FIRST EUROPEAN POLAR SCIENCE WEEK

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Organised online by

The **European Space Agency**
and the **European Commission**
(DG Research and Innovation and EASME),
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PREAMBLE

During the high-level opening session, John Bell, European Commission Director, Directorate General Research & Innovation, European Commission, and Josef Aschbacher, ESA Director praised the cooperation between the EC and ESA, in the context of the Earth System Science Arrangement. They confirmed their willingness to advance towards a better coordination and integration of EC and ESA activities in Polar research.

The European Union has been funding a significant number of Polar projects as part of the Framework programmes for Research and Innovation. In 2015, the funding of the EU-PolarNet project was instrumental as it enables stakeholders to coordinate activities across Europe. EU-PolarNet has delivered a number of key outputs among which the Integrated European Research Programme (EPRP). This report is the result of a process involving many players identifying key research and knowledge gaps, feeding into European Commission's policy making. The launch of the new EU-PolarNet 2 project during the conference showed the willingness of the EU to sustain these coordination efforts. EU-PolarNet 2 will play a key role to reinforce the science to policy interface and to increase coordination of polar research activities at European level, with a better understanding of what is done at national level. EU-PolarNet 2 will also lead the coordination of the EU Polar Cluster in close cooperation with the ESA Polar activities.

The EU Polar Cluster, launched in 2016, has been extending in terms of number of projects (21 projects and 2 initiatives) and it confirmed its objective to reinforce cooperation across projects on a number of areas of common interest. Transnational cooperation of all involved actors (researchers and stakeholders) and European-wide coordination of Polar research efforts are decisively important, particularly in tackling major societal challenges such as climate change.

Scientific knowledge has to be appropriately disseminated to inform policymakers with a high level of expertise and to support evidence-based policy making.

The projects from the ESA Polar Cluster confirmed the need to work closer with the EU funded projects. This is fully supported by ESA, which launched a call for tender to facilitate innovative scientific developments through collaborative research and networking opportunities in the Polar research domain and in particular between the ESA and EU Polar Clusters.

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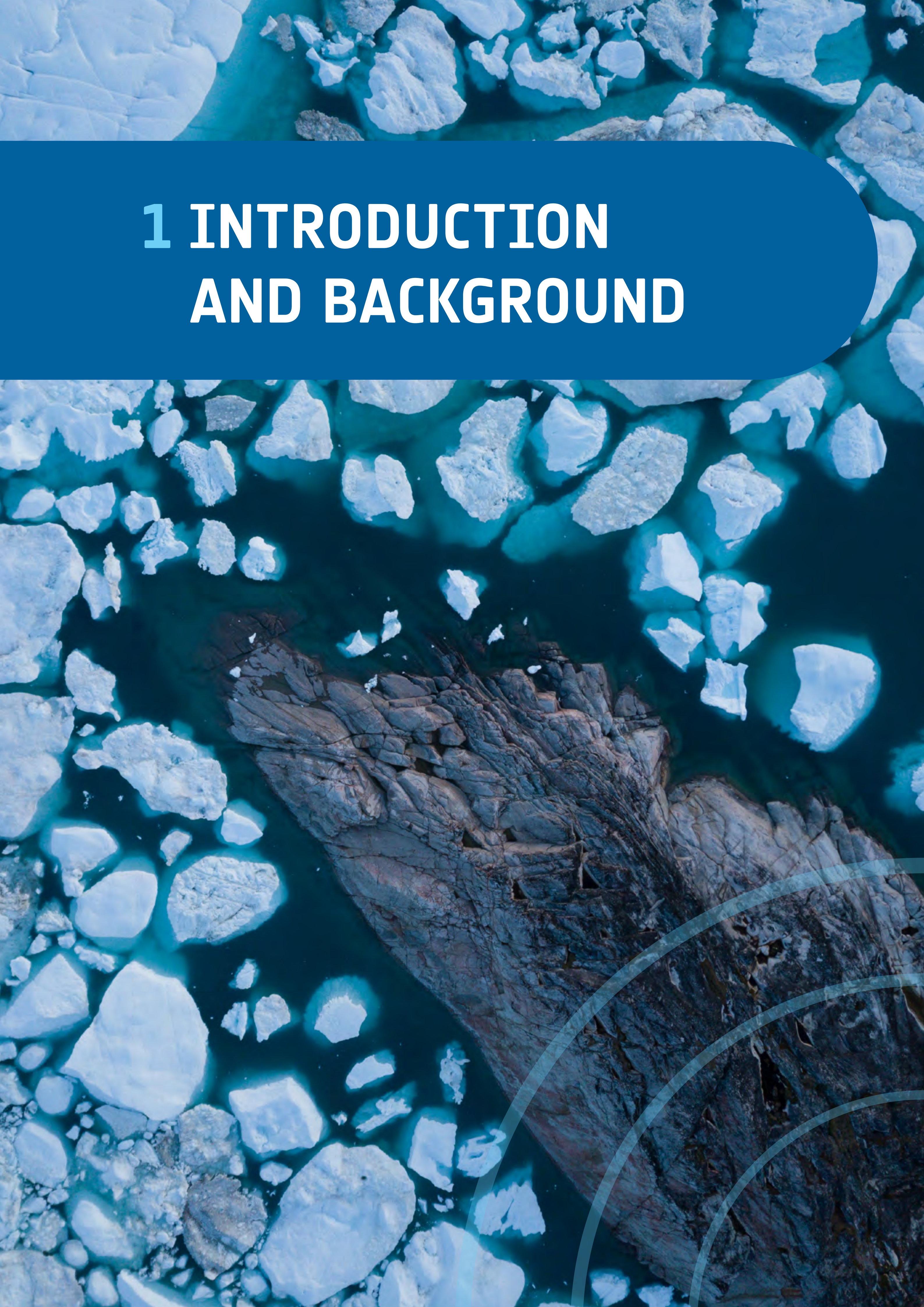
1 INTRODUCTION AND BACKGROUND



The European Polar Science Week was organised by the European Commission together with the European Space Agency with support from EASME and EU-PolarNet 2. This first European Polar Science event, part of a new ESA-EC joint Earth System Science initiative, was aimed at fostering closer collaboration and networking across the EU and ESA Polar activities.

The overall objective of the European Polar Science Week was to bring together the European Polar science community, EC and ESA project teams, stakeholders and key scientists worldwide to discuss the major challenges and opportunities in front of us, promote networking and collaboration across projects and activities.

More than 1350 Polar stakeholders from more than 50 countries gathered virtually to enhance cooperation at European level and set common challenges and priorities.

The event featured the launch of the new EU-PolarNet 2, a Horizon 2020 funded project aiming to improve coordination between EU polar research institutions, building on existing networks and providing a platform to co-create and co-design European polar research actions with all relevant stakeholders.

The EU Polar Cluster - consisting of European Polar Board and Svalbard Integrated Arctic Earth Observing System and 21 Horizon 2020 Polar projects was presented together with the ESA Polar Science Cluster. The Polar Clusters aims at optimising synergies across projects and maximising their impacts on society.

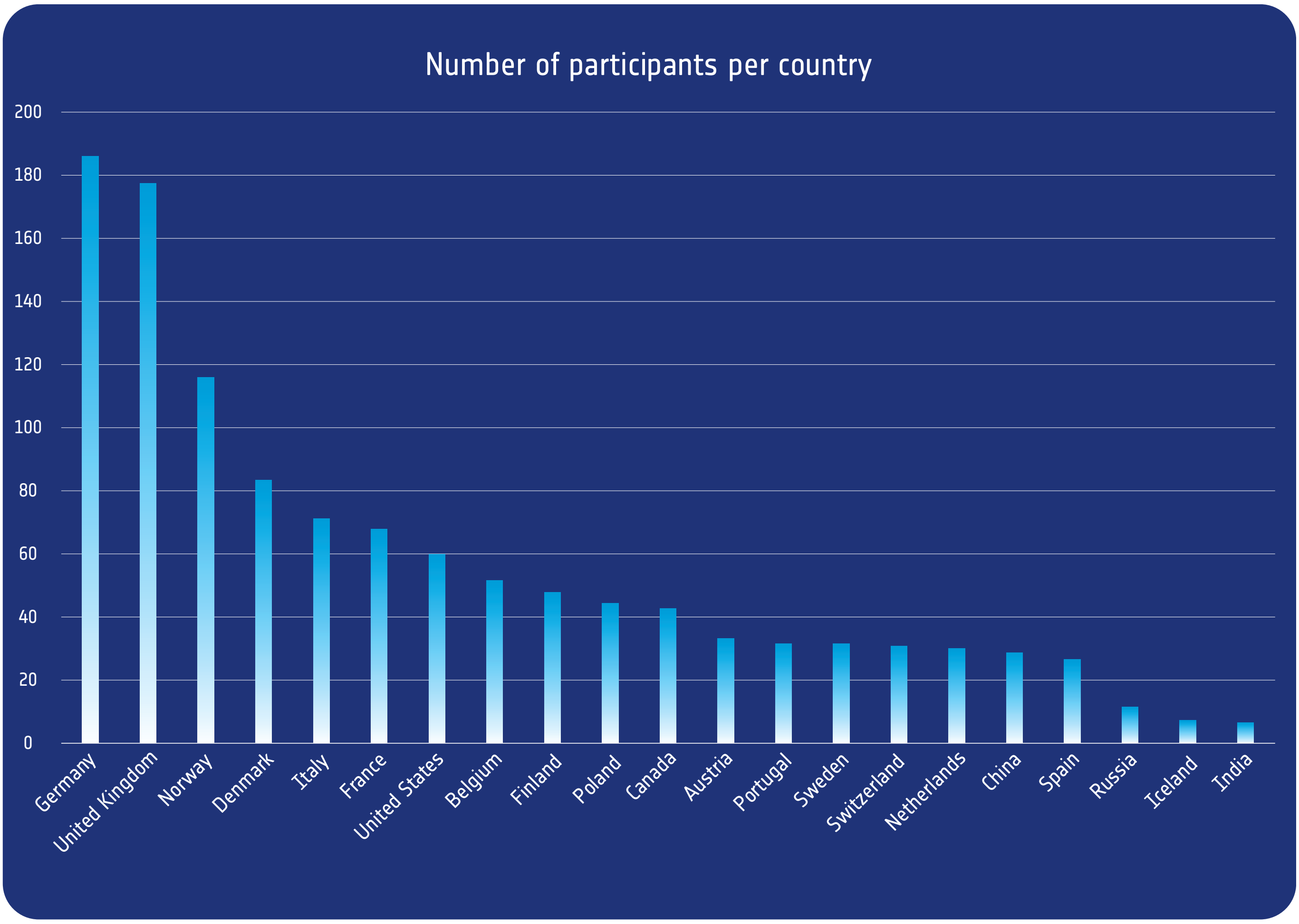
The European Polar Science Week will help consolidate the EU contribution to the coming 3rd Arctic Science Ministerial[1] (8-9 May 2021, Tokyo), and will also contribute to the new Joint communication on the Arctic and northern dimension policy, to be adopted in October 2021[2].

[1] The Arctic Science Ministerial meetings are intergovernmental events, hosted on a biannual basis, by countries with an interest in Arctic research. This third meeting (planned for 8-9 May 2021, taking place in Tokyo, Japan), hosted by Japan and Iceland, aims to further strengthen Arctic research cooperation, to respond to major societal and global warming challenges.

[2] https://ec.europa.eu/fisheries/press/summary-public-consultation-way-forward-european-union%E2%80%99s-arctic-policy_en

The specific goals of the European Polar Science Week were to:

1. Kick-off the EC-ESA Flagship Action on Polar Regions;
2. Kick-off the EU-PolarNet 2 - coordinating and co-designing the European Polar Research Area – EC funded project which will coordinate the European Polar Research and provide a platform to jointly develop European polar research actions;
3. Introduce the EU Polar Cluster and the ESA Polar Cluster to establish a coordinated EC-ESA European Polar Cluster - promoting and fostering closer collaboration and networking across the EU and ESA Polar activities;
4. Inspire a future Common Science Agenda for future ESA-EC joint activities and a more effective and coordinated European Polar Science Programme.



2 OPENING SESSIONS

2.1 WELCOME SESSION

Welcome Session

The opening session of the European Polar science Week was moderated by Nicole Biebow, Head of International Cooperation Unit at Alfred Wegener Institute from Germany.

Five key-notes were provided as part of this session:

John Bell, Director, European Commission, DG Research and Innovation

Josef Aschbacher, Director ESA EO Programmes

Michael Mann, EU's Special Envoy for the Arctic

Michael Meredith, Science leader at BAS

Stefanie Arndt, Sea-ice physicist at AWI

Here is a summary of the main messages provided by the keynote speakers:

John Bell, Director, European Commission, Directorate General Research and Innovation

- DG Research and Innovation and the European Space Agency signed an Earth System Science Initiative, in early 2020. Polar regions are central to this initiative and for the overall understanding of climate change dynamics, and for developing resilience, adaptation and mitigation measures.
- The European Union developed an action plan to fight climate change within planetary boundaries – the European Green Deal, aiming to make Europe the first climate neutral continent by 2050, proposing a European Climate Law to turn this political commitment into a legal obligation. Science and research are central to the Green Deal becoming a success.
- The last call of the Horizon 2020 Programme was a European Green Deal call – it mobilized close to 1 billion € to encourage innovative solutions to respond to the climate crisis and help protect Europe's unique ecosystems and biodiversity.
- On science diplomacy, the Commission has been building a successful All Atlantic Research Alliance (involving the Galway and Belem Statements on North and South Atlantic Ocean research cooperation). The intention is to build a Pole to Pole research community, and to include Polar research in the All Atlantic conversations more often.
- Horizon Europe, the new Framework Programme for Research and Innovation (2021-2027) –will continue to support Polar research and to help drive the blue and green transitions. The Programme introduces five missions - commitments to solve some of the greatest challenges facing our world like fighting cancer, adapting to climate change, protecting our oceans, living in greener cities and ensuring soil health and food.
- A climate resilient Europe mission will help prepare Europe to deal with climate disruptions, accelerate the transition to a healthy and prosperous future within safe planetary boundaries and scale up solutions for resilience that will trigger transformations in society, while the Ocean mission will help with cleaning marine and fresh waters, restoring degraded ecosystems and habitats, decarbonising the blue economy.

Josef Aschbacher, Director ESA EO Programmes

- The EC-RTD / ESA Joint Initiative on Earth System Science is a very important step in the collaboration we have together. We are successfully working together since a decade and the Polar Flagship is really one of the highlights in the cooperation.

- ESA has 15 satellites in operation, 40 under development, and 13 under preparation. Many of these satellites will contribute significantly to monitoring the Polar environments.
- Linking data and earth system models, together with the element of AI is becoming more and more important. Together with other European partners, we would like to put a system together, called Digital Twin Earth. This system would be able to simulate future "what if" scenarios that would help scientists and decision makers predict the future state of the planet.

Michael Mann, EU's Special Envoy for the Arctic

- The European Union has had an Arctic Policy since 2008 – the most recent Communication on the Arctic was issued in 2016. The Communication has three priority areas: climate change and protecting the environment; sustainable development and international cooperation.
- Climate change – and its potentially disastrous effects – represents the biggest security threat that we face In the Arctic. Hence Polar research and science are extremely important to help find solutions to these challenges.
- Science is also an effective tool for international diplomacy in the Arctic, and the Union has supported building some amazing international research networks, putting Europe in the forefront of Polar research. Indigenous peoples from the Arctic possess vital knowledge of these unique eco-systems, and indigenous knowledge and cooperation with indigenous people in the field of research needs to be taken seriously into account as well.
- The EU's Arctic policy is being updated at the moment, and scientific research will continue to play a major role in this context. A public consultation was held between July and November 2020 – the results are shared on the Commission's website [3].

Michael Meredith, Science Leader at BAS

- Climate induced changes in the ocean and cryosphere are having significant impact both locally and globally - every place and person is affected
- Across very many aspects, the ocean and atmosphere of the future will appear significantly different from those of today
- Choices are available that will influence the nature and magnitude of changes potentially limiting their impacts and increasing the effectiveness of adaptation actions.

Stefanie Arndt, Sea-ice physicist at AWI

- Snow on sea-ice controls the heat exchange between sea-ice and atmosphere and needs to be investigated in more detail in the Arctic and Antarctic because a lot of uncertainties still exist. Using satellite remote sensing sensors with different signal frequencies might allow us to describe processes in different snow layers.
- The MOSAiC expedition was a unique possibility to study the Arctic climate system across a full year. A distributed regional network of observational sites was set up on the sea ice in an area of up to ~50 km distance from RV Polarstern. The ship and the surrounding network drifted with the natural ice drift across the polar cap towards the Atlantic in 300 days, which is much faster than expected before.

[3] https://ec.europa.eu/fisheries/press/summary-public-consultation-way-forward-european-union%E2%80%99s-arctic-policy_en

2.2 EU- POLARNET-2

Summary

EU-PolarNet 2 – “Coordinating and co-designing the European Polar Research Area” is a coordination and support action which has been implemented to better coordinate European Polar Research and to support the European Commission in all their actions affecting the Polar Regions. EU-PolarNet 2 is a successor of EU-PolarNet 1 and will build on its achievements. EU-PolarNet 1 has established an on-going dialogue between policymakers, business and industry leaders, local communities and scientists to increase mutual understanding and identify new ways of working that will deliver economic and societal benefits. The results of this dialogue have been brought together in an Integrated European Research Programme (EPRP) co-designed with all relevant stakeholders and coordinated with the activities of polar research nations beyond Europe. The EPRP is accompanied by an implementation plan which provides an important assessment of the needs, as well as a set of key recommendations for addressing existing and forthcoming scientific and logistical needs, in alignment with the EC Green Deal and UN SDGs. EU-PolarNet 2 will maintain the vast network which has been brought together in EU-PolarNet 1 and will build on its results. EU-PolarNet 2 will bring this work to a higher level by going several steps further to develop and work towards the implementation of a European Polar Research Area. The project will provide a platform to further develop the coordination of Polar research actions in Europe and with overseas partners. By involving all relevant stake- and rightholders it will support the development of transdisciplinary and transnational Polar research actions of high societal relevance. These will contribute new knowledge to the international protocols to which the EC has committed, and enable EU-PolarNet 2 to provide evidence-based advice with impact on policy making. To ensure that such an important platform is sustained after the four years of project duration, the project will work with national and international funding agencies to implement the identified research actions. The final goal of the project is to create a permanent European Polar Coordination Office which will continue the work of EU-PolarNet 2 in a sustained way.

