European Commission

Copernicus polar roadmap for service evolution

COPERNICUS POLAR TASK FORCE

PROGRAMME OF THE EUROPEAN UNION

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EUROPEAN COMMISSION
Directorate-General for Defence Industry and Space
Joint Research Centre

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FOREWORD

Polar regions are unique in the world. Not only is the Arctic disproportionately affected by climate change, warming about four times faster than the globe on average, it is also increasingly subject to the ambitions of a number of countries with geoeconomic and geopolitical interests. Given the intertwining issues that characterise the region, such as the thawing of permafrost and melting of ice, and its relevance for security, supply of energy and raw materials, fishing, transport and shipping, Earth observation (EO) can play a major role in supporting policy development and implementation. The crucial role of Antarctica within the climate system also mandates the provision of Earth observation data for this region.

The updated EU Arctic policy, which was jointly published by the European Commission and the High Representative of the Union for Foreign Affairs and Security Policy in October 2021, highlights the EU's commitment to addressing climate change and environmental protection. The policy also puts strong emphasis on security and enhanced cooperation, acknowledging that the high level of interconnectedness of issues in Arctic regions requires an integrated strategy to protect both people and the environment.

Copernicus, as a component of the EU space programme, is a world leader in providing Earth observation space data and information to user communities worldwide, based on state-of-the-art space technologies and world-renowned expertise. Copernicus' role in support of the EU Arctic policy is set to become even more pertinent and provide the EU with sustained capacity for monitoring and tracking the impacts of the main drivers of change in Arctic regions, thus helping to strengthen the EU's overall role in the area. Over the past few years, the European Commission has analysed the needs for Earth observation data and value-added services related to the polar regions, including contributions from the European Commission's Polar Expert Group and projects funded under the EU's Horizon programmes, which have led to better understanding of user communities' needs in the polar regions. This work has laid the basis for building an operational Copernicus polar observing system within the existing Copernicus Services, using both space-based and in-situ observations as well as modelling capacities.

A Polar Task Force of external experts was established by the European Commission at the end of 2022 to further elaborate and facilitate coordination of the polar activities carried out by the various Copernicus Services and stake out the direction for the polar dimension of Copernicus, including the further development of the Copernicus Arctic thematic hub. The next phase of Copernicus will provide higher spatial and temporal resolution of data through new satellites (the Copernicus Expansion Missions). Synergy and integration with existing space assets, in-situ data and modelling capacities will also be enhanced with a view to establishing an integrated and comprehensive observation system for the monitoring of both poles, to the benefit of all stakeholders. This will contribute to the EU's long-term environmental targets as set out in the Green Deal, and to the EU geopolitical targets described in the Arctic policy and the global strategy for the EU's foreign and security policy.

The Polar Task Force provides three types of recommendations in its roadmap for the evolution of the polar dimension of Copernicus Services:

- recommendations for improved products, e.g. products related to sea ice modelling and wildfire monitoring;
- recommendations for new products, e.g. iceberg forecasting and avalanche monitoring;
- recommendations for service management, e.g. the provision of cloud-based tools.

The conclusions and recommendations in this Copernicus polar roadmap for service evolution are timely and well elaborated, based on intelligence gathered from the Copernicus Services, a user survey, input from the Polar Task Force's experts, and from previous work of the Polar Expert Group and EU-funded projects. This roadmap for the next 5 to 10 years is highly valuable for future decisions on programmatic evolution of Copernicus.

Timo Pesonen, Director-General of DG Defence Industry and Space

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Clara Ganslandt, Special Envoy for Arctic Matters, European External Action Service

EXECUTIVE SUMMARY

The EU's increasing interest in monitoring the polar regions, as highlighted in the 2021 updated EU Arctic policy, led the European Commission to set up a Polar Task Force composed of external experts, chaired by Commission officers, to focus on the evolution of the Copernicus Services[1] in the polar domain. Their work takes into account the major progress made in space observation capabilities and the in-depth knowhow that is the result of providing operational services to polar users for more than a decade.

To this end, a questionnaire was widely circulated to user communities in autumn 2023, both in Europe and Canada, an important Arctic partner. Some 61 comprehensive responses from 17 countries were received, mostly from a mix of governmental operational agencies and the academic and research sector. From these survey responses and the contributions of external experts, invaluable information was obtained, highlighting the current status of polar services, as well as gaps and weaknesses. The polar task force experts formulated a number of clear key messages, including:

- There is demand for improved and/or new quality products (e.g. area fraction of melt ponds on sea ice, glacier facies and extent, fire radiative power, snow water equivalent) that are well validated and made available to users in a timely manner. Specific mention was made of the need for higher accuracy of sea ice surface temperature and sea surface salinity products, and of the need for higher spatial resolution for some products.
- Similar services and products need to be provided above latitudes of 60°North, as well as over additional geographical zones such as the Baltic Sea and Antarctica.
- There is a pressing need for continuous scientific research on polar physical and biogeochemical processes and algorithms, advanced data assimilation techniques and forecasting models (e.g. for sea ice, ice sheet and glacier parameters).
- The European Ground Motion Service (EGMS) should be expanded to a pan-Arctic scale to provide high accuracy (to the millimetre) ground motion information on the ongoing thawing of permafrost and implications for the environment and infrastructure.
- The establishment of the Copernicus thematic hubs to ease/facilitate user access is strongly endorsed; in particular the Arctic Hub which is recommended to be extended into a polar hub. A strong preference emerged for harmonisation and coordination of these thematic hubs (Arctic, Coastal, Energy and Health) regarding standards and interoperability (in areas such as catalogues and data access protocols).
- There is a need to develop user-friendly tools that can be accessed easily, with users able to download data and products. A strong preference emerged for products to be standardised in terms of quality, accuracy, format and grid projection.
- Strong recommendations are made for better coordination between polar activities and

[1] C3S (Copernicus Climate Change Services), CAMS (Copernicus Atmosphere Monitoring Services), CLMS (Copernicus Land Monitoring Services), CEMS (Copernicus Emergency Management Services), CMEMS (Copernicus Marine Environment Monitoring Services), EGMS (European Ground Motion Service, part of CLMS).

initiatives both European (e.g. Horizon projects) and national levels, as this would lead to efficient implementation of EU Arctic policy.

- It is important to use citizen science initiatives to involve local populations in polar monitoring activities and decision-making processes.

- Promotion and outreach activities are needed to develop awareness and encourage users to participate in demonstration projects.

- There is a crucial need for continuity of current microwave and optical observations from space, and for additional space observations, in particular from planned Copernicus Expansion Missions (specifically CIMR, CRISTAL and ROSE-L). Such data should be supplemented, as appropriate, with validated data from contributing missions from space agencies/operators worldwide (including commercial operators). Higher spatial resolution for imaging sensors is also requested.

- There is an essential need for additional and sustainable in-situ observations, which are still too sparse in the polar regions. These would not only validate space observations but also provide data that cannot be measured from space. Developing new and innovative in-situ platforms/sensors is strongly encouraged.

The proposed Copernicus polar roadmap for service evolution for the next 5 to 10 years should enable the Copernicus Services to provide fully operational and efficient services and products for the polar regions, which meet users' requirements.

LIST OF ACRONYMS

ACAP	Arctic Contaminants Action Program
ACCIBERG	Arctic Cross-Copernicus forecast products for sea Ice and iceBERGs
ACTRIS	Aerosol, Clouds and Trace Gases Research Infrastructure
AI	Artificial intelligence
AMAP	Arctic Monitoring and Assessment Programme
AOSS	Arctic Observing System of System
APIs	Application programming interfaces
ARC	Arctic Research Center
ARCOS	ARCtic Observatory for Copernicus SEA Security Service
ARCTIC ROOS	Regional Ocean Observing System
ASCAT	Advanced SCATterometer
C3S	Copernicus Climate Change Services
CAMS	Copernicus Atmosphere Monitoring Service
CARRA	Copernicus Arctic Regional Reanalysis
CDSE	Copernicus Data Space Ecosystem
CEMS	Copernicus Emergency Management Service
CIMR	Copernicus Imaging Microwave Radiometer
CLMS	Copernicus Land Monitoring Service
CMEMS	Copernicus Marine Environment Monitoring Service
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
CMS	Copernicus Maritime Surveillance Service
CO2M	Copernicus Carbon Dioxide Monitoring Mission
CO2MVS	CO2 and CH4 emissions monitoring capacity
CORDA	Copernicus reference access data
CRISTAL	Copernicus polar ice and snow topography altimeter
CSS	Copernicus Security Services
DG DEFIS	European Commission Directorate-General for Defence Industry and Space
DEMs	Digital elevation models
EC	European Commission
DG ECHO	European Commission Directorate-General for European Civil Protection and Humanitarian Aid Operations
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential climate variable
EEA	European Environment Agency
EFAS	European Flood Awareness System
EFIS	European Forest Fire Information System
EGBCM	Expert Group on Black Carbon and Methane
EGMS	European Ground Motion Service
ELF	European Location Framework
EMODnet	European Marine Observation and Data Network
EnMap	Environmental Mapping and Analysis Program

EO	Earth observation
EPPR	Emergency prevention, preparedness and response
EPSG	European Petroleum Survey Group
ERA5	ECMWF Reanalysis v5
ERCC	Emergency Response Coordination Centre
ESA	European Space Agency
ESA-CCI	ESA Climate Change Initiative
ETL	Extract-transform-load
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EUROGOOS	European Global Ocean Observing System
FAIR	Findability, accessibility, interoperability and reusability
FRP	Fire radiative power
GEO	Group on Earth Observation
GEOSS	Global Earth Observation System of Systems
GFAS	Global Fire Assimilation System
GFM	Global flood monitoring
GHG	Greenhouse gas
GHGSat	Greenhouse Gas Emissions Monitoring Service
GloFAS	Global Flood Awareness System
GMS	Ground Motion Service
GOOS	Global Ocean Observing System
GOSAT	Greenhouse gases Observing SATellite
GOSAT-GW	Global Observing SATellite for Greenhouse gases and Water cycle
GTN-P	WMO Global Terrestrial Network for Permafrost
GWIS	Global Wildfire Information System
HEO	Highly elliptical orbit
HLOP	High-level operations plan
IABP	International Arctic Buoy Programme
ICOS	Integrated Carbon Observation System
IMO	International Maritime Organization
IOM	Input output method
inSAR	Interferometric synthetic aperture radar
INTAROS	Integrated Arctic Observation System
INTERACT	International Network for Terrestrial Research and Monitoring in the Arctic
IOC	UNESCO’s Intergovernmental Oceanographic Commission
IPA	International Permafrost Association
ISC	International Scientific Council
JCOMM	Joint Technical Commission for Oceanography and Marine Meteorology
JRC	European Commission’s Joint Research Centre
KCEO	Knowledge Centre on Earth Observation
KEPLER	Key Environmental monitoring for Polar Latitudes and European Readiness
LIDAR	Light detection and ranging
MERLIN	Methane Remote Sensing LIDAR Mission
MFCs	Monitoring and forecasting centres
ML	Machine learning

MLS	Microwave limb sounder
MODIS	Moderate Resolution Imaging Spectroradiometer
MOI	Mercator Ocean International
MOSAiC	Multidisciplinary drifting Observatory for the Study of Arctic Climate
MS	Member States
NASA	National Aeronautics and Space Administration
NEC	National emission reduction commitments
NGU	Geological Survey of Norway
NMCA	National mapping and cadastral agencies
NOAA	National Oceanic and Atmospheric Administration
NORCE	Norwegian Research Centre
NRT	Near real time
NSF	National Science Foundation
PEG	Polar Expert Group
POLAR ORA-IP	Oceanic Reanalysis Intercomparison Project
Prisma	PRecursore IperSpettrale della Missione Applicativa
PTF	Polar Task Force
R&D	Research and development
RHM	Roshydromet
RNA CoObs	Research network activities for sustained coordinated observations of Arctic change
ROADS	Roadmap for Arctic observing & data systems
ROSE-L	Radar Observing System for Europe in L-band
SAFs	Satellite application facilities
SAON	Sustaining Arctic Observing Networks
SAR	Synthetic aperture radar
SCAR	Scientific Committee on Antarctic Research
SIN'XS	Sea Ice-thickness product iNter-comparison eXerciSe
SIOS	Svalbard Integrated Arctic Earth Observing System
SMOS	Soil moisture and ocean salinity
SOOP	Ship Of Opportunity Programme
SUDARCO	Sustainable development of the Arctic Ocean
SWIR	Short-wave infrared
SZA	Solar zenith angle
TACs	Thematic assembly centres
TROPOMI	TROPOspheric monitoring instrument
TSP	Thermal state of permafrost monitoring
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WCS	Web coverage service
WMO	World Meteorological Organization
WMS	Warehouse management system

INTRODUCTION

Copernicus is the Earth observation (EO) component of the EU space programme and constitutes a key contribution to the objectives of the European Union's strategies. It is a civil, user- and policy-driven programme, building on existing national and European capacities.

In the current Regulation for the EU Space Programme[2], polar monitoring is spelled out as a priority. This is in line with the 2021 EU Arctic policy[3], which describes the importance of space assets and Earth observation in following the rapid changes in the Arctic due to climate change.

The updated EU Arctic policy was launched in October 2021[4] and has three main objectives:

- contribute to peaceful cooperation in the region;
- address the issues arising from climate change;
- stimulate inclusive and sustainable development.

In the related Arctic policy action plan, the following priorities are spelled out for Copernicus:

- strengthen the capacity of the Copernicus Marine Environment Monitoring Service to address the specific needs of the Arctic Ocean;
- expand the Arctic services of Copernicus, and use knowledge and data gathered by projects like Arctic Passion;
- explore the establishment of a Copernicus Arctic thematic hub to present as a "one-stop-shop" all relevant services to monitor the poles, both inland and at sea.

Copernicus is a complete Earth observation system, ensuring availability of the full value chain from space observation to user-oriented products and tools. Currently this system includes a space component with seven European satellites in orbit, the Sentinels, developed and managed by the European Space Agency (ESA), and operated in cooperation with EUMETSAT. Future development includes six new Sentinel types, known as the "Copernicus Expansion Missions". In addition to the space component, six Copernicus Services provide operational products and information in the fields of atmosphere monitoring, marine environment monitoring, land monitoring, climate change, emergency management and security. Sentinel data is complemented by Copernicus Contributing Missions (CCMs), which enable the Copernicus Services to access data from commercial or national missions. Copernicus also includes an in-situ component that ensures coordinated access to additional data from airborne, seaborne and ground-based sensors. Earth observation data and services from Copernicus are available on a full, open and free of charge basis. Copernicus contributes significantly to Europe's competitiveness, growth and jobs in the strategic high-tech domain of space. It is also a major asset for the EU's climate and environment policies, from the local to the global level.

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[2] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R0696&from=EN

[3] https://ec.europa.eu/commission/presscorner/detail/en/ip_21_5214

[4] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021JC0027

In 2022, the European Commission set up a Polar Task Force (PTF) with external experts to form the polar dimension of the Copernicus Services, to explore coordination with other polar activities and initiatives and to determine how to optimise the use of the EU's Earth observation capabilities in implementing EU Arctic policy.

In the autumn of 2023, the task force released a user survey to collect input from the Copernicus polar user base on needs and suggestions for products, service elements and activities the Copernicus Services should implement in the next 5-10 years. The results of the survey were used by the task force as the basis for this roadmap. The roadmap also draws on the conclusions of the EU's Horizon 2020 project KEPLER (Key Environmental monitoring for Polar Latitudes and European Readiness) and the recommendations in its roadmap from 2021[5]. Although the Copernicus roadmap focuses on the Arctic and boreal regions, a separate chapter is included for Antarctica.

It should be noted that the Copernicus Security Services are not covered in the roadmap. This is because the user interaction differs from the other Copernicus Services. Moreover, the task force considered the development of services in the polar domain to be already well covered, e.g. through the strategic research agenda for the Copernicus Security Services. In addition, both Copernicus Security Services and other Copernicus services will draw on significant ongoing research work, e.g. under the Horizon Europe framework, benefiting users in the field of security and safety. This is further described in the chapter on cross-cutting activities.

This report outlines the Polar Task Force's recommendations and is organised as follows:

i. recommendations for Copernicus evolution in the Marine, Climate Change, Atmosphere monitoring, Land monitoring and Emergency management Services;

ii. recommendations on specific service elements, topics on cross-cutting activities, the European Ground Motion Service (EGMS), Antarctica, permafrost, the Copernicus Arctic thematic hub and outreach activities;

iii. recommendations on observations, with a focus on the in-situ component.

[5] https://kepler380449468.files.wordpress.com/2021/08/kepler-deliverable-report-5.2-1.pdf

COPERNICUS MARINE SERVICE

Policy, description and current status

Policy relevance

The Copernicus Marine Environment Monitoring Service (CMEMS) contributes directly to the European Union's marine and maritime-related policies and to general EU policies such as the EU Arctic policy. CMEMS particularly addresses sea ice monitoring to assess environmental, safety, economic and societal impacts. CMEMS provides key data products for a better understanding of: (i) the environment at both poles and its impact on global ocean circulation and climate; and (ii) the marine food chain and global carbon cycle. CMEMS provides improved knowledge of sea ice conditions for enhanced transport safety, ship routing and search and rescue operations.

Description and status

The CMEMS relies on a network of European marine data producers. Data collection and data processing are handled by 'production centres'. These consist of: (i) thematic assembly centres (TACs), focusing on direct processing and reprocessing of observation data; and (ii) monitoring and forecasting centres (MFCs), which provide a 3-dimensional description of the ocean's state through forecasts, analyses and reanalyses or hindcasts. All TACs can in theory include polar latitudes. Eight TACs have been defined: sea ice, sea level, in-situ, ocean colour, waves, surface wind and multi-observation products. There are seven MFCs, two of which, the Arctic Ocean MFC and the Global Ocean MFC, cover the polar latitudes.

CMEMS provides a wide range of variables, data and graphical products to describe the polar oceans. The catalogue contains essential ocean variables classified into three categories: the **blue ocean** monitors the ocean's physical state, the **white ocean** monitors sea ice parameters, while the **green ocean** monitors the biogeochemical parameters. These data come from different sources including satellite, in situ and model data, with spatial resolutions ranging from 100 m to 25 km, available from the surface to the ocean bottom and with hourly, daily, monthly and annual frequencies. Analysis and forecasting systems provide daily 10-day ranges. The catalogue offers long time series going back up to around 40 years. The ocean monitoring indicators are computed from long time series of model and observation products. These are key variables used to track the ocean's vital signs and its changes due to climate change. CMEMS' annual ocean state report provides a comprehensive and state-of-the art assessment of the state of the oceans and regional seas for the ocean scientific community and for policy and decision-makers.

