Integrated Arctic Observation System

Research and Innovation Action under EC Horizon2020
Grant Agreement no. 727890

Project coordinator:
Nansen Environmental and Remote Sensing Center, Norway

Deliverable 6.19

Synthesis Report from WP6: Application studies of Arctic Observing Systems towards Stakeholders

Start date of project:	01 December 2016	Duration:	63 months
Due date of deliverable:	30 November 2021	Actual submission date:	12 March 2022
		Resubmission after review	19 August 2022
Lead beneficiary for preparing the deliverable:		IMR	
Person-months used to produce deliverable:		na	

Authors: Geir Ottersen (IMR), Mikael K. Sejr (AaU), Ralf Döscher (SMHI), Mathias Göckede (MPG), Lisbeth Iversen (NERSC), Tim Kruschke (SMHI), Marie Maar (AaU), Gro I. van der Meeren (IMR), Hanne Sagen (NERSC), Anne M. Solgaard (GEUS), Andreas Ahlstrøm (GEUS), Ole B. Andersen (DTU Space), Fanny Ardhuin (Ifremer), Agnieszka Beszczynska-Möller (IOPAN), Erik Buch (EuroGOOS), Asbjørn Christensen (DTU Aqua), Hervé Caumont (Terradue), Bin Cheng (FMI), Finn Danielsen (NORDECO), Eva de Andrés (UPM), María Isabel de Corcuera (UPM), Martin Enghoff (NORDECO), Florian Geyer (NERSC), Agata Grynczel (IOPAN), David Gustafsson (SMHI), Torill Hamre (NERSC), Holt Hancock (UNIS), Cecilie Hansen (IMR), Georg Heygster (GEORG-Lab), Siwei Hu (NERSC), Larysa Istomina (U Bremen), Truls Johannessen (UiB), Thomas Juul-Pedersen (GINR), Andrew King (NIVA), Shfaqat Abbas Khan (DTU), Armin Köhl (UHAM), Janus Larsen (AaU), Ruibo Lei (FMI), Carsten B. Ludwigsen (DTU Space), Kjetil Lygre (NERSC), Guokun Lyu (UHAM), Kenneth Mankoff (GEUS), Christian Melsheimer (U Bremen), Frode Monsen (NERSC), Eva Friis Møller (AaU), Francisco Navarro (UPM), Tor I. Olaussen (NERSC), Are Olsen (UiB), Fabien Ors (ARMINES), Jaime Otero (UPM), Roberta Pirazzini (FMI), Michael K. Poulsen (NORDECO), Nicholas Roden (UiB), Laura Rontu (FMI), Nuno Serra (UHAM), Elena Shevnina (FMI), Morten D. Skogen (IMR), Gunnar Spreen (U Bremen), Detlef Stammer (UHAM), Espen Storheim (NERSC), Mathilde B. Sørensen (UiB), Zhongxiang Tian (FMI), Arantxa Triana-Gomez (U Bremen), Ilona Valisuo (FMI), Peter H. Voss (GEUS), Waldemar Walczowski (IOPAN)

(all contributors to WP deliverables are listed in Appendix A.1)

Version	DATE	CHANGE RECORDS	LEAD AUTHOR
1.0	01.10.2021	Outline	G.Ottersen
1.1	01.11.2021	1st Draft	All
1.2	21.12.2021	2nd Draft	G. Ottersen, M.K. Sejr
1.3	04.03.2022	3rd draft following revision	G. Ottersen
1.4	07.03.2022	Technical revision and submission	K. Lygre/S.Sandven
2.0	19.08.2022	Revision after external review	G. Ottersen/S. Sandven

Approval	Date: 19 August 2022	Sign. Stein Sandven Coordinator

USED PERSON-MONTHS FOR THIS DELIVERABLE					
No	***Beneficiary***	***PM***	***No***	***Beneficiary***	***PM***
1	NERSC	***X***	**24**	TDUE	
2	UiB	***X***	**25**	GINR	
3	IMR	***X***	**26**	UNEXE	
4	MISU		**27**	NIVA	
5	AWI		**28**	CNRS	
6	IOPAN		**29**	U Helsinki	
7	DTU		**30**	GFZ	
8	AU	***X***	**31**	ARMINE	
9	GEUS	***X***	**32**	IGPAN	
10	FMI		**33**	U SLASKI	
11	UNIS		**34**	BSC	
12	NORDECO	***X***	**35**	DNV	***X***
13	SMHI	***X***	**36**	RIHMI-WDC	
14	USFD		**37**	NIERSC	
15	NUIM		**38**	WHOI	
16	IFREMER		**39**	SIO	
17	MPG	***X***	**40**	UAF	
18	EUROGOOS	***X***	**41**	U Laval	
19	EUROCEAN		**42**	ONC	
20	UPM		**43**	NMEFC	
21	UB		**44**	RADI	
22	UHAM		**45**	KOPRI	
23	NORUT		**46**	NIPR	
			47	PRIC	

DISSEMINATION LEVEL		
PU	Public, fully open	X
CO	Confidential, restricted under conditions set out in Model Grant Agreement	
CI	Classified, information as referred to in Commission Decision 2001/844/EC	

Table of Contents

EXECUTIVE SUMMARY

This report, INTAROS Deliverable D6.19 - Application studies of Arctic Observing Systems towards Stakeholders, gives an overview of the activities, results and impacts of INTAROS Work Package 6 (WP6). The aim of WP6 is to demonstrate how an integrated observation system can be of specific benefit for society at local, regional or pan-Arctic scale. Through WP6 we show the capability of an enhanced Arctic Observation System towards advancing the economic role of the Arctic by providing support for better-documented processes and better-informed decisions within key sectors such as shipping, petroleum, fishing, and tourism. Further, WP6 demonstrates how the Arctic Observation system may be applied to further develop the accuracy of climate models, improve the understanding of biogeochemical cycles and ecosystem functioning, enhance fisheries and environmental management, increase the level of preparedness towards natural hazards, and develop better management and decision making concepts for selected local communities. Through WP6 INTAROS demonstrates enhanced data search and retrieval, assimilation into models, validation of estimated and projected climate parameters, scientific analysis, decision-support and policy-making.

Following a general introduction to INTAROS WP6, eight chapters summarise, for each topic covered, the main activities and results, data and models used, stakeholder/user benefits, and further development and exploitation of results. The topics span broadly and target very different end-user groups but they all share the same overall challenge: how to synthesize data across time and space from different sources, formats and scientific disciplines into aggregated synoptic data products that are relevant for end-users. The following topics are addressed: Improving skill of model predictions in the Arctic, Applying observations and models for environmental and fisheries management, Ice-ocean statistics, Remote sensing applications, Natural hazards in the Arctic, Greenhouse gas exchange in the Arctic, Case studies of community-based observing systems and Benefits of ocean observing for blue growth in the Arctic. The report then describes concrete showcases, software applications. Selected main results across WP6 are then presented, before the report ends with Conclusions and perspectives.

1. Introduction

One of the main reasons for monitoring the Arctic environment and its change is to optimize the possibility for decision makers at all levels to make data-driven and well-informed decisions that ensures the continued health and sustainable use of Arctic ecosystems for the benefit of the inhabitants in the Arctic and beyond. The realization of the Arctic as a hot spot for climate change with global relevance combined with technical development has driven an exponential increase in Arctic data production and resulted in groundbreaking scientific advances in our understanding of the Arctic, the rate of climatic change and consequences for ecosystem and societies. Obviously, there are still essential open questions for science to address, but the increase in data production and scientific knowledge highlights the challenge of communicating and synthesizing expert knowledge to decision makers, industry and the general public. The importance of embedding Arctic observations and natural science production in a societal context is central for EU's Arctic Strategy in general and specifically in the Integrated European Polar Research Programme through its socio-ecological focus. It highlights that climate change will shape or constrain societies in the future -especially in the Arctic but in Europe in general.

The aim of Work Package 6 (WP6) in INTAROS is to demonstrate how an integrated observation system can be of specific benefit for society at local, regional or pan-Arctic scale. Through WP6 we show the capability of an enhanced Arctic Observation System towards advancing the economic role of the Arctic by providing support for better-documented processes and better-informed decisions within key sectors such as shipping, petroleum, fishing, and tourism. Further, WP6 demonstrates how the Arctic Observation system may be applied to further develop the accuracy of climate models, improve the understanding of biogeochemical cycles and ecosystem functioning, enhance fisheries and environmental management, increase the level of preparedness towards natural hazards, and develop better management and decision making concepts for selected local communities.

Through WP6 INTAROS demonstrates enhanced data search and retrieval, assimilation into models, validation of estimated and projected climate parameters, scientific analysis, decision-support and policy-making. Seven specific tasks address a wide range of end-user groups, but they all share the same overall challenge: how to synthesize "point" data across time and space from different data sources, formats and scientific disciplines into aggregated synoptic data products that are relevant for and could be communicated to non-specialist end-users. This is a very complex task. Figure 1.1 exemplifies some of the numerous processes and their interactions.

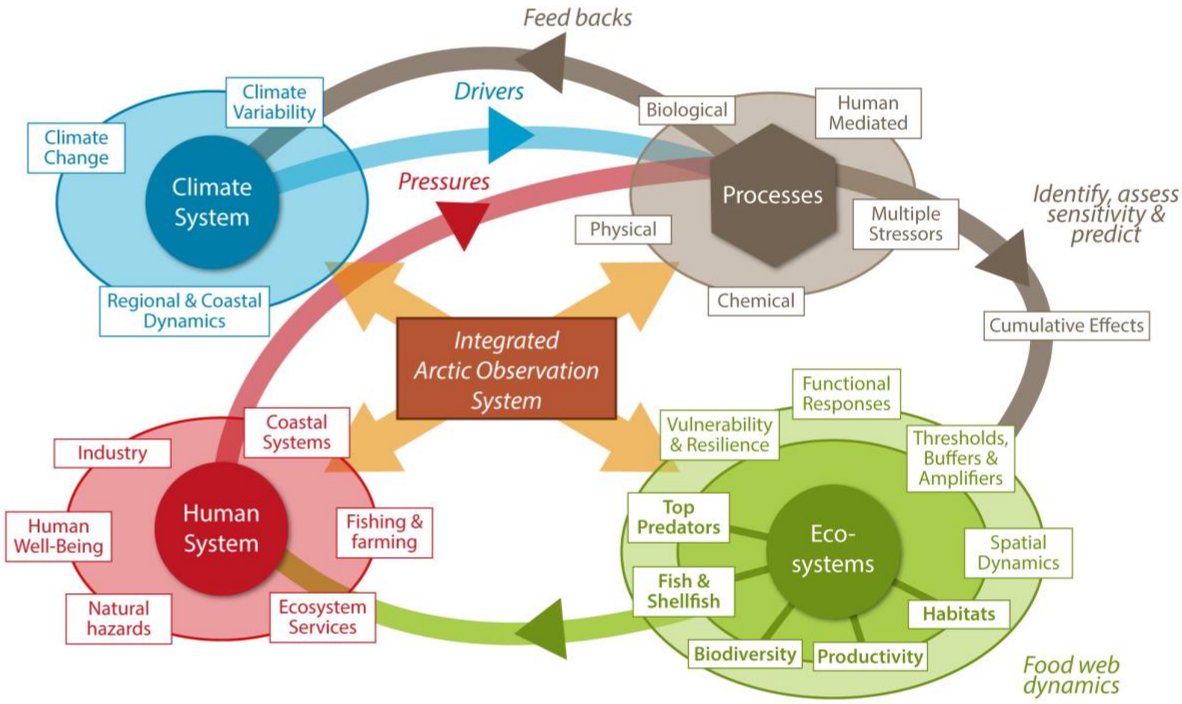


Figure 1.1. Conceptual diagram of the Arctic socio-ecological system supported by an Integrated Observation System. It shows the complexity processes and feedbacks that needs to be resolved through dialogue across sectors, disciplines, institutions and nations. Adapted from Bograd et al., 2019 10.3389/fmars.2019.00333.

Within INTAROS WP6 has had a key role in integrating between the work packages that have their main role as data collectors and providers, and various services and end-user groups (Figure 1.2).

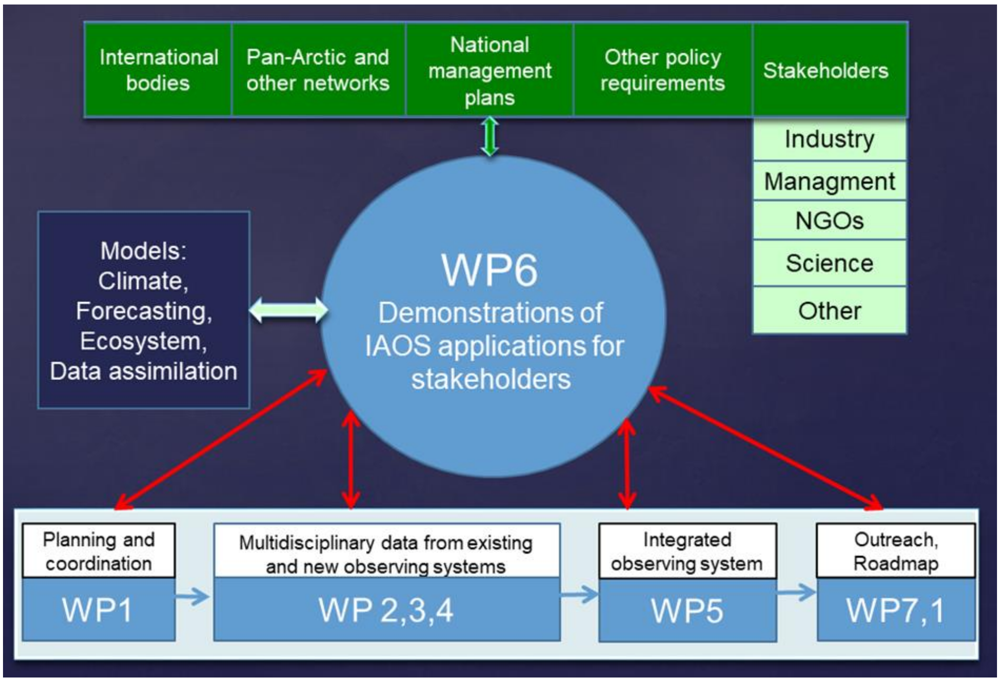
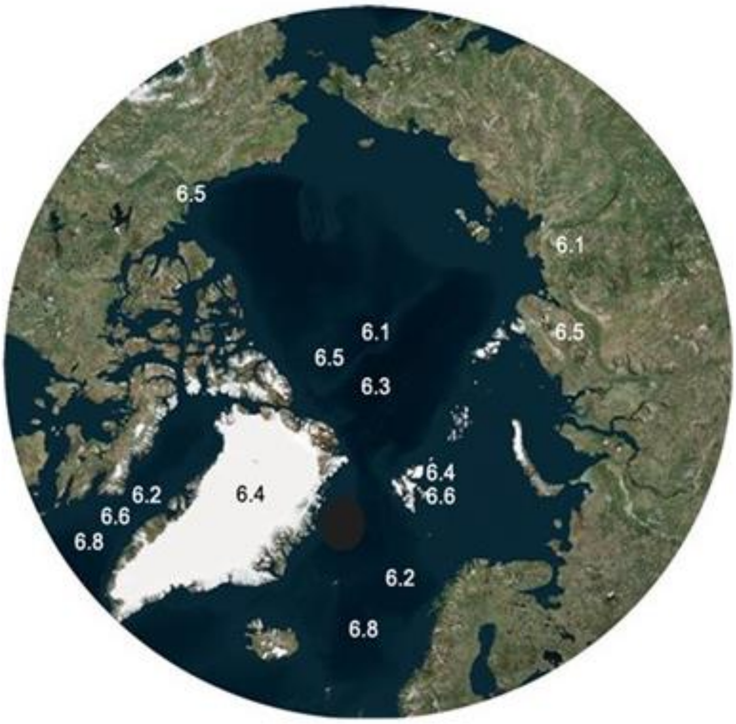


Figure 1.2. INTAROS structure, as seen from WP6.

In the following, each of the seven specific tasks is presented with focus on outlining which data were used for the service, who the service was relevant for and how the products be of use beyond INTAROS. In additions to the tasks that were outlined in the proposal writing phase, several additional demonstration cases were identified and developed during the project. Activities covered all spheres (land, ocean, atmosphere, and cryosphere) and produced a range of services or products that spanned from snow avalanche hazards to marine ecosystem models to policy briefs targeting different end user needs (Figure 1.3).



Task	Data	Aim	End user	Scale
6.1	Sea ice, land	Improve model prediction	Modellers	Circum-Arctic
6.2	Ocean	Integrate ocean data for management	Fishery managers	Regional
6.3	Ice, ocean	Improve operability of ocean risk assessment	Shipping, turism	Circum-Arctic
6.4	Cryosphere	Assess and map natural hazards	Decision makers	Local to global
6.5	Land, ocean, atmosphere	Better knowledge of Arctic Greenhouse gas exchange	Modellers, scientists	Regional and circum-Arctic
6.6	Land, ocean	Synoptic data products based on local and scientifc sources	Decision makers and industry	Local
6.8	Ocean	Integrated data products for living resource management	Managers	Regional

Figure 1.3. Overview of some of the main pilot services produced in WP6. Locations of the focus areas of the services are indicated, in addition several services are near pan-Arctic.

WP6 contains seven different tasks, each with several sub-tasks, involves a wide range of partners and has resulted in many Deliverables, listed in Appendix, Table A.2.

2. Improving skill of model predictions in the Arctic

2.1 Climate prediction

Main contributors: Ralf Döscher and Tim Kruschke (SMHI), Francois Counilon (NERSC), Juan C. Acosta Navarro (BSC)

2.1.1 Main activities and results

Three different climate modeling centres (SMHI, BSC, NERSC) were involved in T6.1. The common aim was to demonstrate the potential of new datasets produced as part of a unified Arctic Observation System to positively impact our ability to carry out skillful initialized climate predictions for the Arctic region (and beyond). The climate predictions serve as input or reference for planning and decision-making in various economical and societal sectors via upcoming climate services.

First, sensitivity studies were performed by NERSC and SMHI, employing their respective seasonal-to-decadal climate prediction systems, demonstrating the general benefit from initializing sea-ice information for these forecasts: The assimilation of anomalies of sea ice concentrations in NorCPM (developed and used at NERSC) was shown to be particularly beneficial for seasonal predictions along the sea-ice edge while sea-ice thickness is more important for the central Arctic.

A similar study by SMHI in collaboration with the Danish Meteorological Institute (a coordinated liaison with the Nordic Council of Ministers project ARCPATH; 2016-2020) using their own seasonal-to-decadal prediction system based on the model EC-Earth3 confirmed this positive result for longer forecast lead times up to several years and even for the temperature predictions over remote areas, such as the North Atlantic Ocean (Figure 2.1).

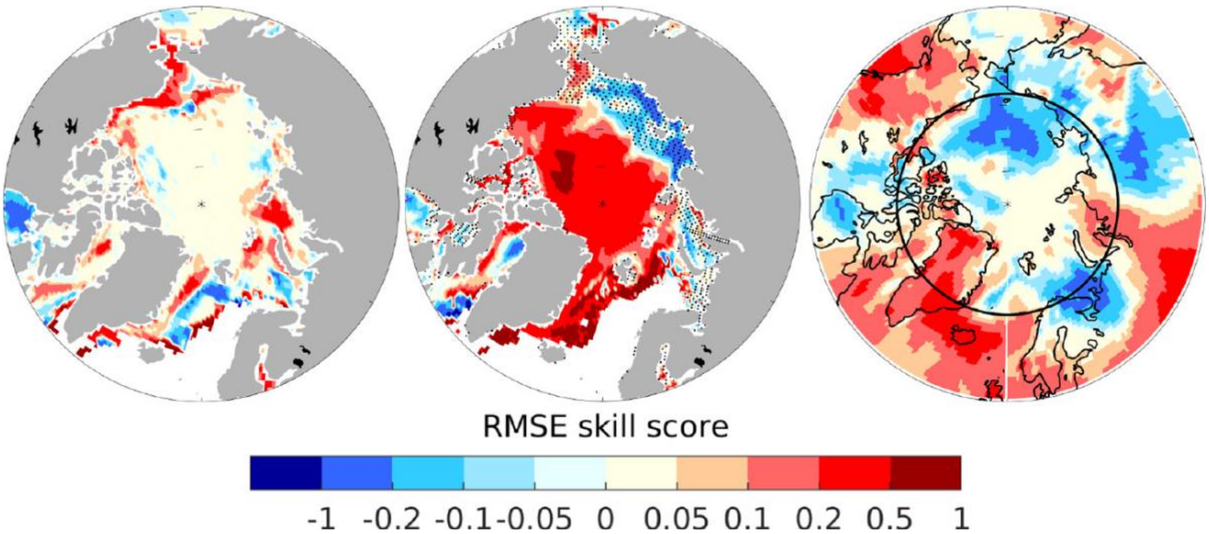


Figure 2.1. Seasonal prediction skill (measured by the RMSE skill score) gained by the initialization of sea-ice variables for the first winter (DJF) average of sea-ice concentrations (left), sea-ice thickness (center), and 2m-temperature (right). Positive values indicate higher skill (smaller forecast error) than when initializing only ocean temperature and salinity. Figure taken from Tian et al. (2021; https://doi.org/10.5194/gmd-14-4283-2021*, distributed under the Creative Commons Attribution 4.0 License)*

Second, datasets actually produced within INTAROS as part of the Arctic Observation System were used *(i)* to independently assess the quality (skill) of the conducted climate predictions and *(ii)* for assimilation to provide potentially improved initial conditions for the next generation of climate predictions. *(i)* was done by SMHI, using CERSAT sea-ice concentrations to validate decadal climate predictions regarding NH sea-ice area/extent as well as new assimilation experiments that should pave the way for the next generation of decadal climate predictions at SMHI (see D6.11 for more details). *(ii)* was done by BSC and NERSC. BSC assimilated the very same CERSAT sea-ice concentrations for their EC-Earth3-based seasonal prediction system, finding that this assimilation of sea-ice concentrations does not yield significant benefit for winter seasonal predictions (started on 1 November) but do have a remarkable positive impact on summer seasonal predictions (started on 1 May) regarding the sea-ice edge but also remote North Atlantic SSTs. The latter was shown to be the result of a so-called atmospheric bridge translating the improved sea-ice representation via more realistic large-scale atmospheric variability into the SST-signal. NERSC used anomalies derived from sea-ice concentrations as well as C2SMOS and ENVISAT CCI sea-ice thickness estimates and assimilated these in NorCPM, the seasonal-to-decadal climate prediction system developed at NERSC. It could be shown that the assimilation of sea-ice concentrations is particularly beneficial for predictions along the sea-ice edge while sea-ice thickness is more important for the central Arctic. Hence, the assimilation of both is complementary and yields the best overall result.

2.1.2 Data and models used

The INTAROS data that has been used in the climate prediction efforts in T6.1 is summarized in Table 2.1.

Table 2.1. Summary of INTAROS data used in T6.1

Product	Variable	Producer	Period covered	Spatial & temporal resolution
SMOS	sea-ice thickness	ESA	2010-2020	~25km; daily
CERSAT	sea-ice concentrations	IFREMER	1992-2021	12.5 km; daily
Arctic-HYCOS	river discharge	SMHI	1979-2020	daily values at 428 river gauging station locations

An overview of the three climate prediction modeling systems is given in Table 2.2.

Table 2.2. Overview of climate prediction systems and basic characteristics.

model	institution	resolution	ensemble size	reference
EC-Earth3	EC-Earth-Consortium (BSC)	Atm.: 80km Ocean: 1°	10	Bilbao et al. (2021)
EC-Earth3	EC-Earth-Consortium (DMI/SMHI)	Atm.: 80 km Ocean: 1°	15	Tian et al. (2021)

NorCPM	NCC (NERSC)	Atm.: 280x200km Ocean: 1°	10	Bethke et al. (2021)

It is worth noting that the current prediction system of SMHI/DMI used for CMIP6-DCPP does not make use of any thorough data assimilation. Instead, observed anomalies of ocean and sea-ice parameters are just added to the model climatology. BSC and NERSC however performed complete assimilation experiments, applying very different assimilation techniques, to create the initial conditions for their climate predictions.

2.1.3 Stakeholders/users benefiting from the results

The primary stakeholders/users of the results produced in T6.1 is the climate prediction community itself, given that the T6.1-partners demonstrate the benefit and usability of Arctic Observation System data for climate prediction purposes. Seasonal-to-decadal climate prediction however is an increasingly important source for planning and decision-making in various economical and societal sectors via upcoming climate services, hence different actors, e.g. in the energy sector, agriculture and forestry or tourism are interested users. Furthermore, other research disciplines working on climate impacts on these and other sectors are important and interested stakeholders. An example for the latter is an ongoing activity via the liaison with the Nordic Council of Ministers project ARCPATH, providing decadal climate prediction data to researchers trying to understand climatic reasons behind migration of fish and whales around Iceland - of relevance for the regional fishing and tourism industry.

2.1.4 Further development and exploitation of results

The above-mentioned dissemination and exploitation of the results is ongoing. Further peer-reviewed publications are in preparation, climate prediction data is freely provided via CMIP6-DCPP and the ESGF and the T6.1-partners SMHI and BSC contribute with quasi-operational decadal predictions to the WMO Exchange of Annual-to-Decadal Climate Predictions, led by the UK MetOffice (https://hadleyserver.metoffice.gov.uk/wmolc/). Collaboration with climate impact researchers and climate services is actively pursued by the T6.1-partners. The results found in T6.1 and the benefit from INTAROS Arctic Observation System data for climate prediction builds an essential element to developing the next generation of climate prediction systems for the T6.1-partners (see also D6.11-report in this respect). One conclusion is that sea-ice concentrations and sea-ice thickness together should be assimilated routinely into the assimilation procedures that generate initialization conditions for the respective climate model. Updates of those observations data should be utilized as soon as available. Thereby, also improvements of past observations, decades back, would have a positive effect on the initial fields. Further, the assimilation of sea-ice concentration is particularly beneficial for predictions along the sea-ice edge while sea-ice thickness is more important for the central Arctic. Hence, the assimilation of both is complementary and yields the best overall result.

2.2 Hydrological forecasting

Main contributor: David Gustafsson, SMHI

2.2.1 Main activities and results

The aim of this activity is to demonstrate the added value of integrated Arctic Observation Systems for enhancing and make available hydrological model predictions for the major Arctic rivers. The main objective is to combine the river discharge data from the Arctic Hydrological Cycle Observing system (Arctic-HYCOS) - that was assessed and enhanced in INTAROS WP2 – with the pan-arctic hydrological model Arctic-HYPE provided by SMHI (http://hypeweb.smhi.se), to predict and monitor fresh water inflow to the Arctic Ocean and changes in Arctic hydrological regimes. The demonstration case consists of an operational application of the Arctic-HYPE model providing daily analyses of the last 60 days, and medium range forecast of the coming 10 days. The Arctic-HYPE analyses and forecasts are stored at SMHI open data repositories and will be made available using OPeNDAP server technology. Arctic-HYCOS observations are accessed by the operational service using the tools and metadata provided by INTAROS WP2 catalogue (https://catalog-intaros.nersc.no/dataset/arctic-hycos-hydrological-data/).

For the above-mentioned demonstration case, a sub-set of the Arctic-HYPE model covering the Republic of Sacha (Yakutia) in Far East Russia, was used to develop a spring flood and river ice breakup forecasting service (Figure 2.2). This use-case is developed in collaboration with the HYPE-ERAS and Hydrology TEP projects with partners from Russian and Japan, funded through a Belmont Forum Arctic II collaborative research action and the European Space Agency, respectively. For the spring flood 2020, the new version of Arctic-HYPE (v4.2) was implemented to run operationally in the SMHI production system, publishing the outputs of the 10-day forecast and 60-day analysis daily in an internal offline version of the OPenDAP server. Results were extracted for selected locations in the Yakutia domain as exemplified in Figure 2.2, which shows the forecast issued 2020-05-08 for the Lena River just upstream of the city of Yakutsk. Similar forecast plots were produced for about 90 points of interest (Figure 2.2). The forecast points were selected based on availability of in-situ observation as well as stakeholder interest. A summary of the forecasts providing information on the expected river ice breakup dates, and river water level tendencies were made every day by collaborators at the Melnikov Permafrost Institute in Yakutsk and communicated with the local stakeholders. The 2020 river ice breakup in the Lena River at Yakutsk took place on the 11th of May, which was correctly predicted by the Arctic-HYPE forecast issued on the 8th of May (not shown here). A few days after the on-set of ice flow in the river, an ice jam was developed in the Lena River at Kangalassy; downstream of Yakutsk; with flooding of parts of the city. This use-case illustrates how the Arctic-HYPE data may be used in a future application when it is made available in the open OPeNDAP server.