Session objectives

The EU-PolarNet 2 kick-off meeting took place just after the opening session of the European Polar Science Week. The meeting was divided into a public kick-off part for all conference participants and a closed general assembly for EU-PolarNet 2 partners and guests only. The open kick-off meeting showcased the transition from EU-PolarNet 1 to EU-PolarNet 2 and informed about the future plans of EU-PolarNet 2 to motivate the European Polar community to engage in the project. The six presentations gave an overview about the achievements of EU-PolarNet 1, which are the backbone of the work to be performed in EU-PolarNet 2. EU-PolarNet 2 strives to provide a coordination platform to co-develop strategies to advance the European Polar Research action and its contribution to the policy-making processes. It will operate as such a platform for the 4-years of the project`s lifetime. Once EU-PolarNet 2 ends, the gained experience, the established network and the developed tools to facilitate better coordination and co-design of Polar research actions will be transferred to a European Polar Coordination Office. The EU-PolarNet 2 consortium consists of 25 partners representing all European and associated countries with Polar research programmes and activities. This allows EU-PolarNet 2 to significantly improve the coordination and co-design of European Polar research actions but also to provide evidence-based advice on behalf of the whole European Polar community. The conclusion of the meeting highlighted that EU-PolarNet 1 was an exciting endeavour and all the partners are looking forward to the work of EU-PolarNet 2, which can make a game change in developing a European Polar Research Area.

Key messages

European-funded researchers have made significant contributions to understanding the consequences of climate change and the structure and functioning of ecosystems at both Polar Regions, and their global interconnections. Coordinating and disseminating all those actions plays a key role in the generation of knowledge with relevance for society, economy, environment and policy making.

EU-PolarNet has involved and will involve all interested European and international researchers and stakeholders in all its activities. All strategic research planning documents and the different white papers of EU-PolarNet have been developed jointly by European scientists and stakeholders. Especially the development process of the European Polar Research Programme (EPRP) revealed how important it is to exchange and interact with the stake-and right-holders when it comes to defining research priorities which are directly relevant and beneficial to society. Judging from the few communication events that have already been organised to present the EPRP to polar stakeholders, one can anticipate that the potential of the EPRP in terms of providing answers to current society needs and expectations can be very high. The actual impact of the EPRP will of course depend on the European capacity to implement the EPRP which EU-PolarNet 2 aims to facilitate.

The EC and other decision-makers critically need better evidence-based information on the ongoing changes affecting the Polar Regions, and their feedback to global and regional processes. Informed policy advice as performed in EU-PolarNet allowed them to identify and support relevant research themes, and to develop and implement effective policies in response. EU-PolarNet`s cooperation with the EC has proven instrumental for the implementation of the latter's research agenda related to the Polar Regions.

KEY RECOMMENDATION

- Transnational cooperation of all involved actors (researchers and stakeholders) and European-wide coordination of Polar research efforts are decisively important, particularly in tackling major societal challenges such as climate change.
- Scientific knowledge has to be appropriately disseminated to inform policymakers with a high level of expertise and to support evidence-based policy making.
- A sustained and stable platform for European Polar Research coordination with tangible long-term benefits for the EC and national European Polar research communities should be implemented since the European Polar community and also national funding agencies and the EC will benefit from improved European alignment, coordination, interaction and collaboration in Polar research

2.3 EU POLAR CLUSTER PROJECTS

Summary

The EU Polar Cluster is a network of Horizon 2020 funded polar projects. Currently it comprises 21 projects: APPLICATE, ARCSAR, ARICE, ArcticHubs, Beyond EPICA, BLUE-ACTION, CAPARDUS, CHARTER, ECOTIP, EU-PolarNet, FACE-IT, FORCeS, iCUPE, INTAROS, INTERACT, JUSTNORTH, KEPLER, FORCES, SO-CHIC, TiPACCs and NUNATARYUK. Also, the Svalbard Integrated Arctic Earth Observing System (SIOS) and the European Polar Board (EPB) are partners. The cluster merges a broad spectrum of research and coordination activities – ranging from the most up-to-date findings on permafrost and sea ice, from enhancing observation to improving predictions, and from networking research stations to coordinating access to icebreakers.

The EU-Polar Cluster has established five task groups (Communication, Stakeholder Engagement, Data Management, Education and Policy Advice in which the different projects are working closely together, exchanging experience and performing joint actions. The aim of the EU Polar Cluster is Scientific to appropriately disseminate the knowledge gathered in the EU funded projects and to inform policymakers with a high level of expertise to support evidence-based policy making.

The EU Polar Cluster Annual Meeting took place online during the 2020 European Polar Science Week and all the projects of the Cluster participated. The meeting was divided into a public part for all conference participants and the closed annual session for Cluster members and guests only. The public part of the meeting was directed to showcase the EU Polar Cluster projects achievements and future outcomes. The first session of the public part highlighted the results of different projects with common goals towards relevant topics in polar research. The following public session aimed at presenting the objectives and current activities of the EU Polar Cluster and introducing the ESA Polar Science Cluster. It included presentations from the new projects, in an elevator pitch format, discussing their objectives and future outcomes. In addition, The EU Polar Cluster is seizing the EC initiative Horizon Results Booster Service to make the Cluster more cohesive and increase its impact. This service includes community building, social media, web and graphic design, web hosting and maintenance, copyrighting, events management and custom software development.

Session objectives

The overarching objective of the EU Polar Cluster`s sessions was to bring the insights from our various areas of expertise together in order to showcase the commonalities among the EU funded Polar research actors. Jointly, the Cluster projects presented all the many facets that they are bringing to Europe aiming at providing policy-relevant and scientific information, and supporting the EU in disseminating the outcomes of a long-standing funding effort towards:

- Fostering international cooperation,
- Reporting on the impacts of climate change on the Poplar's fragile environment
- Promoting sustainable development and in cooperating with policy-makers, Indigenous peoples and local communities, business and NGO`s representatives and other societal actors.

Summary of key messages

The EU Polar Cluster member projects aim at creating synergies between their already planned activities to maximise their impact and to avoid duplicating the efforts.

Closer cooperation has led to increased knowledge sharing and to developing joint activities within the five Cluster task groups. The EU Polar Cluster will also maintain the legacies of the finalised projects.

EU-PolarNet 2 has officially taken over the coordination of the EU Polar Cluster. It will secure the advancement and coordination of the current initiatives and identify synergies between the member projects.

The EU Polar Cluster brings added-values to the member projects and the European polar research area that comes from a better collaboration of the different projects and the expertise from all of them by improving the outputs and upscaling the efforts of the member projects alone. All these realities are grounded on the pillars of knowledge-sharing aiming at maximising the engagement with the polar stake- and right-holder groups and, in the long run, serving as a platform for future research initiatives.

SUMMARY OF RECOMMENDATIONS

Three key messages came out of the sessions:

- Polar Regions are crucial to the global climate dynamics and we Europeans are facing unprecedented socio-ecological changes. There is a need for a unifying polar framework for studying and managing climate-driven rates of socio-ecological change.
- The improved coordination on scientific initiatives during the next ten years are crucial to the understanding of the Polar Regions. It means that scientific output will leverage an impact that should not be lost to improve the Polar Regions knowledge and citizens` welfare.
- The European polar research community with the support of EC and ESA is pooling together first-class scientific resources and polar research infrastructures to keep the momentum and maximise any of the on-going and future scientific outcomes. Here the dialogue between the ESA Science Polar Cluster and the EU Polar Cluster will serve as a cornerstone tool to capitalize on already existing resources and the design of the future ones.

2.4 ESA POLAR SCIENCE CLUSTER PROJECTS

Summary

ESA's Polar Science Cluster initiative involves a wide range of activities and projects covering some of the major science questions and societal challenges associated with the dramatic changes affecting polar regions and its global impacts. Addressing these challenges will require a significant collaborative effort and an integrated approach to science where the synergistic use of EO satellite data, in-situ and citizen observations, advanced modelling capabilities, interdisciplinary research and new technologies will be essential elements.

The ESA Polar Science Cluster aims at contributing to this objective, promoting networking, collaborative research, and fostering international collaboration. It involves different ESA funded projects and activities bringing together different expertise, data and resources in a synergistic manner ensuring that the final result may be bigger than the sum of the parts.

With this approach ESA wants to contribute to establish a stronger European Polar research area in close collaboration with the European Commission Directorate General for Research and Innovation and other European and international partners.

Information about the ESA Polar Science Cluster projects presented can be found at https://eo4society.esa.int/projects/?tags=polar

Session objectives

1. Presentation of some of the ESA Polar Science Cluster projects;
2. A roundtable discussion on how to better coordinate European Polar research actions, specially ESA and EC Polar science activities,
3. Collect recommendation to advance towards coordinated and ambitious European approach to address the most urgent science challenges in Polar science.

SUMMARY OF RECOMMENDATIONS

Several challenges in Polar science would need to be addressed in the coming next 5-10 years. This includes a large range of urgent issues: e.g.,

- Understanding the carbon and water cycle in the Arctic is very important. That involves observing ice, snow, permafrost, seasonal frost and how they are interlinked with different processes releasing carbon into the atmosphere. And the flux of freshwater into the Arctic oceans and the effect of that, locally and globally;
- There is a knowledge gap regarding fundamental baseline datasets for Antarctica in order to estimate the evolution of the ice sheet and mass balance. There are also big holes in the understanding of the fundamental geophysics and geodynamics for the ice sheet. Major international efforts are required to implement Antarctica projects and campaigns, exploiting the already existing national science and field stations;
- There is co-variability in the Polar components of the Earth systems, but they are poorly understood. This is an area where machine learning could play a role to better understand the processes and feedback mechanisms. One example is the co-variability between sea-ice variability and the upper ocean below. This cannot be parameterized in models today;

- There is a need for improved modelling capabilities to provide scenarios for the next 50-100 year;

Observations represent a major element to ensure advances in Polar science and its downstream applications:

- There is a lack of availability and access to in-situ data in Arctic and Antarctic regions;
- In addition, combination of satellite data and in-situ observations is crucial and should be reinforce;
- In the years to come new satellite missions will provide completely new opportunities for enlarging the scope of our observation capacity in the Arctic. As an example, ESA's Earthcare satellite can be used for monitoring solid precipitation. In addition, the coming candidate Sentinel mission will actually provide a significant step further in terms of new capabilities. It is important that we prepare for the advent of these wide set of novel observations.
- Lessons should be learned from the Cryosat/Icesat experiment in terms of considering both synergistic and collaborative approaches to observer key processes and new satellite constellations.
- We are looking at a system that is changing faster than we can understand it. That is why the European Polar Research Program promotes a Polar Observing decade, to study the ocean, the atmosphere, the ice, the ecosystems, glaciers, to increase the observation capacity.

To achieve the above objectives, it is fundamental athat we advance in the way we coordinate European Polar research actions, specially ESA and EC Polar science activities. This may include:

- Joint conferences like this one is very important and should be repeated, maybe bi-annually;
- Jointly funded projects are preferred, but if not possible, at least the projects should be aligned;
- EU should fund projects that for sure cannot be done from space, like the deep drilling project in Antarctica;
- Funding is lacking for long term in-situ monitoring, since these are expensive in the northern areas and are needed to support the space-based observations;
- Acoustic tomography for the Arctic Ocean should be further explored. An array of real time cabled acoustic tomography systems would provide new measurements that could help resolve current data observing gaps in the Arctic Ocean;
- In terms of making sure that field data is released to the wider scientific community, one could learn from the NASA Icebridge program. In this program, all data was released and made open after 6 months, and this is an example that could be followed.
- Polar science needs to be better communicated to target audiences including citizens and politicians, to make sure they understand the rate at which the planet is changing;

3 SCIENCE SESSIONS

3.1 ICE SHEETS 1 - GEOPHYSICS & PROCESSES

This session aimed at reviewing the major outstanding science questions in ice sheet research. In particular, the discussion followed five seed questions:

1. What is the next frontier of monitoring the ice sheets and understanding the processes driving change?
2. Do EO satellites provide adequate coverage of land ice in the polar regions at present? Are there observational gaps, or new types of measurements required?
3. Are satellite observations properly validated? Regions not covered, what are the greatest uncertainties?
4. What are the unsolved major science questions in glaciology that can now be addressed? Are there interesting new science projects that should be started now
5. What new collaborations would benefit EO science?

MAIN FINDINGS AND RECOMMENDATIONS

Ice sheet dynamics involve a large range of complex processes and interactions that require urgent attention: e.g.,

- We are only starting to fully understand and connect the different processes involved in better characterizing ice sheet dynamics. Activities such as 4DGreenland and 4DAntractica should continue and expanded. Especially it is fundamental to further connect the EO and modelling communities.
- Surface mass balance needs to be constrained better. It's hard to observe using EO data but microwave radar and field measurements can be used. Ocean change is a key driver of ice loss on the Antarctic ice sheet. In-fact, ice dynamics account for almost 100% of ice loss in Antarctica. There are currently ESA projects measuring changes on the ice sheet and ice shelves, but no funded project that brings together the ocean and glaciology communities together to better understand the processes driving this change. We recommend that ESA initiate a project to use EO data to tackle this important gap in our scientific knowledge.
- On ice shelf collapse, hydro fracture is an atmospherically driven process that is also not fully understood.
- Projects investigating ocean primary productivity, and how this is driven by nutritious freshwater input to the oceans from the ice sheet, hasn't been examined using Earth Observation data. Great EO datasets exist to tackle these questions, but as far as we are aware there are no projects looking at this. It has knock on implications for understanding wild life and ecosystems in the Polar regions.

EO satellite data coverage of the ice sheets is magnificent today in comparison with the historical record. But there are still many unresolved processes that are not properly captured today. Dedicated efforts are needed to further expand our observation capacity over polar regions including the following elements:

- As ESA and EU continues to expand SAR data spatial coverage, and reduce the temporal baseline between repeat observations, it allows us to study entirely new physical mechanisms that haven't been observed before (e.g. weekly changes in calving front position and ice speed).
- We recommend early launch of Sentinel-1c, as if placed in a short repeat orbit with the S1a and S1b platforms (i.e. a 0 (SPiNSAR in pursuit monostatic setup) or 1 -day repeat maximum), it will enable InSAR capability in regions of persistent incoherence due to very fast flowing ice. For example, 1 day repeat S1 SAR images would enable the grounding line location to be measured in the Amundsen Sea Sector of West Antarctica, for the first time since the final days of ERS-2 operation in 2011. SPInSAR would allow to monitor ice volume changes in complex areas of Peninsula with high resolution.
- CryoSat-2 has exceeded its original mission objectives and has outlived its intended mission lifetime. This data is essential for extending the 30-year long record of ice sheet elevation change, mass loss, and ice shelf thickness change and basal melt. When CryoSat-2 dies, as it sadly will, it will leave a well-documented gap in the record. We recommend ESA take practical action to minimise the gap in the satellite radar altimetry record, by for example prioritising the early launch of the CRISTAL HPCM mission.
- Sentinel-3 coverage of small outlet glaciers need to be improved. Swath mode processing of CryoSat-2 SARIn data is essential.
- To apply IOM for estimating mass budget ice thickness at grounding line is needed. This is often known with high uncertainty only. Airborne measurements of the ice thickness (or bedrock elevation) are grounding line are required.
- Uncertainty sources need to be properly quantified for all measurements. In particular surface elevation change, mass balance, ice flux and sea level rise are a particular priority. Need to have reliable projections in order to develop appropriate adaptation and mitigation strategies.
- The EO record is short in East Antarctica where historical coverage is particularly poor.

That to latest advances in EO research we are now able to measure ice sheet mass balance using a variety of techniques. The errors on these measurements have been significantly constrained by projects like IMBIE. However, IMBIE doesn't tell us is why mass balance is changing in different regions of the ice sheets, and it doesn't explain what physical mechanisms are driving this change (e.g. atmosphere or ocean). In this context:

- We support a future iteration of IMBIE that performs an intercomparison of mass balance estimates at the basin scale, rather than at the ice sheet wide scale. Some techniques are spatially limited, particularly historically (e.g. IOM). While there are tens of groups producing mass balance estimates using some techniques (e.g. gravimetry), there are other techniques that only have one or very few estimates. We recommend providing additional funding to grow the communities of scientists that are expert in the severely under-represented techniques (e.g. IOM).
- We recommend projects are funded to understand the processes driving mass loss. This will enable these mechanisms to be better represented in our ice sheet models, which will in turn improve the accuracy of future sea level rise predictions. (e.g. ice ocean interactions; short term surface mass variability; the importance of ice damage (i.e. crevassing)).

Finally, it is important to stress the fact that none of the above recommendations can be achieved without the proper collaboration mechanisms. Therefore, we strongly recommend that further efforts are dedicated to:

- Bring together the glaciology and oceanography communities on dedicated funded projects.
- Develop a mechanism for allowing ESA project teams to collaborate internationally with non-ESA member states (e.g. Dragon but for other countries), and national projects in individual ESA member states.
- Lining the ESA and EC communities is extremely scientifically valuable. Unfortunately, the UK is going through Brexit, but as an important scientific partner on many ESA and EC projects, a mechanism for continuing scientific collaborations even in the face of political change is essential. Our knowledge about the way the Earth's environment is changing will be poorer without continued collaboration, and ESA and the EC can be important brokers in facilitating the change in this relationship and strengthening it for the future.

3.2 ICE SHEETS 2 - NOVEL MISSIONS, METHODS & PRODUCTS

The objective of the Novel Missions, Methods & Products session was to provide a forward look towards the new streams of data that will confront us over the next 5-10 years, and the methods that shall be needed to fully exploit their information potential. The fundamental problem that this session aimed to address was twofold; (1) How does the community need to adapt to fully transition into a new era of big, heterogeneous data, and (2) What support is required within Europe to drive this adaptation, and to catalyze the greater collaboration between communities that it will entail.

In particular, three key messages came out of the session:

- Long term continuity of land and sea ice thickness observations up to 88 N/S is essential for securing both the long-term climate record and future climate services. The HPCM CRISTAL is key to this process and needs to be launched as soon as possible, in order to avoid a critical and highly negative hiatus in observational capability; as Sentinel-3 only covers up to 81.5 N/S. The CryoSat-2 mission is now extended to 2022 but considering the status of the mission, its lifetime beyond that is uncertain. If selected, the launch of CRISTAL is currently planned only for 2027-2028, leaving a critical gap if no mitigation is put in place. This needs to be addressed with urgency.
- The massive increase in data volumes that is currently underway requires more investment in informatics and data science expertise. This requires dedicated training and resources in order to attract experts in statistical and computer science techniques (e.g. Machine Learning, Deep Learning) to work on Polar challenges. Alongside this, there is also a need for investment in standardized toolkits and platforms to support non-expert users (e.g. cloud computing infrastructure).
- More dedicated activities are needed to improve uncertainty estimation for Polar EO measurements and EO-derived products, as the uncertainties in polar regions are often more poorly constrained than at mid-latitudes. Closer collaboration with modelling communities is needed in order to co-design approaches; to make sure that uncertainties are fit for modelling purposes and are well understood. Estimating uncertainty in EO measurements themselves requires dedicated activities to develop robust methods; including collaborative activities with the metrology community. It also requires greater investment in long term fiducial reference measurements; both ground-based and airborne campaigns.

