European Polar Science Week 2024

Summary Report

3rd - 6th September 2024, Copenhagen

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01 Introduction

Polar regions are sentinels of climate change, biodiversity, and human resilience. They have experienced the most rapid rates of warming in recent years and the expected impacts will likely exceed those forecast for many other regions, resulting in significant consequences affecting natural ecosystems and human activities. Improving our observational capacity and enhancing understanding of the drivers and processes governing those changes, and translating knowledge into solutions for society, are major scientific challenges. Addressing **the major challenges in polar research requires significant and sustained collaborative effort and an integrated approach through the synergistic use of satellite Earth Observation (EO) data, in-situ and citizen observations, advanced modelling capabilities, interdisciplinary research and innovative technologies**. This is why the **European Commission (Directorate General for Research and Innovation) and the European Space Agency are working together** to improve cooperation and to identify and address the grand science challenges in polar research that may drive joint EC-ESA scientific activities in the coming years.

The **2nd European Polar Science Week** is an **important milestone in the cooperation between the European Commission and the European Space Agency**. The event took place from 3 to 6 September 2024, in Copenhagen, at the Black Dimond, Royal Danish Library.

The **overall objective** of the European Polar Science Week has been to bring together the European polar science community and reinforce European cooperation for polar science. More specifically, the 2nd Polar Science Week has aimed at:

- Sharing latest results in polar science with a focus on Earth observation, and promoting networking and collaborative research in polar sciences, bringing together different expertise, data, and resources in a systemic manner;
- Discussing progress in addressing recommendations from the 1st European Polar Science Week;
- Identifying major polar scientific challenges, observation gaps and research needs for the coming years;
- Formulating recommendations for a Polar Science Agenda, in particular regarding maximising synergies between the ESA and Horizon Europe Programme; and
- Developing and providing policy relevant recommendations.

During this week, key scientists and stakeholders of polar science have had the opportunity to discuss the major challenges and opportunities in front of us, promote networking and collaboration across projects and activities advancing the EC-ESA Polar research cooperation.

The EPSW2024 was organised around the following seven **key topics**:

1. The current state and forthcoming changes in the polar regions
2. Polar ice, ocean, climate dynamics and tipping points
3. Polar ecosystems, biodiversity and carbon cycles
4. Humans in the Arctic
5. Societal impacts of polar change
6. Polar observations, models and data
7. New methods for understanding the polar regions

The scientific advancements, identified research gaps, and recommendations are highlighted in the body of this report.

In addition, the EPSW2024 has featured, for the first time, a photographic exhibition and a school educational outreach activity.

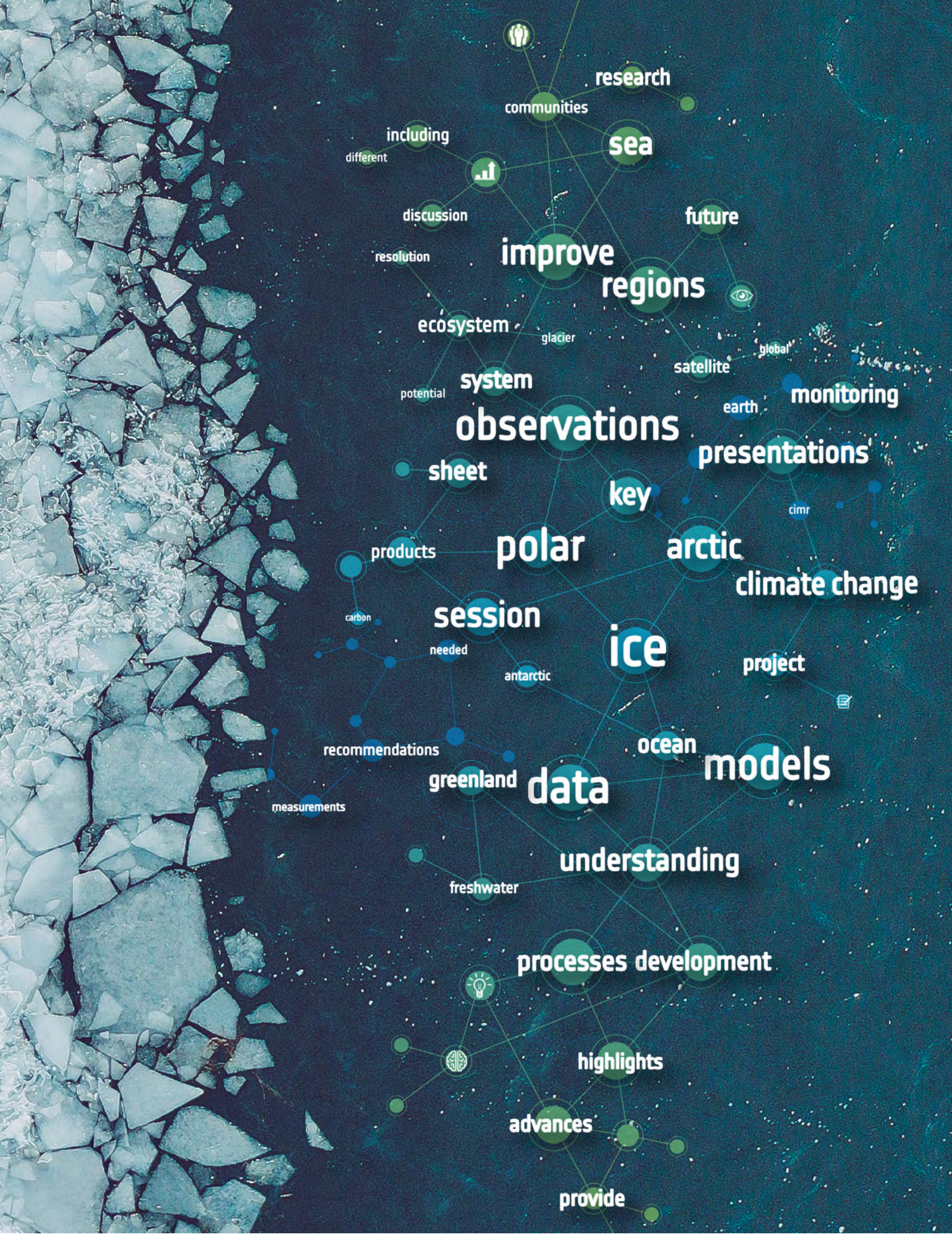
We, the organisers, hope that this report will inform the future work of the polar scientific community and national and European and international funding agencies. We would like to hereby extend a word of thank you to all the members of the organising committee and all the participants who have helped us achieve a successful and informative event.

Open Air Photography Exhibition

STORIES TRAPPED IN ICE POLAR OBSERVATIONS

SCHOOL LABS AT EU POLAR SCIENCE WEEK 2024

Education Activities for Primary and Secondary Schools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02 Key messages from Scientific Sessions

Understanding polar regions as a holistic system

- Our understanding of Ocean-Ice-Atmosphere interactions in polar regions remains limited, but this can be improved by combining interdisciplinary knowledge from each element of the system.
- Coupling components together (atmosphere, ocean, ice, solid Earth) gives new insights into the sensitivity of ice sheets to the ocean, atmosphere and solid Earth and potential feedbacks.
- There have been great advancements in understanding the polar regions in recent years, but some tipping points remain highly uncertain.
- Future research should focus on feedback mechanisms and interactions between various polar components, such as ice, atmosphere, bedrock, ocean, and ecosystems, at present time and in the past.
- Better understanding of the role of atmospheric processes in Polar regions has been achieved, but more work is needed.
- The Southern Ocean plays a critical role in the global climate by absorbing anthropogenic heat and CO^2 from the atmosphere. The future of its function and ecosystem is highly uncertain, but the potential impact of the recent decline of the sea ice and the rapid melting of glaciers, ice shelves and ice sheets is alarming.
- For the Antarctic Ice Sheet, ice shelves are the first sentinels of changing atmospheric and oceanic conditions. In recent decades ocean melting has intensified, ice shelves have thinned, retreated, and weakened. This has led to increased flow of grounded ice to the ocean, increasing the sea level contribution.
- The response of ice sheets to ocean variability is not well constrained, this concerns the frequency, amplitude, and relative timing of the response.
- Permafrost temperatures are steadily increasing across the Arctic, but uncertainties in estimation need to be reduced.

Enhance connection of models and data

- The continued development of climate and ice sheet models is a long-term project that requires stable funding and collaboration between different fields.
- Polar regions remain poorly observed and understood, so it is important to create synergies and deal with the large uncertainties. Challenges occur when it comes to observations and their alignment with models. Earth Observation (EO) is key to understanding.
- Rapid advances are being made in the remote sensing, modelling and in-situ observing of the permafrost. There are improved permafrost products used for validation of models and a lot of new datasets. More effort is needed to ensure reconciled understanding of permafrost processes in the Arctic connecting EO, modelling and in-situ.
- There is need for better model representation of ice shelves processes (calving, melting, ice viscosity, and grounding zones processes) for improved sea level projections.

Advancing the development and use of Earth Observation (EO) data

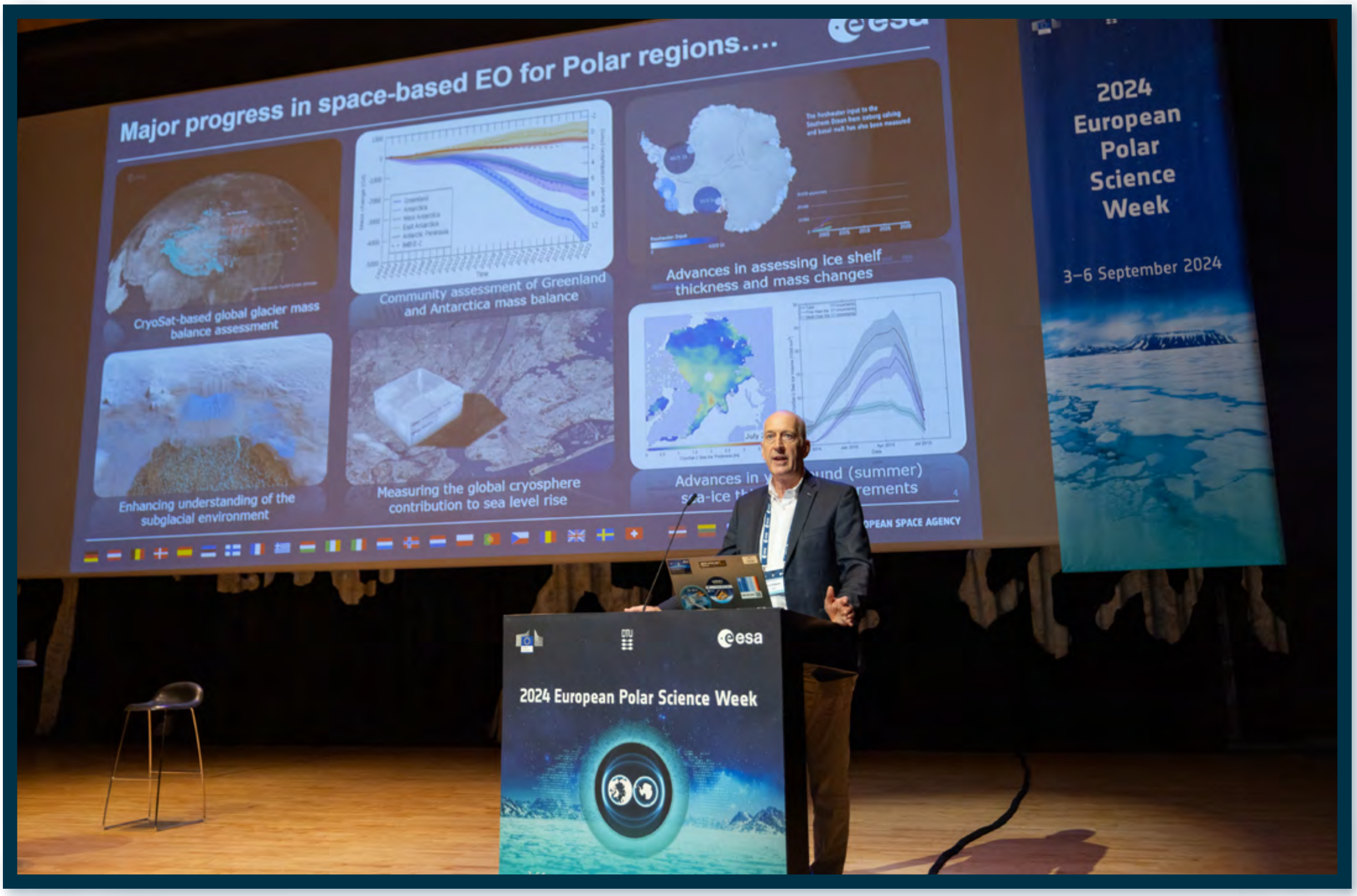
- More effort should be dedicated to defining errors and evaluating EO datasets with in-situ measurements.
- High temporal and spatial resolution of observations is needed. Importance should be given to both, as they are equally important.
- Earth Observation and modelling communities working closer together can improve our understanding and reduce uncertainties.
- We need to maintain and expand the current portfolio of Earth Observation datasets. Many key variables are generated from Earth Observation, and there needs to be a dedicated programme for product generation and dissemination.
- Providing operational sea ice products is crucial for the safe and efficient navigation in maritime operations. There is now higher demand and an expectation of more semi-automated processes. Embedded on-board services, providing NRT satellite imagery alongside ice charts are future options.
- There has been progress in retrieving ice sheet dynamics and key variables, but there is a lot of potential in new methods for their exploitation in the future, especially with the Copernicus future missions (Expansion Missions).
- Continuous ice sheet wide data SAR acquisition is essential for continuation and extending the monitoring of ice dynamics and surface properties of Antarctica and Greenland.
- With the CIMR mission coming up, novel science and retrievals are expected, for which new algorithms are being developed and presented. Some of the variables expected to be retrieved are sea ice concentration, snow on land, Snow Water Equivalent (SWE), snow freeze/thaw state, as well as Sea Surface Salinity (SSS) and Sea Surface Temperature SST.
- There is a need for undertaking an intercomparison exercise of ice shelf basal melt products derived from satellites and in-situ measurements.
- It is important to continue community-based projects, such as IMBIE and GlaMBIE (aiming to estimate the ice sheet and glacier mass change, using all available observation methods) to improve the understanding of the different mass-balance components. Higher spatial and temporal resolution, as well as longer temporal coverage are recommended.
- Support is needed for the development and improvement of high-latitude methane retrievals, and the capacity of ongoing and future satellite methane detections needs to be maximized.
- Significant advances have been made in measuring key variables to characterise ice sheets from satellites, but there is still work to be done, including high-resolution velocity maps, monthly ice discharge, ice damage, supra- and sub- lake inventories, a time series of surface melt phases, the temporal evolution of the surface refreezing depths and firn density.
- Consider Arctic permafrost areas as key regions in the planning of acquisitions of future missions (e.g. ROSE-L, NISAR, Harmony, ...).

Advancing institutional and international collaboration

- There is great potential for collaboration between EC and ESA:
  - High resolution & extensive spatial geophysical coverage of ice sheet and ocean including close to ice sheet margins, especially in under sampled key regions.
  - High resolution internal structure and bedrock information beneath the ice sheet
  - Access to ice core and sediment core archives to improve paleo constraints.
  - Advanced modelling tools to improve coupling of components and physical processes.
  - Interdisciplinary collaboration platforms.
- It is crucial to effectively coordinate research efforts and develop a fully integrated Polar research system, that will ensure long-term monitoring and year-round research.
- The polar regions show high sensitivity to global warming, constantly changing, so monitoring them is crucial. Copernicus expansion missions are being prepared to aid in their monitoring, fostering collaboration through European Institutes, the EC and ESA.
- Antarctica InSync is an international, multi-disciplinary project that aims in establishing a comprehensive understanding of the Antarctica and SO response to climate change. The success of the project relies on establishing synergies and international cooperation and including data from multiple sources.
- The Arctic Methane Permafrost Challenge (AMPAC) is a collaboration between ESA and NASA, offering a public dataset that will drive the science community to research more about the permafrost.
- The EU-PolarNet 2 project, funded by the EU Horizon 2020, has generated 80 practical recommendations to policymakers to develop a fully integrated Polar observing system, emphasizing international collaboration and sustained long-term observations.
- The EU Horizon Europe-funded POLARIN project will play a pivotal role in supporting this by providing access to 64 top-level research infrastructures in the Arctic and Antarctic.