Since the service's launch, more than 800 regular users from all over the world have downloaded polar ocean products, with European countries remaining by far the most representative. The products are being used in more than 1 000 organisations, mainly for scientific studies at universities and in the public sector.

Gaps and limitations

CMEMS has provided a strategy to develop the service for the entire second operational phase of Copernicus, i.e.. 2021-2027. The strategy was updated in December 2023. The Arctic is the only ocean basin identified as a priority area for dedicated operational monitoring by CMEMS. The points mentioned for improvement in the strategy stem from shortcomings and limitations already identified through CMEMS' user feedback. The Horizon 2020 KEPLER project provided a roadmap for a European end-to-end operational system based on a comprehensive list of gaps and limitations in oceanic monitoring and information. Together with the PTF user survey, this yields the following identified main gaps and limitations.

The relevance of observations for system evolution

The current lack of in-situ data for product validation/verification and assimilation into models constitutes a considerable gap. Of high interest are in-situ data related to snow and sea ice parameters, essential physical variables (salinity, temperature) and, more generally, essential biogeochemical variables (e.g. pH, O2), as well as coastal water quality biological components (e.g. dissolved organic matter, turbidity). Another major issue is the lack of a comprehensive in-situ (sea ice) data repository. For more detail see: (i) the document on developments in the in-situ component in CMEMS; and (ii) the 'Observations' chapter of this document.

Description of floating ice

In general, greater accuracy can be expected by improving models and assimilation methods in the

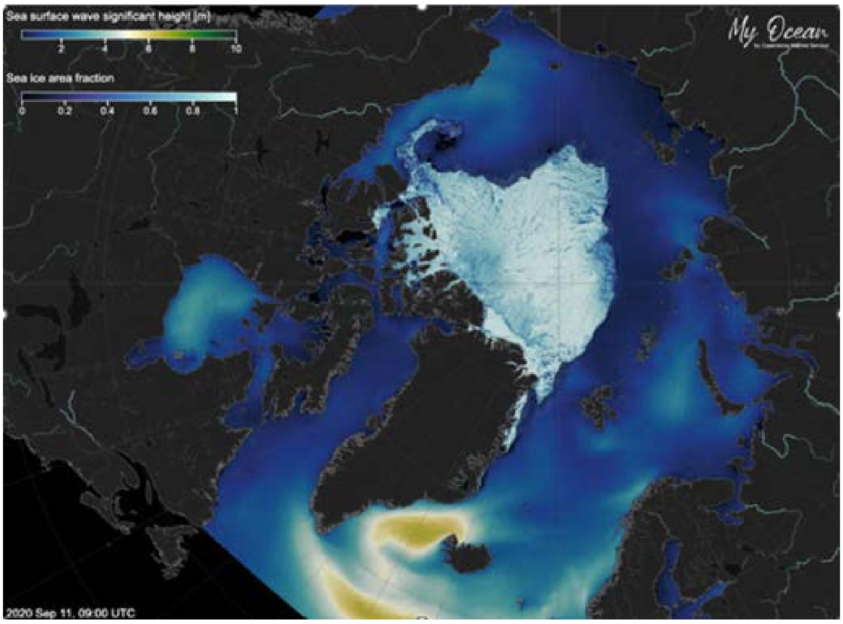

Figure 1: Sea ice area fraction and significant wave height for 11 September 2020 from the Arctic MFC 3 km resolution

operational system. This is particularly true for sea ice dynamics (rheology) and thermodynamics (melt ponds), with interaction processes involving sea ice interfaces (waves) and the life cycle of snow on sea ice. Current assimilation methods deployed in CMEMS are highly advanced in blue ocean physics and master multi-variety and multi-data approaches (altimetry, in-situ profiles, L4 sea ice concentration and L3 sea surface temperature satellite data). For sea ice, the assimilation of L4 sea ice concentration has been used for a long time, but the multi-varied approach is still very recent and operational implementation is still in its infancy. The situation is even worse for biogeochemistry, where the lack of data prevents a realistic constraint by data assimilation.

A more complete portfolio of sea-ice variables (e.g. melt ponds, pressure ridges) is needed to better describe sea ice cover. Furthermore, the provision of surface air/ ocean-sea ice fluxes is needed to close energy, mass and momentum budgets.

A recurring requirement is the provision of: (i) higher spatial resolution (10 m or even better) for SAR data; and (ii) data from SAR operating at different frequencies such as L-band (as will be provided by the future Copernicus ROSE-L mission) and X-band. Similar requirements exist for higher spatial resolution passive microwave radiometer and thermal infrared data.

Analysis and forecasts are missing for iceberg monitoring. The uptake of the ACCIBERG Horizon Europe project will be a significant first step that will provide tools to monitor icebergs and iceberg trajectory forecasts using Copernicus data.

Boosting the capacity of the service

Users of the service are requesting better spatial and temporal resolution, and reduced latency of model forecasts and remotely sensed observations. However, the very high (less than 100 m) resolution required by end-users cannot currently be attained by operational systems on a pan-Arctic scale. There are many reasons for this, including computing and storage capacities, new physics, model evaluation and assimilation systems. These requests are unlikely to be fulfilled within this Copernicus period (2021-2027) and new ways to fulfil the demand should be explored, e.g. using deep learning methods (downscaling).

At present, CMEMS does not provide any information on uncertainties. An ongoing change of paradigm is the move to approaches (including stochastic/ensemble-based) to systematically produce 'reliable' uncertainty estimates associated with reanalysis, nowcast and forecast products. This is crucial for eddy resolving-type modelling systems, as mesoscale dynamics limit their predictability. In CMEMS, only the ARC MFC has implemented the ensemble approach capacity. The probabilistic products which such systems provide will be ideally suited to the needs of stakeholders and users, in particular as far as decision-making is concerned. Alternatively, AI techniques can be used to infer uncertainty estimates.

Southern Ocean

The current operational service in the Southern Ocean is part of the Global MFC. Putting in place a dedicated service (TAC and MFC) for the Southern Ocean and

Antarctica constitutes a substantial challenge (cf. the section on Antarctica).

Recommendations

Based on the points discussed above, the Polar Task Force made several recommendations for the further development of CMEMS in the polar domain, within the following categories:

Improved observational products

Expanding the CMEMS catalogue with in-situ sea ice observations should be explored. It is recommended to propose a roadmap at European level to put in place a permanent and well-maintained in-situ sea ice repository designed for operational applications.

Advanced signal processing and data science/AI methods should be developed to explore downscaling and to enhance multi-sensor fusion and quality of combined polar regions Earth observations, targeting sea ice age, melt ponds, albedo, snow thickness, detection of leads and iceberg tracking.

The possibility of introducing a framework that facilitates dialogue and discussions with information providers should be addressed, along with: (i) the introduction of new multi-sensor products for risk assessment; and (ii) development of a system that can provide overlapping information for users to choose from, for decision-making in near real-time activities.

Model and assimilation enhancements

CMEMS has identified a series of priorities, set out below. These cannot be entirely dealt with by Copernicus alone and could be considered as part of external collaborations and projects. Specifically, these recommendations are:

- encouraging the development of improved sea ice models for a better description of polar oceans and to provide users with additional quantities;
- basing sea ice models on a more realistic rheology, on better interactions and coupling with surface waves, with the upper ocean layers in general, with the snow layer and its life cycle and with the melt ponds schemes;
- examining in an operational context: (i) a new generation of sub-kilometre-scale dynamic sea ice models able to resolve ice floes; and (ii) specific development for modelling the marginal ice zone. The representation of biological cycles in and under the sea ice should complement the role played by sea ice in marine ecosystems;
- guaranteeing continuous investment in the development of reanalysis, high-resolution forecast systems and appropriate data assimilation techniques;
- providing R&D to advance on assimilating essential variables measured by satellites and made available to the scientific and operational community (sea ice surface temperature, sea ice drift, sea ice thickness, ice types and sea surface salinity);
- studying the viability of assimilating satellite information at lower processing levels (L1 and L2) to better control remote sensing measurements within the analysis and forecasting systems, in closer collaboration with data providers.

Enhanced product lines from forecasting and reanalysis

Long-term R&D activities are as crucial as short and mid-term activities for development towards an integrated Arctic Ocean monitoring and forecasting capacity.

Moving towards an ensemble/probabilistic forecasting capacity with extended (monthly) range forecasts is already part of CMEMS strategy and remains a very substantial change. An incremental approach is to be expected. The Horizon Europe ACCIBERG project partly addresses approaches to calibration of sea ice concentration forecasts. A large archive of reforecasts for calibration and machine learning approaches will need to be explored.

It is important to develop the quality metrics of sea ice products to meet the requirements of the large number of end-user applications. The existing assessment needs to be enhanced, with a dedicated plan and roadmap, one that will also consider external metrics and the assessment of ocean monitoring indicators. It appears that linking validation/verification experts from the MFCs with the ocean community's OceanPredict[6] initiative for the Arctic or the poles would be highly relevant for the UN Decade of Ocean Sciences for Sustainable Development (2021-2030). Furthermore, an initiative of the POLAR ORA-IP (Oceanic Reanalysis Intercomparison Project) type should be renewed to assess the state of current reanalysis at the poles. Progress on operational systems should also be shared within the ARCTIC ROOS forum, which is contributing to the UN Ocean Decade.

[6] https://oceanpredict.org/

The Copernicus seasonal prediction service should be complemented by the development of capabilities for producing seasonal forecasts of marine environment changes in the Arctic (e.g. physics, biogeochemistry, biology and high trophic levels, including the main exploited fish species).

Cross-cutting activities

Copernicus services ensure cross-cutting interfaces to improve products and offer better consistency in products and services. For instance, the ambition to close the hydrological balance at Arctic basin scale cannot be achieved without interactions between C3S, CEMS and CMEMS. Surface properties of atmospheric reanalyses from C3S are used to drive CMEMS' reanalysis and the Global Flood Awareness System (GloFAS) from CEMS, and initial developments are under way for CMEMs' use of GloFAS rivers outflow. Quantification of uncertainty and biases in these C3S reanalyses is then needed to improve state estimates of the ocean and the river discharge reanalysis. Other cross-service applications include the monitoring of coastal erosion along the Arctic under climate change, and iceberg drift forecasts such as those developed by the HE ACCIBERG project.

In general, better consistency of datasets and products across the different domains of land, ocean and atmosphere is desirable, and efforts are needed to develop modelling systems that couple the different domains. This will eventually result in higher-quality products for each domain, to the benefit of users, and in better understanding of the energy and water budgets in polar regions.

For instance, surface properties of atmospheric reanalyses are used to drive ocean models, while quantification of uncertainty and biases in these reanalyses is needed to improve state estimates of the ocean.

Variations in Arctic river discharge are very important for freshwater, heat and nutrient fluxes into the ocean, but current modelling systems lack a direct link to atmospheric precipitation. Developing coupled (re-) analysis and forecast products that incorporate these links offers potential to close the Arctic water cycle, leading to improved products across the ocean and land domains.

The **ARCOS** (ARCtic Observatory for Copernicus SEA Security Service) Horizon 2020 project comes under the remit of Copernicus Security Services. Due to its cross-cutting nature, it is also of relevance for the Copernicus polar domain.

COPERNICUS CLIMATE CHANGE SERVICE

Background and policy relevance

Climate change has profound impacts in the polar regions. Warming is stronger than anywhere else on the planet, and the thawing of the cryosphere has far-reaching consequences for local ecosystems, human activity in the regions, and even for weather and climate beyond the polar regions. Each year, the Copernicus Climate Change Service (C3S) publishes the *European State of the Climate*[7], which includes chapters dedicated to the polar regions.

Current portfolio

C3S provides a wide range of data and graphical products relevant to the polar regions. These cover the land, atmosphere and ocean domains, and span the past, present and future time ranges. In 2023, more than 10 000 users from over 170 countries accessed polar-related C3S products (Fig. 2). Most active users identified themselves as being from the academic sector. C3S also offers a range of education and training resources – these currently do not cover the specificities of polar regions but should do so in future, given the polar regions' crucial importance in the context of climate change.

At the time of writing, the C3S portfolio contains 134 products: 36 for climate projections, 14 for in-situ observations, 40 for reanalysis, 37 for satellite observations, and 12 seasonal forecast products. Many of these products are relevant in the polar regions because they are either global datasets (85 in total) or have a polar or cryosphere regional focus (about 25 in total). Examples of global products relevant to polar regions are the ERA5 reanalysis and the CMIP5 and CMIP6 climate projects; examples of dedicated polar products are the CARRA Arctic reanalysis and the gravimetric mass balance for the Antarctic and Greenland ice sheets from satellite data. While there are quite a few non-global products that cover Arctic regions, the portfolio currently only contains four non-global products that are relevant in Antarctica (sea ice edge, sea ice concentration, ice sheet mass balance and ice sheet surface elevation change rate); all four of them are satellite observation products.

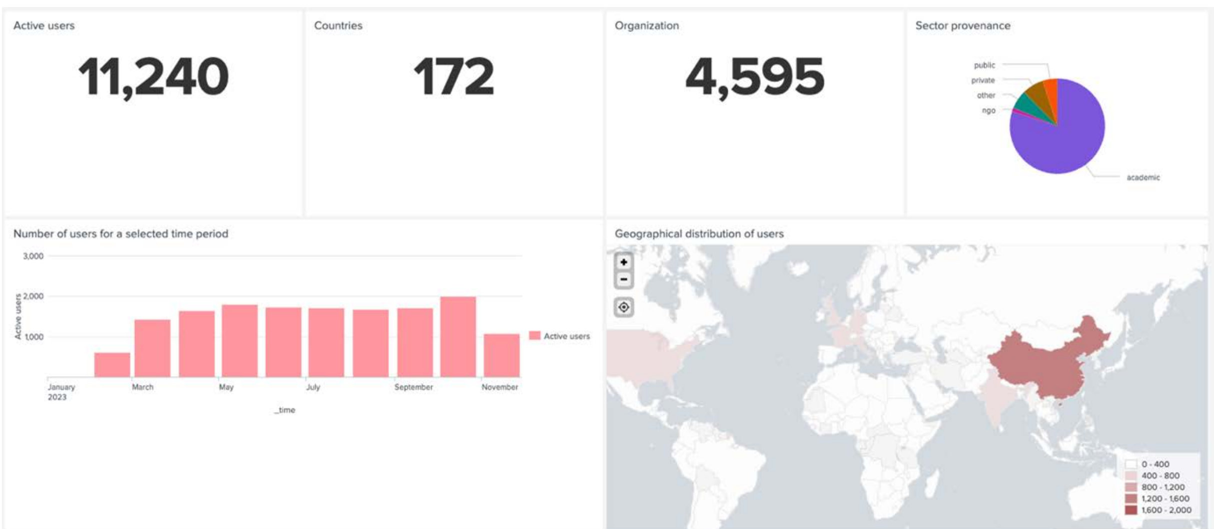

Figure 2: Active users for popular C3S products relevant in the polar regions (2023)

[7] https://climate.copernicus.eu/ESOTC

Gaps and limitations

Copernicus space observations

Observations from satellites are crucial for developing climate data records and reanalyses in the polar regions, and for developing and initialising Earth system models that can produce predictions and projections of future climate in the polar regions.

The uncertainty of satellite-derived observations of sea ice thickness and snow depth on sea ice currently hampers uptake of observations for model development and verification, as well as data assimilation. In this context, concerted efforts are needed to better quantify uncertainties for these parameters, possibly following the example of the ongoing ESA-funded sea ice thickness intercomparison project SIN'XS.

In addition, the fusion or merging of data from the current Sentinels and Next Generation Sentinels and from Expansion Missions should be further developed, so that climate data records can be constructed reaching back as far as possible. An example of such an activity is the construction of sea ice thickness datasets from radar freeboard observations onboard the Envisat, Cryosat-2 and Sentinel-3 missions.

In-situ observations

About 10 datasets containing in-situ observations in polar regions are currently available from C3S, for instance atmospheric profiles from the GRUAN reference network and global marine surface observations from 1851 to 2010. These are essential for calibration and validation of satellite remote sensing products, as well as verification and initialisation of weather and climate models. In-situ observations are also invaluable for process studies and developing parameterisations of sub-grid processes in weather and climate models. We recommend continuing such an approach, where in-situ observations form a basis for spatio-temporal scaling: from point measurement to ground remote sensing to airborne remote sensing (or regional numerical models) to satellite remote sensing and finally weather and climate models. Further discussion can be found in the 'Observations' chapter.

Climate monitoring

C3S provides a number of climate data records relevant for the polar regions. Among these are several related to sea ice, such as ice edge and type, concentration and thickness. Additional key sea ice parameters are needed, namely melt-pond fraction, snow depth, albedo, and lead fraction. Copernicus should support research and development activities to make these observation types ready for inclusion in the C3S portfolio. The already included climate data records for sea ice drift need to mature further.

Several products related to ice sheets are already available. These include mass balance, elevation changes and velocities, as well as products on glacier mass change and extent. There is demand for additional glacier and ice shelf products such as grounding line location and surface melt extent.

Thawing of permafrost in a warming climate is a major concern because of its direct detrimental impact on infrastructure in the Arctic regions and the associated release of methane and CO_2. Yet no permafrost monitoring products are currently available from C3S. As the research on developing these matures, supported by programmes like the ESA-CCI projects, they should be taken up by C3S at the earliest appropriate stage of development. For more see the cross-cutting section on permafrost.

Reanalysis developments

Atmospheric reanalyses are among the most widely used products of C3S, and their continued development and improvement should have high priority. Currently available reanalyses covering the polar regions are the 'ERA5' global reanalysis and the 'CARRA' regional Arctic reanalysis covering the Greenland and Barents Sea regions. Future developments in global reanalysis will provide higher spatial resolution, improved model physics and use more and better observations. Known issues with surface temperatures in polar regions need to be addressed in future developments, especially over sea ice. For the CARRA regional reanalysis, an update is planned that will for the first time cover the whole Arctic domain, together with substantial enhancements of land surface processes, including snow on sea ice. There is currently no regional reanalysis for Antarctica available from C3S.

Going forward with these developments, it will be important to keep improving the representation of surface processes in the reanalyses. This is both because of the practical relevance to users and because these reanalyses are critical for producing model-based estimates of ocean circulation, sea ice and land surface. In particular, representing the atmosphere's interaction with glacier, permafrost and sea ice surfaces requires improvements.

Improved consistency between C3S reanalysis products in polar regions should be targeted. One way of achieving this is to develop strategies to perform coupled reanalyses of the atmosphere, ocean and land surface together. Such efforts are already under way and should be strengthened. Improved consistency between domains is also key to faithfully representing and closing the energy and water budgets of the polar regions, which is essential to produce accurate climate predictions and projections.