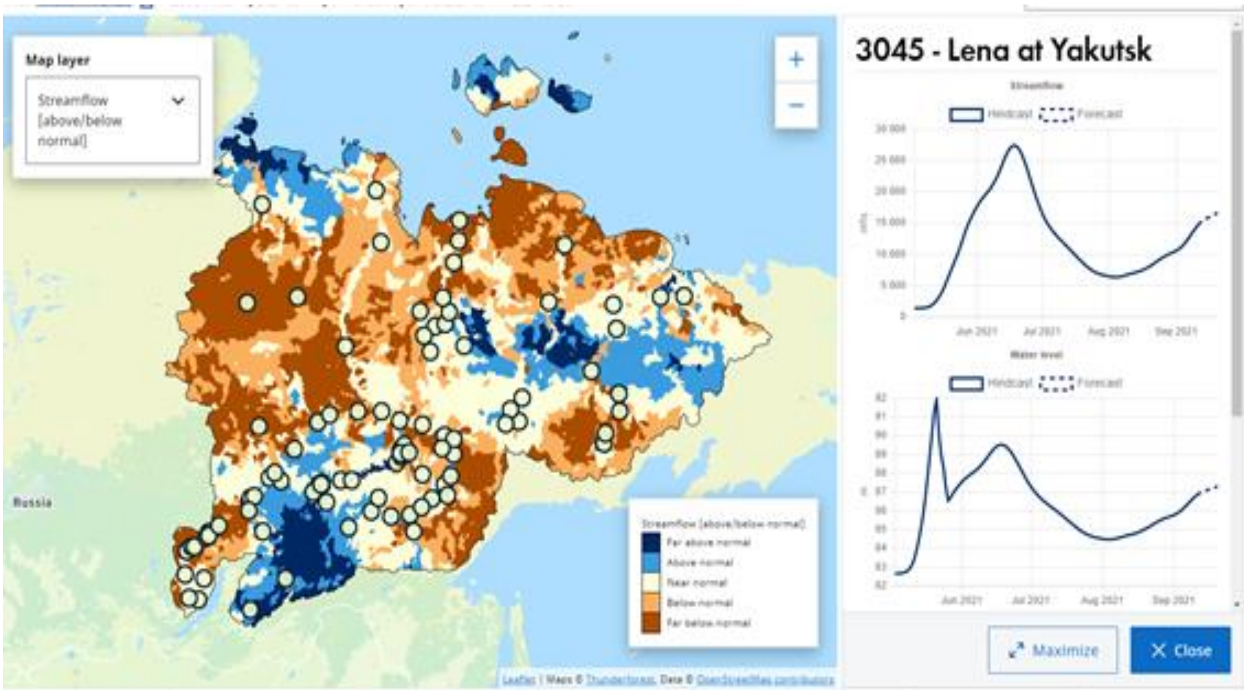


Figure 2.2. Left panel: Map of Yakutia-HYPE sub-domain of the Arctic-HYPE model, local station network, and forecast points.Right panel: forecast issued 2020-05-08 for the Lena River just upstream of the city of Yakutsk.

2.2.2 Data and models used

Arctic-HYPE version 4.2 is a new pan-arctic application of the hydrological model HYPE (Hydrological Predictions for the Environment; Lindström et al. 2010; SMHI http://hypeweb.smhi.se) simulating water balance of glaciers, snow, soil, lakes and rivers, representing processes such as runoff, river discharge and water level, and river ice growth, melt and breakup. It is based on Arctic-HYPE version 3.1 which was previously applied to the Lena River basin (Gelfan et al., 2017) and the Hudson Bay complex (MacDonald et al, 2018). The model domain covers the land areas draining into the Arctic Ocean and related water bodies in the northern seas. The total model area is 26 Mkm^2 distributed on 34421 sub-basins with a median area of 623 km^2. The forecast model is initialized by an analysis of the previous 60 days, forced by the HydroGFD v3 temperature and precipitation data (Berg et al, 2018), in which the Arctic-HYCOS data will be assimilated to improve the initialization. The historical simulations include daily river discharge for the period 1979 to 2019.

2.2.3 Stakeholders/users benefiting from the results

As part of the demonstration case for Yakutia, a summary of the forecasts providing information on the expected river ice breakup dates, and river water level tendencies were made every day by collaborators at the Melnikov Permafrost Institute in Yakutsk and communicated with the local stakeholders. Similarly any kind of authority and decision-makers facing with the risk of flooding in the Arctic region can benefit from these products.

2.2.4 Further development and exploitation of results

To improve the Arctic-HYPE data access, and to open up for structured retrieval through the INTAROS Arctic Observation System a new data dissemination service have been developed using a THREDDS data server implementing the OPeNDAP protocol. The server will be hosted at www.smhi.se providing Arctic-HYPE data in NETCDF format following the CF-convention (http://cfconventions.org/). The operational implementation of the server is still on hold due to security measures following the COVID-19 pandemic, but it is expected to be online later during 2021. Once this is done, any local user can combine the open available data provided by the INTAROS integrated Arctic Observation System with their own data to produce enhanced forecasting products. One recommendation from our work is that Arctic river runoff predictions for regional and/or pan-Arctic applications can be improved by assimilation of observational data, but the access to provisional data need to be improved for real-time analyses. Also, runoff data should be, were available, routinely used for reanalysis products. Those in turn could be used for improved runoff predictions providing river discharge to the climate prediction community and forecast products for local and regional stakeholder.

References

Bethke, I., Wang, Y., Counillon, F., Keenlyside, N. et al. 2021. NorCPM1 and its contribution to CMIP6 DCPP, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2021-91.

Berg, P., Donnelly, C., and Gustafsson, D. 2018. Near-real-time adjusted reanalysis forcing data for hydrology, Hydrol. Earth Syst. Sci., 22, 989–1000, https://doi.org/10.5194/hess-22-989-2018.

Bilbao, R., Wild, S., Ortega, P. et al. 2021. Assessment of a full-field initialized decadal climate prediction system with the CMIP6 version of EC-Earth, Earth Syst. Dynam., 12, 173–196, https://doi.org/10.5194/esd-12-173-2021.

Gelfan A. et al. (2017) Climate change impact on the water regime of two great Arctic rivers: modeling and uncertainty issues. Climatic Change,141 (3): 499-515. doi:10.1007/s10584-016-1710-5.

Lindström G. et al (2010). Development and test of the HYPE (Hydrological Predictions for the Environment) model – A water quality model for different spatial scales. Hydrology Research 41.3-4:295-319.

Lindström G, Pers C, Rosberg J, Strömqvist J, Arheimer B. 2010. Development and testing of the HYPE (Hydrological Predictions for the Environment) water quality model for different spatial scales. Hydrology Research 41: 295–319. DOI:10.2166/nh.2010.007.

MacDonald M. K. et al. (2018). Impacts of 1.5 and 2.0 °C warming on pan-Arctic river discharge into the Hudson Bay Complex through 2070. Geophysical Research Letters, 45, 7561–7570. https://doi.org/10.1029/2018GL079147.

Tian, T., Yang, S., Karami, M. P., Massonnet, F., Kruschke, T., and Koenigk, T. 2021. Benefits of sea ice initialization for the interannual-to-decadal climate prediction skill in the Arctic in EC-Earth3, *Geosci. Model Dev.*, 14, 4283–4305, https://doi.org/10.5194/gmd-14-4283-2021.

3. Applying observations and models for environmental and fisheries management

The main aim here is to demonstrate how observational and model data from an Arctic observation system may be used to enhance the environmental and fisheries reporting and management systems of the Barents Sea and Disko Bay, western Greenland (Figure 3.1).

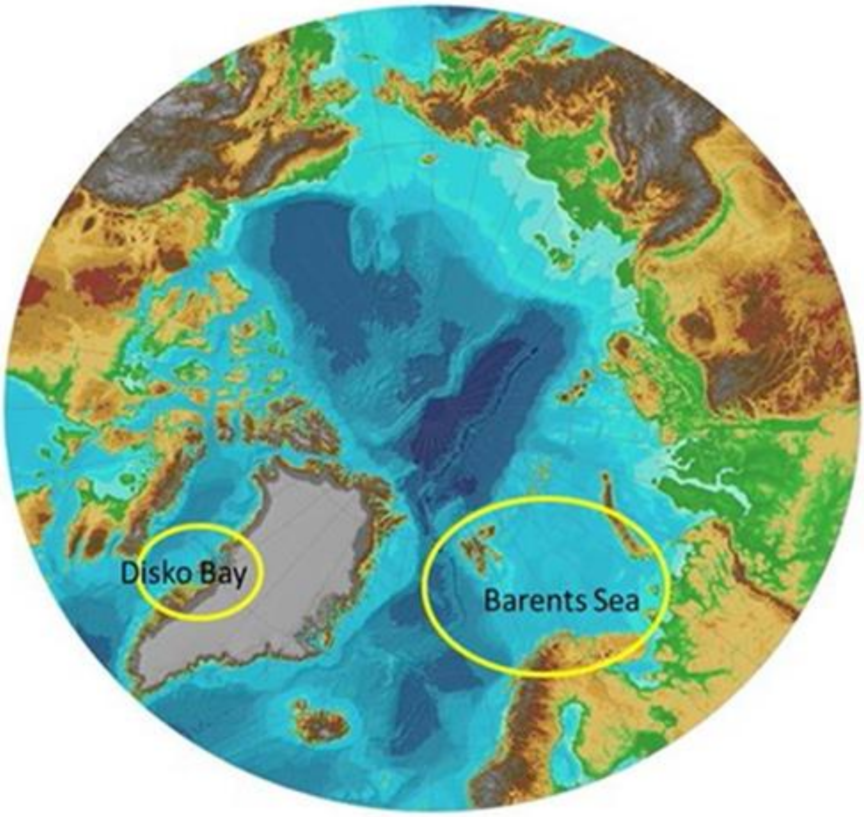


Figure 3.1. Location of the two main study areas, the Barents Sea and Disko Bay, Western Greenland.

Further, when such systems are established, this is valuable for implementing similar procedures in other parts of the Arctic. Towards these goals we use a range of state-of-the-art ecosystem models. The work has been carried out in close collaboration with stakeholders, through workshops and one-to-one interaction with representatives from Greenlandic and Norwegian fisheries and environmental management agencies. We use selected cases to analyse how data from observations and models, including that available through INTAROS, may contribute to advances in ecological and environmental understanding and allow for expanding existing environmental and fisheries reporting and management systems into new geographic areas.

The expected impact is to provide enhanced scientific basis for better-informed decisions and better-documented processes for managers and policy makers on local, regional and pan-arctic scales. The work described in this chapter is further documented in D6.2, D6.3, D6.10, D6.12, and D6.13. In the following, monitoring, modelling and stakeholder interaction is described for first the Barents Sea and then Disko Bay.

3.1 Barents Sea

Main contributors: Gro van der Meeren, Morten D. Skogen, Cecilie Hansen and Geir Ottersen, all IMR

3.1.1 Background, motivation and application

A main focus of the Barents Sea case was to evaluate the appropriateness and significance of the indicators in the Norwegian Barents Sea ecosystem management plan (BSMP). These indicators were selected earlier, assessing the quality of data for each suggested indicator, the length of time series, and the access to systematic updates. The data sets used for indicators in the existing management plans consists mainly of a simple time series, here we explore more complex time series, including some with a spatial component and focus on ecosystem-type.

3.1.2 Monitoring the ecosystem

Each year, a number of research cruises are carried out in the Barents Sea to monitor the status of abiotic and biotic factors and changes of these in the Barents Sea ecosystem, to support science and management. Traditionally the main focus has been on the commercially harvested fish stocks, but over the recent decades this has expanded to also become more ecosystem-oriented. Water samples are used to study hydrographical properties and the quantity of chemical nutrients and algae in the sea, while acoustic instruments like sonar and echo sounders are used to find and survey fish. By means of combined use of trawl sampling, echo sounding and sonar, we get estimates of the size and age structure of fish stocks. The most extensive ecological research cruise in the region is the Barents Sea Ecosystem Survey (annually August-October), joint between IMR and VNIRO Arctic, Russia. The survey collects information on physical and chemical oceanography, meteorology, phyto- and zooplankton, fish, benthos, marine mammals, seabirds, litter and contamination. The extensive spatial and temporal coverage since 2004 makes this survey especially important for evaluation of the state of the Barents Sea ecosystem.

3.1.3 Models applied

In the Barents Sea management plans, more than 70 indicators have been suggested, both simple and complex and with different degree of covariance. We used two end-to-end ecosystem models to evaluate how they respond to changes in climate and fisheries management, NORWECOM.E2E and NoBa Atlantis (Hansen et al. 2021). Net primary production is one of the simpler indicators obtained from the models (Figure 3.2).

Time series of a set of the proposed indicators have been estimated using the suggested methodology in BSMP under a future climate projection. Through an Observing System Simulation Experiment (OSSE) the effect of sampling scheme has been investigated, and the design of a minimum cost monitoring program has been suggested (Hansen et al., 2021). To reduce the number of indicators from the 70 suggested without losing to much information, the models have also been used to search for an optimal indicator subset. We found that both the area where the indicators are sampled and the timing of the observations are important for their performance. The indicators give a good overview of the Barents Sea ecosystem, but the management plans lack socio-economic indicators, which prevents a holistic view of the system. While the concrete outcome is specific for the Barents Sea, the approach and methods developed may be adjusted to be applicable to other regions. By building on models in addition to observations, the approach may also be applicable to data poor regions.

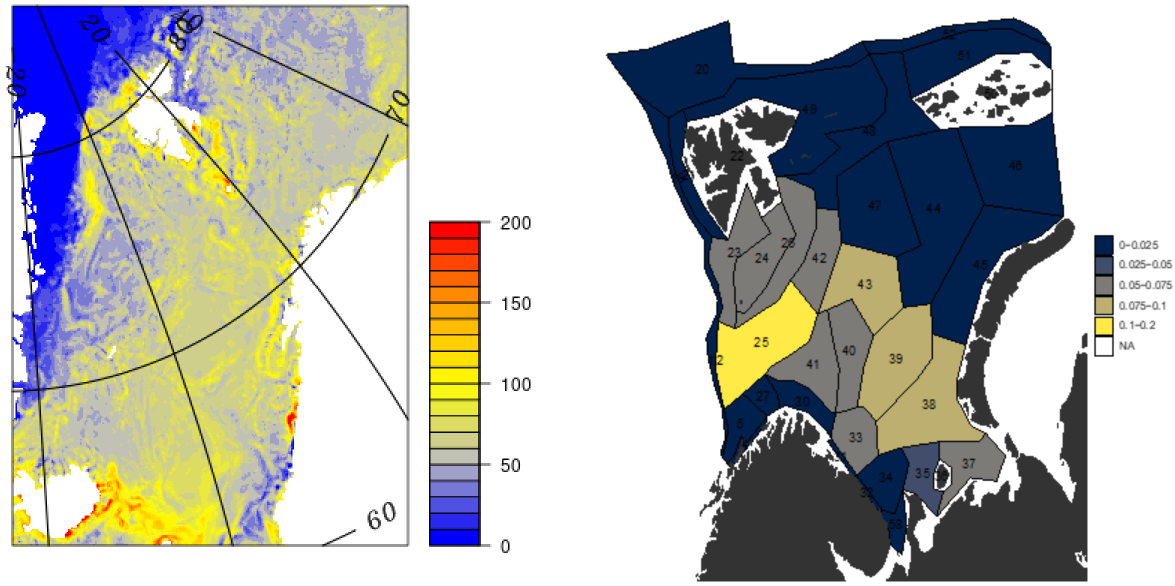


Figure 3.2. Examples of Barents Sea model products. New primary production from NORWECOM.E2E to the left, cod biomass distribution (winter) per Atlantis polygon to the right.

NORWECOM.E2E

The NORWegian ECOlogical Model system End-To-End (NORWECOM.E2E), a coupled physical, chemical, biological NPZD model system (Skogen et al., 1995), was originally developed to study primary production, nutrient budgets and dispersion of particles such as fish larvae and pollution. The model is now extended with several IBM (Individual Based Models) modules for key species in the Nordic and Barents seas. In INTAROS the model is run in offline mode using the NPZD and ocean acidification modules.

Physical ocean fields (velocities, salinity, temperature, water level and sea ice) from the ROMS downscaling were interpolated from 5-daily means and used as physical forcing together with daily atmospheric (wind and short wave radiation) fields from the NorESM1-ME simulation. The horizontal grid used is identical to a subdomain of the original ROMS grid.

Our simulation started on January 1, 2006. After a 12 year spin-up (running the first year 12 times) the full model period (2006-2070) was run sequentially. The time step used was 3600 seconds. The biochemical model is coupled to the physical model through the light, the hydrography and the horizontal and vertical movements of the water masses. For more details, see description in Skogen et al. (2018).

The Nordic and Barents seas NoBa Atlantis model

The Nordic and Barents Seas Atlantis model is an application of the Atlantis framework (e.g. Fulton et al., 2011), implemented for the Nordic and Barents seas by Hansen et al. (2019a,b). Atlantis is an end-to-end model, including multiple modules depending on the complexity of the model.

In this study, a harvest module was included in addition to physics and biology. Atlantis includes the same bottom-up physical forcing as Norwecom.E2E for the period from 2006-2068. However, the model started with spin-up in 1981, using two other applications of the ROMS model to cover the period until 2006. The version applied here included 53 functional groups and species, representing key components of the ecosystems in the Nordic and Barents Seas, ranging from bacteria, phytoplankton, and zooplankton to fish, seabirds and marine mammals.

The components are coupled through a somewhat flexible diet matrix, where the prey availability for the predator is defined. Fisheries for the 12 components in the model that are harvested, were implemented as time series of fisheries mortality for the period from 1981-2017. From 2017 and onward, the fisheries followed a flat maximum sustainable yield fishery for a majority of the commercially important species, prawns, capelin and snow crabs being the only ones excluded from this strategy. In this study, 112 simulations were run (Hansen et al. 2019b). Within each scenario there were 14 different simulations, each somewhat changing the mesozooplankton.

The changes in fisheries between the simulations provide us the opportunity to evaluate how the indicators were able to pick up differences in the harvest level or in the number of components that are being harvested.

3.1.4 Optimal sampling strategy

When estimating the value of an index, one is often limited to available observations from existing monitoring programs. Regarding the validity of an index this is not necessarily the best approach, as one also should ask how many observations is needed to achieve an acceptable precision. The quality of observations is largely affected by the sampling scheme. Numerical models can contribute to the efficient design and optimization of observing systems for science and operational uses.

OSSE was successfully conducted for the Barents Sea monitoring program. Using monthly mean outputs from the NORWECOM.E2E model the following question has been asked: which polygon in which month is the best one to approximate the inter-annual variability in the full regional indices. The answer to this question was approximated by comparing detrended annual time series to similar time series from each polygon and each month within a region.

3.2 West Greenland

Main contributors: Marie Maar, Mikael K. Sejr, Eva Friis Møller, and Janus Larsen, all AaU; Asbjørn Christensen, DTU Aqua; Thomas Juul-Pedersen, GINR

Our work in Greenland was centered around two activities; 1) developing an ecosystem model for Disko Bay and using it for sensitivity studies of the combined impact of sea ice changes and glacial melt water on coastal productivity. 2) a synoptic retro-perspective analysis of the coupling between key ecosystem drivers and the demersal fish community on the western Greenland shelf.

3.2.1 Monitoring

Disko Bay is located at the west coast of Greenland at the southern border of the Arctic sea ice and is influenced by both sub-Arctic waters from southwestern Greenland and Arctic waters from Baffin Bay (Gladish et al., 2015). The large glacier Jakobshavn isbræ is found in the bottom of the bay. It has been estimated that about 10% of the total Greenland ice sheet (GIS) solid ice discharge occurs from this glacier (Mankoff et al., 2019), and that it drains about 5% of the GIS. Over the last three decades, Disko Bay has experienced a large decrease in sea ice cover, and also year-to-year variations have increased in the last decade (Hansen et al., 2006), the Greenland Ecosystem monitoring program, http://data.g-e-m.dk). Disko Bay is an important "hot spot" for biodiversity and fisheries, and one of the best studied areas in Greenland. Still, integration of physical measurements of oceanography, GIS discharge and the impact on the marine ecosystems has been limited.

GIOS–Greenland Integrated Observing System. GIOS is a new, comprehensive, and coordinated, joint effort from the Danish realm, to provide new knowledge about the climate change in the Arctic environment, how quickly the changes occur and how they can affect the rest of the globe. GIOS boosts collaboration between all Arctic research environments within the Danish realm to ensure it maintain a leading role in Greenland environmental research and a well-informed Arctic voice in the international debate. GIOS develop sustainable research infrastructure in and around Greenland. Where possible, GIOS stations will be supplied with green energy and will continuously monitor condition of the air, ice, sea and land. GIOS covers the entire climate gradient in the Arctic and ensures an easy, open and fast access to measured data for everyone worldwide.

3.2.2 Disko Bay Ecosystem Model

An important aim was to demonstrate downscaling from large-scale regional models to fine-scale local models of Arctic coastal waters with focus on the Disko Bay. A coupled hydrodynamic and biogeochemical model was set up using the FlexSem model system (Larsen et al., 2020). FlexSem is a modular framework for 3D unstructured marine modelling. The system contains modules for hydrostatic and non-hydrostatic hydrodynamics, 3D pelagic and 3D benthic models, sediment transport and agent based models (https://marweb.bios.au.dk/flexsem). The biogeochemical model ERGOM was coupled to a 3D hydrodynamic module in the FlexSem framework. Several datasets from INTAROS and other sources were used to set-up and improve the model.

The developed model was used to evaluate external impacts of climate and environmental change on local marine resources to support management decisions and stakeholder involvement. The downscaling approach provides intelligent extrapolation of ocean parameters to un-sampled or under-sampled areas, as well as a platform to conduct OSSE design studies to optimize future observational deployment. We evaluated the relative importance of sea ice cover and freshwater discharge from the ice sheet for primary productivity by means a coupled hydrodynamic-biogeochemical model (FlexSem-ERGOM). Glacier meltwater discharge had a strong local effect near the glacier (Figure 3.3), but when considering the primary productivity at bay scale, sea ice cover was the most important factor. Considering the seasonal impact, variations in the sea ice cover had the strongest impact on spring production, whereas the changes in freshwater discharge had the largest effect on the later summer production. Primary production is a relatively simple indicator that is easy to understand and use in management when considering changes in the system due to environmental change or the link to higher trophic levels.

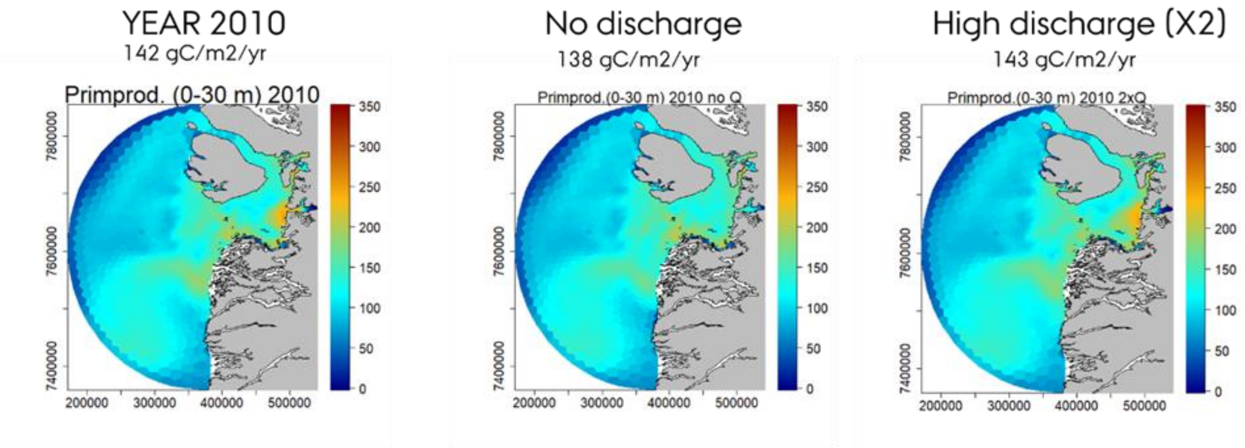


Figure 3.3. Annual primary production (0-30 m) for Disko Bay and the surrounding area for year 2010 (left), with no freshwater discharge (mid) and double freshwater discharge (right).

The experience from Disko Bay study will be used to evaluate how data from an Arctic observing system may contribute to advances in ecological modelling and understanding of Arctic ecosystems and allow for expanding of developed management tools into new geographic areas, e.g. in other Greenland coastal areas.

3.2.3 Demersal fish community and ecosystem drivers

The impact of climate variability on Greenland fish distributions was analyzed based on 24-years of fish surveys. Abundance and weight for 33 key species were recorded in 5713 net trawls along the shelf bottom during annual surveys (1993-2016) conducted by the Greenland Institute of Natural Resources along the West Greenland Shelf (59-73 °N). This data set is one of the most comprehensive biological data sets from the region and is thus ideal to explore links between potential ecosystem drivers and marine resources essential for the Greenland society. The ecosystem drivers included were water mass properties and temperature, sea ice cover, melt water from the Greenland Ice Sheet and trawl efforts. Time series of drivers were compiled based on open data repositories, remote sensing products and large-scale modelling.

The aim of this study was to characterize biological change and to assess potential drivers of change. We found extensive changes in the fish community, with an increase in biomass, average individual weight and trophic level combined with changes in the composition of the dominant species (Figure 3.4). Using previous studies as a base-line we found a partial recovery of the fish stock took place with a return to condition found in the mid 1980s. Most species showed a range expansion, but a general northern displacement was not observed. The development of all drivers (sea ice cover, water temperature, glacier run-off, shrimp trawling) appears to exert a positive effect on the fish community, hence the apparent recovery is partly facilitated by the climate change driven melt of the sea ice and Greenland ice sheet, which have contributed to increasing the productivity of the coastal ocean off SW Greenland.

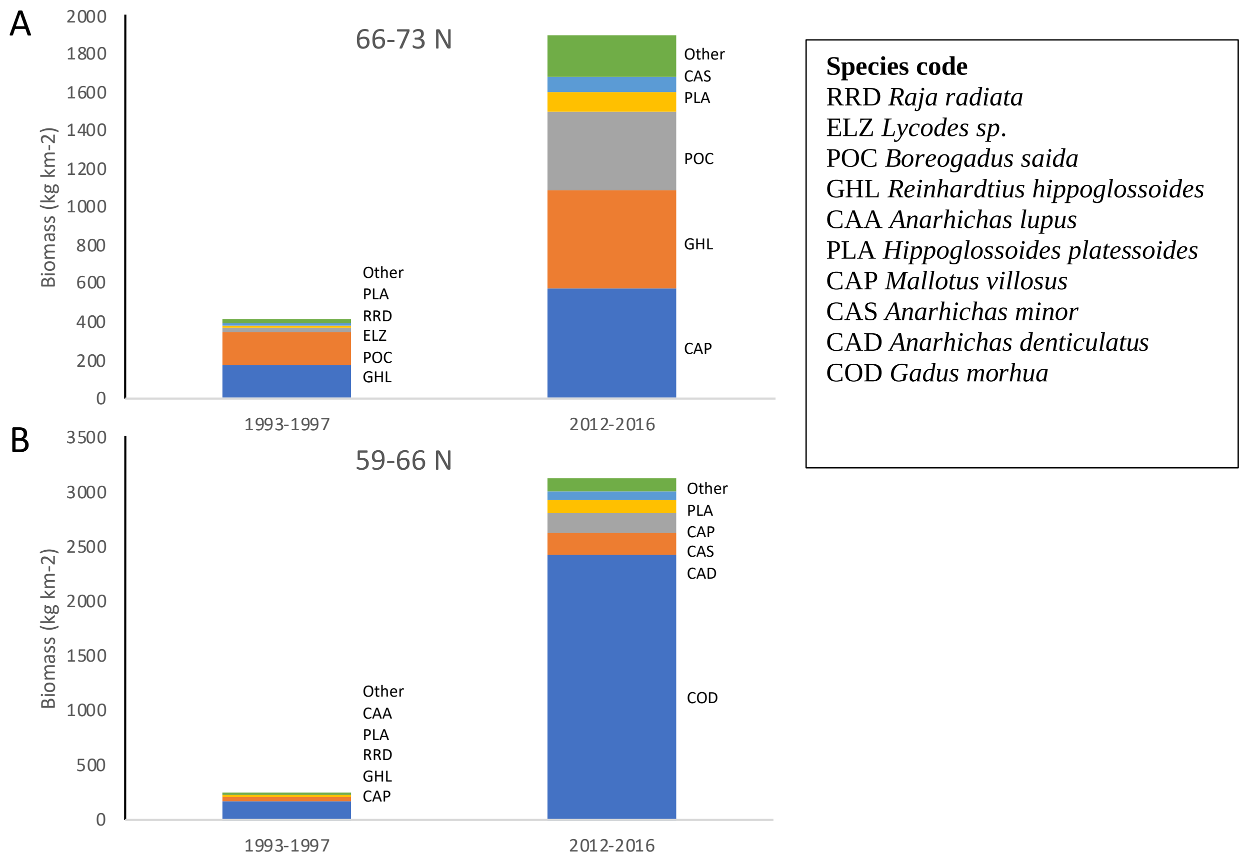


Figure 3.4. Changes in average summer demersal fish biomass in two regions of the SW Greenland Shelf.

The documented variability of the marine ecosystem off west Greenland, and the complexity of biotic and abiotic drivers involved, pose a substantial challenge for a society that relies almost exclusively on marine living resources. Developing social–ecological resilience and successfully managing the sustainable delivery of ecosystem services requires an ability to detect causal relationships between populations and environment and react to ecological feedbacks. For the West Greenland coast and shelf, it will require an improved dynamical understanding of food-web changes in response to multiple stressors. However, the study provides an example of how glacial and sea ice melt have increase light and nutrient availability for primary producers to facilitate recovery after improved mitigation actions to decrease by-catch. It is thus an example of how climate change may not be detrimental to the pace of recovery of exploited ecosystems. The findings of the study was presented at a workshop with Greenland stakeholders and the findings are being prepared for a peer-reviewed paper including scientists from AU and the Greenland Institute of Natural Resources.