Biodiversity and ecosystem services

- Biodiversity and its effects on the carbon cycle are important in polar regions. Policymakers need to consider these aspects when planning for the future.
- Seasonal lipid pump and overwintering zooplankton are drivers of carbon cycling in the Arctic and Antarctic regions.
- It is crucial to monitor the marine ecosystems in the Arctic and Greenland, as these areas change faster than the rest of the world.
- Remote sensing paired with AI techniques provides better coverage and novel information on ecosystems, but there is still a need for in-situ measurements and campaigns, so that they are studied as one.
- More temperate-climate species are, and will be, introduced in Greenland and the Arctic. Tthere needs to be effort in monitoring them effectively.
- Plastic pollution is a major issue both in the Antarctic and in Greenland. Antarctica is significantly under sampled, while studies in Greenland have shown the ingestion of plastic from the fauna and the need for better monitoring techniques.
- Polar regions, contain some of the highest abundances of fibres reported and plastics are being ingested by species across polar food webs from zooplankton to seabirds, with potential negative physiological impacts and unknown consequences to overall populations.
- Stakeholders from the local communities should be engaged, as their expertise of the local biomes is much needed in the conservation.
- A systematic support of long-term monitoring of biodiversity, including non-native species, is needed for the timely detection of changes and approaching ecosystem tipping points.



AI as an opportunity for polar science

- AI facilitates the understanding, monitoring, and research in the polar regions. It is important that stakeholders are engaged and work with researchers, as their input is invaluable when creating models and can aid in the process of obtaining realistic results.
- Moreover, AI and ML techniques make modelling easier in data sparse regions, which is usually the case in the polar regions. There needs to be long-term datasets for training, validation, and development.
- AI can be used to facilitate the modelling of ice parameters in high resolution, especially when it comes to SAR data, which are rich in information. However, using them in models would require a lot of time and resources.
- Sea ice deformation, ice drift estimates and the segmentation of sea ice, which is done manually for ice charting, can be done easier and faster using AI. These algorithms can be trained to reduce biases in sea ice concentration models.
- It is important to develop high quality datasets for algorithm training, and incorporate physical constraints, for their explainability. Independent datasets for validation are needed, as well as interdisciplinary collaboration to facilitate user needs.

Enhancing and maintaining in-situ data collection in polar regions

- In-situ observations in Antarctica need to be enhanced and be year-long, to complement the satellite observations. Having datasets of fine temporal and spatial resolution can have a ground-breaking effect in improving our understanding of the processes through ocean and sea ice simulations.
- It is not possible to monitor all the variables related to ice sheets using EO, so airborne, ground- and ocean-based measurements are still needed. These data work complementary with EO datasets and can also be used for validation of these.
- There are challenges with implementing technologies in the Arctic for data collection and infrastructure. This points out the need for an international science hub to focus on research and development in the Arctic. It is also crucial that Greenland is a part of whatever is being implemented there.
- There is a need for dedicated campaigns airborne (Grav./Mag/Radar and Ultra Wideband Radar) and in-situ (GNSS, Rapid ice drilling, seismic, Magnetotellurics) to bridge the gap to satellite observations, particularly in critical areas (i.e. Antarctica: Margins and Dome C, Central and SE Greenland).
- Expansion and continuation of bedrock displacement observations in the polar regions, e.g. from GNSS stations and measurements from space such as InSAR (Interferometric Synthetic Aperture Radar), to improve estimates of GIA models.
- New observations needed for shelf seas; sea level height, sea-ice volume, ocean bathymetry, ice thickness and near-ice ocean properties.
- Southern Ocean requires sustained observations at high resolution with year-round and under ice coverage.
- Some areas remain critically under-observed but initiatives (e.g. RINGS, AntarcticaInSync, MOSAiC) can benefit multiple different fields and should be prioritized.
- POLARIN project aims to facilitate international collaboration and access to research stations in the Arctic and the Antarctic

- The Atlantic-Arctic Distributed Biological Observatory (A-DBO) goals are to centralize and harmonize information and datasets and facilitate their dissemination, include yearly and long term in situ observations, as well as coastal monitoring programs.
- Cal/Val super-sites across all permafrost zones (continuous, discontinuous) dedicated to permafrost studies are needed.

Data Management needs

- There needs to be a centralised and coordinated effort to harmonize Polar datasets and documentation.
- FAIR-compliant data implementation should be followed, with support to be given to data providers for their harmonization.
- There is an urgent need for international collaboration and coordinated efforts, adaption of standardized protocols and the creation of a robust observing network. The observations should prioritize key variables, and the science community should focus on key scientific priorities.

Tourism in polar regions

- Tourism is rapidly growing in the Arctic region, as both Greenland and Svalbard are gaining significant popularity. Tourism development in these areas should go hand-in-hand with local societal growth and the conservation of the natural environment.
- There should be adaptive co-management in the way tourism is handled to facilitate sustainable practices and integrate it into monitoring, regulating and governing activities.

03 Detailed session reporting

1
THE CURRENT STATE AND FORTHCOMING CHANGES IN THE POLAR REGIONS

1.1

Enhanced Understanding of Polar Ocean-Ice-Atmosphere (OIA) Interactions Within the Climate System

Chairs:
Risto Makkonen (FMI), **Jennie Thomas** (CNRS / IGE)

Summary of session presentations and discussion

The polar regions play a crucial role in the Earth's climate system, influencing global weather patterns, regulating sea levels, and providing valuable insights into the planet's past and present climate conditions. Understanding and monitoring polar regions are essential for addressing climate change and preserving biodiversity. Furthermore, Earth System Models with accurate Polar components can guide informed decisions about sustainable development and environmental conservation. It is crucial to understand the role of polar processes, such as feedback loops, in both polar and global climate.

The session was organised by the EU H2020 CRiceS (Climate Relevant interactions and feedbacks: the key role of sea ice and Snow in the polar and global climate system) project and presented key results from our project. The talks provided insight to air-ice-sea interactions in present and future Arctic and Antarctic, processes controlling polar aerosols and clouds in the sea ice environment, biogeochemical dynamics of ice-covered oceans, and the role of polar climate in the coupled Earth System.

The ability to describe high-latitude Ocean-Ice-Atmosphere (OIA) systems is currently limited by knowledge of the processes governing the transport and exchange of heat, mass and momentum; aerosols and clouds; biogeochemical cycles/greenhouse gas exchanges; and fully coupled system behaviour. This session aims to showcase progress towards an improved understanding, by enhanced model predictions of the role of polar processes in the climate system, encompassing the oceans, ice and snow cover, and the atmosphere. Reliable future projections and effective climate policies require a better understanding and formulation of the underlying processes within each compartment of the OIA system, the functioning of the coupled OIA system within polar regions, and interactions within the Earth system. This session has addressed the significance of ocean-ice-atmosphere interactions in shaping polar and global climate dynamics. One of the primary ways scientists can enhance our understanding of environmental change is by combining knowledge from different disciplines in a coordinated manner.

Major advances and highlights

Arctic and European communities depend on high-resolution climate projections to assess vulnerabilities, such as impacts on infrastructure, ecosystems, and human health. These projections are essential for local adaptation, helping address challenges like permafrost thaw and sea ice change. They inform resource management, infrastructure design, emergency preparedness, and cultural practices, while promoting international cooperation for Arctic sustainability. Kilometre-scale climate projections are in demand (e.g., Destination Earth), but currently these high-resolution methods must limit certain Earth System Processes due to computational costs. Accurate projections of the Arctic and Antarctic require better representation of polar ocean-ice-atmosphere processes in climate models. Polar regions are highly sensitive to climate change, with feedback loops, like albedo changes from melting ice, that amplify warming. Capturing these processes is essential for predicting global impacts, such as shifts in weather patterns and ecosystems due to sea ice loss. Current models struggle with these complexities, risking inaccurate predictions. Improving how these coupled processes are represented in climate models is key to strengthening scientific confidence in both polar and global forecasts.

Improvements in the complexity of coupled ocean-ice-atmosphere processes at the poles within climate models will contribute to international climate assessments through IPCC, strengthening the scientific basis and improving confidence in polar and global predictions.

KEY MESSAGES AND RECOMMENDATIONS

The impacts of climate change in the polar regions are extended to Europe and the rest of the planet. Polar teleconnections can pose significant climate risks to lower latitude regions - knowledge about these, and how they may interact with underlying, global climate change is a prerequisite for adaptation. Polar regions involve complex interactions between the atmosphere, ocean, sea ice, land, and biosphere. Earth System Models can struggle to represent these processes and feedbacks accurately, risking the underestimation – or overestimation – of future changes. A combination of observationally constrained climate model improvements as well as regionally relevant information through enhanced spatial resolution is needed to enable informed decision making.

1.2
Glacier change observations for hydrological and sea-level rise assessments

Chairs:
Michael Zemp (University of Zurich), **Livia Jakob** (Earthwave)

Summary of session presentations and discussion

This session was set in the context of the Glacier Mass Balance Intercomparison Exercise (GlaMBIE), the first community-based estimate based on all available observation methods for measuring glacier mass changes, with the aim to quantify glaciers' implications on regional hydrology and global sea-level rise. Strengths, challenges, and limitations of the individual observational methods for measuring mass balance (gravimetry, altimetry, glaciological/in-situ measurements and DEM differencing) were explored, identifying that there is a need for improved methods and uncertainty assessments for all observational sources, as well as a more systematic understanding of differences between the methods. This is especially crucial in the context of data needs to improve glacier modelling and future projections of glacier change.

Major advances and highlights

- A wealth of observations now provide a truly global assessment of glacier mass balance since 2000, leading to a new observational baseline of regional and global mass change estimates from all methods;
- This new observational baseline confirms the results of the last IPCC report at a global level, but also shows regional differences/disagreements as well as systematic biases between methods (e.g. between altimetry and DEM differencing);
- The new wealth of observational data allows for calibrating models now both at regional and glacier scale.

KEY MESSAGES AND RECOMMENDATIONS

- Continuation of community approach is essential for the future of glacier monitoring;
- Continuation of satellite missions should be guaranteed: move from science satellite missions and in-situ campaigns to operational missions that fulfil the requirements for glacier monitoring;
- Improvements in the observational baseline are fundamental for future projections;

Specific recommendations and themes:

- Mass-balance components: improve understanding and quantification of mass-balance components (surface, internal, basal, and frontal) and of mass changes below lake and sea levels for glaciers;
- Homogenize uncertainty assessments within and between observational methods;
- Density conversion: improve glacier density conversion for annual and seasonal geodetic surveys;
- Understand the apparent systematic differences between altimetry and DEM differencing;

Recommendations from a modelling perspective:

- Increasing the availability of mass balance and other datasets: data requirements include:
- Higher temporal resolution of geodetic mass balance (e.g. annual, seasonal, monthly);
- Higher spatial resolution of geodetic mass balance (e.g. glacier-scale and gridded mass balance, fields of ablation and accumulation);
- Longer temporal coverage of geodetic mass balance (pre-2000) will improve model initiation;
- Link to additional specific datasets, such as snow cover, ice thickness, albedo, frontal ablation, to inform the model calibration;
- Model hindcasting & forecasting: foster dialogue between the modelling community for comparison of observations and scenario runs;

Recommendations and gaps per observational method:

Gravimetry - recommendations:

- Methodology improvements (e.g., isostatic corrections, hydrological models) needed, especially for regions with a small glacier area;

- More efforts towards the combination of multiple sensors needed to increase spatial resolution of gravimetry outputs (e.g. gravimetry and altimetry);
- Inform future gravity mission concepts, e.g., assess the benefits of the MAGIC mission for monitoring glaciers with higher accuracy than previously with gravimetry;

Altimetry - recommendations:

- Fully exploit and combine IceSat/IceSat-2/GEDI and CryoSat-2 over glaciers;
- Tap into the potential of seasonal mass balance estimates from altimetry;
- Improve elevation to mass change conversion for high temporal resolutions and different climatic regions;

Glaciological / in-situ - recommendations:

- Maintain and extend the in-situ network to ensure the continuation of long-term series (importance of using long-term time-series for validation);
- Strengthen the international coordination of glacier monitoring through the World Glacier Monitoring Service;
- Push in situ networks towards continuous and near-real-time monitoring, including Automatic Weather Stations and new sensors (e.g., SnowFox, SmartStake, GNSS reflectometry-refractometry);

DEM differencing - recommendations:

- Tapping the full potential of DEM differencing from multiple spaceborne sensors by unlocking data archives of the various current providers (e.g., SPOT, Pléiades, WorldView).
- Unlock historical airborne and spaceborne (e.g., Corona, Hexagon) archives.
- Push glacier elevation change assessments to the highest spatial resolution by combining results across available sensors.

1.3

The ESA-NASA Arctic Methane Permafrost Challenge (AMPAC) - Moving to the future

Chairs:

Dirk Schuettemeyer (ESA—ESTEC), **Chip Miller** (NASA/JPL/Caltech)

Summary of session presentations and discussion

This session was dedicated to identifying the up-to-date achievements of the ESA-NASA Arctic Methane Permafrost Challenge (AMPAC), a cross Atlantic initiative for tackling the uncertainty surrounding the possible future emissions of methane from permafrost thaw. The session was split into two distinct sections, the first covering European activities related to AMPAC, and the second to North American activities. The first section covered the main achievements of the AMPAC-Net project, including a number of workshops, conferences and training schools. MethaneCAMP was also presented and results from the project were showcased. In MethaneCAMP several algorithmic improvements have been applied to Shortwave Infrared and Thermal Infrared retrievals.

The second section focused on the North American activities. The first of these presentations pivoted away from methane emissions from the permafrost directly and tackled the broader implications of a thawing permafrost which covered topics from the reanimation of ancient microbes to the release and storage of heavy metal, nuclear waste and other pollutants. The last of the scientific presentations leveraged the use of AI to understand the dynamics of high-latitude carbon in the context of the permafrost carbon feedback. The GeoCryoAI model was presented, that replicates thaw-induced carbon release from permafrost.

Major advances and highlights

A key output from the AMPAC-net project was the identification and publication of a catalogue of AMPAC relevant datasets, that are available at the following website (https://apgc.awi.de/group/about/ampac).

The MethaneCAMP results include a preliminary new post-processing quality filtering that has been developed for GOSAT, a Japanese satellite, which shows that it is possible to obtain approximately 20-50% more soundings over high-latitudes. The project also showed that there is potential of anthropogenic methane hot spot emission detection at high latitudes by using in combination Sentinel-5P and GHGSat. Methane trends in the Arctic have also been studied, in general, increased methane fluxes were seen especially during summer months. It is also found that by using a spectrometer designed for Mars, it is possible to identify microbes in the permafrost, which may be useful for observing thawing permafrost.

GeoCryoAI ingests a huge amount of data (~15.7B measurements and observations) to learn, simulate, and forecast the primary constituents of the permafrost carbon feedback with prognostic and retrospective capabilities, and was found to accurately simulate the nonlinear dynamics of the permafrost carbon feedback.