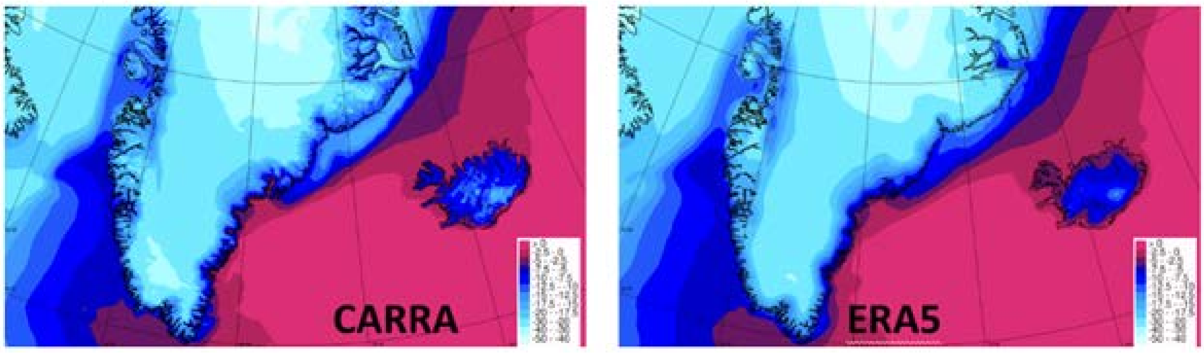

Figure 3: 2 m air temperature over Greenland and Iceland on 15 February 2014 0 UTC for CARRA (left) and ERA5 (right). Figure from CARRA user documentation.

Climate predictions and projections

Currently, the C3S catalogue provides global seasonal predictions from five European forecast models, plus contributions from Canada, the US and Japan. The product's multi-model character enables users to estimate the structural uncertainty of the forecast. This is particularly relevant in the polar regions, where uncertainty in climate predictions and projections is expected to be particularly high due to poor observational coverage and deficits in modelling and initialising the cryosphere. Sustained efforts to improve seasonal predictions in the polar regions are needed, building on the legacy of the WMO Polar Prediction Project and other programmes.

New data products are being added for seasonal forecasts based on user requests and the available levels of forecast skill. In the Marine Arctic, the presence of sea ice is a major factor for industry, shipping and fishing, and there is substantial demand to improve sea ice climate predictions and projections to aid with long-term planning and policy decisions. To fulfil this demand, major investments in improving ocean and sea ice models are needed, as well as assimilation of satellite and in-situ observations. In particular, the modelling and initialisation of sea ice thickness needs to be improved, as there is currently a lack of consistency between different atmosphere and ocean reanalysis products, and insufficient representation of climate trends and a changing observing system.

Quantifying the skill of seasonal predictions in polar regions requires dedicated efforts, as the fast change in the mean state needs to be taken into account. To help with interpretation and user relevance, seasonal predictions should be provided together with a characterisation of their uncertainties and expected level of skill.

There is user demand for seasonal forecasts of biogeochemical variables both over land and in the sea, and for further development of climate projections for bioclimatic indicators.

Recommendations

Several gaps and limitations have been identified in the previous sections. To address these, the Polar Task Force makes the following recommendations for developing the Copernicus Climate Change Service:

Observations and climate monitoring

- support the development of back-extensions of climate data records such as sea ice thickness;
- maintain and expand the catalogue of climate-quality in-situ observations;
- provide additional cryospheric parameters related to sea ice, ice sheets and glaciers;
- add permafrost climate data records to the portfolio.

Reanalyses

- increase spatial resolution and introduce pan-Arctic coverage;
- provide a regional reanalysis for Antarctica;
- improve representation of surface processes in polar regions, especially over glacier, permafrost, and sea ice surfaces;

- improve consistency between different reanalysis products and provide closed energy and water budgets for the polar regions;
- drive the development of coupled reanalysis systems to achieve the above two targets.

Climate predictions and projections

- for seasonal predictions, take into account the strong climate trends in the polar regions when constructing and presenting forecasts;
- invest in improving high-latitude ocean model quality and sea ice models, as well as more assimilation of novel observations such as sea ice thickness;
- provide seasonal forecasts of biogeochemical variables.

Cross-cutting topics

- dedicated efforts to improve consistency of climate datasets and products across land, ocean and atmosphere;
- develop products for Arctic river discharge that have a direct link to atmospheric precipitation and can be used as freshwater input to the Arctic Ocean in reanalyses, predictions and projections;
- foster collaborations with partners outside Europe such as third-country space agencies and international research programmes;
- further explore the use of machine learning to improve C3S products, for instance to correct biases, downscale global datasets to regional scales, or to merge data records across different satellite instruments;
- develop collaborations with partners outside Europe, as this will be essential to improve Copernicus' climate services in the polar regions. This concerns collaborations with other space agencies, to ensure best use is made of satellite missions, but also with international research programmes to ensure that in-situ observations collected by any nation are shared internationally. For the Arctic, international expertise and collaboration gathered in the WMO Arctic Regional Climate Centre should be leveraged for developing C3S.

COPERNICUS ATMOSPHERE MONITORING SERVICE

Background and policy relevance

The Copernicus Atmosphere Monitoring Service (CAMS) provides continuous data and information on atmospheric composition by monitoring and forecasting constituents such as greenhouse gases, reactive gases, and ozone and aerosols. CAMS delivers consistent and quality-controlled information useful in developing applications for air pollution, greenhouse gases and climate change-related topics, health and solar energy that can help policymakers, businesses and the public address environmental concerns.

CAMS supports the implementation of the EU Arctic policy by providing services and products relevant for monitoring climate change and air pollution such as CH_4 fluxes and black carbon deposition, directly addressing topics highlighted in the EU Arctic policy This provides additional support through science for diplomacy, as these products are also relevant for the activities of the Arctic Council and several of its working groups and expert groups, in particular AMAP (pollution, black carbon, permafrost), EPPR (wildfires), ACAP (black carbon), and the EGBCM (black carbon, methane). The relevance of black carbon for the Arctic has also been stressed in the EU Arctic policy. CAMS also supports non-polar specific EU directives such as the National Emission Reduction Commitments Directive (NEC Directive).

The polar survey identified emissions of methane and carbon dioxide, deposition of black carbon, wildfires and stratospheric ozone as the most relevant CAMS parameters and processes for the polar regions.

Portfolio overview

Wildfires

Climate change makes the Arctic more vulnerable to wildfires through changes in fuel availability (e.g. poleward expansion of vegetation and permafrost thaw) and drier and warmer conditions impacting fire risk and behaviour. Research is needed to better understand the key contributors of fuel availability (including peat and organic soils), ignition sources (including lightning and hold-over/zombie fires), and fire behaviour in Arctic regions. High-latitude wildfires are a concern for air quality and potential health impacts on local populations, and for the increased risk of black carbon deposition on snow and ice in the Arctic, potentially accelerating melting.

The CAMS Global Fire Assimilation System (GFAS) assimilates fire radiative power (FRP) observations from satellite-based sensors to produce daily estimates of wildfire and biomass burning emissions. It also provides information about injection heights derived from fire observations and meteorological information from the operational weather forecasts of the European Centre for Medium-Range Weather Forecasts (ECMWF).

Black carbon

Although the Arctic regions are mostly far away from human activity, long-range transport of aerosols from industry, shipping and increasingly from wildfires reach the Arctic regions, where the aerosols are deposited on the ground. In addition to long-range transport, gas flaring during oil extraction can have a strong impact on the deposited amount. Dark aerosols such as black and brown carbon are impurities, which potentially decrease the albedo of snow and ice surfaces and increase the absorption of solar energy at the surface. The CAMS system already simulates emission, deposition and long-range transport of these pollutants, but in-depth studies are required for inferring climate change impact. Better understanding of the radiative feedback of aerosol deposition on snow and ice on weather and climate is desirable, but is a challenging research goal.

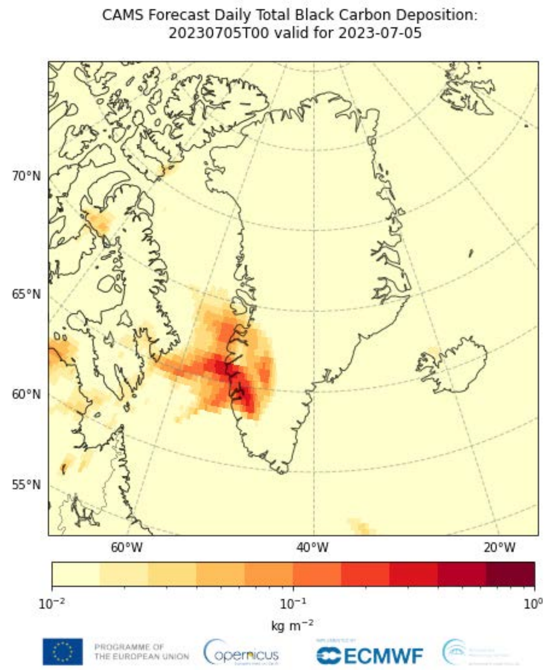

Figure 4: CAMS forecast daily total black carbon deposition on 5 July 2023 due to smoke from wildfires in Quebec. High values of deposition over Greenland were forecast to last for several days.

Stratospheric ozone

Stratospheric ozone monitoring (ozone hole over Antarctica, mini ozone holes, and ozone depletion in the Arctic) is a key task in CAMS. The global CAMS system was recently updated to explicitly simulate stratospheric chemistry to better model the underlying chemical causes for stratospheric ozone loss. This also makes it possible to assimilate other chemical species into the global CAMS system in the future. However, this will require high-quality satellite retrievals of stratospheric species, profile data and nighttime observations.

Methane

In Arctic regions, wetlands and freshwaters (lakes and rivers) represent the largest natural terrestrial sources of methane, with a smaller contribution coming from wildfires. Marine sources are represented by gas hydrates and the decomposition of organic carbon in subsea permafrost areas.

Anthropogenic sources of methane in Arctic regions are mostly oil and gas production, and gas leakage from gas distribution. These emissions are relevant for United Nations Framework Convention on Climate Change (UNFCCC) reporting and the evaluation of emission reduction efforts through the global stocktake exercises.

Current CAMS services in the context of CO_2 and CH_4 monitoring include:

- observations of greenhouse gases;
- computer simulations of the atmosphere;
- monitoring fluxes and emissions;
- services related to anthropogenic emissions.

A new CAMS CO_2 and CH_4 emissions monitoring capacity (CO2MVS) is currently being developed and is expected to be operational by 2026. This will significantly increase the information provided on GHG emissions globally.

Gaps and limitations

Wildfires

- The largest limitation is the observation of fire radiative power in the infrared spectrum. This is due to the age of the MODIS satellite-based sensor and to Sentinel-3 being an insufficient replacement because of orbit and quality issues during daytime.

- The quality of GFAS products is further limited by uncertainties regarding vegetation maps and maps of peat and permafrost, which are needed to specify the correct biomes providing fuel for fires.

- Currently the modelling is tuned for the tropics, where certain characteristics, e.g. regarding the diurnal cycle, are quite different from high latitudes.

- Spurious signals in the infrared observations emanating from gas and oil flaring cause additional problems.

- Burned areas are not available in near real time and are not included in GFAS. Non-real time estimates are available in the Global Wildfire Information System (GWIS), a joint initiative of the Group on Earth Observation (GEO) and the Copernicus work programmes: https://gwis.jrc.ec.europa.eu.

- MODIS observations may be limited by smaller fires below the instruments' detection threshold or by the presence of clouds, meaning that the instruments are not able to observe the surface.

Black carbon

- Black carbon deposition is currently not available in the reanalysis.
- Data continuity is at risk due to the age of the MODIS instrument.
- Current atmospheric correction algorithms cannot effectively process observation data with solar zenith angles greater than about 70 degrees, which is a severe limitation for the polar areas.

Ozone

Data continuity is at risk due to the age of the microwave limb sounder (MLS) onboard the Aura satellite.

CH_4 and CO_2

Satellite retrievals of methane and CO_2 over the polar regions are impacted by the following issues:

- long periods of darkness;
- large solar zenith angle;
- frequent cloudiness;
- water surfaces (coastal areas and lakes) and snow have a low albedo in the short-wave infrared range

Thus, coverage for passive instruments is not truly global. For example, in the case of the TROPOMI instrument, measurements are cut off at a solar zenith angle of 70°. At a latitude of 58°, this means that observations are not useful between mid-October and mid-February. During the winter peak, this issue affects latitudes as low as 45°. The MERLIN mission, with its active LIDAR instrument and launch readiness anticipated for 2027, is expected to resolve some of the polar observation issues. Preliminary data are available from the airborne CoMet 2.0 Arctic campaign, using the same instrument type that will be used on MERLIN.

The CAMS inversion currently does not provide CH_4 fluxes from thawing permafrost, hydrates or geologic sources.

Area flux mappers like Sentinel-5P or GOSAT are primarily designed to quantify total methane emissions on regional to global scales, but their relatively coarse resolution is often not sufficient to identify the source of the detected plume. On the other hand, point source imagers like Sentinel-2, Prisma, EnMAP or the GHGSat satellites quantify emissions from individual point sources by imaging the atmospheric plume. MethaneSat, launched 2024, though also an area flux mapper, does not provide continuous global coverage but rather retrievals over target areas of 200x200 km2, with a high resolution of 130x400 m2.

Recommendations

Survey participants highlighted the following topics of relevance to CAMS: methane products, ERA5, the ESA's CCI_Permafrost project, ozone, permafrost and CO_2 exchange, quasi real time wildfire monitoring, forest and vegetation fires, black carbon deposition on snow and ice, clouds, and aerosols over snow/ice. This made the basis of the Polar Task Force's recommendations for the evolution of CAMS, which is described below:

Wildfires

- Regular updates of vegetation, peat, and permafrost maps.
- Inclusion of burned areas in addition to active wildfires.
- Optimising the data assimilation system and models for fires at high latitudes.
- More research to better understand how to filter out spurious signals.

Black carbon

- Include black carbon deposition on the ground in the reanalysis.
- Include observations from TROPOMI on Sentinel-5P and Sentinel-5 onboard MetOp-SG A (expected for 2025) in the assimilation. This would ensure continuity of data, particularly given the anticipated termination of MODIS data streams.
- Look into the possibility of improving the assimilation procedure at high latitudes by assimilating data from Aeronet stations, or by exploring alternative algorithms based on e.g. machine learning techniques.

Ozone

The remaining operational lifetime of the microwave limb sounder is limited. If a new microwave limb sounding instrument becomes available in the future, it is recommended to use retrievals from this instrument (see the 'Observations' chapter).

CH_4

- Ongoing activities to include retrievals from the TROPOMI instrument on Sentinel-5P for the assimilation of CH_4 should be finalised and considered for the inversion, taking advantage of TROPOMI's higher spatial resolution and improved global coverage compared to GOSAT's GHG sensor. Once available, additional methane retrievals from GOSAT-GW, Sentinel-5 and CO2M should be investigated for inclusion in the assimilation and/or inversion process. The expected launch dates are 2024, 2025 and 2026 respectively.

- The complementary features of area flux mappers and point source imagers should be exploited by first identifying areas of interest with area flux mappers, and then zooming in with point source imagers to identify the precise locations of the methane source for areas of interest.

- Data from MethaneSat should be used to increase understanding of methane dynamics on smaller scales in Arctic regions.

- The limitation on retrieving methane over dark surfaces can be addressed by using observations in sun-glint mode over those areas. It is worth exploring whether operation in sun-glint mode can be used as the default to facilitate exploiting this feature.

- Data from the MERLIN mission should be considered for use in the CAMS reanalysis and inversion once available.

- Additional XCH_4 column products might be taken up from ESA's GHG-CCI+ project and used in the assimilation process or for inverse modelling.

- In the CAMS inversion, separate fluxes should be provided for CH_4 fluxes from thawing permafrost. Priors could be created from data provided by ESA's MethEO or MethaneCAMP projects for terrestrial permafrost, and from the Nunataryuk Horizon 2020 project for subsea permafrost. Flux data might also be available through the Arctic Methane and Permafrost Challenge (AMPAC) project, an ESA/NASA collaborative initiative.

- Winter CH_4 emissions should be constrained with freeze/thawing (F/T) data (e.g. from SMOS), which has been shown to improve inversion results.

COPERNICUS EMERGENCY MANAGEMENT SERVICE

Background

The Copernicus Emergency Management Service (CEMS) provides support to all actors (typically civil protection authorities) involved in the management of natural or man-made disasters. It also provides timely and detailed geospatial information for decision-making. CEMS covers the whole disaster cycle, including prevention, preparedness, response and post-event information on damage and recovery. CEMS products are created using satellite imagery, in-situ (non-space) and model data. CEMS is managed directly by the European Commission via the Joint Research Centre (JRC), which issues warnings and risk assessments for floods, forest fires and droughts. Operational coordination, including interfacing with users and authorising activations, is the responsibility of DG ECHO's Emergency Response Coordination Centre (ERCC). CEMS has been operational since 2012.

Activations for Arctic regions and Nordic countries are primarily concerned with floods and fire events.

Policy relevance

The EU has a unique role to play in the Arctic. Many of its Member States are observers in the Arctic Council, with three serving as members. The EU also has institutional linkages with two additional states, Iceland and Norway, through the European Economic Area.

CMES is fully in line with the 2016 integrated European policy for the Arctic, which highlighted the EU's three main priorities in the region: (i) first and foremost, climate change and safeguarding the environment; (ii) sustainable development; and (iii) the role of the EU as a civilian power to promote international cooperation in the Arctic. The new EU Arctic policy, which was published in October 2021, renews Member States' commitment to addressing climate change and environmental protection, making a stronger link with the EU Green Deal. Both the EU Arctic policy and the EU Space Programme Regulation, which entered into force in 2021, explicitly spell out polar monitoring as a priority.

Status/portfolio overview

CEMS is divided into three main modules:

- early warning and monitoring (fires, floods and droughts);
- on-demand mapping (rapid mapping and risk & recovery);
- exposure mapping (not relevant in the context of this roadmap).

The early-warning and monitoring services of interest to polar regions include **EFAS** (European Flood Awareness System) and **EFFIS** (European Forest Fire Information System). These are briefly described below.

EFAS is designed to support preparatory measures for flood events across Europe, particularly in large transnational river basins. To this end, EFAS relies on a hydrological forecasting chain, including meteorological forcing and land surface data and hydrological models.

The CEMS' Global Flood Monitoring (GFM), launched in 2022, provides fully automatic Sentinel-1 based flood monitoring. The monitoring covers the Arctic and boreal regions. In addition, the European and Global Flood Awareness Systems (GloFAS) provide complementary flood forecasts for the Arctic regions, except for glacier-covered areas in Greenland.

EFFIS supports services in charge of protecting forests against fires in EU Member States and provides the European Commission and Parliament with updated and reliable information on wildland fires in Europe. In the coming years, CEMS envisages the service developing to include the Global Wildfire Information System (GWIS). This will enable regular wildfire monitoring and fire danger forecasts for the entire Arctic circumpolar region.

