conditions and the presence of icebergs were more severe than expected from the climatology information available from C3S and sea ice products available from CMEMS. Safe recovery of hazardous materials took place, and the planning for salvage in the summer is started.

The salvage plan takes into account the expected climatology and seasonal forecasts from C3S. However, it is a severe ice year not matching the climatology, and the salvage contractors have to abandon their attempt as even during mid-summer there was still multi-year sea ice and icebergs around the wreck site that were not visible in CMEMS sea ice products and forecasts. The plan is revised for the following summer using additional ice management vessel support and with mapping by high-resolution satellite imagery procured from a commercial satellite operator.

The salvage takes place using meteorological information and sea-ice information support from the NWA. These draw heavily on non-Copernicus data and services to provide high-resolution information in this coastal area and the salvage is successfully completed.

Actions that have to be taken to set up service: Existing CMEMS services have to be upgraded to better support users in the coastal zones, particularly where sea ice and icebergs occur. To do this will require improved satellite data, particularly from SAR, with the capability to provide accurate mapping that is also robust to summer melt conditions. This should be assimilated in the initialisation of sea ice models, to provide these with an accurate starting point for forecasts.

Climatology information should also be upgraded to better cover the details needed in the coastal zone, and this could be achieved using the archive of SAR data stretching back into the 1990s.

Recommendations: Stimulate R&D related to polar coastal zone monitoring. Ensure that archive SAR data is incorporated into climatological products.

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The pyramid diagram of the introduction revisited

The pyramid diagram from the introduction (fig.1) is extended with traffic light coloured arrows symbolizing the interactions of the different layers in and around Copernicus that are working well, could be improved, or running not well according to KEPLER's findings (Fig. 8).

In general, Copernicus is an outstanding programme bringing together almost all European actors for the benefit of monitoring and forecasting, not only but as well, in the Polar Regions. Most of the interactions between the actors are running well which can be seen in Figure 8 - the majority of the arrows are displayed in green. However, even well working systems can be improved and KEPLER gives a lot of recommendations on these components of Copernicus and the interplay with external actors.

Displayed in orange ('could be improved') are interactions within the complex Copernicus systems but also with externals where actions should be taken with some priority. For instance, several shortcomings have been identified with respects to the interaction between the Copernicus core services, such as the need to ease the transfer and/or distributed access to climate data products across C3S, CMEMS, CLMS but also with external actors like the ESA-CCI and the EUMETSAT SAFs.

Displayed in orange is as well the flow of data from sea ice mapping and forecasting for targeted data products and the delivery of the targeted data products to private Downstream Services. KEPLER's 'user stories' reveals some shortcomings.

However, the most urgent action has to be taken with respect to the in-situ component. The list of recommendations from KEPLER ranges from recommendations (i) to establish a "one-stop-shop" for the Polar region under the leadership of Copernicus because in-situ data are extremely scattered among several platforms, if present at all within Copernicus (ii) to include more research on observational impacts studies and intensification of Cal/Val of satellite products with appropriate in-situ data (iii) to encourage, support and facilitate more CS projects to be involved in the Cal/Val of the present and future Copernicus products and services (iv) to improve the availability of relevant sea-ice observations in order to facilitate forecast evaluation and calibration.