KEY MESSAGES AND RECOMMENDATIONS

AMPAC-net project: Identification and publication of a catalogue of AMPAC relevant datasets, that are available at the following website (https://apgc.awi.de/group/about/ampac). The aim is for this resource to help drive science in the AMPAC sphere for the foreseeable future. These communities are required to solve complex problems.

The AMPAC research communities (atmosphere, land surfaces) are still quite separate. Regular meetings would support cooperation between the different scientific communities.

MethaneCAMP: Support for the development and further improvement of high-latitude methane retrievals are highly important and urgently needed to maximize the scientific benefit of current and future (CO2M, Sentinel-5) satellite methane detections.

GeoCryoAI: The future of GeoCryoAI includes expanding the flexibility, efficiency, and knowledge base of the model to minimize loss and improve performance with spaceborne observations, supercomputing (HPC), and hybridized AI model development in support of current and future scientific applications targeting critical infrastructure needs and bolstering ongoing and future field campaign and earth observation missions.

1.4

From circulation change to sea level rise: the polar regions in the Earth System

Chairs:

Ruth Mottram (DMI), **Priscilla A. Mooney**, (NORCE, BCCR), **Gael Durand** (IGE)

Summary of session presentations and discussion

The polar regions play an important role in the global climate system yet they remain poorly observed, poorly understood, and poorly modelled. This session brought together experts from three EU funded projects (OCEAN:ICE, PolarRES, and PROTECT) to discuss progress and highlight synergies in addressing the large uncertainty in future projections of sea level change. This uncertainty stems from different sources that includes our limited understanding and inadequate model representation of key polar processes.

Presentations in this session described recent advances in deepening our knowledge of important polar processes such as cloud-aerosol interactions, cloud microphysics, snowpack characteristics, snow processes, and freshwater fluxes from melting ice shelves. Improved understanding and modelling of atmosphere, ocean, ice interactions were also central to the discussion. Discussion also included the important interactions between the ocean and ice shelves, the atmosphere and ice sheets, and the interactions between the ice sheets and other components of the climate system. In summary, this session discussed the benefits and future directions for addressing knowledge gaps and improved modelling of key polar processes and the interactions between different components of polar climate system in a global context.

Major advances and highlights

Several major advances have been made in closing key knowledge gaps and improving our capacity to model the polar climate and global climate system. Major advances have been in model representation of the missing but key interactions between the ice sheets (Greenland and Antarctica) and the other components of the climate system.

A key highlight from this session was the development of a deeper understanding, and greater appreciation, of the role of snowpack characteristics and snow processes as a source of uncertainty in future projections of sea level change. A related highlight was the importance of cloud microphysics and cloud-aerosol interactions in the uncertainties arising from sea level projections. Pathways to improving model representation of both snow and clouds were identified that leverage emerging advances in machine learning approaches and Earth Observations.

The development of a new gravimetric based mapping of Antarctic bathymetry product offers unique opportunities to investigate the ocean-ice shelf interactions and better project future changes in ice shelf freshwater fluxes.

KEY MESSAGES AND RECOMMENDATIONS

Three key messages emerged from this session. The **first key message** was that collaboration between Horizon projects can accelerate the discovery of new knowledge and greatly enhance the value of new knowledge, data products (observational and modelled), and model advances.

The **second key message** pertains to unexpected challenges in evaluating climate models in these data sparse regions. There is a large observational data gap in the polar regions which contrasts starkly with the neighbouring regions of Europe and North America. This lack of observational coverage in space and time necessitates the use of both in-situ and Earth Observation (EO) data to evaluate climate models and study important polar processes. Consequently, there are unique challenges to evaluating polar climate models and studying polar processes that can be better addressed through greater collaboration between the climate modelling and EO communities.

The **third and final key message** points to the untapped potential of EO data for tackling the stubbornly large uncertainty in polar climate projections from both global and regional climate models i.e. CMIP and CORDEX models. This large uncertainty is most striking in projections of future sea level change, and it stems from many sources such as gaps in our knowledge of polar process, and limitations in high performance computing. The latter limits climate models from properly resolving important polar processes that occur on small scales. This limitation is overcome by either parameterising the effects of these small scale polar process or neglecting them entirely e.g. blowing snow. However, some of these limitations could be overcome through greater exploitation of EO data for (1) developing a deeper understanding of key polar processes e.g. snow processes and characteristics, and (2) developing faster model parameterisations through machine learning trained on EO data.

1. Improved understanding and model representation of
    - snow-related process and characteristics,
    - cloud processes in the polar regions,
    - ocean-ice shelf interactions, and
    - interactions between ice sheets and other earth system components.
2. Development of climate and ice sheet models is a long-term project and requires stable funding as well as collaboration across different types of data.
3. Increased observational coverage of the polar regions and greater collaboration between the climate modelling and EO communities.

2
UNDERSTANDING PROCESSES IN THE POLAR REGIONS

2.1
Heterogeneity in Subglacial Conditions: A Key Influence on Solid Earth-Ice Sheet Interactions

Chairs:
Jörg Ebbing (Kiel University), **Fausto Ferraccioli** (OGS)

Summary of session presentations and discussion

The structure of the Solid Earth in Greenland and Antarctica is gaining an increased interest in recent years as it provides critical boundary conditions for the dynamic behaviour of the overlying ice sheets. So far, no consensus on some of the key structures and parameters has been reached. including Geothermal Heat Flow (GHF). Some of the recent and advanced models are still ignored as the differences between individual models and their uncertainties are not easily understandable particularly by non-experts in the field that are end users of the data products.

The presentations in the session highlighted that geothermal heat flow models appear to be particularly unconstrained, even though GHF has an impact on subglacial hydrology and ice sheet dynamics. Although, modern models exist, which have a clear observational basis, vintage models are still used (e.g. for ISMIP-6) that are no longer adequate. Furthermore, such vintage models have a resolution that is not in line with the recent progress made in modelling the details of ice sheet dynamics.

Progress in recent Solid Earth and ice temperature (e.g. from SMOS satellite mission) models offer the possibility of developing coupled models leading to more robust assessments and overcoming the disparity of existing heat flow models. Ice temperature estimates retrieved from SMOS are becoming increasingly reliable for cold based regions of Antarctica and are also improving in Greenland. To glean a more complete understanding of the interactions between the solid earth, subglacial hydrology and ice sheet dynamics requires the acquisition of new high-resolution data in key areas at both the grounding line and at the onset of glaciers and for marine-based glaciers that are more vulnerable to ocean and climate change in both Antarctica and Greenland. Satellite data can help to monitor the conditions at the ice surface with much detail but are less successful in monitoring the state of the ice-bed interface, where bedrock topography, bedrock composition and hydrology exert strong controls on the basal conditions. An improved understanding of basal conditions requires dedicated collection of in-situ and near surface observation to help bridge the gap between satellite observations of ice sheet dynamics and basal conditions, which is critical for process understanding (including tipping points) at different spatial and temporal scales.

Major advances and highlights

The importance of an improved understanding of sub-glacial conditions (e.g. GHF and sub-glacial geology) has been demonstrated and is a critical link in a complete understanding of the evolution of the Antarctic and Greenland icesheets.

Models with higher spatial and temporal resolution require such details, which are also needed for the tighter integration of satellite and in-site/near surface data.

The activities of the SCAR Action Group RINGS support such coordinated efforts to address data gaps and data sharing along the currently poorly surveyed Antarctic grounding zones, resulting in community driven products, that will help reduce the uncertainty in estimates of ice discharge, which is critical to improve our knowledge of Antarctic contributions to future global sea level rise.

KEY MESSAGES AND RECOMMENDATIONS

- The ongoing comprehensive compilation of Antarctic heat flow measurements by the SCAR INSTANT Heat Flow group is vital for a quality-controlled observational dataset for modellers and it is recommended to accelerate this effort.
- This effort and joint with an ad-hoc group for Greenland should provide recommendations which GHF models should be explored in ice sheet dynamics (and for example as input to ISMIP-7)
    - Any model must be validated by data and provide realistic uncertainties.
    - Vintage models should be retired due to their poor observational basis.
- Further efforts should be made to integrate ice temperature models (from SMOS) with Solid Earth models (lithosphere and near-surface geology) and ice sheet dynamics.
- Dedicated campaigns are needed for critical areas (Antarctica: Margins and Dome C, Central and SE Greenland), where airborne campaigns and in-situ data should be collected for validation of satellite data and an improved understanding of sub-glacial conditions.
    - Airborne: Grav./Mag/Radar and Ultra-Wideband Radar (as for the EE12 candidate mission CryoRad)
    - In-situ: Rapid ice drilling, passive and active seismic and magneto telluric data

2.2
Exploring Polar Dynamics: Insights from the Mid Pleistocene Transition to Future Climate Scenarios

Chairs:

Carlo Barbante (University of Venice), **Dorthe Dahl-Jensen** (University of Copenhagen) with contributions of **Peter Köler** (Alfred Wegener Institute, Germany), **Laura De Santis** (National Institute of Oceanography and Applied Geophysics, Italy), **Olaf Eisen** (Alfred Wegener Institute, Germany)

Summary of session presentations and discussion

This session investigated the complex dynamics shaping the polar regions, from the enigmatic climate transitions of the past to the pressing challenges of the future.

It offered a comprehensive exploration of our current understanding of global mean surface temperature and sea level during the Mid Pleistocene Transition. It showed how upcoming new data from the EU-funded Beyond EPICA Oldest Ice Core project, aiming to reconstruct local temperature and atmospheric carbon dioxide, will help to further improve our knowledge about the evolution of the polar ice sheets over the last 1.5 million, the intricate interplay of bedrock change, ice sheet and ocean dynamics and biogeochemical cycles in polar environments in the past.

Looking at these phenomena, we highlighted their profound implications for understanding climate change and its relevance for societies and inform future scientific endeavours, which requires the use of coordinated in situ and satellite observations data acquisition to constrain models.

Major advances and highlights

Polar regions serve as sensitive indicators and amplifiers of global climate change, and their rapid warming has significant implications for the entire planet. Investigating past biogeochemical cycles recorded in polar ice and sediments, as well as estimating their current and future role in feedback mechanisms, will provide critical insights into the key processes governing Earth's climate.

The benefits of this research include:

- A better understanding of the carbon and other biogeochemical cycles as recorded in polar regions, leading to more accurate climate predictions and projections.
- Enhanced ability to assess the sensitivity of polar regions, including carbon and ice storages, to climate change, enabling more informed policy decisions (e.g. SLR).
- Insights into past climatic conditions and their linkages to present and future changes, aiding in the identification of effective mitigation and adaptation strategies.

KEY MESSAGES AND RECOMMENDATIONS

Next research priorities/challenges:

new developments in interdisciplinary research for an understanding of boundary conditions for constraining models* and the feedback mechanisms and interactions between various polar components, such as ice, atmosphere, bedrock, ocean, and ecosystems, at present time and in the past.

* *To simulate the Mid Pleistocene transitional regime, the models need good knowledge about initial boundary conditions in the time preceding it.*

Potential for EC-ESA collaboration:

- High resolution & extensive spatial geophysical coverage on the ice and at sea (close to ice sheets, especially in under sampled key regions).
- High resolution internal structure of and bedrock information beneath the ice sheet.
- Access to ice core and sediment core archives to improve paleo constraints.
- Advanced modelling tools to improve coupling of compartments and physical processes.
- Interdisciplinary collaboration platforms.

2.3

From ice sheets to oceans: a comprehensive view of Arctic freshwater fluxes

Chairs:

Marta Umbert, Institut de Ciències del Mar (CSIC), Spain, mumbert@icm.csic.es, **Nanna B. Karlsson**, Geological Survey of Denmark and Greenland, Denmark, nbk@geus.dk, **Anne Munck Solgaard**, Geological Survey of Denmark and Greenland, Denmark, aso@geus.dk

Summary of session presentations and discussion

The session "From Ice Sheets to Oceans: A Comprehensive View of Arctic Freshwater Fluxes" aimed to provide an integrated perspective on the advances and challenges in understanding Arctic freshwater fluxes and their impacts on ecosystems.

Louise S. Sørensen presented the current capabilities of Earth Observation (EO) in building a freshwater budget for the Greenland ice sheet. She highlighted both the strengths and limitations of EO capacities, noting its growing role in quantifying freshwater fluxes but also pointing out gaps in data availability and accuracy, particularly near coastal regions. **Laurent Bertino** discussed freshwater fluxes from a modelling perspective. He emphasized the limitations of these models, particularly in capturing the full complexity of the freshwater cycle in the Arctic and the need for better integration of observational data. **Rafael Gonçalves-Araujo** shifted the focus to the biogeochemical impacts of freshwater fluxes on the East Greenland Shelf, discussing how freshwater influences nutrient cycling and the structure of marine ecosystems. **Johnna Holding** expanded on this by presenting results from the EU project FACE-IT, which examined the effects of freshwater on Arctic ecosystems. She demonstrated how freshwater fluxes can significantly alter ecosystem dynamics, affecting species distributions and ecosystem types. Finally, **Estrella Olmedo** presented on the use of satellite measurements of Sea Surface Salinity (SSS) to improve freshwater estimates in the Arctic Ocean. She highlighted how satellite measurements provide a direct view into salinity variations, which are closely linked to freshwater fluxes, and can offer critical data for constraining models and validating freshwater estimates.

Major advances and highlights

1. EO Data for Runoff Constraining: EO data has demonstrated its capability to constrain monthly runoff from ice sheets. This marks a major step forward as Regional Climate Models (RCMs) often assume instantaneous runoff, which does not always align with actual conditions. The ability to capture these discrepancies through EO data holds great potential for improving model accuracy.
2. Altimetry for Seasonal Runoff Monitoring: Altimetry techniques have proven to be effective in capturing seasonal variations in ice sheet runoff. This adds a critical tool for monitoring the timing and volume of freshwater fluxes in Arctic regions.
3. Identifying Melt Biases in RCMs Using EO Data: EO data is increasingly being recognized for its ability to identify potential melt biases within RCMs. This is a crucial development for refining the predictions of freshwater contribution from ice sheets to the ocean.
4. ARCFRESH Project Goals: The ARCFRESH project by L. Bertino will have the ambitious plan to compute freshwater fluxes using ocean box models and evaluate the sensitivity of different freshwater sources. This work will provide vital insights into the Arctic's changing hydrological system.
5. Increasing Arctic Freshwater Volumes and Ecosystem Impacts: Rising volumes of freshwater from the Arctic Ocean, particularly through the Fram Strait, are having significant impacts on ecosystem services. However, there is still a lack of basic knowledge regarding the current functioning of these ecosystems, which is necessary for reliably assessing ongoing and future changes.
6. Need for Multidisciplinary Research and Funding: To address the gaps in knowledge about Arctic ecosystem functioning and freshwater fluxes, there is a clear need for more multidisciplinary research projects. This requires increased funding and support for initiatives that bring together expertise from different fields to better understand and predict the future of the Arctic environment.
7. Need for more in-situ observations: The Arctic continues to be sparsely sampled and despite advances in recent years we still have limited understanding of several key processes due to the limited number of observations. Funding for studies coupling in-situ observations with EO will add more value to the EO data and ensure robust interpretations of remotely sensed observations.

KEY MESSAGES AND RECOMMENDATIONS

The session highlighted several key issues, challenges, and science gaps that still need to be addressed to advance our understanding of Arctic freshwater fluxes and their impacts on the broader ecosystem:

Collaborating Across Communities: Closer collaboration between EO, in-situ and modelling communities is essential to improve our understanding of Arctic freshwater fluxes and reduce uncertainties. Such cooperation will help bridge the gap between remote sensing observations, in-situ data and predictive modelling.

Multiple Origins of Freshwater: Freshwater in the Arctic comes from a variety of sources, including rivers, the Pacific Ocean, sea ice, glacial melt, and precipitation. Constraining these fluxes is vital for marine life and fisheries, as the biogeochemistry and health of ecosystems are significantly influenced by the input of freshwater.

