POLARIN

POLAR RESEARCH INFRASTRUCTURE NETWORK

Deliverable 1.4
Overview report of existing science priorities by major Arctic and Antarctic organisations and validation/calibration needs by in-situ observation, remote sensing, and modelling communities

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TABLE OF CONTENTS

SUMMARY

The EU funded project POLARIN provides integrated, challenge-driven, and combined transnational access (TA) to research infrastructures (RIs) in the polar regions to facilitate interdisciplinary research on complex processes. To this end, POLARIN will open calls for proposals to access these RIs.

To set the frame of the POLARIN challenge driven calls, the project must define a science framework to serve as guidance to the call for proposals to TA, and to evaluate the project contribution to the different research topics. This science framework covers two main categories of research challenges relating to the polar regions: one addresses the priority topics which are associated with major current knowledge gaps on the polar regions and the other addresses current data validation and calibration needs.

The POLARIN science strategy reflects the overarching research priorities identified by national, European and international organisations and programmes. A desk study analysis was performed of the most recent science strategy documents and reports. Seven overarching research topics have been identified that can be targeted by the POLARIN RIs: Sea Ice and Polar Oceans in the Climate System, Polar Ice Sheets, Glaciers and Sea Level, Terrestrial Carbon Cycle and Permafrost, Polar Ecosystems and Biodiversity, Atmosphere Dynamics and Chemistry, Paleoclimate Processes and Variability, Humans, Societies and Global Changes, each of them described in terms of several subtopics. Regarding data calibration/validation needs, three categories have been considered: In-situ Observations, Remote Sensing and Modelling, for which improvement in the polar data quality and consistency is needed.

The POLARIN TA calls for proposals will address the entire range of research topics which have been identified in this report to attract as many potential user groups as possible towards the POLARIN services. In successive calls, specific key research topics might be prioritised to promote the focus of research projects on key geographical, thematic or analytical gaps

1. Introduction

The POLARIN project aims to provide international scientists with transnational access (TA) to a portfolio of polar Research infrastructures (RI) in support for world-class research on the Polar Regions. TA provision is made through call for proposals which are managed in such a way that projects benefiting from TA should deliver excellent science while addressing the most pressing research challenges in the Polar regions. The scientific management of TA therefore relies on two pillars: (i) identification of the research priorities which should shape the scientific framework of the TA calls, and (ii) proper evaluation of the submitted proposals to guarantee the scientific excellence of the selected projects but also their adequation to the call research priorities. Deliverable 1.4 "*Overview report of existing science priorities by major Arctic and Antarctic organisations and validation/calibration needs by in-situ observation, remote sensing, and modelling communities*" deals with the first pillar.

Implementation of TA to RIs through *challenge driven* calls for proposals is indeed a specificity of POLARIN in comparison with earlier European projects which have provided TA to RIs (e.g. EUROFLEET and EUROFLEET++, ARICE, INTERACT). This original approach implies that POLARIN must define a science framework which will serve as guidance to call for proposals to TA, but also will be used to evaluate the contributions of funded projects towards the key research topics. Work package 1 in POLARIN is responsible for supporting this approach. For some aspects which require a dedicated scientific expertise like, e.g., reviewing the POLARIN scientific priorities during the successive TA calls, evaluating the proposals or following the outcome of the funded projects, POLARIN will be supported by a Scientific Liaison Panel (SLP), a team of experts whose composition and tasks are described in detail in Deliverable 1.1.

The science framework supporting TA to POLARIN RIs covers two main categories of research challenges relating to the Polar regions: one addresses the research topics which are associated with major current knowledge gaps on the Polar regions and the other addresses current data validation and calibration needs. While identification of research topics is essential to ensure that POLARIN TA will contribute to answer the most pressing challenges in the Polar regions, promoting research to improve the data quality and consistency is also a major concern for POLARIN given the potential of TA projects to generate new datasets through field work and access to RIs.