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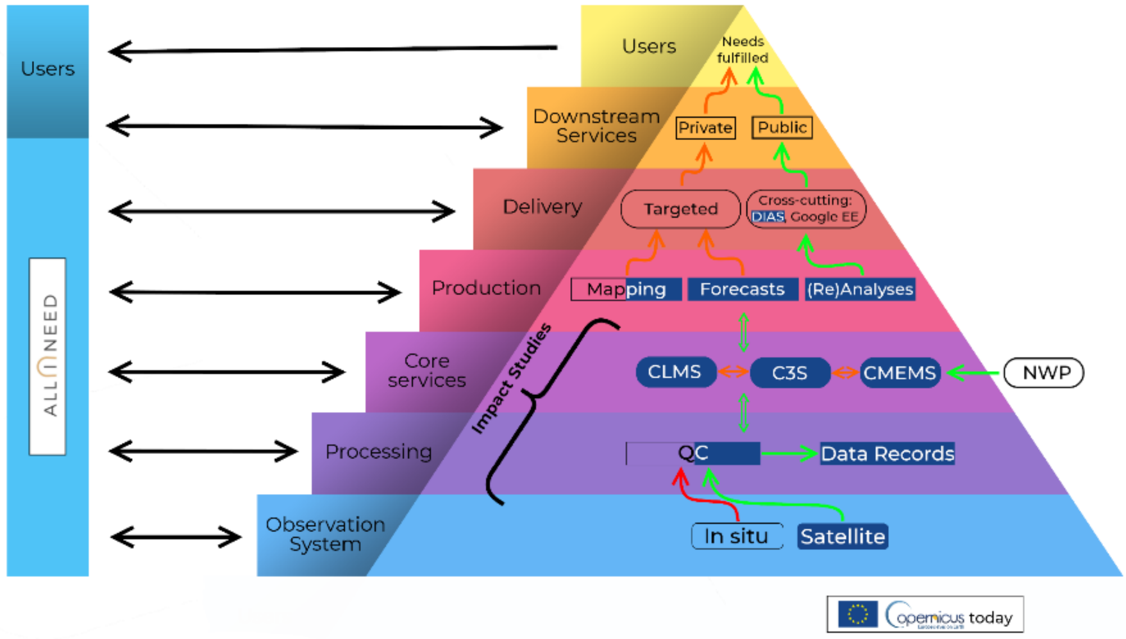

Figure 8: The pyramid diagram (Fig.1) extended by a traffic light colored arrows symbolizing the interactions with and within Copernicus that are working well, could be improved, or running not well according to KEPLER's findings.

Closing words

The KEPLER roadmap moves us towards a comprehensive European end-to-end operational system by addressing design aspects, such as the set of required observations, and the potential inclusion of prior information to better constrain sparsely observed areas/variables. It suggests strategies to close gaps in our current forecasting capabilities, and ways to develop and sustain the observing system.

With the uptake of our recommendations KEPLER is confident that the Copernicus monitoring system for Earth, including both in situ and satellite components, data handling capabilities, forecast and reanalysis modelling systems, and dissemination procedures will support the varied needs of climate change monitoring and prediction, waste/pollution management, safe and efficient navigation in ice infested waters, and facilitate the shift towards a low carbon economy. The roadmap towards an European end-to-end operational system addresses the design aspects and recommends strategies to close gaps in our current capabilities and ways to evolve and sustain the observing system.