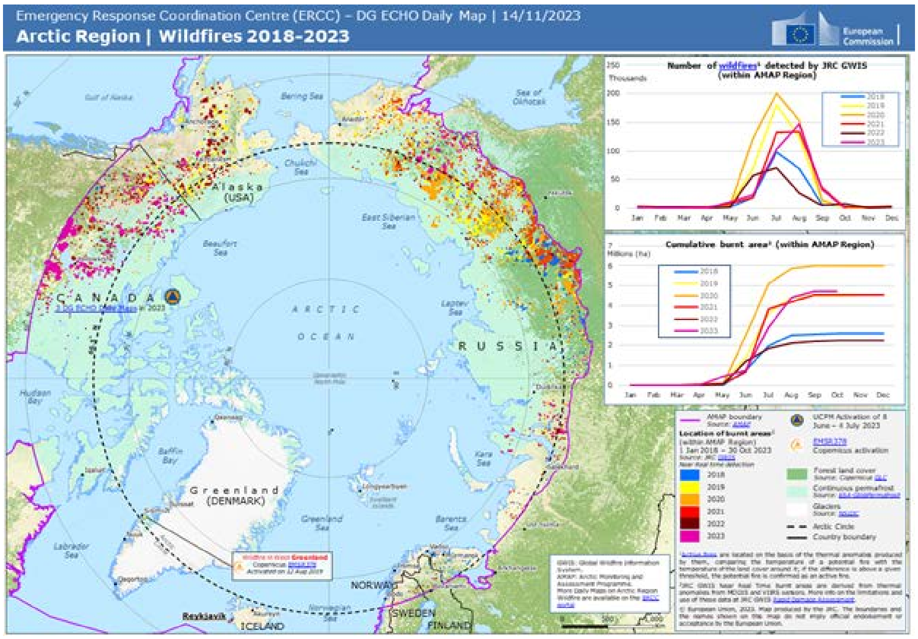

Figure 5: Overview of wildfires monitored in the Arctic region between 2018 and 2023, with estimated burnt areas provided by the GWIS

On-demand mapping

CEMS provides emergency mapping assistance in countries above 60 degrees latitude, with 17 activations in Finland, Greenland, Iceland, Norway and Sweden since 2012.

Most of the assistance provided was for floods (65%). During these activations, maps based on near real time) acquired satellite images are provided to the national authorities for situational awareness: flood extent is delineated and regularly updated until flooding begins decreasing. In recent years, wildfires and volcanic eruptions have also been monitored by CEMS rapid mapping, following requests from Danish and Icelandic authorities. While SAR satellite imagery is typically used to monitor floods, optical satellite imagery is instead analysed to delineate the burned area or lava flow, and to assess damage to infrastructure such as roads and buildings. In recent years, there have been several requests for CEMS on-demand activations in the boreal zone and in Greenland to evaluate wildfire damage.

For events other than floods and forest fires, only a few CEMS activations were requested. Examples include activations in Norway for wind/storms in November 2021 and in Greenland for icebergs in July 2018.

CEMS data requirements

The CEMS mapping component requires a range of basic reference data on topography (natural land surface and man-made features), as well as risk-related information (population distribution, event probability). It also relies on the availability of, and rapid access to, geometrically corrected, georeferenced pre- and/or post-event imagery (ortho-imagery) as well as digital elevation models of the affected or risk-prone areas. Datasets with global coverage are preferred (where they exist); alternatively, regional or national datasets are considered. Availability of meteorological and hydrological conditions during the events is also essential for the mapping.

Today, ortho-imagery (georeferenced and geometrically corrected imagery) can be provided by a variety of high- to very high-resolution optical sensors (e.g. Pleiades, SPOT 6&7, DEIMOS, Sentinel 2 ...) and by high-resolution, all-weather, day-and-night SAR sensors (e.g. Sentinel 1, Radarsat, TerraSAR-X, PAZ, CosmoSkyMed, ICEYE, ...). Medium-resolution sensors (MODIS, VIISR, ...) are also of interest for the wide geographical coverage they provide.

Digital elevation models (DEMs) are most commonly used for ortho-correction of satellite imagery, but also to support the extraction of post-crisis information and as an input to modelling. DEMs provide a representation of continuous elevation values over a topographic surface by a regular array of height values, referenced to a common vertical datum. They can currently be provided by all-weather SAR sensors using InSAR interferometry techniques based on current SAR missions (Sentinel-1, TerraSAR-X, CosmoSkyMed, PAZ operating at C and X-bands, …).

Recommendations

The Polar Task Force made the following recommendation for development of CEMS in the polar domain:

- Improve timely availability of ortho-imagery and make it accessible through direct download or standard web services (e.g. WMS or WCS) to meet demanding CEMS requirements.
- Ensure that pre-event imagery acquisition is generally not older than 2 years.
- Give high priority to expanding the availability of digital elevation models on a pan-Arctic scale and more generally in polar regions, as described in the chapter on the European Ground Motion Service. Use of future SAR missions (e.g. ROSE-L SAR at L-band) is recommended.
- Make digital elevation models accessible through direct download or at national/regional level. This is generally provided by the authorised user or downloaded through the CORDA (Copernicus Reference Access Data) portal, especially for the Risk and Recovery Mapping Service.

Gaps, limitations and recommendations for in situ data in the Copernicus Emergency Management Service

The main challenge is to access and exploit in-situ data within the demanding emergency management timeframe (delivery within hours to days). Service providers need information in advance (access details, data formats/models) to develop ad hoc extract-transform-load (ETL) procedures. In some cases, access must be granted by national mapping and cadastral agencies (NMCAs). Technical and infrastructure-related restrictions (such as downtime and file size limits) also play a role.

For reference topographic datasets and pre-event aerial ortho-imagery, global datasets are often insufficient (in terms of coverage, accuracy, authoritativeness and licensing). At the global level, the lack of consistent, accessible datasets with full coverage in fit-for-use format (such as single building features) is a challenge. For example, OpenStreetMap data describes assets at the global level, but often they are incomplete and sources are not authoritative; better alternative datasets are provided by several NMCAs in Europe. The goal would be for all countries to make their NMCA datasets accessible, within the emergency timeframe.

The quality of products would be significantly improved by access to higher-resolution and up-to-date datasets, e.g. for assets, elevation and population. Such resolution can be found in national datasets, with access granted in some cases through official agreements or under contract.

While local in-situ data may exist, they are either inaccessible, not accessible within the required timeframe, or are made available in an inappropriate format (e.g. raster vs vector).

The availability and quality of in-situ data can be substantially improved by building on the lessons learned from ongoing initiatives and projects such as the European Environment Agency's EuroGeographics agreement, CORDA and the European Location Framework (ELF).

COPERNICUS LAND MONITORING SERVICE

Background and policy perspectives

The Copernicus Land Monitoring Service (CLMS) provides land cover and land use datasets at various levels of detail and to various extents, including for focus areas, known as priority areas and hotspots. Additionally, the CLMS provides bio-geophysical products of the land surface and status, and on the development of the land surface. These bio-geophysical products are grouped in five thematic blocks: soil moisture, vegetation, temperature and reflectance, water bodies and snow. The latter is a key topic for polar monitoring. For polar areas, fractional snow cover, snow cover extent and snow water equivalent are essential variables, which at the moment are partially available over Europe or in the northern hemisphere, up to 66˚N excluding Greenland, Iceland, Svalbard and the Arctic ice caps. CLMS also provides satellite data in the form of mosaics, a service that is also available for the Arctic. It features pre-made mosaics covering Europe in certain years, as well as a dynamic service providing data in mosaic form on request. For the latter, the maximum mosaic area is equivalent to the coverage of two or three Sentinel-2 scenes. Furthermore, CLMS provides ground-based observations for validation, containing a single dataset for the entire Arctic regions. The EGMS is also organised under CLMS (see the section below).

To summarise, CLMS provides excellent datasets over vast areas, which is an ideal foundation for an extension into polar areas. As CLMS currently does not cover significant Arctic and Antarctic areas, it is recommended that a future CLMS ensures that the land masses of the polar regions are covered entirely.

Gaps and limitations

The current version of CLMS has several gaps in the service provided for Arctic regions, such as wetland datasets. Datasets of land cover water bodies should contain a more detailed breakdown of water bodies (rivers, streams, lakes, waterfalls etc.) to meet the needs of users in the field of hydrology. Moreover, the service provided lacks sufficient information on permafrost over both poles (currently restricted only to areas with persistent snow).

The land cover datasets of the ESA-CCI initiative are of higher quality in the Arctic than the CLMS datasets that are currently available. Examples include snow cover extent, land cover, surface soil moisture, and surface albedo. These products should be taken up by the service when sufficiently mature, and should also be coordinated with C3S. Improvement is also expected with the upcoming 10 m global CLMS land cover dataset.

Furthermore, harmonisation and evaluation of the existing CLMS Arctic datasets is recommended, to ensure that the highest quality dataset in each category is provided. The European CLMS land cover products do not extend over Greenland and Svalbard, and the 100 m global land cover is too coarse and shows ‘permanent water bodies’ around Greenlandic grid cells in the ocean, and does not cover areas above 79°N. The limitation of 100 m grid cells is also the reason why forest data are not detailed enough to be used and show forests where no forest exists, and inland water bodies inside the ocean. The upgrade to 10 m global land cover is expected to provide improvements in this case too.

Recommendations

The Polar Task Force made the following overall recommendations for the evolution of CLMS in the polar domain:

- Include ESA-CCI permafrost products after validation. See the sections on permafrost and the EGMS for additional details. Also, the variables of surface soil moisture, lake ice extent, and land surface temperature from the respective ESA-CCI projects, should be taken up into the service when they are sufficiently mature.
- Include coastal zones and protected areas in the Arctic regions.
- Evaluate and harmonise existing datasets.

In addition, the PTF recommends the service to further develop within the following areas:

Recommendations for extending the service

Slope stability and landslide/slope failures are becoming more important for the Arctic, in particular Greenland and northern Norway. Thawing of permafrost is expected to increase the risk of slope failures. Some of the regions affected are close to inhabited villages or in areas with shipping traffic. Here regional data products are required as a land monitoring service, since the number of unstable slopes is exceeding the capabilities of on-site monitoring. It is recommended to increase the Sentinel-1 coverage of ice-free areas around Greenland for this purpose.

Another recommendation is to include avalanche monitoring. This may require increased Sentinel-1/2 coverage in the respective areas. It is suggested to add this to a snow product, with a quality comparable to the ESA-CCI snow product.

In addition to permafrost products (see the chapter on permafrost for details), it is important to add products for thermokarst lakes, wetlands, and peatlands to a polar CLMS. A spatial resolution of 50 m x 50 m is recommended, although the ground temperature might only be available at a coarser resolution.

Furthermore, it is recommended to add a wetland dataset with a spatial resolution similar to other datasets for Arctic regions.

In general, the products provided should be appropriate and reflect the actual changes in the regions, e.g. time series products are becoming even more important. This includes products of land cover change and habitat change, which should be updated at convenient intervals. Grids of the different products should be chosen to make it possible to assemble the products in layers.

Recommendations to increase service availability

The current CLMS data viewer does not allow switching to polar projection maps, which are more suited to visualise data in the polar areas. This should be included in future versions, ideally with the Arctic in polar projection (e.g. EPSG 3413, 3031), similar to https://geoportal.arctic-sdi.org/.

As coverage of different data products may vary in polar areas, it is recommended that the spatial extent of the data products should be given as text and maps. This is particularly important for users in remote parts of the Arctic with limited bandwidth, as it would mean they could avoid downloading datasets for areas that are irrelevant to them.

In many fields of data provision, application programming interfaces (APIs) have proved to be extremely useful for data access and download, so it is recommended that CLMS offers this possibility.

Significant benefits have been noted when users have access to a cloud platform with tools available to work on the data without the need to download. The benefit only occurs, however, if the tools are properly working and are state of the art.

Customisable thematic maps are recommended to complement the data provision. These maps are not expected to deliver a high spatial or temporal resolution, but an overall overview of a particular land cover variable, such as permafrost areas.

Since CLMS is a monitoring service, it is recommended to develop ready-made, citable maps, which would be useful for non-academic users and the general public.

European Ground Motion Service

Background and policy relevance

The European Ground Motion Service (EGMS) is a component of CLMS that provides consistent, regular, standardised, harmonised and reliable information on natural and anthropogenic ground motion phenomena over the Copernicus participating states and across national borders, with millimetre accuracy. Since the failure of Sentinel-1B, the polar-orbiting Sentinel-1A is the main satellite used for the EGMS. The Sentinel-1 satellites carry a C-band synthetic aperture radar (SAR) instrument. They can acquire images both day and night, regardless of weather conditions, and provide high-resolution data over large areas. The EGMS also uses other satellite sources, such as TerraSAR-X, COSMO-SkyMed, and ALOS-2, to complement the Sentinel-1 data and provide more detailed ground motion information for selected areas of interest. These satellites also carry SAR instruments, but operate at different frequencies (X-band, L-band) and have different spatial and temporal resolutions. The EGMS integrates and harmonises the data from different satellites to produce consistent and reliable ground motion products.

The EGMS supports the implementation of EU policies on the environment, climate change, civil protection, regional development, transport and energy by providing data and information on ground motion hazards and risks.
The EGMS is designed to serve a wide range of users, such as public authorities, policymakers, scientists, engineers, insurers and the general public, who need access to ground

motion data and information for various purposes. The EGMS is a free and open service that can be accessed through the CLMS portal.

In the future, the EGMS will be able to use data from upcoming missions to improve its ground motion products and services in various ways, such as:

1. The NISAR mission (the joint Earth-observing mission between NASA and the Indian Space Research Organization) will provide complementary data to Sentinel-1 at different radar frequencies (L-band and S-band), which can improve the detection and measurement of ground motion phenomena over different types of terrain, such as vegetated, urban or mountainous areas. The L-band data can also penetrate deeper into the ground and provide information about the subsurface structures and processes.

2. A JRC technical report (2021) (Boniface et al. 2021) highlights the role of ROSE-L (L-band synthetic aperture Radar Observing System for Europe). It is planned that ROSE-L will carry an L-band SAR. Since the longer L-band signal can penetrate through many natural materials such as vegetation, dry snow and ice, the mission would provide additional information that cannot be gathered by the Copernicus Sentinel-1 C-band radar mission. It can be used to support the monitoring of ground movement, landslides and soil moisture. In addition, the mission would contribute to the monitoring of polar ice sheets and ice caps, sea ice extent in the polar regions, and of seasonal snow.

3. The combination of C-band Sentinel-1 and L-band ROSE-L SAR interferometry will provide stable, long-term and consistent information on land surface movements due to freezing or thawing of the active layer.

Current status/portfolio overview

The EGMS platform allows users to view and download the latest ground motion data over Europe, as well as historical data from previous years. The platform also provides tools and point filters to visualise and analyse the data in 2D or 3D mode. The EGMS Basic product level consists of annual ground motion data derived from Sentinel-1 satellite imagery. The latest update covers the period from 2018 to 2022 and was released in October 2023. The data are available in vector format and covers the entire European continent and some neighbouring countries.

The EGMS advanced products such as calibrated products are referenced to a model derived from global navigation satellite systems time-series data, offering absolute measurements, while ortho product includes components of motion (horizontal and vertical) anchored to a reference geodetic model and resampled to a 100 m grid.

The EGMS also provides a search interface for the product archive that allows users to query and access the historical ground motion products from various sources, such as the ESA, national mapping agencies, research institutes, etc. The product archive is continuously updated with new data and metadata.

Gaps and limitations

The KEPLER project report (Layer 3, Core Services: on 'Polar Regions Provision in Copernicus Services') states: '*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 organisations to evaluate the safety of existing and planned constructions and contribute to the Copernicus EMS.*'

The JRC technical report states: '*Complementary measurements of ground displacements can be used as proxies for changes in the state of permafrost, an essential climate variable (ECV) which cannot be monitored directly from space (Boniface et al. 2021). Improving our knowledge of changes in permafrost is relevant for both climate and emergency services. An extension of this service to cover permafrost in high-latitude lowland Arctic-Boreal regions, located mostly outside of Europe, would be desirable.*'

It is necessary to expand the EGMS over Arctic regions because the Arctic is undergoing rapid and dramatic changes due to climate change, which have significant impacts on the environment, society and economy of the Arctic regions and beyond. By monitoring ground motion phenomena in the Arctic, such as land subsidence, uplift, landslides, avalanches, permafrost thaw, etc., the EGMS can provide valuable information to:

1. understand the causes and consequences of the changes in the Arctic regions, such as the feedbacks between ice melting, sea level rise, coastal erosion, vegetation growth, etc.;

2. support the adaptation and mitigation strategies for Arctic communities and stakeholders, such as the indigenous peoples, local authorities, infrastructure operators, managers of natural resources, etc.;

3. improve scientific knowledge and the innovation potential of Arctic research, such as the development of new methods, models and applications for Earth observation and ground motion analysis.

Therefore, expanding the EGMS over Arctic regions is important for the EU and the international community, as it can contribute to protecting the Arctic environment, promoting the sustainable development of the region, and advancing global cooperation on and governance of the Arctic.

Some of the challenges in expanding the EGMS over Arctic regions are technological and operational in nature. The Arctic is a harsh and remote environment, where the weather conditions, ice cover and darkness pose significant challenges for satellite observation and ground motion analysis. The availability and quality of the satellite data may vary depending on the season, location, and satellite source. The operational costs and risks of conducting field surveys and ground validation are also high in the Arctic.