2. Science priorities and validation calibration needs as a guide to accessing research infrastructures in the Polar regions

2.1. Science framework for transnational access to POLARIN research infrastructures

POLARIN provides access to POLARIN services by launching challenge-driven calls for proposals, At the same time, the scientific scope of the calls should be large enough to take advantage of the diversity of European expertise and foster wide cooperation between partners for a coordinated, and possibly combined, use of polar infrastructures. To identify the relevant key research topics and data calibration/validation challenges in support of these objectives, the POLARIN consortium relies on already performed prioritization exercises, in particular that which root in consultations of a wide community of scientists and/or stakeholders. A desk study has been performed of these documents which is the subject of the present report. The key research topics, which are documented in section

4, will provide the initial scientific framework of the first POLARIN TA call. The framework is wide enough to allow a large research community to apply and can be implemented with the research infrastructures offered in POLARIN.

To ensure that proposals submitted to the POLARIN calls for proposals target the research topics defined in the scientific framework, the "relevance to the call topic" is included in the evaluation criteria.

2.2. Refining the science framework during the POLARIN project

Priority topics may be (re)defined in successive calls for proposals taking into account:

1) Input from gap analyses (geographical, thematic or analytical gaps) developed by POLARIN to identify knowledge gaps that can be addressed with POLARIN RIs.
2) The contribution of implemented POLARIN TA to addressing the research topics.

Successive calls for proposals will also take into account updated science programmes developing during the course of POLARIN.

3. Analysis of existing national, European and international polar research programmes

3.1. Categories of research priority topics and calibration/validation needs

Although POLARIN TA encourages multi-disciplinary research favouring integrated use of RIs, the scientific priorities highlighted in POLARIN are organized along overarching topics referring to the different compartments of the Earth System. Yet, the description of the scientific priorities highlights potential connections between topics, encouraging what should be a comprehensive understanding of the Polar regions.

Seven overarching topics have been considered:

- Sea Ice and Polar Oceans in the Climate System
- Polar Ice Sheets, Glaciers and Sea Level
- Terrestrial Carbon Cycle and Permafrost
- Polar Ecosystems and Biodiversity
- Atmosphere Dynamics and Chemistry
- Paleoclimate Processes and Variability
- Humans, Societies and Global Changes

In terms of data calibration/validation needs, three categories have been considered:

- In-situ Observations
- Remote Sensing
- Modelling

3.2. Documents in support of the present analysis

To ensure that the research performed at POLARIN's RIs will contribute to address key research challenges with potentially high societal impacts in the Polar regions, the scope of the calls for proposal should reflect the overarching research priorities identified by national, European and international organisations and programmes. Among these are the EU-PolarNet project (https://eu-polarnet.eu) and other past and ongoing EU Polar Cluster projects (https://polarcluster.eu/), the Intergovernmental Panel on Climate Change (https://www.ipcc.ch), the European Space Agency (https://www.esa.int) and the United Nations Decade of Ocean Science for Sustainable Development (https://oceandecade.org), all concerned with both polar regions, the International Arctic Science Committee (https://iasc.info) for the Arctic, and the Scientific Committee on Antarctic Research (https://www.scar.org) for the Antarctic. A number of research plans and strategy documents have been published in the recent years by these different organizations and programmes which have emerged from a large consensus of the research community. The selection of the priorities is the result of a desk analysis of these documents.

We present below a list of the most relevant documents consulted to draft the present report.

1- Science priorities

International Arctic Science Committee (IASC): IASC is a non-governmental organization that facilitates international Arctic research. It provides scientific advice, promotes coordination of Arctic research, and supports the Arctic science community. Key documents and resources include its strategic plans and reports from its working groups on Cryosphere, Atmosphere, Terrestrial, Marine, and Social and Human sciences. Of particular interest is the decadal International Conference on Arctic Research Planning (ICARP) process (https://iasc.info/our-work/icarp) which invites the scientific community and Arctic stakeholders “to consider the most urgent knowledge gaps and research priorities that lie before us and to explore avenues to address these research needs”. Such a process, ICARP IV, is currently being implemented. IASC is also partnering with the AOS (Arctic Observing Summit) organizing committee (see below).