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Acronyms

Acronym	Definition	Link
AMAP	Arctic Monitoring and Assessment Programme	https://www.amap.no/
AUV	Autonomous Underwater Vehicle	
C3S	Copernicus Climate Change Services	https://climate.copernicus.eu/
Cal/Val	Calibration/Validation	
CAMS	Copernicus Atmospheric Monitoring Services	https://atmosphere.copernicus.eu/
CARRA	Copernicus Arctic Regional Reanalysis	https://climate.copernicus.eu/copernicus-arctic-regional-reanalysis-service
CDR	Climate Data Record	
CIMR	Copernicus Imaging Microwave Radiometer	https://www.d-copernicus.de/daten/satelliten/satelliten-details/news/cimr-copernicus-imaging-microwave-radiometry/?tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Baction%5D=detail&cHash=87f07ad7c0b71e041b3325f0c1b63de6
CLMS	Copernicus Land Monitoring Services	https://land.copernicus.eu/
CMEMS	Copernicus Marine Environmental Monitoring Services	http://marine.copernicus.eu/
CO2M	Copernicus Anthropogenic Carbon Dioxide Monitoring	https://www.d-copernicus.de/daten/satelliten/satelliten-details/news/co2m-copernicus-anthropogenic-carbon-dioxide-monitoring/?tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Baction%5D=detail&cHash=c4bbeae610dabdbcf13c76c7381e63f7
CRISTAL	Copernicus Polar Ice and Snow Topography Altimeter	https://www.d-copernicus.de/daten/satelliten/satelliten-details/news/cristal-copernicus-polar-ice-and-snow-topographic-altimeter/?tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Baction%5D=detail&cHash=b868194fbdfe86741dbb75b057127d3d
CS	Citizen Science	
DIAS	Copernicus Data and Information Access Services	https://www.copernicus.eu/en/access-data/dias
ECMWF	European Centre for Medium-Range Weather Forecasts	https://www.ecmwf.int/
ECV	Essential Climate variable	https://gcos.wmo.int/en/essential-climate-variables
EDA	European Defence Agency	https://eda.europa.eu
EGMS	European Ground Motion Service	https://land.copernicus.eu/pan-european/european-ground-motion-service
EMS	Copernicus Emergency Monitoring Services	https://emergency.copernicus.eu
EMSA	European Maritime Safety Agency / Copernicus Maritime Surveillance Service	http://www.emsa.europa.eu/copernicus.html
ENC	Encoded Format	

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Acronym	Definition	Link
EO	Earth Observation	
EOV	Essential Ocean variable	http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114
EPS	Ensemble Prediction Systems	
ERA5	C3S's Reanalysis v5	https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5
ESA CCI	European Space Agency Climate Change Initiative	http://cci.esa.int/
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites	https://www.eumetsat.int
FCDR	Fundamental Climate Data Record	
FIR	Flight Information Region	
FRM	Fiducial Reference Measurement	https://earth.esa.int/web/sppa/activities/frm
GCOS	Global Climate Observing System	https://gcos.wmo.int
Google EE	Google Earth Explorer	https://earth.google.com/web
GOOS	Global Ocean Observing System	https://www.goosocean.org/
GOVSATCOM	Governmental Satellite Communications	
GPR	Ground-Penetrating Radar	
GWIS	Global Wildfire Information System	https://gwis.jrc.ec.europa.eu
HAPS	High Altitude Pseudo Satellites	
HPCM	Copernicus High Priority Candidate Mission	
IGGE	THORPEX Interactive Grand Global Ensemble	https://www.ecmwf.int/en/research/projects/tigge
QC	Quality Control	
QUIDS	Quality Information Document	
KEPLER	Key Environmental monitoring for Polar Latitudes and European Readiness	https://kepler-polar.eu/
MFC	Marine Forecasting Centre	
NRT	Near-Real-Time	
NWP	Numerical Weather Prediction	
OSI SAF	Ocean and Sea Ice Satellite Application Facility	http://www.osi-saf.org
PEG	Polar Expert Group	https://www.copernicus.eu/en/news/news/new-copernicus-polar-expert-group-report-published
ROSE-L	Radar Observing System for Europe (L-Band SAR)	https://www.d-copernicus.de/daten/satelliten/satelliten-details/news/rose-l-radar-observing-system-for-europe-l-band-sar/?tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Baction%5D=detail&cHash=a04a6343ad86edd934b7d33e53318699
SAR	Synthetic Aperture Radar	
SIDFEx	Sea Ice Drift Forecast Experiment	https://sidfex.polarprediction.net/
SMRT	Snow Microwave Radiative Transfer	https://www.smrt-model.science

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Acronym	Definition	Link
	model	
SPARC	Stratosphere–troposphere Processes And their Role in Climate	https://www.sparc-climate.org/
S-RIP	SPARC - Reanalysis Intercomparison Project	https://s-rip.ees.hokudai.ac.jp/
TAC	Thematic Assembly Centers	
UAS	Uncrewed Aircraft Systems	
UWB	Ultra-Wideband Radar	
WMO	World Meteorological Organisation	https://public.wmo.int

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