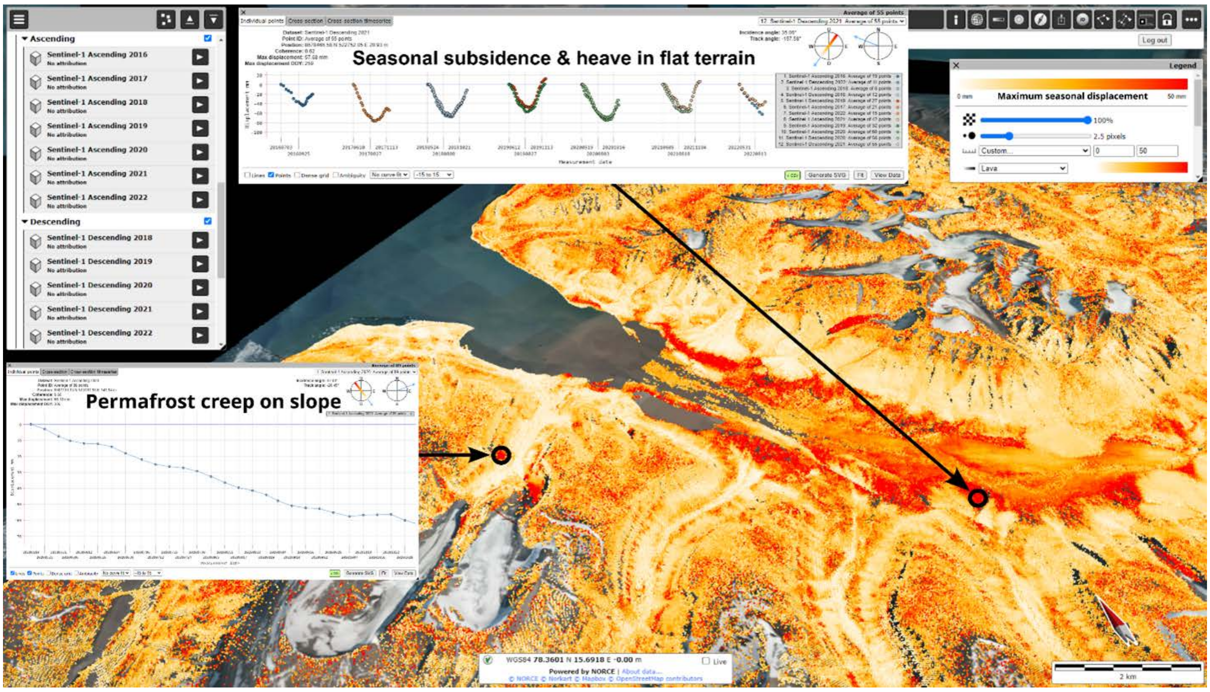

Figure 6: Example of pilot products around Longyearbyen and Adventdalen (Spitsbergen) under development for the InSAR Svalbard Ground Motion Service (GMS). The InSAR Svalbard project (2023-2025) is a partnership between the Geological Survey of Norway (NGU) and the NORCE Norwegian Research Centre AS, with funding from the Norwegian Space Agency. It aims to develop an InSAR GMS tailored to Arctic conditions (modified from Rouyet et al., 2024).

Recommendations

1. In a new project supported by the Norwegian Space Agency (2023-2025), the Geological Survey of Norway (NGU) and NORCE are developing the foundational framework to implement an operational Ground Motion Service (GMS) covering Svalbard. This unique Arctic region presents specific technical challenges and user needs distinct from the mainland. The project's primary objective is to assess infrastructure stability and slope hazards in the Arctic environment using Sentinel-1 and other satellite sources. Additionally, the project includes field surveys and ground validation activities to improve the accuracy and reliability of ground motion products. During its initial phase, the project conducted an online survey and an in-person workshop to gather insights from potential users on future product development needs. The feedback emphasised three key requirements (Rouyet et al., 2024): (1) integration of InSAR Svalbard with local services to improve data comparison and collective analysis; (2) address the different requirements of geoscientific research and operational needs, such as infrastructure and hazard management; (3) develop user-friendly products that support effective decision-making and urban development. While comprehensive coverage across the Svalbard archipelago is considered less urgent, it could be beneficial for monitoring remote sites and for research purposes. In brief, it is recommended to follow these regional efforts as part of the process to expand the EGMS across the polar regions.

2. To fill gaps and serve the requirements of EGMS users in the future, there is an urgent need to have two (or even better, three) C-band Sentinel S-1 SARs operating simultaneously in orbit. They should be deployed in an appropriate orbit phasing configuration to provide increased (ideally daily) temporal coverage repetitiveness and complete geographical coverage of the Arctic and Antarctica (including their coastal areas) during the whole year (all seasons). The high-level operations plan (HLOP)of SAR missions should allow an appropriate operating mode (interferometric wide swath) of SARs over these polar regions.

3. Strong concerns were expressed in the user survey about the loss of Sentinel-1B and the ageing of Sentinel-1A, thus requiring the launch of Sentinel-1C and Sentinel-1D as soon as possible.

4. It is recommended to review the technical aspects of how the EGMS is used over permafrost regions. The merits of bistatic or quasi-bistatic SAR configurations should be explored and should be put into practice if appropriate.

5. The continuous and operational provision of validated EGMS quality products over the polar regions are recommended. Quality information (accuracy estimates, validation methods, etc.) must be provided to users.

6. The EGMS launched a user survey in 2023 to shape the future of the service beyond 2025. The primary objective was to gather feedback from users and industry professionals on how the EGMS is currently working and to frame a new and improved EGMS from 2025 onward, as well as subsequent EGMS updates. The survey, which consisted of 17 questions, closed at the end of 2023. Key areas of focus included data format and coverage, visualisation and download capabilities, and dissemination and user uptake. The results of the survey will be summarised and published on the CLMS website[8]. It is recommended that the results of this survey should be taken into account in a future expansion of the EGMS over the polar regions.

[8] file (copernicus.eu)

ANTARCTICA

The Antarctic Copernicus portfolio is of similar importance for users as the Arctic one. The main focus for observations in the Antarctic is on its relevance for the climate system. This includes the need for large-scale EO datasets for data assimilation into climate models, which will become even more important in the future. Furthermore, the mass loss of the Antarctic Ice Sheet is leading to local sea level rise in the northern hemisphere due to self-gravitation. As a result, monitoring mass loss and its regional distribution in the Antarctic is essential for estimating local sea level change, which is important for coastal planning.

Similar to the Arctic portfolio, the Antarctic products are dispersed across various Copernicus services and components. Many suggested datasets have become standard over the past decade; however, the scientific and general user communities will benefit from improved quality and higher temporal and spatial resolution.
A new dimension for the provision of data over Antarctica comes from the usage for data assimilation and inverse modelling. Suitable datasets are specifically required to assess the stability of the West Antarctic Ice Sheet. Also, the mass balance of the ice sheet in high spatial resolution is needed not only to constrain the ice sheet's contribution to sea level rise, but to also serve as the basis for estimating regional sea level change. Furthermore, the assimilation of sea ice thickness data has been shown to generally improve modelling capabilities.

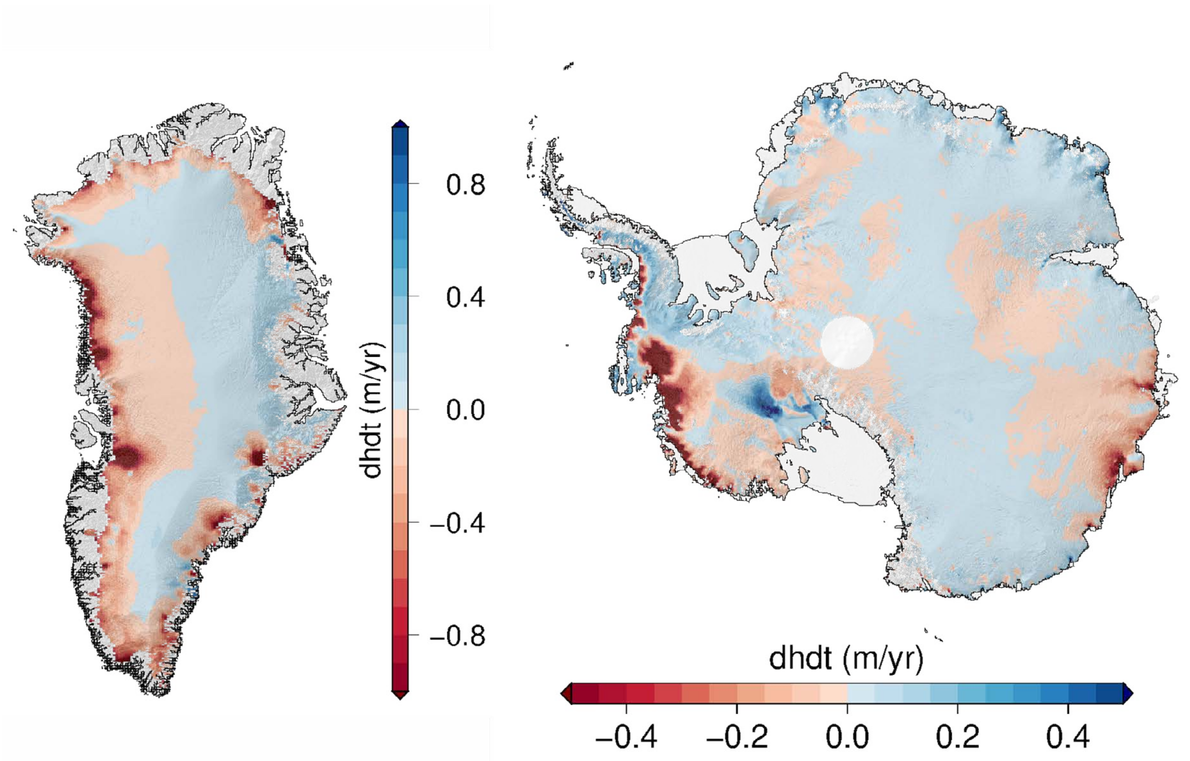

Figure 7: Annual surface elevation change 2011-2022 over Greenland and Antarctica based on CryoSat-2 data. This type of data product is the basis for estimates of the contribution of ice sheets to global sea level change and to compute local sea level change.

User requirements on key products/physical variables over Antarctica to be provided by Copernicus (order does not indicate priority):

1. Ice sheet velocity
2. Grounding line location
3. Inland ice discharge/mass flux
4. Mass balance products (e.g. input output method (IOM) and elevation change)
5. Crevasse fields
6. Calving front position/inland ice extent
7. Front retreat rates
8. Iceberg size (volume) and drift
9. Surface melt extent
10. Supraglacial lake location and size
11. Sea ice thickness
12. Snow thickness on sea ice
13. Sea ice concentration
14. Sea ice extent
15. Sea ice drift
16. Flooded sea ice datasets (time series)
17. Altimeter-based tides
18. Snow cover over ice-free land
19. Snow thickness over ice-free land
20. Albedo
21. Spectral reflectance
22. Surface temperature (for all surface types, including sea, permafrost)
23. Vegetation datasets (time series with highest spatial resolution)
24. Terrain deformation datasets (extension of EGMS)

Key user requirements for the Copernicus Antarctic portfolio

Increase SAR and optical data coverage in Antarctica: Users have requested more frequent and extensive Synthetic Aperture Radar (SAR) data coverage over Antarctica, particularly for monitoring ice velocity, the sea ice margin, iceshelf fronts, grounding line location, and surface melt extent. Users also expect improved optical data coverage over Antarctica to monitor various features like supraglacial lakes, ice shelf changes, and land cover changes. The feedback from the user survey emphasised the importance of launching additional Sentinel radar satellites, such as Sentinel-1C, to ensure continuous and extensive coverage of polar regions. Copernicus is advised to assess the benefit of having more than two satellites in orbit for increased interferometric SAR coverage with a minimum repeat cycle of 6 days, and with crossing orbits (ascending and descending) recommended. The benefit of higher-resolution passive microwave sensors over the Antarctic should also be explored.

Avoid gaps between satellite missions: Given the vulnerability of the West Antarctic ice sheet as a tipping point, it is crucial for Copernicus services to be ready to monitor rapid changes and offer valuable data on accelerated movement, grounding line retreat, and mass loss. To ensure continuity in monitoring ice sheet elevation, and hence mass loss, it is essential to avoid any gaps between the CryoSat-2 and CRISTAL missions.

Expand product range: Users expressed the need for a broader range of satellite-derived products for Antarctica, including products for snow-ice models, freshwater input, iceberg identification, ozone monitoring, and surface elevation change.

Focus on the Southern Ocean: Recognising the importance of the Southern Ocean, users highlight the need for higher-resolution passive microwave data and more frequent SAR coverage to monitor ocean circulation patterns and changes in sea ice cover.

Improved access and portals: Simplifying access and download procedures for satellite products, along with improving portals, would make it easier to use existing resources for scientific research and monitoring activities.

Modelling and reanalysis: The great success of the CARRA reanalysis products over the Arctic demonstrates that a similar reanalysis product over the Antarctic would be extremely beneficial too. To this end, it is suggested to incorporate a regional climate model, to ensure that ice sheet-specific quantities such as surface mass balance, runoff and skin temperature are provided.

Labelled data for artificial intelligence: tagged datasets should be provided to make it possible to apply AI or machine learning approaches. These could include, among others, calving front position datasets, crevasse datasets, supraglacial lake outline datasets and interferograms with tagged flexure limit polygons.

Practical aspects of data visualisation

Copernicus Antarctic products should be displayed in polar stereographic projection, specifically using EPSG 3031. Since the coverage of various data products may vary across Antarctica, it is essential to provide the spatial extent of these products both in textual descriptions and through maps. Special attention must be paid if data interpolation is required to fill in gaps around the pole hole. In such cases, the metadata should include details of the coverage of the original data. In numerous data-related fields, application programming interfaces (APIs) have proven to be highly effective for accessing and downloading data. Therefore, any access point (such as the Copernicus Polar Hub) to Copernicus Antarctic products should offer this capability as well. Moreover, there are significant advantages in providing access to a cloud platform equipped with tools for working directly on the data, eliminating the need for downloading. However, this advantage is contingent upon the proper functioning and technical maturity of these tools.

PERMAFROST

Background and policy relevance

The EU's Arctic policy stresses the urgent need to address the adverse effects of thawing permafrost and associated gas hydrates, which present a clear danger to the Arctic environment and its people, and which have wider repercussions beyond the Arctic as well. Improving our knowledge of changes in permafrost is relevant for both climate and emergency services, enabling local communities and government organisations to evaluate the safety of existing and planned roads and buildings.

Thawing of permafrost impacts the availability of fuel for wildfires, and the release of CH4 and CO2 from the decomposition of organic carbon and could lead to the release of additional CH4 from methane hydrates.

Permafrost is an essential climate variable (ECV) which cannot be monitored directly from space, but permafrost products can be generated using a combination of modelling and certain variables derived from remote sensing. This is the approach followed in ESA's Permafrost_CCI initiative. In some cases, permafrost can also be estimated based on proxies (e.g. land cover, ground deformation), although this approach is not operational and has other limitations.

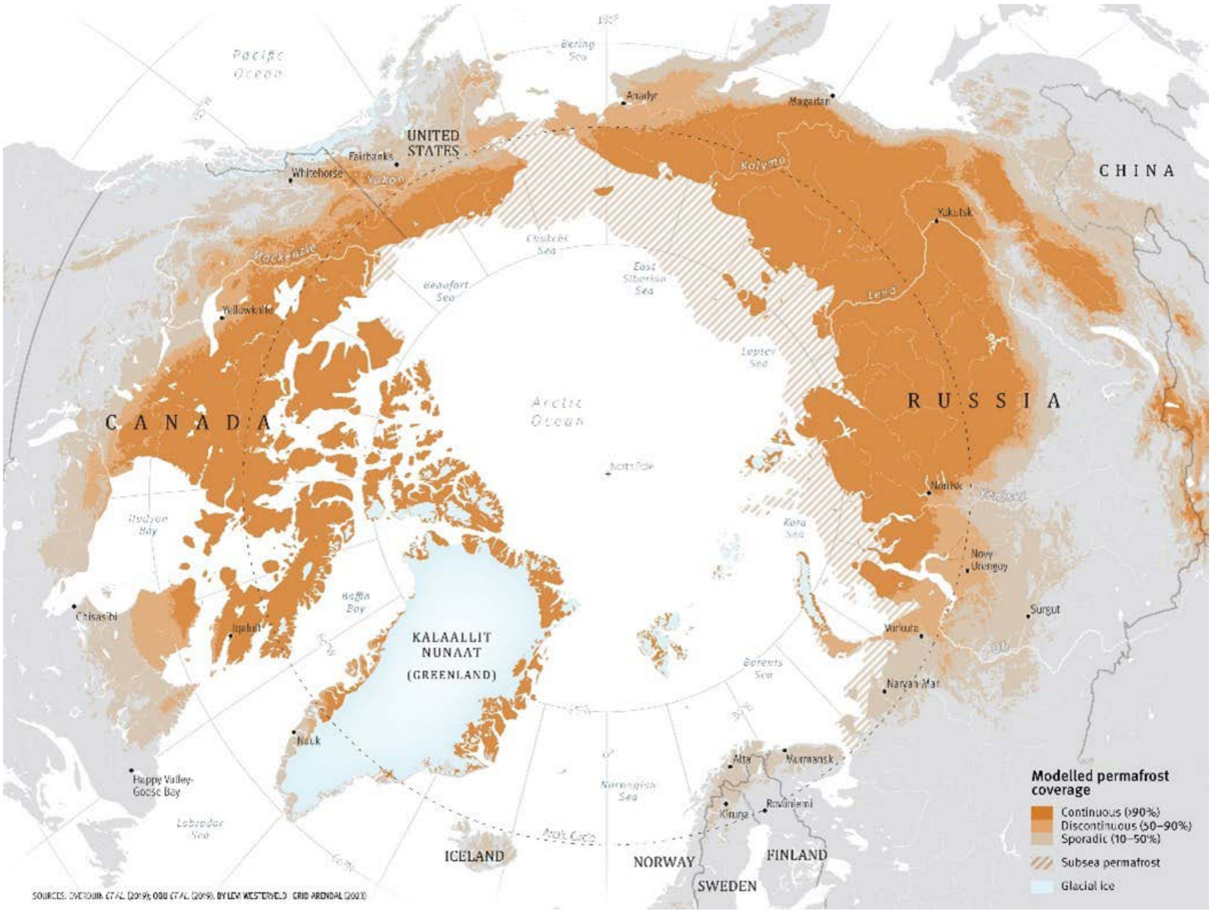

Figure 8: Permafrost in the Arctic. (Source: https://www.grida.no/resources/16250, Levi Westerveld/GRID-Arendal)

Portfolio overview

Currently, permafrost is not included in any Copernicus service. Some variables needed for permafrost estimations are included in the CLMS (e.g. land surface temperature, soil moisture).

The ESA's Permafrost_CCI project provides the ECV variables active layer thickness and permafrost temperature (at several depths), as well as the non-ECV variable permafrost fraction per pixel (based on temperatures at a depth of 2 m). A classification according to the IPA zonation delivers the well-known permafrost zones, distinguishing between isolated (0-10%), sporadic (10-50%), discontinuous (50-90%) and continuous permafrost (90-100%). The maximum depth of seasonal thaw is provided, which corresponds to the active layer thickness. Variables from phase 1 of Permafrost_CCI are provided as annual averages from 1997 to 2019 (to be extended to 2021 in phase 2) with a horizontal resolution of 1 km. Ground temperature is provided at the surface and at depths of 1 m, 2 m, 5 m, and 10 m. The Arctic Polar Stereographic projection is used. The product covers the Arctic and high-mountain permafrost environments of the northern hemisphere, extending down to 35°N latitude in North America and down to 25°N in Asia.