3.3. Stakeholder involvement

Main contributors: Marie Maar and Mikael Sejr, AaU; Gro van der Meeren, IMR; Thomas Juul-Pedersen, GINR

Interaction with stakeholders from fisheries, maritime, and petroleum management and industry, and especially environmental management, has been a central part of our work. A main outcome was two (virtual) meetings for stakeholders with interest in the Barents Sea and off-Greenland marine ecosystems, respectively. The stakeholders represented marine and maritime-related authorities in Norway, Greenland and Denmark, the fishing industry, CAFF, Greenland Institute of Natural Resources, INTAROS partners and other EU project participants.

At the workshops, the ongoing monitoring programs and the applied ecosystem models were presented by the INTAROS scientists, refined and angled to be of relevance and use for the stakeholders. This was followed up by discussions on the users' needs, concerns, and means towards better exploitation in management. Through the workshops the stakeholders described how they want to be informed, and what kind of information they seek, facilitating better communication in the future. This interaction established in INTAROS and other ongoing projects will be continued.

The discussion made it clear that users in charge of sectorial human activity management appreciate scientific testing and suggestions for improving our ecosystem understanding. These seminars further highlighted the importance of inviting stakeholders responsible for all sectors of marine-related human activities to dialogues within research and monitoring of the climate, natural resources and ecosystems.

3.4 Further development and exploitation of the results

In Norway there is no established dedicated long-term support for work along the lines of that done in INTAROS. However, the ecosystem management plans for the Barents Sea and other regions are continuously updated and funding for this, including introducing enhanced methods, and further data, is partly funded by the Ministry of the Environment. Also, the people who have worked on the models and indicators in INTAROS are also heavily involved in the management plan work. Consequently, there is good underpinning for these results from INTAROS being applied in the scientific basis for updates of the management plan.

Stakeholders from both areas emphasized that long-term monitoring data of key variables is important for their work and that models can be useful with supporting information on indicators and future scenarios if the model uncertainty is assessed and explained. It was recommended that the next step could be to look at not only national data sets indicators, but also relate those to an Arctic international setting. The Barents Sea is a relatively data-rich area with well-developed complex ecosystem and food web models that are ready to support management. The data sets used for indicators in the existing Norwegian Barents Sea management plan consists mainly of simple time series. It is recommended to develop indicators based on more complex or a set of time series to better monitor a broader range of human pressures.

The more complex food web indicators presented for the Barents Sea could be useful to apply to the Greenland coastal system. The Greenland coastal ecosystem is a relatively data-poor area, but here the GIOS program has started to support, link and extend the existing monitoring. Modelling of the Greenland coastal ecosystems is still at a relatively early stage and mainly aimed for research, but models provide realistic results for primary productivity patterns. However, more work is needed to include more components of the food web before model results can support specific management actions.

In order to continue the development and exploitation of model products, it was suggested to have a special session at the next physical Greenland Science week, and thereby have more personal and active communication with stakeholders. Further, smaller stakeholder meetings at both sites with a more targeted focus or question could be arranged. It was encouraged to have more collaboration with existing working groups (within ICES, CAFF) and to establish a new NAFO/ICES working group on the west Greenland-Canadian system.

References

Fulton, E.A, Link, J.S., Kaplan, I.C. et. al. 2011. Lessons in modelling and management of marine ecosystems: the Atlantis experience. Fish and fisheries, https://doi.org/10.1111/j.1467-2979.2011.00412.x

Gladish, C. V., D. M. Holland, and C. M. Lee. 2015. Oceanic Boundary Conditions for Jakobshavn Glacier. Part II: Provenance and Sources of Variability of Disko Bay and Ilulissat Icefjord Waters, 1990–2011. J. Phys. Oceanogr. 45(1):33-63. doi: 10.1175/jpo-d-14-0045.1

Hansen, B. U., B. Elberling, O. Humlum, and N. Nielsen. 2006. Meteorological trends (1991–2004) at Arctic Station, Central West Greenland (69°15'N) in a 130 years perspective. Geografisk Tidsskrift-Danish Journal of Geography 106(1):45-55. doi: 10.1080/00167223.2006.10649544

Hansen, C., Drinkwater, K., Jâhkel, A., Fulton, E., Gorton, R., Skern-Mauritzen, M. 2019a. Sensitivity of the Norwegian and Barents Sea Atlantis end-to-end ecosystem model to parameter perturbations of key species. PLoS ONE 14. doi:10.1371/journal.pone.0210419.

Hansen, C., Nash, R.D.M., Drinkwater, K.F., Hjøllo, S.S. 2019b. Management scenarios under climate change – a study of the Nordic and Barents Seas. Frontiers in Marine Science 6:668. doi:10.3389/fmars.2019.00668.

Hansen, C., van der Meeren, G., Loeng, H., Skogen, M.D. 2021. Assessing the state of the Barents Sea using indicators. How, when and where? ICES Jour. Mar. Sci. doi.org/10.1093/icesjms/fsab053

Larsen, J., M. Maar, C. Mohn, and A. Pastor. 2020. A versatile marine modelling tool applied to arctic, temperate and tropical waters. PLOS ONE 15(4)doi: 10.1371/journal.pone.0231193

Mankoff, K. D., W. Colgan, A. Solgaard et al. 2019. Greenland Ice Sheet solid ice discharge from 1986 through 2017. Earth Syst. Sci. Data 11(2):769-786. doi: 10.5194/essd-11-769-2019

Skogen, M. D., E. Svendsen, J. Berntsen, D. Aksnes, and K. Ulvestad. 1995. Modelling the primary production in the North Sea using a coupled 3-d physical, chemical, biological Ocean model. Estuarine, coastal and shelf science 41:545-565.

Skogen, M., Hjøllo, S., Sandø, A., Tjiputra, J. 2018. Future ecosystem changes in the north east atlantic: a comparison between a global and a regional model system. ICES Journal of Marine Science 75:2355– 2369. doi:10.1093/icesjms/fsy088.

4. Ice-ocean statistics

The state of physical underwater environment (temperature, salinity, current and ocean sound) provides the constraint for the marine life (SDG 14). Changes will have strong influence on the ecosystems, and sustainable resource management. How we plan exploitation of resources in the Arctic depends strongly on reliable models and observations of the physical environment as input to our risk assessments. Assessing the acoustic impact of operations on the Arctic should be part of risk assessment to avoid long term and irreversible effects on marine life.

Understanding the complex processes of the Arctic system is critical for predicting its changes in the warming earth and for evaluating its impacts on the other components of the earth system. Despite recent improvements in the observing capability of the Arctic Ocean, the Arctic Ocean remains one of the least observed areas of the global ocean. This situation is mainly caused by the harsh operating conditions and by diplomatic constraints requiring that individual observing system components are deployed uncoordinated between nations. Attempts are being made now to integrate those different components into one sustainable and long-term Pan-Arctic observing system with improved temporal and spatial observing coverages, which could better monitor changes across the entire Arctic basin. On the other hand, data assimilation techniques have been applied to assimilate available observations into state-of-the-art coupled ocean-sea ice models, producing ocean reanalysis for better understanding dynamic processes (see Uotila et al., 2019).

OSSEs were used to evaluate the capacity of the existing Arctic Ocean observing system on monitoring the Arctic Ocean changes. In Task 6.3 OSSE have been used to address how to improve the ocean observing system, and a 10 years reanalysis has been analysed and delivered for use in environmental risk assessment system and in acoustic modelling (UHAM). The risk assessment system with a user-friendly interface has been developed to support different stakeholder groups in planning of safe operations in ice-infested areas (DNV-GL). Acoustic modelling and analysis of passive acoustic observations have been carried out to better understand the peculiarities of the acoustic environment in the marginal ice zone (NERSC). Ice-Ocean statistics have been derived from oceanographic in situ measurements in the Nordic Seas and Arctic Ocean over the last two decades (IOPAN). The ice-ocean statistics are important contribution to model evaluation in the Fram Strait. Observations form several ice buoys have been analysed to better parametrise the melting processes in ice-ocean models (FMI). Satellite remote sensing products are important for estimation of sea ice statistics, because systematic data sets have been built up over many years and is the main data source for sea ice extent (please see chapter 6). Table 4.1 shows the main lines of work documented here.

Table 4.1. Overview of sub-chapters with responsible lead partners and corresponding Deliverables with more detailed descriptions of the work carried out.

Sub-chapter	Lead	Deliverable
4.1. OSSE and reanalysis	UHAM	D6.4
4.2 Risk assessment system	DNV-GL	D6.15
4.3 Acoustic environment	NERSC	D6.14
4.4 In situ ice-ocean statistics	IOPAN	D6.14
4.5 Snow and ice mass balance buoys	FMI	D6.21

4.1 Observing System Simulation Experiments and reanalysis

Contributors: Lyu G, N. Serra, A. Köhl, and D. Stammer, all UHAM

4.1.1 What were the main activities and results from the work?

Two Observing System Simulation Experiments (OSSEs) were used to assess impacts of assimilating near-real-time pan-Arctic Ocean observations, delayed data from moorings, and monthly mapped SLA data on monitoring the Arctic Ocean changes. Results show that both ice concentration and ice thickness are significantly improved after data assimilation. Most of the sea ice concentration improvement occurs in the summer season over the entire Arctic Ocean. In the winter season, sea ice concentration error mainly exists near the ice edge regions, and the data assimilation slightly reduces the error, which may be related to the weak performance of the adjoint model in these regions. Sea ice thickness is significantly improved in the central Arctic Ocean. However, errors remain in the marginal seas and around Greenland. Ice volume after data assimilation matches the nature run well, especially in the summer season. Additional effects of moorings deployed in the Fram Strait and at the continental slope of the Laptev Sea are visible. Salinity changes mainly occur in the upper layers over the ice-cover regions, which are likely a result of ice volume reduction. Further improvements near the mooring locations are also visible but it is accompanied by degradation in the other areas. (Lyu et al. 2021b).

10-year ocean-sea ice synthesis

A coupled ocean-sea ice model (GECCO) and its adjoint were used to assimilate observations into the model. A 10-year ocean synthesis (2007-2016) were produced by assimilating all available observations. As in the OSSEs, the 10-year ocean-sea ice synthesis, the sea ice concentration contributes most to the total cost function and is improved after data assimilation. Sea ice thickness is also improved. Changes in temperature and salinity in the OSSEs and the synthesis show different patterns. In OSSEs, the temperature in the GIN seas is significantly improved, and the additional effect of moorings on the Atlantic inflow is visible. However, in the 10-year synthesis, temperature and salinity changes are mainly in the ice reduction regions due to enhanced air-sea interaction. Changes in the GIN seas are small. Slightly improvement of Atlantic inflow through the Franz Josef Land is visible. There are two possible reasons for the degraded performance in the 10-year reanalysis: 1) moorings have less spatiotemporal coverage in reality than in OSSEs; 2) fewer iterations are performed in the 10-year synthesis, and SST errors are not significantly reduced due to its small contribution to the total cost. Due to the long memory of Atlantic inflow into the Arctic Ocean, the potential effects of moorings deployed in the Fram Strait and the continental slope of the Laptev Sea are noticeable in the OSSEs. However, the mooring system needs to be enhanced since temperature and salinity are only observed at a couple of levels. Although the numbers of in-situ profiles have increased significantly over the past decades, it is still too sparse, and its effects are not apparent in our data assimilation experiments (Lyu, et al. 2021,ab).

4.1.2 What data and models were used?

The reanalysis and OSSE are based on the ECCO model using the 4DVAR assimilation of sea ice from remote sensing, ocean data from moorings and buoys (Table 4.2; Lyu et al., 2021 a,b). Atmospheric forcing fields were from the 6-hourly National Centers for Environmental

Prediction reanalysis 1 (NCEP-RA1) (Kalnay et al., 1996), including 2-m air temperature, 10-m wind vectors, precipitation rate, 2-m specific humidity, downward longwave radiation, and net shortwave radiation, as well as computed surface momentum, heat, and freshwater fluxes.

In the OSSE the pseudo-observations and their uncertainties were generated according to a 4-km Atlantic-Arctic simulation and the spatiotemporal coverage of various observing systems. The observations are then assimilated into a 16-km pan-Arctic Ocean model using the adjoint method and a 3-year assimilation window. The improved simulation is validated against the 4-km Atlantic-Arctic simulation.

Table 4.2. List of data sets used in the OSSE

Expt01		*Expt02*	*Instrument errors*
Data sets	Sea surface temperature	Sea surface temperature	0.35 °C
	Ice concentration	Ice concentration	10%
	Ice thickness	Ice thickness	0.2 m
	Hydrographic profiles	Hydrographic profiles	Temperature 0.02
			Salinity 0.02
	Daily sea level anomaly	Daily sea level anomaly	3 cm
		Monthly sea level anomaly Moorings 1	3 cm Temperature 0.02
			Salinity 0.02

In the re-analysis all available data for the period 2007-2016 were assimilated (Figure 4.1). A 4-year assimilation window is used, and the whole synthesis period is divided into three chunks: 2007-2010, 2010-2013, 2013-2016. The control vectors include daily atmospheric forcing on the model grid, which is linearly interpolated to model time and which includes 2 m air temperature, 2 m specific humidity, precipitation rate, 10 m wind vectors, downward longwave radiation, and net shortwave radiation. For the year 2007-2010, initial salinity and temperature are also adjusted. The reanalysis provided ocean state estimates on a grid represented by 50 vertical z-levels ranging from 10 m at the surface to 456 m in the deep ocean. In the horizontal, a curvilinear grid with a resolution of ∼16 km was used.

These data were published Lyu et al. 2020.

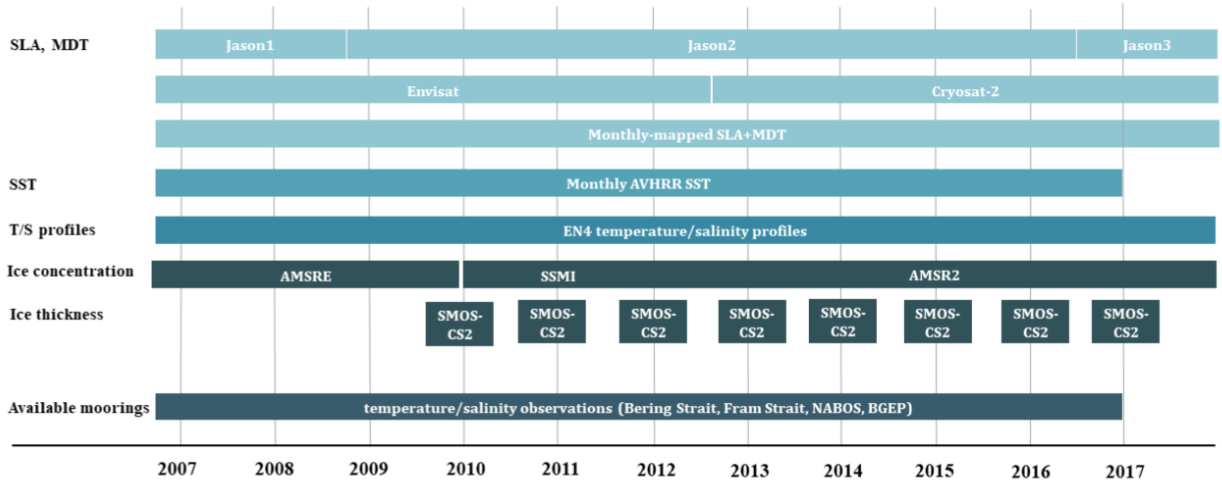


Figure 4.1. Available observations over the period 2007-2017.

4.1.3 Who are the stakeholders/users who will benefit from the results?

The OSSE provide important information about how to enhance the in situ observation systems and how to best complement the satellite based observing systems. The reanalysis provides time series of 3 dimensional product established by combining ice-ocean models with weather reanalysis products, sea ice information from satellites, ocean data from moorings, and ice-ocean data from drifting buoys through assimilation. The four-dimensional multiparameter products has many applications e.g. into risk assessment systems and into acoustic models. The risk assessment systems for the Arctic are usually focused on using satellite remote sensing data to perform sea ice risk analysis for shipping, while including statistics of subsurface environmental conditions from reanalysis products can support stakeholders within resource management, and environmental assessment.

4.1.4 How should the results be further developed and exploited after the end of the project?

The Arctic reanalysis described above must be viewed as a tool that can now be further improved and further developed. Including new observations and prescribing more realistic errors both will lead to more accurate estimates of the Arctic circulation and its impact. Resulting fields will form the basis for developing information for users and stakeholders, such as transports and their changes, sea level change, freshwater or heat content change. Respective fields in the future will be used especially also for analyses of carbon budgets in the Arctic; they will likewise serve to initialize climate prediction efforts.

4.2 Risk Assessment System

Contributors: Øivin Aarnes and Odd Willy Brude, DNV GL.

4.2.1 What were the main activities and results from the tasks?

The initial work included consulting with potential stakeholders including DNV's industry partners (energy companies, maritime operators, and authorities) and thereby selection of relevant use cases. Two use cases were selected and described in D6.5, sea ice analytics and anthropogenic marine noise. Both cases are highly relevant in the context of environmental risk and shipping risk and both cases were outlined regarding analytical needs and data needs (parameters, resolution etc). Due to the complexity of the anthropogenic noise use case and a need to focus resources, only the sea ice use case was brought forward to implementation.

4.2.2 What data and models were used?

The Risk Assessment System itself is built as a web mapping solution running on ArcGIS for Server. The solution will be launched on DNV's GIS platform: https://maps.dnvgl.com .

Main data sources for the current version of the system are a 30-year climatology on sea ice from the National Snow and Ice data Centre (NSIDC) and the Arctic ocean–sea ice reanalysis for the period 2007–2016 from University of Hamburg (UHAM). Data visualisation includes monthly sea ice extent (sea ice index), concentration and thickness, in addition to potential water temperature and ocean salinity (Fig. 4.2). UHAM data are retrieved from the INTAROS catalogue https://catalog-intaros.nersc.no (Lyu et al. 2020).

The risk assessment tool also includes some analytical capabilities. This includes features like

- Infer parametric statistics on sea ice cover and persistence
- Compare and assess change in sea ice cover and variables over time
- Delineate ice edge over a given period by applying custom thresholds
- Extract variable time series for any given location (to be implemented)

1. Determine relevant data sources to the analysis (i.e., the use cases)

2. Qualify data with respect to quality, consistency, and reliability

3. Assemble and integrate data in ArcGIS

4. Spatial analysis to derive statistics on phenomena and their co-variation
   a. Capture spatial and temporal variation
   b. Location specific risk analysis

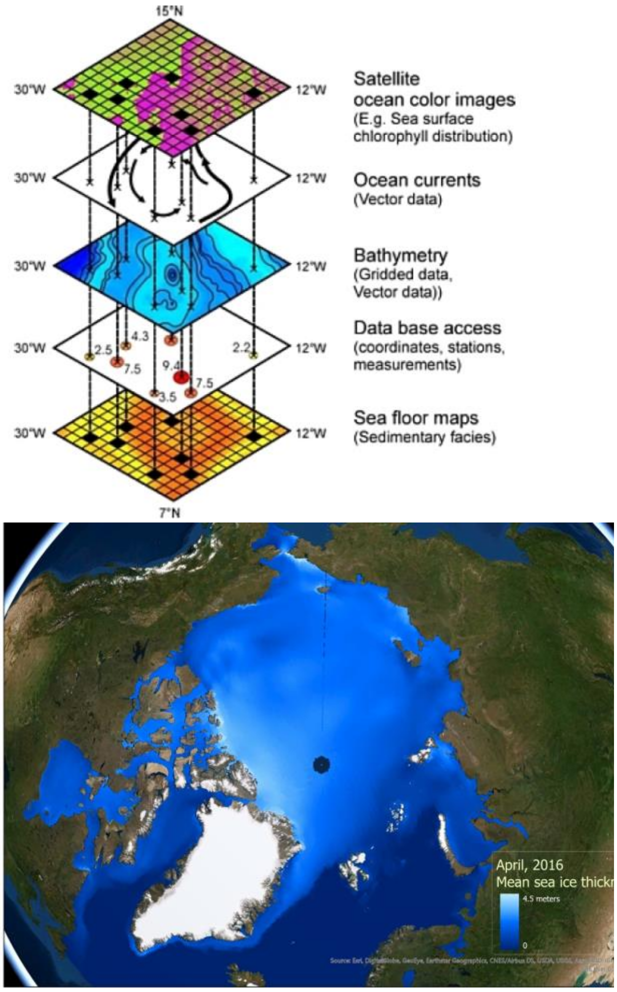


Figure 4.2. Upper left and right panels show schematically the data integration workflow into the risk assessment system. The lower panel shows the coherent representations of ice parameters such as sea ice thickness and ice type relevant to shipping risk assessments. Generated from UHAM reanalysis data for April 2016.

4.2.3 Who are the stakeholders/users who will benefit from the results?

Sea-ice represents a key risk influencing factor and presenting sea-ice data from a coherent study of past and foreseen future sea-ice conditions allows operators, authorities, and other key stakeholders in the Arctic to assess current and emerging risks. Such assessments form a basis for operational and strategic planning. The risk assessment system as such is not about implementing a specific risk analysis methodology, but rather to give access to quantitative data and information concerning important risk shaping factors in the Arctic. Such access enables transparent risk-based discussions targeting various types of marine risk assessments.

4.2.4 How should the results be further developed and exploited after the end of the project?

In addition to ongoing implementation in the Risk Assessment System, stakeholder meetings have revealed several wishes for additional functionality and capabilities. DNV will further develop the Risk Assessment System to support our own advisory services and also meet our customer demands for sound risk assessments for safe navigation and Arctic activities (Figure 4.2).

The Risk Assessment System application will be published on the DNV GIS platform allowing for public access over a trial period of 12 months starting January 1st, 2022. DNV will host the service under agreement with the INTAROS project. Upon trial period end, DNV will evaluate feedback, and reassess needs for further development and improvement.

DNV’s work is further detailed in D6.5 and D6.15.

4.3 Arctic Acoustic Environment and acoustic observing systems

Contributors: Hanne Sagen, Florian Geyer, Espen Storheim, Siwei Hu, Kjetil Lygre, Torill Hamre, Frode Monsen, Tor I. Olaussen, all NERSC

4.3.1 What were the main activities and results from the work?

Arctic Acoustic environment

The climate induced environmental changes in the Arctic will change both the mechanisms and processes producing natural ocean sound, change the ocean stratification, and increased accessibility and traffic to the Arctic region will change the amount of sound from human activities. To assess the effect of the changes in the Arctic it is important to benchmark the current state of the Arctic acoustic observing capacity and to make recommendations for future sustained acoustic observations.

In previous work in WP 2 acoustic data from DAMOCLES (2008-2009) and ACOBAR (2010-2012) were processed and formatted. In WP 6, acoustic recordings from five deep-water moorings (UNDER-ICE 2014-2016) in the Fram Strait has been aggregated and quality controlled within INTAROS. A processing chain for passive acoustic products from distributed acoustic arrays of hydrophones into standard formats (NetCDF), including quality flags, has been established. A significant amount of data from the moorings are of poor quality due to strumming caused by mooring motion, but the bad data has been flagged. Acoustic data from UNDER-ICE are formatted and prepared for publication in Norwegian Marine Data Center (Geyer et al. 2021). By this INTAROS has contributed with benchmark data for future assessment of changes in Ocean Sound in the Fram Strait. In total acoustic recordings from 9 moorings in the Fram Strait have been processed and formatted in INTAROS and published in the Norwegian Marine Data Center.

Analysing the passive acoustic data from UNDER-ICE experiment more in detail shows that the seismic exploration in the Barents Sea and the North Sea are visible in the recording a larg part of the year. The locations of the five mooring positions are shown in the Fig. 4.3 along with examples of spectrograms from each location. Each 120 s long spectragram show the periodic signature of seismics and the much weaker tomographic signal. While the seismic signal is repeated every 12 s for over several days a year, the 90 s long tomographic sweep is transmitted ever 3 hours over 2 years. Comparing the five spectrograms it is seen that both the seismics and the tomographic signal is reduced when propagating into ice covered western part of Fram Strait. This result shows the importance of acoustic monitoring both inside and out side the ice edge to evaluate the anthropogenic impact on the acoustic environment, and to take into account the presence of sea ice.

In INTAROS it was important to get an overview of and assess existing observation systems outside the INTAROS consortium. In Lygre et al. 2021 assessment information about 11 Arctic observing systems were extracted and analyzed using the ARCMAP system (https://arcmap.nersc.no). It was found that a typical acoustic observing system providing ocean sound is project based, funded at the national level and has not advanced routines for data storage and management.

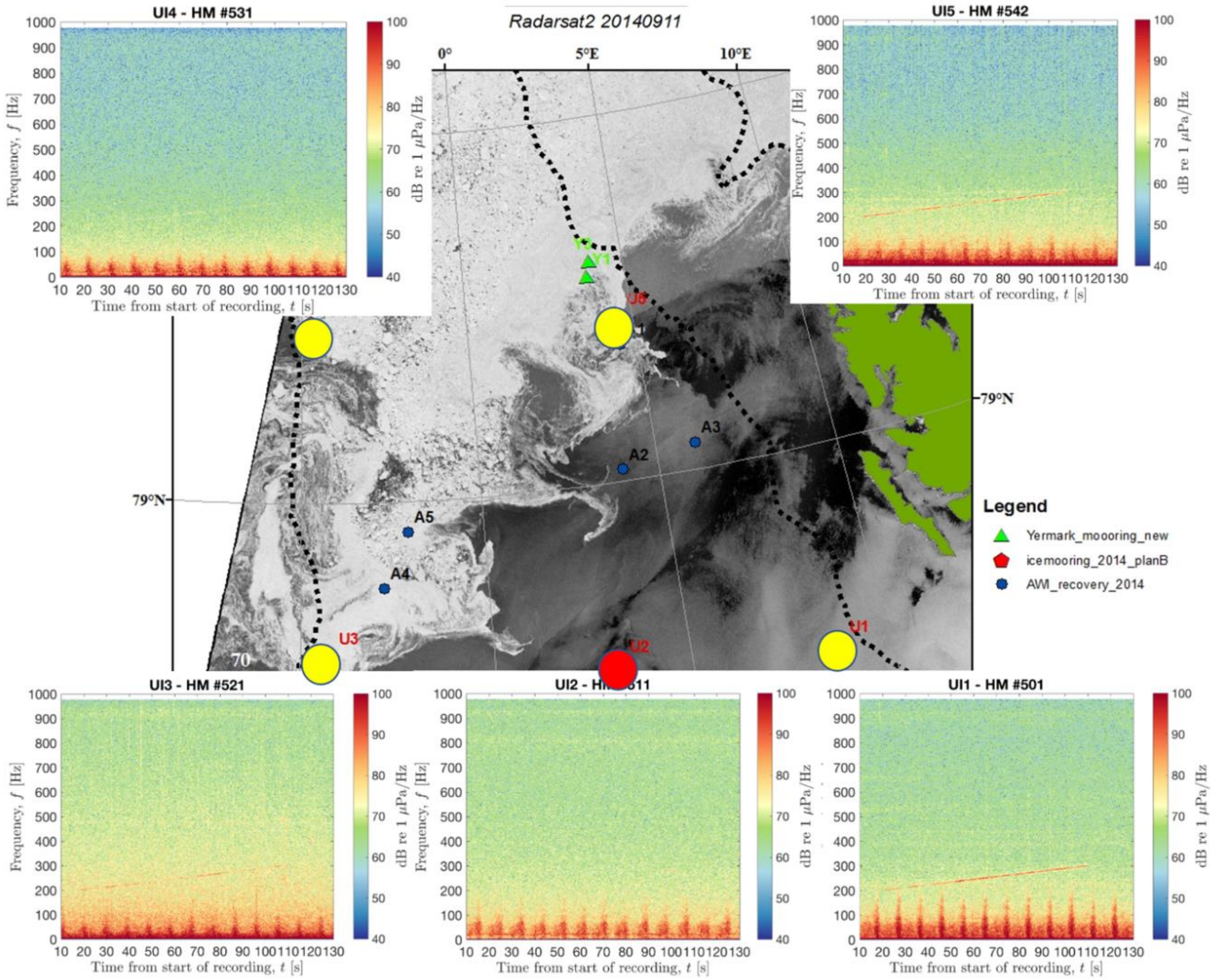


Figure 4.3 Passive acoustic measurements from the five UNDER-ICE moorings. The data show strong impact of seismic between 20-200 Hz. The signature is strongest at the location nearest the Barents Sea, and weakest at the moorings inside the ice edge. The tomographic signal sent from the mooring in red is barely seen, but the signal is detected through advanced signal processing.