SUMMARY OF RECOMMENDATIONS

Four key recommendations came out of the session:

- The looming gap in land and sea ice thickness observations in the polar regions needs to be addressed with urgency.
- Greater emphasis and investment should be made to support the use of data science techniques in EO. There is currently massive investment in polar observation, which is yielding unprecedented volumes of data, but this needs to be accompanied by investment in data science skills and studies; otherwise the full information content of these data will not be utilized to their complete potential. As one example, there is great opportunities to combine multiple complementary datasets, such as radar altimetry and super high resolution DEM's within machine learning frameworks, to yield a step change in technical and scientific understanding of Polar EO. Funding Agencies should therefore consider more dedicated calls that target the "development" and application of data science techniques (e.g. Machine Learning, Deep Learning) to polar EO data. These should be ambitious, and encourage the development of new statistical approaches through a co-design approach with data science and EO specialists, rather than merely applying pre-existing off-the-shelf data science methods.
- More support is required to characterize and constrain uncertainty in EO measurements. This requires the bringing together of multiple communities (e.g. metrology, Polar EO, field specialists), and should be encouraged through a combination of more field-based campaigns and methodological innovation (e.g. dedicated activities to integrate metrology and statistical approaches to uncertainty estimation).
- There is a need to support greater collaboration between the EO and modelling communities. For example, by developing closer ties between EO specialists and Surface Mass Balance modelers, and between EO experts and ice dynamic modelers. This should include experiment co-design, uncertainty characterisation, inter-comparison and dedicated data assimilation activities.

3.3 ICE SHEETS 3 - ESA-NASA IMBIE

Ice loses from Greenland and Antarctica represent a significant contribution to the global sea level rise. The ice sheet mass balance inter-comparison exercise (IMBIE) was established in 2011 as a community effort to reconcile satellite measurements of ice sheet mass balance. IMBIE is an international collaboration between scientists, supported by ESA and NASA, primarily as a contribution to IPCC assessment reports but also to provide critical information on global sea levels for a wide range of stakeholders. IMBIE has led to improved confidence in estimates of the sea level contribution due to the polar ice sheets and has established a lasting framework for repeated community assessments. IMBIE has shown that Greenland and Antarctica are losing ice faster than in the 1990s and are both tracking the Intergovernmental Panel on Climate Change's worst-case climate warming scenarios. Overall, Greenland and Antarctica lost 6.4 trillion tonnes of ice between 1992 and 2017 – pushing global sea levels up by 17.8 millimetres. The combined rate of ice loss has risen by a factor six in just three decades, up from 81 billion tonnes per year in the 1990s to 475 billion tonnes per year in the 2010s. This means that the polar ice sheets are now responsible for a third of all sea level rise.

The first IMBIE assessment involved 47 authors from 8 countries and was reported in 2012 (1). The paper went on to become the most rapidly cited article on Antarctica and Greenland of all time, with over 130 citations per year and 17,000 accesses per year. The second IMBIE assessment involves 97 authors from 13 countries and has been split into individual reports on Antarctica and Greenland. The Antarctica assessment was published in summer 2018 (3) and the Greenland assessment was reported in Spring 2019 (4), and the two papers have together attracted over 150 citations per year and 17,000 accesses per year since they were published. The Antarctic assessment was the 4th highest ranking climate science story of 2018. The project results have featured prominently in IPCC reports, including the Fifth Assessment Report and the Special Report on Oceans and Cryosphere, and will be included in the upcoming Sixth Assessment Report. They have also been used to underpin assessments of IPCC sea level projections and their skill (2,5,6). The project results have been widely reported in the media including in 718 global news articles, in 123 blog posts, and in tweets to 19.3 million followers, and it is now the subject of its own Wikipedia page and referenced in 5 others. The project results have also had broader impact, featuring in 7 international policy documents and as indicators of climate change by the European Environment Agency and by the US Environmental Protection Agency.

IMBIE-3 begins in 2021, and the objective is to deliver annual assessments of ice sheet mass balance. The project will also make use of measurements from new satellite missions including GRACE Follow-On and ICESat-2, perform regional assessments for areas of significant imbalance, and partition mass losses into contributions due to changes in glacier discharge and surface mass balance.

The objective of the session was to assess progress on methods and results related to the generation of ice sheet mass balance estimates from satellite observations. Altogether, 10 speakers were invited to review the latest results on key topics. Petra Langebroek opened the session with a presentation on ice sheet climate interactions, with a focus on the tipping points in the cryosphere. Following this there was a series of talks on satellite altimetry. Louise Sandberg Sørensen presented her latest results on Greenland ice sheet elevation changes, which included a long-term record built from multi-mission radar and laser altimetry. Tom Slater then reported on the use of CryoSat-2 to study seasonal chances in Greenland ice sheet elevation, and Beata Csatho presented a review of ice sheet altimetry over Antarctica, with a focus on the latest results from ICESat-2. There were then two presentations on the use of satellite gravimetry. Andreas Groh presented on spatiotemporal variations in Antarctic ice sheet mass revealed by GRACE and GRACE Follow-On, and Isabella Velicogna presented on the continuity of the GRACE and GRACE-Follow-On observations of ice sheet loss in Greenland.

Stephen Chuter then presented on the use of Bayesian hierarchical modelling to resolve Antarctic Ice Sheet mass trends and driving processes, and Nicole Schlegel presented on what satellite gravimetry and altimetry reveal about the evolution of Antarctic firn.

Finally, there were two presentations on the use of satellite ice velocity measurements. Thomas Nagler presented on advancements in monitoring flow dynamics of the Antarctic and Greenland Ice Sheet using Sentinel-1 imagery, and Jeremie Mouginot presented a 47-year record of Greenland Ice Sheet mass balance determined using the input-output method.

MAIN CONCLUSIONS AND RECOMMENDATIONS

The discussion covered three main topics; (i) methods for combining satellite estimates of ice sheet mass balance, (i) biases among the various satellite techniques, and the specific objectives of IMBIE-3 which are to incorporate measurements from new missions, to perform regional assessments, and to partition mass balance into surface and ice dynamical components.

- IMBIE has been limited to the three main approaches – satellite altimetry, gravimetry, and mass budget assessments. During the last years different global and regional combination approaches using various observational data sets have been developed. These approaches aim to improve mass balance estimates by combining the strengths of the individual data sets, for example making use of the high spatial resolution possible with satellite altimetry and the direct sensitivity to mass changes from gravimetry. The IMBIE approach could be extended to invite submissions from data combination approaches. In this way the number of available mass balance estimates could be increased and insights on how the combination approaches agree with the single techniques results could be gained. The results might complement or be incorporated into the final mass balance assessment.

Recommendation: Explore and evaluate alternative methods for combining satellite data to determine ice sheet mass balance

- IMBIE produces reconciled mass balance estimates from the individual techniques and finally from the three different techniques. It was discussed that IMBIE should put efforts into exposing the differences and identifying their causes. First this needs to be done per technique. Taking gravimetry as an example, it would be interesting to know which part of the differences arises from the applied method, the chosen Level-2 data or from the utilised GIA model correction. Ideally a round-robin inter-comparison could be implemented for each mass balance approach in order to perform a systematic investigation of the revealed differences. This would be extremely valuable for both the IMBIE participant community and for establishing confidence in the methods among the wider scientific community.

Recommendation: Perform a systematic assessment of biases among mass balance assessments from independent techniques

- The primary objectives of IMBIE-3 are to produce annual assessments, to incorporate observations from new satellite missions, to perform regional assessments, and to partition mass balance into surface and ice dynamical imbalance. The use of new and historical satellite missions was strongly support, as was the partitioning between surface and ice dynamical imbalance. In the first two assessments, the main focus and agreement has been at the scale of ice sheets. Breaking the results down further to individual drainage basins would allow the community to better target where the inconsistencies remain between techniques, highlighting aspects that need to be tackled next (e.g. improving SMB models, ice discharge quantification etc). It could also help shed some light on the large inter-annual differences between some techniques in the Antarctic Peninsula, for example. Finally, it would also aid other researchers to use the IMBIE output to compare against their own approaches and against model projections. On a related note, it was considered that the IMBIE approach could be extended to other elements of the cryosphere, including mountain glaciers, sea ice, ice shelves, etc. Finally, further work on developing improved ancillary datasets – e.g. SMB and GIA models and ice thickness measurements, is needed. IMBIE could help by ascribing uncertainties in mass balance estimates to the individual components.

Recommendation: Extend IMBIE to include mountain glaciers to arrive at the total sea level contribution due to land ice

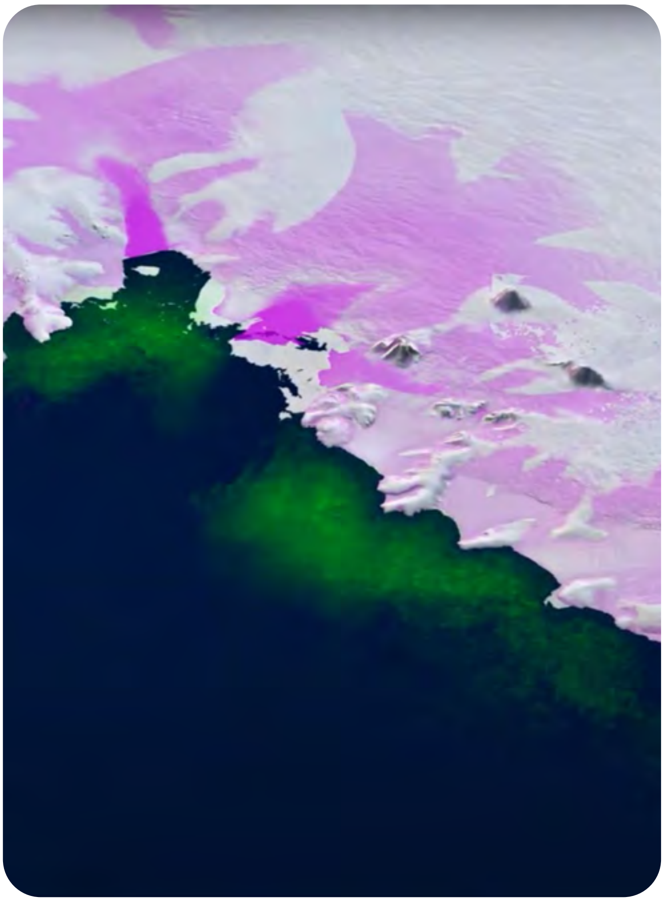
Recommendation: Improve the availability and quality of ancillary datasets, especially ice thickness measurements and SMB and GIA models

3.4 DIGITAL TWIN ANTARCTICA

The session objectives were to 1. introduce to the community the concept and potential of the Digital Twin Earth initiative applied to Antarctica (DTE-A) and 2. Collect feedback from the community in order to shape the current DTE-A demonstrator, and to develop a vision for DTE-A beyond 2021.

A Digital Twin of the Earth is defined today as a system that enables to build an interactive, high-resolution, accurate replica of the Earth. This system will enable activities by a wide range on stakeholders from scientists, to decision makers, to educators, and to the general public. A digital twin of Antarctica will need to include observations, models, and artificial intelligence to in order to represent the ice sheet, ocean, atmosphere and biosphere systems and their interactions.

It is important to consider decision makers and the educational aims of a DTA. In Jo Paisley's talk (GARP) she described how many businesses are very much at the start of this journey to understand climate change. The Bank of England Governor Mark Carney's speech "The tragedy of the horizon" was the start of a shift in approach for the financial system. The way that financial firms are incentivised, they haven't been thinking beyond the end of a century and risks have to be weighed against other often more near-term risks. In order to solve this, there is a need for collective responses across regulators and politicians and increase education and awareness. The minute a financial firm starts doing scenario analysis and the severity of the impact of climate change is understood, it really changes their perspective. Having reliable models that allow companies to do this is crucial for tacking climate change and scenario analysis is the key challenge that firms are currently finding difficult.



There is a huge opportunity for the scientific community to help these firms and potentially something a Digital Twin can help address, but their use cases need to be understood. A key objective to a Digital Twin Earth is bring together these different communities, get them talking the same language and create tools that can be used.

A growing range of Earth Observation is available to quantify and represent the current state and evolution of the ice sheet. Earth observation are also critical for developing, testing, calibrating, or tuning models representing the state, past and future evolution of the ice-ocean-atmosphere-biosphere system around Antarctica. Earth observation products, in particular from past missions, are suffering from spatial and temporal gap that models and data science can help fill. Earth Observation are also largely limited to the last 30 to 40 years. Observation and models therefore are complimentary and joint use should be promoted.

Catherine Ritz (U. of Grenoble) described how Antarctic Ice Sheet Dynamics is one of the key components driving long term uncertainty and there are many interactions with other Earth system components. Satellite observations are very short compared to 1000s of year of evolution dependent on conditions 1000s of year ago. A combination of Artificial Intelligence and physical models via e.g. emulators is an emerging way to tackle large simulation runs, evaluate uncertainty, and resolve the gaps in data particularly when looking back to the past. Its crucial to be able to create historical models in order to constrain the range of uncertainty we have, improve our process understanding, and project the future evolution of the Antarctic system.

Catherine also pointed out the importance of understanding tipping points. The models don't currently capture this very well.

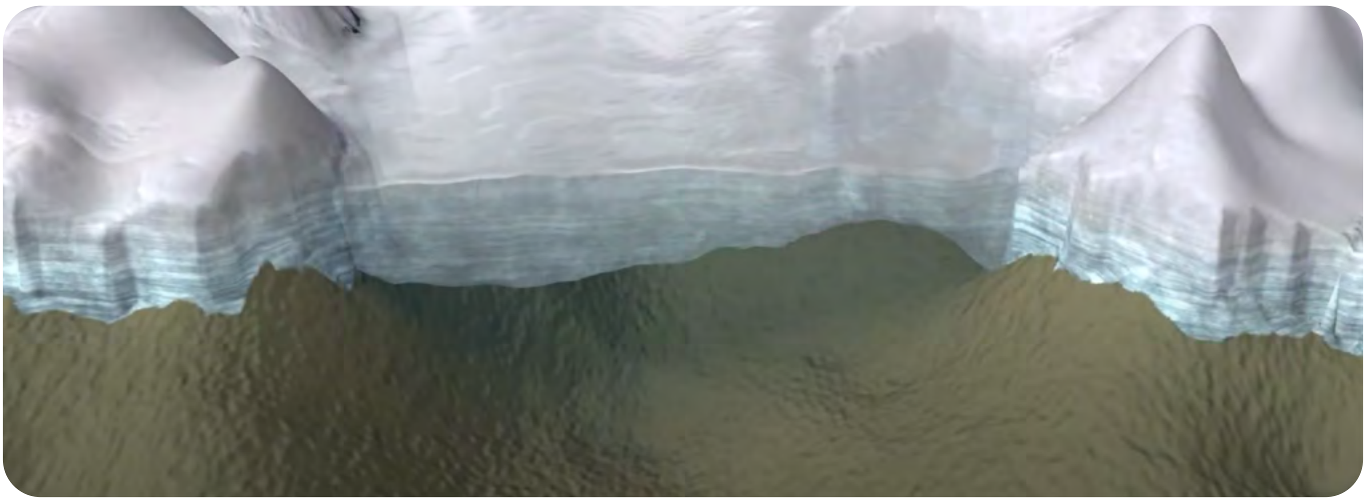
Describing a powerful example, Xavier Fettweis (U. of Liege) detailed how a coupling of atmospheric, ice sheet, and ocean models, would enable to simulation of key processes such as ice shelf collapse and its impact on ice sheet evolution and sea-level change. Using MAR can get a good estimate of the current state of Antarctica today. Satellite data could be included in a melt model to better predict ice shelf collapse and could be estimated in real time. This would be a really nice application of combining observations and models.

There is agreement amongst the speakers that there is a large array of observation, numerical models, and machine learning solution already in place within the community in order to build a Digital Twin of Antarctica. And so there is a general enthusiasm for the initiative and all think that the time is right to launch it.

The glue is needed to these existing solutions together and make them work across Antarctica. To do this both compute and people power are needed. Atmospheric sciences, Earth System modelling and Earth Observation modelling have typically had 3 completely different sponsors. DTA is an opportunity to bring this together.

Computer facilities are needed in both data management and the models themselves. Taking an ensemble approach is very good but each simulation or data assimilation is very expensive and need a huge amount of compute and data storage.

The biggest question is the impact on sea level rise and how that will affect people. However, there is a huge audience for a virtual Antarctica, it is the least accessible place on the planet and so getting information from Antarctica is useful for more than just climate. Using the tool to explore and enable knowledge exchange will gain a wider knowledge. Using real physics on the back end to enable visualisations for people to explore for education. This will make it real and relevant to decision makers for both decision makers and for educational purposes.



CONCLUSIONS AND RECOMMENDATIONS

To summarise, the conclusions and recommendations are:

- The community supports the DTA initiative and believes that the field is sufficiently mature to move quickly in building a digital twin. This should include relevant communities in Earth Observation, in-situ observation, ice sheet, ocean and atmosphere models, and AI.
- The community is pursuing several avenues for combination/coupling/assimilation of Earth Observation, ice-ocean-atmosphere simulation, and Artificial Intelligence. These should be supported and expanded.
- Relevant ongoing initiatives that a full DTE-A should build upon include e.g., 4DAntarctica, POLAR+ Ice Shelves, Imbie, CCI (ESA), PROTECT, SO-CHIC, TiPACCs (EC).
- EO/Model/ML/AI combination should target enhanced observations of the current state and trends (e.g. gap filling, uncertainty, bias, resolution), historical gaps in data and models, and future projections.
- Current computing resources is a bottleneck to running simulation, generating EO datasets, and to perform joint analysis of EO and simulations. A DTE system could be the answer and community requirements need to be collected.
- Such system would be Important for scientists and decision makers, the panel also stresses the benefit for education and exploration of the environment. These communities should drive the system requirements.
- Visualisation and interactivity is key and allowing people to explore data will have a far larger audience than just the climate community.

3.5 GLACIERS, TOWARDS A COMMUNITY ASSESSMENT OF GLOBAL GLACIERS MASS CHANGE

Glaciers distinct from the Greenland and Antarctic ice sheets cover an area of approximately 706,000 square kilometres globally. Glaciers are significant contributors to current global sea level change and impact local communities through availability of fresh water and through increased glacial hazards. Global assessment of glaciers mass changes relies on heterogeneous spatio-temporal distribution of in-situ measurements, and space-based methods such as altimetry, DEM differencing, and gravimetry. Current mass-balance assessments show broad agreement in spatial and temporal trends but significant differences remain. These differences and level of uncertainty in the assessments generated by the scientific community impacts choices of adaptation and mitigation strategies.

Observed differences in mass change estimates and sea-level contributions have several origins such as remaining observational gaps, a lack of a common time frame and region definitions, inherent differences related to the observation techniques, lack of process understanding, limited uncertainty assessment. There is a need therefore for a community exercise that would set a common framework by which ice trends and mass balance estimate from various observation methods can be compared, and in doing so reduce uncertainty and generate a consensus community estimate. This is an ideal time to perform such exercise as in-situ, altimetry (radar and laser), gravimetry, and DEM-based observations are now available globally and over a common time-frame.

The session was devised to address the need for a reconciliation of methods for glacier mass changes (both from remote sensing and in situ). The panellists represented the principal EO protagonists in Europe for different approaches and organisations interested in glacier mass change (IACS RAGMAC, WGMS, IPCC) as well as representative glacier modellers.