- *International Arctic Science Committee (IASC) Strategy*. Available at: https://iasc.info/about/publications-documents/organisational-and-strategic. Also available are the IASC yearly State of the Arctic Science reports: https://iasc.info/about/publications-documents/state-of-arctic-science.
- *ICARP III report: Integrating Arctic Research - a Roadmap for the Future*. Available at: https://iasc.info/about/publications-documents/publications-list/663-icarp-iii-final-report

Arctic Council (AC): The AC is an intergovernmental forum promoting cooperation in the Arctic. The AC serves as knowledge broker and global advocate for Arctic topics through assessments produced by its different working groups

- Arctic Council working group documents available at: https://arctic-council.org/resources/

Scientific Committee on Antarctic Research (SCAR): SCAR is an international body that coordinates scientific research in Antarctica and the Southern Ocean. SCAR's research priorities are outlined in their strategic plan and focus on climate change, polar ecosystems, paleoclimate processes, and human impacts in Antarctica.

- *SCAR Strategic Plan 2023-28*. Available at: https://scar.org/about-us/strategy/strategic-plan
- *SCAR Antarctic Climate Change and the Environment Decadal Synopsis* (ACCE). Available at: https://scar.org/library-data/scar-publications/antarctic-climate-change-and-the-environment

EU-PolarNet Coordination and Support Action: EU-PolarNet is a European network initiated in 2015 under the European Commission Framework Programme Horizon 2020. The objectives are to co-develop and advance European Polar Research actions and to give evidence-based advice to policymaking processes. Several reports and framing documents have been produced by the project since its inception. Among these, a European Polar Research Programme and a report on future research needs in the Polar regions have been published in 2020 and 2023, respectively.

- *Integrated European Polar Research Programme* (EPRP): The EPRP outlines priorities for European research in the Arctic and Antarctic, emphasizing climate change, ecosystem dynamics, and socio-economic impacts. Available at: https://eu-polarnet.eu/the-integrated-european-polar-research-programme/
- *Identification report of critical future research needs in the Polar regions*. Available at: https://eu-polarnet.eu/achievements-2020-2024/

Intergovernmental Panel on Climate Change (IPCC): IPCC is the United Nations body for assessing the science related to climate change. Regular assessment reports are published, including a scientific review of current knowledge and research challenges and recommendations for governments, stakeholders and society. The sixth assessment cycle led to a series of reports (AR6) which have been published between 2018 and 2023.

- *IPCC Special report on the ocean and cryosphere in a changing climate* (2019), available at: https://www.ipcc.ch/srocc/
- *IPCC Climate Change 2021: The Physical Science Basis*. Available at: https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/

National Research Priorities: Various countries have their own polar research priorities, often aligned with international frameworks but focusing on specific national interests. These are typically found in national science strategies and funding agency publications. Example references are:

- *UK Research and Innovation (UKRI) Polar Research Strategy*. Available at: https://www.bas.ac.uk/science/our-research/our-strategy/
- *US Interagency Arctic Research Policy Committee, Arctic research plan 2022-2026*, available at: https://www.iarpccollaborations.org/plan/index.html.

2. Observation data and modelling initiatives

Sustaining Arctic Observing Networks (SAON): The SAON joint initiative of the Arctic Council and IASC aim to strengthen multinational engagement in pan-Arctic observing and data provision for monitoring Arctic environmental changes. Regarding the ocean, a Task Team to advance the development of pan-Arctic Ocean observing alliance with the perspective of an Arctic GOOS Regional Alliance has been established under the SAON board. SAON is also partnering with IASC to support the **Arctic Observing Summit (AOS)**, a biennial summit that aims to provide guidance for the design, implementation, coordination and sustained long-term operation of a comprehensive and inclusive pan-Arctic observing system.

- *SAON Strategy document*, providing a 10-year strategy to address current and future Arctic observing needs. Available at: https://www.arcticobserving.org/strategy
- SAON *Task Team to advance the development of pan-Arctic ocean observing alliance: Terms of Reference*. Available at: https://arcticobserving.org/news

WMO Global Cryosphere Watch (GCW): The WMO GCW initiative provides an integrated, sustained observing network for the cryosphere. It supports data collection, standardization, and accessibility for validation purposes. Available at: https://globalcryospherewatch.org

WCRP Model Intercomparison Projects (MIP): MIPs address specific science questions across the climate and earth science communities and promote international collaboration to improve the understanding and model representation of the Earth System, its variability and changes, by comparing and assessing a large variety of models following a standard experiment protocol. The initial WCRP Coupled Model Intercomparison Project (CMIP) was first established to provide climate scientists with a database of coupled global model simulations.