The Role of EO: EO is critical for advancing our understanding of Arctic freshwater fluxes, particularly in the following areas:

- It can improve our knowledge of ice sheet hydrology processes and the flux of freshwater from ice sheets into fjords and oceans.
- Currently, RCMs and re-analysis products include little, or no data related to these fluxes. EO can help fill this gap.
- The large variability in ice sheet runoff projections from different models underscores the need for EO data to constrain or validate these outputs.
- EO can enhance our understanding of how ice sheets respond to extreme events and how they interact with oceans and fjords.
- By improving EO data integration, we can also enhance the performance of RCMs and re-analysis systems.

Improving Arctic Freshwater Modelling:

- To improve the accuracy of freshwater models, interannual river discharge data must be better incorporated into existing models.
- Key data points, such as sea level in sea ice leads, should be assimilated, and Greenland ice loss should be included in these models.
- Atmospheric models need improvements, such as refining wind measurements to account for sea ice roughness and incorporating historical Russian profiles to enhance understanding of Arctic conditions.

Need for Higher Resolution Models: Higher resolution is necessary to resolve the fjord processes where key ecosystem interactions occur. This is crucial for understanding how glaciers impact marine life, as these effects vary depending on glacier settings and offshore water properties.

Promotion of Satellite SSS: Satellite-based SSS measurements are essential for understanding the drivers of freshwater fluxes and monitoring their changes over time. Promoting the use of satellite SSS and ensuring continuity of these measurements (e.g., through CIMR) is critical.

Focus on Coastal Regions and Variable Synergies: Greater emphasis should be placed on developing satellite products with better coastal resolution and fostering synergies between different observational variables. This will enable better tracking and resolution of changes in freshwater fluxes.

2.4
Ice-ocean-atmosphere interactions – focus on Antarctic Ice Shelves

Chairs:
Noel Gourmelen (U. of Edinburgh), **Pierre Dutrieux** (BAS)

Summary of session presentations and discussion

The session highlighted the importance of ice shelves for sea level rise and global thermohaline circulation. For the Antarctic Ice Sheet, ice shelves are the first sentinels of changing atmospheric and oceanic conditions. In recent decades ocean melting has intensified, ice shelves have thinned, retreated, and weakened. This has led to increased flow of grounded ice to the ocean, increasing the sea level contribution from the Antarctic Ice Sheet. The additional freshwater flux to the ocean is thought to modify ocean circulation on the continental shelf but this process is still poorly understood. While observation and modelling has improved our understanding of the broad picture, there is still many outstanding questions and challenges to answer.

A key outstanding process concerns the ice sheet response to ocean forcing, due to relatively few observations, and of relatively short time span, the response of the ice sheet to ocean variability is not well constrained, this concerns the frequency, amplitude, and relative timing of the response.

Another outstanding issue highlighted during the session is the need for better model representation of ice shelves processes, this is crucial for sea level projections. Improvements in processes such as calving, melting, and in representation of ice viscosity, have been highlighted.

Models are also limited by a lack of, or large uncertainty in, boundary conditions such as ocean bathymetry, particularly under ice shelves, ice thickness, or near-ice ocean circulation and heat content.

The session highlighted major progress in observation of basal melting under ice shelves at high spatial and temporal resolution thanks to the development of new Earth Observation and in-situ sensors and techniques. There is work to do still to fully exploit these new capabilities, as well as investigating discrepancies that exist between the various methods of melt observations.

The various presentations highlighted the wealth of satellite derived observations now available and synthesized for research purposes. This needs to be pursued, consolidated, and expanded.

Major advances and highlights

The session saw the first complete ice shelf mass balance estimate from a large compilation of methods, providing a quantification of each term contributing to ice shelf mass variability, and to freshwater input to the ocean.

Using time-dependant ice shelf elevation and velocity, the first derivation of time-dependant channelised melt was presented, showing that melt in basal channels can be twice as large as the background rate of melt. This highlights the important role that channels play in modulating ocean melting of ice shelves.

Ice flow models are now integrating the impact of spatially varying viscosity, a parametrization of fracture dynamics in continuum mechanics, and showing new, damage-related positive feedbacks, i.e. that damage in turns contributes to create more damage.

A potential tipping mechanism, the Marine Ice Cliff Instability (MICI), has been shown to be stabilized by ice dynamic response to calving, hence likely not the source of significant ice sheet destabilisation in the future.

Finally, several presentations highlighted the importance and lack of understanding of grounding zones processes, observations of intrusions of sea water potentially increasing the sensitivity of ice shelf to ocean forcing was one major example presented.

KEY MESSAGES AND RECOMMENDATIONS

- We need an intercomparison exercise of basal melt products derived from satellites and in-situ observations. This will require dedicated process studies coordinating satellite and in-situ observations.
- Use Antarctica InSync, and ESA's and EC's capabilities, as an opportunity to measure synchronously around Antarctica, Antarctic shelf sea heat and salt content, and the ice response.
- New observations of shelf seas sea level height, sea-ice volume and its variability, ocean bathymetry, ice-thickness, near-ice ocean properties are badly needed.
- We need to maintain, consolidate, and expand the current portfolio of EO-based observations.
- Many key variables are generated from Earth Observations, we need a dedicated programme supporting systematic product generation and dissemination, well beyond what C3S and CCI are currently providing.

2.5
The Role of the Solid Earth for the Evolution of the Polar Ice Sheets

Chairs:
Rebekka Steffen (Lantmäteriet), **Clinton P. Conrad** (University of Oslo)

Summary of session presentations and discussion

The thermal and mechanical structure of the solid earth exerts a primary control on the response of the polar regions to ice mass changes. Knowledge of the solid earth structure beneath the polar regions is thus needed to understand the evolution of the polar ice sheets. Specifically, the solid earth forms the lower boundary condition for ice dynamics, and it can affect glacial flow in two ways:

1. Geothermal Heat Flux (GHF) from Earth's interior provides heat input beneath the ice, which affects both the thermal balance of the ice sheet as well as the bed conditions (frozen or unfrozen) beneath the ice. Geothermal heat flow is difficult to measure beneath an ice sheet, and thus poorly constrained across most of Greenland and Antarctica.

2. Vertical motion of the bedrock beneath the ice sheets affects the bed slope of the ice sheet and the grounding line of marine-terminating outlet glaciers. Vertical ground motions in the polar regions can be rapid (up to several cm/yr) and are occurring due to Glacial Isostatic Adjustment (GIA). GIA is the process by which Earth's crust, lithosphere, and mantle deform as ice loads from the surface are repositioned by deglaciation. Estimates of GIA are important for constraining ice mass changes and sea level changes, both in the past and for the present-day. In most areas, rates of uplift due to GIA are uncertain, but recent geodetic observations are providing important new constraints.

The goal of this session was to discuss recent advances in understanding the structure of the solid Earth beneath the polar ice sheets, and to relate these structures to ice mass changes, vertical motion, and the dynamic response of ice sheets to the solid earth. We also focused on the observational aspects of the solid earth movement in the polar regions.

Geophysical observations can provide constraints on the density, temperature, and water content of the rocks in the upper mantle, improving our understanding of both GHF and GIA processes beneath the ice. Seismic observations are particularly important because seismic velocity depends strongly on the temperature of the rocks, which relates to both GHF and the rock properties (like viscosity) that determine GIA uplift rates. For Greenland, seismic models predict that the interior has a thick and stable lithosphere, from which we would infer low GHF. However, the Iceland plume has thermally influenced the southeast coast of Greenland, and possibly some of the Greenlandic interior as well. Generally, high GHF should accelerate melting beneath the ice, which would accelerate ice flow.

The seismic structure of the solid earth can also lead to constraints on the lithospheric thickness and the viscosity structure of the rocks beneath the ice. For example, seismically slow regions of the upper mantle, such as southeast Greenland or West Antarctica, are generally hotter and thus may have thinner lithosphere and/or lower upper mantle viscosity. Both attributes lead to much faster rates of GIA-induced ground uplift. Geophysical measurements, from magnetic, gravity, seismic, heat flow, geodetic, and magneto telluric observations, can also provide useful data that can be used to constrain lithospheric thickness and/or mantle viscosity structure.

For a given mantle structure and an estimated ice load history, numerical models of the GIA process can provide useful predictions of uplift rates. Such models are necessary to relate observations from ground and satellite observations to rates of ice-mass loss. GIA models produce dramatically different results for different lithospheric thicknesses and different viscosities beneath the lithospheric plates, and thus 3D GIA modelling efforts are required. Uplift rates from modern deglaciation can be quite large (a few cm/yr) if deglaciation is rapid and the upper mantle is weak (low viscosity). This may be the case beneath southeast Greenland (e.g., Kangerlussuaq Glacier), where GNSS (Global Navigation Satellite Systems) observations of rapid uplift are consistent with a mantle that was heated by the Iceland Plume.

If GIA processes are uplifting the ground surface rapidly, then this uplift can move the grounding line of outlet glaciers seaward. This can potentially stabilize the catchment area of the glacier, but ice sheet stability depends significantly on the interaction between rock uplift, ice sheet mass loss, and ocean interaction with the glacier tongue. Coupled GIA – ice sheet models indicate that grounding line retreat in West Antarctica can be delayed by 50 – 130 years when GIA uplift above a hot upper mantle is included, leading to a 9-23% reduction in the Antarctic sea-level contribution by the year 2500. This impact of the solid Earth feedback onto ice sheet projections can be twice as large as the uncertainty due to the climate forcing.

Geodetic constraints are essential for understanding the all-important link between GIA-induced ground uplift and ice sheet dynamics. Right now, networks of GNSS stations collect real-time uplift data across Greenland and Antarctica, and such constraints are essential for understanding how rapid uplift and ice sheet deglaciation processes interact, with implications for future stability of the ice sheet. However, the future of these networks is uncertain. The large expense of station installation and subsequent maintenance have led to questions about the future of some station networks. For example, the future of the POLENET stations in Antarctica (currently supported by funding from the USA) are discussed to be decommissioned due to missing funding in the future. Overall, continuous international support of polar GNSS networks is essential for ice sheet monitoring.

Advancements and highlights

- Improvement of geophysical constraints on the solid Earth structure, by combining ground- and space-based datasets.
- Advancement of 3D GIA modelling capabilities by incorporating realistic Earth model variations as well as sophisticated rock deformation behaviour (i.e., non-linear rheologies and compressibility).

KEY MESSAGES AND RECOMMENDATIONS

- Enhancement of the coupling between ice sheet dynamic models and 3D GIA models, specifically incorporating lithospheric as well as upper and lower mantle structures.
- Expansion and continuation of bedrock displacement observations in the polar regions, e.g. from GNSS stations and measurements from space such as InSAR (Interferometric Synthetic Aperture Radar), to improve estimates of GIA models.

2.6
How satellite measurements can help in better understanding dense water formation in the Southern Ocean and its impacts on the global circulation and climate

Chairs:
Estrella Olmedo (Institute of Marine Sciences), **Alessandro Silvano** (University of Southampton)

Summary of session presentations and discussion

The transformation of upwelling deep water into new water masses, such as Antarctic Intermediate or Bottom Water (AAIW and AABW), is a key climate-relevant process as it can alter the global energy and carbon balance, particularly in a changing climate. While winds fuel the overturning circulation in the Southern Ocean, heat and freshwater fluxes are extremely important in driving water mass transformation.

Open questions:

- Is the high-latitude Southern Ocean a CO2 source or a sink to the atmosphere?
- How can we better understand and possibly quantify the water mass transformation in the sea ice covered ocean, particularly in winter?
- What is the spatial and temporal variability of the destruction of upwelling deep water and the formation of intermediate and mode waters?
- Are there any circulation changes associated with recent Antarctic Sea ice decline?
- What are the processes on the Antarctic continental shelf that control bottom water formation and its unprecedented decline?

KEY MESSAGES AND RECOMMENDATIONS

Need of enhancing in situ observations:

1. **Sustained observations** are needed for the upper cell
   a. ARGO and MEOP essential.
   b. More high resolution, year-round and under ice glider and AUV campaigns (Antarctica InSync).
   c. Targeted experiments / sites (Antarctica InSync).
   d. New observations (sites and instrumentation) should be planned with sustaining these over several years in mind.
2. An **observing system for the lower** cell is also needed.
   a. Key to measure the Antarctic continental shelf and slope year-round.

Need of improved ocean and sea ice simulations: Satellites can aid modelling in the Southern Ocean:

1. **Higher resolution** climate models featuring an eddying ocean at polar latitudes is required to properly resolve processes on and in front of the continental shelf (CMIP7 currently ¼ for ocean).
2. **Including ice shelf cavity** processes in climate models for realistic water mass transformation.
3. **Potential development of a regional atmospheric reanalysis** for Antarctica since coastal wind regimes play a major role in polynya formation, sea ice production and hence bottom water formation.
4. **Satellite products have added crucially to sea ice model development**: extent, concentration, thickness, drift, lead and polynya statistics; model validation will continue to rely on such products.

Need of enhancing satellite measurements:

1. Recent advances in the satellite sea surface salinity measurements in the Southern Ocean allow:
   a. To gain a deeper understanding of the mechanisms driving the decline in sea ice extent in recent years.
   b. To improve the understanding of the drivers of polynyas formation.
2. **Close to coast/ice edge**: Need for understanding which part of the signal is geophysical and which one is residual contamination.
3. **Improvements needed for year-round and circumpolar Antarctic sea ice thickness measurements.**

3
POLAR ECOSYSTEMS, BIODIVERSITY AND CARBON CYCLES

3.1
Overwintering zooplankton, the Seasonal Lipid Pump, and global carbon cycling

Chairs:
Jennifer Freer (British Antarctic Survey), **Nadine Johnston** (British Antarctic Survey)

Summary of session presentations and discussion

One component of the global biological carbon pump that is pertinent to polar ecosystems and associated feedbacks is the Seasonal Lipid Pump (SLP): the transport of carbon to depth during the overwintering migration of lipid (which is rich in carbon)-storing zooplankton (principally copepod crustaceans). Despite the potential for the SLP to contribute significantly to global carbon cycling via respiration and mortality of these animals in the deep ocean, the paucity of biological observations of copepods during the polar winter means large gaps still exist in our understanding of SLP processes and its response to environmental change. This session brought together international researchers to synthesise our current understanding of the SLP in both the Arctic and Antarctic.

Guang Yang (Chinese Academy of Sciences) presented efforts that have begun to quantify carbon sequestration via SLP processes in the Southern Ocean using data from meso-zooplankton (including copepods), krill and salps, finding that these three groups may export up to 77Mt carbon per year via their seasonal migrations, similar to previous estimates of annual Particulate Organic Carbon flux in the Southern Ocean by Boyd et al 2019. **Aidan Hunter** (British Antarctic Survey) described a more targeted approach, compiling historical abundance data for all lipid-storing copepod species of Southern Ocean copepod. These data will provide the foundations for a suite of species distribution models that will reveal environmental drivers of distributions and predict current and future magnitudes of their SLP contribution. **Sigrun Jonasdottir** (Technical University of Denmark) presented results from a novel laboratory study that demonstrated the effect of phytoplankton community on copepod lipid storage, accumulation, and composition. This highlighted how changes at the base of the food web could affect overwintering potential of these species. Finally, **Andre Visser** (Technical University of Denmark) drew on best available data to provide a global estimate of carbon sequestered via the SLP and highlighted the key uncertainties and data gaps that emerged. He introduced the concept that populations of marine species involved in biological carbon pumps are maintaining the vast pools of "legacy carbon" that have been laid down by previous generations. Human activities may push these reservoirs out of balance, emitting legacy carbon back into the atmosphere.