Gaps and limitations

In the Permafrost_CCI project, the active layer thickness is highly dependent on the ground stratigraphy employed. As ground stratigraphies are known to vary over short distances, the performance of the active layer thickness product varies significantly in space, being less accurate especially where ground stratigraphies are incorrect. This can lead to deviations of several metres in extreme cases.

No specific coastal products are included. A resolution of 1 km is typically not sufficient for a risk assessment of existing or planned constructions. The timeliness of the product is also not considered to be sufficient for this purpose.

Some of the in-situ data used for validation was contributed by the Roshydromet programme of the Russian meteorological monitoring network. Due to the current geopolitical situation, these data and the data from GTN-P derived at locations in Russia will not be available for the years after 2021 and for the foreseeable future.

Recommendations

Based on the current status and identified gaps in service provision, the Polar Task Force recommends the following for development of permafrost products within Copernicus:

Data from phase 1 of the Permafrost_CCI project have already been validated and should be taken up by the CLMS. Data from phase 2 should be taken up once the validation has been finalised.

Complementary measurements of ground displacements provided by the Copernicus EGMS have a higher resolution than Permafrost_CCI products (100 m), and can be used for construction risk assessments, and in some cases as proxies for changes in the state of permafrost. It is therefore desirable to extend the EGMS to cover permafrost areas in high-latitude lowland Arctic-Boreal regions, which are mostly located outside of Europe.

For validation purposes, data from the WMO Global Terrestrial Network for Permafrost (GTN-P), managed by the IPA, should be made available by the in-situ component of Copernicus. GTN-P runs the Thermal State of Permafrost monitoring (TSP) for in-situ measurements of permafrost temperature in boreholes and the Circumpolar Active Layer Monitoring Program (CALM) for in-situ measurements of active layer thickness.

With extreme events expected to increase in frequency, it is necessary to investigate the impact of rain-on-snow events on permafrost, where water percolates through the snowpack. For this purpose, it is suggested to fuse several types of microwave satellite observation to create a climate data record (e.g. the from the Advanced SCATterometer and SMOS).

For Arctic coasts, attention should be paid to the following issues:

- Erosion and accretion need to be addressed.
- All high-latitude permafrost coasts should be covered.
- A regular update of satellite retrievals for erosion rates is needed.
- There is a need for higher level products from remote sensing, e.g. gridded representations.
- Some key sites should be identified for higher-resolution products (see also the chapter on observations).
- There is a need to integrate a wide range of datasets.

It is recommended to reach out to the Nunataryuk Horizon 2020 project to obtain available erosion rate maps.

A collaboration between the Copernicus Hubs for the Arctic, coasts and health is recommended to explore the potential effects of synergies between the hubs on the topics of coastal erosion, and the impacts of permafrost thaw on the health of humans, animals and ecosystems (e.g. the release of contaminants such as mercury or the dynamics of pathogens). It is also recommended to contact the Horizon Europe project ILLUQ to develop services and products related to health.

OUTREACH

Respondents to the survey made several recommendations to improve user engagement and access to Copernicus services in the Arctic regions:

Funding for pilot demonstrations: Prioritising funding for pilot demonstrations targeting Arctic users is considered the most effective approach.

Improved interaction with users: The interaction between Arctic user communities and Copernicus should be strengthened and should be better tailored to the needs of the region.

User-oriented services: Developing user-oriented services is crucial to boosting engagement and ensuring that users can easily access and benefit from Copernicus data and products.

Effective dissemination of data: it is essential to ensure that the data and derived products, such as ice charts and weather forecasts, are made readily available in a simple and user-friendly manner.

Training and information: Providing training, information events, demonstrations, and tutorials can help users to use the data and services more effectively.

Open data policy: It is crucially important to make data available in a free, open, and efficient way to encourage user uptake.

Standardised interfaces: Standardised interfaces to search for, find and access data are necessary for seamless integration into decision support systems.

International collaboration: Collaboration between European entities and remote Arctic communities should be encouraged, including through staff exchanges, to improve understanding and build partnerships.

User-friendly interfaces: the user experience can be improved by creating user-friendly interfaces that combine high- and medium-resolution products with national and regional datasets and services.

Language inclusivity: Communicating in several languages, including indigenous languages, can encourage inclusivity in science and improve user engagement.

Error estimates and validation: Showing error estimates in Copernicus services and validating them with in-situ data specific to regions or countries, can boost user trust.

Cloud hosting: Usability of data can be improved by hosting data on cloud systems for easy access and processing on-site without downloading.

Use cases with local needs: It Is essential to create use cases that incorporate local needs and involve local institutions and researchers in information sessions and training.

Highlighting all fields of research: Tutorials and application examples need to include all research fields (e.g. atmosphere physics, atmosphere chemistry, sea ice physics, sea ice chemistry and biology, ocean physics, ocean biology, permafrost, coastal erosion, glaciers, forest fires).

Coupling of outreach activity with the collection of citizen data: Easy to use and attractive apps for data collection need to give feedback to the user. They should be able to give the user information that is location-specific or scaled up to the polar region.

These recommendations collectively aim to make Copernicus data and services more accessible, user-friendly, and effective in serving the diverse needs of the Arctic region and its stakeholders.

COPERNICUS ARCTIC HUB

The Copernicus thematic hubs are single entry points for the ensemble of data, products and information generated by the Copernicus services and components for specific thematic or geographical areas. The hubs correspond to specific EU policy needs and provide simplified access to key information on selected areas for various stakeholders, policymakers and users. In 2023, Copernicus launched four thematic hubs, among them the Copernicus Arctic Hub, coordinated by the Copernicus Marine Service. Today, around 150 EO-based products are available free of charge in the hub catalogue, providing a wide range of data sets from satellite imagery to in-situ observations and model outputs. The Copernicus data and products and use cases made available through this hub focus on three areas: safety, climate change and sustainability. The hub is based on the WekEO platform, which is the Copernicus reference service for environmental data, virtual processing environments and user support. The Polar Task Force has formulated the following recommendations for the development of the Arctic Hub, to serve the Copernicus objectives, and in response to the survey replies:

1. Include Antarctica in the scope of the Arctic Hub and make it a Polar Hub.

2. Set up a Copernicus Polar forum connected to the Hub. This will serve as a consulting body, and a forum to exchange information and knowledge.

3. It is crucial to ensure that some level of coordination and/or harmonisation is jointly set out and implemented between Copernicus Services. This would include the definition of common standards for terminology (e.g. processing levels); the quality and performance of data and products; data architecture; the development of user-friendly tools; ensuring the compatibility of procedures and protocols to access data or metadata; ensuring the interoperability of catalogues; and ensuring that data policies are compatible. The Copernicus thematic hubs should help coordinate this work.

4. Create links with the Knowledge Centre on Earth Observation (KCEO), GEO and relevant international fora. The KCEO aims to act as an efficient internal coordination mechanism inside the European Commission to maximise the use of products and information from Copernicus and Earth observation more broadly, in EU policymaking and implementation.

   The Copernicus Arctic Hub should provide input to the KCEO thematic study, known as deep dive on the Arctic.

International collaboration

Copernicus has a global reach, and strong international collaboration is particularly important for the Arctic regions. Iceland and Norway are Participating States in Copernicus, and both the USA and Canada have cooperation arrangements regarding Copernicus through the Commission's Directorate-General for Defence Industry and Space (DG DEFIS). In addition, Canada contributes to the development of Copernicus through its participation in the ESA.

The Copernicus Arctic Hub is also designed to provide a link to this type of international collaboration, with a portal project to supplement data and information. There are many initiatives and projects aiming at providing data or products and operational services to polar user communities. Among these, we can mention the following:

- ESA's Polar Science Cluster programme is focusing on collaborative research and fostering international collaboration, revolving around different ESA-funded projects and activities, to improve European polar research.

- The Sustaining Arctic Observing Networks (SAON) are engaging with the Group on Earth Observations (GEO) through the Arctic Global Earth Observation System of Systems (GEOSS). The aim is to implement GEOSS in the Arctic in collaboration with Copernicus to produce data and services for Arctic stakeholders.

- The Arctic Passion Horizon 2020 project aims to co-create and implement a coherent, integrated Arctic observing system: the Pan-Arctic Observing System of Systems (pan-AOSS).

- The Research Network Activities for Sustained Coordinated Observations of Arctic Change (RNA CoObs) supports the SAON Roadmap for Arctic Observing & Data Systems (ROADS).
- The Canadian Consortium for Arctic Data Interoperability (CCADI) is an initiative to develop an integrated Canadian Arctic data management system that will make it easier to find information, create standards for sharing data and enable interoperability between existing data infrastructures. It will be co-designed with, and accessible to, a broad range of users.

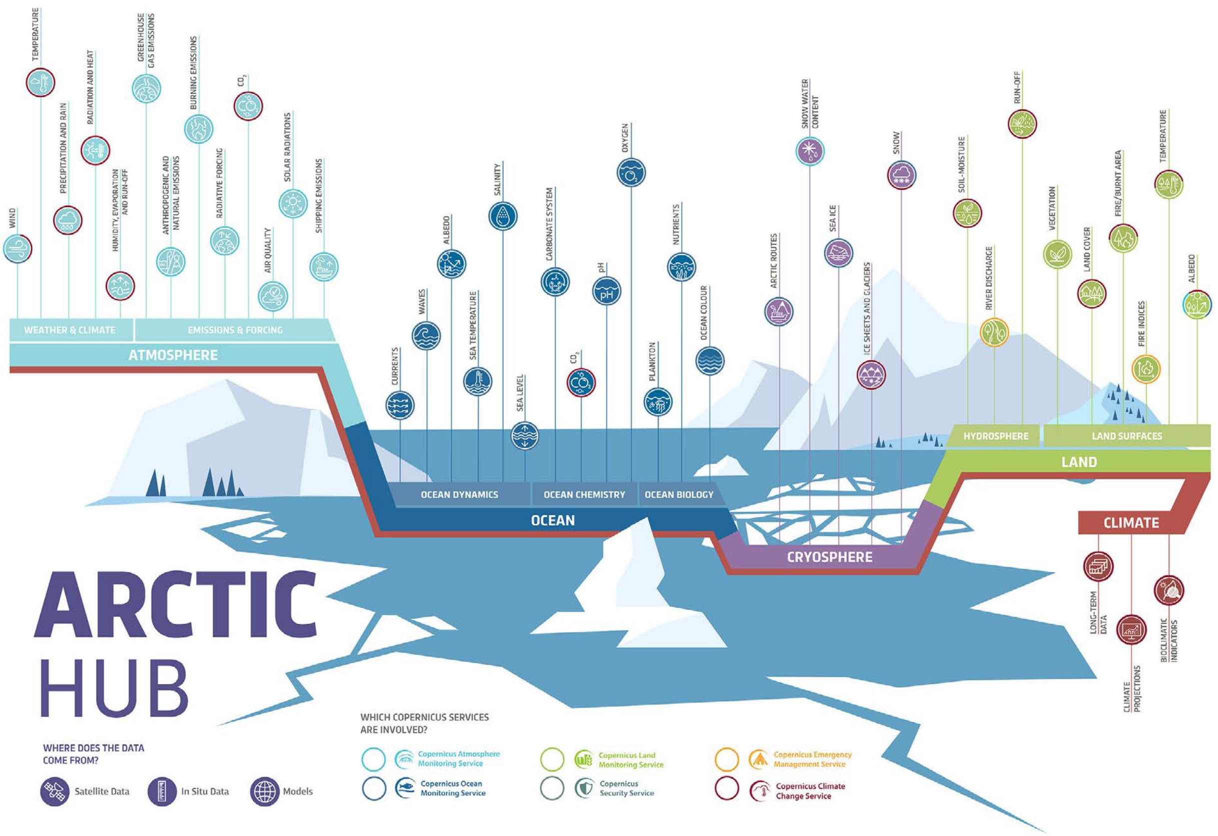

Figure 9: The Copernicus Arctic Hub collects and makes available Arctic relevant data and products from the whole Copernicus ecosystem

OBSERVATIONS

In addition to the polar user survey, this chapter is based on input from the scientific community (from the Nansen Legacy conference, Fram Center projects (e.g. SUDARCO), the Arctic Passion Horizon 2020 project, the Climate and Cryosphere (CliC) project on sea ice data standardisation, the International Glaciological Society (IGS) symposia on sea ice, the International Arctic Buoy Programme (IABP), and the MOSAiC conference); from KEPLER deliverable 3.1 (2020), and the Copernicus report: Arctic in-situ data availability (2019). Inputs from the Copernicus Marine Service requirements for the development of the Copernicus In Situ Component (2021) were also integrated in this chapter.

This roadmap focuses primarily on gaps and recommendations for Copernicus relevant to in-situ observations, to respond to the PTF's mandate, but it also includes some points on satellite retrievals to reflect the responses in the user survey. Both the current Sentinel fleet and the Copernicus Expansion Missions (particularly CIMR, CRISTAL and ROSE-L) were mentioned, in addition to relevant third-party missions, to be included in the CCMs or through bilateral agreements.

Background

Satellite remote sensing products are observations that are essential for any climate model evaluation (see Table 1, for example). These indirect measurements also require 'ground truth' measurements, often referred to as 'in-situ'. In addition to the calibration and validation of satellite remote sensing retrievals, in-situ observations are needed to understand signals (including radiative transfer modelling) and to estimate uncertainty. Some in-situ data are used directly in studies of local (small-scale) climate-relevant processes, in evaluating regional and climate models, and in data assimilation for forecasting. In-situ observations also complement observations which cannot be obtained from space (e.g. deep ocean profiles of temperature, salinity or permafrost).

Polar regions are crucial for understanding and forecasting the global climate. Climate research observations from satellite remote sensing are collected from information on atmosphere physics, atmosphere chemistry (including aerosols), sea ice (including its chemistry and biology), ocean surface (including its chemistry and biology), glaciers, snow, river runoff, permafrost (including wetlands), and landslides (land stability and coastal erosion). Because of the remoteness of the polar regions, in-situ observations are very scarce. A complete inventory of in-situ observations required to evaluate satellite remote sensing products is provided in the table of Annex 4 of the PEGIII report.

The European Environment Agency (EEA) coordinates the Copernicus in-situ component, maintaining an overview of the state of play on data requirements, providers and gaps in information, with reference to the needs of the Copernicus services[9]. Moreover, each of the six Copernicus services obtain additional in-situ data. The services work directly with national and international networks (e.g. the national meteorological services, national mapping and cadastral agencies, research infrastructures and other international cooperation initiatives)[10].

[9] https://insitu.copernicus.eu/

[10] https://community.wmo.int/en/activity-areas/Marine/JCOMM/Overview Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM), an intergovernmental body bringing together the expertise and technological capabilities of the World Meteorological Organization and UNESCO's Intergovernmental Oceanographic Commission.

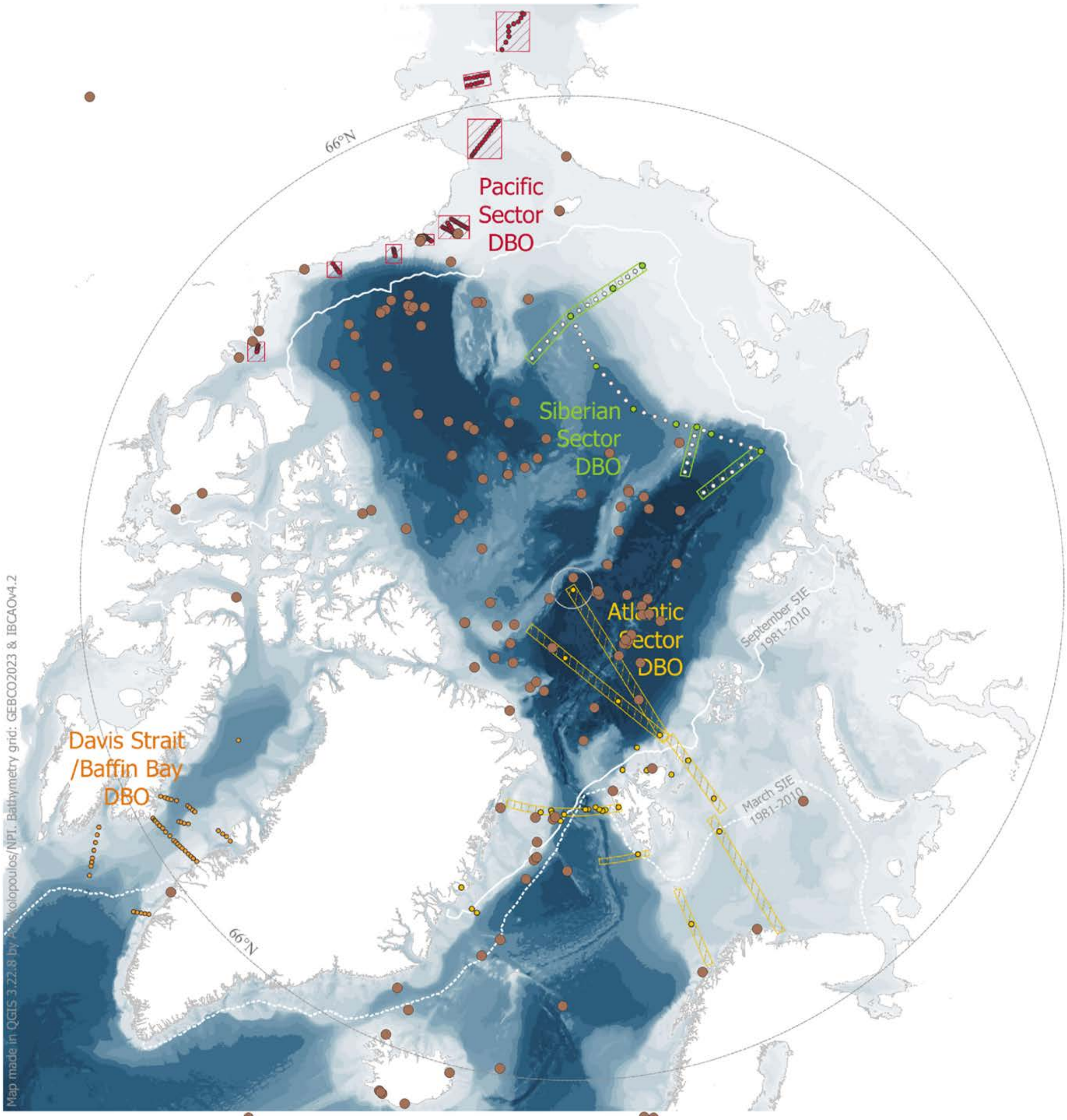

Figure 10: Map of the Arctic with plans for the coordinated Distributed Biological Observatories (DBO), (credit: Anna Nikolopoulos, Norwegian Polar Institute) and current positions (April 2024) of the buoys of the International Arctic Buoy Programme (brown dots).