- List of MIPs and related publications available at: https://wcrp-cmip.org/mips/
- CMIP reports available at: https://wcrp-cmip.org/cmip-reports/

WMO Polar Prediction Project (PPP): The WMO Polar Prediction Project and its flagship activity, Year of Polar Prediction (YOPP) aim at improving weather and environmental prediction capabilities in polar regions. The project supports integration of data from in-situ observations, remote sensing, and models, making it a key resource for understanding validation and calibration needs. Available at: https://www.polarprediction.net/yopp

- PPP related publications available at: https://www.polarprediction.net/publications/research-publications/
- PPP science plans and YOPP recommendations available at: https://www.polarprediction.net/about/implementation-and-science-plans/

Key Environmental monitoring for Polar Latitudes and European Readiness (KEPLER) project: KEPLER is a Horizon 2020 funded project aiming to enhance European capabilities for monitoring and forecasting the polar regions for improved understanding and informed decision-making.

- KEPLER review paper: *Improving satellite-based monitoring of the polar regions: Identification of research and capacity gaps* by Gabarro et al., 2023 available at: https://doi.org/10.3389/frsen.2023.952091

ESA Earth Observation Science Strategy, documents available at: https://nikal.eventsair.com/eo-science-strategy-review-workshop-2024/workshop-documents

4. POLARIN science priorities and validation/calibration needs

4.1. Research priorities in the Polar Regions

The polar regions play a critical role in the global climate system, altogether acting as key players and experiencing the most rapid changes and significant environmental shifts that impact ecosystems and societies at the regional and global scales. To improve knowledge of polar processes, develop more accurate and reliable climate models and projections, and inform policies to protect these critical environments and the communities that depend on them, the following research priorities have been identified:

4.1.1. Sea Ice and Polar Oceans in the Climate System

Understanding the properties and dynamics of the sea ice covers and polar oceans and their mutual interaction, their variability at all time scales and their relations to the atmosphere and land is essential to evaluate their role in shaping regional and global climate and major biogeochemical cycles. This includes addressing the following topics:

Sea Ice properties: Focus should be put on monitoring and understanding changes in the sea ice distributions in both the Arctic and the Antarctic, including the sea ice extent, thickness, snow depth, drift and age. This includes understanding the seasonal and long-term trends in the sea ice properties and their implications for the Earth's surface energy balance and air-sea interactions.

Polar oceans in the climate system: Focus should be put on understanding the changes in ocean currents and transports in response to atmospheric circulation changes and determining the causes of changes in ocean water properties including bottom water properties, volume and production rates in relation to their source waters, and the impact on the global overturning circulation.

Ocean-sea ice Interactions: Focus should be put on investigating processes that govern the interaction between sea ice and the underlying ocean. This includes understanding the response of the sea ice thermodynamics and dynamics to ocean circulation, temperature and salinity distributions, mixing rates and associated transports; and, conversely, understanding how the sea ice distribution and transport affect the properties and dynamics of the underlying ocean.

Extreme events, marine heatwaves and sea ice retreat: Focus should be put on characterizing the conditions of formation of extreme events such as atmospheric polar lows or marine heatwaves, in polar regions, understanding the causes of their increasing frequency and intensity, and investigating the response of the sea ice and upper ocean, including accelerated sea ice retreat by marine heat waves and the broader implications for marine ecosystems.

Ocean role in biogeochemical cycles: Focus should be put on the biogeochemical processes in polar oceans in relation to nutrient cycling, marine primary production, ocean carbon uptake, or the release of methane and other greenhouse gases from under-ice waters; focus also includes how changes in ocean circulation and properties currently affect these processes.

4.1.2. Polar Ice Sheets, Glaciers and Sea Level

Understanding the behaviour of the polar ice sheets and glaciers is essential to narrow down the uncertainties on their contributions to global sea-level rise under current and future climate scenarios, including risks of possible collapse in the future. This includes addressing the following topics:

Ice Sheet Dynamics: Focus should be put on understanding the dynamics of the Greenland and Antarctic ice sheets and the leading processes controlling their stability, and their impact on the ice sheet mass balance. This includes investigating the processes controlling the ice flow and the outlet glacier grounding lines, the role of subglacial processes (basal melting and sliding, subglacial lakes and hydrographic networks), the functioning of ocean cavities and the drivers and mechanisms of ice-shelf damaging.