In a final panel discussion, a range of topics were highlighted including: the importance of sea ice to seasonal lipid pump, communicating and reducing uncertainties in observational data, satellite imagery (to assess the state of the SLP and gather information on phytoplankton blooms which fuel copepods and other carbon transferring zooplankton) and possible role of citizen science and AI in acquiring observations.

Major advances and highlights

The circumpolar and global scale of the work presented underscores the scale of the carbon that these species have sequestered in the past (legacy carbon), are sequestering now, as well as the potential for future disruption via climate change and fishing.

Biogeography, physiology, and modelling studies show that polar copepods are essential to the lipid pump, ecosystem structure and functioning, and are also sensitive to climate-induced changes in diet (phytoplankton) and environment.

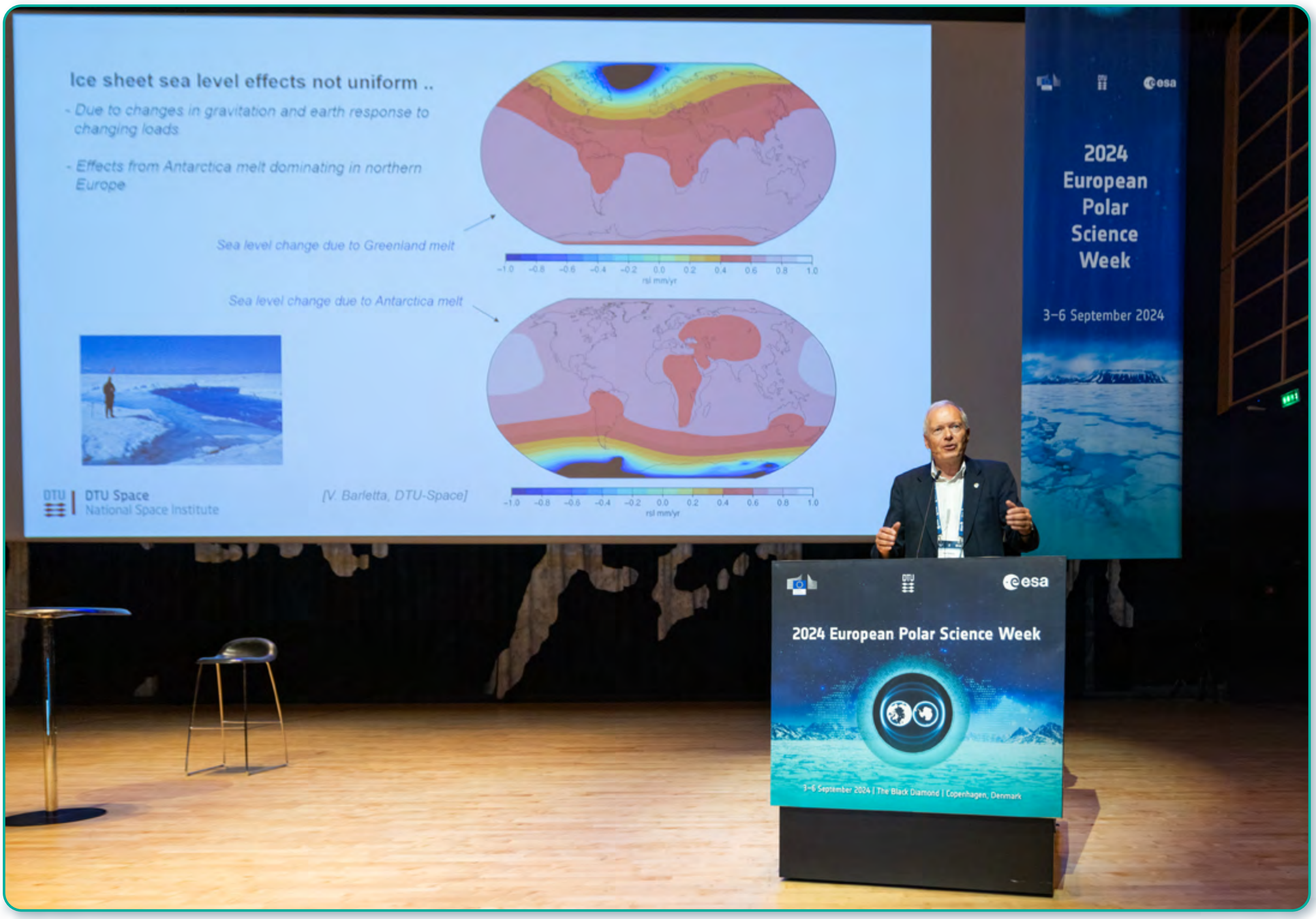
KEY MESSAGES AND RECOMMENDATIONS

Key messages:

- The seasonal migration of polar zooplankton sequesters significant amounts of carbon to ocean depths via the seasonal lipid pump, a component of the biological carbon pump – just 5 species alone may contribute 35Gt of carbon or 3% of the total carbon sequestered.
- Major efforts are underway to refine these estimates and predict how the lipid pump may change in the future (e.g. BIOPOLE, ECOTIP, SEA-Quester, CAS-PML-BAS, PolarRES).
- Major knowledge gaps remain in understanding this component of the biological carbon pump e.g. overwinter distribution and physiology, mortality rates, diapause entry/exit queues and species-specific sensitivity to changing conditions.

Recommendations:

- Resources are required to improve our understanding of the seasonal lipid pump via novel field and laboratory observations, modelling activities, and increased access to and leverage of existing data.
- Polar zooplankton researchers must aid and encourage the wider science community and policymakers to incorporate seasonal lipid pump species and processes into their projections (e.g. within Earth System models), carbon budgets, and within their conservation and management objectives.



3.2
Towards a three-dimensional monitoring of Greenlandic Marine Ecosystems

Chairs:

Rafael Gonçalves-Araujo (DTU Aqua), **Thomas Juul-Pedersen** (GINR)

Summary of session presentations and discussion

The Arctic and Greenland are changing faster than the rest of the globe and understanding the impact of those changes to the ecosystem functioning is paramount to project the effects of climate change to other environments. On top of that, there is limited knowledge regarding the functioning of those environments, which is partially due to the limitations and caveats inherent to available technologies to monitor the Greenlandic marine ecosystem, from fjords and coasts to shelf and open sea environments.

The session brought together scientists from different areas of expertise to discuss effective ways to monitor the Greenlandic marine ecosystem, considering the need for a multidisciplinary point of view and focusing on the marine primary production-relevant parameters, such as light availability/attenuation, phytoplankton biomass (the major primary producer in those waters) and hydrography/environmental factors.

Traditional *in situ* water sampling provides detailed information on phytoplankton community composition, which have further impact on ecosystem services such as CO_2 sequestration and fisheries provision. At the same time, it allows for conducting incubation experiments where process rates (e.g., primary production, nutrient assimilation, and CO_2 uptake/release) can be determined. However, given the time-demand and limitations to conduct frequent sampling, this technique is limited in both space and time, relying on monitoring programs, such as the Greenland Ecosystem Monitoring (www.g-e-m.dk), and occasional scientific cruises conducted by diverse international research projects.

Aquatic optics (or bio-optical measurements) can be used to derive relevant biogeochemical parameters (e.g., phytoplankton biomass, light availability, nitrate concentrations, etc.) based on measurements of light above- and/or underwater. Those instruments can be integrated with traditional and autonomous platforms such as ship based CTD/Rosette systems, automated underwater vehicles, gliders, moorings and floats and can largely increase sampling efforts and thus, the spatial and temporal coverage.

Satellite remote sensing has emerged as a state-of-the-art technique to monitor those remote environments by providing daily coverage of relevant parameters, largely increasing both spatial and temporal resolutions. However, those measurements are limited to the surface layer and absence of sea ice and cloud coverage, and current algorithms for polar regions still need fine tuning, given the complexity of those waters leading to relatively poor performance, especially in dynamic fjord systems often with high sediment loads.

In that sense, Argo floats can fill in the gaps left by remote sensing techniques by significantly increasing the sampling efforts over the water column and reaching areas of difficult access by vessels and other platforms. However, those still cover a relatively limited geographical area.

Major advances and highlights

Ecosystem modelling appears as a powerful tool to provide an overview on the entire ecosystem from a multidisciplinary point of view. However, more parametrizations are required to reach reliable representations and predictions.

An effective 3D monitoring and understanding of Greenlandic waters can only be achieved by combining complementary techniques. Still, it is clear that current available techniques present limitations and caveats, which can only be properly addressed and improved by increasing the *in-situ* sampling efforts for ground-truthing and validation.

There is great potential for a scientific breakthrough regarding understanding the primary production and carbon cycling in the Greenlandic marine ecosystem by combining the different observational and modelling techniques and employing machine learning and AI tools.

KEY MESSAGES AND RECOMMENDATIONS

Although there has been significant advances and development of the observational techniques, it is still needed to improve and validate them in the complex Greenland waters/marine ecosystem. Ocean colour remote sensing techniques are successfully employed in diverse marine environments, but there is still lots of room for improvement in the complex Greenlandic waters. This calls for the development of regional algorithms and parametrizations. There is also a clear need for increasing *in situ* sampling efforts so that we can reach a full understanding of current ecosystem conditions and processes. Those measurements can be used for several other purposes such as validation of diverse sensor-based measurements, satellites, and model outputs.

There is a need for conducting international, multidisciplinary campaigns/projects focusing on advancing the state-of-the-art when it comes to understanding the marine systems as a whole. The marine system is fully integrated, and a holistic view can only be reached by combining experts from different fields. This can only be achieved by increasing funding possibilities for traditional water sampling monitoring alongside expanding observational capacities with autonomous sensor-based monitoring and development of regionally suitable remote sensing algorithms and parametrizations.

Finally, fostering a better communication and data transfer from observation to modelers could significantly advance earth system modelling approaches. This could be achieved by fostering communication among those two groups through the development of joint workshops to stimulate the conversation and exchange among those.

3.3

Arctic biodiversity at a crossroads - Research directions along the land-coast-ocean continuum

Chairs:
Simon Jungblut (University of Bremen), **Bruce Forbes** (University of Lapland)

Summary of session presentations and discussion

The Arctic environment is changing across the terrestrial, coastal and open ocean domains. The Arctic cryosphere is experiencing a tremendous loss, resulting in sea ice decline and glacier retreat, leading to shifting physical interfaces. This impacts organisms at all taxonomic levels, from microbes to mammals, in all areas and habitats. Biodiversity shifts include the northward expansion of boreal-temperate species and a decline of Arctic species, which may induce shifts in ecosystem functioning to an extent that ecosystem tipping points are very likely to occur.

Ecosystem tipping points are large scale impacts which directly affect human livelihoods, as ecosystems accommodate for multiple human uses (e.g., food provisioning, fisheries, reindeer herding, etc.). However, emerging human uses, which are partially only possible due to anthropogenic climate change effects, induce additional environmental pressures (e.g., aquaculture, new shipping routes, etc.). These pressures and the speed of environmental change in approaching tipping points clearly limit adaptation possibilities for humans, biodiversity, and ecosystems. Newly emerging risks for local operations (e.g., avalanches, unforeseeable ice conditions, and extreme weather events) are hampering economically important sectors like fisheries and (nature-based) tourism.

One particularly important ecosystem service is carbon capture through carbon sequestration in the open ocean, in coastal areas and in the terrestrial realm. However, the biological processes influencing carbon stocks, their fluxes and the residence times of carbon once sequestered are largely unknown. Moreover, the interaction of high amounts of sequestered carbon with the changing environment is unclear.

This session revealed that the current improvements in remote Earth observations may lead to useful and promising tools for Arctic biodiversity research. While the EU is a facilitator of these developments via research funding, ESA and the scientific community will aim to work closer together to provide the much-needed ground truthing for the Earth observation tools and sensors to be developed.

Major advances and highlights

Especially in biodiversity research, long-term monitoring is the essential tool to investigate changes over time which may lead to changes in ecosystem functioning and ecosystem services ultimately essential for human live. Monitoring via environmental DNA (eDNA) has been proven to be rather effective especially to observe the distribution of non-native species. Technologies like remote sensing, drones, and artificial intelligence are helpful tools in the monitoring context and, e.g., create helpful rain-on-snow datasets. However, ecological surveys in situ remain crucial to characterize and understand biodiversity change. Finally, it is critical to invest in co-production of knowledge with local and Indigenous communities.

In Arctic fjord systems, glacier fronts will be further retreating and consequently become land-terminating. As they recede, meltwater run-off releases large amounts of sediment into the fjords which is “trapped” in a freshwater lens on top of the water column, a so-called sediment plume. These sediment plumes are blocking light to penetrate the water column (“coastal darkening”) which severely decreases primary production and may lead to cascading effects like shifting zonation patterns of organisms. Furthermore, calving of glaciers and iceberg scraping the coastal zones as well as nutrient influx via sub-glacial meltwater intrusion are reduced.

Current projects working in Arctic cryosphere loss related to biodiversity revealed the importance of local factors for Arctic socio-ecological systems. Consequently, this local context has implications to a general governance system (e.g., EU policies) as it needs to be flexible enough to accommodate local needs.

KEY MESSAGES AND RECOMMENDATIONS

A systematic support of long-term monitoring of biodiversity, including non-native species, is needed for the timely detection of changes and approaching ecosystem tipping points. Therefore, biodiversity research needs to reach beyond emblematic and harvested species, as for instance lower trophic levels provide the food web basis for them. Novel ecosystems will be more frequent and its opportunities and challenges for local and Indigenous communities are a key avenue for research.

Arctic areas should be studied as cultural landscapes and not only as wilderness. This can only be achieved by integrating inter- (i.e., natural, and social sciences) and trans-disciplinarity (i.e., stakeholder needs) into all Arctic research. Therefore, long-term research personnel are needed to build trust and relationships with local and Indigenous communities. This is the basis for nexus governance approaches being holistic and include environmental governance and cross-sectoral policies. Ultimately, solution-oriented actions are needed to safeguard the Arctic environment, it's global ecosystem services and the local populations.

Gaps on Arctic biodiversity research, integrated by the projects ECOTIP, FACE-IT, and CHARTER can be found here: https://www.face-it-project.eu/outreach/brochures/

4

ENHANCING OBSERVATIONS IN POLAR REGIONS

4.1

Taking the pulse of the Southern Ocean: an internationally coordinated, circumpolar, and year-round mission - Antarctica InSync

Chairs:

Stefanie Arndt (AWI / UHH), **Alexander Haumann** (AWI / LMU)

Summary of session presentations and discussion

The presentations focused on the urgent need for a coordinated international effort to address major knowledge gaps in the Antarctic and the Southern Ocean systems. This urgent need arises from the Southern Ocean's critical role in buffering global climate change impacts by absorbing significant levels of anthropogenic heat and CO_2 from the atmosphere, thereby slowing global warming. The speakers highlighted the interconnectedness of the region's ecosystems, emphasizing that changes in Antarctica have cascading effects on global climate, biodiversity, and human societies. However, the speakers also pointed out that projections with climate models on whether this role can persist in future remain highly uncertain due to limitations in model accuracy, data scarcity, and gaps in our understanding of key processes. The discussions stressed that this issue becomes particularly alarming in light of the recent decline in sea ice as well as the rapid melting of glaciers, ice shelves and ice sheets, which contribute to rising sea levels and potentially disrupt global ocean circulation.

The presentations provided a scientific vision to address these challenges through the Antarctica InSync program, a UN Ocean Decade initiative aiming to establish a comprehensive understanding of the Southern Ocean and Antarctica's response to climate change. The key research priorities outlined in the presentations included investigating the heat, freshwater, carbon, and other element budgets of the region, examining the rapid decline of sea ice and its consequences, understanding the melting of ice shelves and ice sheets and their connection to coastal and continental margin zones, and improving knowledge and protection of Antarctic life. Another focus of Antarctica InSync that has not directly been addressed during this session is to identify anthropogenic signatures in Antarctica such as pollution and other pressures. The presentations also emphasized the importance of international collaboration, data sharing, and the development of standardized protocols for observations to effectively address these research priorities. The speakers advocated for a multi-scale approach to research, integrating ship-based, autonomous, and remote sensing observations with modelling efforts. The sessions concluded with calls for community pledges to leverage existing data, to fill major data gaps, to collect data that furthers process understanding and improves model simulations, and to deploy a circumpolar network of instrumentation.