Responses to the seed questions

- The message received was an emphatic yes in the light of the success of IMBIE, the nascent efforts of IACS RAGMAC to coordinate an assessment, the increased number of estimates from different approaches and the limitations of the methods used in SROCC (Hock et al 2019) where only two global estimates were available – one from Zemp et al (2019, Nature) based on glaciological and geodetic observations (from DEM differencing) and one from Wouters et al (2019, Frontiers Earth Science) based on GRACE.
- It was observed that while an increasing number of regional estimates are now becoming available but the results differ and glaciological, geodetic (from DEM differencing), altimetric and gravimetric methods all have weaknesses and strengths in different contexts. An effort to reconcile these estimates into a global assessment of glacier mass change would be very welcomed for different scientific applications (sea level projections, global ice imbalance assessments etc) and in particular is crucial to help constrain models of glacier change. RAGMAC, while good in providing an organizational framework and the international research community, does not have the resources to do a well constrained, consolidated assessment like IMBIE. A community assessment would lead to reduced uncertainty in regional glacier mass-change estimates and provide critical information on global sea-level rise. Furthermore, comparing estimates computed from different techniques over common geographical and temporal domains would also be a very useful activity and is required to provide insights into why these agree/disagree.
- The timing is right given any output cannot now impact the AR6 but the work needs to be done over the next 2-3 years to potentially impact the AR7 should there be one. The set up will require approximately 6 months hence planning needs to start now in particular in light of the expected

release of new datasets (e.g. for new TDX data released) and publications (e.g. global assessments from ASTER, TDX, CryoSAT-2). This means the process of looking for funding should start immediately. Now is also a good time as all the key missions in still in place and targeted acquisitions for non-global products could be planned if in time for the respective science plans (e.g.TDX). This type of assessment is in line with RAGMAC, and could be a good follow-on. The community also welcomed the preparation for a CRISTAL mission, and in general for the critical need for a mission whose operational goal is to map global glacier change. The community stressed the importance of continuity of satellite missions used for glacier assessment. Several speakers noted that none of the current missions has guaranteed continuity, gap in mission coverage will impact the ability of the community to monitor and quantify changes.

- It was generally agreed that the glacier community led by RAGMAC should be the main protagonist/ coordinator but a number of other groups were identified and a general discussion on the objective of the assessment was initiated. Global Cryosphere Watch (WMO) were keen to be involved and CliC were also identified. On the technical side in addition to those groups already identified, working groups on glacier inventory (RGI) and glacier modelling (GlacierMIP), snow density and firn modelling experts, the hydrological and climate communities, machine learning and statistics groups and finally EO groups not currently represented were also suggested.
- Since RAGMAC is already up and running, working through them is the easiest and most acceptable route for the community. The option of having the organisation done by ESA and NASA following the model of IMBIE could be followed BUT the community is more complex and involves organisations and countries with strong regional interest. While NASA was immediately identified the panellist from JPL was not available and this would need to be followed up. In addition, the NSIDC may have an interest in US. Other Space Agencies may also have interest e.g. ISRO, JAXA, DLR. It is therefore better to act through the community.
- Nevertheless, the concept of GLAMBIE seems very well suited to an easy win component of the ESA-EC Polar Cluster with ESA taking the role of organisation in a similar manner to IMBIE with support for some of the necessary research (e.g. firn, snow and ice dynamic modelling) coming from EC RTD. It was also noted that most of the recent progress on glacier mass change has come through European groups and organisations.

Apart from the organisational issues already highlighted above, there are a number of technical issues to address as part of the assessment: e.g.,

- Observation periods need to be agreed and matched over satellite/in situ data availability
- Regional, global or glacier by glacier focus and consistency globally given different dataset availability/coverage
- Agreement on which datasets/satellites will be included (all or representative sample?)
- Uncertainties/Errors including consideration of systematic bias, common error model, understanding of differences.
- Representativity of estimates with elevation and time
- Density conversion reconciliation/re-assessment
- Agreement on and consistent use of inventories/outlines e.g. RGI v7
- Agreement on the assessment strategy (dh/dt, dM(t)/dt or dM(t)…)
- Inclusion (or not) of pattern and amount of mass redistribution as well as mass change (to incorporate instability and surging).
- Normalising the participants' datasets (e.g. different temporal and spatial sampling).
- Consideration of the various geophysical corrections required for certain techniques.
- Inclusion (or not) of calving ice tongues with ice thickness where possible.
- Coordination/improvement/availability of in situ observations relevant for assessment (airborne, helicopter, in situ etc radar/lidar).
- Storage eventual of results and their combination (or not) with other glacier information (RGI, GLIMS, WGMS etc).
- Consistency with IMBIE (spatially and temporally, separation of peripheral glaciers and ice sheets).

3.6 ESA-NASA ARCTIC METHANE AND PERMAFROST CHALLENGE

In a warming Arctic, longer and warmer growing seasons may accelerate the microbial breakdown of organic carbon stored beneath and within permafrost increasing the magnitude and timing of CO2 and CH4 release to the atmosphere. In addition, rapid permafrost thaw may occur throughout the Arctic, altering surface hydrology, which may contribute to further thawing. Due to these localized feedbacks, permafrost degradation may occur at a much faster rate than would be predicted from changes in air temperature alone. This may lead to a potentially irreversible acceleration in the methane emissions that may have a significant impact on the climate system.

What are the current methane emissions in the Arctic and what are the sources and sinks? Will the fraction of the carbon permafrost feedback increase in the future? Why we see rapid changes in permafrost not followed by a commensurate net rise in methane emissions? What can we learn from the increasing number of satellite observations over the Arctic high latitudes? These are only some of the critical questions that several scientific communities around the world are facing today using a variety of techniques, data and models.

Addressing those questions requires to overcome major scientific and technical difficulties associated to the scarcity of observations, the complexity of satellite retrievals, the discrepancies between bottom-up and top-down approaches, the understanding of complex processes and its transfer to advanced models, the disentanglement of anthropogenic vs. natural emissions and many others...

In order to further support existing efforts NASA and ESA recently launched a transatlantic initiative to help solving the Arctic Methane and Permafrost Challenge (AMPAC) to build upon existing and planned capabilities and promote interdisciplinary and collaborative research across communities bringing together different data, results and expertise across the Atlantic to ensure that the final result is bigger than the sum of the parts.

The initiative is articulated across the following Working Groups:

- **WG1** - Enhanced retrievals, observations and data sets: Enhances in satellite retrievals over land and atmosphere, enhanced collection of data and in situ observations, validation, inter comparisons, building a pan-Arctic constant data set.
- **WG2** - Reconciling observation strategies and modelling approaches: Advance in the effective integration and reconciliation of data and modelling approaches, reconciling bottom up and top down approaches, promoting synthesis analysis of models and data driven results and integrated process studies at different scales, from local scale to pan-Arctic scale studies.
- **WG3** - Future observations and next generation of missions: Preparing for future missions, future observations, future campaigns, exploiting advanced technologies.

The three AMPAC sessions during the European Polar Science Week aimed at supporting the definition of the community goals and in planning topics for multi-year trans-Atlantic science collaborations to advance our capacity to better understand, quantify and predict methane emissions from permafrost changes in the Arctic.

SUMMARY AND RECOMMENDATIONS

- Foster community efforts to assess how important the Arctic is in the overall methane budget, ranging from "just a drop in the ocean" to "doomsday scenarios" with climate feedbacks.
- Community efforts should be encouraged to gather results and data from different teams across the Atlantic and perform a community assessment of where we stand right now and what would we need to robustly predict potentially changing methane emissions in the future.
- Those efforts should be supported by an open science approach and data sharing mechanisms. This may include the development of an easy-to-use consistent (format, grid, temporal sampling, UQ) catalogue of available data sets to be used by the community for comparisons, data-driven analysis, model verification and inverse modeling.
- Approaches are needed leading towards a robust and flexible observing system for monitoring the Earth's greenhouse gas evolution in the Arctic comprising ground-based, airborne, and spaceborne observations.

Reccomendaation: promote a community paper gathering the latest results and knowledge on the status of the Arctic permafrost and CH4 emissions, the knowledge gaps and the needs to advance towards robust predictions in the future.

Develop a community catalogue and data sharing platform ensuring an easy access to EO and non EO dataset as a basis for implementation of the initiative.

- EO based products need development. Novel satellite capabilities offer potential for enhancing the current situation: e.g.,
    - In general, a consistent circumpolar wetland distribution with adequate typology is needed. Development of SAR products for soil moisture supported by validation (e.g., advanced techniques over the tundra zone for high resolution SAR-based wet versus dry and state).
    - Satellite CH4: tailored algorithms for high latitude retrievals supported by validation and promote the reprocessing of XCH4 retrievals using arctic specific radiative transfer models.
    - Indicators for monitoring abrupt land-parameter changes in different scales, maps of changes (long-term impacts) at different scales, maps of changes. Very high resolution satellite data are key to capture small scale processes.
    - Consideration of seasonality: e.g. monthly updates of inundation data required from satellite observations
- It is important to work across different spatial scales (0.5 m to 50 km) to provide pan-arctic remote sensing observations that represent biophysical features that determine methane emissions, and the coarser resolution products available with more frequent revisit and available for longer time periods.
- Scale matters, new Arctic/Boreal vegetation maps are needed including information on different landscape and land cover types to be considered.

Advance in the EO satellite retrievals of CH4 in the Arctic through the development of dedicated methodologies exploring and advancing the potential of the latest EO sensors.

Develop a new generation of high resolution dedicated products over the Arctic and boreal zone matching the needs of the permafrost and methane communities.

- Discrepancies between top-down and bottom-up estimates are significant. Efforts are needed to bridge the gap. The AMPAC initiative should encourage a community effort to perform a dedicated inter-comparison and reconciliation exercise between bottom up and top down approaches.
- Achieving this target will require bringing these two communities together and agree on the right scheme and protocol to perform such an experiment: e.g., common temporal and spatial coverage, **comparison metrics, computation of** uncertainties, data sets.
- In addition, further development of top-down and bottom-up approaches is needed and some limitations in models need to be addressed: e.g.,
    - advances on methods to scale up (e.g. benefitting from the developed similarity measures);
    - improved use of observations, alternative data driven methods;
    - Specific focus on analysis on temporal variability of methane fluxes is needed.
    - More years needed for bottom-up accounts (from static to dynamic).
    - New, regional atmospheric inversions using satellite CH4 (if we can properly account for boundary conditions and mid-latitude exchange).
    - New data-driven upscaled CH4 models for both inland waters and wetlands.
    - Abrupt thaw – model resolution limiting, statistical upscaling as potential solution
    - Microbial activity modelling important, dry versus wet important
    - Novel ways to evaluate CMIP type models using remote sensing observations, expanding on iLAMB, for example.

Promote an inter-comparison and reconciliation exercise between bottom up and top down approaches ensuring the comparison of methods is done on the same time scales, spatial coverage and sharing data inputs when possible and common standards for uncertainty estimation.

- Finally, in-situ data should be a key component of these effort. It is important to define key areas that require more instrumentation and coordinate the different campaign efforts across the Atlantic.

Promote a community effort to coordinate in situ and remote sensing campaigns, both on the ground and from aircraft, to collect data, and to enable access and sharing of those data across the communities.

3.7 ARCTIC LAND-SURFACE CHARACTERIZATION: NEEDS, CHALLENGES AND GAPS

Arctic terrestrial environments are changing at fast pace due to climate change with permafrost degradation being core to the dynamics of the land surface. As such, the encompassing relevance of permafrost shows as cross-cutting in the five Research Needs recently identified in the Integrated European Polar Research Programme.

Remote sensing techniques supported by a well-planned strategy of field observations, feeding into modelling are key to the understanding of the new Arctic. Priority research areas include upscaling of carbon fluxes and pools, permafrost feature mapping and transition monitoring, proxies for subsurface conditions, biodiversity and landcover change, hydrological changes, socio-ecological systems, impacts on infrastructure, among others. One key environment that needs further investigation are permafrost coasts, bridging important terrestrial and marine ecosystems, home to Indigenous and local populations, settings of valuable infrastructure and pathways of new transport routes. Arctic coasts are key for the understanding of connectivity and gradients in the Arctic as recognized by the Terrestrial Multidisciplinary distributed Observatories for the Study of Arctic Connections Program (T-MOSAiC) of IASC. They are extremely dynamic areas and increasingly vulnerable to coastal erosion, caused by rapid warming and thawing of permafrost, as well as by changes in sea ice cover and associated exposure to waves and currents.

This session, promoted by the Remote Sensing Action Group of T-MOSAiC aimed at discussing (I) the more urgent needs to identify and quantify climate change impacts, (II) the needs to address subsurface conditions in the terrestrial Arctic, such as permafrost temperature, ice content and carbon in the soils, (III) the ways to collaboratively developing science and supporting Arctic communities.

The session started with five presentations, followed by a community discussion on future priorities for EO. A. Bartsch presented a synthesis on the new advances and initiatives on Arctic terrestrial remote sensing and remaining challenges. Numerous studies show potential of currently available data, but circumpolar implementation still needs to be done, for example related to coastal erosion and landcover. Further on, current solutions which are feasible circumpolar are at the limit of required spatial resolution. G. Grosse addressed the progress and gaps on quantifying and monitoring permafrost thaw with multi-decadal optical time-series. He highlighted the needs for higher spatial and temporal resolution imagery to understand the tipping character of permafrost, to facilitate the access to VHR EO data as well as to high performance processing and storage platforms. I. Myers-Smith focused on the use of drones to bridge the gap between in situ and satellite observations, explaining the new advances on vegetation monitoring through the HiLDEN network and its relevance across scales, especially for addressing the need for a landscape perspective that is missed in many studies. M. Siewert presented a review on the status and challenges of detecting soil carbon from EO, emphasising on the new applications of predictive modelling using machine learning. For improving soil carbon mapping, better integration of DEMs and multispectral data is needed, while scaling issues need to be tackled, since there are considerable differences on soil carbon estimates depending on resolution. T. Ingeman-Nielsen presented success examples of active layer monitoring based on Sentinel-1 for hazard assessment and infrastructure management in Greenland. He showed how remote sensing can contribute to improving engineering solutions at site-specific scale.

CONCLUSIONS AND RECOMMENDATIONS

Although local to regional applications of EO data for characterization of the natural environment do exist, circumpolar coverage with adequate resolution and quality is still lacking. The Sentinel-1 and -2 missions of the Copernicus program provide data with unprecedented detail. However, the Arctic shows a complex 3D land mosaic, where the interactions between the subsurface and the surface phenomena, can only be understood through synergistical applications involving new tools and methods, from improved ground data collection (e.g. drones, community observations) to new modelling approaches including the use of machine learning/AI.

The following are the key recommendations from this session:

- Improve open access to very high spatial resolution imagery (to a minimum of ca. 50 cm) and continuously acquired imagery.
- Guarantee the future continuity of acquisitions (optical such as Landsat and Sentinel-2 as well as SAR) over northern permafrost regions.
- Ensure data from similar sensor configurations are acquired across the entire Arctic to facilitate mapping algorithm development and spatial inter-comparisons.
- Facilitate the access to existing high-resolution commercial satellite data.
- Develop and consolidate drone-based protocols for extensive ground-truthing and improving the assessment of the quality and limitations of remote sensing products.
- Investigate scale-dependency of ecosystem properties.
- Support the creation of infrastructure and management system to promote the open access to drone data.
- Promote the synergistic use and integration of field observations and remote sensing data.
- Foster circumpolar implementation of monitoring schemes.
- Support early career researchers in projects and with relevant thematic training courses.

3.8 THE ARCTIC FRESHWATER FLUXES BUDGET

This session was organized to optimize the use of EO data to better assess the Arctic FWF. The main goal was to identify possibilities and to identify challenges and potential gaps in the estimates. First demonstration of fully utilizing EO data to estimate Arctic FWF was investigated in the ESA Arctic+ STSE ArcFlux (2016-2018) and Salinity (2018-2020) projects. Based on output from these projects, we identified 3 main themes/questions used, as input for the discussion session, as described in the main conclusions and recommendations.

A variety of sensors (e.g. altimetry, SAR and optical images, passive microwave, GRACE) are used to estimate the independent FWF, each having different advantages and disadvantages. Long-term consistent time-series are of high priority. The estimated fluxes in the ArcFlux project, i.e. ocean, sea ice, rivers and land ice, based on remote sensing data agree within 5% of previous publications of individual fluxes based on models and in situ data, but uncertainties remain large.

To estimate the total Arctic freshwater budget is an interdisciplinary task which will only be possible by collaboration between the EO and the modelling community through a combination of EO, in situ and models. For some of the individual fluxes modelers already work closely with EO groups to develop products that are useful for both. For example, near-real time estimates of Greenland FWF are available by combining EO data and models, permafrost probability maps are calculated by a combination of model and satellite land surface temperature and snow area coverage.

MAIN CONCLUSIONS AND RECOMMENDATIONS

Quantifying FW fluxes in the Arctic is important as they have an important influence on heat events on European air temperature, precipitation and storms.

In addition:

- The origin of FW anomalies south of Greenland are defined by a negative NAO anomaly which is correlated to SSS anomalies and sea ice loss, however the origin of the FW anomalies are unknown, and needs to be tracked.
- The Beaufort Gyre has been freshening by ~25% of the total FW reservoir in the Beaufort Sea, and there is a need to investigate the causes (e.g. sea ice melt, river discharge) and the potential link to the North Atlantic Deep Water formation, i.e. export of the FW liquid content through the Fram Strait.

- The study of impacts on the Arctic carbon budgets has not been a focus of the ESA projects, but there is clearly a relevance which should be investigated in future projects. This is highly relevant with respect to future HPCM CO2M.
- It also remains open how we best quantify freshwater now that the common approach by subtracting a reference salinity no longer appears valid (Schauer and Losch, 2019).

EO capabilities offers an opportunity to enhance the way we observe and quantify FW fluxes in the Arctic. For the Atmospheric circulation studies, seasonal estimates of FWF is sufficient – monthly is not needed. But, if we want to observe the rapid changes in e.g. river spring flood or rapid changes in ice discharge we need much better temporal resolution.

However, there are still several limitations and drawbacks that would need to be addressed: e.g.,

- The poor temporal sampling of altimetry derived fluxes (e.g. ocean fluxes in the main straits and river discharge) is generally a main limitation.
- Different FWF and different sensors have different needs: e.g., For monitoring ice in ground by indicators, very high spatial resolution (better than 250 m) and circumpolar monitoring is needed. This yields high processing effort since spatial resolution needs to be preserved; For soil moisture global products are too coarse and in situ comparisons not encouraging for tundra.
- There is a need for reducing the uncertainties in EO data, e.g. Inter-annual and regional variations of snow depths on sea ice are poorly known and contribute to large uncertainties in the altimetry derived sea ice thicknesses; Sea ice drift from PMW sensors is estimated to be 50% too low.
- Other gaps include: e.g., Summer sea ice thickness from altimetry, Ocean altimetry time-series due to the presence of sea ice; Knowledge of sea ice salinity, together with subsurface water; Optical images still hampered by cloud contamination; Use of SAR requires consistent acquisitions or an approach how to deal with the patchwork; Observations of land ice bedrock are poorly sampled; however, this needs only to be done once; Long term monitoring is required to derive FWF trends. So it is recommended to use AVHRR, ERS-1 and ERS-2 SAR data from the 80s.
- To support models EO data needs to be assigned input of e.g. cloud contamination, correct snow/ice masks, formats, quality control (QC) flags

It is crucial to have key in situ observations for validation in fixed positions (moorings), and focus on long time series, random measurements in space and time are less useful. We should explore to use satellite observations to identify which locations would be optimal for in-situ monitoring.