Glacier Melt and Retreat: Focus should be on monitoring the polar glacier mass balance, including tidewater glaciers, and their responses to atmospheric and oceanic warming.

Sea-Level Projections: Focus should be put on development of improved models for narrowing down the uncertainty on future sea-level rise projections by incorporating the latest data on the different contributions from the ice sheet and glacier mass loss and the ocean thermal expansion.

4.1.3. Terrestrial Carbon Cycle and Permafrost

Investigating the terrestrial carbon cycle in polar regions, particularly the role of permafrost and polar ecosystems in storing and releasing carbon, is essential to understand the implications for the atmospheric greenhouse gas concentrations and potentially global warming. This includes addressing the following topics:

Permafrost Thaw: Focus should be on understanding the permafrost dynamics, distribution and state in Arctic regions, including for subsea permafrost on the Arctic shelves, monitoring regions of permafrost thaw and the subsequent formation of lakes and wetlands, and understanding events of rapid thawing.

Carbon Fluxes and possible climate feedbacks: Focus should be put on understanding and quantifying carbon dioxide and methane fluxes emissions from permafrost regions, including both direct emissions from thawing soils and indirect emissions from lakes and wetlands, and investigating possible feedback mechanisms linking permafrost thaw, increased carbon emissions and enhanced surface warming.

Role of polar ecosystems in carbon sequestration: Focus should be put on understanding the role of polar ecosystems, including tundra and boreal forests, in carbon sequestration and how these systems are changing with regional warming.

4.1.4. Polar Ecosystems and Biodiversity

Understanding the structure, function, and biodiversity of polar ecosystems and how these are affected by environmental changes across different geographical sectors and habitats, including the cumulative effects of multiple drivers, is essential to plan for improved management of these unique ecosystems. This includes addressing the following topics:

Marine Ecosystems: Focus should be put on the characterization and drivers of the changes, including impacts of sea ice loss, ocean acidification, changes in coastal matter fluxes and ocean warming on ecosystem structure and phenology, species distribution, food webs, ecological interactions and productivity of ecosystems. This also includes identifying thresholds or irreversible changes and understanding the connectivity of the polar ecosystems with the lower latitudes and the impacts of human activities such as contamination by anthropogenic pollution.

Terrestrial Ecosystems: Focus should be put on understanding the effects of warming on tundra vegetation, soil microbial communities, soil processes and hydrology, and terrestrial fauna. This includes the study of phenological changes, such as earlier plant blooming and shifts in species distributions.

Biodiversity Monitoring: Documenting and monitoring biodiversity in polar regions implies using advanced techniques such as remote sensing, environmental DNA (eDNA) and automated instrumentation camera to assess changes in species abundance and diversity.

4.1.5. Atmosphere dynamics and chemistry

Investigating the atmosphere dynamics and processes in polar regions and their influence on local and global climate systems is essential to improve regional and global climate projections and to plan for the extent of regional and global warming, including changes in extremes in the polar regions and beyond. This includes addressing the following topics:

Atmospheric circulation patterns: Characterizing changes in weather systems, clouds, and precipitation in the polar regions, including atmospheric river activity, the polar vortex and its interaction with the jet stream, and how polar warming and its amplification can influence these atmospheric patterns, including weather extremes (cold air outbreaks and heatwaves) in mid-latitude regions.

Atmospheric Chemistry: Investigating the unique atmospheric chemistry of polar regions, including the role of halogens in ozone depletion and the formation of polar stratospheric clouds.

Cloud and Radiation Processes: Understanding cloud formation, radiation processes, and energy balance in polar regions, including the impacts of changing sea ice and snow cover on cloud conditions and the implication of clouds in major climate feedbacks (e.g., albedo or cloud-phase feedback).

Aerosol-Climate Interactions: Understanding the role of aerosols in polar climates, including natural sources like sea spray, volcanic dust or biogenic aerosols, as well as anthropogenic sources, and their effects on cloud formation, albedo and key feedback mechanisms like the cloud-aerosol feedback.