Major Advances and Highlights

Despite the recognized need for comprehensive data on the Southern Ocean and Antarctica to better understand the system and its changes, the speakers point to a significant lack of observations in this region. However, there have been some notable advances in scientific methods for observing and understanding the Southern Ocean and Antarctica:

The use of instrumented seals has emerged as a valuable tool for mapping coastal hydrography, providing continuous data from regions that are otherwise difficult to access. In addition, the systematic deployment of profiling Argo floats with biogeochemical sensors has led to new insights in the primary production, the carbon cycle, and under ice processes in this region, especially during the sparsely observed winter months. These data have helped reveal large-scale patterns and teleconnections in the Southern Ocean, contributing significantly to our understanding of its dynamics. Another significant advancement is the use of in-situ radar (ApRES) observations to measure ice shelf thinning rates and, consequently, melt rates. This technology allows for the detection of interannual, seasonal, and sub-seasonal changes, providing crucial data for validating satellite products and identifying coherent patterns across distributed observatories. The speakers advocate for the expansion of these observing networks to enhance data collection and improve our understanding of crucial processes.

The session highlighted the importance of synchronous, circumpolar, and year-round observations in the

Southern Ocean and Antarctica, as proposed in SCAR's Horizon Scan and the Southern Ocean Action Plan under the UN Ocean Decade. These reports resulted in the proposed Antarctica InSync program under the UN Ocean Decade and is coordinated internationally. This multi-national, interdisciplinary initiative presents an unprecedented opportunity to bring together modelling, in-situ observation, and remote sensing communities.

KEY MESSAGES AND RECOMMENDATIONS

The key message emerging from the presentations is the urgent need for international collaboration and coordinated action to address the lack of understanding of the rapidly changing Antarctic and the Southern Ocean environment. The speakers emphasized that these changes have profound implications for global climate, biodiversity, and human societies. To achieve this, the participants recommend establishing a robust observing network that integrates ship-based, autonomous, and remote sensing technologies. They advocate for the adoption of standardized protocols for measurements, data publishing, and metadata, ensuring data quality and facilitating global data sharing efforts as well as data synthesis.

International collaboration is crucial to establish a circumpolar perspective, with a focus on identifying strategic distributed study sites and "hotspots" for targeted observations. These observations should prioritise key variables, including Essential Climate Variables, and be aligned with modelling requirements to support robust projections. Expanding the circumpolar observation network with radar systems, buoys, and moorings will underpin sustained observations, while the inclusion of autonomous platforms and sailing vessels will enhance data collection capabilities. The speakers also call for a global effort to mitigate climate change and ocean acidification, raising awareness of the Southern Ocean's vulnerability and its global importance.

The participants suggest that these efforts should focus on several key scientific priorities. These include: understanding seasonal variability in circulation, sea ice, and water mass transformations, with an emphasis on winter conditions and under-researched sea ice regions; observing the full carbonate system, air-ice-ocean flux variability, storm and extreme event impacts, coastal hydrography, ice shelf melt rates, sub-ice shelf topography, snow properties, and ice thickness; assessing the role of biological processes in carbon and nutrient cycles and monitoring habitat and biota shifts across diverse ocean zones; and understanding the role of pollution and the anthropogenic footprint. Building and sustaining diverse and inclusive research teams and leveraging existing programs will be crucial to support these research efforts.

4.2

Beyond Borders: Strengthen Global Polar Research through Advanced Research Infrastructures

Chairs:
Nicole Biebow (AWI), **Anneli Strobel** (AWI)

Summary of session presentations and discussion

The EU-PolarNet 2 project, funded by the EU Horizon 2020, focuses on identifying priority topics for future research in the polar regions and proposes ideas for Large-Scale Initiatives to support these priorities. A key output is a White Paper offering 80 practical recommendations to policymakers to develop a fully integrated Polar observing system, emphasizing international collaboration and sustained long-term observations.

The EU Horizon Europe-funded POLARIN project will play a pivotal role in supporting this by providing access to 64 top-level research infrastructures in the Arctic and Antarctic. Sharing infrastructures encourages international collaboration, capacity building, and minimizes duplication, as demonstrated in projects like POLARIN and Antarctica INSYNC. Access to these challenging environments, such as the Arctic and Antarctic, is crucial and is sustained through policy and funding support.

The Tara Polar Station offers a unique opportunity for year-round research in extreme polar environments, enabling multi-year studies on sea ice dynamics, local biodiversity, and polar transformations, driven by community-driven research priorities. However, polar observations face challenges such as funding, holistic coordination, and system integration. Long-term funding, user needs assessments, and coordinated efforts are essential to address these gaps and improve our understanding of polar transformations. Collaboration between remote sensing and in-situ observations is critical, such as snow over sea ice measurements improving satellite ice thickness data. Cooperation between Earth Observation and in-situ efforts enhances data accuracy, especially in polar regions.

The recommendations within the EU-PolarNet White Paper were developed with input from polar research, observation, and data communities, including Arctic and Antarctic organizations. The focus is on user needs, particularly Indigenous communities, improving governance, and fostering collaboration. The EU-PolarNet research prioritisation process ensures that research targets the most pressing issues, while large-scale initiatives, such as Antarctica InSync, aim to address high-impact topics through international cooperation, optimizing resources and expertise.

Major advances and highlights

- Integration of Long-Term Monitoring Systems is essential to enhance our understanding of complex ecosystem dynamics. An integrated, long-term monitoring systems, such as a "Polar System of Systems" should include biological, chemical, and physical observations, with a focus on international collaboration.
- The EU-PolarNet 2 White Paper offers 80 recommendations for policymakers to establish a fully integrated polar observing system, addressing gaps in collaboration, data sharing, and systematized observations across international polar research efforts.
- Sharing infrastructures fosters international collaboration, and there is an increasing willingness to share infrastructures, exemplified in the POLARIN Horizon Europe project or the Antarctica INSYNC initiative. This accounts particularly for regions which are difficult to access and where many countries are not operating infrastructures, such as in the Arctic or Antarctic.
- Year-round research at the heart of the polar pack ice is one important objective to document and understand the dynamics of polar transformations, objectify scientific data and identify the wealth of local biodiversity. The requirements and adversity of the extreme and dynamic polar environment make it very difficult for scientists. The Tara Polar Station, starting in 2026, which drifts with the ice and which is an alternative infrastructure will allow such investigations. It offers a unique opportunity for year-round research in extreme polar environments, enabling multi-year studies on sea ice dynamics, local biodiversity, and polar transformations, driven by community-driven research priorities.
- Collaboration between remote sensing and in-situ observations is critical, such as snow over sea ice measurements improving satellite ice thickness data. Cooperation between Earth Observation and in-situ efforts enhances data accuracy, especially in polar regions.

KEY MESSAGES AND RECOMMENDATIONS

- Sharing access to research infrastructures in polar regions, as seen in projects like POLARIN, fosters polar research, international collaboration, reduces duplication, and lowers environmental impact. It enables a coordinated approach to addressing global challenges.
- To ensure sustained transnational access to research infrastructures in polar regions, a comprehensive approach involving collaboration, funding, policy development, and technological innovation is needed. We need to encourage international research networks and alliances to enhance cooperation and resource sharing.
- Enhancement of Understanding of Climate-Driven Changes: large scale initiatives should prioritize research on the impacts of climate change on critical polar processes, such as the functioning of major polynyas in northern Greenland, the stability of the Antarctic Ice Sheet, and the fluxes at Arctic Ocean gateways. Long-term and seasonal observations in the polar areas are crucial to improve predictive models and to better understand the drivers and consequences of these changes.
- Collaboration Between Remote Sensing and In-Situ Data: Remote sensing (e.g., satellite data) and in-situ observations must collaborate closely, such as for snow measurements over sea ice, which help correct satellite-derived ice thickness data. We need to enhance integration of in-situ and remote Earth observations, expand satellite capabilities, and collaborate with ESA for polar monitoring.
- Need for Comprehensive Coordination: A fragmented polar research landscape calls for holistic coordination, long-term funding, and targeted efforts to fill scientific gaps, especially in pollution tracking, climate reconstruction, and integration of monitoring systems.

4.3
Challenges With Implementing Technologies in the Arctic

Chairs:
Henrik Navntoft Sønderskov (Danish E-Infrastructure Consortium), **Sheila M. S. Christiansen** (SheileX)

Summary of session presentations and discussion

Sheila M. S. Christiansen talked about grand solution visions and their obstacles in the Arctic when facing an extreme environment. This was followed by **Michael Linden-Vørnle** who took the focus to how this influenced conducting research, with a presentation concerning problems and challenges to better scientific results. From here **Alexandru Csete** focused on the challenges in collecting data from the Arctic Region and how technology can help us solve common obstacles. Finally, **Nanna Vangkilde** put the various presentations in perspective with a presentation concerning Infrastructure and data needed to provide a backbone for implementation in the Arctic, and problems implementing them.

KEY MESSAGES AND RECOMMENDATIONS

A need for an international science hub was identified to develop and maintain focus on Arctic development and corporation. Both from the audience and presentations there was consensus that anything that happens in Greenland happens with Greenland.

4.4

Developing the Atlantic-Arctic Distributed Biological Observatory (A-DBO): Improved observational capacity in the high Arctic.

Chairs:
Arild Sundfjord (Norwegian Polar Institute)

Summary of session presentations and discussion

The Arctic marine domain is under-sampled compared with other regions of the Earth, and the need for improved in situ monitoring was emphasized. Currently, there is no overarching structure for coordinating such observations, which are often carried out through short-term science projects. A major effort, on international basis, in maintaining both yearly and long-term in situ measurements is needed, to guarantee the understanding of the complex Arctic ecosystem.

As part of the EU H2020 Arctic PASSION project, a network of institutions carrying out national monitoring programs and research projects in the Atlantic sector of the Arctic Ocean has been established. This network, called the Atlantic-Arctic Distributed Biological Observatory (A-DBO), aims to cover climate, environment and ecosystem indicators in the region. The network builds on a collaborative model successfully established in the Pacific-Arctic region for more than a decade. In parallel with the A-DBO establishment, two additional DBOs are being formed between Greenland and Canada, and in the Eastern Arctic Ocean. Together, these form the pan-Arctic DBO network which strives to harmonize sampling and analysis protocols, data sharing and other key issues for improved ocean observing.

The utility of observations and data sharing within the A-DBO was illustrated through the example of Atlantification, which cannot be understood by e.g. remote sensing products only, but requires long-term in situ monitoring of a variety of variables in the water column. Moreover, there is a strong need to include coastal monitoring programs in the DBO system; to provide vital data for local communities and management of resources there, to establish best practices for sampling and analysis, and to enable understanding of drivers and responses between the open ocean and coastal areas. Finally, needs for in situ observations for ocean modelling purposes was discussed. There is a need for multidisciplinary, spatially comprehensive and temporally extensive, quantitative measurements to improve and constrain coupled sea ice-ocean-biogeochemistry-ecosystem models.

Major advances and highlights

The A-DBO network has established routines for pre-season planning, metadata sharing and post-season assessments to facilitate the information sharing between all actors. We are working towards common practices for sampling and analysis adhering to the FAIR principles for data dissemination. Both the regional framework and the pan-Arctic network of DBOs, evolves through an annual cycle with biannual open community meetings. This opens for a responsive approach based on the latest findings, and a communal shaping of our onward efforts and priorities for joint pan-Arctic assessments.

KEY MESSAGES AND RECOMMENDATIONS

There is an obvious need for better coordination of Arctic marine in situ observations, e.g. a regional ocean observing alliance, to get more out of our efforts in this under-sampled and logistically challenging area. Observations should cover the whole spectrum of variables from sea ice, physical oceanography, biogeochemistry and biology, to enable detection and understanding of climate and ecosystem change. The pan-Arctic DBO network could be an integral part of a future regional ocean observing alliance for the Arctic.

There is a need for a coordination and collaboration system also for coastal and fjord in situ observations, e.g. in Greenland. Ideally, open ocean and coastal networks should be connected since these regions mutually influence each other. Expanding the observational sites to coastal regions considerably improves the integration with local communities and the potential for indigenous-led efforts. The approach adopted by the DBO network could be a model.

The A-DBO session highlighted usefulness of applying remote sensing products and model simulations to fill in the picture when analysing in situ observations. There is a large potential within the DBO network to be a partner in identifying possibilities to obtain more useful data for calibration of new remote sensing data and for model evaluation.

4.5

FAIR scientific data in support of polar monitoring and assessment efforts

Chairs:

Øystein Godøy (MET), **Mathias Bavay** (WSL/SLF), **Ilkka Matero** (SIOS KC)

Summary of session presentations and discussion

The session featured 5 presentations that provided an overview of existing polar data management frameworks, their purpose, and the need to harmonise data to establish a greater whole. Fragmented data documentation and access means that human resources are wasted massaging data into a common documentation standard before analysis can take place. Harmonisation of data documentation is needed to integrate independent and fragmented observing and data generation efforts into a unified whole representing the Earth System (exemplified through WMO Global Cryosphere Watch and SAON/AMAP assessment). This is particularly important for monitoring efforts, but highly beneficial for process studies as well. The session was built around the FAIR guiding principles, but while FAIR has been around for a while as a concept, the understanding of the implications, at the use level, is often poor. FAIR has primarily been addressed at the discovery level and in the exchange of discovery metadata that allows data consumers to find data, but the aspect of self-describing data allowing the user to readily understand and interpret the data has gained less focus. This was addressed in the session through examples of FAIR data implementation at the use level (exemplified by SIOS Core data and PROMICE and GE-NET data). The challenge of harmonising data is well known from a number of large-scale frameworks, e.g. WMO and GBIF. To support data providers, an existing software package, MeteoIO, has been further developed into a web service that helps standardising datasets in netCDF according to the Climate and Forecast Conventions and to publish them as interoperable and reusable datasets. The discussion centred on how to support data providers in harmonising data.

Major advances and highlights

1. Data providers and centres provide harmonised data allowing direct integration of data in decision support tools without human massaging of data as data are self-describing. Examples were provided from PROMICE and GE-NET stations in Greenland as well as for SIOS Core Data.
2. Extended metadata on observation stations are provided for datasets through linked data approaches where descriptions of observation facilities are linked to datasets
3. Tools (including web services) are becoming available for data harmonisation with the MeteoIO as an example that was presented in the session.

KEY MESSAGES AND RECOMMENDATIONS

- Publish data for reuse:
  - Publish to reach those that doesn't know the data.
  - Publish in a FAIR compliant self-describing formats where semantic annotation follows governed terminology.
- Publish data in usable granules:
- Computers can easily help integrate granules through discovery metadata, while decomposition is more costly to achieve since discovery metadata is the guide to usage.
- Make coordinated actionable data an action of IPY preparations
- Actionable data have impact on services and communities.