Acoustic propagation conditions

During the ACOBAR in 2010-2012 were carried out mostly under ice-free conditions, and signals were retrieved during the whole experiment. Analysing the acoustic receptions from the UNDER-ICE experiment it was observed that signal transmitted from one of the sources disappeared for longer and shorter periods. In WP 6 (Task 6.3) acoustic simulations have been carried out using oceanographic fields from the 10 years reanalysis as input to an acoustic model. The acoustic model was a modified Bellhop model allowing for range dependent ice thickness and roughness. This analysis indicated that transmitting a sweep signal (200-300 Hz) across the marginal ice zone can be difficult (Storheim et al. 2021). The loss of signals can be attributed to strong horizontal oceanographic gradients near the acoustic source (Hu et al 2021), and that scattering from rough sea ice further hampers the signal to reach the receiver array inside the ice edge. Our results clearly show that acoustic system to be implemented in MIZ need a careful design (e.g. depth of sources and length of the acoustic receiver array) and the design must take into account that the transmission conditions will vary significantly over time (Hu et al. 2021). Through this work we have improved the methodology and capacity to design acoustic systems for tomography, geo-positioning as well as for communications.

4.3.2 What data and models were used?

The 10-year reanalysis (2006-2016) produced using the GECCO model and 4 DVAR (Gukun et al 2020) were used in the acoustic modelling. The reanalysis is made available at http://thredds.nersc.no/thredds/gecco/catalog.html. More information is found at https://oalib-acoustics.org/AcousticsToolbox/Bellhop-2010-1.pdf.

XBT sections between moorings were also used in the acoustic modelling and they were available through NMDC at https://doi.org/doi:10.21335/NMDC-NERSC-1232980327.

The assessment of the capacity to observe ocean sound were carried out by using ARCMAP database https://arcmap.nersc.no/#ac_3575/2/90.0/0.0.

Acoustic data from UNDER-ICE moorings were used to describe the Acoustic Environment and to develop data formats to hold aggregated and quality controlled passive acoustic data these data are to be made available through the NMDC.

4.3.3 Who are the stakeholders/users who will benefit from the results?

Climate and Environmental monitoring

'Ocean Sound', is an essential ocean variable like ocean temperature which directly influences the well-being of marine life (Marine Strategy Framework Directive https://ec.europa.eu/environment/marine/good-environmental-status/descriptor-11/index_en.htm). Managers, researchers, and operators in the Arctic are more aware of observations and results concerning ocean sound and addressing it more frequently in environmental and climate assessments.

4.3.4 Research, Innovation, and Technology development

Knowledge about the acoustic environment (e.g. ambient noise and propagation conditions) is useful for technology developers to tailor and improve acoustic technologies for the Arctic. Ambient noise stems either from natural sources or human activities, and together with acoustic propagation conditions (e.g. ocean stratification and sea ice roughness) it influences capabilities in underwater acoustic communication, navigations, and observation technology. Long term implementation of future multipurpose acoustic network can support innovation activities within underwater observing platforms (e.g. improved geo-positioning of gliders and subsurface floats operating under ice) and technology for search and rescue operations (e.g. localization of transmitting objects). By installing hydrophone arrays in clusters or networks of moorings it is possible to detect, localize, and track the marin mammals or other sources of sound e.g geological events (e.g. Mikhalevsky et al. 2015).

4.3.5 How should the results be further developed and exploited after the end of the project?

Improve the knowledge about the Arctic Acoustic Environment

The Arctic Council Working group PAME delivered a status report in 2019 about ambient noise in the Arctic https://www.pame.is/projects/arctic-marine-shipping/underwater-noise-in-the-arctic. The PAME report recommends increasing the observing capacity of 'ocean sound' in the Arctic, and to include the effect of ice in acoustic propagation models. The INTAROS project have contributed with more ocean sound data from the high Arctic and including the effect of sea ice into the acoustic model.

Improve and sustain observations ocean sound

There is no complete inventory of where acoustic observations are made in the Arctic. However, there is a large gap in monitoring of ocean sound in the Arctic both in time and space. By continuing updating the ARCMAP with observing systems that include ocean acoustic measurements it can be used as a quantitative basis for, e.g., gap analyses, support processes how to deploy continue and expand acoustic observing systems in the Arctic, perform informed negotiations versus funding agencies or other stakeholders, support development of coordinated European or international research projects or programs, etc. The passive data available through the NMDC forms an excellent data set to further analyse in combination with other data sets in the region. To further develop the observing capacity, the INTAROS consortium should support the International Quiet Ocean Experiment (IQOE) (https://www.iqoe.org) in their effort to guide the implementation of the 'ocean sound' as an EOV under the Global Ocean Observation System (GOOS).

Operationalization of 'Ocean Sound' data delivery chain

INTAROS have contributed to operationalization of acoustic processing including steps to make data inter-comparable through standardised formatting of data and meta data. Other important parts of operationalisation are to ensure that instruments are calibrated, communicate how acoustic instrumentation should be integrated into different platforms, and how products are presented for different users. Acoustic recordings produce a lot of data which need to be processed and quality controlled. In future work we recommend considering using machine learning (ML) where it can be beneficial e.g. in recognizing poor data, and recognizing different known signals e.g. shipping, seismic and known mammal vocalization. For intercomparison of measurements (in time and space) it is important to ensure that data delivery chain follows standards for calibration, processing, and quality control procedures. NERSC will follow up the work with operationalization of processing and quality control of passive acoustic data in upcoming project proposals and projects.

The regional multi purpose acoustic networks in the Fram Strait (DAMOCLES, ACOBAR and UNDER-ICE) were used for thermometry, underwater GPS for gliders and floats and passive acoustics (Mikhalevsky et al 2015, Sagen et al. 2017, and Worcester et al. 2020). A similar system, but basin wide, is under evolution for the central Arctic. The feasibility of such a system were shown in the Trans Arctic Acoustic Experiments in 1994 and 1999 using a source at 20 Hz. In the Coordinated Arctic Acoustic Thermometry Experiment a full year of travel time measurements were made across the Arctic Basin from Nansen Basin north of Svalbard to the Beaufort Sea north of Alaska using a M-sequence signal at 35 Hz. New source and receiver technology was used. In the next phase we will use the results and methodologies developed in CAATEX to design, build and operate a system comprising several sources facilitating for thermometry and underwater acoustic geo-positioning of ARGO floats and gliders in the e central Arctic. The multipurpose acoustic network therefore be an integrating part of the overall Arctic Ocean Observing System.

In the Fram Strait system the tomographic signal were sweeps from 200-300 Hz. The signal was received on 40-100 m long receiver arrays. The result from these experiments shows that gliders and floats cannot expect to receive the sweep signal everywhere in this region (Storheim et al. 2021, Hu et al. 2021). Furthermore, it might be difficult to detect correct arrival time through standard procedures currently used in gliders and floats. The propagation conditions in the central Arctic and Beaufort Sea are different from the Fram Strait. This indicates that the detection of signals must be more adaptive to the arrival structure in different regions of the Arctic, and that different frequencies and signals might function better in some regions than in other. Vehicles or floats, therefore, need to be programmed to listen at optimal depths based on the sound speed profile and to be able to detect signals from different sources. NERSC and collaborators are preparing a proposal to the Research Infrastructure program under Horizon Europe (2022) addressing several bottlenecks in bringing observations from the ocean under the Arctic sea ice.

The details of this work are reported in D6.14.

4.4 Ice-Ocean Statistics from in situ observations

Contributors: Agnieszka Beszczynska-Möller, Waldemar Walczowski, Agata Grynczel

4.4.1 What were the main activities and results from the work?

The main activities were focused on obtaining ocean statistics from oceanographic in situ measurements in the Nordic Seas and Arctic Ocean, collected by IOPAN in the last two decades. Statistical analysis of oceanographic data collections from ship-borne measurements during annual summer field campaigns AREX and mooring observations north of Svalbard aimed to characterize long-term changes in ocean climate and variability of ocean key physical variables on different time scales. The results include spatial maps and time series of key ocean variables (temperature, salinity, ocean currents) and derived properties (e.g., Atlantic layer properties, ocean heat content) in selected locations. Example of data product is shown in Figure 4.4. Background statistics of sea ice concentration in the mooring region were obtained based on satellite remote sensing. The ultimate goal is to aggregate in one place (website with open access) long-term series of in situ observations (including their statistics) and results of integrative analysis of measured ocean variables and derived quantities together with available sea ice and atmospheric information for further use by external users.

4.4.2 What data and models were used?

To obtain large-scale maps of ocean properties and their statistics and long-term time series of key ocean climate variables, in situ ship-borne measurements from the IOPAN AREX long-term monitoring program (2000-2020) were used. To obtain statistics of seasonal to interannual variability of ocean physical parameters, in situ observations collected at three INTAROS moorings north of Svalbard were employed in combination with mooring data from earlier deployments in this region. Sea ice statistics for the mooring region north of Svalbard were obtained from available remote sensing product. Data from in situ measurements of sea ice at moorings are under processing and their statistics will be added at the later stage when the final data product is ready.

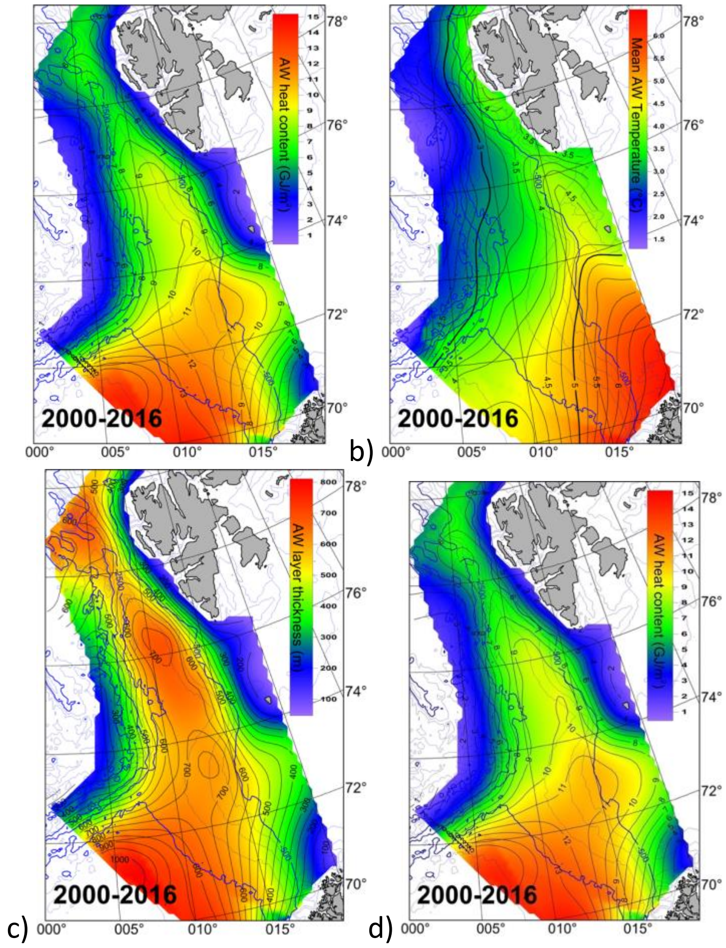


Fig. 4.4 Long-term (2000-2016) mean spatial fields of the Atlantic water (a) temperature, (b) salinity, (c) layer thickness, and (d) relative ocean heat content based on in situ observations from the AREX program.

4.4.3 Who are the stakeholders/users who will benefit from the results?

Data will be used in further research activities focused on the ocean physical state and dynamics in the region of the Atlantic water inflow towards and into the Arctic Ocean. Time series of variables measured by moored instruments can be also used to provide derived products for other research activities, e.g. environmental background for biological or carbon system studies in the central Arctic. Potential users include scientists across a wide range of different disciplines, including modelers working with ocean and climate forecast and prediction or groups working on assessments of Arctic ecosystems and natural resources. Interactions between ocean and sea ice and ocean-ice statistics in poorly observed parts of the Arctic Ocean can be of a special interest for planning and operating future shipping routes in the opening for navigation Arctic areas.

4.4.4 How should the results be further developed and exploited after the end of the project?

The derived data products, including spatial maps, time series and basic statistics of measured ocean physical variables from ship-borne and mooring measurements will be available as visual information (graphic files) and data products in netCDF format from the dedicated IOPAN website and/or data base. The long-term time series will contribute to different reports on the ocean and climate states, e.g. to the ICES Report on Ocean Climate (IROC), published annually. Derived data products will be available for providing the physical background for the biogeochemical and biological studies and ecosystem assessments. They will be also available for validation of and assimilation into numerical models and for the purpose of optimizing components of a future Arctic observing system. Presented results will be also used in the PhD work of the IOPAN PhD student (Agata Grynczel), working in INTAROS. The results are also used as input to the work on the Fram Strait acoustic environment.

The details of this work is reported in D6.14

4.5 Snow and Ice Mass Balance Buoy

Contributors: Bin Cheng, Ruibo Lei, Zhongxiang Tian and Roberta Pirazzini

The Arctic snow and sea ice mass balance is a critical component of the earth’s cryosphere. The most important thermodynamic processes are the sea ice freezing-up, bottom evolution, surface melting, sea ice breakup, as well as snow to ice transformation. The results of the work are presented in D6.21.

4.5.1 What were the main activities and results from the work?

Several snow and ice mass balance buoys (SIMBA) have been deployed in various locations in the Arctic Ocean as part of several icebreaker expeditions (See figure 4.5). The buoys have been placed on undeformed ice floes to measure time series of vertical temperature profiles through air-snow-ice-ocean. The seasonal evolution of snow and ice thickness has been derived from the SIMBA temperature profiles. Several studies based on SIMBA observations are carried out, including snow and ice physics, seasonal dynamics, and thermodynamics, as well as remote sensing and processing modelling (e.g. Lei et al. 2021, Cheng et al. 2021).

4.5.2 What data and models were used?

Data from at least 44 SIMBA ice mass balance buoys have been obtained thanks to many international collaborations, in particular the Chinese partners in the INTAROS. We are currently working on processing and validating the data and uploading them to https://zenodo.org/deposit. Similar work is ongoing to archive previous SIMBA data from the Arctic. The data are registered in the INTAROS Data Catalogue.

4.5.3 Who are the stakeholders/users who will benefit from the results?

SIMBA data are primarily important for researchers who are focused on understanding how the ice melting processes and heat transfer between ocean-ice-atmosphere varies with seasons. This is important for better parametrization in ice-ocean models and climate models.

4.5.4 How should the results be further developed and exploited after the end of the project?

SIMBA data will be valuable for future scientific research as well as development of operational marine weather forecasting system for the Arctic Ocean. Snow and ice thickness along Arctic Northeast Passage (ANP) is of great important for the commercial shipping industry. The COSCO (China Ocean Shipping Company, Limited) has operated cargo transportation along ANP during summer for several years. So far, we have not been able to deploy SIMBA buoys in the Kara Sea. However, stakeholders and users, such as COSCO are very keen to have operational snow and ice service along the ANP.

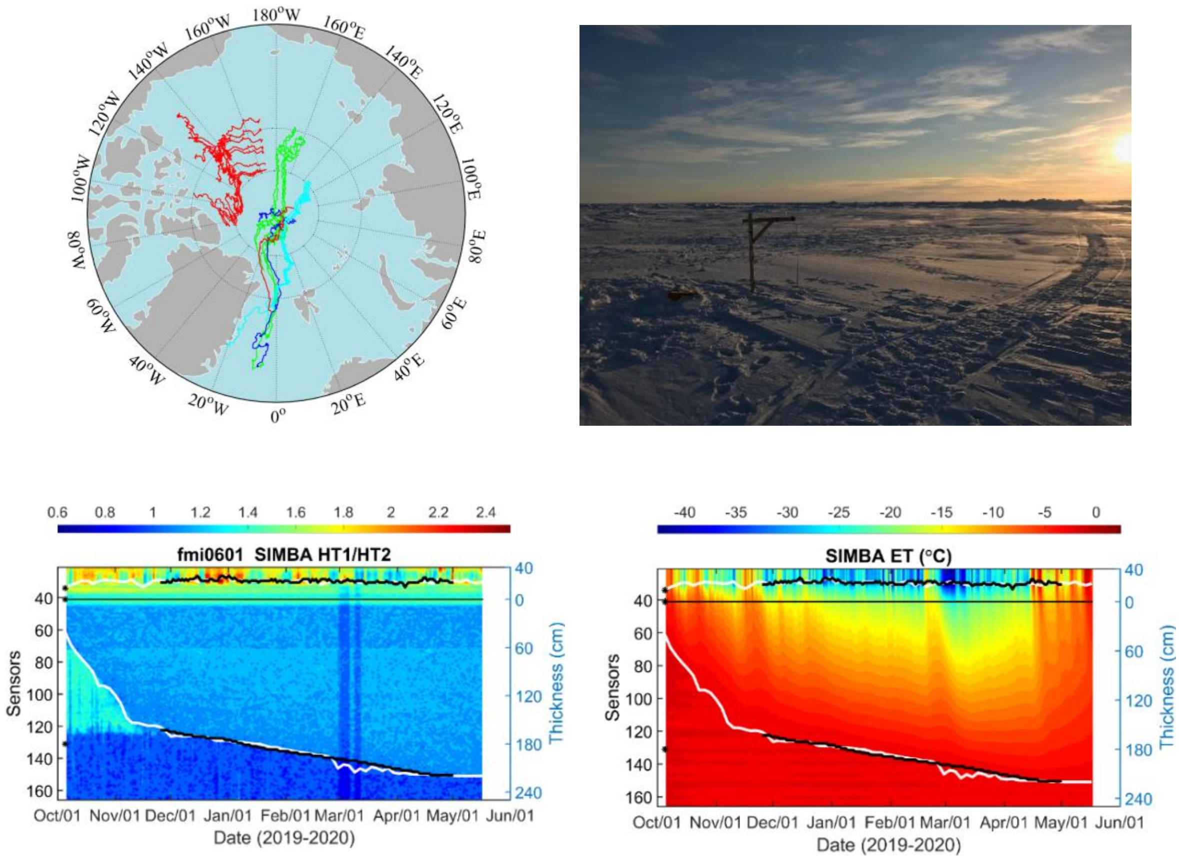


Figure 4.5. SIMBA. The upper left panel shows trajectories of SIMBAs deployed in the Arctic in the period 2018 - 2020.The photo to the right shows SIMBA (FMI0703) deployed during CHARCOT test cruise at the North Pole on 8 September 2021. The lower left panel shows a time series of the SIMBA-HT profiles and the lower right panel time series of the SIMBA-ET profiles. The white lines are results from the SIMBA algorithm and the black lines are results from the manual processing. This SIMBA was deployed during MOSAiC leg 1.

References

Cheng, B., Cheng, Y., Vihma, T., Kontu, A., Zheng, F., Lemmetyinen, J., Qiu, Y., and Pulliainen, J. 2021. Inter-annual variation in lake ice composition in the European Arctic: observations based on high-resolution thermistor strings, Earth Syst. Sci. Data, 13, 3967–3978, https://doi.org/10.5194/essd-13-3967-2021

Geyer F., H. Sagen, E.Storheim, 2021. A dataset of underwater passive acoustic recordings from a 2-year mooring deployment in Fram Strait (UNDER-ICE). Proc. Mtgs. Acoust. 44, 070034 (2021); https://doi.org/10.1121/2.0001507

Hu S, H. Sagen, E. Storheim, W. Chen, and J. Yin (2021)., Using ice-ocean environment from reanalysis into Bellhop to better understand sound propagation in the Fram Strait. Proc. Mtgs. Acoust. 44, 070038 (2021); https://doi.org/10.1121/2.0001513

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Woollen, J. (1996). The NCEP/NCAR 40-year reanalysis project. Bulletin of the American meteorological Society, 77(3), 437-

Lei, R., Hoppmann, M., Cheng, B., Zuo, G., Gui, D., Cai, Q., Belter, H. J., and Yang, W. 2021 Seasonal changes in sea ice kinematics and deformation in the Pacific Sector of the Arctic Ocean in 2018/19, The Cryosphere, 15, 1321–1341, https://doi.org/10.5194/tc-15-1321-2021

Lyu G, Koehl A, Serra N, et al. Assessing the current and future Arctic Ocean observing system with observing system simulating experiments[J]. Quarterly Journal of the Royal Meteorological Society, 2021a.

Lyu G, A. Köhl, N. Serra, D. Stammer, and J. Xie, “Arctic ocean–sea ice reanalysis for the period 2007–2016 using the adjoint method.” Q. J. R. Meteorol. Soc. 147(736), 1908–1929. 2021b.

Lyu G, N. Serra, A. Köhl,and D. Stammer, “Arctic Ocean synthesis 2007-2016”. Available online: http: //thredds.nersc.no/thredds/catalog/gecco/GECCO/catalog.html. 2020.

Lygre K., T. Hamre, F. Monsen, T. I. Olaussen, and H. Sagen 2021. Analysis of passive acoustic in situ observing systems in the Arctic Ocean using ARCMAP. Proc. Mtgs. Acoust. 44, 070018 (2021); https://doi.org/10.1121/2.0001485

Mikhalevsky P., H.Sagen, P.Worcester et al. 2015 Multipurpose Acoustic Networks in the Integrated Arctic Ocean Observing System. Arctic 2015; Volum 68. (5) s.1-17.

Sagen, H., P. F. Worcester, M. A. Dzieciuch et al. 2017. Resolution, identification, and stability of broadband acoustic arrivals in Fram Strait. The Journal of the Acoustical Society of America 141, 2055 (2017); https://doi.org/10.1121/1.4978780

Storheim E., H. Sagen, F.Geyer. 2021. Analysis of signal propagation in the UNDER-ICE experiment. Proc. Mtgs. Acoust. 44, 070031; https://doi.org/10.1121/2.0001500

Worcester, P., M. A. Dzieciuch, H. Sagen. 2020. Ocean Acoustics in the Rapidly Changing Arctic. Acoustics Today Journal of the Acoustical Society of America. 16 (1). https://doi.org/10.1121/AT.2020.16.1.55

5. Remote sensing applications

Sub-chapter	Lead	Deliverable
6.1 Sea ice remote sensing	U Bremen, Ifremer	D6.22, D6.23
6.2 Sea level	DTU	D6.20
6.3 Water vapour	U Bremen	D6.23
6.4 Use of drones	NORCE	D6.24

5.1 Sea ice products from satellite remote sensing

Contributors: Fanny Ardhuin, Ifremer; Arantxa Triana-Gomez, Larysa Istomina, Christian Melsheimer, and Gunnar Spreen, U Bremen; Georg Heygster, GEORG-Lab

5.1.1 What were the main activities and results from the work?

The activities have focused on further development of sea ice products from passive microwave (PMW) and scatterometer sensors. These sensors have been used over many years to retrieve sea ice variables, in particular sea ice concentration (SIC)/extent, sea ice type and sea ice displacement. Daily SIC data are used for (1) initialisation of and assimilation into global climate models (GCM) and numerical weather prediction (NWP), (2) for shipping in polar seas, and (3) various climate and environment studies. The sea ice products are provided under the Copernicus Marine Services and are updated continuously with new data (LeTraon et al., 2021). Detailed description is given in D6.22 and D6.23.

In this project, six new or improved data products from satellites were demonstrated. University of Bremen provided high resolution sea ice concentration (Spreen et al., 2008), thin sea ice thickness and sea ice type, i.e., the multiyear ice concentration. IFREMER provided sea ice displacement products and testing of new scatterometer data from CFOSAT (Chinese-French Oceanography Satellite) for sea ice variables. The satellite products are available from the institutional data repositories and from the INTAROS data catalogue. Two examples of sea ice products are presented in Figure 5.1.

Ifremer has combined passive microwave sea ice concentration data with scatterometer data to calculate sea ice displacement across the whole Arctic with 3- and 6-day interval. The grid resolution of this product is 62.5 km and covers the months from October to May. Data from the summer months cannot be used because the signals are disturbed by the melting. Ifremer is also using scatterometer data to separate multiyear ice from first year ice by defining a threshold in the backscatter values. Higher backscatter represent multiyear ice while lower values represent first year ice.

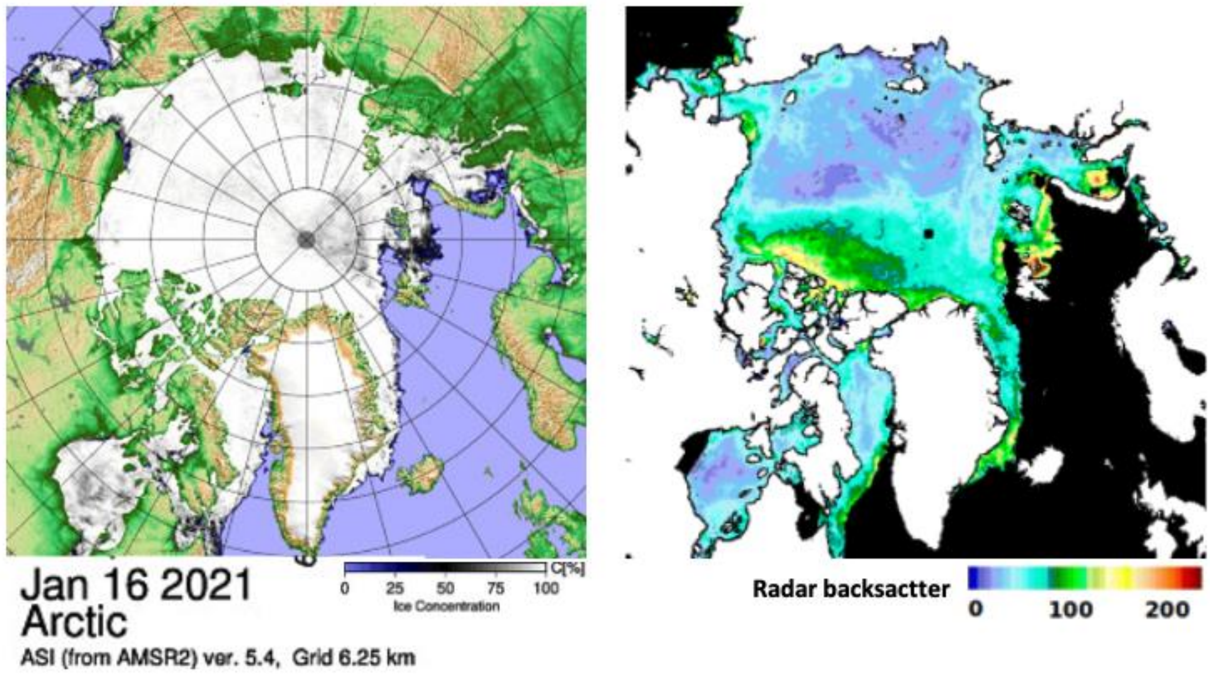


Figure 5.1. Left: Universiy of Bremen's ice concentration map produced from AMSR2 passive microwave data. Right: Ifremer's radar backscatter map from ASCAT scatterometer, where different ice types can be distinguished. Both products are obtained on the same day, 16 January 2021.

5.1.2 Who are the stakeholders/users who will benefit from the results?

The satellite sea ice products are used in operational modelling and forecasting systems, in sea ice model development and in many application studies of sea ice and oceanography in the polar regions. The sea ice concentration data set is a unique climate data record because it provides a continuous time series of total ice extent in both Arctic and Antarctic. These data are used in numerous studies and assessment reports, including the IPCC reports. In INTAROS the climate modelling work described in D6.11 used the ice concentration data sets provided by Ifremer. In the OSSE work a number of different satellite sea ice and ocean products were used, see Fig. 5.1. During the icebreaker expeditions with KV Svalbard from 2018 to 2021, which all contributed to the INTAROS data collection, sea ice products from University of Bremen were used in planning the field work and support the ice navigation.

5.1.3 How should the results be further developed after the end of the project

The satellite sea ice products presented in this task have been developed through long-term efforts where standard products (concentration, extent, ice edge, ice displacement) become operational products provided by national and international organisations. The operational products are well documented and have been evaluated against the requirements of the WMO OSCAR data base of Observational Requirements, by CGOS and the Copernicus services (CMEMS and C3S). New passive microwave satellites will be launched, such as AMSR3 (2024) and CIMR (2028), where data will be included in the production of sea ice concentration and extent. Other sea ice products (ice thickness, ice displacement) will be improved to serve new research as well as support the Copernicus services. The development of the products will continue, and the application of the products will be exploited in new services such as the Risk Assessment system described in D6.15.

5.2 Observing systems for sea level in the Arctic

Contributors: Carsten B. Ludwigsen and Ole B. Andersen, DTU Space

DTU has investigated the Arctic Ocean sea level change and helped to validate observed sea level change in one of the least accessible and harsh regions of the world. We have used in-situ measurements, satellite observations and modeling. The detailed description is presented in D6.20.

5.2.1 What were the main activities and results from the work?

The results have been published in three papers, which combined give a comprehensive analysis of the effects of climate change on the contributions to Arctic Ocean sea level (Figure 5.2).