Air pollution: Understanding the impacts of legacy and emerging pollutants, including those trapped in sea ice, permafrost and terrestrial glaciers over the last decades, the local and remote sources of air pollutants, including short-lived climate forcers (black carbon), and their preferred pathways and impacts.

4.1.6. Paleoclimate Processes and Variability

Collecting and analysing ice and sediment cores and reconstructing past climate conditions in polar regions is essential to improve understanding of long-term trends and natural climate variability, including past glaciations, ice sheet extent and retreat patterns, and to inform climate projections. This includes addressing the following topics:

Ice Core Records: Focus should be put on collecting and analysing ice cores from Antarctica and Greenland to study past climate conditions, including temperature, atmospheric composition, and volcanic activity over hundreds of thousands of years.

Marine and Lake Sediments: Focus should be put on collecting and analysing marine and lake sediment cores to reconstruct past ocean conditions, ice sheet dynamics, and climate variability over millennial timescales.

Glacial Geology: Focus should be put on investigating glacial geology and geomorphology to understand past glaciations, ice sheet extents, and retreat patterns, and to provide context for current ice sheet changes and potential future scenarios.

Proxy Data Synthesis: Focus should be put on integrating multiple proxy data sources, such as tree rings, pollen, organic geochemical proxies and isotopes, to create comprehensive reconstructions of past climate variability and its drivers.

4.1.7. Humans, societies and global changes

Assessing the impacts of global changes on humans and societies in the polar regions is essential to develop strategies for adaptation and resilience. Focus should be put on:

Socio-economic impacts of climate change and human activities in the polar regions: Characterizing and quantifying the socio-economic impacts on Arctic communities, including cumulative impacts, and their effects on livelihoods. Impacts include infrastructure damage, as a result of permafrost thaw, changes in ecosystems and landscapes due to human activities, and changes in access to resources like, e.g., shifting species distributions altering fishing activities.

Indigenous Knowledge, culture and community adaptation: Understanding how indigenous communities in the Arctic are adapting to changing environmental conditions, investigating the potential of cultural revitalization versus innovation, including learning from the past, and understanding methods for co-production of knowledge in which local and traditional knowledge informs scientific understanding and policy-making.

Sustainable development of Arctic communities: Understanding how economic development and innovation contribute to welfare, monitoring the development through indicators, analyzing the interdependency between subsistence economy and industrial activities, and impacts on education and schooling trends.

Health and Well-being: Investigating the health and well-being of polar communities, focusing on the impacts of environmental changes, such as increased exposure to pollutants, food security issues, and mental health challenges associated with rapid environmental change.

4.2. Validation and calibration needs

Quality-checked environmental and socio-ecosystem data are crucial to advance scientific knowledge on the Polar regions. The necessary information can rely on three different approaches, namely in-situ observation, remote-sensing, and modelling, which all contribute, independently or in combination, to identifying, characterizing and understanding the processes and changes in the Polar Regions. While each approach has its own strengths and limitations, cross-validation is often performed between these different types of data making their quality interdependent. As an example, the sparsity of in-situ observations in Polar regions, mostly due to the extreme environment and logistical challenges, limits their potential to serve as ground-truth for remote sensing observations or to inform and validate models and forecasting systems.

Quality-checked data are fewer in the Polar regions than anywhere else for various reasons which will be mentioned in the following sections. Therefore, most scientific advances must rely on integration of different approaches/type of data which can provide complementary information. This integration requires rigorous validation and calibration efforts to ensure data reliability, accuracy and consistency. Below, we explore the specific validation and calibration needs for each type of information and how these can complement each other in polar research. By addressing these validation and calibration needs, it is expected that the data accuracy and model performance will be improved, leading to a better understanding of polar processes and more reliable predictions of future changes in these critical regions

4.2.1. In-situ observations

In-situ observations involve direct measurements or sampling on-site. These measurements are critical for producing direct information on the Polar regions, but also for ground-truthing information obtained from remote sensing and for informing and validating models. However, in-situ observations face unique challenges due to the extreme environment, logistical difficulties, and high operational costs. Limited spatial and temporal coverage remains a significant challenge in polar regions due to the vast and remote nature of these areas: extensive regions remain unexplored and data time series are often too short to enable signatures of changes to be detected and attributed.