In addition:

- The use of drones might be a good solution, which could provide routine monitoring of specific areas, e.g. the Fram Strait.
- There is a recommendation to produce higher-level datasets of existing validation campaigns to be of better use to the EO community.
- Making time series of ocean salinity to monitor FW from Argo floats (and from moorings in the Arctic) is not sufficient to deduce large-scale and long-term trends because of near-surface stratification.

Finally parameters coming from modelling approaches (e.g. ice sheet run-off, snow depth, wind, precipitation, evaporation, summer sea ice thicknesses) are needed to support RS based estimates of the FWF budget. This include:

- precipitation/evaporation (P/E) is necessary to close the balance
- Calving and submarine melting are still poorly represented in dynamic ice sheet models
- Inclusion of Ice-slabs
- The wind is going to be increasingly important due to the decline in the sea ice, and thus we need to include these in future estimates of FWF
- Publicly available model data are needed, e.g. for rivers and smaller ice caps to calculate the overall budget
- There are often large discrepancies between models, e.g. ocean models both due to circulation and mixing problems in the Labrador Sea, different precipitation models results in ice sheet mass variations between ~100 Gt/Yr / 700 Gt/Yr
- Model estimates can be improved by including EO and in situ observations, e.g. to determine future runoff as the percolation zone expands up ice sheet improvements in firn.

3.9 BELOW THE SURFACE: THE CHALLENGE OF A STRATIFIED ARCTIC

The Arctic Ocean and its drainage basins are experiencing rapid change, with rising temperatures and increasing freshwater supply (from rivers and ice melt). Additionally, the loss of sea ice coverage stands to dramatically change light penetration and atmospheric heat exchange in the Arctic Ocean. Many Arctic marine waters are already characterized by a high degree of vertical stratification. While this is common for coastal and shelf waters globally, in the Arctic this stratification persists in across the central basins. Ongoing changes in Arctic heat and freshwater budgets will likely lead to the establishment of stronger vertical stratification and the consequences for the functioning of Arctic waters is currently unclear. A stronger pycnocline prevents vertical mixing, potentially limiting nutrient supply to surface waters and increasing the importance of primary production at depth through deep chlorophyll maximum (DCM) phytoplankton communities. Increased dissolved organic matter and suspended particulates associated with freshwater run off can also potentially limit light penetration. Combined, these factors represent a considerable observational challenge where there is a need for increased focus on coupling of in situ and remote sensing efforts.

Given the limitations for Arctic oceanographers to access to the region, ocean colour remote sensing (OCRS) is able to increase both spatial and temporal sampling resolution while monitoring global biogeochemical processes. However, this technique is limited by sea-ice and cloud coverage and lack of data due to low sun elevation during winter. Furthermore, OCRS is limited to retrieve information only from the surface of the ocean. With the predicted displacement of the primary production towards the pycnocline, OCRS may not be able to accurately monitor the Arctic Ocean's primary productivity. On top of that, sea ice melt creates a thin surface layer where the CDOM content is diluted and OCRS cannot properly assess the high CDOM content present in the Arctic Surface and Halocline waters. On the other hand, bio-optical sensors (e.g., Chlorophyll-a and CDOM fluorometers, spectral radiometers, absorption- and backscatter-meters, etc.) can be attached to autonomous platforms (moorings, gliders, floats and ice-tethered profilers) and can provide a wealth of information over the water column. Thus, those sensors can fill the gaps left by OCRS and allow for further extrapolation from RS data. This requires a more extensive and coordinated sustained in situ observation program and data exchange and will provide a significant improvement to our understanding of the Arctic Ocean's biogeochemistry and to allow for a more efficient monitoring of future changes.

The goal for this session was to discuss a path forward to developing approaches to tackle some of the challenges that the highly stratified marine Arctic poses for remote sensing applications. The proposed seed questions were:

- What are the implications of the change in stratification for the Arctic marine environment?
- What are the challenges of employing satellite remote sensing to monitor biogeochemistry in a changing Arctic Ocean?
- How reliable are current OCRS products/algorithms for the Arctic Ocean?
- What are the next steps towards a comprehensive monitoring of the Arctic Ocean when applying satellite remote sensing?

MAIN CONCLUSIONS AND RECOMMENDATIONS

- With the increase in open water area in the Artic Ocean, satellite remote sensing coverage will be enlarged, yet there are still inherent limitations to the technique (e.g., max latitudinal coverage of satellites, presence of clouds, absence of light in winter);
- Remote sensing of coastal and shelf areas reveals large temporal and spatial heterogeneity which is difficult to capture with in situ sampling. This in part can hinder satisfactory ground truthing (validation) of salinity, dissolved organic carbon (DOC), and phytoplankton pigments. However, remote sensing products can be used to plan and guide in situ sampling for validation;
- It is important to derive empirical local/regional algorithms linking the properties of the surface layer measured by EO, to the properties of the integrated water column. This is particularly relevant for regions with strong seasonal or river derived thermocline and halocline, or waters with pronounced DCM. This can be achieved through a combination of in situ observations and models;
- There is great potential to couple ocean color remote sensing and altimetry towards quantifying freshwater and DOC fluxes in Arctic rivers and major ocean gateways (Fram, Bering, Davis straits).

3.10 SCIENCE CHALLENGES IN THE ARCTIC OCEAN

The Arctic Ocean is changing dramatically responding to significant global atmospheric warming by pan-Arctic sea-ice retreat and thinning. Measurements of geophysical change are the evidence to underpin the establishment and proper management of policy decisions. In terms of the Arctic region, several extreme concerns have been recently raised.

Satellite records have revealed a significant decrease in sea-ice extent in all months, especially in summer. Strong reduction in areal ice coverage is accompanied by a decrease in winter sea-ice thickness, shifting sea-ice state from one dominated by multi-year ice cover to a seasonal and much thinner (first year) ice cover. This is a fundamental shift in the sea-ice regime in the Arctic that is increasingly controlled by thinner, more dynamic, first year ice. The increase in open water leads in the Arctic results in further oceanic uptake of atmospheric heat which contributes to amplified warming.

Some projections suggest that the Arctic Ocean may become seasonally ice-free as early as 2040. As sea-ice retreats, more open ocean is revealed leading to a more dynamic sea state regime, the sea-ice becomes thinner and sea-ice drift and deformation rates accelerate. Attenuation of waves in the marginal ice zone caused by ice flexure combined with basal friction is reduced when the ice layer is not continuous over which the ice is broken up by waves over a 100 to 200 km wide region as observed in SAR imagery. Ice breakup induced by waves has become much more important in a warmer Arctic, with larger waves - from longer fetch - leading to larger areas of broken ice. In addition, the ice is becoming thinner which allows the waves to travel further in the so-called Marginal Ice Zone (MIZ) and in the pack. This will inhibit the formation of new ice and accelerate the retreat of sea-ice further exacerbating Arctic regime change.

The well-reported increase in Arctic Ocean freshwater storage over the past 15 years is directly related to Ekman pumping and consequent spin-up of the Beaufort Gyre. While summers are confidently predicted to become ice-free by the end of the century, a substantial area of sea ice still survives through the winter at present. Even so, the observation of gyre spin-up indicates the potential for the Arctic Ocean circulation to change dramatically consequent to changes in atmospheric circulation and sea ice. A future summer ice-free Arctic Ocean will likely circulate faster as momentum transfer from the atmosphere to the ocean becomes more efficient. It is therefore further possible that the current very low level of ocean turbulent mixing will increase. Should this mixing become strong enough, it would bring sub-surface heat from the Atlantic water layer up to the surface. If it did, it could prompt further decline in the sea ice cover, perhaps impacting seasons outside summer.

As more of the Arctic Ocean water is exposed to the atmosphere, properties of the ocean related to heat, gas, freshwater and energy fluxes are likely to change quite rapidly and with increasing regional variability. Such a dramatic regime change has potential for profound impact on global ocean circulation patterns, the distribution of nutrients and carbon dioxide, biogeochemical cycling and changes in Arctic ocean stratification. In addition, the action of strong winds over a larger Arctic ocean surface will modify the vertical structure of the upper ocean bringing nutrient-rich deep waters up to the sunlit surface enhancing phytoplankton productivity and potentially impacting the absorption of CO_2, increasing the ocean's ability to act as a carbon sink for greenhouse-gas emissions.

Since the Arctic Ocean is a remote and inhospitable region in which to work, data coverage is extremely sparse and thus remains a poorly understood environment. Substantial uncertainties of sea-ice and ocean-interaction processes, as drivers of Arctic change, still exist. Earth Observation is unique in this respect, providing a wealth of measurements every day from different instruments. The question then arises: how can EO data be used to improve knowledge of the role played by the Arctic ocean in exchanging heat, gas, mass, freshwater and energy fluxes in the Marginal Ice Zone?

This session demonstrated some new developments in this context including:

- The monitoring of dissolved organic carbon (DOC) in the Mackenzie River Delta region (Bennet Juhls' study) linked to permafrost thaw and increasing mobilization of organic carbon land into the ocean. It was displayed that Ocean Color Remote Sensing (OCRS) can be used to monitor the seasonal variation of DOC on large spatial scales in high temporal resolution offering a great tool to monitor potential future changes in Arctic carbon fluxes and its implications for the global carbon cycle. In addition, as most of the DOM is of terrigenous source, a strong relationship is anticipated between freshwater (low salinity values) and DOM concentration. Spreading of freshwater into the offshore region may, as such, be explored through the concentration change in the DOM.
- Laurent Oziel presented work related to faster Atlantic Currents that drive Poleward expansion of temperate phytoplankton towards the Arctic Ocean. This posted a discussion on the estimation of errors in the altimeter-based velocity field and subsequent accuracy in the volume transport (e.g. mass versus thermo-halosteric changes). It was commented that despite the validation using drifters, the existence of new products like Stokes drifts and Ekman transport may help reduce uncertainties.
- Felix Lucian Müller showed that surface ocean currents in polar regions can be monitored by satellite altimetry-derived geostrophic currents. In particular, a novel altimetry waveform re-tracker applicable in mixed sea ice and open ocean areas in combination with a principal component analysis for linking ocean model output with altimetry observations are developed to enable a consistent computation of ocean surface currents. The method is dependent on the spatial and temporal resolution provided by the model, and with the corresponding uncertainties contained in both the forcing field and the regional freshwater fluxes.
- Finally, Matthew Hammond, National Oceanography Centre – presented the new NOC GNSS-R derived global ocean wind speed and sea-ice products and how signals from the Galileo constellation show promise for future remote-sensing using GNSS-R.

RECOMMENDATIONS

- In the coming few years a new generation of satellites including the Copernicus expansion missions (e.g., ROSE-L, CMIR, CRISTAL) and the next generation of meteorological satellites (e.g., MetOp-SG) will complement the series of Sentinels (e.g., Sentinel 1, 2, 3, 6) offering an unique and unprecedented capability to observe the Polar regions from space. It is strongly recommended to initiative as soon as possible dedicated preparatory activities aimed at exploring the full synergistic potential of such an unique capacity for Polar science and applications.

- Johnny A. Johannessen emphasized, as demonstrated by ESA's Arktalas Hoavva project how the synergistic use satellite measurements complemented with in-situ data and modelling offered a unique opportunity to understand and characterise some of the key processes driving changes in the Artic sea ice and Arctic Ocean. In particular, the it is strongly recommended to focus dedicated research activities on a number of Arctic Scientific Challenges:
    - Characterize and predict the Arctic ocean spin-up;
    - Characterize the impact of more persistent and larger area of open water on sea ice dynamics;
    - Characterize and predict the impact of extreme event storms in sea-ice formation; and
    - Characterize Arctic Amplification and its impact.
    - Understanding changes in air-sea ice-ocean interaction and exchanges of momentum, heat and gases;
    - Changes in the layering of the Arctic upper ocean in the presence of more meltwater;
    - Circulation and transport in the Arctic Ocean in the presence of declining sea ice extent;
    - Changes in biogeochemistry, biology and ecosystem under the transition towards a blue Arctic;
- There is a need to understand the ocean and sea-ice processes better, including multi-annual thinning and decay of sea-ice, sea-ice deformation, pan Arctic sea-ice transport, changing wind and wave conditions, mesoscale ocean variability and the influence on primary production. A key challenge is to develop new approaches to use multiple native resolution satellite measurements (i.e. single image snapshots, altimeter transects etc) rather than gridded fields (that smear and smooth features) in a broader data-driven analysis framework. This shall include synergy between different measurement types (e.g. altimetry, visible/thermal infrared, microwave imaging radiometry and synthetic aperture radar imagery) using native resolution (i.e. ungridded) data products.
- High-resolution satellite observations can play a major role here and efficiently constrain mid-latitude ocean mesoscale activity and surface properties in ocean models. Simulating accurate sea-ice thickness distribution, which is especially important for predicting regional winter climate and Arctic amplification remains a challenge. Sea-ice motions plays an important role in the ice thickness distribution and a more realistic ice rheology is required that is consistent with the observed mechanical behaviour of sea-ice. In addition advances in AI may open the door to simulate complex processes that today, sea ice model cannot properly characterise. More efforts in this direction are needed.
- Characterized by strong winds and high waves play a major role in vertical mixing processes that can affect the cold halocline layer and possibly leading to a positive feedback that affects sea-ice formation. Understanding the impact of these events on climate is still unknown and needs to be investigated.

- Whereas the above issues are specific to the Arctic Ocean the consequences of these changes the Earth system at large may include impact at global scale. It is urgent that research activities are dedicated to assess the potential impact of Arctic changes worldwide with focus on:
    - Ocean and atmosphere circulation patterns;
    - the regional water cycle, energy cycle and carbon cycle;
    - teleconnection and influence of changes in the Arctic on weather and climate at lower latitudes (globally in fact)

3.11 DIGITAL TWIN ARCTIC

Regional warming in the Arctic appears very fast compared to the rest of the world in both observations and model simulations. It has been described as the Arctic amplification (AA) and occurs across a wide range of spatial and temporal scales, encompassing numerous multi-variable feedback mechanisms, still very difficult to evaluate, assign and then disentangle. Hence the understanding of the causes for the AA is deficient. It is therefore highly important to accelerate a more cross-disciplinary approach to:

- combine model outputs with statistical analysis to jointly exploit multi-resolution model outputs and observations;
- fully capitalize on the wealth of present multi-modal observations (in situ, satellite) with advanced deep learning strategies;
- contribute to the design and implementation of future performant observation networks along with numerical models.

MAIN CONCLUSIONS AND RECOMMENDATIONS

- Undertake multi-modal data driven exploration and co-variability analyses including use of more advanced techniques to jointly analyze multi-modal observations and model outputs to calibrate (parameterize) small scales and rapidly varying air-sea-ice exchanges. In that context, revisiting events and building on high-resolution, new methods, including AI/ML developments, are underway. Note that sea ice type classification using ML is emerging and expected to improve operational services. In this endeavour, L-band passive microwave radiometer measurements (e.g. SMOS) have also been shown to inform about sea ice volume.
- More systematic exploration and joint co-variability analyses of brightness temperature; normalized radar backscatter and dielectric constant, are necessary; ML/DL methods to perform feature extraction, to further help reveal conditioning and analogs, seem fully adapted, and will contribute to propose a dimension reduction framework for identification/reconstruction of the dynamical system.
- Execute coupled atmosphere - sea ice - ocean model simulations for studies of feedback mechanisms.
- Design and execution of experiments and field campaigns for advances in:
  process understanding, dominant interactions and feedback mechanisms;
  model validation;
  model parameterization and initialization.
- Improve quality of wind forcing in the Arctic tailored to surface roughness and drag, sea ice bottom drag and feedbacks in the atmospheric boundary layer;
- Advance the ability to connect sea ice motion, damage and thickness variability and change with upper ocean thermodynamics and mesoscale processes.
- Strengthen the ability to determine the sea ice break-up leading to both increased outgoing longwave radiation and heat fluxes from the open water, and the subsequent conditional contribution to AA.

3.12 THE SOUTHERN OCEAN CHALLENGE

This session, bringing together a number of recognized Earth Observation (EO) experts and science leaders of EC/ESA projects, aimed at presenting some of the latest results, technical challenges and key science questions to be addressed in the area of the "Southern Ocean". The objective was to discuss on how recent developments for improving geophysical retrievals from EO satellites (from past, present and future missions) associated to a better integration of these multi-source data (e.g. Sea Surface Salinity, Temperature, Gravimetry and sea ice/ocean surface topography) with in-situ observations and modelling could help to fill some knowledge gaps. Improved EO data products generated from tailored processing methods should improve not only our understanding of the seasonal and inter-annual variations of the Antarctic land ice and sea ice, but also their multi-scale interactions with the surrounding ice-shelves and polar ocean, including (sub)-mesoscale dynamics, as well as their local and global impacts linked to biogeochemistry, carbon cycle, ecosystems and on Climate Changes.

The session was focused on four presentations including the following main messages:

- The presentation of Sallée (et al.) highlighted the Southern Ocean as being one key and highly policy relevant knowledge gap in climate sciences. In particular, the Southern Ocean has a central role to shape (i) the relationship between human greenhouse gas emission and Earth Warming; (ii) the spatial pattern of Earth Warming that will control future change in climate sensitivity; and (iii) the future sea level contribution of the Antarctic Ice Sheet through ocean thermal forcing. Those aspects need to be understood to design appropriate climate policies in response to International agreement (Paris Agreement). One key lock to further advance is the availability of observations and understanding of feedback between ocean and cryosphere. The growing maturity of a number of satellite-based products urgently need to be analysed in combination has a timely and unique opportunity for a major step forward.
- Tsamados (et al) presented the first findings from the ESA CryoSat+ Antarctica (CSAO) project. Over the last 10 years CryoSat-2 has allowed a radically new view of the ice covered Arctic Ocean and Southern Oceans, providing us with the first pan-Arctic/Antarctic sea ice thickness maps, dynamic topography and geostrophic currents, and indirectly a wealth of geophysical products ranging from Eddy kinetic energy, Ekman upwelling / downwelling, to snow on sea ice, and improved tidal models, or better resolved bathymetry at the bottom ocean. The presentation focused on the recent algorithm and technological developments proposed by the CSAO ESA project consortium in developing the next generation sea ice and sea surface altimetry products with homogeneous coverage over the entire Southern Ocean and increased spatio-temporal resolution. Highlights included the presentation of novel physical and threshold retrackers and surface type discrimination AI algorithms.
- Kolodziejcyk et al discussed the status of satellite SSS observations in the Southern Ocean. In Southern Ocean, especially in cold high latitudes, salinity is a key variable that control ocean stratification and dynamics, with a major impact on heat, carbon and oxygen ocean uptake. Salinity is also an indicator of the freshwater cycle and intense freshwater flux interplaying with the high latitudes' cryosphere. Since 2010, the satellite SSS L-Band missions have provided unprecedented SSS global timeseries with a resolution allowing the observation of large to mesoscale features of the Southern Ocean mid latitudes. However, many challenges are still remaining since L-Band resolution and accuracy is still crude for observing SSS mesoscale features

at the higher latitudes. Future ESA, EC and CNES satellite SSS missions (CIMR, SMOS-next) will be designed to address these challenges with more accurate and higher resolved SSS measurements.