5
SOCIETAL IMPACTS OF POLAR CHANGE

5.1
Plastic pollution in polar regions: sources and solutions

Chairs:
Elizabeth Boyse (British Antarctic Survey), **Emily Rowlands** (British Antarctic Survey)

Summary of session presentations and discussion

The session started with a focus on the abundance and environmental impacts of plastic pollution in both the Arctic and Antarctica, covering micro to macro plastics, different environments (*i.e.*, beach litter, seawater, ice) as well as ingestion in different marine fauna (*i.e.*, copepods, seabirds). **Giuseppe Suaria** (CNR-ISMAR) highlighted that Antarctica has been under-sampled compared to elsewhere globally, although recent efforts have been made to increase sampling across the Southern Ocean. Suaria discussed results from an Antarctic circumnavigation expedition highlighting that floating microplastic fragments from seawater samples were more abundant north of 40°S, although, in bulk and underway seawater samples, higher latitudes had a higher number of synthetic fibres compared to lower latitudes. Whilst fibre composition was not homogenous, across ocean basins 70-80% were identified as cellulosics. The question was posed whether polar regions may be a sink for textile microfibres.

Jakob Strand (Aarhus University) focused on West and East Greenland, where a combination of shoreline litter, ingested plastic and microplastics in sediment were used to assess the overall amounts and impacts of plastic debris. Generally higher levels of single-use plastics were found in West Greenland, likely corresponding to higher population density, whilst plastics in East Greenland largely came from sea-based sources, i.e., fishing gear. Fulmars stomach contents analysis revealed almost all birds to have ingested at least one piece of plastic, with greater abundances of plastics in East Greenland.

Rachel Coppock (Plymouth Marine Laboratory) focused on the potential implications of microplastic ingestion by zooplankton, highlighting that ingestion of microplastics could potentially have population-level impacts due to reduced feeding capacity, declines in energy reserves and lower reproductive outputs. In-situ observations from the Fram Strait in the Arctic showed that ice-associated amphipods ingested more microplastics than copepods. Since zooplankton underpin the Arctic ecosystem, this could result in bioaccumulation up the food chain.

Amy Lusher (NIVA) highlighted the need to adapt microplastic detection methods to the sampled ecosystem. She highlighted the value of multi-matrix monitoring, i.e., joint sediment and water samples, to provide a more complete picture of microplastic contamination, where water can potentially track rapid fluctuations whilst sediment provides a spatiotemporally integrated signal.

The final talk from **Aanchal Jain** (British Antarctic Survey) discussed potential policy solutions to reduce local sources of microplastic waste, focusing on research facilities in Antarctica. Based on the number of facilities and wastewater treatment systems, the Ross Sea region and the Antarctic Peninsula are high-risk areas for microplastic waste. In the short term, low-cost solutions such as washing machine filters can be effective at reducing pollution in wastewater, whilst in the long-term wastewater treatment systems were most recommended.

Major advances and highlights

The talks highlighted the prevalence of plastic pollution in the polar regions, likely from a range of local and long-range sources. Polar regions, contain some of the highest abundances of fibres reported and plastics are being ingested by species across polar food webs from zooplankton to seabirds, with potential negative physiological impacts and unknown consequences to overall populations.

Long-term monitoring over seasons and years is beneficial to understanding spatiotemporal differences in plastic pollution, whilst method development continues to be a hot topic, especially concerning polar environments where methods developed elsewhere may be unsuitable. For monitoring, it is advantageous to adopt a multi-matrix approach, i.e., by incorporating water and sediment samples, to gain the most thorough overview of plastic pollution, as different sampling mediums will represent different spatiotemporal coverage.

Finally, we need more policy-based solutions to help reduce or prevent plastic pollution from reaching the environment, for example, through increased wastewater treatment systems to reduce the impact of scientific research stations in Antarctica.

KEY MESSAGES AND RECOMMENDATIONS

Overall, a harmonized and coordinated effort is required to tackle plastic pollution. Whilst sampling for microplastics has increased in the polar regions in recent years, surveys covering more environmental mediums and larger spatiotemporal scales are required to fully assess the impact of plastics on polar ecosystems. For example, in the Arctic, most of our knowledge comes from offshore water and sediment sampling, whilst inshore areas and freshwater still have limited data.

We still need to understand what the main sources of plastic pollution are in the polar regions, for example, the polar regions may act as sinks for fibres, but we only just starting to understand how they are being transported to and retained in polar ecosystems.

To further understand population-level impacts of plastics on fauna, laboratory ecotoxicology studies need to align with in-situ observations so that environmentally relevant concentrations and multi-stressor scenarios are considered.

Finally, increased focus on implementing scientific findings into policy at both regional and global scales to reduce inputs of plastic to the marine environment is necessary, as once plastics are in the marine environment, it is extremely difficult to remove them. For this, it is important to consider the policy question being addressed from the outset as well as the resources available.

5.2
Studying and Managing Arctic Tourism in Transition

Chairs:
Halvor Dannevig (Western Norway Research Institute), **Carina Ren** (Aalborg University)

Summary of session presentations and discussion

All five presentations were centred around the interconnected issues of rapid tourism growth and rapid climate- and environmental change in Svalbard and Greenland, community responses to these changes and governance solutions. The very different approaches to sustainability and governance in Svalbard and Greenland have been used to explore and discuss the potential for more adaptive approaches to tourism governance. **Anna Sveinsdottirs** presented Svalbard's top-down governance regime, with its strict regulations, aims to maintain the archipelago's vast wilderness and prioritizes environmental protection over other activities. **Carina Reis** presented that the concentrated seasonal visitors of Greenland contribute minimally to local economies, contrasting with local objectives of increased smaller destinations and community well-being. Longyearbyen in Svalbard is shifting from being a "company town" relying on coal mining to becoming a major Arctic tourism destination. Narratives of Svalbard's future range from playground to wilderness, from an adventure tourism destination to ambitions for strict nature conservation of the Arctic wilderness. What Svalbard's wilderness is, and how it should be managed, remains a contested issue tightly connected to the narratives of its past, present, and future. There is also a huge untapped potential in learning and cross-fertilization on destination management, tourism governance and community responses between Svalbard and Greenland. The presentation of **Ragnhild Freng Dales** identified the dominant narratives shaping responses to policy and environmental changes, which included the potential dilemmas and different levels of feasibility of national policy for tourism development in the context of a rapidly changing environment and climate. Svalbard has seen a rapid growth in expedition cruise ship arrivals. **Dannevig** presented results that showed how this corresponds to a significant growth in amount, distribution, and mileage of the expedition cruise vessels length of travel. Impacts of disturbance are hard to quantify at population levels, and species differ in how they react and adapt to disturbances. Precautionary approach to management is wise in a situation where more stressors than ever are threatening Arctic wildlife, principles of more adaptive forms of management would strengthen the legitimacy of regulations.

Major advances and highlights

- Cross-case learning for tourism destination management in the Arctic.
- Identification of 5 tools and best practices for cruise tourism management: pricing, regulations, investing in renewable energy for building, networking.
- Adaptive co-management of both the environment and tourism may reduce conflict and enable sustainable arctic tourism practices.

KEY MESSAGES AND RECOMMENDATIONS

- Current and future Arctic tourism activities increasingly affect and is affected by climatic and socio-ecological changes.
- Tourism activities, plans and strategies need to be integrated into (or at least considered) in monitoring, regulation, governance, and management.
- Small Arctic destination may gain from increasing cross-destination learning and collaboration (planning, regulation, monitoring, taxing...).

5.3

Arctic Navigation - Practical application of sea ice information in current and future maritime operations

Chairs:

Andrew Fleming (British Antarctic Survey), **Frank Kauker** (O.A.Sys / AWI)

Summary of session presentations and discussion

The overall aim of the session was to provide a summary of both the status and key issues related to the provision of operational sea ice information to the Arctic shipping community. The established national ice services, coordinated through the International Ice Charting Working Group, continue to provide ice charting services to ships operation in or near sea ice. But the increase in shipping in the region, due to changing sea ice conditions and increasing commercial activity, have highlighted the need to continually improve the information available to ships to support safe, efficient navigation. The recent introduction of the IMO Polar Code reinforces and introduces regulation about the need for such information.

The session presented a range of topics related to this subject. It started with an historical analysis of changes in shipping activity and risk in the region, which showed an increase in traffic, but no significant increase in levels of risk related to sea ice, although some indication of increased operation in high-risk ice areas in more recent years.

The session also covered new developments in the delivery of sea ice information and how the national ice services were adapting to changing needs including a demand for more frequent and higher resolution information and forecasts. There is an expectation of more semi-automated processes in the future driven by advances in processing power, data availability, requiring ongoing verification and QC.

The session also addressed novel developments in the delivery of sea ice information to ships including embedded onboard services (e.g. IcySea app) providing improved real-time satellite imagery alongside ice charts. The use of AI based approaches for novel information is clearly a developing theme. In addition to automated extraction of sea ice parameters from satellite imagery, new approaches to calculation of optimal shipping routes in polar waters was described. This approach will potentially offer direct support to ship navigators route decisions based on assimilation of all available satellite data and other observations.

Finally, the session addressed current gaps in the provision of operational sea ice information. This includes limitations with the POLARIS risk assessment system which currently does not account for icebergs or sea ice pressure. However, there is potential for improved forecasts of POLARIS based on coupled ocean-ice models, but a clear need to improve the spatial resolution of such models to be useful for tactical navigation purposes. But there are also gaps in information about key sea ice parameters including thickness, pressure, and snow depth. Advances in developing operational products for such parameters, supported by increasing volumes of satellite data, including planned new polar focused satellites, will support bridging these gaps in the coming years.

Major advances and highlights

- Analysis of POLARIS risk maps provide the first long-term pan-Arctic dataset on the risks of operating in the Arctic.
- Forecasts of POLARIS risk have been demonstrated based on ocean-ice model output.
- Drift&Noise showcased examples where ships were able to avoid unnecessary detours by using IcySea's satellite imagery, highlighting the practical value of the application in improving maritime efficiency.
- The potential of AI-based route optimization has been demonstrated.
- Manually generated ice charts still outperform ice maps based on numerical models and AI models.

KEY MESSAGES AND RECOMMENDATIONS

- POLARIS risk maps of Arctic navigation have been analysed for about 10+ years and have identified locations of high risk for ships that have specific ice classes.
- Drift&Noise shared insights from the past years of building a business around the development of IcySea, an application for the maritime industry that uses Earth observation data, including Copernicus satellite imagery. IcySea provides near real-time satellite imagery to improve navigation, particularly in ice-covered regions such as the Canadian Archipelago.
- POLARIS risk maps were calculated from a set of short-term sea ice-ocean model predictions. The simulated sea ice thickness of the set of models has been validated against CryoSat-2 summer sea ice thickness.
- There are still significant limitations with generation of POLARIS risk information which is limiting uptake by mariners.
- Manually generated, numerical model based, and AI based ice maps were verified and compared against each other.
- It should be evaluated if the Polar Code needs to be adapted to accommodate new high-resolution observations/forecasts.
- Calculations of optimal shipping routes based on AI have demonstrated their usefulness. The potential of AI-based route optimization should be further developed.
- For the evaluation of sea ice forecasts (either based on numerical physical or AI models) uncertainties in observed snow depth and sea ice thickness needs to the reduced.
- Verification metrics for ice charts need to be refined.

6
ADVANCING EO SATELLITE OBSERVATIONS OF POLAR REGION

6.1
Copernicus Polar Expansion Missions: preparing the users for a quantum step in monitoring the Arctic and Antarctica

Chairs:
Maria Berdahl (DG.DEFIS), **Diego Fernàndez Prieto** (ESA)

Summary of session presentations and discussion

The polar regions are highly sensitive to the current global warming. Understanding how these regions are changing is crucial to understand global climate change and predict its evolution, as well as its impacts on society. Monitoring the changes in the polar regions and safeguarding their pristine habitats are key elements in EU policies, which also put a special focus on the Arctic, following the work and recommendations of three Polar Expert Groups (PEG) convened by the EC. Copernicus is preparing a significant step up in capability to monitor the polar regions, from 2027 onwards, with the launch of three Copernicus Expansion Missions (CEMs) specifically designed for polar observations: the Microwave Radiometer CIMR, the dual-band radar altimeter CRISTAL, and the L-Band Synthetic Aperture Radar ROSE-L.

The session focused on future capabilities based on observations from the expansion missions and how these will support both the science community and policy needs. The presentations described a coherent system and collaboration, where for example recommendations from the EC Polar Expert Groups have been taking into the mission requirements for the CEMs, and preparatory activities to make use of the data are already ongoing through the EU Horizon framework and the ESA Sentinel User Preparation (SUP) initiative. This will ensure faster uptake into products and services, and co-designed tools.

Major advances and highlights

Improved polar observations with CRISTAL, CIMR and ROSE-L.

The Earth Observation Strategic Research and Innovation Agenda lists polar monitoring as a priority and mentions the CEMs as important means for polar service evolution.

CRISTALair and CIMRair will open the door to preparatory activities such as those planned already by ESA including the Sentinel User preparation programme.

Many of the specific products identified in PEG III are carried forward in the Copernicus Polar Roadmap for service evolution.

KEY MESSAGES AND RECOMMENDATIONS

Further strengthen the cooperation and "production line" between the different parts of the Copernicus ecosystem – from observations to research to operational services, by use of frameworks and initiatives such as Horizon and SUP, and user involvement at an early stage. Attention to the FAIR principles.

6.2

Gaps and opportunities of future sensors in monitoring ice sheet dynamics, discharge and surface processes

Chairs:

Thomas Nagler (ENVEO), **Anna Hogg** (University of Leeds)

Summary of session presentations and discussion

This ice sheet dynamics session included 5 presentations, addressing the primary ice sheet parameters observed from space and in situ observations including ice velocity, grounding line location, mass discharge, surface mass balance, surface melt, lakes, and surface mass balance. Progress on retrieving these parameters was presented and opportunities for potential and expected improvements using new systems or synergy of different systems were outlined. Regarding ice velocity and grounding lines, increasing the temporal frequency of EO products with monthly to multiannual products was shown.

Further improvements are expected from L-Band SAR satellites (e.g. ROSE-L, NISAR) which will work in synergy with Sentinel-1 promising better coverage and improved accuracy. L-Band SAR will allow the research community to foster InSAR ice velocity retrievals in combination with offset tracking techniques for fast moving areas. Ice mass discharge is provided continuously for most outlet glaciers in Greenland and several glaciers in Antarctica. The estimates will improve by having better ice velocity products and by getting more accurate ice thickness measurements at the grounding line, e.g. potentially provided in the near future by the RINGS initiative.

Regarding surface conditions, methods for monitoring the evolution of surface melt extent at coarse resolution using ASCAT data (almost daily) has been presented and at lower time intervals but higher spatial resolution from Sentinel-1. Improvements are expected from combining C-Band with closely acquired L-band SAR data from near future missions (NISAR, ROSE-L) which allows the estimation of the refreezing depth of in melting areas.

Surface lakes are monitored using optical and SAR data in combination with ML techniques. New developments are enabling frozen lakes to be mapped on the ice sheet. Monitoring of ice shelf damage and extent has been shown, and this represents a new and exciting capability demonstrating that new ECV's products for ice shelves are being developed.

It is acknowledged that it is not possible to monitor all required parameters using EO, therefore there is a need to observe those using airborne, ground-based and ocean-based (buoys, ships, etc.) measurements and continuous in situ observations. These data are needed for algorithm development, error measurement improvements and for calibration/validation of EO products. Some largely EO dependent products (e.g. mass ice discharge) requiring multiple non-EO datasets (e.g. bed topography and SMB) in addition to satellite observations. Greenland has several in situ stations providing observations, but Antarctica the coverage is much sparser, and many regions have no in-situ observations. There is a need for international collaboration between space agencies and national programmes to coordinate validation and in situ campaigns.

Major advances and highlights

Highlights in monitoring ice sheets are the continuous systematic observation of ice sheet dynamics providing monthly, annual and multi-annual ice velocity maps from Sentinel-1. Advanced high resolution velocity maps from multiple techniques combining InSAR and offset tracking show a big step forward towards the next generation of products but require systematic acquisitions of crossing orbits of SAR.