Gaps and limitations

The general problems encountered in all areas of polar observations are threefold: 1) lack of data; 2) information bottlenecks; 3) interoperability.

Specifically, these have been demonstrated as:

- The general lack of observations in all fields – an overview is given in the 2019 Copernicus report and in Annex 4 of the PEG III report. This is especially critical in the following cases:
    - discontinuity of established time series (e.g. due to funding issues)
    - discontinuity of calibration and validation (Cal/Val) activities for satellite products
    - very poor availability of data for the territory controlled by the Russian Federation - this has worsened during Russia's war of aggression against Ukraine.
- Information bottlenecks and technical barriers may delay or prevent access to the existing data:
    - Data exist in different formats, and metadata is not standardised and can be written in different languages. The associated documentation does not meet the needs of users. Efforts to mitigate this are ongoing, and have made significant progress, though the results are still restricted to individual projects, and are incomplete and scattered.
    - Restricted access to data for political and security reasons or due to their commercial nature: good progress has been made here, however further work is needed, and some areas of research are lagging (e.g. permafrost).
    - Lack of knowledge and skills to access the data, and lack of investment of time or funding. For example, some historical data are not digitalised or accessible online.
    - Data latency hinders the use and forecasting of near real time (NRT) data in all fields of research, with the notable exception of certain atmosphere physics data (see also Table 1).
- Data interoperability may be limited if different collection methods are used. The new Copernicus Data Space Ecosystem (CDSE) should increase the harmonisation of Copernicus data and products, and further improve data interoperability.

General recommendations and opportunities

- Greater political cooperation across borders in the polar regions is highly recommended. This is especially critical in the Arctic regions. This cooperation must be the foundation of the collaboration between national space agencies and private space companies, as well as monitoring and research institutions that collect in-situ data. The existing intergovernmental bodies must be used: the key organisation is the Arctic Council, but several others exist. An overview of them is provided in the KEPLER 3.1 report and the Copernicus PEG III report.
    - There has been a major increase in space satellites and programmes of several space agencies. The activities on the collection of observations required for space missions need to be coordinated to foster scientific collaboration and exchange. One example where such a collaboration could be useful is highly elliptical orbit (HEO) missions, which are of special interest for the polar regions since they enable rapid revisit observations. Copernicus should work with the Canadian Space Agency, which is currently leading two missions - the Arctic Observing System and the Terrestrial Snow Mission - in which NASA and EUMETSAT are already partners. HEO missions also have the potential to improve the observation of fire radiative power and ozone. ESA's Arctic Weather Satellite (launched in August 2024) could also provide relevant observations for the polar component of Copernicus.
    - The private sector is becoming an active player in the market for Earth observation from space, with the emergence of dynamic start-ups (e.g. ICEYE), telecommunications and data transfer (e.g. StarLink), and satellite launch capabilities (e.g. SpaceX). This development needs to be addressed and integrated into the management of public resources.
- Several science networks are collaborating within their research fields on observational data harmonisation. Many are listed in the Copernicus 'Arctic in situ data availability' report from 2019, but the list is incomplete and needs to be updated (e.g. SION, European Marine Observation and Data Network - EMODnet, NSF Navigating the New Arctic (NNA) programme, research infrastructure initiatives

(e.g. SIOS, ACTRIS, INTERACT, Polar Research Infrastructure Network (POLARIN), the Interactive Polar Infrastructure Database (POLARDEX), any committees under International scientific council – ISC, like SCAR and the Global Ocean Observing System (GOOS) etc.). Collaboration between these networks on polar-specific issues would be particularly encouraged. Scientific collaboration in Antarctica is better coordinated than in the Arctic.

 - The data storages and inventories of scientific networks must follow FAIR (findability, accessibility, interoperability, and reusability) data principles.
 - Efforts must be made to improve the near real time (NRT) availability of the in-situ data and reduce the latency below 10 days so that the in-situ data can be used for forecasting of numerical models (see also Table 1).

- Increased cooperation between national funding agencies is needed to improve intergovernmental and research collaboration. Specifically, the following actions are required:
  - Data from all research projects must be stored in public databases of scientific networks with the appropriate documentation and following FAIR principles (see above);
  - Funding is required to ensure the continuity of data collection, and ongoing efforts on data harmonisation and data storage;
  - Infrastructure funding is required to ensure harmonisation in methods and equipment;
  - Training funding is required to secure free exchanges of knowledge on different methodologies.
- The International Polar Year 2032-2033 should be used as a planning opportunity. The preparation for the extensive work must start now since will take several years.
- Polar research infrastructure projects and initiatives play a crucial role in facilitating in situ data collection and in making these data accessible to wider scientific communities. It is recommended to establish connections with data portals associated with initiatives like SIOS, INTERACT, ACTRIS, and the Polar Research Infrastructure Network (POLARIN) project (2024-2029).

Citizen science

Engaging in citizen science and community-based observations in the Arctic, which involve occasional visitors/tourists, permanent inhabitants, and indigenous populations, holds significant promise for collecting valuable scientific data on-site. These community-based observations play a vital role in complementing long-term monitoring programmes, research infrastructure-based observations, and in-situ data networks. They help address data gaps, support satellite calibration and validation efforts, contribute to capacity building, and enhance scientific research in the Arctic regions.

Action to be taken immediately

Drawing from the current situation, user needs and identified gaps and limitations, the Polar Task Force recommends the following actions for a robust service evolution in the polar domain:

- Link the mapping service of the Copernicus In Situ Component to the Copernicus Arctic Hub.
- Immediate action must be taken to rescue data - this applies to all research areas, but is especially crucial for atmospheric sciences, where historical data has the potential to extend (or improve the quality of) the climate record. See the KEPLER 3.1 report for details.
- Observatories distributed across the Arctic (Figure 10) should be set up to coordinate the collection and sharing of Arctic in-situ data. This effort is currently coordinated by the Arctic Passion project.
- Copernicus should encourage the integration of new technologies into observations, e.g. drones and other autonomous equipment, underwater robots and the new generation of stations and ice drifters.
- The National Oceanic and Atmospheric Administration (NOAA), in collaboration with the Global Ocean Observing System (GOOS), already operates a ship of opportunity programme (SOOP) that includes all polar regions and nations. Copernicus is recommended to join this effort. The current decrease in the number of ships of opportunity can be reversed with the rise in polar travel and transportation. The requirements of the International Maritime Organization (IMO) as regards the Polar Code have prompted ship operators, including

tour vessels, to make routine sea ice observations to support the risk assessment tools mandated by the IMO. In addition to sea ice, SOOP is also relevant for ocean and atmosphere in-situ observations.

- Russia's war of aggression against Ukraine is obstructing collaboration with Russia on Arctic matters and prevents the collection of data. As Russian territories are critically important to understanding the Arctic climate as a whole, the issue should be addressed by a better coverage by satellite remote sensing observations.

- Citizen science has great potential, and its use should be encouraged where appropriate. Both occasional visitors and permanent inhabitants should be included. Special care must be taken when addressing the indigenous communities. Report 3.1 of the KEPLER project contains extensive recommendations on the topic.

Sea ice and terrestrial ice

- Until now, cal/val activities of satellite remote sensing have been carried out with limited success in this field. The spatial heterogeneity of snow and ice conditions, as well sea ice drift, were the biggest problems. A spatial scaling 'pyramid' approach is recommended, where ground measurements are complemented with drone measurements, numerical modelling and airborne campaigns. The combination of all these data is necessary to produce a result that can be compared withs satellite remote sensing products.

- Collaborative cal/val missions, involving several space agencies, should be carried out. One critical example of this are altimetry missions that observe ice sheets and sea ice thickness. Ongoing missions are in their extended lifetime and new missions are planned, but not yet confirmed.

    - Operation Ice Bridge II must be designed to cover the transition between CryoSAT-2, IceSAT-2 and the upcoming CRISTAL mission.

- The IABP is a long-established and much used programme coordinated by the University of Washington. The Copernicus In Situ component should connect with the IABP to explore opportunities for additional buoy deployments (Figure 8). The overview of the required data is given in the PEGIII report, such as requirements for NRT data. Ideally, the spacing between the buoys should be 200 km. Information on positions should be provided at least hourly and at least daily on sea ice thickness. The precision of the positions should be in the order of a few metres.

- Icebergs are currently only monitored around Greenland. These observations should be carried out in all polar seas.

- The Baltic Sea should be monitored at the same level of detail as the polar regions.

Atmosphere and ocean

- The data from moorings in Drake Passage and the Fram Strait is highly relevant for Copernicus, and data should continue to be collected.

- In addition, IABP data (Figure 8) and other buoy data, including data from instruments carried by mammals (seals), is of great importance, especially in the marginal ice zones. It is recommended to measure the temperature/salinity profile every 200 km in the ocean, with denser measurements in key areas (e.g. the Fram Strait and the Barents Sea opening). The spatial resolution for biological variables should be even higher, and data should be provided on weekly basis.

- Acoustic tomography data for the ocean is of good quality in the seasonal ice zone. These data are suitable for assimilation into numerical models, so its collection should continue.

- Satellite retrievals of CH4 and CO2 should be made available in sun-glint mode where possible.

- Highly Elliptical Orbit (HEO) missions would also be useful for monitoring ozone. Copernicus services should connect with space agencies to explore the options to develop such a mission. Specifically, a microwave limb sounding instrument could be developed to mitigate the degradation in the CAMS ozone monitoring after the end of the MLS mission.

Land systems

- Terrestrial supersites within all relevant disciplines of research should be developed to ensure the development and harmonisation of methodologies. This is particularly important for improving wetland characterisation and addressing the dynamics of CH4 emissions in the non-growing and shoulder season.

- Permafrost and wetlands issues should be addressed with the following specific actions:
  - Create links with global and regional networks providing in-situ surface atmospheric GHG data, e.g. the Total Carbon Column Observing Network (TCCON), the Integrated Carbon Observation System (ICOS), the National Oceanic and Atmospheric Administration (NOAA); and also look into the uptake of AirCore measurements.
  - Connect with international networks that are monitoring permafrost and methane, e.g. the Arctic Methane and Permafrost Challenge (AMPAC) and the Nunataryuk projects[11]. In addition, links should be created with initiatives focusing on high-resolution GHG monitoring from aircraft[12].
  - Additional high-latitude campaigns are recommended to optimise and advance satellite retrievals of methane for high-latitude conditions.

OBS	T/S	SST	Surface Currents	Currents at	Ice Drift	Nutrients	Waves	Sea Level	Ice Thickness	Snow
Source	CMEMS + Ext	CMEMS	CMEMS	Ext	Ext	Ext	Ext	Ext	Ext	Ext
Assim.	NRT+RAN					RAN				
Valid	NRT+RAN	NRT	NRT	RAN	NRT+RAN	NRT+RAN		RAN	RAN	
Impact	Real	Ind	Science	Science	Ind	Ongoing	None	Ind	Ind	None
Priority	A	B	B	B	C	A	A	B	A	A

Table 1: Overview of the use of different in-situ data in the ARC MFC.

NRT = near real time

RAN = reanalysis.

CMEMS = data taken from CMEMS portal.

Ext = external data source

Real = has been documented

Ongoing = is being documented

Ind = indirect data through calibration of remote sensing products

Science = data are used for process studies

None = data not available or insufficient.

Priority A = urgent, B= second-level priority, C = not a priority for the time being

[11] https://www.ampac-net.info/, https://nunataryuk.org/, and http://www.permafrostcarbon.org/index.html

[12] https://above.nasa.gov/, https://halo-db.pa.op.dlr.de/ and https://comet2arctic.de

High level recommendation on machine learning

The global artificial intelligence (AI) and machine learning (ML) community is growing rapidly, with machine learning becoming increasingly important across various fields. Recent advancements in AI, particularly in big data analytics to process large volumes of data from Copernicus satellites and Copernicus reanalyses, are relevant for all Copernicus services. To capitalise on these developments, it is advised to set up a task force on AI and ML to explore methods for implementing AI and ML across the Copernicus Services. While labelled data is essential for AI models, the general scarcity of labelled data in polar regions poses challenges to developing new models. It is recommended that Copernicus services make training data available globally to support the development of ML approaches. Efforts should also be directed towards attracting the broader AI community to topics related to polar regions and encouraging their involvement in Copernicus services to expand the range of offerings.

CONCLUSIONS AND RECOMMENDATIONS TO THE EUROPEAN COMMISSION FOR A ROBUST EVOLUTION OF COPERNICUS SERVICES IN THE POLAR DOMAIN

Copernicus operational polar products have been provided to users for more than a decade through several different service components including CMEMS, CLMS, CEMS, C3S and CAMS. Experts of the Copernicus Polar Task Force carried out a comprehensive review of the current situation, which has been complemented by the responses to the questionnaire released in the autumn of 2023 to European and Canadian users and providing detailed recommendations for an improvement in the polar services as follows.

The availability and continuity of space and in-situ observations are crucial requirements for the provision of products and services to users, to avoid any gaps leading to the degradation of product quality or even to the loss of services.

Recommendation 1: *The EU, ESA and EUMETSAT must ensure the continuity of the Copernicus Space Component (First and Next Generation Sentinel series), complemented by Expansion Missions and validated Contributing Missions. It is strongly recommended to maintain the simultaneous operation in orbit of two identical satellite units, as is the case today, for the current and Next Generation of Sentinels to: (a) maximise the revisit frequency of observations, and (b) prevent degradation, or even complete loss of services in case of a satellite failure if there is only one satellite operating at a time. Contingency plans, including launch spots, should be prepared to replace failed satellites at short notice. The use of research or demonstration Earth observation missions should also be considered as potential future candidates for the Copernicus operational satellite component.*

Recommendation 2: *The European Environment Agency and EU Member States must ensure the continuity and timely availability of quality in-situ observation data in the polar regions, to be coordinated by the Copernicus In Situ component. This should include further development of in-situ platforms through international cooperation mechanisms within the polar research community, as well with the private sector operating in these regions.*

The Polar Task Force review has also identified the needs of users for specific new and improved quality products over extended geographical areas in the Arctic regions (with a specific focus on Greenland), the Baltic Sea and Antarctica, based on a thorough product review.

Recommendation 3: *Develop new products (related to sea ice, ice sheets and glaciers) and provide greater accuracy and higher spatial resolution for some existing products. This also requires a continuing scientific research effort on polar processes and close cooperation with similar existing research activities in Europe* *(e.g. the ESA Polar Science cluster, Horizon research projects) and at national level to further develop new and improved processing algorithms, advanced data assimilation techniques and forecasting skills. In this context, the extension of the EGMS (European Ground Motion Service) to the Arctic and Antarctica is strongly recommended.*

Copernicus services have been developed mostly independently via consortia with the primary objective of satisfying the needs of specific user communities focusing on different aspects, e.g. on land, the atmosphere, climate, the ocean, emergencies, and providing operational products tailored to these specific communities. A number of thematic hubs have been created (Arctic, coastal, health and energy) as one-stop-shops to make is easier for communities of users to access specific products. The experience gained over the last decade demonstrates that benefits would result from a cross-cutting approach to Copernicus services. To go further, exploring links and developing interfaces between services should be encouraged, offering greater consistency in products and services.

Recommendation 4: *Copernicus should explore cross-cutting areas, including: (i) the definition and adoption of common standards for terminology (e.g. processing levels); (ii) data/product quality and performance; (iii) data architecture; (iv) the definition of user-friendly tools; (v) the compatibility of procedures and protocols; (vi) access to data and metadata; (vii) the interoperability of catalogues; (viii) compatible data policies, etc. Particular attention should be given to interoperability between hubs (e.g. to ease the exchange and use of information between hubs, use of the Copernicus Data Space Ecosystem (CDSE) Platform, use of common map projections and grid systems). This work should be taken up in the appropriate Copernicus working groups.*

The Polar Task Force outlined the need for wide international cooperation and coordination with organisations active in polar regions. Equally important is the involvement of local populations in monitoring activities (citizen science initiatives) and decision-making processes as appropriate.

Recommendation 5: *The European Commission should strengthen cooperation and coordination at all levels and where appropriate. This should be done both internally within the Commission (with ongoing Arctic projects such as Arctic Passion, and by exploiting services and products produced by past projects such as KEPLER, ARCOS, or INTAROS) and outside the Commission with relevant programmes and activities of major international organisations, such as the activities of the WMO Polar Groups, GEO/Arctic GEOSS, the ESA Polar Science Cluster, the activities of EUMETSAT SAFs, and Arctic ROOS. The creation of a local citizen science portal should be considered and, if viable, set up.*

The Polar Task Force experts underlined the importance of consulting users, and of promotion and outreach activities to increase awareness and user engagement. They recommend that action should be taken on this issue.

Recommendation 6: *Copernicus should regularly consult its users to identify evolving requirements in terms of products and services. The Polar task Force also recommends funding pilot demonstration projects, and organising training and communication activities in several languages, including indigenous languages.*

The Polar Task Force experts and the responses to the survey have highlighted the need to continue Copernicus' current data policy.

Recommendation 7: *Copernicus should maintain a free, open, and efficient data policy, which is of paramount importance to encourage user uptake and downstream activities.*

In conclusion, to maintain Europe's leadership in polar services over the next decade it is crucial that the appropriate resources (in terms of funding and staff) are allocated as per the recommendations of the Task Force to further expand and improve the current polar services.

The proposed Copernicus polar roadmap for the next 5 to 10 years should enable the implementation of a European fully operational end-to-end system providing efficient services and products for the polar regions that meet users' requirements.

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ANNEX I: POLAR TASK FORCE SURVEY QUESTIONNAIRE – ANALYSIS AND SYNTHESIS OF REPLIES

General Information

Country of residence/Resident or not of the Arctic regions/Category of your organisation

Some 60 responses to the survey questionnaire were received from 17 countries

It can be noted that :

- More than half of the responses (33) originate from 5 Nordic countries
- 3 responses come from North America
- 18 responses from residents in Arctic regions
- The majority of responses come from the public sector including research institutes, academia and governmental national and federal agencies. 8 responses were from the private sector/private companies.
- 7 responses are indicated as from « International organisations »

Question 1: Please state your field of work and briefly describe your current use of Copernicus services and products for the polar regions.

Activities are briefly reported and cover both scientific/academic research and provision of operational services related to polar regions, focusing mostly on the Arctic and Greenland (only two responses specifically relate to activities for Antarctica).