Validation and Calibration Needs:

- **Instrument Quality Control**: Maintenance of instruments and rigorous quality control procedures are needed to ensure the expected precision and measurement accuracy in harsh polar environments where instruments are subject to, e.g., extreme temperatures, ice accumulation, and mechanical stress. Regular calibration of field sensors against known standards and field calibration campaigns to check instrument performance under polar conditions are essential.

- **Consistency and Standardization**: There is need for standardized measurement protocols to ensure consistency between different production methods and across different time periods. This is crucial for accurately characterizing the variability of the observed properties, detecting long-term trends and comparing data from different locations.

- **Cross-Comparison**: Cross-comparison of data from different in-situ observation systems can help identify biases and discrepancies. Collaborative efforts, such as, e.g., the Global Cryosphere Watch (GCW) and the Sustaining Arctic Observing Networks (SAON), are working towards harmonizing observational datasets.

- **Enhanced Temporal and Spatial Coverage**: Increased deployment of automated instrumentation and autonomous platforms such as weather stations, sampling hubs, buoys, floats, drones are needed to improve coverage, although logistical constraints and harsh conditions often limit their distribution and longevity. New observational technologies which are being developed for environment monitoring should be made available for systematic use in the polar regions. Better coordination between polar observing networks, in association with the use of Observing System Simulation Experiments to optimize the distribution of the observing systems, should be encouraged.

4.2.2. Remote sensing

Remote sensing involves collecting data remotely from sensors mounted on satellites, aircrafts, or drones. This method is invaluable for providing continuous observations over areas that are otherwise difficult to access, or for offering synoptic views over extensive areas that could not be obtained from the ground. However, the processing and parameter retrieval algorithms from remote sensing observations must be validated and calibrated against ground-truth data to ensure the reliability and accuracy, with known uncertainties, of the retrieved information.

Validation and Calibration Needs:

- **Ground-Truthing for calibration/validation of satellite-derived parameters**: Parameters retrieved from remote sensing data must be validated against in-situ observations to ensure that satellite-derived parameters accurately represent the reality. Ground-based campaigns that measure essential parameters (EV) throughout a product lifetime are essential with proper spatial and temporal coverages so that the calibrated products are fully representative.

- **Algorithm calibration for improved/consolidated satellite products:** Calibration/validation is needed to improve retrieval methods. This is particularly important for sensors that must detect changes in properties which can vary significantly depending on environmental conditions (e.g., ice and snow). In particular, technical developments on optical and microwave modelling of cryospheric objects are needed, such as improvement of e.g. sea ice emissivity representation in retrieval algorithm from passive microwave radiometer measurements.

- **Sensor calibration for temporal consistency**: Calibration of remote sensing instruments must account for changes over time, such as sensor drift or degradation. This requires continuous monitoring and updating of calibration algorithms to maintain data accuracy over the lifespan of the satellite. In particular, accurate radiometric calibration, comparing satellite measurements to known reference targets, like ground-based radiometers or calibration sites, is essential for measuring surface properties, such as reflectance and temperature, with sufficient precision/accuracy.

- **Integration of data from multiple satellite instruments**: Enhanced synergy to combine data from multiple satellite sensors (optical spectrometers, passive microwave radiometers, SAR, radar and lidar altimeters, …) and to integrate them with in-situ measurements should be encouraged. This synergy is essential to support data processing services. Alternatively, use of similar instruments on board different missions can potentially improve the measurement uncertainty. Combining different datasets requires careful calibration to ensure consistency across them. Techniques like data assimilation and machine learning can help reconcile discrepancies and improve the overall quality of merged datasets.

4.2.3. Modelling

Modelling is an essential tool to understand processes and their variability on all time scales in the Polar regions, to predict their evolution thanks to forecasting systems and to build projections under future scenarios. In general, models are useful tools for extrapolating data in time and space, especially when their coverage is limited like in Polar regions. However, models rely heavily on accurate input data and must be validated against observations.