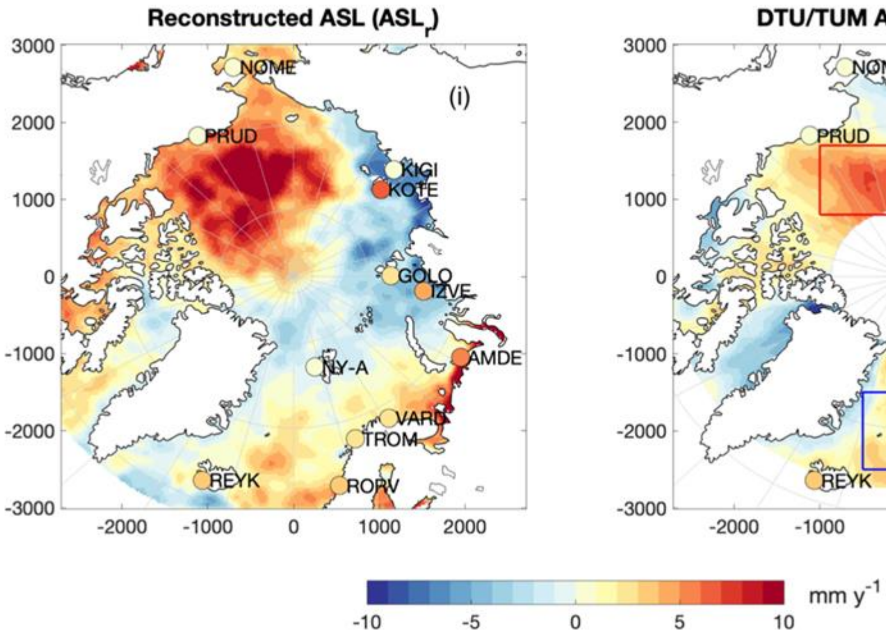


Figure 5.2 (i) Absolute sea level trend of the reconstructed product (ASL_r) and (ii) from DTU/TUM Altimetry (ASL_A) from 1995 to 2015 [mm/y]. In both maps is the sea level trend of the 12 VLM-corrected tide gauges (ASL_{TG}) shown with circles.

In the first paper (Ludwigsen and Andersen, 2021a) we presented the available sea level products in the Arctic Ocean in the era of the GRACE-satellites. Sea level estimates from GRACE and satellite altimetry showed disagreements in areas of the Arctic while only few in-situ measurements are present to validate satellite products. By using an independent in-situ based dataset of hydrographic data (DTUSteric), this study compared different available datasets from GRACE and altimetry.

In the second paper (Ludwigsen et al, 2020) presented a high-resolution vertical land motion (VLM) model for the wider Arctic, that includes both present-day ice loading (PDIL) and glacial isostatic adjustment (GIA). The model showed that the nonlinear elastic uplift is significant (0.5–1 mm yr^{-1}) in most of the wider Arctic and exceeds GIA at 15 of 54 Arctic GNSS sites. The high resolution of the VLM-model enables it to be used in glaciated regions, which would not be properly represented with the relatively low spatial resolution of GRACE.

The VLM-model derived in the second paper made it possible to integrate tide-gauge stations into the analysis of Arctic sea level, presented in the third paper (Ludwigsen et al, 2021b). Rather than using GRACE for mass estimates, the sea level fingerprint of the ice model used in the second paper and GIA was used to estimate the mass component of Arctic sea level from 1995 to 2015. From the assessment we conclude that:

- Large spatial variability of halosteric sea level change (-5 - 15 mm/y) and a smaller mass component (≃ 1 mm/y) confirmed the analysis of the first paper.
- In the Norwegian Sea, where the steric component and VLM is well-constrained, the sea level measured from tide gauges are restored in the derived mass + steric sea level estimate. The sea level trend of the mass component equals the steric sea-level change along the Norwegian coast.
- A sea level rise in the Kara and Laptev seas because of freshwater outflow is not captured by altimetry but is clearly visible from the halosteric contribution and matches the sea level rise measured with tide gauges. A sea level decline in the East Siberian Seas in both the halo- and thermosteric sea level is not recognized by the tide gauges, which show a sea level rise. Large differences between neighbouring tide gauges, indicate that tide gauges are affected by unknown local contributions. However, assessment of multiple Siberian tide-gauges shows that the sea level rise on the Siberian Shelf has been consistent since the 1980's.
- Large variability associated with the dynamic mass component is estimated from ECCOv4r4. It contributes to the general spatial (and temporal) variability of the Arctic Ocean. Dynamic changes are associated with Arctic Oscillation and is not necessarily a climate change signal.
- The 1995-2015 sea level trend is explained within the uncertainty in 95% of the Arctic and at 7 out of 12 utilized tide gauges. However, large uncertainties in the steric and dynamic mass component contributes to the result. Large differences with altimetry are evident in the Beaufort Gyre and Siberian Seas.

On basis of this research, and from the third paper, is it clear that many of the observations and models are showing large uncertainties, mainly due to poor and inconsistent data from remote sensing and hydrographic T/S profiles that are difficult to validate.

5.2.2 Further work

Further work on sea level studies need to include the following elements:

1) Install more GNSS tide gauge instruments. The largest challenge in the Arctic is the limited number of observations of sea level by tide gauges. There are roughly 50 usable tide gauges in the Arctic Region (north of 65N), but only a few with GNSS ties. It has been shown (Larson et al., 2017) that the signal to noise ratio of coastal GNSS receivers can, in favorable circumstances, be used to make a geocentric coastal sea level measurement with centimetric accuracy.
2) Improve the steric sea level estimates from interpolated T/S data to create a 4D gridded temperature and salinity dataset. Use of reanalysis from modelling systems such as ECCO (NASA JPL), GECCO (University of Hamburg) or EN4 (British Met Office) will contribute to the steric calculations.
3) Sea level observations from satellites are in constant development. The launch of IceSAT-2 and the upcoming Surface Water and Ocean Topography (SWOT)-mission significantly

improves the spatial resolution of altimetric observations in the Arctic and should improve future versions of absolute sea level products from altimetry.

4) The calculated elastic mass component and VLM is **not** obtained by solving the sea level equation, which would also include the viscoelastic part of present-day ice loading change. Applying models of Little Ice Age deglaciation and 3D-earth models could further help separate PDIL from past changes. Recent work by Shijie Zhong (CU Boulder, yet unpublished) significantly improved the computational workload needed to utilize high resolution 3D-models, making it feasible to conduct region-wide 3D GIA models.
5) The mass and VLM predictions did not include the effect of terrestrial water storage (TWS), which has limited effect in the Arctic, but is the largest land-to-ocean mass flux in mid and low-latitudes. TWS-estimates from GRACE could be used for the purpose of creating global predictions of VLM and mass-fingerprint.
6) If the steric contribution to sea level is improved, a complete Arctic sea level budget assessment should include temporal variations. This would enable the possibility of accurately estimate freshwater in and outflow of the Arctic Ocean. Predicting the freshwater contribution that goes into the North Atlantic is important for predicting the behavior of the Atlantic meridional overturning circulation (AMOC) and thus influences the Earth's climate system.
7) Extend altimetric timeseries and to make use of the new SAR and SARin altimetry which are particularly useful in sea-ice covered regions, and to prepare for the SWOT mission which is expected to improve the coastal resolution still further.
8) Maintain and refine global mean sea surface maps extending the work of DTU21MSS presented in the INTAROS project increasing the averaging period for the Mean sea surface. Care must be taken to ensure appropriate altimeter corrections, such as tide corrections, are used and do not degrade the spatial coverage which is problematic in ice-covered regions.

5.3 Water vapour

Contributors: Georg Heygster, GEORG-Lab; Arantxa Triana-Gomez, U Bremen;

The work performed on water vapour data is further described in D6.23.

5.3.1 What were the main activities and results from the work?

Total water vapor (TWV) in the atmosphere has been available over open ocean from passive microwave (PMW) imagers since 1987. Over land and sea ice, methods for retrieval of TWV from the PMW imager have only recently been developed. In the INTAROS project, three improvements have been developed:

1. Inter-calibration between and validation of retrievals from sounders AMSU-B and MHS which have slightly different channel definitions (Triana-Gomez et al., 2020).
2. Masking erroneously low retrievals caused by high ice clouds.
3. Sub-algorithm (channel triplet) merging optimized.

Based on the described methods (see D6.23), daily TWV maps have been calculated for the 18 years 2003 to 2020, the period of complete AMSR-E and AMSR2 years. All data including the User guide (Triana-Gomez et al., 2021) are available in png format for discovery and netcdf for analysis at the University of Bremen repository https://seaice.uni-bremen.de/water-vapor/ .

By using AMSR-E retrievals alone, only the open water areas are covered. However, by combining data from AMSR-E and humidity sounder data from AMSU-B and MHS data, all areas are covered in winter and ocean and sea ice areas are covered in summer (Figure 5.3).

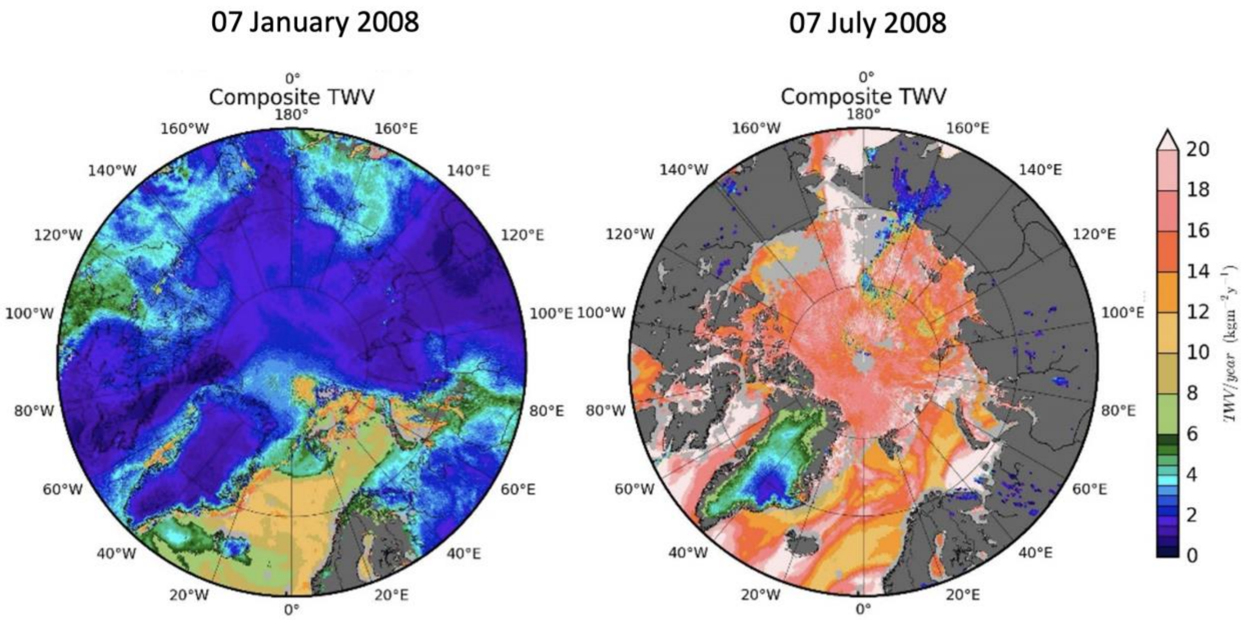


Figure 5.3. Combined AMSU-B and AMSR-E TWV retrieval for a winter and a summer day.

5.3.2 Who are the stakeholders/users who will benefit from the results?

Climate research and climate modelling are the primary users of these data. Water vapour is the most important greenhouse gas and data on this gas is scarce, in particular in the polar regions.

5.3.3 How should the results be further developed after the end of the project?

The launch of AMSR3 in 2024 will improve the quality of the data product because the instrument will carry two additional channels at frequencies near 183 GHz. Work will continue to improve the retrieval of water vapour from satellite PMW imagers and humidity sounders.

5.4 Use of drones for sea ice observations

Contributors: Tom Rune Lauknes and Rune Storvold, Norce

5.4.1 What were the main activities and results from the work?

There is an increasing interest to use drones equipped with sensors to observe snow and other surface properties as part of field research in the polar regions (e.g. Jensen and Jacobsen, 2021; Tan et al., 2021). During the CAATEX cruise 14/8–9/9, 2019 with KV Svalbard to the North Pole, NORCE operated a fixed-wing Unmanned Aircraft System (UAS), which was used to collect high-precision optical imagery, providing information about ice morphology and sea-ice properties. Furthermore, NORCE operated an ultra-wideband radar system UWiBaSS on a multirotor UAS platform in collaboration with University of Tromsø and the CIRFA project. The radar, which can detect layers in the snow and ice, was operated along selected profiles where also snow and ice samples were collected by Norwegian Polar Institute.

In addition, NORCE operated an imaging radar on board the vessel when it was stationary in the ice, provided information about ice drift and ice conditions. In addition to the science data collection, the potential of using a high-resolution imaging Ku-band radar for navigation in ice-infested waters was also demonstrated. To support ice navigation, Norwegian Met Institute provided Sentinel-1 SAR images and CIRFA provided Radarsat-2 SAR images.

The experiment demonstrated a novel use of an imaging radar system combined with drone-based operations for increased real-time situational awareness in support of sea-ice navigation. Comparison between a traditional marine radar and the ship mounted interferometric imaging radar demonstrates clear potential for improved characterization of ice conditions, as well as the need for tight integration with timely satellite SAR observations. Furthermore, the drone mounted UWiBaSS radar could be used to provide valuable information about sea ice types, being important to supplement and validate satellite SAR imagery. The use of inexpensive fixed wing drone allows for accurate mapping of leads and ridges beyond visual and radar line-of-sight from the vessel. The joint use of satellite, drones, and ship-based radar systems, coupled with ice drift models, is important to increase the situational awareness for the navigators. The *nLive* visualization and dissemination platform is now in operational use for different projects, e.g. by the European Maritime Safety Agency (EMSA) who is using drones for operational pollution monitoring, and where *n*Live is used for visualisation and dissemination of data (Figure 5.4).

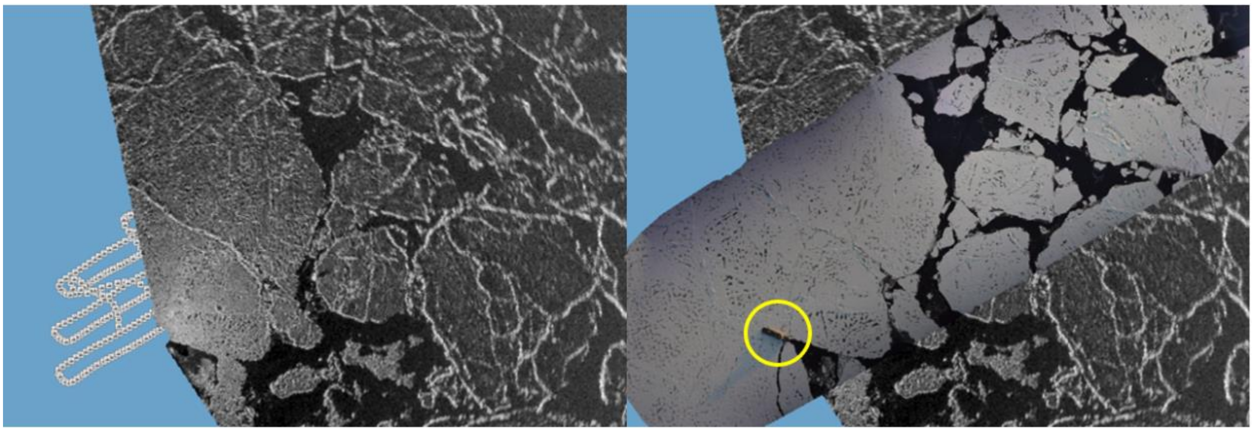


Figure 5.4. Left: A GPRI Ku-band radar image from 31.08.2019. Right: On top of the radar image is shown an orthomosaic produced by the fixed-wing UAS platform. The size of the ice breaker KV Svalbard is about 100 m (inside the yellow circle).

5.4.2 Who are the stakeholders/users who will benefit from the results?

The Norwegian Coast Guard ice breaker KV Svalbard will be one important user. Others are companies developing observing sensors and data transmission on drones, environmental agencies and research institution planning to user drones in new projects.

5.4.3 How should the results be further developed and exploited after the end of the project?

The data collected during the expedition will be used to develop a real-time ice navigation support system. The work will continue under the Digital Arctic Shipping project funded by Research Council of Norway (2019-2023), where key stakeholders will be ship operators wanting to use the northern sea routes for transport between the Far East and Europe as well as expedition cruise operators and fishing vessels operating close to the ice edge. The collected dataset, using these sensors, will be used for validation of satellite-based ice classification and segmentation algorithms, as well as providing novel information about sea ice dynamics at high temporal and spatial scales. This work will contribute to the development of a future sustainable observing system by laying the foundation for collection of important climate variables by developing sensor systems for retrieval of sea-ice morphology and sea-ice properties like leads, ridges, snow on ice, and drift that can be carried by inexpensive drone systems.

The full description of the work is presented in D6.24.

References:

Jenssen, R.O.R. and Jacobsen, S.K. 2021. Measurement of Snow Water Equivalent Using Drone-Mounted Ultra-Wide-Band Radar. Remote Sens. 13, 2610. https://doi.org/10.3390/rs13132610

Larson, K. M., R. D. Ray, and S. D. P. Williams. 2017. A ten-year comparison of water levels measured with a geodetic GPS receiver versus a conventional tide gauge, J. Atmos. Oceanic Technol., doi:10.1175/JTECH-D-16-0101.1.

LeTraon, P. Y. et al. 2021: The Copernicus Marine Service from 2015 to 2021: six years of achievements. Special Issue Mercator Océan Journal #57. DOI :https://doi.org/10.48670/moi-cafr-n813.

Ludwigsen, C. B., and Andersen, O. B. 2021a. Contributions to Arctic sea level from 2003 to 2015. Advances in Space Research, 68(2), 703–710. https://doi.org/10.1016/j.asr.2019.12.027

Ludwigsen, C. B., Andersen, O. B. and Rose, S. K. (2021b, in review). Assessment of 21 years of Arctic Ocean Sea Level Trends (1995-2015). Ocean Science.

Ludwigsen, C. B., Khan, S. A., Andersen, O. B., & Marzeion, B. 2020. Vertical Land Motion From Present-Day Deglaciation in the Wider Arctic. Geophysical Research Letters, 47(19), e2020GL088144. https://doi.org/10.1029/2020GL088144

Spreen, G., L. Kaleschke, and G.Heygster. 2008. Sea ice remote sensing using AMSR-E 89 GHz channels J. Geophys. Res., vol. 113, C02S03, doi:10.1029/2005JC003384

Tan, A. E. -C., J. McCulloch, W. Rack, I. Platt and I. Woodhead. 2021. Radar Measurements of Snow Depth Over Sea Ice on an Unmanned Aerial Vehicle. IEEE Transactions on Geoscience and Remote Sensing, vol. 59, no. 3, pp. 1868-1875, March 2021, doi: 10.1109/TGRS.2020.3006182.

Triana-Gómez, A. M., et al. 2020. Improved water vapour retrieval from AMSU-B and MHS in the Arctic. Atmos. Meas. Tech., 13, 3697–3715. doi:10.5194/amt-13-3697-2020

Triana-Gómez, A. M., et al. 2021. Composite Total Water Vapor dataset from AMSU-B/MHS and AMSR-E/AMSR2. User Guide. Institute of Environmental Physics, University of Bremen.

6. Natural Hazards in the Arctic

In Task 6.4 "Natural Hazards in the Arctic" we showcased how the INTAROS Arctic Observation System can be exploited to better understand natural hazards in the Arctic by focusing on three selected hazards:

- Snow avalanches
- Earthquakes, landslides, and tsunamis
- Mass loss from ice sheets and glaciers: Sea level rise and freshwater discharge

We illustrate how the data and methods available through the Arctic Observation System increases our understanding of the hazards, but we also identify gaps and possibilities for improvement to better fulfill stakeholder needs. For more details on each component, stakeholder needs, and recommendations to the INTAROS roadmap please refer to D6.16 "Natural Hazard Assessment in the Arctic".

The work within the task was aimed towards two deliverables:

1. The outcome of the work on the three hazards is described in detail in D6.16 "Natural Hazard Assessment in the Arctic" including a thorough description of stakeholder needs as well as input to the INTAROS roadmap.
2. The effort to separate ice discharge from marine terminating glaciers to the ocean into a liquid and solid part is demonstrated in D6.17 "Ice discharge from glaciers to the ocean: Model-based demonstration of calculations of ice discharge from selected glaciers to the ocean, aimed to predict the contribution of glaciers to sea level rise". The demonstration includes a 20 min video + a 5 min version for promotional purposes.

6.1 Snow avalanches

Contributors: Roberta Pirazzini (FMI), Ilona Valisuo (FMI), Holt Hancock (UNIS), Laura Rontu (FMI), Elena Shevnina (FMI)

The snow avalanche work focuses on Longyearbyen, Svalbard (Figure 6.1) where a disastrous event occurred in 2015. Extreme cyclone events over Svalbard are increasing by about 3-4 events per decade in November-December (Rinke et al., 2017) in association to the decreasing sea ice extent and the change in atmospheric circulation pattern. Heavy precipitation, in the form of snow or rain, generally occurs during these extreme events, challenging infrastructures and local communities because of the high risks of avalanches and landslides.

Snow avalanche forecasting in the Longyearbyen area is necessary to protect the population and the infrastructures concentrated at the bottom of the valley. Avalanche forecast models rely on output from numerical weather prediction models of snow precipitation and snow accumulation as input.

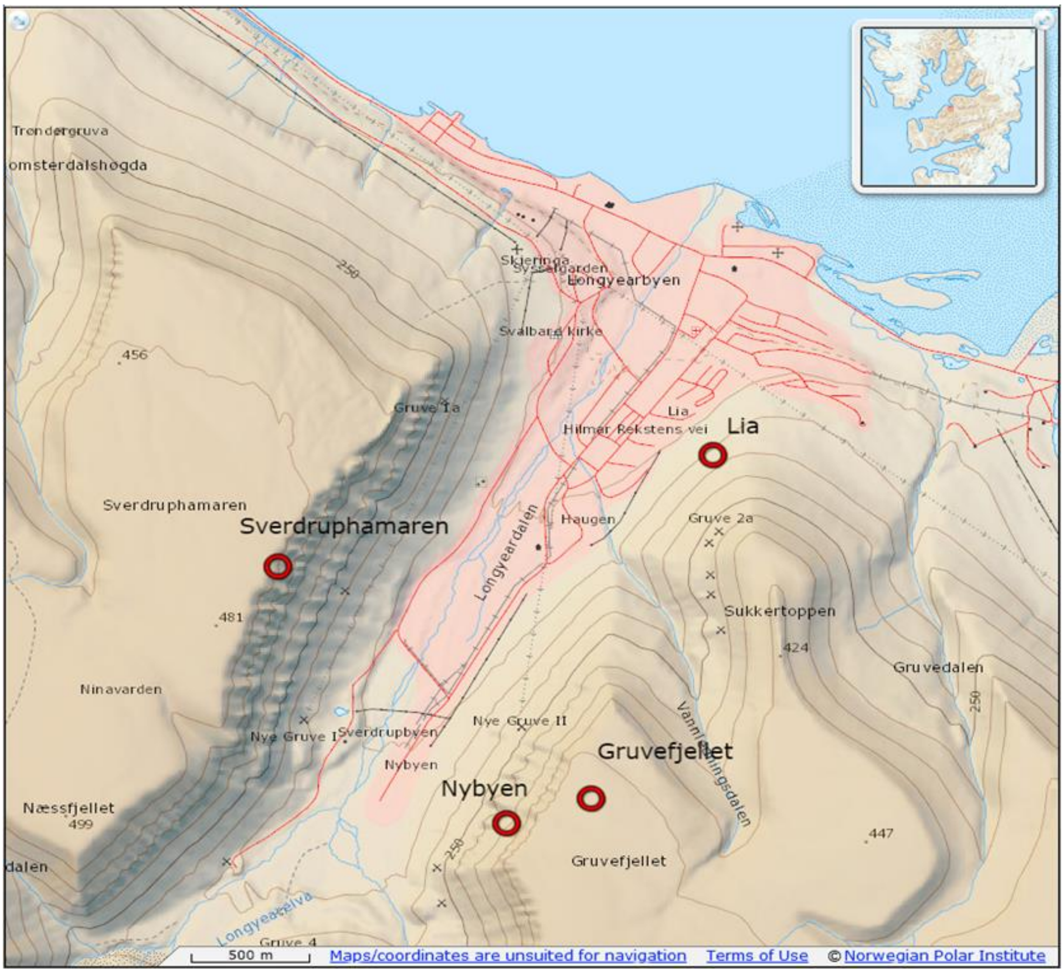


Figure 6.1. The Longyeardalen valley with the location of the Longyearbyen town and of the utilized snow stations (Lia, Nybyen, and Sverdruphamaren) and of the closest automatic weather station (AWS) Gruvefiellet.

However, numerical weather prediction models cannot resolve the complex Svalbard topography and therefore cannot provide accurate snow precipitation and snow accumulation on the mountain slopes where avalanches can take place.

In Task 6.4 the aim is to derive statistical relationships between the in-situ measurements of snow depth and the meteorological parameters that affect the distribution of snow accumulation on the mountain slopes surrounding Longyearbyen in order to improve the input to avalanche forecast models. Observations of snow depth from three stations and meteorological data from two weather stations around Longyearbyen (Figure 6.1) was used together with data from the Copernicus Arctic Regional Reanalysis (CARRA) at the grid points closest to the observation stations. Statistical analysis of the data shows that it is possible to identify the local atmospheric conditions in which snow erosion and accumulation are most probable on the slopes where snow avalanches have been observed in the past although data only covers one season. An empirical correction of the precipitation from the numerical weather prediction model using the observed snow depth evolution was also tested showing a potential for developing the methods further by adding weather-based correction factors to the scheme.

To reinforce the statistical approach described above, we also utilized the geostatistical tool RIntaros/RGeostats developed by ARMINES and available in the INTAROS Arctic Observation System, to produce gridded maps of snow depth on the Longyearbyen valley at high horizontal resolution (25 m). A detailed description of the snow map product and the method is provided in deliverable D5.10.

The improvement of inputs to avalanche forecast models, as well as the testing and development of the snow models themselves, heavily rely on the availability of local observations of snow depth and meteorological variables, possibly existing as a long time series. Although this study could only be based on a very limited dataset, it showed the potential of applying in situ observations to downscale or train the meteorological variables used as input to the snow model, highlighting the necessity of permanent snow and meteorological stations that could provide the time series necessary for the development of the method.

6.2 Earthquakes, landslides, and tsunamis

Contributors: Peter H. Voss (GEUS), Mathilde B. Sørensen (UiB)

Seismometers can provide information on earthquakes, but also on landslides, snow avalanches and, to some extent, tsunamis. Stakeholders (e.g. communities) need clear information that can be implemented in decision making. This includes information on previous events, the potential for future events with associated uncertainties, as well as on the potential impact of events on societies and the environment. And for stakeholders to be able to react quickly and adequately to hazardous events, real time data collection and transfer is required.

The detection capacity of a seismic network is controlled by inter-station distance, the noise level at station locations and the quality of the equipment. Good detection requires a dense network of stations, also covering the ocean areas, at locations with a low noise level. Permanent seismic stations are currently restricted to land areas, leading to large monitoring gaps in the ocean areas. Even in the Arctic land areas, instrumentation is sparse due to logistical challenges.

Within INTAROS three ocean bottom seismometers (OBS) were deployed to fill the observational gap in the oceans. In addition, community-based seismometers were deployed in West Greenland.

In Task 6.4 the observations from these deployments were analyzed. The results show that observations from the OBS improve our understanding of the ridge seismicity (Jeddi et al., 2021) and demonstrates how even very few stations can significantly improve earthquake detection and locations. Community based seismometers have been demonstrated to be a useful low-cost supplement to permanent seismic stations on land (Jeddi et al., 2020). They contribute to better earthquake locations and to raise awareness among community members where they are deployed.

Data from INTAROS seismic stations in Greenland have been used in a study of landslides in West Greenland combining seismic observations with remote sensing. The combination of seismic and satellite data provides accurate locations in time and space of landslide events, since the seismic data have high time resolution but low spatial resolution whereas the satellite data have a low time resolution but a high spatial resolution. The much more precise monitoring of landslides using seismic and satellite data combined, is providing new information on landslide prone areas and the frequency of landslides. This information is important in the evaluation of future landslide risk. Considering the tsunamigenic potential of some large landslides, it is important to understand the landslide risk even in remote and unpopulated areas. The work is presented in several places, e.g., Svennevig et al. (2020).

For an improved future integrated Arctic Observation System, additional data are required to provide knowledge beyond spatial and temporal location of seismic events. The mechanisms that release the seismic events, such as the stress induced by plate tectonics, are only well understood for larger earthquakes (magnitude 5+), based on the permanent monitoring. For smaller earthquakes and other seismic events, a denser, long-term monitoring is needed. In coastal regions, this can be obtained using existing technology, but power supply and internet access is challenging at remote locations, especially in the ocean. Effort should be put into multi-hazard and -risk assessment in the arctic region, considering the effects of climate change and the potential for cascading events. Such effort should allocate sufficient resources to visualization and provision of data to relevant stakeholders.

6.3 Mass loss from ice sheets and glaciers

Contributors: Anne Solgaard (GEUS), Andreas Ahlstrøm (GEUS), Kenneth Mankoff (GEUS), Francisco Navarro (UPM), Eva De Andrés (UPM), María Isabel de Corcuera (UPM), Jaime Otero (UPM), Shfaqat Abbas Khan (DTU)

Mass loss from glaciers and ice sheets from either melt or calving eventually ends up as a freshwater input to the local fjords and ultimately the oceans contributing to sea level rise. It therefore constitutes both possible local and global hazards making it important to both local and global stakeholders.