Combination of S1 C-Band and SAOCOM L-Band InSAR retrievals show the potential of advanced products when L-Band SAR systems (NISAR, ROSE-L) are systematically acquired. Monthly ice discharge calculations for most Greenland outlet glaciers and glaciers of Antarctic Peninsula have been shown, major uncertainties are ice thickness data at the grounding line needed for estimation.

A unique lake ice inventory for Greenland has been derived using optical and SAR data. Unique time series of surface melt phases with daily coverage for Greenland and Antarctica is important for climate warming monitoring. A concept for monitoring the temporal evolution of the surface refreezing depth and demonstration products has been presented using C-Band SAR data, but further developments of the product are needed. Improvements are expected by combining C- and L-Band SAR data.

KEY MESSAGES AND RECOMMENDATIONS

Continuous ice sheet wide data SAR acquisition is essential for continuation and extending the monitoring of ice dynamics and surface properties of Antarctica and Greenland. This means Sentinel-1 C/D all year 6 days coverage with crossing orbits.

In Antarctica there is a strong community request for 6-Day repeat S1 data primarily on the ice sheet margins and ice shelves, and IW mode data is essential.

In Greenland full ice sheet monitoring all around the year is recommended as the melt extent changes regularly and speed change is occurring in the ice sheet interior.

Crossing orbits are needed for advanced ice velocity maps (InSAR combined with offset tracking) and surface melt/refreeze maps and improved grounding line migration monitoring.

Characterization of surface properties (surface melt, and lakes) are important for surface mass balance processes and energy exchange processes.

Damage/crevasse data products are new and exciting, but it is challenging to map these, so these methods need further investment. These parameters show a high potential to be improved by integrating C- and L-Band, so there is the need for support of R&D to prepare for the integration of C- and L-Band SAR data (S1, NISAR, ROSE-L). 3rd party SAR missions (ALOS4, RCM, CSK, TSX, ICEYE, etc.) should densify and fill gaps in the acquisitions of S1/ROSE-L/NISAR for key regions with significant changes. This coordination could be done by reinitiating the WMO Polar Satellite Task Group (PSTG).

Additionally, there is a need to initiate and coordinate acquisition of not-space data sets in Antarctica and Greenland (airborne, ground, ocean based, field campaigns), needed for validation and generation of advanced products. Sufficient and long-term continuous R&D funding for developing and improving the algorithms and error measurements is required, for products in early development stage but even for mature products like ice speed and for improving processing systems for analysing the increasing amount of SAR data from different missions in the future. This is a big data problem and will continue when reprocessing of the EO archives is required.

On a higher level, it is recommended to develop and implement an ambitious and comprehensive network of polar observations for ice and ocean parameters providing basic information for climate change adaptation including EO data, airborne, ship and in situ observations.

6.3
Space-borne studies of permafrost in the Arctic

Chairs:
Tazio Strozzi (Gamma), **Annett Bartsch** (b.geos)

Summary of session presentations and discussion

In the session we discussed the general requirements for ground temperature modelling and validation and presented various results obtained from space-borne studies of permafrost in the Arctic. Six presentations documented the rapid advances in permafrost studies from space, including modelling and in-situ observations. In the discussion we highlighted that validation of the Permafrost_cci Phase II products was successfully completed using international and national monitoring networks.

Major advances and highlights

- Improved accuracy of CCI permafrost products "Ground temperature" and "Active Layer Thickness".
- "Rock glacier velocity" is a new product of ECV permafrost, rock glaciers predominantly accelerate with rise in air/ground temperature.
- Seasonal and multi-year Sentinel-1 subsidence have the potential to deterministically determine subsurface properties.
- Spatially and thematically detailed landcover information at full circumpolar extent provides advance for many permafrost-related applications, including monitoring of thaw impacts and climate model development.
- Climate data records from satellites are potentially of high value for climate models focusing on polar issues, but the high product uncertainties in this region remain an open issue.

KEY MESSAGES AND RECOMMENDATIONS

- Permafrost temperatures are steadily increasing across the Arctic, but uncertainties in estimation need to be reduced.
- Cal/Val super-sites across all permafrost zones (continuous, discontinuous) dedicated to permafrost studies are needed.
- Resume Sentinel-1 IWS acquisitions over Siberia asap (6 days are better than 12 days).
- Consider Arctic permafrost areas as key regions in the planning of acquisitions of future missions (e.g. ROSE-L, NISAR, Harmony, ...).

6.4
A New Era of Polar Observations: The Copernicus Imaging Microwave Radiometer (CIMR) for Polar Ocean, Sea Ice, Snow, Land and Climate Change Monitoring

Chairs:
Emy Alerskans (DMI), **Gunnar Spreen** (U Bremen)

Summary of session presentations and discussion

The Copernicus Imaging Microwave Radiometer – CIMR is one of the six Copernicus expansion missions with a planned launch in 2029. CIMR features a large, 7-meter deployable antenna, which allows to retrieve key ocean, sea ice, and land variables with for a microwave radiometer unprecedented high spatial resolution and accuracy. Based on existing satellite sensors like AMSR2, SMOS and SMAP currently new algorithms for CIMR are developed. This session gave insight into the development of several of such geophysical parameter retrievals and what to expect for CIMR.

Craig Donlon gave a mission overview and status. CIMR is developed to support the EU Arctic Policy and Green Deal. Its design was driven by the requirements set out by the Polar Expert Group. CIMR addresses the complexity of the polar system in all compartments. Especially the high CIMR spatial resolution will allow for new applications and better EO datasets.

One of the primary variables retrieved by CIMR is sea ice concentration (SIC). In the presentation by **Thomas Lavergne** (presented by **Gunnar Spreen**) simulated CIMR data was used to evaluate the SIC capabilities of CIMR. Pan sharpening using the higher frequencies can be used to increase resolution but still maintain high accuracy. New algorithms are needed for CIMR since it is a new instrument. The CIMR L2PAD project develops algorithm prototype for all CIMR products.

Snow on land is a further CIMR target from the cryosphere domain. **Kari Luojus** presents the open-source algorithm development for snow water equivalent (SWE) and terrestrial snow area. A new algorithm using the (lower) CIMR frequencies was developed, which shows high accuracy on test cards representing the expected CIMR measurements. The snow retrievals will work best on flat, non-mountainous regions similar to current missions. Currently SWE is produced daily from SSMI data and CIMR will extend that climate time series. Also soil freeze/thaw state can be retrieved by CIMR. The algorithm was demonstrated with SMOS data. However, the low CIMR RFI will help to improve the accuracy.

Several ocean parameters can be retrieved by CIMR. **Nicolas Reul** presents the examples sea surface salinity (SSS) and wind speed. He highlights the importance of SSS for ocean stratification, dynamics and freshwater distribution. SSS can be retrieved from CIMR's L-band channels and will build on the heritage from SMOS. However, CIMR's much better NEDT will help the accuracy (despite having slightly lower spatial resolution compared to SMOS/SMAP). Main error sources for SSS are 1. wind speed, 2. NEDT and sensor stability, and 3. SST. Accurate knowledge of wind speed under all-weather condition is important for numerical weather prediction and also on its own. For example, polar lows are a threat for shipping and coastal communities. CIMR provides for the first time a unique combination of L-, C-, and X-band with full Stokes parameters.

Sea surface temperature (SST) is the second prime objective of CIMR. **Emy Alerskans** presents the new CIMR SST algorithm. An important advantage of microwave radiometers (MWR) compared to infrared sensors, is their independence of cloud and aerosol influence. Currently the main disadvantage of MWR is the low spatial resolution, which is especially important for coastal regions. With its more than three times better resolution CIMR will improve on that. This improvement is shown for an example in the Baltic Sea, where CIMR shows much improved SST coverage compared to IR and current MWR. The SST performance tested with Picasso test scenes mainly depends on distance to sea ice or land. Further improvements could be achieved by algorithms taking non-linear effects into account, e.g., by using machine learning (in addition to physical (OEM) ones).

Major advances and highlights

- CIMR will provide year-around improved observations of sea ice, ocean, and land variables like ice concentration, thickness, ocean temperature, wind, and snow cover independent of clouds and daylight.
- The higher spatial resolution, better accuracy, and unique channel combination are major advancements compared to current MWR missions.

- CIMR is designed to address key aspects of the EU Arctic Policy and Green Deal.
- CIMR will strongly advance the EU's observational capability for polar regions and worldwide to address near-real time operational applications (shipping, disaster management), numerical weather prediction, and climate monitoring.

KEY MESSAGES AND RECOMMENDATIONS

- CIMR will start a new era for Europe's spaceborne microwave radiometry.
- New algorithms need to be developed and the science community is invited to contribute to that.
- All algorithms are developed as open-source and are open for community input: https://github.com/CIMR-L2PAD and https://github.com/CIMR-Algos

7
NEW METHODS FOR UNDERSTANDING THE POLAR REGIONS

7.1
The Real-World Impact of AI in the polar regions

Chairs:
Pilvi Saarikoski (British Antarctic Survey), **Andreas Stokholm** (Technical University of Denmark)

Summary of session presentations and discussion

There has been an exponential growth in the application of Artificial Intelligence (AI) in the polar regions. AI and ML now form core methodological pillars of modern polar science and offer a growing means to deliver novel scientific insights to stakeholders. This growth has been supported both by algorithmic development, as well as progress in hardware and software capabilities in the last decade. Key to the success of these projects is their engagement with stakeholders that will use the data and products developed. This interdisciplinary session showcased five different projects that have been co-developed with a diverse range of stakeholders, including local communities, ice analysts, ship personnel, and ecologists to increase the impact of the research conducted.

Major advances and highlights

This session highlighted the advancement of the use of AI to detect and forecast sea ice concentration for marine vessel navigation, map rough ice and slush for safe travel by Inuit communities, automatically detect polar bears via thermal cameras to reduce human-bear conflict, calculate benthic species abundance and diversity in Antarctic underwater imagery to guide future sampling regimes, and forecast changes in atmospheric pollution in the Arctic to inform local to regional policy decision making.

KEY MESSAGES AND RECOMMENDATIONS

The key takeaway was that stakeholders need to be centred when designing AI and ML systems for impactful science; AI systems are more impactful when grown "bottom-up" rather than applied "top-down". For example, we heard about the *Sikuttiaq* project, meaning 'good ice', that aims to generate local travel safety maps by using AI to determine ice surface roughness. The success of the project has hinged upon the early involvement of the Inuit community to tap into pre-existing networks working on ice safety, and to identify the outputs required, such as a red-amber-green safety map which provides easily accessible information for all.

A point mentioned in most talks was that AI systems will not and should not replace humans; they should be designed to assist human judgement and provide information to contextualize human decision-making. This point was emphasized when discussing the use of AI to produce regional ice charts. Although the automated nature of the AI algorithms provides great benefit in producing low-latency layers for near real-time use, the remaining errors and uncertainty in the AI outputs, especially at low sea ice concentrations, means these tools can only compliment, rather than replace, human interpretation of satellite imagery of the polar regions. All talks highlighted uncertainty quantification and probabilistic methods as keyways to help build the trustworthiness of AI systems.

An advancement repeatedly mentioned in all talks was the speed at which AI outputs can be produced by a trained model, compared to human interpretation of the data. This is particularly important for developing sea ice charts for in-ice navigation by marine vessel, over ice travel by Inuit and northern communities and detection of polar bears to avoid human-bear conflict.

Some talks highlighted recent developments in the use of AI in data sparse regimes. It was discussed that such systems have improved air quality forecasts in the European Arctic in locations where the density of observation monitoring stations is low, although forecasts remain less accurate than in more heavily populated regions. Models to improve identification of benthic species have also improved, despite the paucity of labelled data to train supervised ML tools. These advancements are particularly noteworthy as low data regimes are commonplace in the polar regions, particularly when analysing parameters not detectable by satellite, due to the remote nature of the region.

Concluding remarks from all the talks as well as the subsequent discussion highlighted several key challenges when applying AI techniques in the polar region. Taking an AI system from proof-of-concept or even from published scientific paper to operational use is nontrivial and requires significant engineering, validation, and refinement. Key to the success of these polar science projects is the availability of long-term, consistent datasets for training, validation, and development. It is essential, therefore, that long-term funding and support is available for such projects, spanning far longer than what most funding schemes currently last for.

Seeing AI as a tool to support humans is a more productive path forward than seeing them as means to replace humans. AI has the power to eliminate repetitive, tedious tasks and free scientists to use their time more effectively in interpretation and analysis. One of the biggest barriers to further adoption of these systems is trustworthiness; experts are wary of model reliability; thus, further validation of model performance and characterization of model uncertainty is necessary to build trust. International collaboration was emphasized as a keyway to address this by ensuring the sharing of data, methodology and infrastructure across borders.

7.2
Machine learning for observing and forecasting sea-ice

Chairs:
Julien Brajard (NERSC), **Matilde Brandt Kreiner** (DMI)

Summary of session presentations and discussion

The session focused on connecting the observation and the dynamical modelling of the sea ice, with a particular emphasis on exploring the potential of AI to achieve this goal. Sea ice observation often requires a complex and resource-intensive processing chain, such as to produce sea ice charts. This processing is not always grounded in physical principles, which can increase uncertainty in the derived products or limit the use of spatial data. This is the case of SAR data, which contains a very rich signal at high resolution, but the inherent ambiguities in the SAR observations has for many years challenged full exploitation of the data. Similar challenges apply to sea ice dynamical models. Their high computational demands restrict their resolution, and they continue to exhibit biases due to processes that are difficult to constrain, such as the sea ice rheology.

In the session's first part, dedicated to observations, **Anja Frost** (DLR) demonstrated how statistical techniques can be effectively applied to estimate sea ice deformation. **Anton Korosov** (NERSC) illustrated how AI can enhance both the computational speed and robustness of ice drift estimates from two successive SAR images. **Tore Wulf** (DMI) presented how AI can accelerate the segmentation process of analysing sea ice in SAR imagery, which is traditionally done manually for ice charts.

The second part of the session, which focused on dynamical models, included **Cyril Palerme's** (MET) presentation on how ice charts can be used to train AI algorithms to correct biases in sea ice concentration forecasts from dynamical models. **Charlotte Durand** (CEREA) demonstrated that these models, which are computationally expensive, can be emulated by AI to improve computational efficiency and enable rapid, efficient data assimilation. Finally, **Andrew MacDonald** (BAS) showed how AI can also be applied to seasonal prediction.

Major advances and highlights

- Traditional statistical, physical, and data assimilation processing methods can be accelerated through the integration of AI techniques.
- AI facilitates the generation of high-resolution outputs that may be difficult to achieve with conventional methods alone.
- AI-based classification can enhance and inform traditional processing techniques, improving their accuracy and efficiency.
- AI enables the integration and fusion of diverse data sources, providing a more comprehensive analysis of sea ice dynamics.
- AI techniques can be applied to quantify uncertainty in retrievals or to manage ensembles of retrievals, improving the robustness of the results.
- Current studies often rely on training datasets that were not specifically designed for the task at hand (e.g., ice charts), limiting their effectiveness.

KEY MESSAGES AND RECOMMENDATIONS

- There is a need for the development of training datasets tailored to push the AI and sea ice community towards new parameters or high(er)-resolution applications. These datasets should be specifically designed for statistical processes, covering extended spatial and temporal ranges, while ensuring efficient accessibility.
- Incorporating physical explainability into AI models can enhance trust. It is particularly recommended to integrate explainability algorithms during the development of machine learning approaches to improve transparency and interpretability.
- The validation of AI algorithms presents significant challenges due to the scarcity of independent datasets and appropriate validation metrics, including high-resolution and in-situ data. The digital transformation of Arctic observation and modelling must be accompanied by efforts to acquire and distribute high-quality observational data.
- AI development requires close collaboration between domain experts and end users to ensure a thorough understanding of the data characteristics and to produce solutions that are practical and relevant to the users' needs.