- Auger et al provided new insights into the ice-covered Southern Ocean circulation from multi-altimeter combination. A new Sea Level Anomaly (SLA) product has been constructed to document sea-level in the ice-covered Southern Ocean. This product benefits from a multi-mission analysis (including AltiKa, Cryosat-2, Sentinel-3A) and up-to-date processing techniques (e.g. neural network waveform classification algorithm, physical retracker for AltiKa) to retrieve Sea Level Anomaly with an upgraded resolution and accuracy. Validation is challenging due to the lack of in-situ measurements such as tide gauges or bottom pressure recorders to compare with. Despite this difficulty, this new altimetry-based multi-mission product allows to describe further the SLA and geostrophic currents seasonal cycle in the Subpolar Southern Ocean, and to investigate their forcing.

MAIN CONCLUSIONS AND RECOMMENDATIONS

- From the presentations and discussions, it follows that the key science challenge over the Southern Ocean is to better understand how the ocean circulation is coupled with high latitude cryosphere. For that, it appears fundamental to observe and quantify the main mechanisms governing interactions between the Ocean (sea level change, freshwater fluxes) and the Cryosphere (ice shelf, land ice, sea ice) and assess their respective impacts on both regional and global scales. This can only be achieved by considering the Southern Ocean as a truly coupled system with cryosphere, via the federation of community efforts bringing together ocean and cryosphere experts (sea-ice, land ice and ice shelf) and different satellite EO communities (passive microwave, altimetry, SAR etc.).
- The lack of in situ validation data is today one of the most serious limitations when analyzing and exploiting satellite data as well as for developing ad-hoc algorithms for, e.g., ice type classification, snow depth, ice thickness and retrieval of sea-ice and ocean properties (e.g. salinity, temperature and topography). This represents a major difficulty in our ability to well characterize regional ice/ocean dynamics, quantify fresh water fluxes, understand processes underpinning warming periods over the continental shelf regions and predict impacts on the large-scale thermohaline circulation. For example, most of Antarctica tide gauges has not been updated for decades in global databases and are not corrected from tides and sea-level pressure. Up-to-date, corrected, calibrated and homogeneous in situ data networks (e.g. Fiducial Reference Measurements, FRM) would be a key asset to improve the reliability of products from current satellite missions and pave the way for the future ones (e.g. CRISTAL and CIMR).
- Meanwhile the potential deployment of Polar FRM over the Southern Ocean, satellite multi-mission synergies could already help resolving some of this in situ data gap, and in particular observations of sea-level (and associated circulation), sea surface temperature/salinity (as an important fingerprint of freshwater fluxes from sea-ice and ice shelf), sea-ice thickness, concentration, drift, as well as spatial and temporal ice-shelf melt. There is also a need for long-term and continuous time series, including multiple-mission processed consistently. Indeed, a full reprocessing of past and present missions with methods tailored for the Southern Ocean should improve the understanding of the large-scale circulation and variability over the last decades. Moreover, fusion of multi-mission products and their analysis could make a major step forward in our understanding of the coupled ocean/cryosphere southern hemisphere system, which remains one of the key gaps (if not THE key gap) in our understanding of climate system as a whole.
- To do so, it would be first necessary to demonstrate the possibility of retrieving robustly, regionally and with optimal resolutions, key geophysical parameters under certain controlled cases and areas where we have gained knowledge from modelling and in situ measurements collected for several years (e.g. over the Weddell, Ross and Amundsen Seas). This would also require the completion of some current studies (e.g. CryoSat+ Antarctica), and eventually their extension to address unresolved technical and science challenges. It is also expected that new altimetry capability over sea-ice marginal zone (and melt ponds) will be explored. This could be done, for example, by exploiting machine learning methods applied to multi-missions (e.g. Cryosat -IceSat2) and multi-sensor observations (Sentinels, SMOS etc.) and where possible, by new Antarctic campaigns in collaboration with International agencies and European institutions.

3.13 OBS. CHALLENGES IN THE DETERMINATION OF FRESHWATER FLUXES IN THE SOUTHERN OCEAN

The Southern Ocean, and particularly the seas around Antarctic Peninsula, is a key region to understand Climate Change and its impacts in the Earth Climate System. One of the most pressing questions nowadays is the knowledge of the magnitude of freshwater fluxes in the interface ocean-continent-atmosphere, because they are likely the heralds of many changes to come. Estimating the continental ice loss, explaining the variability in quantity and quality of sea ice, or describing how melting water and continental run-off impact ocean circulation are several of those questions that definitely require an answer.

Oceanographic predictions in the Antarctic might be hindered by the limited ocean observing system compared to most areas of the global ocean. Hence this knowledge gap can be seen in the spread in ocean and sea ice reanalyses for polar regions which provide an estimate of their uncertainty.

Since weather forecasting systems like the European Center for Medium Range Forecasting (ECWMF) now include a dynamic coupling with ice-ocean models, ocean observations may have an impact beyond polar regions on mid-latitude weather predictions. For short lead-times (hours to days), model forecast skill depends strongly on initial conditions, which in turn depend on real time observations ingested through data assimilation, and particularly on the not always well known role of freshwater fluxes.

This session discussed the current status of existing near real time ocean observations efforts in the Antarctic, discuss knowledge gaps. The final objective of the discussion is to explore the need of first improving current SSS satellite products in the Antarctic; and second discuss the need to plan for future mission to ensure continuation of SSS measurements in the Antarctic beyond the lifespan of SMOS.

MAIN FINDINGS AND RECOMMENDATIONS

- The Southern Ocean plays a key role in ocean circulation with an important impact on climate connecting all ocean basins. It is critical for the uptake of anthropogenic carbon and heat. Buoyancy is a critical aspect in the Southern ocean and a better observation and understand of the fresh water fluxes and its related processes is essential (e.g., wind driving upwelling, sea ice and cooling removing fresh water, salinity dominating fluxes of freshwater)
- An important question today is what is the role of polynyas (open water in the sea ice) on exchange carbon and buoyance of sea ice. Ships collect data but far from polynya but they are poorly understood and satellites can help (Size of polynyas some 100x10o).
- In situ observation in Polar regions of both temperature and salinity are highly limited by lack of real time Argo profiling floats and by additional errors in different satellite products (e.g. difference dielectric constants at cold waters, ice cover variability and cloud cover). Major challenges include that there is an increased number of observations of both Temperature and Salinity (e.g. Argo, gliders, ship-based ob., etc.), but these are still very sparsely observed. Autonomous vehicles represent an opportunity offering new way to observe salinity and gradients at small scale, AV at VHR can bring more data for correcting satellite observations.

- In 2010 satellite missions of Sea Surface Salinity (SSS) provided the opportunity to gain a greater understanding. However, we still have difficulties to observe salinity from satellites in the Southern Ocean: measurements different from in situ, oceans more difficult than tropical, resolution issues, trends visible but ARGO and satellite different.
- There is a need to enhance the retrieval of SSS from satellite on the Southern Ocean. Recent ESA activities demonstrate the potential to develop dedicated methods and algorithms that may overcome limitations in the Southern Ocean (e.g., cold waters temp decreased and therefore larger error of salinity than in warm, sea ice and land contamination aspects, Antarctic signal more challenging than Arctic one).
- The community expressed the need to have SSS data as close to the ice shelf as possible. EO experts informed the minimum distance to the ice sheet one can get SSS retrievals from SMOS is 45 km. This distance is based on instrument specifications (i.e. SMOS which the mission with the longest time series). This new retrieval should be especially performed and validated as currently there are not SSS products in the Southern Ocean region. Even though if there are SSS products (e.g. seen in PiMEP) showing information around Antarctic peninsula, these data have not been validated and still show large uncertainties compared to the in situ observations.
- Dedicated SSS products would need to be related to specialized validated process in a few key regions where there is a good understanding of the ocean processes taking place in there. These regions include Weddle Sea (i.e. including the study of Polynyas as seen in Alessandro's presentation) and the Ross Sea. This study regions are of interest of other EU funded projects like SOCHIC (ref. to presentation on SOCHIC).
- The importance of improving SSS estimates might be related to improve the freshwater fluxes and the monitoring of changes in sea ice. Therefore, science effort must be in creating an integrated system of both satellites and in situ observations that help understand these changes.
- Furthermore, there should be exploration of potential synergies of SSS with other variables retrieved from satellites like Ice Shelf from altimetry sensors. Another example would be to explore to what extend SSS could aid current limitation seen in other EO communities like could be providing additional information on snow cover over the Antarctic peninsula.
- Finally, it was discussed what would be importance of SSS related to the study of the Carbon budget. Participants posed open questions that included: What is the Solubility of carbon in surface? Effect on stratification and mixing in deeper ocean and gas exchange? Is it possible to infer carbon syncs from SSS?

3.14 SATELLITE OBSERVATIONS FOR HIGH-LATITUDE NWP

The Numerical Weather Prediction (NWP) systems used to produce weather forecasts, analyses and reanalyses have massively improved over the last decades.

Advances in NWP represent a quiet revolution because they have resulted from a steady accumulation of advances in fundamental science (numerical techniques, physical parameterizations, data assimilation methodologies) and the use of vast amounts of observations and supercomputing capacities and technologies (Bauer et al., 2015). This quiet revolution resulted in today's forecasts of the weather six days ahead being as good as forecasts four days ahead twenty years ago. It also led to considerable improvements of long-term reanalyses, which constitute our best reconstruction of the past atmospheric state obtained with state-of-the-art NWP systems by blending a forecast model and observations through a data assimilation process. High-resolution global and regional atmospheric reanalyses such as the latest ERA5 and CARRA (Copernicus Arctic Regional ReAnalysis) produced by ECMWF and MET Norway for the Copernicus Climate Change Service (C3S), run at 32 km resolution globally and at 2.5km over the Arctic region, respectively, can now be confidently used to monitor the climate and its changes.

In parallel to the NWP revolution, climate models have also steadily improved. While weather and climate models were historically developed, maintained and run by distinct communities, they are increasingly sharing common elements (e.g. dynamical core, parameterizations of atmospheric processes, ocean dynamics and physics, sea ice, land, atmospheric composition). The drive towards a more unified (seamless) approach for weather and climate modelling capabilities across the different earth system components is motivated by the need to face common science and computing challenges, and by a growing interest for initialized predictions from sub-seasonal to seasonal and decadal scales. Similarly to medium-range forecasts, predictions at sub-seasonal and seasonal time scales have also improved considerably over the past decades (Vitart and Robertson, 2018; Stockdale et al., 2018). For example, the prospect for seasonal sea ice predictions in the Arctic looks bright (Zampieri et al., 2018) given that we can now deliver seasonal forecasts of the summer sea ice that are more skilful than climatological and even anomaly persistence forecasts, which was not the case 10–15 years ago.

In polar regions, however, producing reliable predictions between hours and seasons ahead is even more difficult than in other regions due to specific challenges related to process understanding (including those unique to the polar regions), modelling and observations (Jung et al., 2016). Challenges include: (i) the model representation of processes such as sea-ice, snow, stable boundary layers and mixed-phase clouds, (ii) the small number and maintenance of in-situ observations, and (iii) the suboptimal assimilation of the large data volumes from polar orbiting satellites due to ambiguous signal properties and larger systematic model errors than at lower latitudes. Further technical and scientific challenges arise with the emergence of coupled atmosphere-ocean-sea-ice prediction systems. These are related both to the coupled modelling of the atmosphere-ocean-sea-ice system and to the initialization of coupled predictions across the interfaces. For example, the uptake of sea-ice/ ocean observations in data assimilation systems for initialization is challenged by the large model and observational uncertainties (e.g., sea ice thickness).

This session focused on one particular aspect that limits predictive skill from hours to years ahead in polar regions: the suboptimal use of existing satellite observations. The keynote speakers revealed that at present we do not make optimal use of satellite observations for weather prediction and climate monitoring in polar regions. The aim was to spark a discussion which would result in recommendations on how we can increase the uptake of these observations in our numerical prediction systems and thus extract better value in terms of predictive skill and monitoring capabilities from the investment in, and fantastic opportunities offered by, current satellites.

Specific challenges exist which limit the benefits of polar satellite observations for predictive skill. Over the past 20 years, satellite data have become increasingly important for NWP and climate reanalysis, due to both an increase in the number of observations and the development of sophisticated data assimilation systems to fully exploit these data (Bauer et al. 2015). Polar regions are the most densely observed regions of the globe in terms of the data obtained from low Earth orbit (LEO) (or polar-orbiting) satellites, which include observations from high-impact microwave and infrared temperature and humidity sounders. Given the high availability of satellite data over the poles, there is therefore huge potential for reducing forecast errors with good use of satellite observations.

However, as shown in the keynote talks, there are several challenges that need to be overcome to increase the uptake of existing polar observations in prediction systems. For example, comprehensive experimentation performed with several operational global and regional NWP systems (ECMWF, ECCC, DWD, MET Norway) in the framework of the H2020 APPLICATE project and WMO's Year of Polar Prediction demonstrated that the use of microwave sounder observations is suboptimal during winter, particularly in areas with snow and sea ice (Lawrence et al., 2019). This is possibly related to issues in (i) the modelling of snow, sea-ice, mixed-phase clouds and shallow stable boundary layers, (ii) the assumptions regarding the surface emission and reflection over sea-ice and snow, made in the radiative transfer computations used to project model variables into satellite observation space (radiances) and (iii) the associated specification of background error covariances which is important for the weights given to the observation and model fields in the data assimilation. The strong positive impact of microwave observations on short and medium-range predictive skill in the summer season suggests that improving their use over snow and sea-ice is likely further improve forecasts in the Arctic and the mid-latitudes. Improving the use of microwave data would also benefit future reanalyses for time periods as far back as 1979, when the first microwave sounding instrument was launched.

Satellite observations of sea ice are not optimally used either. For example, Arctic sea-ice reanalyses are well constrained when it comes to their areal extent, because large-scale concentration of sea ice is easily assimilated; but are highly scattered for thickness which is not yet routinely assimilated. Recent works have demonstrated the benefit of assimilating sea-ice thickness information for seasonal Arctic sea-ice predictions (e.g., Blockley and Peterson, 2018). An investigation of sea-ice thickness in state-of-the-art reanalyses and climate models has revealed the large spatial coherence of variability for this field. This suggests that a limited number of well-placed in-situ monitoring stations could be sufficient to estimate the large-scale changes in sea-ice thickness at interannual time scales (Ponsoni et al., 2019), especially if this new data is complemented by improving existing satellite retrievals for which large uncertainties remain (Zygmuntowska et al., 2014). A more systematic consideration of satellite observational uncertainty in modelling studies is essential given that large-scale estimates of sea-ice thickness require assumptions about, or estimates of, the depth of snow sitting on sea-ice, which is currently poorly constrained.

SUMMARY OF RECOMMENDATIONS

The overarching message of this session is that to enhance the uptake and maximize the benefits of existing and emerging satellite observations for predictive skill and climate monitoring of polar regions, investment in observing systems must be carried out synergistically with the investment in numerical prediction systems. Investments for further improving all key components of prediction systems (coupled modelling, use of observations, data assimilation and ensemble prediction techniques) may be at least as important as investments in observations themselves, in particular in polar regions where the specific challenges posed in each of these aspects are larger than in other parts of the globe. These challenges limit the extent to which satellite observations can contribute to creating accurate initial conditions for weather forecasts, as well as an accurate, consistent and comprehensive depiction of past conditions through long-term reanalyses.

- Reanalyses are among the most-used datasets in the geophysical sciences. Emerging evidence of the added value of high-resolution regional reanalyses compared to global reanalyses for polar regions, reemphasizes the need for further investments in the joint development of global and regional coupled prediction systems. As recently demonstrated by Batrak and Muller (2019), improvements to the operational NWP systems underlying reanalyses are crucial to reduce systematic surface biases: the addition of a snow-on-sea-ice module in the regional HARMONIE-AROME system did largely alleviate a warm temperature bias in winter clear sky conditions, due to a better representation of the insulating effect of the sea-ice – snow layer on the underlying relatively warm ocean.
- The quality of predictions and monitoring at high-latitudes obviously also critically depends on ensuring that all cryosphere relevant parameters and in particular the sea ice, which experiences dramatic changes at the moment (e.g. thickness, extent, age, kind), are monitored as continuously as possible and that no data gaps occur due to discontinued or postponed satellite missions.
- Moreover, models and observations should form a "healthy ecosystem" where cross-fertilization is enriching and driving the development of each effort. An increased collaboration and cross-expertise between the observation and modelling communities is thus strongly encouraged as models benefit from observations and vice-versa.
- As recently demonstrated in the H2020 APPLICATE project and related projects, numerical experimentation with comprehensive modelling systems is very informative both for documenting the impact of current observing systems (see recently opened special collection in QJRMS on the Impact of Polar Observations on Predictive skill) and for guiding the design of future observing systems.
- Strengthening efforts towards the convergence of weather and climate modelling capabilities, and more generally resource and expertise sharing as well as mutualisation of efforts, as illustrated with the development of a unified sea-ice model (SI³) in the NEMO ocean model, will be key to improve prediction capabilities in polar regions.
- Finally, it is also important to continue to (financially) support coordination of community efforts such as those led by the WMO WWRP Polar Prediction Project which are instrumental for defining the scientific challenges and priorities and for channelling efforts for increasing predictive skill in polar regions and beyond.

3.15 POLAR AMPLIFICATION

Some areas of the polar regions have warmed two to four times faster than the global average since the late 20th century, a phenomenon termed as polar amplification (PA). Interestingly while polar amplification has been observed in the Arctic, the Antarctic region has not experienced such phenomena and the lack of sea-ice retreat here is often termed the Antarctic sea ice paradox. Understanding polar amplification further is important to understand the future of the Arctic and Antarctic regions, but is also vital to predict the impacts on global climate.

In particular, this session aimed at:

- Synthesise the current state of scientific research around polar amplification
- Provide a summary to assist decision-making on polar observations in this area.

Amplification in the Arctic: Polar observations were historically very sparse (e.g. Nansen expedition), and with sparse observations it is difficult to get an accurate picture of the whole environment or to reconstruct the climate history. The satellite era has enabled year-round monitoring since the 1970s and we can now track changes in sea ice extent with high accuracy, so seasonal variability is much better understood.

Local impacts of amplification in the Arctic are also very apparent. Shrinking snow cover in some regions, enhanced snowfall in others, reduced sea ice thickness and cover, glacier mass loss and retreat, permafrost thaw, and sea level rise have all been observed in the region. Along with these changes in the physical environment follow changes in ecosystem functioning, biota and wildlife. However, local changes are hard to predict or model. For example, permafrost conditions are very heterogeneous, and warming/thawing factors are very small-scale and localised.

We have recently begun to also understand global factors and impacts. Arctic warming is connected to remote changes such as in mid-latitude weather, but our mechanistic understanding of these linkages is still under development. For example, observational studies support that Arctic amplification is contributing to winter cooling at lower latitudes but most models do not currently show this connection, leading to a divergence between model and observational studies reflecting a basic lack of process understanding.

Arctic amplification also adds complexity and uncertainty to predictions and projections, but our near future predictions have improved greatly, thanks to the inclusion of observations.