Three main fields of work can be identified, although often mixed/interleaved, namely:

- Scientific research on polar processes in oceanography (biological, physical), glaciology (ice sheet and glacier changes, iceberg detection and drift), sea-ice cover change (thickness, drift), lake ice monitoring, snow cover, permafrost status (and associated methane emissions), land changes, wetland monitoring and climate changes (including Arctic atmospheric composition of various GHGs). These scientific research activities include modelling and algorithm development/validation, data assimilation of space (and in-situ) data in models to advance scientific knowledge of polar processes and to develop improved Arctic climate models.
- Provision of operational services. The above-mentioned research activities provide major contribution/input products, including quality assessment and validation, to Copernicus operational polar service providers. Operational services benefitting of these research activities include Copernicus Marine service (CMEMS), Copernicus Climate Change (C3S), Copernicus Atmospheric Monitoring Service (CAMS) and Copernicus Land Monitoring Service (CLMS). Key economic/trade user domains include maritime transport, maritime safety, shipping industry, fishing and aquaculture industry, and the energy/oil industry. These operational services are also essential for the protection of the marine environment (e.g. oil and plastics pollution monitoring, coastal erosion monitoring) and biodiversity protection as well as for climate change forecasts and consequences.

- Space data used are primarily microwave data from several missions including those from Sentinel-1 SAR operating in various modes (IW/EW) and providing sea level change data for InSAR interferometric applications. These European SAR data are complemented as necessary with Canadian Radarsat data. Microwave data also include those from AMSR-2 passive microwave radiometer, Altika Altimeter and Cryosat-2 SIRAL (Synthetic aperture Interferometer Radar ALtimeter). Use of optical multispectral imagery from Sentinel-2 is also mentioned as well as products of existing projects e.g. ESA CCI permafrost products, ERA5, EGMS products and CAMS products (methane data). Specific use and importance of Sentinel-5P/ TROPOMI data for CH4 is mentioned in one Canadian response. Use of Copernicus Contributing Missions is also outlined for a variety of terrestrial, maritime and atmospheric applications.

Question 2: Do you have any specific polar monitoring needs that are currently not met?

What could a suitable response be from Copernicus to address these needs?

Question 2 raised a large number of detailed responses outlining major shortfalls and weaknesses of today's Copernicus polar products and services. These can be broadly categorised as follows:

- Lack of in-situ data: Nearly all replies are concerned with the current lack of in-situ data for product validation/ verification and assimilation into models. The absence of firm proposals for the implementation of permanent and well-maintained in-situ observation equipment is stressed (one proposal suggests an Arctic in-situ programme as part of Copernicus).
  Of high interest are in-situ data related to soil, moisture, water salinity (including salinity of river runoff), snow and sea-ice parameters, physical water variables (e.g., temperature, pH, O2), coastal water quality biological components (e.g., Dissolved Organic Matter, turbidity), air quality, and GHG emissions. A candidate in-situ sensor for ice is also mentioned for further consideration.

- Status and availability of existing Copernicus space observations: There is a major concern expressed about the continuous availability of key satellite data such as from C-band SAR on Sentinel S-1A after the loss of Sentinel-1B (need for S-1C and 1D data required as soon as possible). This is also the case for the approaching end of life of Cryosat-2, in orbit since 2010, and the still distant launch of its successor mission, CRISTAL. Equally, the situation is critical for the microwave radiometer data from AMSR-2 (in operation since 2012) to be followed with AMSR-3 scheduled for launch in 2024 (TBC) and Copernicus CIMR.

- Major concerns are expressed about the incomplete geographical coverage of important areas, covered today with C-band SAR (e.g. coverage of the west coast of Greenland, land part of Greenland, Svalbard, Canadian and Russian Arctic, no full Antarctic coverage). Furthermore, high revisit frequency is required, e.g. full daily Arctic coverage. The present SAR observation strategy needs to be revisited in particular to resolve conflicting situations in relation with the different SAR operating modes (IW/EW). This is crucial, for instance, to meet requirements for interferometric products for fast moving glaciers in Greenland and Antarctica. Multiple (three) similar satellites simultaneously in orbit would improve the situation or even solve the issues.

- There is a quasi-unanimous requirement for higher spatial resolution (10 m or higher) at high latitudes (48 N-72 N) for SAR data as well as a need for data from SAR operating at different frequencies such as L-band (as will be provided by the future ROSE- L mission) and X-band. A similar requirement is expressed for higher spatial resolution of passive microwave radiometer data (as will be provided by the future CIMR mission) and of thermal infrared data (as will be provided by the LSTM mission). These data will be necessary for monitoring coastal waters, lakes, wetlands, peatlands, etc. Consideration of satellites in High Elliptical Orbits (HEO) is strongly recommended (e.g. by Canada) which would allow longer duration and rapid revisit observations (around the apogee) for Arctic regions.

- Improvement of the availability of/access to additional high resolution data and products such as Arctic atmospheric profiles of aerosols and clouds, albedo, winds, methane emissions from polar sources (permafrost), high resolution optical imagery (e.g. for discrimination between cloud and snow/ice), Snow Water Equivalent (SWE) product

- Several responses mention the need to significantly improve/reduce delivery time and latency of Copernicus data and products. Example of ice services distributed by DMI over VDES (VHF Data Exchange System) network is mentioned as an efficient system. Recommendation is made to provide products (e.g. ice products) in cloud optimized formats.

Question 3: Do you have suggestions for polar relevant elements that should be added or improved in Copernicus within the next 5-10 years? Please specify.

Question 3 *overlaps to a large extent* with the previous question 2 where recommendations were already made. Similar suggestions are proposed for:

- In-situ observations: Considering the reduced availability of Russian observations, a better coordination is needed at European level (via a single entity) and collection of in-situ data for product validation and assimilation into forecast models. The use/deployment of drones for the collection of observations is encouraged.

- Space observations: An overall requirement is stated for the provision of higher resolution space data than currently available. There is a clear need expressed to ensure that several similar SAR satellites (two or even better three) are simultaneously in orbit (e.g. S1 series including S1 NG) to overcome failures of one unit and provide adequate coverage of polar regions. It would thus provide long time series of observations. Development of HEO missions is again proposed to enable rapid revisit observations not achievable with LEO missions. Recommendation is made to develop additional frequency SAR (L-band, X-band, Ka-band) and bi-static coverage at X-band and Ka-band of key polar regions; it is strongly recommended to ensure an early launch of CIMR in view of the high demand for improved passive microwave radiometer data and with a guaranteed continuity with a second CIMR unit. Inclusion of EarthCare mission within the Copernicus Space Component (CSC) is also recommended as well as the addition of an optical mission to provide NIR (1000-1500 nm) observations.

- Revisit the current HLOP (High Level Operation Plan) to ensure more interferometric SAR operations over Antarctica in particular, and less conflicting SAR operating modes. InSAR processing is also essential for monitoring changes due to thawing permafrost leading to landslides. More generally, a review of observation priorities should be made to also serve other user communities than Copernicus.

- Better timeliness and NRT delivery of SAR data to ensure NRT delivery of CMEMS derived products

- Provision of additional products by C3S's ice sheet service (e.g., grounding line location, surface melt extent, calving fronts/ice extent, ice discharge/mass flux, IOM mass balance), and by CMEMS (e.g., sea ice thickness, snow depth on ice, sea ice concentration, melt ponds on sea ice). More generally, develop and provide new products related to glaciers, snow, lake properties, wetlands, ocean colour, permafrost, etc.

- Encourage development of improved sea-ice models with data assimilation and encourage an "open-source code" approach to promote Copernicus results.

- Ensure a better integration/harmonisation of Eumetsat OSI-SAF, CMEMS and C3S activities.

- Improvement of data latency and accessibility to users including analysis ready products and increased awareness for indigenous populations to meet their needs.

Question 4: From your perspective, what would be the key elements to enhance the visibility and user uptake of Copernicus data and products for polar regions (e.g., trainings, free and open data policy, information events, …)?

Responses to question 4 are all unanimous to further encourage and develop visibility and user uptake of Copernicus data and products for polar regions. Activities proposed include a number of concrete actions which can be broadly categorised as follows:

Interactions with Arctic user communities

- Funding of pilot demonstration projects involving Arctic user communities
- Development of Arctic user-oriented services, again in close interaction with these communities. Increased promotion and use of international networks ,e.g. Arctic GEOSS
- Develop use cases with local institutions and authorities, researchers, and universities
- Encourage Arctic Council members to further cooperate and exchange information at the pan-Arctic scale (despite the complicated situation with Russia)
- Develop long-term partnerships and sustained support to citizen science groups

Training and education activities

- Training sessions, information events, tutorials, summer schools, online seminars
- Communications (e.g. on the web) and training and education activities to be delivered, to the maximum extent possible, in appropriate languages, namely European languages including Northern languages (Danish, Swedish, Finnish, Norwegian) and appropriate indigenous communities languages (e.g., North Sámi, Inari Sámi, Inuit)
- Exchange of staff between Arctic communities and appropriate European entities (e.g., ESA, EC)

Access to data and products

- Improve practical access conditions to data and products (user-friendly interfaces to ease finding and downloading of data and products). This also applies to ESA CCI products.
- Provide easy access to appropriate documentation on data/products (e.g., performance, quality, formats, algorithms, updates)

Data policy aspects

- Unanimity of responses for an open and free data policy

Question 5: Would you consider coverage of Antarctica and the Southern Ocean by Copernicus relevant for your institution/work? Do you have any examples of useful products that could be added to the Copernicus portfolio?

There is (quasi-)unanimity in favour of the coverage of Antarctica and the Southern Ocean by Copernicus, being justified by the major role/contribution of Antarctica to climate change and to the provision of input data to climate models (quote: « It's mandatory »). Today C3S provides an ice velocity service for Antarctica but limited to observed margins and a better coverage of Antarctica with Sentinel S-1 is required. Full and frequent coverage with S-1 SAR (and other SARs) is required as well as with high resolution passive microwave radiometer (CIMR?). Use of InSAR for operational ice shelf edge monitoring is demonstrated.

In principle all Copernicus Arctic products should also be made available for Antarctica such as sea-ice drift, snow on sea-ice, ice thickness, ice shelf changes, icebergs, ice discharge, supraglacial lakes, etc. It is stated (one response) that the provision of Copernicus Antarctic products and services should not impact the provision of Arctic services.

Question 6: Several Sentinel expansion missions are expected to be in orbit by 2030. What are your expectations and suggestions for new and improved products and tools in the polar domain derived from these missions?

There is again unanimity to support the Sentinel Expansion Missions and to outline their importance with the following merits:

- Provision of higher revisit frequency, higher spatial resolution, more complete geographical coverage, with their advanced and/or complementary on-board instrumentation (e.g. L-band SAR, multifrequency microwave radiometer) than provided today with Copernicus missions for polar services;

- Expansion Missions (CIMR, CRISTAL) are essential in case of failures of old missions used today (such as AMSR-2 and Cryosat-2 in orbit for than 10 years) and there is a unanimous request to launch these Expansion Missions as quickly as possible (concerns are also expressed for their funding status and priorities)

- Provision of major improved polar products and of new ones through the fusion/merging of data from current Sentinels and those from Expansion Missions. Several combinations of missions and simultaneous operations in orbit between CIMR, ROSE-L, CRISTAL and Sentinel S-1 are mentioned to illustrate the associated benefits for many polar products related to sea-ice, ice sheets, iceberg detection, glaciers, snow, SWE, permafrost, ocean salinity …

- For atmospheric services, CO2M will yield improved CO2, CH4 and solar induced fluorescence observations over Northern regions. Algorithms will have to be developed to minimize data loss in the challenging conditions of the Arctic (low sunlight, low shortwave IR albedo)

(Note: A detailed information is available in the DEFIS PEG III report published in 2021 in which individual contributions in terms of polar products for each Expansion Mission are provided as well as merits of possible combinations with Sentinel S-1, S-2 and S-3)

Question 7: A Thematic Hub dedicated to the Arctic is currently being deployed under Copernicus. What are your main expectations from this hub in terms of data, information and outreach?

There is generally a positive reaction for the deployment of a Copernicus Arctic Thematic Hub (noting that more than 1/3 of the survey responders have not replied to that question). If well designed, the Arctic Polar Hub will provide major advances as outlined hereafter:

- It will allow more collaboration, and more efficient work with European Arctic national programmes/projects and activities.

- It will benefit the outreach and the promotion of Copernicus activities and services to local, national, regional authorities and user entities.

- A one-stop shop for Arctic variables will provide a good (better?) accessibility to a large variety of data and products including in-situ measurements collected by different organisations/entities (e.g. for sea-ice) and auxiliary data.

- Design of the Copernicus Arctic/Polar Thematic Hub should allow access to time series of high quality and high resolution data sets, allowing easy reprocessing with improved algorithms (a good example is provided by the Copernicus Coastal Hub currently in operation). It is strongly recommended to involve production centers in the hub design.

- Responses also outline the need for good, easy-to-use Graphical User Interfaces (GUI) and the provision of good documentation on products (e.g., quality, performance, algorithms)

- A need for coordination with existing platforms (e.g. ESA Polar Thematic Exploitation Platform, EU Polar Cluster, Polar-TEP) is expressed to minimise duplication.

- An equal focus should be put on Antarctica and the Southern Ocean.

Question 8: In your opinion, should the role of citizen science be enhanced in Copernicus? If so, do you have any recommendations for how citizens in polar regions could be involved?

There are positive reactions from the responses (noting that 1/3 responders did not provided inputs) to encourage citizen science (CS) activities. Use of local and traditional knowledge is considered of high importance for the Arctic regions. Benefits of CS, description of successful cases and techniques but also of limitations/constraints are provided as follows:

- CS will allow the collection of important in-situ data (e.g., validation of data/products, space instrumentation, calibration, inputs to models) but will need proper data quality control.
- Involvement of local indigenous populations will raise awareness and scientific knowledge about climate change in their living areas. However, there are significant challenges to integrating citizen science in complex scientific programmes.
- Several successful examples are given such as in Canada (SmartIce) and in Alaska. A Norwegian crowd sourcing App (called Varsom) is providing crucial information for snow avalanches, lake and river ice, floods and landslides. The WMO VOS programme is also successfully involving coastal populations.
- The government of Canada has a “citizen science portal” to engage the public and benefit from their knowledge. They are exploring how to incorporate traditional knowledge to improve existing products and services.
- Development of user-friendly mobile Apps is strongly supported (possible use of drones?)
- There are limitations due to the low population density in polar regions, thus limiting the collection of in-situ data/ground truth data.
- A number of suggestions to improve the current situation are made, including: make translations in local languages available of Copernicus information (e.g., objectives, products, plans); offer financial compensations.
- Regarding data collection, a FAIR (Findable, Accessible, Interoperable, Reusable) approach is recommended.

Question 9: Concerning international cooperation in the polar regions, are there any initiatives that Copernicus could benefit further from? Do you have suggestions of areas where collaboration should be improved? Please provide specific examples of organisations, activities, programs, data to be shared, etc.

There is general support expressed for the development of international cooperation in polar regions (again 1/3 of missing responses), in particular for the acquisition/exchange of space and in- situ data. Proposals include:

- Closer cooperation between space agencies for the development of additional space missions to maximise coverage and frequency of observations over polar regions. Besides the planned Copernicus Expansion Missions (e.g., CO2M, CIMR, CRISTAL, ROSE-L), specific space missions are being under definition by Canada and considered for possible multilateral development, namely:
  - Arctic Observing Mission (AOM), in partnership with the USA and Europe, consisting of two satellites in a HEO to overcome spatial/temporal gaps of existing LEO and GEO satellites. Instrumentation would include a meteorological imager, a GHG Fourier transform spectrometer, a dispersive spectrometer for air quality observations and space weather instruments.
  - The Terrestrial Snow Mass Mission (TSMM) with a Ku-band radar for snow mass and SWE retrieval
- Further develop cooperation with China to access their EO satellite data in Europe.
- Use of commercial space operator’s missions as appropriate to complement Copernicus space missions.

- Make open and free of charge the satellite data acquired over polar regions.
- Participation in high level Committees/Boards (e.g. Arctic Observing Summit, European Polar Board, Arctic Council), international organisations (IMO, WMO -IOC IICWG), tourism associations (IAATO, AECO, CLIA, BIMCO). Link to WMO Global Cryosphere Watch
- Improve the coordination between EU projects (e.g., EEA COINS project, Horizon Europe and H2020 projects such as Arctic PASSION/SAVs) related to polar science.
- Improve coordination/interaction between EC DGs (e.g., RTD, MARE, CLIMA) activities and projects.
- Reinforce cooperation for Antarctica with non-European countries having EO satellite ground receiving stations, such as USA, Japan, China, and South American countries.

Question 10: Do you have additional advice? How could the Copernicus Services be developed to improve their application to the polar domain?

A number of recommendations was made (50% response rate) providing useful guidelines for the future development of Copernicus polar services, namely:

- Continuous involvement/consultation of local users and indigenous communities to identify their requirements for new/improved products and services.
- Increased effort for the collection of in-situ observations essential for data/products validation via a better cooperation with indigenous local communities living in polar regions.
- Need to further address and develop polar land products and services for the benefit of local populations, with Copernicus being more focused today on maritime services.
- Develop simple APIs and GUIs to easily access and use data and products.
- Ensure that all data collected by European projects are made available openly and free-of-charge.
- Improve forecasting modelling and data assimilation for ice/ocean models. More generally, Copernicus should devote more effort to scientific and research activities for development of new parameters (e.g. new ice sheet and glacier products for Greenland and Antarctica) and not be only focused on business development activities.
- Development of services should be opened up for wider competition and not only awarded to «entrusted entities».
- Provide consistent and full geographical coverage of polar regions.
- Continue and further develop international cooperation e.g. with NASA (such as Operation Ice-Bridge and CryoVex for Cryosat-2)
- Ensure coherence between Copernicus roadmap and the EU Arctic policy

Conclusions

The survey questionnaire has provided a large number of useful recommendations for improving the Copernicus polar services. These recommendations are addressing various aspects/elements of the Copernicus programme including:

- Technical aspects: Development of tools allowing easy access and downloading of data and products by users.
- Operational aspects: Provision of timely and high quality products/services to users with the associated documentation. Services should cover both the Arctic and Antarctica and the Southern Ocean. A Polar Thematic Hub is welcome as a one-stop shop to ease access for users to polar products and data.
- Scientific aspects: Need for an increased effort for the development of new models, parameters, algorithms and data assimilation techniques.
- Space component: Ensure continuous availability of key space observations (with higher resolution) and prepare for the venue of new Sentinel Expansion Missions to be launched as quickly as possible. Further develop cooperation with space agencies/operators worldwide (including commercial operators) to access their EO data if relevant.
- In-situ observations: Development and deployment of equipment/facilities for the collection of in-situ observations in polar regions with the support/involvement of local indigenous populations as appropriate (implementation of a "citizen science portal" to be considered)
- Data policy aspects: Provision of all data and products developed by Copernicus on an open and free-of-charge basis.
- International cooperation: Further development of international cooperation with space agencies and European Arctic and appropriate global organisations
- Outreach: Development of training and learning activities for the outreach and promotion of Copernicus at all levels (e.g., students, scientists, engineers, managers)

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