The rise in the global mean sea level represents a natural hazard to coastal communities worldwide causing coastal flooding, erosion, damage to buildings and infrastructure, changes in ecosystems, and contamination of drinking water sources. On the local scale, changes in the amount and timing of the freshwater input to fjords and near coastal waters impact the marine ecosystem and thus fishery which in turn may impact local economies. Policymakers and coastal planners require an estimate as accurate as possible of the projected sea-level rise under various emission scenarios. Local communities rely on results from ecosystem models to plan for changes in fish stocks and on hazard maps for safety and securing infrastructure. These all require good quality, easily accessible and continuous monitoring of ice mass loss as well as a better process understanding. This also includes that data are provided at high temporal and spatial resolution. As the uncertainties are expected to be large, error estimates play a relevant role.

Monitoring and understanding this mass loss from the ice sheet is essential in order to project its future contribution, yet even separating the mass loss between the main processes of surface mass balance (snowfall and melt) and marine mass loss (iceberg calving and glacier front melting in the ocean) remains elusive. Continued observations of ice-sheet-wide mass change and an improved understanding of the processes leading to this change are needed to improve projections.

In Task 6.4 we have generated multiple data products quantifying the total mass loss, solid mass loss, liquid mass loss, and freshwater runoff from the Greenland Ice Sheet. We have also developed tools to improve the error estimates of the solid ice discharge and a model based approach to separate the frontal ablation of tidewater glaciers into its two main components iceberg calving and submarine melting.

6.3.1 Products

Two products relating to the **total mass balance** of the Greenland Ice Sheet have been created as part of Task 6.4:

- One using data from the GNET stations to improve the spatial resolution of a mass loss product based on gravimetry data from the GRACE satellite mission.

- And a second based on the input-output method where each ice sheet mass loss component (surface, marine, and basal mass losses) is subtracted from the mass inputs (e.g. snowfall). During the completion of D6.16 it was still under development but is now published in Mankoff et al, 2021. The product combines output from the HIRHAM/HARMONIE (Christensen et al., 2006), MAR (Fettweis et al. 2020), and RACMO (Noël et al. 2018) RCM surface mass gain terms, the same three RCM surface mass loss terms (combined as surface mass balance or SMB), a solid ice discharge product for the marine mass balance (MMB) term (Mankoff et al. 2020; described below), and a new data product (Karlsson, 2021) for the basal mass balance (BMB) term. The mass balance is then computed as MB = SMB - MMB - BMB. The product spans the period 1840 to next week.

Solid ice discharge

A tool delivering highly resolved spatially (glacier scale) and temporally (bi-weekly) estimates of where and when solid ice and submarine melt discharges into the surrounding fjords and seas exists (Figure 6.2). It is an “operational” product from 1986 until last month, updating approximately every 12 days with a one-month lag. The product is described in detail in Mankoff et al, 2020a. Inputs to this product are the PROMICE Sentinel Ice Velocity product (Solgaard et al 2021) which can be accessed through the INTAROS catalogue, and the BedMachine dataset (Morlighem et al., 2017) for ice thickness. The ice discharge uncertainty is primarily due to uncertainties in the ice thickness at the flux gates. As the ice thickness dataset is updated, the uncertainty will decrease. This solid ice discharge is either submarine melt (which impacts ecosystems as described in the Freshwater Runoff section below), or icebergs, which are both an important part of the Greenlandic tourism economy, a navigation hazard for boats and ships, and a potential tsunami-source hazard for coastal towns (in 2018, a large iceberg near Innaarsuit made international news as a tsunami hazard).

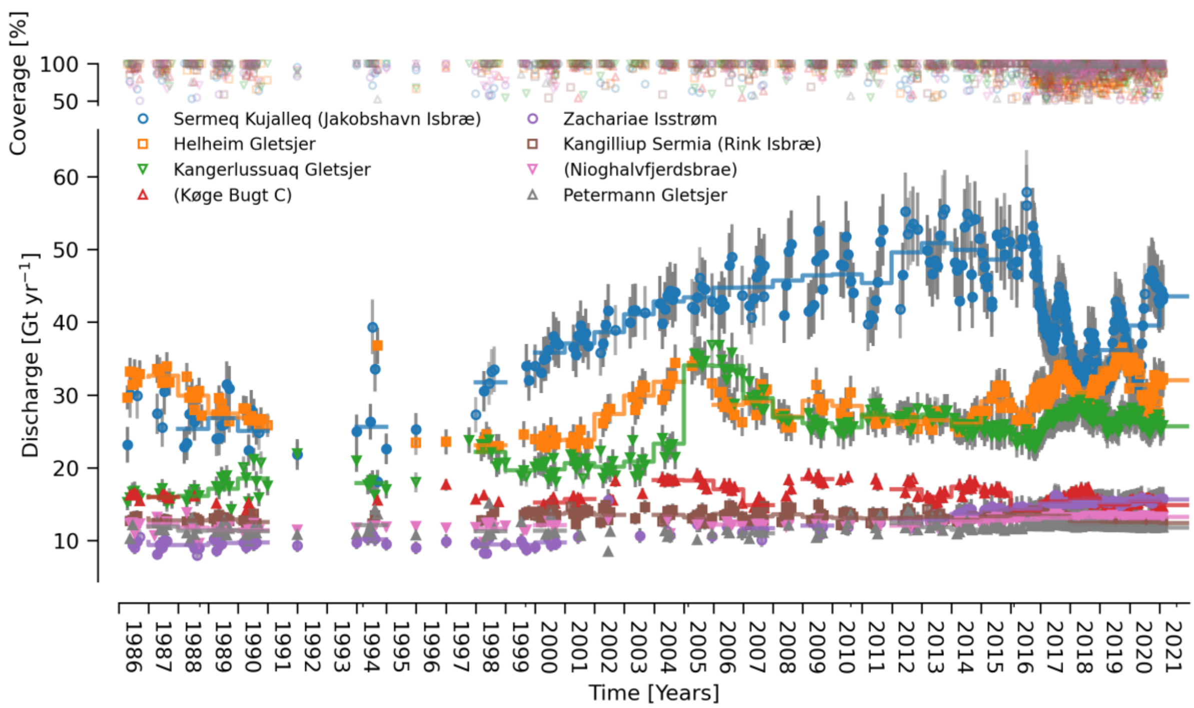


Figure 6.2. Discharge time series for eight major glaciers.

Freshwater runoff

This product includes melted ice (a mass loss term) but also rainfall which is mass neutral. We have created a high spatial (outlet scale) and temporal (daily) estimate of where and when liquid freshwater (i.e. rainfall, melted ice, and melted snow) discharges into the surrounding fjords and seas from 1958 through 2019. The freshwater product is described in Mankoff et al, 2020b and is generated using output from two RCMs and the ArcticDEM surface topography (Porter et al, 2018). With this product quantifying liquid water runoff, stakeholders now have access to a dataset that can be used for a variety of ecosystem model studies related to the regional fishery economy or safety and hazards.

Quantifying ice discharge errors

An important aspect of the ice discharge estimates is the quantification of the errors involved in its calculation. The usual error estimates for ice discharge are often based on rough estimates of upper and lower bounds for the error, rather than doing a statistical error analysis based on error propagation. Within INTAROS we have developed tools (Sánchez-Gámez and Navarro, 2018), based on statistical error propagation techniques, to estimate the error in ice discharge as a function of the errors in the variables and parameters involved in the discharge computation. This fills a significant gap in the uncertainty estimates associated with ice discharge computations, by narrowing their error ranges.

Separating marine mass loss into iceberg calving and submarine melting

Two model based approached has been developed in Task 6.4 to separate frontal ablation of tide water glaciers into iceberg calving and submarine melting. One relying on a coupled glacier dynamics-fjord circulation model, which is the most complete approach but also the computationally most expensive. And a second, where the glacier dynamics model is coupled with a plume parameterization model, which is computationally less heavy. Both approaches are published in open-access journals (De Andrés et al., 2018, 2020, 2021). The Elmer/Ice model is applied as the glacier dynamics model while the MITgcm is used as the fjord circulation model. The methods contribute to closing the gap in understanding the partitioning of ice discharge into its two main components. This, again, is fundamental to the model-based estimates of the future evolution of the Greenland Ice Sheet.

Both approaches require many datasets from the glacier, fjord waters and overlying atmosphere environments. Because the method is mostly aimed at process understanding, such data are only needed for selected glaciers. However, it often happens that a given glacier has plenty of glaciological and atmospheric/radiation data but lacks the necessary fjord water data. Conversely, for some glacier-fjord systems many oceanographic measurements are available, but the glaciological data is scarce.

6.4 Further development of observing systems

Contributors: Anne Solgaard (GEUS), Andreas Ahlstrøm (GEUS), Kenneth Mankoff (GEUS), Francisco Navarro (UPM), Shfaqat Abbas Khan (DTU), Peter H. Voss (GEUS), Mathilde B. Sørensen (UiB), Roberta Pirazzini (FMI)

How the results from the studies relating to each of the three hazards should be improved and exploited are detailed above. In this section we synthesize the specific findings of all the studies included in Task 6.4 into more general findings relating to tending to stakeholder needs and future development of methods and monitoring services (for more details please refer to D6.16):

- **Long timeseries** (and high temporal/spatial resolution) of observations are the backbone for quantifying the hazard and risk of natural hazards, for increased process understanding and improved predictions.

- Having **data freely available** through various platforms makes it easier to use, as well as visible to users from different fields. This facilitates interdisciplinary studies e.g. the landslide study combining seismic observation and remote sensing products.

- Creating **super sites** where multi-disciplinary data is acquired will help to overcome the problem of the lack of observations co-located in time and space and will enable the reduction of the cost/benefit ratio.

- Providing **data in real time** is important for operational services to allow authorities respond timely e.g. in the event of an earthquake or an increase in the risk of an avalanche.

References

De Andrés, E., Otero, J., Navarro, F., Promińska, J., Lapazaran, J., Walczowski, W. 2018. A two-dimensional glacier–fjord coupled model applied to estimate submarine melt rates and front position changes of Hansbreen, Svalbard. Journal of Glaciology, 64(247), 745-758, doi: 10.1017/jog.2018.61.

De Andrés, E. , Slater, D. A., Straneo, F., Otero, J., Das, S., Navarro, F.J. 2020. Surface emergence of glacial plumes determined by fjord stratification. The Cryosphere, 14, 1951–1969. doi:10.5194/tc-14-1951-2020.

De Andrés, E., Otero, J., Navarro, F.J., Walczowski, W. 2021. Glacier–plume or glacier–fjord circulation models? A 2-D comparison for Hansbreen–Hansbukta system, Svalbard. Journal of Glaciology, First View, doi:10.1017/jog.2021.27.

Jeddi Z, Voss PH, Sørensen MB. Et al. 2020. Citizen Seismology in the Arctic. Front. Earth Sci. 8:139. doi: 10.3389/feart.2020.00139

Jeddi, Z., Ottemöller, L., Sørensen, MB. Et al. 2021. Improved Seismic Monitoring with OBS Deployment in the Arctic: A Pilot Study from Offshore Western Svalbard. Seismological Res Letters, accepted.

Karlsson, N.B., Solgaard, A.M., Mankoff, K.D. et al. 2021. A first constraint on basal melt-water production of the Greenland ice sheet. Nat Commun 12, 3461. https://doi.org/10.1038/s41467-021-23739-z

Mankoff, Kenneth D., Solgaard, Anne, Colgan, William, Ahlstrøm, Andreas P., Khan, Shfaqat Abbas, Fausto, Robert S.: Greenland Ice Sheet solid ice discharge from 1986 through March 2020, *Earth System Science Data* 12(2), Copernicus GmbH, 1367–1383, 6 2020

Mankoff, Kenneth D., Noël, Brice et al. 2020. Greenland liquid water discharge from 1958 through 2019, *Earth System Science Data* 12(4), Copernicus GmbH, 2811–2841, 11.

Mankoff, K. D., Fettweis, X., Langen, P. L. et al. 2021. Greenland ice sheet mass balance from 1840 through next week, Earth Syst. Sci. Data Discuss. [preprint], https://doi.org/10.5194/essd-2021-131

Morlighem, M., Williams, C. N., Rignot, E. et al. 2017. BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multi-beam echo sounding combined with mass conservation , *Geophysical Research Letters* 44(21), American Geophysical Union.

Porter, C, Morin, P, Howat, I. et al. 2018. ArcticDEM , Harvard Dataverse V1, 2018, Date accessed: 2019-11-14

Rinke, A., M. Maturilli, R. M. Graham et al. 2017. Extreme cyclone events in the Arctic: Wintertime variability and trends. Environmental Research Letters 12(9): 094006.

Sánchez-Gámez, P., Navarro, F.J. 2018. Ice discharge error estimates using different cross-sectional area approaches: a case study for the Canadian High Arctic, 2016/17. Journal of Glaciology, 64(246), 595-608, doi:10.1017/jog.2018.48.

Solgaard, A., Kusk, A., Merryman Boncori, J. P. et al. 2021. Greenland ice velocity maps from the PROMICE project, Earth Syst. Sci. Data, 13, 3491–3512, https://doi.org/10.5194/essd-13-3491-2021.

Svennevig, K., Dahl-Jensen, T., Keiding, M. et al. 2020. Evolution of events before and after the 17 June 2017 rock avalanche at Karrat Fjord, West Greenland – a multidisciplinary approach to detecting and locating unstable rock slopes in a remote Arctic area, Earth Surf. Dynam., 8, 1021–1038, https://doi.org/10.5194/esurf-8-1021-2020.

7. Greenhouse gas exchange in the Arctic

7.1 Atmospheric case studies of GHG budgets

Main contributor: Mathias Göckede, MPI BGC

7.1.1 Main activities and results

The atmospheric component of Task 6.5 used a data assimilation scheme based on a geostatistical inverse modeling framework to constrain methane emissions over the East Siberian Arctic Shelf (e.g. Shakhova et al., 2019), identify environmental conditions that explain spatio-temporal patterns in surface-atmosphere emissions, and link the latter to biogeochemical and biogeophysical processes governing the methane cycle in the target domain. After establishing a reference model framework, and using it for in-depth model sensitivity studies and process investigation, a second step added new data layers from the INTAROS catalogue and tested their effect on model performance (Figure 7.1).

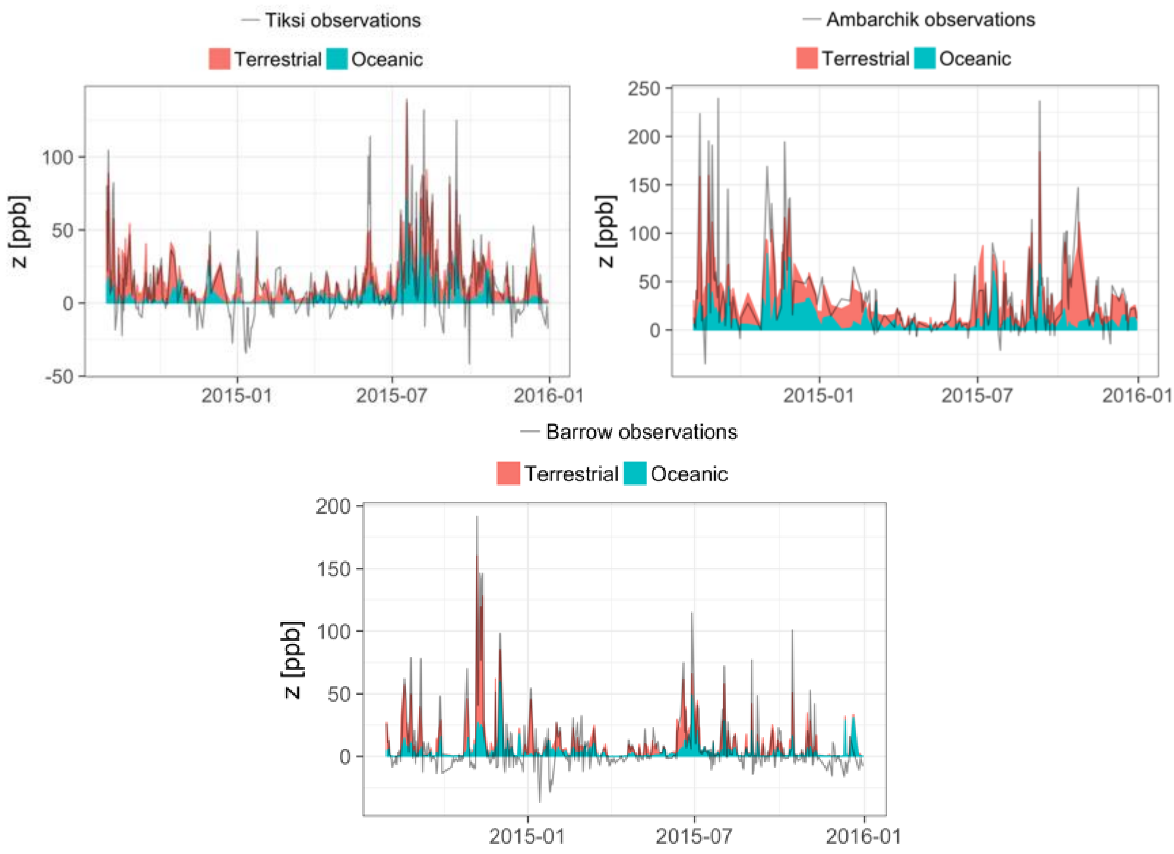


Figure 7.1 Example of modeled atmospheric CH_4 mole fractions at Tiksi (left), Ambarchik (center) and Barrow (right) based on posterior emission estimates of a single inversion scenario ("Coastal flux + Sea ice growth", with relaxed atmospheric data selection).

Based on the reference modeling framework, we estimated annual methane emissions from the East Siberian Arctic Shelf to the atmosphere at 0 – 1.4 Tg CH_4 yr^{-1}, which is on the low end of existing literature estimates. Highest emissions were attributed to shallow waters, while no emission spike was observed during sea ice retreat, indicating low accumulation of methane under the ice in winter. We also found potentially substantial emissions in fall and sustained emissions during winter, but these findings were sensitive to filters applied to atmospheric observation data, thus we have lower confidence in them. All results could be explained by two underlying processes: first, trapping of methane below the pycnocline could be responsible for a dominance of emissions from shallow waters, the potential emissions in fall (sea-ice growth, storms) and the missing emission spike during sea ice retreat (meltwater barrier). Second, significant emissions through cracks in sea ice could explain winter emission estimates and the missing methane spike during sea ice retreat (low accumulation).

Addition of new data layers from the INTAROS database focused on two products, provided by University of Hamburg - UH (Lyu et al., 2021) and University of Bremen - UB (Scarlat et al., 2018), which fulfilled the format requirements for data assimilation into the chosen atmospheric inversion framework, i.e. provision of spatially continuous, gridded information. In addition to the five parameters that could be extracted from these new datasets, several derived products were developed, all of which were tested as potential auxiliary data layers to explain spatio-temporal variability in methane emissions. Our results revealed that the improved sea ice concentration product was preferred over the previously used dataset. Moreover, the surface heat fluxes from that same dataset was clearly superior over the ERA interim cooling flux data product that had previously been used in the inversion. Other new parameters played only a marginal role (e.g. the total water vapor product by UB), or were not used in model selection at all (e.g. the sea ice thickness parameter from UH). Accordingly, the assimilation of new data slightly improved model performance, while no major effects on the computed deterministic flux fields of methane was found. Since the overall structure of chosen data layers combined in the top-ranking models did not substantially change, and successfully chosen new data layers mostly replaced similar products from other sources that were previously used, no new insights about processes and controls governing the shelf area methane cycle could be derived.

7.1.2 Data and models used

Our method constrains methane emissions from surface sources to the atmosphere based on measurements of the atmospheric methane mole fraction observed at a distributed network of monitoring towers. The link between these quantities is atmospheric transport, and solving for fluxes means inverting the transport equation. In other words, atmospheric transport modeling allows us to identify which areas within the target domain influenced an atmospheric greenhouse gas (GHG) observation taken at a specific time and place, and therefore facilitates to attribute sink and source strengths to these areas that correlate with the observed patterns in atmospheric GHG mixing ratios. Since observational datasets are scarce, usually the problem is under-constrained, and thus requires additional information sources to allow for non-equifinality across large subsets of potential solutions. In this context, valuable information can be assimilated from data layers that describe the structure of sources and sinks within the target domain, and their temporal variability – termed auxiliary variables in our framework.

Since inverting the transport equation is in general an under-constrained problem, meaningful results in atmospheric inverse modeling can only be obtained with some form of additional regularization. In greenhouse gas modeling, the Bayesian inverse modeling approach is often applied, where fluxes are nudged towards a prior estimate, and spatial and temporal covariances are imposed. Within the atmospheric component of Task 6.5, we employed a geostatistical inverse modeling approach (e.g. Michalak et al., 2004), which can be thought of a Bayesian model where prior and covariances are inferred from the atmospheric data.

The reference version of our atmospheric inversion relies on reanalysis data to simulate atmospheric transport, tower-based in-situ observations of atmospheric greenhouse gas mixing ratios, and a suite of 33 gridded data layers termed 'auxiliary variables' which help to explain spatio-temporal variability in the surface-atmosphere flux patterns. The basic requirement for the provision of new auxiliary data layers taken from the INTAROS catalogue was a continuous spatial grid of information that covered the entire target domain. Such data layers may both be static or time-varying. Since the majority of information provided by the INTAROS catalogue is either at site-level or episodic coverage of ocean transects, only two datasets remained that could be tested for our data assimilation approach.

The first product which was additionally assimilated into the geostatistical inverse modeling framework in the context of the presented study, provided atmospheric Total Water Vapor (TWV) over ice and open ocean (University of Bremen). This dataset merged the precipitable water vapor content from the microwave imager AMSR-E/2 over open water and from the microwave sounder AMSU-B and MHS over ice. The results was an Arctic-wide daily dataset for total water vapor of 50 km resolution with seamless coverage from the high Arctic to mid latitudes from 2002 to date. This new approach (Scarlat et al., 2018) allows to apply the method also to regions where previously no data were available, and ensures a more consistent physical analysis of the satellite measurements by taking into account the contribution of the surface emissivity to the measured signal.

As a second new dataset, our approach assimilated information from the Ocean-Sea Ice Synthesis from 2007-2016 provided by University of Hamburg. Using the Massachusetts Institute of Technology general circulation model (MITgcm, Marshall et al., 1997) and its adjoint, in this project both in situ and remote sensing observations were used to produce new synthesis products for the Arctic. The model domain covers the entire Arctic Ocean, north of the Bering Strait and ~44N in the Atlantic Ocean. The data assimilation produced a substantially improved representation of the daily mean state of Arctic sea surface temperature (SST), sea ice concentration (SIC), and sea ice thickness (SIT). Datasets also include continuous grids of e.g. ocean potential temperature, salinity, zonal and meridional velocity, freshwater, or heat fluxes at the sea surface (Lyu et al., 2021).

7.1.3 Stakeholders/users who will benefit from the results

Our activity specifically targets the ESM modelling community as stakeholders, with the aim of supporting the representation of biogeochemical processes in high-latitude ecosystems as well as the assimilation of the most relevant data layers into existing modelling frameworks. Reduced uncertainties in the resulting future climate simulations will in turn help local communities as well as decision makers in economy and management to improve adaptation measures towards climate change impacts in the region.

7.1.4 Further development and exploitation of results after the end of the project

The presented study sheds new light on disagreements on the magnitude of methane emissions from the East Siberian Arctic Shelf to the atmosphere in the literature and provides insights into the controls of the emissions. Our study suggests that in the selected model domain, which is supposed to be representative for the high Arctic coastal region, terrestrial emissions from northern wetlands are at present more important than shelf emissions for the atmospheric methane burden. Our inversion results placed shelf emissions predominantly into shallow water areas, which is compatible with the assumption that pycnocline inhibition strongly limits emissions from deeper areas, among other factors. Sensitivity studies revealed the importance for future studies focusing on improving inaccuracies in atmospheric transport modeling in the Arctic especially in winter, which is particularly relevant for coastal sites that may temporarily be affected by small-scale circulation systems that complicate the separation between terrestrial and oceanic air masses. In this context, there is a general need for expanding the atmospheric greenhouse gas observation network in the Arctic, with a particular demand in observations representing the oceanic domain. Alleviating these constraints, the data assimilation approach presented herein could be demonstrated to be a powerful research tool for exploiting additional data sources to generate new information on carbon budgets and underlying processes in previously understudied, data-poor domains. Future research should focus on assimilating additional datasets that e.g. take into account the role of transport with ocean currents, or provide novel links to oceanic biogeochemistry, in order to provide a more comprehensive view of the role of ocean shelves in the Arctic carbon cycle.

7.2 Ocean case studies of GHG budgets

Main contributors: Truls Johannessen, Are Olsen, and Nicholas Roden, UiB; Andrew King NIVA; Mikael Kristian Sejr, AaU.

The work presented here is described in detail in deliverable D6.8. The goal was quantification of the advective net exchange of Greenhouse gas **(**GHG) between the Atlantic and the Arctic Ocean based on mass balances along the intersection between the regions, including the characterization of transport and carbon transformation processes, and the role of ocean chemistry and acidification patterns.

7.2.1 Main activities and results

The aim is and will still be in potential future projects, to monitor how the uptake of CO_2 by the ocean adds to the total dissolved inorganic carbon content of the ocean, which results in reduction of seawater pH – termed ocean acidification – and the saturation state of calcium carbonate minerals, e.g., aragonite and calcite.

The carbonate system chemistry in the Arctic and Subarctic oceans is very dynamic due to strong/seasonal variability in biological activity (production/respiration), wind and other physical mixing mechanisms, and sea surface temperature. Precise estimates of the oceans uptake and release of CO2 and knowledge and predictions of susceptibility to change from various feedback mechanisms is essential to predict the rate of climate change in earth system models. It is also equally important to observe present day carbonate system chemistry as a baseline and to understand the impact/role of major drivers in carbonate system dynamics. This was the rationale for the observing system design and implementation that was carried out in WP3, and data collected through observations near Svalbard, the Barents Sea Opening, and Coastal Greenland in WP3 were integrated and synthesized as part of WP6 and reported in D6.8.

A self-organising map technique and data synthesis

The main result from the ocean biogeochemistry team is the development of a self-organising map technique. This is a type of artificial neural network that uses machine learning, which was implemented to estimate surface water pCO_2 values for the Barents Sea opening (Figure 7.2; 10°E-30°E; 70°N-77.5°N). Initially, the network was trained using satellite observations of chl-*a*, sea ice concentration, sea surface temperature and salinity, as well as bathymetry and estimates of mixed layer depth. The training data was labelled with pCO_2 observations from the SOCAT database, which enabled preliminary maps of monthly sea surface pCO_2 for the year 2018 to be created. The network is now ready to include the training and labelling data sets from INTAROS partners and atmospheric inverse modelling.

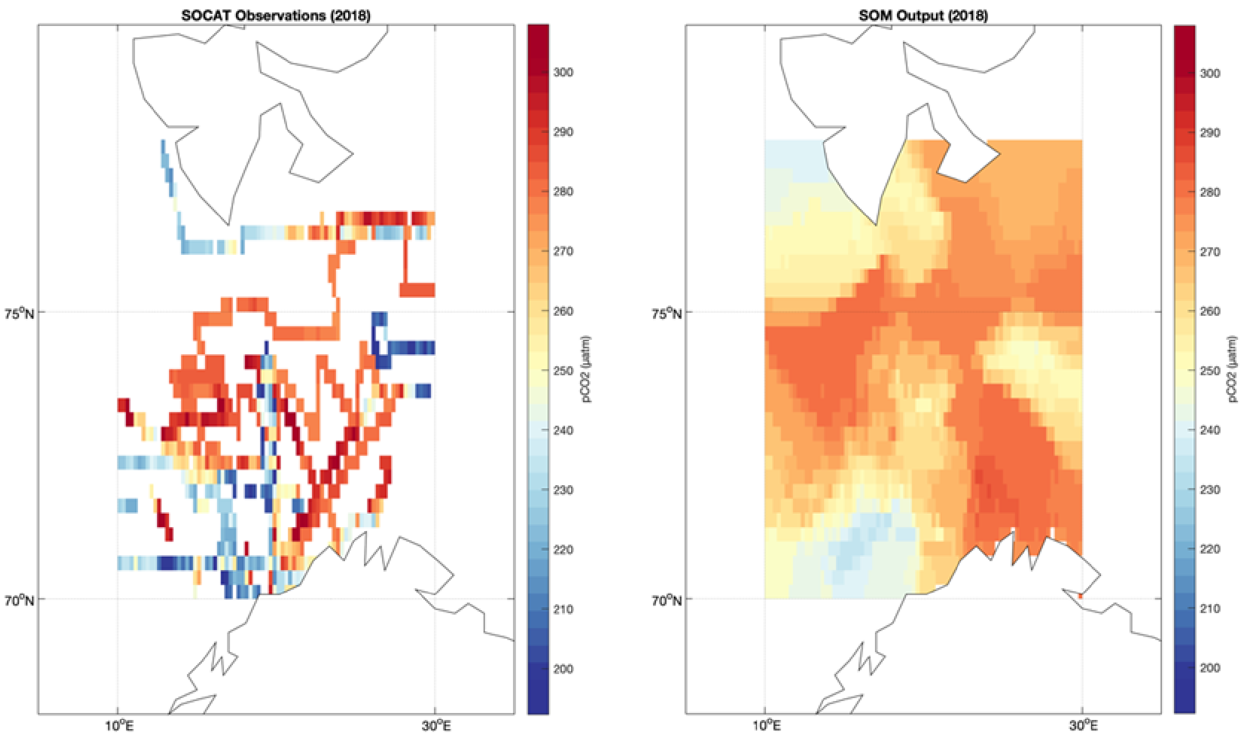


Figure 7.2. Data extracted from the SOCAT-database for year 2018 (left panel) and an example of output, a self-organization map (right panel).