Amplification in the Antarctic: There is strong recent warming in the Arctic, but in the Antarctic warming is slow or even shows a slight cooling. Even in the IPCC RCP8.5 scenario, by the end of the century, the Arctic is still warming strongly, but in the Antarctic we observe similar warming to global mean. So what is happening?

Current work is focused on understanding the many processes that can delay polar amplification. A major reason is the role of the ocean. Heat absorbed at the Southern Ocean is transported by circulation and reaches the surface further north, thus having a limiting effect on the warming in the Antarctic region. In contrast, there is also a strong uptake of heat in the North Atlantic, but ocean circulation takes this heat further northwards, contributing to the warming of the Arctic.

A second reason for delayed Antarctic warming is the polar lapse rate feedback, a climate feedback in which more warming occurs near the surface than at higher altitudes in the atmosphere. Antarctic elevation drives hemispheric asymmetry in warming by weakening base-state atmospheric stability and therefore limiting surface-trapped warming and the Antarctic lapse rate feedback. A modelled flat Antarctica (with uniform elevation of 0 m) shows warming more comparable to the Arctic.

In addition, the ocean and cryosphere are strongly coupled, but the coupling is not sufficiently understood to quantify the impacts on polar amplification in the Antarctic. Research is needed to better understand different processes and their interconnections. Overall, Antarctic amplification is an emergent pattern of a warming climate - it may not be observed yet, but this is likely to change as predicted in all CMIP models and we need to understand when this might occur.

State of the art – PAMIP

Coordinated sets of experiments are being conducted to address our understanding of polar amplification, such as PAMIP.

The Polar Amplification Model Intercomparison Project (PAMIP) seeks to improve our understanding of this phenomenon through a coordinated set of numerical model experiments.

For example, models investigating NAO show a weaker response than observations, even when constrained, suggesting there are other factors driving observed signals. These first results from PAMIP demonstrate how imperfect models can still help us to come closer to an understanding of drivers, sensitivities and global impacts of Polar Amplification.

SESSION OF RECOMMENDATIONS

Polar amplification is an issue of high relevance to policy-makers:

- In understanding the global climate system, and how the global system will respond to warming over the coming decades (e.g. Antarctic warming)
- In understanding what is likely to happen to regional climate: for example a warming Arctic may lead to colder winters in Europe and North America or more extremes.
- In understanding how changes in the Arctic can be used as a window into other areas that may be warming more in future.

The challenge for the future is to improve our understanding of the processes influencing Polar amplification, and the subsequent impact on global climate.

To do this, we can make better use of observations:

- To use an observations-as-reference evaluation cycle to help drive model improvement.
- To correct model biases, the largest issue for improving projections / predictions.
- Through data assimilation, with supermodels assimilating observations to remove model biases.
- To speed up model development, such as semi-automatic model tuning.

Provision of observations is therefore a strong limitation. The recommendations for observational priorities for improving understanding of polar amplification moving forward are:

- Generally more complete, fit for purpose polar observations such as sea ice thickness and at ocean-ice interface- across disciplines, polar observations are sparse compared to other regions, in particular in the ocean.
- Improved observations of ocean surface salinity
- Improved observations of ice shelf forcings of ocean
- Improved temperature inversion observations
- Mesoscale observations to better understand local/regional/rapid changes – ice, ocean, atmosphere.

3.16 BIODIVERSITY

This session addressed Arctic biodiversity change and its implications across scales and (eco-) systems. In particular, the session focused around three issues: Science-policy interface, knowledge gaps and conservation needs, with most of the talks addressing more than one of these issues. Main identified policy messages and research recommendations include the following.

Key policy-relevant messages

A key issue is how to shorten the time that it takes for research to translate into policy. Institutional barriers, silo-thinking, slow and non-reflective governance are common challenges. While reflective governance implies longer time of reaction, barriers between disciplines and scientific communities should be addressed urgently.

- An example for a successful approach is the Arctic Council Action Plan for Biodiversity that presents concrete actions based on the recommendations of the Arctic Biodiversity Assessment report. The new and ongoing EC projects should be explicitly asked to provide science-to-policy feedback, including, for example, contributing to the new action plan for biodiversity 2023-2030 and the Arctic biodiversity congress in Russia 2022 as well as participating in the organization of policy feedback workshops and documents in close cooperation with the relevant EC services.
- The approach to conservation that typically starts from the impacts of environmental problems to humans, is short-sighted and probably misleading, and should be replaced by a more holistic view recognizing biodiversity as a precondition for people's well-being, livelihood and ability to respond to change. This should, for instance, include building in knowledge ('we won't conserve what we don't value and we don't value what we don't know' - principal) and combining disciplines, issue fields (e.g., climate mitigation and conservation often have similar targets) and knowledge systems.
- Biodiversity should be recognized as a political issue, since our perspective will influence how the issues are framed which in turn will influence the discussion on management, rights, conservation and so on. For instance, whether we consider a northern landscape as a wilderness, or as a cultural landscape created by reindeer herders, will influence our views about its management. New, ground-breaking thinking is needed to address perspective deficits and to achieve understanding of cumulative consequences, for example in land use planning. Terminology and semantics are important to consider explicitly as how we name and frame have real consequences. A stakeholder approach should be complemented with a right-holders approach applicable to e.g. indigenous and local communities, or even nature itself

Research & innovation gaps

- Although there is sufficient knowledge to move on with conservation, there are also substantial knowledge gaps, related both to the environment itself (biodiversity, ecosystem services) and related to the governance structures, management practices, human behaviour and other issues promoting biodiversity conservation. The knowledge gaps and successful approaches discussed in the session included:
- How to better understand and anticipate the biodiversity loss, its drivers and mechanisms, and its effects on ecosystem services. Long-term monitoring data can be used to describe the biodiversity change both in terms of taxonomy and functional traits. New approaches will allow for a better understanding of the role of cryptic diversity, and the trait-based approaches will improve our understanding of the connection between biodiversity, ecosystem functions, ecosystem services and human well-being.

- Multiple stressors, cumulative impacts, least studied ecosystems should be the subject of further research, including:
- Biodiversity in sea-ice versus glacier fronts.
- Links between biomes: implications of ongoing Arctic sea ice degradation for terrestrial biodiversity; implications of run-off from land on coastal processes.
- Knock-on effects of increasingly frequent/severe extreme events (including for example weather events and fires) for Arctic social-ecological systems.
- Carbon sequestration – and the role of biodiversity in it - is complex, and poorly understood, especially in terrestrial belowground environment and in marine environment. Nevertheless, these are critical processes for climate feedbacks, and need to be included in the climate change scenarios as well as in Earth System Models, where they are currently under-represented.
- There are many questions related to human behavior and practices that need to be investigated to promote effective governance / management / policy-change. These include:
- identifying what worldviews, policies, and practices facilitate conservation of Arctic biodiversity in different settings.
- Better define what knowledge can help to activate, promote and institutionalize conditions supporting conservation.
- How to improve the role of participation in the production and ownership of knowledge, and the sharing of personal experiences.
- What are the knowledge needs for effective conservation in management tools and governance mechanisms?
- Practice-based knowledge, including traditional knowledge, has been undervalued despite that traditional land use practices often have been instrumental in creating and maintaining biodiversity and other associated values. Practice-based knowledge systems and local knowledge experts can provide important insights into more holistic and landscape-based management approaches.

Priority areas for conservation need to be identified and conserved without delay. WWF has a comprehensive map that suggests priority areas for Arctic biodiversity. Knowledge and methods to identify hotspots for conservation need to be consolidated and translated in actionable results. In addition, given the crucial importance of carbon sequestration for the climate, the areas with large carbon storage should be high in the priority list. Locally situated and participatory processes should complement the science-based identification of priority areas for conservation.

3.17 COPERNICUS HPCMS FOR POLAR REGIONS

In the coming few years, the Copernicus Sentinel fleet will enlarge significantly its current capacities to observe the different components of the earth system thanks to the advent of the new Sentinel caudate missions:

CHIME

Copernicus Hyperspectral Imaging Mission. CHIME is designed to provide routine hyperspectral observations to support new and enhanced services for sustainable agricultural and biodiversity management, as well as soil property characterisation. For this mission, it will utilise a unique visible-to-shortwave infrared spectrometer.

CIMR

Copernicus Imaging Microwave Radiometer. The CIMR mission will provide observations of sea-surface temperature, sea ice concentration and sea-surface salinity using a wide-swath conically-scanning multi-frequency microwave radiometer. It will be capable of observing a wide range of other sea-ice parameters as well.

CO2M

Copernicus Anthropogenic Carbon Dioxide Monitoring. Equipped with a near-infrared and shortwave-infrared spectrometer, the CO2M mission will measure carbon dioxide produced by human activity – with an aim to reduce current uncertainties in estimates of emissions of carbon dioxide from the combustion of fossil fuel at national and regional scales.

CRISTAL

Copernicus Polar Ice and Snow Topography Altimeter. CRISTAL will monitor sea-ice thickness and overlying snow depth using dual-frequency radar altimeter and microwave radiometer technology from Airbus.

LSTM

Copernicus Land Surface Temperature Monitoring. The LSTM mission responds to priority requirements of the agricultural user community for improving sustainable agricultural productivity at field-scale in a world of increasing water scarcity and variability. Airbus is prime contractor for this next generation satellite, including its high spatial-temporal resolution thermal infrared sensor.

ROSE-L

L-band Synthetic Aperture Radar. Since longer L-band signals can penetrate through many natural materials – such as vegetation, dry snow and ice – the ROSE-L mission will provide additional information that cannot be gathered by the Copernicus Sentinel-1 C-band radar mission – supporting forest management, precision farming and food security.

This session explored the opportunities offered by these new missions for Polar research. In particular, the discussion focused around two main questions:

Considering both maturity and impact aspects, what are the most promising information products likely to benefit from the synergies between the 3 future Copernicus missions?

Operational products such as sea ice charts, Arctic-wide maps of SIC, SIT and sea ice drift for assimilation into model simulations and forecasting of sea ice conditions / (climate) science have been identified. However, a wide range of additional examples were mentioned in the session:

- Synergy could bring continuous monitoring of the variation of the topography, the volumes, the masses, and by the way the energy transfer.
- Sea ice drift a promising multi-mission parameter in which drift patterns are mapped by ROSE-L/ CIMR and drift effects such including appearance and dynamics of leads are captured by CRISTAL.
- Synergy of microwave radiometer data and altimetry though models - improvements when using both passive radiometer (AMSR-2 -> CIMR) and altimetry (CryoSat-2 -> CRISTAL) could provide high quality NRT observations and short/mid-term forecasts.
- Optimization of algorithms for retrieving sea ice freeboard from radar altimeter data through joint assessments of lead detection in SAR images and altimeter data (with additional context from microwave imaging radiometers)
- Thickness of thin ice can be retrieved from CIMR and from ROSE-L data. For thicker and multi-year ice, CRISTAL, which is a dual-frequency altimeter system operating at Ku and Ka-band, provides data along profiles from which the thickness of sea ice and of the snow layer on the ice can be retrieved with a horizontal resolution of 80m. CRISTAL's ice thickness profiles and indications of the presence of snow on the ice may be used to complement the ice classification based on ROSE-L, Sentinel-1 and CIMR imagery.
- To investigate the interplay between sea ice deformation and ice thickness changes, combined analyses of ROSE-L and CRISTAL data would be most beneficial as demonstrated for past missions. Sea ice drift routinely derived from microwave imaging radiometers will be significantly improved using CIMR data that brings additional synergy.
- For icebergs that are equal or larger than the altimeter footprint and within the narrow ground track of the altimeter, CRISTAL may deliver iceberg height and ROSE-L areal extension (i.e. horizontal cross-section).
- SIC from a combination of CIMR and S1/ROSE-L (the combination of C- and L-band for SAR improves the ice -water separation, but each frequency can also be used as stand-alone in the combination with PMR).
- While each mission brings a suite of features and competence, scientific challenges remain to determine the optimal combination of data in an operational context. This needs further study to move forwards.

What concrete actions can still be taken to facilitate the synergistic use of the CIMR, CRISTAL and ROSE-L missions for enhanced applications and services?

- Triggering a project to get an overview over state-of-the-art in combining different sensor data (specifically here localised high-resolution SAR, narrow-track nadir radar altimeter, and broad context microwave imaging radiometry) and the motivation of the respective studies, asking for judgement by scientists and operational analysts on the usefulness and necessary improvements of those methodologies.
- Developments toward multi-mission automated sea ice forecasting and analysis remain at the root of R&D in an operational context. New multi-mission algorithms building on the strengths of each mission while mitigating their shortcomings are essential are required to move forwards.
- New tools for efficient searching of matching multi-sensor satellite data => SAR, microwave imaging

radiometry, altimeter (both radar and laser), optical and thermal sensors within the context of Copernicus are required.

- Support studies on information retrieval from multi-sensor satellite data, including comparisons of different methodologies ("classical" fusion, deep learning, machine learning, and information theory) should be encouraged. Using one sensor to train the other was considered promising in this context e.g. using CIMR to train Sentinel-1 to avoid the details of the SAR imagery
- Strategies are required to address temporal gaps between data acquisitions from different sensors (important for fast changing surface conditions such as drifting sea ice, glacier surges, oil on the ocean etc.) building on the strengths of each specific mission (carpet multi-temporal mapping from imagers complemented by unique high fidelity along-track measurements)
- Develop and further enhance simulations of ocean, ice and snow responses electromagnetic interaction with target surfaces to improve the quality and the uncertainties of the retrievals and propagation of uncertainties – particularly from missions used in synergy.
- Implement coupled ocean-ice-snow models that can assimilate both 2D microwave brightness temperature images (CIMR, ROSE-L?) and, along-track nadir altimeter data (the 3rd height dimension (CRISTAL)) in NRT.
- Consider dedicated joint campaigns serving the needs of synergy development i.e. Campaigns focused on CIMR, ROSE-L, CRISTAL. S1, Cryosat-2 and S3 in the context of coupled atmosphere-ocean-ice-snow assimilation systems and automated Arctic forecasting systems.

3.18 CROSS-WEAVING CITIZEN OBSERVATIONS, LOCAL KNOWLEDGE AND SCIENTIFIC RESEARCH IN THE ARCTIC

In the new Central Arctic Ocean fisheries agreement, cross-weaving of knowledge approaches is mandatory, but further work will be required to find out how this should to be undertaken in practice. In Greenland, community-led observing has led, and continue to be leading, to many natural resource management proposals but policy initiatives and frameworks are needed to enable cross-weaving. In Svalbard and Greenland, expedition cruise operators visit areas of the Arctic that nobody else goes to. The operators are eager to expand cooperation with scientists and citizen science programs. Overall, substantial theoretical work has been made on the needs for cross-weaving knowledge approaches. The Multiple Evidence approach is one approach. In the coming years it will be very important to get further from theory to practice with cross-weaving of knowledge approaches in the Arctic

Mobilizing all relevant knowledge, observations and data on the Arctic environment will be transformational. It will bring better understanding that can transform natural and social science research and natural resource management in the Arctic. This has great potential to impact the lives of Arctic peoples.

However, a number of technical and cultural barriers would need to be addressed:

- Insufficient consideration among scientists for the knowledge and observations of community members;
- Incomplete understanding of how to obtain and use data from different people (with varying beliefs, epistemologies, rationalities and cosmologies) and different knowledge systems in mutually beneficial ways;
- Lack of shared protocols enabling cross-weaving, and insufficient dialogue on how to ensure knowledge synthesis;
- Lack of government policy in support of cross-weaving knowledge;
- Asymmetric power relationships (and financial resources);
- Digital divide;

To address the above barriers, the following key research needs and opportunities have been identified:

- Develop a holistic data “ecosystem”: bridging conceptual, political and geographic distance;
- Establish an understanding of how to obtain and use data from different people and different knowledge systems;
- Develop ways to enable knowledge production and monitoring across scales;
- Explore appropriate ways for combining Indigenous and Local Knowledge, Community Based Monitoring data, and science data for improved "real-world" decision-making;
- Improve coordination of research efforts (related to cross-weaving knowledge) and mobilize all research results for operational contexts;
- Further develop observing-logistics and research infrastructures, including cyber infrastructure for cross-weaving knowledge.

3.19 DATA INTEROPERABILITY AND OBSERVING SYSTEMS

The polar regions are of increasing interest to the world because of their linkage to global climate systems, importance as sensitive ecosystems, geo-political strategic importance, opportunities for economic development, and home to Indigenous populations and other residents.

Polar data are required by the scientific community to support research on topics such as climate, atmosphere, land, oceans, ecosystems, ice and snow, permafrost, and social systems; and by the operations community to support impact assessments, engineering design, safe navigation and operations, risk management, emergency response, weather forecasting, and climate change adaptation. These activities contribute to environmental protection, heritage preservation, economic development, safety of life and property, and national sovereignty.

The polar data community is well organized and is pursuing activities to improve data acquisition, access, and management for all the diverse members of the polar community. Increasingly, the infrastructure associated with polar data is evolving from systems where data are discovered in data catalogues and downloaded to the local machines of users, to distributed platforms made interoperable using standards and providing users with storage and computational capacity close to large repositories of data.

There is still much to be done to move towards an enhanced model for polar data management, and by working together, we believe the polar community can achieve significant improvements in polar data interoperability. However, making significant progress will require adequate financial, technical, and human resources. The first step in acquiring the necessary resour ces is to define what is required. This session discussed what will be needed over the next five years to tackle the most significant challenges facing the polar data community.

OVERALL SESSION RECOMMENDATIONS

1. Improve coordination among funders.
2. Enhance global data communities and governance structures.
3. Support data community building, coordination, and engagement.
4. Ensure long-term support for data management and curation.
5. Engage with and enhance existing activities rather than create new initiatives.
6. Facilitate a change in attitude from proprietary data to data as a common good.
7. Improve education and training in data science.
8. Build on interoperable standards and ethically open and FAIR[4] data principles.
9. Involve and respect the perspective of Indigenous peoples in data collection and management.
10. Embrace cloud platforms and new analytical techniques (e.g., AI).

[4] FAIR data principles: Finable, Accessible, Interoperable, Reusable.

Building towards these long-term objectives, there are a number of tasks that could achieve short-term results:

A. **Arctic Data Cube** – Data cube technology has the potential to provide significant benefits in accessing and analyzing analysis ready data, particularly in the context of data fusion, machine learning applications, and as the foundation for digital twins. Use of this technology is currently underdeveloped within the polar data community. An Arctic data cube demonstration project could investigate applications in the polar context and act as a building block towards the realization of a Digital Twin Arctic. Canada has expressed interest in the concept. This task will contribute to Session Recommendations 4, 8, and 10.

B. **Polar Data Semantics** – Building on the progress that has been achieved in making polar data 'FAIR', the polar data community is now working on technologies to perform spatial-temporal semantic search[5]. Examples of such work are the Horizon 2020 ExtremeEarth project and the Canadian CCADI project. Now that the underlying ontologies are being developed, it is time for a demonstration project to illustrate how supporting software platforms can be implemented. This will be of particular interest to the Arctic Data Committee of IASC and SAON. This task will contribute to Session Recommendations 8 and 10.

C. **Polar Data Education Infrastructure** – The polar regions are experiencing the most rapid pace of climate change and thus they have become a critical component in courses concerning the environment and monitoring of the earth. Polar data platforms currently serve researchers with expertise in computer programming and earth observation data, but they do not yet have adequate tools to support the education of the next generation of researchers. Educators across Europe and Canada have expressed the need to have pedological tools and course material to help them teach about the methods for analyzing polar observations using state-of-the art cloud platforms and analytical tools. This task will contribute to Session Recommendations 7 and 10.

[5] Semantic search denotes search with meaning, as distinguished from lexical search which looks for literal matches of the query words or variants of them, without understanding the overall meaning of the query. Such technologies enable the formal articulation of domain knowledge at a high level of expressiveness and could enable the user to specify their intent in more detail at query time.

3.20 SNOW RETRIEVALS IN POLAR REGIONS

In the last years, significant progress has been made on the use of optical and microwave systems to better characterise snow processes in Polar regions (including mountain areas). However, there are still several challenges and opportunities that needs to be addressed.

- For instance, detecting significant trends in sea ice thickness changes requires snow information. However, snow on sea ice is still the largest source of uncertainty for radar sea ice thickness retrievals with sea ice thickness trends depending on snow models used.

On the active microwave side, over land and land ice, Sentinel-1 has been proven to provide unique information to better characterise wet snow and snow melting processes. However, still several aspects need to be addressed: e.g., investigate capabilities for mapping active melt and refreezing areas, quantification of liquid water in the snow pack, separation of processes for snow melt/snowpack structure change, which may not be only due to rain-on-snow events, i.e. attribution issues.

A new method on snow depth retrieval from Sentinel-1 cross/copol backscatter ratio has been presented, e.g., Sentinel-1 backscatter polarisation ratio processed at 100 m pixel spacing was correlated with snow pack model simulations of snow depth. The proposed retrieval algorithm converts the temporal change of Sentinel-1 cross/copol backscatter ratio to snow depth applying an empirical scaling factor which varies with elevation by an order of magnitude. The physics behind this empirical approach is not clear as well as the neglected role of C-Band sensitivity to underlying soil properties, variable snow properties and microstructure in this retrieval.

The potential of higher frequency radar for SWE retrieval is still to be investigated. Emerging experimental datasets with ground-based wide-band scatterometry from 1-40 GHz may be applicable to refine the physical basis of SAR retrievals at different frequencies e.g. L-band, C-Band and X-Band used by current spaceborne missions, as well as the role of higher frequencies proposed for SAR candidate missions. Experiments should be pursued in different snow regimes and conditions.

Synergy from multiple radar systems at different frequencies and times are beneficial (e.g., SAR and scatterometers). In addition, the combination of information from active and passive systems providing complementary information about the melting processes, its time and depths may represent an opportunity to better characterise surface processes.

On the optical side, Sentinel-3 has demonstrated a great potential to derive snow information such as fractional snow extent, surface snow albedo and surface grain size. Still some major challenges remain that need dedicated research such as cloud/snow discrimination (need for smaller bandwidth and probably additional bands and recommendation to incorporate these in Sentinel-3 next generation), enhancing the retrievals over step terrain (limitation over mountain ranges) accounting for solar illumination and sensor viewing angles, and better accounting for aerosols in the retrieval process. Detection of impurities content and type (dust, black carbon and algaea) is still to be studied. Melting water detection by optical sensors is challenging yet possible if a dedicated band is to be incorporated in future sensors.

Recommendations during panel discussion

- Complementarity of the data in the Copernicus Era is the way to go forward.
- Learn to deal with all the Copernicus data and the opportunities that new methods including machine learning will bring.
- Synergistic use of Copernicus mission will provide improved snow monitoring. Sentinel-1 and Sentinel-3 together with HPCM Copernicus Satellites will provide the basis for synergistic snow monitoring e.g. use of Sentinel-3 for total snow extent (dry + wet) Sentinel-1 SAR for detecting wet snow, ROSE-L for estimating SWE for dry snow regions in mountain areas and CIMR for SWE estimates at coarse resolution out side of mountains. Coordination of acquisition strategy of the missions is needed. Such synergy of sensors can also be useful for the retrieval of other snow parameters such as surface roughness, grain size and density. Studies to fully exploit the synergistic use of Copernicus missions for snow parameter retrieval should be initiated in preparation to HPCMs.
- SWE over land retrievals – physical based retrievals should be developed to allow the applicability in different environments; users require finer scales, resolve up to 100m. Future missions could help to satisfy some of the needs (e.g. Copernicus HPCM ROSE-L and CIMR).
- SWE Retrieval: InSAR is a promising physical based method to retrieve changes of SWE providing a direct relation of the interferometric phase to SWE changes, but several open issues need to be investigated: e.g. perform dedicated studies and campaigns to improve knowledge and understanding of temporal decorrelation of InSAR phase signal at different frequencies (of Copernicus SAR missions L-, C-Band) in dependence on various parameters like snow accumulation / ablation, time interval between InSAR image pair, snow pack properties, etc. Enable a spaceborne demonstration of the method using currents L-Band SAR data (e.g. SAOCOM A&B, 8 days repeat pass) and study the regional applicability of the method. The combination of InSAR SWE retrieval and distributed snow pack models to bridge temporal gaps SAR data acquisitions and spatial gaps (e.g. InSAR decorrelation) should be studied. Also the synergy of S1 (dry/wet snow discrimination) and L-Band SAR (SWE retrieval for dry snow) and should be tested.
- Sensor and acquisition planning important to ensure appropriate collocated data.
- Campaign data should be acquired to support development of new algorithms and later the validation of satellite based products. Transition of scales from campaign to satellite products are important.
- Recommendation on Algorithms: several retrieval approaches still require further refinements and research. Physical basis and understanding of retrieval algorithms is needed to allow transfer to different regions / environments.
- Composite backscatter from multi-sensor constellations allow synergy from multiple SAR satellites.
- A Dedicated snow SAR mission (shorter wavelengths & extensive coverage as Sentinel-1) is also of relevance with respect to Rain on Snow (ROS) monitoring. ROS has significant impact on the environment and the occurrence is changing with respect to climate change
- Over land, priority should be on development of open source and cloud-based tools to properly merge all EO data that we collect or have been collected. This can be done by data assimilation into a snowpack model or a land surface model.
- Upcoming thermal infrared missions Trishna (CNES/ISRO) and LSTM (Copernicus) should be extremely useful to improve our knowledge of the snowpack energy budget.
- Include new and/or narrower bands in next generation of Sentinel-3 and Sentinel-2 to improve the discrimination of snow and clouds for global monitoring. This will have a high impact for the quality of snow products and Copernicus land services. Start preparatory studies now.

3.21 SEA-ICE, ENHANCED ASSIMILATION AND IMPROVED FORECAST AND MODELS

Observation operators are important for data assimilation of EO data. These may allow data and models to meet somewhere between L1 and L4, e.g. by assimilating radar freeboard instead of sea ice thickness, L2 rather than spatially and temporally averaged L4 sea ice concentrations or even L1 brightness temperatures. A challenge is how we can merge passive microwave, scatterometer and SAR sea ice drift products to obtain better temporal and spatial resolution? Efforts must be sustained towards community sea-ice and snow microwave emissivity and backscatter models. EO and DA communities should work together to develop interfaces and observation operators.

Different models at different temporal and spatial scales have different needs for data to assimilate. Ice concentration data assimilation is limited by biases in ocean models. New generation ice model has significantly reduced errors in modelled ice drift. Systematic observations of snow on sea ice is important as well as improved temporal and spatial resolution in ice thickness observations. A merger of SAR and passive microwave ice drift data would be great.

Consistency between reprocessed and operational data is very important. Spatial continuity and consistency between observations of ocean and sea ice is important (surface temperature as well as SLA). Summer observational coverage needs improvements for ice concentration, ice drift and ice thickness. All data should come with proper uncertainties. Models develop towards higher spatial resolution and inclusion of more complex physics which can be constrained by new observations such as snow depth and melt ponds and also sub-grid scale lead and pressure ridge distribution. Assimilation of L1/L2 data is underway. More shared projects between modellers and observation teams would be good. We also need improved in-situ observations of the polar oceans, including standardised distribution of products. OSSE experiments can help prepare for future missions.

Stable long-term observations are needed to account for internal variability in model evaluation. Better process understanding is required to link aggregated TOA radiation changes to physical processes related to sea ice. Model runs with prescribed low-latitude SSTs for decadal predictions but interactive sea ice could be useful to evaluate models against observations.

Models are tools that have no inherent quality. Observations can provide answers to relevant questions even without models. Climate relevant evaluations of sea-ice simulations often would benefit more from better understanding than from new sea ice observations. The most important long-term policy questions related to Arctic sea ice require above everything else improved atmosphere models. The most pressing open questions relate to the regional evolution of sea ice, and to answer these we need reliable regional atmospheric forcing. More interdisciplinary efforts between observationalists and modellers should be encouraged and facilitated.

MAIN CONCLUSIONS AND RECOMMENDATIONS (NOT PRIORITIZED)

- The modelling community needs to improve the representation of ice-atmosphere interactions in models. This can be aided by higher resolution EO (both spatial and temporal) of e.g., ice motion, leads, ridges and other deformation features.
- The remote sensing, modelling, and forecasting communities need to gain better understanding and measurements of snow on sea ice.
- The forecasting community needs a consolidated and consistent ice drift record encompassing the various observations available today from SAR, scatterometry, radiometry etc. Ideally, the drift should come together with well-validated deformation.
- Improved measurements of top-of-the-atmosphere radiation are needed for better quantification of the Arctic amplification
- The necessity for long consistent data sets, especially for climate studies. This holds especially for ice concentration and thickness. For climate studies long consistent data sets are more important than new products.
- The potential of network design (e.g., by OSSE, QND, or statistical like Bayesian Hierarchical Modelling) for prioritizing satellite programs, as well as help with the design of sensors, deciding the spatial and temporal coverage needed, and determining the desired accuracy.
- The modelling and remote sensing communities should collaborate on developing better observation operators for assimilation of lower-level EO data in models.
- The modelling community needs better observation products for the summer months (concentration, thickness, drift and melt-ponds).

3.22 SEA-ICE, CALIBRATION AND VALIDATION

The lack of validation data is one of the most serious problems when analysing satellite data acquired over sea ice and developing algorithms for, e.g., ice type classification and retrieval of ice properties. Another example is the urgent need of an intercomparison of retrievals and measurements of sea-ice thickness and depth of snow on the ice.

Satellite radar and laser altimetry delivers essential ice thickness information but there are several uncertainties that result in significant challenges to meet the GCOS requirements in the near future. A way forward requires new methods fusing model simulations and EO data, as well as extensive validation data acquired following standardized protocols.

There is a wide range of autonomous underwater sensors that can provide information on ice and ocean properties and processes throughout the seasons. These observations can support sustainable management of Arctic waters and can be integrated with ecosystem monitoring and management.

A new surface-based Ku and Ka band polarimetric radar (KuKa) has acquired in situ observations of snow-microwave interaction at dual frequencies, and has potential to become a demonstrator for satellite snow thickness retrievals. It will be invaluable with future sea ice cal/val activities.

CNN-based algorithms have been advanced to improve the sea ice type classification in SAR imagery in order to achieve automatic charting of ice concentration and stage of development.

Given the importance of satellite altimetry and other sea ice thickness data products and their variety and uncertainties, there is a need for coordinated sea ice and snow thickness intercomparison projects that should include satellite observations, model results, and independent validation data. Recently, the WMO Global Cryosphere Watch (GCW) has proposed such a coordinated effort that will include derivations of uncertainties, and that will inform current and future activities of the ESA science program.

MAIN CONCLUSIONS AND RECOMMENDATIONS

The presentations and discussions from the SEA-ICE, Calibration and Validation session further reinforced the importance of such initiative and urgent need for sea-ice Cal/Val activities addressing uncertainties of sea ice and snow variables. They are critical for EO-algorithm development, validation and reconciliation of products derived from space-based EO data, and for tuning of AI/ML techniques and satellite simulators. Results will also help to derive uncertainty characteristics for near real time and reprocessed data record products that are operationally used in data assimilation for numerical weather prediction and short-term and seasonal ice forecasts as well as for climate reanalyses. Given that presently both, CryoSat-2 and IceSat-2 are in orbit and that their orbits are optimized within the Cryo2Ice project, this is a crucial time window for intensified community efforts. In addition, validation should include product intercomparison with data from different sensors and algorithms. Any such effort should include the computation of "traceable" uncertainty parameters for which methods should be improved, fully documented and accessible to users (e.g. see concept of maturity matrix). In this regard also the suitability of Fiducial Reference Measurements (FRM) should be examined as a means of sea ice product Quality Assurance (QA). Likewise, validation and intercomparison initiatives should be coordinated within the science and operational communities and should be based on standardized Best Practice protocols, e.g., CryoNet's Best Practices, that can be adapted by present and future initiatives. These will be invaluable in the preparation of future missions: e.g., the CRISTAL and CIMR Expansion Sentinel Missions, both with strong focus on sea ice. Based on community recommendations from an ESA/EUMETSAT co-funded workshop in November 2019 (Bremerhaven), the WMO GCW program has already defined a roadmap and developed a thorough proposal which could be supported by Space agencies and development programs such as the ESA and/or EU polar cluster.

3.23 SEA-ICE, NEW GENERATION SATELLITE-BASED PRODUCTS

Despite the wealth of satellite data, there are still gaps in sea-ice monitoring, especially during summer when the melting processes complicate the retrievals of sea ice parameters. Estimation of snow depth and ice thickness requires efforts, and data fusion is a solution. We still lack reliable pan-Arctic sea ice volume estimates at daily and weekly time scales, and measurements from missions such as CIMR and CRISTAL could help. It is difficult to cover all the spatial and temporal scales, for operational, seasonal, and climatological applications. Monitoring processes at the boundaries (e.g., sea ice /ocean) is another challenge. Observing the sea ice stress is needed, requiring instantaneous sea ice drift data currently not available. Finally, the satellite observations have to be available both in real-time (for assimilation) and over long time periods (for climatology), with a continuous Cal/Val program to evaluate the algorithms.

Satellite remote sensing is an inverse problem, and in the absence of robust forward modeling, e.g. based on radiative transfer, for sea ice, statistical methods can be a solution. There are many statistical approaches, depending on the problem complexity, from regressions to deep learning. How to exploit all the available information to improve the retrievals? Information can come from multiple instruments, from model outputs, from the spatial structure of the information, from additional physical constrains etc. Optimal estimation methods and neural networks are suitable to merge multiple data. Simple a posteriori merging of multiple parameters retrieved separately is not optimal, and the synergy between the information 'a priori' should be exploited. Collecting multiple EO products from diverse sources is not enough and strategies should insure their consistency for their use for geophysical problems. Model outputs can also be used efficiently with statistical methods to help retrieve surface variables: it improves the retrieval and facilitates its assimilation in the model (method adopted at ECMWF for soil moisture). Innovative statistical methods can leverage on the use of multiple information. Interactions between the remote sensing community, the modelers, and the applied mathematics experts (AI) are strongly encouraged to optimize our exploitation of the EO information.

The winter sea ice growth in the Arctic is analysed with satellite-derived sea ice concentration, sea ice thickness, and sea ice drift generated by CCI programs, and compared with model outputs. The total volume growth, (both dynamic change and thermodynamic growth) is estimated from satellite observations and models and compared over several seas. Its trend is studied for 2002-2019 and the impact of the ocean heat flux on the trend is quantified. The need for consistent data over these long timescales is emphasized. An increasing thermodynamic ice growth during winter is observed in the Arctic marginal seas eastward from the Laptev Sea to the Beaufort Sea, driven by the increasing sea ice retreat in summer. In the Barents and Kara Seas, there is a negative trend in the thermodynamic ice growth, due to the increasing oceanic heat flux.

Panel discussion

Seed questions:

- Multi-instrument / multi-parameter retrievals. How to optimize accuracy and resolution (time and space)?
- How to exploit synergy with models and in-situ information and insure consistency between products?
- How to evaluate the new methods and realistically quantify their uncertainties?
- How to insure seamless transition between ocean and ice?
- Application of the synergy to long time record?

The importance of having complementary EO-observations was emphasized. As an example, the use of CryoSat-2 and SMOS for generating maps of ice thickness was mentioned for assimilation into sea ice models. The need for mission planning to ensure data continuity was highlighted. One example is altimetry data for sea ice thickness estimation following the demise of ICESat-2 and CryoSat-2. Continuity and inter-calibration (hence, overlap between old and new missions) is required, so that parameters can be continuously monitored.

Merging data of different sensors and instrument channels has already been carried out, but there is not yet a systematic way to do this optimally. For instance, how to handle time gaps between different measurements, with possibly fast variations of sea ice conditions? This issue is more severe for high spatial resolution data. Are the different interaction mechanisms between E.M. radiation and sea ice taken into account when combining data? One possible solution for merging different temporal and spatial scales is to quantify uncertainties and the degree of variations of the measurements. How can the uncertainties be handled to get the most accurate merged product? This is a major issue for the assimilation community. Product uncertainties certainly have to be quantified.

For merging, one needs consistent operators for radiometry, scatterometry, and altimetry. Should they be derived from radiative transfer (RT) operators, from statistical approaches, or other methods? With a large frequency range and passive and active modes, it is, e.g., very difficult to develop a consistent RT model, and statistical approaches can be preferable. The advantages of RT are the physical equations, but to match the measurements, parameterizations are needed that are not physical anymore. In situ and EO data from field campaigns are useful to investigate combinations of data from different instruments and to assess the resulting products. However, a RT model based on one campaign data might not be applicable globally, given the spatial and temporal variations at the Poles and the emission/scattering diversity. Less physical and more statistical models work reasonably for practical inversions.

In situ information can be used to constrain the inversion of the products: one example is the use of snow depth climatologies based on in situ measurements, to learn about the snow density. For the marginal ice zone, sea ice cannot be treated as an isolated component, and a smooth transition is needed between ocean and sea ice retrievals, possibly using integrated multi-parameter retrievals. GNSS can also provide interesting complementary information in these areas, with its small footprint.

When using multiple data sources, the consistency of the parameters has to be ensured. For instance, for sea ice mass, different consistent parameters are needed to constrain the volume. Simultaneous retrieval of multiple parameters from multi-frequency and /or multi-satellite observations is a possibility.

CONCLUSIONS AND RECOMMENDATIONS

- Need to develop innovative merging strategies to fully exploit the synergy between the multi-observation missions and produce consistent retrievals of multiple sea ice / ocean parameters (e.g., ice thickness, snow on ice, sea ice concentration, sea surface temperature).
- Support of investigations related to methodologies to handle observations with different spatial and temporal scales, with estimation of the noise related to upscaling / downscaling
- The two previous items should benefit characterization of transition zones (ice/ocean/coast/atmosphere).
- Forward radiative transfer operators have severe limitations over sea ice, especially for the simulation of data from multi-sensor missions. Support efforts toward other approaches (e.g., satellite-derived parameterization)
- Encourage long term in situ measurements of key variables (cal/val), under a broad range of environments.
- Foster interaction between remote sensing community, modelers, and AI experts.