Validation and Calibration Needs:

- **Improved model physics**: Models must rely on appropriate representation of the simulated system dynamics. In practice however, discretization errors and incomplete model physics limit this representation and must be overcome by using parameterizations of unresolved or misrepresented processes. In current models, including the most sophisticated ESM, many poorly known polar-specific processes, such as fine scale ice dynamics, processes and fluxes at the atmosphere-ice-ocean-land interfaces, or biogeochemical processes inherent to cold, rapidly changing environments, are still dealt with using parameterizations. Calibration of these parametrizations against in-situ and remote sensing data is essential to fine-tune model parameters and improve model performance.

- **Initialization and boundary conditions**: To produce reliable outputs, model simulations must be properly initialized and constrained by accurate boundary conditions. This implies using high-quality observations with the relevant spatial and temporal resolution. Lack of quality checked observations or data products, capable of providing realistic and dynamically consistent conditions as inputs to model simulations, is currently a severe obstacle to model performance in the polar regions.

- **Reanalyses and forecasting systems**: Data assimilation techniques, which incorporate observational data into models, are essential tool for improving model accuracy. Assimilation techniques are key elements of analysis and forecasting systems which are widely used for reconstructing or predicting environmental conditions in the Polar regions or to support operational applications (e.g., through the Copernicus Services, including the Copernicus Arctic Hub). Such systems require high-quality, real-time data acquisition and distribution from both in-situ observations and remote sensing which remains a challenge in Polar regions. Assimilation of new satellite data, including data at low processing level, is needed. Assimilation techniques are also used to generate reanalysis products which are widely used to reconstruct consistent datasets over long time periods, with the requirement that long time series of data be available.

- **Model validation and uncertainty**: Models need rigorous uncertainty quantification to evaluate model solutions and improve confidence on these solutions. This requires comparing model outputs with independent, comprehensive, observation-based data sets with known data uncertainty. The validation can involve model sensitivity experiments, which are used to test the model response to different parameter ranges or to explore future scenarios, and the use of ensemble modelling to assess the range of possible outcomes. Model Intercomparison Projects (MIP), such as the Coupled Model Intercomparison Project (CMIP), or more polar-specific intercomparison projects like PAMIP (Polar Amplification Model Intercomparison Project), SIMIP (Sea-Ice Model Intercomparison Project) or ISMIP (Ice Sheet Model Intercomparison Project), play a crucial role in validating models against each other and against observations, exploring their performances and identifying model biases and uncertainties.

4.2.4. Integrated approaches to data validation and calibration

As mentioned above, to improve the data accuracy and reliability in the Polar regions requires combining in-situ observations, remote sensing, and modelling. To do so, integrated approaches should be implemented such as:

- **Collaborative Campaigns**: Coordinated field campaigns that collect in-situ data alongside satellite overpasses can provide critical validation data for remote sensing and modelling. Collaborative initiatives, such as the WMO Polar Prediction Project and its flagship activity, Year of Polar Prediction (YOPP), have facilitated this integrated approach.

- **Data Sharing and Accessibility**: Open data sharing and the development of accessible data repositories, such as the Polar Data Catalogue and the European Space Agency's Climate Change Initiative, are crucial for enabling cross-disciplinary validation and calibration efforts. Coordination with international coordinating programmes like Sustaining Arctic Observing Networks (SAON) and its Arctic Data Committee, should be encouraged.

- **Technological Advancements**: Advances in technology, such as autonomous sensors, machine learning algorithms, and high-performance computing, are enhancing the ability to collect, process, and analyse polar data. These innovations are helping to overcome some of the traditional challenges associated with polar research.

- **Community Engagement**: Engaging the scientific community, including local and indigenous populations, in data collection, validation, and calibration efforts ensures a more comprehensive understanding of polar environments and fosters collaboration across disciplines.

5. Conclusions

The overall POLARIN objective is to serve polar science by supporting coordinated and efficient access to polar research infrastructures. One of the key challenges of the access management is to ensure that the implemented research will provide answers to the most urgent research priorities in the Polar regions. The ambition of this report is to provide a synthesis of these priorities, which should be understood not only in terms of science topics, but also in terms of the required data collecting and processing strategy to best inform these topics. Recalling that access to the field in the Polar regions remains a challenge, developing a coordinated strategy to collect and deliver quality-checked, meaningful data which will inform the best science must be a priority. This report provides guidelines to support this strategy by identifying the priorities and needs which will frame the access to the POLARIN RIs.

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