Data synthesis

A FerryBox system was equipped on M/S Norbjørn, which made approximately 25-30 round-trip crossings per year through the Barents Sea Opening between Tromsø, Norway and Longyearbyen, Svalbard. The FerryBox system included a number of physical, chemical, and biological sensors: a Seabird SBE38 inlet temperature sensor, a Seabird SBE45 conductivity-temperature sensor, a Franatech/NIVA membrane equilibrator pCO_2 sensor, a NIVA spectrophotometric pH sensor, and a TriOS microFlu *chl a* fluorometer. Observations from fCO2 from 2020 are shown in Figure 7.3.

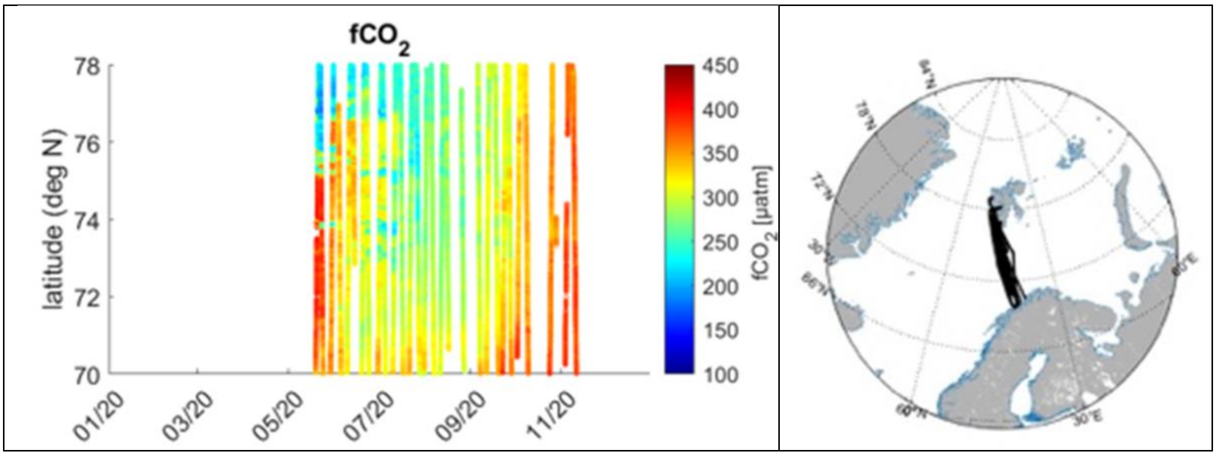


Figure 7.3. Location of M/S Norbjørn crossings (right) and synthesis of fCO_2 data by NIVA (left).

Greenland Ecosystem Monitoring (GEM) Programme

In Greenland, measuring ocean CO_2 and carbonate chemistry is included in the Greenland Ecosystem Monitoring (GEM) Programme. A scientific paper is being prepared by a student and upon publication the data will be open access. About 750 individual CO_2 measurements were made across 11 different fjord transects. In spite of the considerable variation within local fjords primarily related to the amount of glacial meltwater, clear differences between summer surface (0-50 m) conditions in pCO_2 where found. Most notable the variation between sites and with depth was notably smaller along the East Greenland coast compared to West Greenland. This result in lower undersaturation (on average) in west Greenland, but also over-saturation at depth.

Data and models used

Data products from INTAROS put into the context of global databases as SOCAT and GLODAP have been used. In addition, a self-organising map technique to prepare gridded data to be compared with output from inverse modelling has been developed (see also above).

The aim of comparing output from inverse atmospheric modelling with output from self-organising maps could not be reached because of covid-19 related delays and shut down of societies making face-to-face communication impossible. In addition, to do this work-intensive comparison properly a dedicated project is needed.

7.2.2 Stakeholders/users who will benefit from the results

The data produced in INTAROS will be publicly available for the scientific community as well as for society; specifically aiming towards management of global warming caused by fossil fuel emission. The Arctic is an important part of the global climate system and changes in the Arctic can potentially have an impact on a global scale. For this reason, changes in Arctic biogeochemical cycles can significantly affect climate change. Thus, enhanced knowledge on these matters are important for policymaking at all scales, from global to local communities, i.e., the COP process, research strategies within EU infrastructure program like ICOS, EMSO, EURO floats, local governments, education, technological development, down to individuals taking responsibilities to reduce their carbon footprint.

7.2.3 Exploitation - further development of results after the end of the project

There is a clear potential to produce carbonate system data in an autonomous fashion using ships of opportunity and other observing platforms, such as moorings, that complement conventional research cruise-based observations. Combined, these observations will give better seasonal, annual, interannual and decadal coverage of the carbonate system and ocean acidification. It will be important to continue to use these data together with existing data in models and data intercomparison exercises for validation of model results. A self-organising map technique, a type of artificial neural network that uses machine learning seems to be a promising approach and unfortunately it was impossible because of delays due to COVID-19 to pursue this approach and to interact with the atmospheric modelling group in INTAROS.

INTAROS has implemented different platforms and sensors for measurement of carbonate system variables and approaches for integrating/synthesizing existing and new observations. These activities are needed for improving our understanding of the marine carbonate system in Arctic and Subarctic Oceans, and therefore to better manage the region in a sustainable manner. There are still some challenges that need to be addressed before these platforms can produce reliable data that is high quality with good spatial and temporal coverage that can be used to answer questions related to ocean uptake and transport of CO_2 related to both natural and anthropogenic processes, and to assess the rate of change in ocean acidification. There is also the need to improve observations related to phytoplankton blooms and biological production to fully characterize and understand carbon system dynamics. However, the developments in ocean acidification-related sensors in addition to other biological and biogeochemical sensors (e.g., nitrate and oxygen) are on track to be used to measure changes in carbonate system chemistry and deoxygenation in Arctic coastal and open ocean systems.

Monitoring challenges:

Ensure sustainable long-term monitoring activities north of Svalbard, across the Barents Sea opening, and in Artic fjords on Svalbard and Greenland. There is a strong need to establish such platforms within the Arctic Ocean itself.

A technological challenge

There is a strong need for making individual sensors monitoring biogeochemical properties more reliable and robust. Successful development of an autonomous biogeochemical mooring, or other platform, will rest upon further development of sensor technology that can meet the extreme Arctic environmental challenges.

A synthesis challenge

Further develop tools to synthesis data, for instance self-organizing data assimilation techniques etc.

A continuity challenge

Technologies used in INTAROS can further be implemented at new sites, but at the same time activities already implemented should be sustained on a long term. There is a strong need for a project which can keep the team in INTAROS together to complete, further develop and close gaps identified in INTAROS.

References

Lyu, G., A. Koehl, N. Serra, D. Stammer, and J. Xie. 2021. Arctic ocean–sea ice reanalysis for the period 2007–2016 using the adjoint method. Quarterly Journal of the Royal Meteorological Society **147**:1908-1929.

Marshall, J., A. Adcroft, C. Hill, L. Perelman, and C. Heisey. 1997. A finite-volume, incompressible Navier Stokes model for studies of the ocean on parallel computers. Journal of Geophysical Research: Oceans 102:5753-5766.

Michalak, A. M., L. Bruhwiler, and P. P. Tans. 2004. A geostatistical approach to surface flux estimation of atmospheric trace gases. Journal of Geophysical Research-Atmospheres 109:D14109.

Scarlat, R. C., C. Melsheimer, and G. Heygster. 2018. Retrieval of total water vapour in the Arctic using microwave humidity sounders. Atmos. Meas. Tech. 11:2067-2084.

Shakhova, N., I. Semiletov, and E. Chuvilin. 2019. Understanding the Permafrost–Hydrate System and Associated Methane Releases in the East Siberian Arctic Shelf. Geosciences 9:251.

8. Case studies of Community-Based Observing systems

In Task 6.6, we prepared a series of policy briefs intended to demonstrate 'real world' examples of the benefits of cross-weaving data from local and scientific observation systems. Through dialogue with civil society organizations, research institutions and the local authorities, we identified three topics of high priority to local communities where local/citizen-based and scientific observations are important and where recommendations for better-informed decisions and better-documented processes are pertinent:

- Local and scientific observations for improving fisheries in Greenland
- Natural disasters in Disko Bay, Greenland and Longyearbyen, Svalbard
- Monitoring Svalbard's environment and cultural heritage by expedition cruises

Below we summarize the main activities and results, and we describe the data and models used, the key stakeholders, and the tasks ahead, beyond the lifetime of the project. This chapter is a modified version of Deliverable 6.6.

8.1 Local and scientific observations for improving fisheries in Greenland

Contributors: Finn Danielsen, Michael K. Poulsen, Martin Enghoff, NORDECO

Fisheries are of great importance in Greenland but there is uncertainty as to future sustainability and stock dynamics. Fisheries management advice is currently based mainly on catch statistics and researchers' surveys although there is growing international recognition that user knowledge is valuable. The new agreement on the future of fisheries in the Central Arctic Ocean gives user knowledge from coastal communities a central role in the future management of fishery resources.

In the 1st policy brief of Task 6.6, we summarized what we know about how user knowledge can be incorporated into fisheries management in Greenland. The policy brief was prepared in collaboration with KNAPK, Oceans North, University of Alberta, and Ilisimatusarfik.

8.1.1 Main activities and results

For the past ten years, the Greenland government has been testing ways of incorporating user knowledge in the management of fish and other living resources in Disko Bay. Experienced fishermen have been systematically discussing and reporting on the status of several fish species. They have also provided possible explanations for changes in stocks and have proposed specific management measures. The methods tested have provided valuable knowledge on the development of several stocks. Using these tested methods, users have come up with management proposals that both expand and limit fishing activity. In addition to bringing important knowledge into play on the various fish stocks, the inclusion of user knowledge in fisheries management offers better opportunities for: 1) Obtaining knowledge from wider geographical areas; 2) Early detection of stock changes; 3) Establishing user and site-specific knowledge for management plans in specific management areas; 4) Promoting realistic local regulations e.g. of trawling; and 5) Strengthening the use of regulatory tools such as quotas, legal gear, zoning and seasons. Increased incorporation of user knowledge helps to create a meaningful dialogue between users, researchers and managers. This can lead to fewer conflicts and greater co-ownership in relation to the management decisions that are made. The methods tested are based on recognized international practice, the "multiple evidence-based approach". Ten years of collecting user knowledge on fishing in Disko Bay has shown that it can significantly contribute to the understanding of fishing and the status of fish stocks. User knowledge has been shown to be able to quickly detect changes (Figure 8.1). Despite the fact that a process has been underway regarding the use of user knowledge in Disko Bay, there is a lack of systematic support for the inclusion of user knowledge in Greenland. If there is to be real involvement of user knowledge in fisheries management then concrete support is needed to ensure that this knowledge is incorporated at national level. It is recommended that the inclusion of user knowledge be written into the aims of the new Fisheries Act.

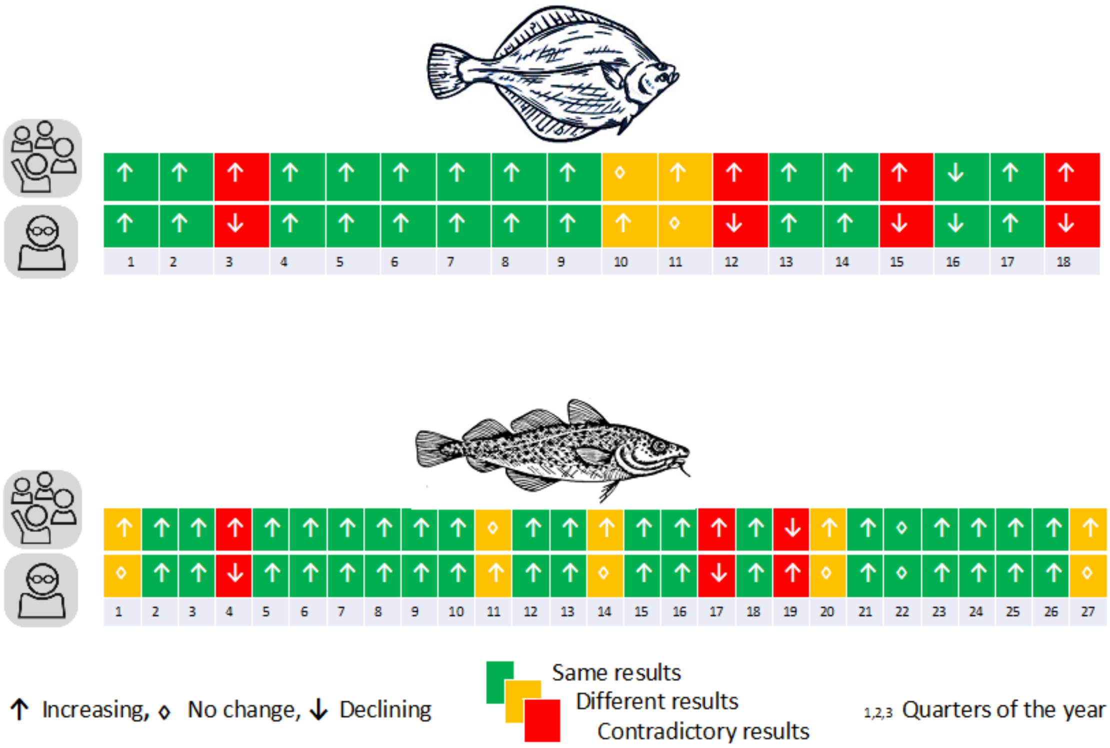


Figure 8.1. Incorporating user knowledge in the management of fish and other living resources in Disko Bay. Degree of agreement between established management results and reports from experienced fishers for flatfish (upper panel) and cod.

8.1.2 Data and models used

We used the results from test of systematic focus group discussions with resource users as part of the PISUNA program in Disko Bay, Greenland (homepage: www.pisuna.org; searchable database of observations in PISUNA-net, link: https://eloka-arctic.org/pisuna-net/en). The results can inform the further development of CBM programs in the Arctic including in Greenland, e.g. the current preparation of an executive order on the use of local knowledge and observations for informing natural resource management decisions in the country. The data and results are described in D4.3. The PISUNA program was awarded the Nordic Council Environment Prize (Oct. 2018). The results of the PISUNA program were highlighted by Greenland Premier Kim Kielsen in his New Year Speech, 31 Dec. 2018.

8.1.3 Stakeholders

Key stakeholders are community members, small-scale resource users, CBM program organizers, civil society organisations, government agencies (Ministry of Fisheries and Hunting; Qeqertalik Municipality), Ilisimatusarfik, and Greenland Climate Research Centre.

8.1.4 Work ahead, beyond the lifetime of the project

The approach has already been adapted and introduced in Finland and in Yakutia, Kola Peninsula, and Bikin, Russia. The experiences are documented in numerous publications, including in 2021 in Danielsen et al. (2021a-b), Eicken et al. (2021), Johnson et al. (2021), and Tengö et al. (2021). The policy brief about user knowledge for fisheries management has been published in Greenlandic/Danish and presented for Greenland's Fisheries Commission (https://www.uarctic.org/media/1601946/policybrieflokalvidenfiskeriforvaltning_final_8june2021.pdf).

8.2 Natural disasters in Disko Bay, Greenland and Longyearbyen, Svalbard

Contributors: Peter H. Voss, GEUS; Mathilde B. Sørensen, UiB; Finn Danielsen, NORDECO; Lisbeth Iversen, NERSC

Both Greenland and Svalbard have been exposed to several natural hazard events in recent years. With climate change, more landslides, earthquakes and other natural disasters are to be expected in the Arctic.

In the 2nd and 3rd policy brief, led by GEUS and UiB, we summarized what we know today about landslides and earthquakes in Disko Bay and Longyearbyen, we proposed what can be done to better understand such incidents, and what can be done by authorities and contractors to adapt new buildings and roads to these conditions.

8.2.1 Main activities and results

Hunters and fishermen in Disko Bay have, for some time, been participating in measuring earthquakes. In collaboration with local actors, we have also installed seismological measuring instruments in Longyearbyen. This experiment has given us useful new knowledge. Longyearbyen is an area with permafrost, and most buildings are founded with wooden piles to avoid settlement damage. We therefore only found opportunities to install the instruments in buildings that were founded on wooden poles, which meant that the noise level in the data was high.

In Disko Bay, to reduce the effects of landslides and earthquakes, including possible abrupt changes in topography (land uplift), it is recommended that: 1) The municipal councils look at whether the critical infrastructure is secured against strong earthquakes, landslides and tidal waves. Moreover, it is suggested that they assess the potential consequences of such natural disasters and have action plans ready when they occur; 2) The Ministry of Housing and Infrastructure should develop guidelines for protection from natural disasters; 3) The contractors in Disko Bay should look at the strength of vibrations that all planned installations can withstand and whether precautions should be taken against strong tremors in the planning phase. The advantages of these measures are that, when the natural disaster occurs, the damage is less and they are better prepared to deal with the consequences. The risk of landslides and earthquakes will always be present but, with a better understanding of the risk, one can prepare and reduce the damage caused by landslides and earthquakes. Measurements taken by hunters and fishermen have provided important contributions to the mapping of earthquakes and thus contributed to a better understanding of the risk of landslides and earthquakes in and around Disko Bay.

In Longyearbyen, it is of great importance for urban planning to know how large the risk is for natural hazards, and how the risk will be affected by climate change. To reduce the effects of natural hazards, it is recommended that: The local council and contractors ensure that critical infrastructure and buildings are built outside the runways of potential landslide events and adequately secured against earthquakes. In addition, the consequences of major natural disasters should be studied, and action plans should be developed. In order to improve the data base, work should continue on mapping the risk of landslides and floods. Further research on the potential of combining different data types (eg. seismological, satellite and geodetic data) could provide an improved data base and thus better risk analyses. A new experiment with the use of home seismographs should be considered, if suitable locations can be made available. Significant actions have been taken in Longyearbyen to mitigate natural hazards in the area. A new project at the Arctic Safety Centre at UNIS starting in 2021: *Risk governance of climate-related systemic risk in the Arctic* (Arct-Risk) will propose measures on how manage snow avalanche and other risks in the area.

8.2.2 Data and models used

We used the results of the test for preparing the two policy briefs and for developing a scientific publication on citizen seismology (Jeddi et al. 2020). The results can inform the further development and roll-out of citizen seismology in the Arctic. The data and results are described in D4.3.

8.2.3 Stakeholders

Key stakeholders are government agencies, education and research institutions, entrepreneurs and other in the private sector, both in Disko Bay and in Longyearbyen.

8.2.4 Tasks ahead, beyond the lifetime of the project

It will be important to have meetings with the communities in Disko Bay and Longyearbyen to discuss community awareness of natural hazards, and roll-out of citizen seismology in Greenland and Longyearbyen (subject to funding, and assuming continued community interest).

8.3 Monitoring Svalbard's environment by expedition cruises

Contributors: Michael K. Poulsen, NORDECO; Lisbeth Iversen, NERSC; Finn Danielsen, NORDECO

Climate change and increasing human activities in the Arctic call for rapid environmental management responses based on monitoring of environmental variables. Expedition cruises are able to travel around the Svalbard waters like nobody else. Guides and guests are already observing and contributing to citizen science programs. Increasing relevant monitoring and creating improved ways of communicating monitoring information could ensure that those responsible for environmental management decisions (the Governor's Office) are provided with a better basis for making those decisions.

8.3.1 Main activities and results

In a 4th policy brief, we summarized the potential that expedition cruises have for contributing to environmental monitoring, and what can be done by authorities and citizen science programs to make full use of this potential. The policy brief recommends that cruise expedition vessels are equipped with tablets containing apps for citizen science programs to enable easy uploading of records. The selected programs should be popular among users, gather information that can improve the basis for environmental management, and present results in a form that can be used by environmental management planners and decision-makers. Work must be done to understand how the right type of data can be gathered and be made available to those responsible for environmental management. For Svalbard, this will be institutions such as the Governor's Office, but also researchers and the public. Clear lines of communication should be further developed between contributors, citizen science programs, the scientific community and decision-makers. A well-funded intermediate organization should facilitate this communication. The policy brief concluded that further development of expedition cruise monitoring is a high priority, especially so in Svalbard, Greenland, South East Alaska and the Antarctic.

8.3.2 Data and models used

We used results from test of expedition cruise operator-based observing in Svalbard and Greenland in 2019. The results can be used by authorities and citizen science programs to make full use of the potential of expedition cruises for monitoring the environment. The data and results are described in D4.3. The test built on discussions at a workshop in Longyearbyen in March 2019.

8.3.3 Stakeholders

Key stakeholders are citizen science programs, cruise guides, expedition cruise operators, government agencies, education and research institutions.

8.3.4 Tasks ahead, beyond the lifetime of the project

Funds will be sought for further developing systematic expedition cruise operator-based monitoring with key industry, government and research partners in Svalbard and Greenland. It will also be a high priority to test cultural heritage monitoring by expedition cruises in collaboration with cultural heritage experts.

References

Danielsen, F., Johnson, N., Lee, O., Fidel, M., Iversen, L., Poulsen, M. K.,… & Enghoff, M. 2021a. Community-based Monitoring in the Arctic. University of Alaska Press.

Danielsen, F., Enghoff, M., Poulsen, M. K., Funder, M., Jensen, P. M., & Burgess, N. D. 2021b. The Concept, Practice, Application, and Results of Locally Based Monitoring of the Environment. BioScience, 71(5), 484-502.

Eicken, H., Danielsen, F., Sam, J. M. et al. 2021. Connecting top-down and bottom-up approaches in environmental observing. BioScience, 71(5), 467-483.

Jeddi, Z., Voss, P. H., Sørensen, M. B. et al. 2020. Citizen Seismology in the Arctic. Frontiers in Earth Science 8: 139. https://www.frontiersin.org/articles/10.3389/feart.2020.00139/full

Johnson, N., Druckenmiller, M. L., Danielsen, F., & Pulsifer, P. L. 2021. The use of digital platforms for community-based monitoring. BioScience, 71(5), 452-466.

Tengö, M., Austin, B. J., Danielsen, F., & Fernández-Llamazares, Á. 2021. Creating synergies between citizen science and Indigenous and local knowledge. BioScience, 71(5), 503-518.

9. Benefits of ocean observing for Blue Growth in the Arctic

Main Contributor: Erik Buch, EuroGOOS

The main objective of the activities outlined here and described in more detail in D6.9 and D6.18 is to demonstrate the value and benefits of an upgraded Arctic Observing System in support of Blue Growth in the Arctic. This to foster business development, increase safety and protect the environment by integrating data, products and services from EMODnet and Copernicus Marine service with those produced by INTAROS. Work has focused on two main analyses.

9.1 Support to business planning and development

Climate warming in the Arctic Region opens up for new or changes and expansion of existing maritime business activities. The future business development perspectives for three important components of the Arctic Blue Economy – maritime transport via the Arctic Ocean (Figure 9.1), cruise industry in the Svalbard area and fishery in the Barents Sea has been analysed. The maritime transport and cruise industry will potentially increase substantially over the coming years due to retreat of Arctic sea ice. Barents Sea fishery will have to address changes in the pursuit of their profession due to changes in fish stock composition and distribution originating from climate change and other human pressures.

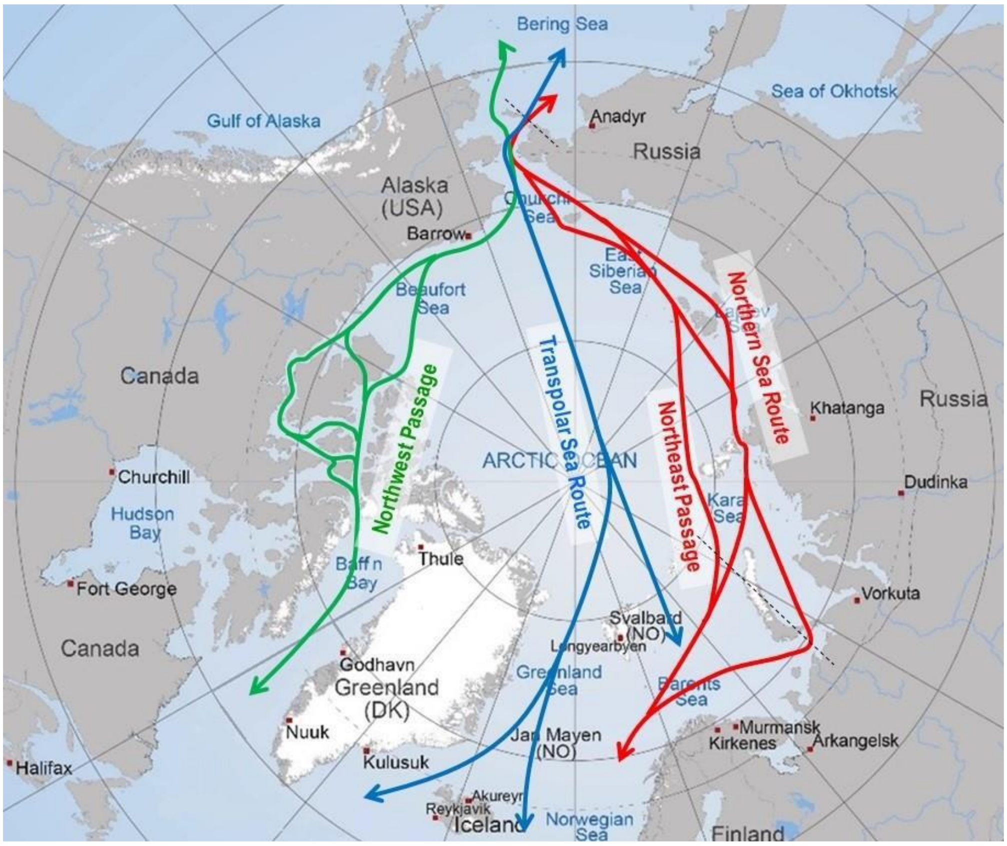


Figure 9.1. Arctic Sea Routes (Dyrcz, 2017; D6.9). Alternative Arctic routes between Europe and Eastern Asia are shown: Red: The Northeast Passage along the Russian Coast; Green: The Northwest Passage, and Blue: The Transpolar Sea Route.

Entering into operations in the harsh Arctic environment requires good knowledge and understanding of the physical environmental conditions to ensure a sound decision process on economy, efficiency, safety of ship, crew and cargo and protection of the vulnerable Arctic environment. Therefore, examples of basic statistical analysis of relevant parameters like sea ice, wind, waves, temperature and salinity has been performed to outline the trends in change of environmental condition of importance for maritime operations in the Arctic. Additionally, operational meteorological and oceanographic near real time products and services are important when actually operating in the area.

Satellite observations and outputs from numerical models are essential data sources for generation of operational products and services; but the trustworthiness of the information's from these two data sources depends critically on the availability of in situ observations of key variables for assimilation in the models and especially for validation of quality of the generated data products. Unfortunately, the availability of enough relevant and high-quality in situ observations of oceanographic and meteorological variables from the Arctic Region is far from satisfactory for this purpose.

It is therefore crucial to design and implement a fit-for-purpose Arctic Observing System to ensure the availability of high-quality in situ data needed for model assimilation as well as validation of the quality of model and remote sensing products used both for statistical trend analysis and particularly operational purposes.

In the perspective of increased maritime activity in the environmentally vulnerable Arctic Region it would be advisable to perform monitoring and analysis of environmental pressures similar to the one performed by European Maritime Safety Agency (EMSA) and European Environmental Agency (EEA) for the European Seas (EMSA & EEA,2021). These include emission of greenhouse gases and air pollutants and discharges of oil spill, ballast water and alien species into the ocean. Also marine litter and acoustic noise need to be observed.

9.2 Economic benefits from an integrated Arctic Observing System

The potential for growth of the Arctic Blue Economy is increasing due to climate change, fast technological development and strong demands from the global economy. Such development will however put severe stress on the vulnerable Arctic environment and there is a growing consciousness among nations surrounding the Arctic to ensure a responsible and sustainable development of Arctic Blue economy, which calls for a science-based management approach.

Mandatory for such an approach is good knowledge and understanding of the Arctic Ocean environment and ecosystem, which demands a well-coordinated, integrated, sustained fit-for-purpose Arctic Ocean Observation System. The design of a proper Arctic Ocean Observation System is recommended to follow the concept outlined in the "Framework for Ocean Observations" (UNESCO-IOC, 2012). This will require a strong international coordination and governance structure responsible for dialog with users and stakeholders, sustained funding, maintenance of observation requirements (spatiotemporal resolution, quality, timeliness), technology development, free and open access to data.

An important component of the design process is an assessment of the costs and value of the observing system i.e., justify that the benefit exceeds the costs. Costs are easier (although not unproblematic) to quantify than the benefits. OECD (Organisation for Economic Co-operation and Development**)** has in recent years, in cooperation with various ocean observing communities, started to establish ways to quantify the value of ocean observations and proposes some pragmatic approaches.

For future development of valuing ocean observations and a cost-benefit analysis, the OECD (OECD, 2018a) recommends to follow three pragmatic steps:

- *Tracking the users and user groups and mapping the observations value chain;*
- *Advancing on common and agreed methodologies of valuation;*
- *Expanding the international knowledge base*

It is therefore recommended that the management of the future Arctic Ocean Observation System works closely with experts from OECD on the establishment of a robust cost-benefit analysis methodology for the Arctic Ocean.

The analysis documented in INTAROS' D6.18 focuses on the economic potential associated with ocean observatories in support of Blue Growth in the Arctic region and the work is split in four components:

- Blue economy in the Arctic which is influenced by:
  - Climate change
  - Technology developments
  - Global economy demands
- Ocean observations
  - Phenomena and essential ocean variables
  - Requirements
  - Costs – optimization and international coordination
- Benefit categories of ocean observations
- Cost benefit analysis

Methods and findings obtained by the H2020 AtlantOS project, OECD reports on values of ocean observations and published analyses of blue growth potential in the Arctic Ocean has formed the basis for the analysis.

References

Dyrcz, C., 2017. Safety of navigation in the Arctic. Zeszyty Naukowe Akademi i Marynarki Wojennej (Scientific Journal of Polish Naval Academy) https://www.researchgate.net/publication/321687663_Safety_of_Navigation_in_the_Arctic

EMSA & EEA, 2021. European Maritime Transport Environment Report-EMTER. http://www.emsa.europa.eu/emter

UNESCO-IOC, 2012. A Framework for Ocean Observing. By the Task Team for an Integrated Framework for Sustained Ocean Observing, IOC/INF-1284, doi:10.5270/OceanObs09-FOO

10. Showcases of an integrated Arctic Observing system

Main contributors: Herve Caumont (Terradue); Fabien Ors, ARMINES, Torill Hamre, NERSC

In close collaboration with WP5 several showcases were planned to demonstrate concrete use of Arctic observational data. The works has been described in D5.11 and D5.13 and the geostatistical methods described in D5.10.

For each showcase, the following work was done:

- Definition of the overall need for data integration and management, as well as the technical use cases and resources to be involved;
- Integration of data sources in preparation of the showcase applications, and description of the data products generated;
- Use of Geostatistics by exploiting specific RGeostats / RIntaros software developments, and by developing methods and related ad-hoc RGeostats software libraries

In this report, we briefly summarize four showcases (Table 10.1), outlining objectives, selected data sources, data exploitation tasks, and results delivered.

Table 10.1. Four cases demonstrating the application of an integrated Arctic Observation System. For each case Objectives, Data sources, Data exploitation, and Results are summarized (from D5.10, D5.11, and D5.13).

<table>
<tr><th colspan="2">Pan-Arctic Hydrological Modelling (Task 6.1, SMHI)</th></tr>
<tr><td>Objectives</td><td>Data sources</td></tr>
<tr><td>● Have the “observational” data available for search & download from the INTAROS Arctic Observation System Portal
● Have the Arctic-HYPE produced at SMHI and provide the data as open data from SMHI repositories:
○ Daily analyses of last 60 days
○ Medium range forecast of coming 10 days
● Improve predictions of spring floods, river ice breakup and freshwater flow to Arctic Ocean, cf.INTAROS D6.1 Climate model initialization v1.4</td><td>● River discharge data from the Arctic Hydrological Cycle Observing system (Arctic-HYCOS) https://catalog-intaros.nersc.no/dataset/?q=hydrology
● HydroGFD v3 temperature and precipitation data
● ECMWF deterministic medium range weather forecasts</td></tr>
<tr><td>Data exploitation</td><td>Results delivered</td></tr>
<tr><td>● Implement HYCOS pre-processing (both archive of quality controlled data with 4months/2years lag, or provisional datasets)
○ In-house server at SMHI
○ Cloud-based, use Ellip to comp.</td><td>● OpenDAP server publishing Pan-arctic hydrological model Arctic-HYPE results http://opendata-download.smhi.se/opendap/catalog/catalog.html (provided by SMHI)</td></tr>
</table>

<table>
<tr><td>Schedule HYCOS pre-processing operations daily at a certain time
Setup OpenDAP server for publishing the Arctic-HYPE model results</td><td></td></tr>
<tr><td colspan="2">Barents Sea Multi-depth Temperature & Salinity Maps (Task 6.2 IMR)</td></tr>
<tr><td>Objectives</td><td>Data sources</td></tr>
<tr><td>Use the Geostatistical Library (RIntaros / RGeostats) and build the R software for interpolating maps from CTD datasets (Fig. 10.1)
Generate temperature and salinity fields for:
modelling of Arctic Ocean biogeochemistry
validation of climate model projections (NorCPM)
Build a Web Processing Service for the INTAROS Arctic Observation System</td><td>CTD data from IMR research vessels
Acquisitions between 7th January 1995 and 29th November 2016.
over 63 500 vertical profiles.
All files are freely available on an OPeNDAP server (operational and test instances): http://opendap1.nodc.no/opendap/physics/point/yearly/contents.html
NetCDF files (one file by year and per vessel).
The whole dataset volume is 880 GB.</td></tr>
<tr><td>Data exploitation</td><td>Results delivered</td></tr>
<tr><td>Use of the Arctic Observation System OpenDAP server at NODC
Explanatory data analysis and variography
Modelling spatial patterns for temperature and salinity</td><td>Geostatistical spatial analyses of temperature and salinity
Standalone solution (R software)
Map productions per run
Base maps
Average per cell
Cross-validation (blind test) maps
Estimation (Temperature / Salinity) and corresponding uncertainty maps
Solution as-a-Service (Cloud software)
Map productions per WPS run
On-demand, self performed by each user from the Portal
Split tiles for large areas</td></tr>
<tr><td colspan="2">Maps for Svalbard Avalanche Forecast Modelling (Task 6.4 FMI)</td></tr>
<tr><td>Objectives</td><td>Data sources</td></tr>
<tr><td>Use the Geostatistical Library (RIntaros / RGeostats) and build the R software for interpolating maps from snow stations, arome model output and terrain model
Generate snow depth maps at regular time intervals as input for avalanche forecast model</td><td>Norwegian Meteorological Institute Frost API historical weather and climate data stations
(selected files on shared Drive)
Norwegian Meteorological Institute arome model: https://thredds.met.no/thredds/catalog/aromearcticarchive/catalog.html</td></tr>
</table>

	• Norwegian Polar Institute Svalbard Terrain Model: https://doi.org/10.21334/npolar.2014.dce53a47
Data exploitation	**Results delivered**
• Explanatory data analysis and variography • Handle the different spatial distributions and resolutions of the data ("support") • Modelisation of spatial and temporal behavior for snow depth through co-variables (temperature, wind speed by class of wind direction)	Pre-analysis of the data: • Few stations: temporal series of snow thickness measured at short time steps • Arome models: various maps covering the whole area, every 6 hours, on large scale grid (incl. snow thickness derived from model) • Several co-variables Processing: • Regularization of the station time series by averaging over 6 hours • Correlation (space-time) of snow depth variable with arome model output • Estimation using both information sources (with relevant co-variables) over a small scale grid, at regular 6 hours intervals
Baffin Bay Bottom Temperature Maps (Task 6.8, Aarhus University)	
Objectives	**Data sources**

• Use the Geostatistical Library (RIntaros / RGeostats) and build the R software for interpolating ocean floor temperature maps from CTD and Trawl datasets
• Generate temperature fields at bottom of the ocean in support of:
  ○ Analysis of long term global warming influence
  ○ Analysis of the fish stock correlation to bottom temp.
	• CTD from ICES (3700 vertical profiles, 1977-2017)
	• Water bottles from ICES 7800 vertical profiles, 1977-2017)
	• Trawl data from GINR 1988-2016
	• Bathymetry (Gebco)
	• .. and more

Data exploitation	**Results delivered**

• Explanatory data analysis and variography
• Local and global temperature analysis
• Modelling of spatial and temporal development of ocean floor temperature through Bathymetry co-variable
	• Temporal evolution (global and local)
	  ○ Between 1960 and 2015, T°C has gained 1°C (around 1995)
	  ○ Lower T°C values around 2008 have been recorded
	• Map productions
	  ○ Basemap of data
	  ○ Bottom temperature estimation by year and its standard deviation
	• Time series of average temperature by region (Lat/Depth)

An example of a data processing service powered by Terradue's Ellip Solutions was implemented by ARMINES using CTD datasets in the North Sea, provided by IMR (Fig. 10.1). The service used a RGeostats-based data interpolation application, providing gridded fields based on APIs of the iAOS cloud platform. This API empowers the application with an interoperable data access mechanism (based on OpenDAP), scalable data processing capabilities (based on Hadoop MapReduce) and standard processing invocation and results retrieval (based on OGC WPS), for integration with the iAOS Portal or other Geobrowser applications.

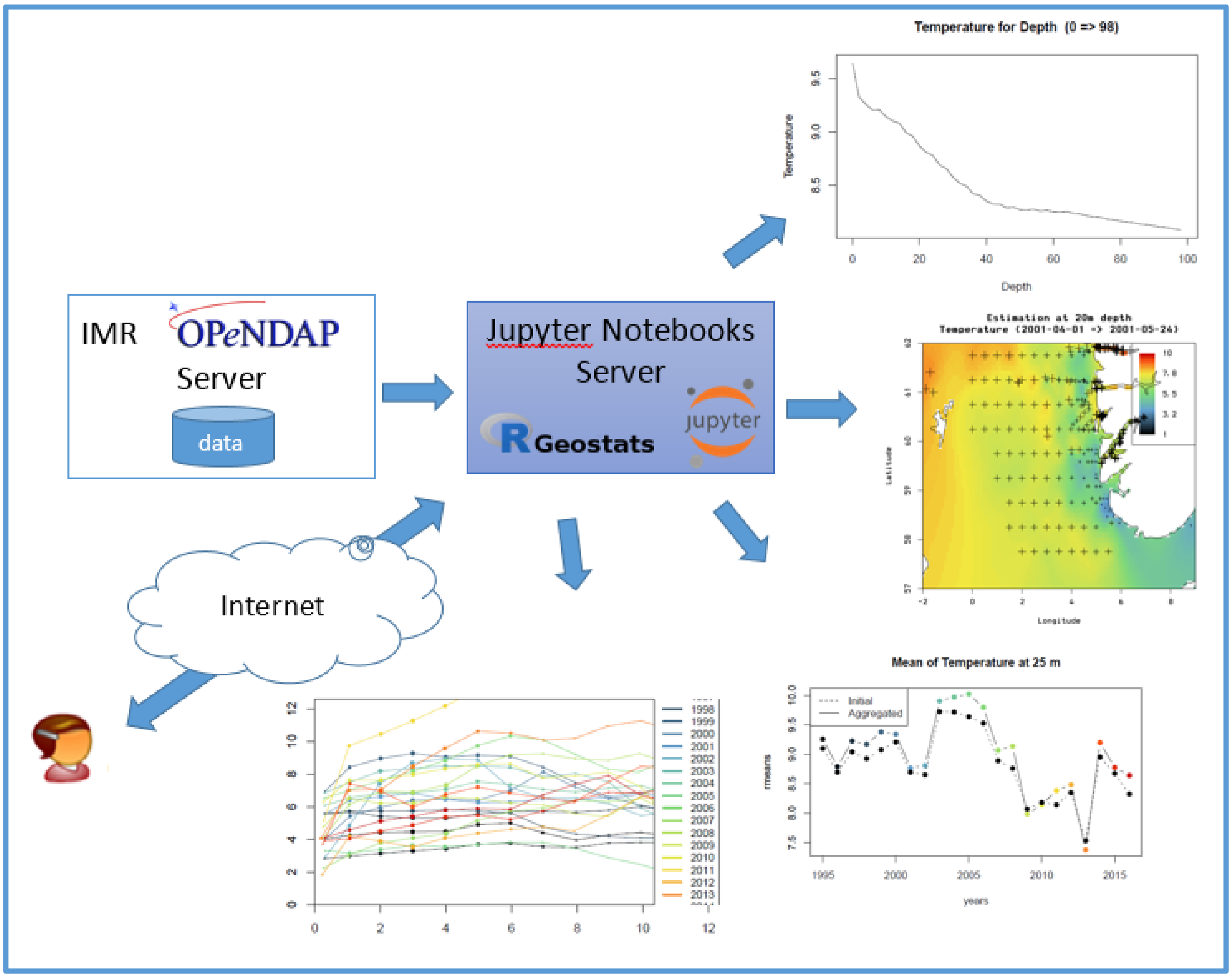


Figure 10.1. The flow of data and information in the Barents Sea Multi-depth Temperature and Salinity Maps showcase.

11. Selected main results and impacts

Improving skills of model predictions in the Arctic (T6.1, SMHI)

- Sensitivity studies were performed by seasonal-to-decadal climate prediction systems, demonstrating the general benefit from initializing sea-ice information for these forecasts. The assimilation of anomalies of sea ice concentrations in NorCPM (NERSC) was shown to be particularly beneficial for seasonal predictions along the sea-ice edge while sea-ice thickness is more important for the central Arctic.
- Arctic river runoff predictions for regional and/or pan-Arctic applications were improved by assimilation of observational data. River discharge data from the Arctic Hydrological Cycle Observing system (Arctic-HYCOS) was combined with the pan-arctic hydrological model Arctic-HYPE (SMHI).

Applying observations and models for environmental and fisheries management (T6.2, IMR and T6.8, AaU)

- Models used to evaluate impacts of climate and environmental change on local marine resources to support management decisions and stakeholder involvement.
- Successful Observing System Simulation Experiment (OSSE) for Barents Sea monitoring program carried out.
- NORWECOM.E2E simulations of fishing vessel «behaviour» during calanus finmarchcus zooplankton fishery attracted a lot of interest and media attention.
- A coupled hydrodynamic and biogeochemical model was set up for Disko Bay, W Greenland, using the FlexSem model system.
- Analyses of impact of climate variability on Greenland fish distributions indicates positive effects on fish community, including range expansion, of reduced sea ice.
- Good involvement and interaction with stakeholders from fisheries, maritime, and petroleum management and industry, and especially environmental management, both in Norway and on Greenland

Ice-ocean statistics (T6.3, NERSC)

- Two Observing System Simulation Experiments (OSSEs) were used to assess impacts of assimilating near-real-time pan-Arctic Ocean observations, delayed data from moorings, and monthly mapped sea level anomalies data on monitoring the Arctic Ocean changes. Results show that both ice concentration and ice thickness estimates are significantly improved after data assimilation.
- A Risk Assessment System applicable for the Arctic Marine environment has been developed by DNV. The system will continue to be developed and used by industry working in the Arctic
- Arctic acoustic environment and acoustic observing systems have been extensively studied in collaboration with other projects, resulting in several publications.

- Observations from a network of drifting ice buoys have been obtainwed and studies of sea ice thickness and snow depth have been conducted.
- Statistics products were developed from oceanographic in situ measurements in the Nordic Seas and Arctic Ocean, collected by IOPAN in the last two decades.

Remote sensing applications (T6.3, NERSC)

- Sea ice products from passive microwave (PMW) and scatterometer sensors were further development.
- Satellite observations, in-situ measurements and modeling were used by DTU to investigate and evaluate Arctic Ocean sea level change, especially in the context of climate change.
- Methods to estimating total water vapor in the atmosphere, especially over land and sea ice, from passive microwave (PMW) imagers have been improved by University of Bremen

Natural hazards in the Arctic (T6.4, GEUS)

- Snow avalanches, earthquakes and mass loss from ice sheets and glaciers represent some of the most important natural hazards in the Arctic. Studies have been done to show what the data and tools need to be used to better plan mitigation actions in the communities
- In Longyearbyen it was shown how in-situ observations can improve output from numerical weather prediction models using statistical analysis to improve snow avalanche forecast models .
- Seismometers can provide information on earthquake, landslides, snow avalanches and, to some extent, tsunamis. Analysis of data from the Ocean Bottom Seismometers deployed in INTAROS show that these observations improve understanding of the ridge seismicity and demonstrate how even very few stations can significantly improve earthquake detection and locations.
- Community-based seismometers deployed through INTAROS are a useful low-cost supplement to permanent seismic stations on land. They contribute to better earthquake locations and to raise awareness among community members where they are deployed.
- Mass loss from ice sheets and glaciers constitute both a local and global hazard. Multiple datasets were generated and published quantifying the total mass loss, solid mass loss, liquid mass loss, and freshwater runoff from the Greenland Ice Sheet. These datasets can be applied in studies of local conditions in a fjord or help inform global scale studies.
- Several process studies using numerical modelling were developed and published to separate the marine mass loss from glaciers into iceberg calving and submarine melting

Case studies of greenhouse gas exchange in the Arctic (T6.5, MPG)

- New results of CH_4 emissions from East Siberian Arctic shelf based on atmospheric inverse modeling conducted by MPG showed that emissions were on the low end compared to previous estimates.
- A geostatistical approach was used to identify important processes that dominate the regional CH4 budget. In this context, factors that control the mixing of the water column, and cracks in the ice, turned out to be important.
- The ocean and sea-ice reanalysis and the Arctic water vapor data obtained from the INTAROS catalogue were tested as constraints to the CH4 processes, and their integration into the scheme led to some improvements in the simulations.
- Different platforms and sensors were used for measurement of carbonate system variables in ocean areas. Furthermore, approaches for integrating/synthesizing existing and new observations were tested, including a self-organising map technique, a type of artificial neural network that uses machine learning.

Community-based observing systems (T6.6, NERSC)

- Four policy briefs were prepared and published to demonstrate 'real world' examples of the benefits of cross-weaving data from local and scientific observation systems in Greenland and Svalbard.
- NORDECO summarized how user knowledge on fish, fisheries and the environment can be incorporated into fisheries management in Greenland. The work was done jointly with Greenland Association of Fishermen and Hunters (KNAPK), Ilisimatusarfik (University of Greenland) and other key actors.
- Current knowledge about landslides and earthquakes in Disko Bay and Longyearbyen were reviewed and measures were proposed on what can be done by authorities and contractors to adapt new buildings and roads to the challenging conditions.
- The potential of expedition cruises to contribute to environmental monitoring was explored through workshops and dialogue meetings. Recommendations were formulated on how to further develop such community-based observing systems or Citizen Science projects.
- The Svalbard Social Science Initiative (SSSI) was established with support from INTAROS. Three workshops were organized by the SSSI where local and national stakeholders and researchers identified knowledge gaps and challenges in communication between researchers and decision makers.
- The work has identified and number of challenges that need to be addressed to improve the community-based observing systems. These include cultural and language difference between scientists and local communities, lack of funding, lack of governmental policies, lack of standards and best practices, lack of communication between the relevant actors and more. By establishing CBM and CS systems, they can engage much more people in data collection and add valuable supplement to an Arctic Observing System.

12. Conclusions and perspectives

In WP6 a wide range of research and demonstration activities have been performed. A common feature is that data from multiple sources have been integrated to perform a specific study, provide a data set or improve a service in collaboration with stakeholders. The INTAROS project has provided an opportunity to improve international collaboration while at the same time encompass a cross-disciplinary perspective and engagement with stakeholders. The synergy, size and scope of INTAROS led to several spin-off projects that are important contributions to the overall impact of the project and document the importance of EU projects for establishing productive networks.

What are the perspectives:

Examples of products/activities that build on or extend results from WP6 tasks include:

- Funded ERC-Synergy project and additional proposal (pending) that further extends data assimilation strategies from T6.5
- Workshop on marine ecosystem indicators for the Barents Sea based on discussion in T6.2 (WGINOR 22.-25-November 2021)
- Policy Brief submitted to the Fisheries Commission in Greenland (based on D6.6)
- Establishing (with numerous partners) The Svalbard Social Science Initiative (partly based on T6.6) which creates linkages among social scientists working with issues related to Svalbard and it facilitates communication with local communities.
- New project adding additional components to the Disko Bay ecosystem model and a new proposal (pending) for setting up the model in NE Greenland fjord (T6.8)
- Numerous scientific publications, conference talks and dissertations at Bsc, Msc and PhD levels.

The international and interdisciplinary network created through INTAROS is an important stepping-stone towards addressing the research needs outlined in the EU Polar Research Programme. As can be seen in Fig. 12.1, the activities in WP6 all contribute towards resolving important research needs.

RESEARCH NEEDS	KEY QUESTIONS	WP6 Task
1. Better understanding of climate change in the Polar Regions and its links to lower latitudes	1.1: Key processes in polar-specific components of the climate system. 1.2: Polar coupling and feedback processes at the regional and global scales. 1.3: Modelling and predicting the polar climate system. 1.4: Assessing the impact of human activities on polar climate.	T6.2 T6.5
2. Informed weather and climate action	2.1: Identifying relevant indicators of polar climate change. 2.2: Designing new approaches to test the chain of processes from climate indicators to decision making. 2.3: Supporting decision making through predictions and projections of polar climate and socio-ecological systems. 2.4: Assessing the added value of the Polar Regions in relation to climate change and human activity impacts.	T6.1
3. Resilient socio-ecological systems	3.1: Understanding key issues of polar ecosystem structure, functioning, and change. 3.2: Designing a healthy socio-ecological system. 3.3: Expanding observation of socio-ecological systems. 3.4: Ecosystem-based management, governance and transformative solutions toward a sustainable future.	T6.2 T6.3
4. Prospering communities in the Arctic	4.1: An infrastructure plan in support of sustainable community development. 4.2: National and sub-national governance challenges in the Arctic Regions. 4.3: Economic innovations for sustainable development of Arctic communities. 4.4: Education as a tool to expand the capacity of Arctic residents to respond to changes. 4.5: Learning from the past for a socio-economically balanced and gender-equal development of the Polar Regions. 4.6: The demography of the future Arctic population. 4.7: Cultural vitality for prosperity in the Arctic.	T6.6
5. Challenges and Opportunities for Polar Operations	5.1: Understanding the impacts of changing environmental conditions and operations on risk and vulnerability. 5.2: Minimising the environmental impacts of polar operations. 5.3: Understanding and promoting the concept of social license for polar operations. 5.4: Identifying policies, frameworks and governance which ensure safe, sustainable, and just operations.	T6.4
6. Inclusive creation, access and usage of knowledge	6.1: Developing new technologies and improved capacities in observation, modelling, and research in the Polar Regions. 6.2: Co-production of knowledge as a benefit to societal stakeholders. 6.3: FAIR data management principles for polar data collections. 6.4: Ensuring knowledge access and capacity building in Polar Regions. 6.5: Exploiting knowledge to inform decision making for the Polar Regions.	T6.8

Figure 12.1. Left panels are from the Integrated European Polar Research Programme and right panel show the coverage by INTAROS WP6 tasks.

Appendix

Table A1. List of contributors to all WP6 deliverables

Andreas Ahlstrøm	GEUS	Marie Maar	AU
Ole Baltazar Andersen	DTU	Kenneth Mankoff	GEUS
Agnieszka Beszczynska-Möller	IOPAN	Frode Monsen	NERSC
Odd Willy Brude	DNV GL	Eva Friis Møller	AU
Erik Buch	EUROGOOS	Francisco Navarro	UPM
Ann Dorte Burmeister	GINR	Juan C. Acosta Navarro	BSC
Jakob Carstensen	AU	Tor I. Olaussen	NERSC
Bin Cheng	FMI	Are Olsen	UiB
Asbjørn Christensen	DTU	Jaime Otero	UPM
François Counillon	NERSC	Geir Ottersen	IMR
Trine Dahl-Jensen	GEUS	Roberta Pirazzini	FMI
Finn Danielsen	NORDECO	Jean-François Pollé	IFREMER
Eva De Andrés	UPM	Michael K. Poulsen	NORDECO
María Isabel de Corcuera	UPM	Frank Rigét	AU
Ralf Döscher	SMHI	Friedemann Reum	MPG
Martin Enghoff	NORDECO	Nicholas Roden	NIVA
Vicente Fernández	EUROGOOS	Laura Rontu	FMI
Yongqi Gao	NERSC	Hanne Sagen	NERSC
Florian Geyer	NERSC	Mikael Kristian Sejr	AU
Fanny Girard-Ardhuin	IFREMER	Nuna Serra	UHAM
Mathias Göckede	MPG	Elena Shevnina	FMI
Marina González	UPM	Morten Skogen	IMR
Agata Grynczel	IOPAN	Thorsten Skovbjerg	AU
David Gustafsson	SMHI	Anne Solgaard	GEUS
Torill Hamre	NERSC	Gunnar Spreen	UB
Holt Hancock	UNIS	Detlef Stammer	UHAM
Cecilie Hansen	IMR	Espen Storheim	NERSC
Rune Roland Hansen	DNV GL	Rune Storvold	NORCE
Georg Heygster	UB/Georg-Lab	Peter Stæhr	AU
Larysa Istomina	UB	Mathilde B. Sørensen	UiB
Christian Melsheimer	UB	Jakob Thyrring	AU
Siwei Hu	NERSC	Zhongxiang Tian	NMEFC
Lisbeth Iversen	NERSC	Arantxa Triana-Gomez	UB
Zeinab Jeddi	UiB	Ilona Valisuo	FMI
Truls Johannessen	UiB	Gro I. van der Meeren	IMR
Rolf-Ole Rydeng Johansen	NORCE	Peter H. Voss	GEUS
Mehdi Pasha Karami	SMHI	Waldemar Walczowski	IO PAN
Shfaqat Abbas Khan	DTU	Mie S. Winding	GINR
Andrew King	NIVA	Øivin Aarnes	DNV GL
Armin Koehl	UHAM	**Reviewers**	
Tim Kruschke	SMHI	Ralf Döscher	SMHI
Javier Lapazaran	UPM	Torill Hamre	NERSC
Vladimir Lapin	BSC	Georg Heygster	UB
Janus Larsen	AU	Helene R. Langehaug	NERSC
Tine B. Larsen	GEUS	Kjetil Lygre	NERSC
Tom Rune Lauknes	NORCE	Magnús Magnússon	IGS
Ruibo Lei	PRIC	Pablo Ortega	BSC
Harald Loeng	IMR	Geir Ottersen	IMR
Carsten Bjerre Ludwigsen	DTU	Torsten Sachs	GFZ
Kjetil Lygre	NERSC	Hanne Sagen	NERSC
Guokun Lyu	UHAM	Stein Sandven	NERSC

Table A.2. Overview of chapters, sub-chapters, lead partner, corresponding task and deliverables

Main chapter	Sub-chapter	Lead	Task	Deliverables
1. Introduction		IMR, AU	6.0	D6.19
2. Improving skill of model predictions	2.1 Climate prediction	SMHI	6.1	D6.1, D6.11
	2.2 Hydrological forecasting	SMHI	6.1	D6.1, D6.11
3. Applying observations and models for environmental and fisheries management	3.1 Barents Sea	IMR	6.2	D6.3, 6.13
	3.2 West Greenland	AU	6.2	D6.2, D6.3, D6.12, D6.13
	3.3. Stakeholder involvement	IMR, AU	6.8	D6.10
	3.4 Further development and exploitation of the results	IMR AU	6.2, 6.8	D6.13
4. Ice-ocean statistics	4.1. OSSE and reanalysis	UHAM	6.3	D6.4
	4.2 Risk assessment system	DNV-GL	6.3	D6.5, D6.15
	4.3 Arctic Acoustic Environment and acoustic observing systems	NERSC	6.3	D6.14
	4.4. Ice-Ocean Statistics from in situ ..	IOPAN	6.3	D6.14
	4.5. Snow and ice mass balance buoy	FMI	6.3	D6.21
5. Remote sensing applications	5.1 Sea ice products from satellite …	Ifremer	6.3	D6.22, D6.23
	5.2 Observing systems for sea level	DTU	6.3	D6.20
	5.3 Water vapour	U Bremen	6.3	D6.23
	5.4 Use of drones for sea ice obs.	NORCE	6.3	D6.24
6. Natural hazards in the Arctic	6.1 Snow avalanches	GEUS	6.4	D6.16
	6.2 Earthquake, landslides, and tsun.	GEUS	6.4	D6.16
	6.3 Mass loss from ice sheets- glaciers	UPM	6.4	D6.16, D6.17
	6.4 Further development of obs. Syst.	GEUS	6.4	D6.16, D6.17
7. Greenhouse gas exchange in the Arctic	7.1 Atmospheric case studies of GHG	MPG	6.5	D6.7
	7.2 Ocean case studies of GHG	UIB	6.5	D6.8
8. Case studies of Community-Based Observing systems	8.1 Local and scientific observations for improving fisheries in Greenland	NORDECO	6.6, WP4	D6.6, D4
	8.2 Natural disasters in Disko Bay, Greenland and Longyearbyen, Svalbard	GEUS, UiB, NORDECO, NERSC	6.6	D6.6, D4.3, D4.4
	8.3 Monitoring Svalbard's environment by expedition cruises	NERSC	6.6	D6.6, D4.1, D4.3, D4.4
9. Benefits of an enhanced Arctic Observing System for Blue Growth in the Arctic	9.1 Support to business planning and development	EuroGOOS	6.3	D6.9
	9.2 Economic benefits from an integrated Arctic Observing System	EuroGOOS		D6.18
10. Showcases of an integrated Arctic Observing system		Terradue, Armines, NERSC, IMR	6.1, WP5	D5.10, D5.11, D5.13
11. Selected main results and impacts		IMR	6.1	D6.19
12. Conclusions and perspectives		IMR, AaU	6.1	D6.19

INTAROS

This report is made under the project
Integrated Arctic Observation System (INTAROS)
funded by the European Commission Horizon 2020 program
Grant Agreement no. 727890.

Project partners: