ICE-ARC

ICE • CLIMATE • ECONOMICS

PROJECT FINAL REPORT

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Final Publishable Summary Report

Executive Summary

ICE-ARC (Ice Climate and Economics- Arctic Research on Change) *results reveal that the combination of the thawing Arctic permafrost and melting sea ice could cause up to* ***$130 trillion worth of extra economic losses globally*** *under current business-as-usual trajectory over the next three centuries. Importantly if we stay within the* ***limits for the Paris Agreement,*** *global warming is limited to 1.5°C, then additional cost will be* ***reduced significantly, to under $10 trillion; a major incentive to urgently reduce our emissions****.*

The ICE-ARC project is a €12 million EU funded Framework 7 Programme that sits within the European Commission's **Environment** theme. To provide a holistic understanding of the impact of Arctic change in the marine environment, ICE-ARC united over a **100 experts** from **24 institutions** across **12 countries,** as well as working in collaboration with **indigenous population, industry, policy makers**, and the **public**. This **inclusive approach** ensured that we combined the latest knowledge of the Arctic marine system, with up-to-date climate predictions, global economics, and local societal concerns. **ICE-ARC's unifying aim was to assess, for the first time, the social and economic impact of past, present and future Arctic sea-ice loss.** This was achieved through a tight collaboration between a broad range of expertise, disciplines, and sectors.

Increasing the understanding of how the Arctic Ocean, sea ice, atmosphere, and the marine ecosystem interact with each other is one of the best ways to **improve the accuracy and reduce the uncertainties** in current climate models. ICE-ARC collected **new observations** of the Arctic through the deployment of **47 robotic platforms** across the Arctic Ocean, participated in **12 ship-based research expeditions**, and flew **17 scientific aircraft campaigns** over the Arctic sea ice. Results from our basin wide observational programme, together with observations from the international community, enabled our climate modelling experts to improve our predictive capabilities regarding Arctic change and ecosystem function. For example, ICE-ARC **improved the model representation of sea-ice thickness**, which in turn reduces the uncertainty associated with predictions of how sea ice conditions will vary throughout this century. Changes in sea ice will influence the industrial use of the Arctic, in particular our results suggest that increased future **Arctic shipping** will likely lead to **increases in atmospheric pollutant concentrations** and the pollutants in marine ecosystems.

To model the monetary value of the projected physical changes in the Arctic upon the **global economic and social system**, we integrated the results from the different research efforts within ICE-ARC. This was a **ground-breaking move** as it was the first time a leading global impact assessment model had been coupled with (1) the latest results from climate models, including sea ice and permafrost simulations, and (2) current socio-economic information. This allowed us to **directly assess the global economic impact** of observed and projected climate change events in the Arctic.

In order to better appreciate the socio-economic impact of current and future changes in Arctic sea ice to **local indigenous Arctic communities** ICE-ARC undertook a **community-based partnership**. This co-production of knowledge delivered a better understanding of the nature of the **vulnerabilities of high Arctic communities**, in our case North West Greenland, to accelerating climate change by placing climate change impacts in context with societal, political, economic, institutional, and legal barriers. **Inuit communities** report that reductions in **sea-ice are affecting seasonal hunting practices** and mobility, with fewer months having ice that can be safely used for hunting and fishing by dog sledge.

Past sea ice changes off NW Greenland have been constructed based on satellite data, historical archives, and marine sediment core records, showing that the present rate of **ice loss is unprecedented in at least the last 117 years.** Changes in sea ice and primary production over the past millennia coincide with important Paleo-Inuit migrations, highlighting the close historical link between human societies and sea ice in the Arctic.

The **knowledge gained** within ICE-ARC was **widely distributed** beyond our traditional scientific networks. We talked with **school children** in remote Arctic villages, interacted with participants of the **World Economic Forum**'s annual meeting, organised **industry-driven roundtables**, and held high-level Arctic sessions **with the UNFCCC**. Our success can be attributed to the hard work and dedication of the team and its focus on **building bridge**s between the different disciplines such as economists, social scientists, and natural scientists.

A summary description of project context and objectives

Objectives of ICE-ARC as a whole

The Arctic system is probably one of the most complex and diverse on Earth. It is a region undergoing a state of accelerated flux; we are witnessing environmental, economic, and societal changes that not only have regional implications, but profound global consequences. Understanding the changes in the Arctic marine environment, and predicting and anticipating their socio-economic impact is a formidable task. It requires the coordinated efforts of a broad range of expertise, including the involvement of indigenous and local communities. ICE-ARC has spent four years rising to this multi-disciplinary challenge. Possibly for the first time in Arctic science, chemists, physicists, biologists, and engineers have worked in unison alongside economists, social scientists, and the indigenous communities to provide a holistic understanding of the impact of Arctic change, and to quantify the global economic and societal costs of responding to it –or failing to respond. The objectives of the ICE-ARC programme include:

- Improved climate prediction for the Arctic Ocean, and the reduction of uncertainties in those predictions;
- Improved understanding of climate change impacts on Arctic marine ecosystems;
- Assessment of socio-economic vulnerabilities, both to the peoples of the north and to the planet as a whole;
- Improved understanding of the marine living resources for Arctic human communities;
- Provide the information needed for effective strategies and management options for societal responses to climate change.

To address the scientific and socio-economic challenges ICE-ARC was structured around six complementary and interlinked Work Packages (WPs). These were:

WP1: Improving observational capabilities and reducing uncertainties.
WP2: Improving modelling capabilities and reducing uncertainties.
WP3: Identifying socio-economic vulnerabilities within the Arctic region.
WP4: Modelling socio-economic vulnerabilities and assessing management options arising from Arctic marine.
WP5 Dissemination of results: An impact strategy for developing policy and management options.
WP6: Project management and coordination.

This WP structure was focused around the objectives of our programme, and by doing so it allowed the independent foci of each WPs to be realised, whilst ensuring the different WPs worked productively together. Thus allowing the interlinked deliverables to be fed into the over-arching socio-economic work packages in order, to ‘*Directly assess the social and economic impact of Arctic sea ice loss*’. The aims and objectives of each WP are summarised below.

Objectives of WP1: Improving observational capabilities and reducing uncertainties

Continuous monitoring of a dynamic and changing Arctic marine environment is a difficult challenge. But a challenge we must overcome if we are to better understand the Arctic marine environment, and to predict the impact of Arctic change. Recent technological developments, some achieved within ICE-ARC, mean that many fundamental processes can be monitored year-round through the use of cutting-edge robotic technology. These systems are designed to function within the harsh Arctic marine environment in order to remotely capture and communicate their measurements. Sustained and comprehensive measurements of key areas of Arctic change, including the ocean, sea ice, atmosphere and the ecosystem will provide a better understanding of the Arctic system and reduce uncertainties in our climate predictions. With this in mind the objectives of WP1 were:

- Gather year round observations of the atmosphere, sea ice, ocean, and associated ecosystem within the Arctic marine environment;
- Provide appropriate data sets for validation and development of remote sensing products and model parametrisations;
- Test quantitative and novel methods for monitoring sea thickness and ridge distribution changes in time and space (autonomous platforms, airborne, and satellite methods).

ICE-ARC researchers within WP1 deployed nearly 50 robotic platforms from a dozen ship-based expeditions right across the Arctic Ocean. We collected data that encompass the marine environment; from cloud thickness, solar radiation and air temperature through to sea-ice thickness, ocean salinity, zooplankton species and abundance, and beyond. A larger synoptic view of the Arctic marine environment was performed from the collection and analysis of data obtained from satellite and dedicated aircraft operations. WP1 provided an improved understanding of the workings of the changing Arctic system, as well as a better appreciation of the interlinked nature of the processes that amplify Arctic marine change.

Objectives of WP2: Improving modelling capabilities and reducing uncertainties

Global climate models are the best tools available to predict the future climate of our planet, a product of a complex series of interactions and feedbacks between the atmosphere, ocean, ice, and land. Quantifying and reducing uncertainties in climate model projections is a focus, but other key objectives include:

- To improve the understanding of coupled atmosphere, cryosphere, and ocean processes (physical and biological), and climate impacts.
- To quantify freshwater input and flow in the Arctic Ocean.
- To assess pollution effects and climate change impacts on marine Arctic Ecosystems.
- To provide input data to the socio-economic model (WP4) for selected climate simulations.
- To assess the impacts of the accelerated warming on the productivity and Carbon budget of terrestrial ecosystems in the Arctic and boreal regions.

Uncertainties in current climate models can best be reduced by increasing the understanding of how the Arctic Ocean, sea ice, atmosphere, and the ecosystem interact with each other, and for this reason a close link to the in situ data collected within WP1 was established. WP2 used global and regional oceanic, terrestrial and atmospheric model systems to improve our understanding of these interactions, and to better quantify freshwater input and flow in the Arctic Ocean. We also performed research in order to assess climate change effects on productivity and the carbon budget of both marine and terrestrial ecosystems. In addition, our modelling efforts allowed us to better assess the effect of an increase in Arctic shipping, due to reducing sea ice cover, on air pollution in the Arctic. Outputs from climate models were feed into PAGE-ICE, the project’s advanced decision-making tool (WP4). This integrates climate predictions, in line with the Paris Agreement, with socio-economic consequences to assess the full impact of a changing Arctic under a range of global emissions and socio-economic scenarios.

Objectives of WP3: Identifying socio-economic vulnerabilities within the Arctic region

This work package had an interdisciplinary, community-based focus on communities, sea ice and living resources in Northwest Greenland. Our concern is with understanding and assessing current and future changes in Arctic sea ice and the broader environment in Northwest Greenland – both from changing atmospheric and oceanic conditions – and the social and economic consequences of these changes. Our research is collaborative across the social and physical and natural sciences, and combines scientific and local knowledge. The main objectives were:

- to understand the present impact of changes in sea ice, marine living resources, environment and socio-economic conditions on the livelihoods of indigenous communities in northwest Greenland,
- to investigate how past changes affected previous indigenous cultures and their adaptive capacities and livelihood strategies;
- to develop strategies for the application of anticipatory knowledge by communities to help them prepare for and negotiate change in the future. This will help improve climate predictions for understanding the impacts of climate change on marine ecosystems and Arctic societies and enable communities to build capacity towards ensuring sustainable livelihoods;
- to understand the nature of the vulnerabilities of high Arctic communities to accelerating climate change by placing climate change impacts in context and will examine societal, political, economic, institutional, and legal barriers to adaptation.

We focused on building a comprehensive understanding of local knowledge and the historical and contemporary resource use and occupancy of Northwest Greenland, specifically in the Upernavik, Melville Bay and Qaanaaq areas. This includes the integration of marine and terrestrial evidence for past sea ice and primary production changes during the Holocene in relation to human migration and settlement patterns, as well as mapping the present day use and knowledge of sea ice, and its importance for communities in the region. We assessed how past adaptive strategies and human-environment relations and how people today think about sustainable livelihoods and anticipate the future. Community vulnerability and resilience are being influenced and affected not just by climate change but by rapid social, economic and political change, as well as by contemporary exploratory activities by extractive industries, and so we seek to understand how north Greenlandic communities have been affected historically, how they are situated within contemporary Greenland, and how they are affected by a range of global processes.

Objectives of WP4: Modelling socio-economic vulnerabilities and assessing management options arising from Arctic marine

Arctic change has the potential to trigger significant changes in global and regional economies because of the region's critical role in the global climate system. To date, most discussions about the economic implications of a warming Arctic focus on benefits to the region, with increased oil-and-gas drilling and the opening up of new shipping routes. However, there is little known about potential global socio-economic impacts related to Arctic change. To assess the global cost of Arctic change WP4 needed to integrate results from other ICE-ARC work packages along with current environmental and socio-economic information to produce a more accurate integrated assessment model (IAM): PAGE-ICE. This was an update to the IAM known as PAGE that was used in the 2007 UK Stern Review of the Economics of Climate Change.

PAGE-ICE specifically integrated the key climatic processes in the Arctic to estimate the resulting global and regional socio-economic impacts. The analysis included estimating the impacts of the sea ice albedo feedback and permafrost carbon feedback on the global economy under a wide range of scenarios that are consistent with the Paris Agreement. We also estimated global economic losses from the climate feedback caused by emissions from the growing transit shipping through the Northern Sea Route, and compared these losses with the associated benefits from the enhanced trade between Europe and East Asia. The objectives of this Work Package were three-fold:

- To adapt the leading integrated assessment model, PAGE, to include the main influences of changes to the Arctic marine environment.
- To assess the social and economic impacts of changes to the Arctic marine environment and identify key socio-economic vulnerabilities and opportunities globally and regionally for the Arctic.
- To value the impacts of Arctic-related climate change and the costs of policies to abate and adapt to the changing Arctic marine environment.

The cost of net additional warming from Arctic feedbacks is significant. If climate targets are to be met, adequate financing is needed, for example a carbon tax that covers the additional cost associated with Arctic change, which has also been calculated by PAGE-ICE. The mitigation of climate change must be a partnership between society, government, and industry; a key step in understanding how the Arctic influences the net cost of climate change has been one of the developments within PAGE-ICE.

Objectives of WP5: Dissemination of results: An impact strategy for developing policy and management options

Arctic change has the potential for environmental, social, and economic impacts which extend beyond the region. It is for this reason that ICE-ARC developed a broad impact strategy to disseminate the latest findings to Arctic communities through dedicated meetings and workshops, to the science community through high impact scientific papers and educational programmes, to industry through dedicated round-tables, to the public through wide-reaching outreach events including schools and science festivals, and to high-end policy makers through high-level sessions and discussion sessions. The main objectives were:

- To establish an effective and efficient dissemination mechanism for the project's deliverables, milestones, results and conclusions to the appropriate output forums.
- To broaden the stakeholder knowledge on matters relating to change Arctic marine environment, especially, although not exclusively, through the results of ICE-ARC.
- To spur top-level discussions and the development of policy measures and action plans aimed at protecting the Arctic marine environment based upon the results of ICE-ARC.

An increase in the dissemination of Arctic knowledge, from ICE-ARC and other key programmes, brings benefits to all, and enables evidence-based planning, policy and management systems to be developed.

Objectives of WP6: Project management and coordination

The objective of this work package is to ensure that the proper controls and processes are in place for efficient and effective project operation and coordination. The structure of this work package allows for the transparent and effective monitoring of the progress of the project according to the contractually agreed objectives, methods, and standards. The decision-making body is based around the Project Coordinator, the Steering Committee, and an international renowned Advisory Board. The objectives are to ensure that management of the project is in conformity with the planned allocation of resources, and abides by rules and procedures contractually agreed, and to address the issues related to the intellectual property rights, gender, and other significant subjects.

Summary

The interlinked objectives and work package structure of ICE-ARC, combined with its strong and supportive management team, ensured that the co-production of knowledge between different disciplines and sectors was at the heart of our programme. Just as important as the generation of new knowledge was our objective to ensure this information was clear, concise and accessible to a broad range of decision makers, including local communities, industry, science, policy and the general public. With this in mind ICE-ARC produced a Synthesis Report that summarised our findings. It is available in both English and Greenlandic.

It is through this inclusive approach to knowledge generation and dissemination that we have been able to provide a knowledge-based framework for improving EU and international policies that are aimed at protecting the marine environment, safeguarding living resource for human communities, and more effective policy and management options for societal responses to climate change. This in turn creates opportunities for innovation and allows for the sustainable development of the Arctic.

A description of the main S&T results/foregrounds

Overview

ICE-ARC's findings make clear that understanding, assessing and responding to Arctic change in the marine environment requires a multidisciplinary, international and integrated response. It is not possible to look at one aspect of this system in isolation; a coupled atmosphere-ice-ocean (including marine ecosystem) approach is needed. However, to fully understand Arctic change this approach must go beyond the natural sciences, we must also understand the human dimension. This involves working in partnership with a broad range of disciplines, sectors and stakeholders in order to investigate and better comprehend the socio-economic impact of Arctic change.

One of ICE-ARC's greatest successes can be attributed to its focus on cross-disciplinary, cross-sectorial and community-based collaborations. This is not an easy task as it involves different cultures, different disciplines, and different geographic regions. Even when speaking the same language the terminology used by these different groups can be incomprehensible. It requires patience, understanding, trust, and range of multidisciplinary skills in order to synthesise and co-produce knowledge from different disciplines and sectors. It is credit to the ICE-ARC team that we were able to work our way constructively through these difficulties. However, it is not all plain sailing there are challenges to overcome, successes to be relished, and knowledge to be disseminated. ICE-ARC was particularly privileged to have a strong management and decision-making body which had clear structure and vision. Our independent Advisory Board, whose main task was to ensure scientific rigour and effective dissemination of results, was particularly useful element of this approach. ICE-ARC is however fundamentally a research programme that consists of six interlinked WPs. All of these WPs were divided into Tasks and Sub-tasks. In the following pages we describe the main science and technological results from the WP1 to WP5. Each WP contains a summary of the main tasks. The management and coordination work package (WP6) is not described here.

Key highlights of WP1: Improving observational capabilities and reducing uncertainties

The sea ice pack in the Arctic has changed rapidly from a thick multi-year ice (MYI) dominated system to a thinner and more mobile first-year ice (FYI) dominated system. These changes affect the thermodynamics and dynamics of Arctic sea ice, ocean physics, the biogeochemical properties of the ocean, and ecosystem function. As our knowledge is based on the multi-year ice regime we need to develop a new understanding of the Arctic marine system as we find it today. This calls for a re-evaluation of algorithms in models describing the ocean, sea ice and atmosphere. Current model parameterisations are largely based on observations in a multi-year ice regime, and need to be updated to represent the recent shift to first-year ice. The aim of this WP was to develop and deploy new observational platforms that can provide year round observations, and by doing so provide new insight into key processes for a better understanding of the annual cycle of sea ice, the upper-ocean, atmosphere and ecosystem in this new Arctic.

Task 1.1 - Sea ice processes; dynamics and thermodynamics, radiation and albedo, and topography

We have not only developed an advanced sea-ice mass balance system, but also integrated radiation sensors within these systems in order to better understand the role of solar radiation within sea ice growth and melt processes. These systems were deployed right across the Arctic. Some of these systems made novel observations of the thermal regime in melt ponds of different salinity (fig 1.1). By doing so we identified new processes that reveal a different thermal evolution from the one that is presently being used in climate models, and as such may give climatologically-significant perturbations to sea-ice energy budget.

Working in collaboration with the Norwegian N-ICE2015 programme, in the sea ice covered region north of Svalbard, we deployed a number of buoy arrays to monitor the deformation of the first-year and second-year ice. Analysis of these arrays found a general increase in deformation associated with the younger and thinner Arctic sea ice, as well as to highlight the potentially destructive role of winter storms near the ice edge. Furthermore coincident aircraft operations, with scanning Lidar, revealed the three dimensional surface topography before and after a substantial deformation event. This unique dataset, from a 9 km^2 area of first year and second year ice in the Transpolar Drift north of Svalbard, allowed us to estimate for the first time the redistribution of mass from an observed deformation event.

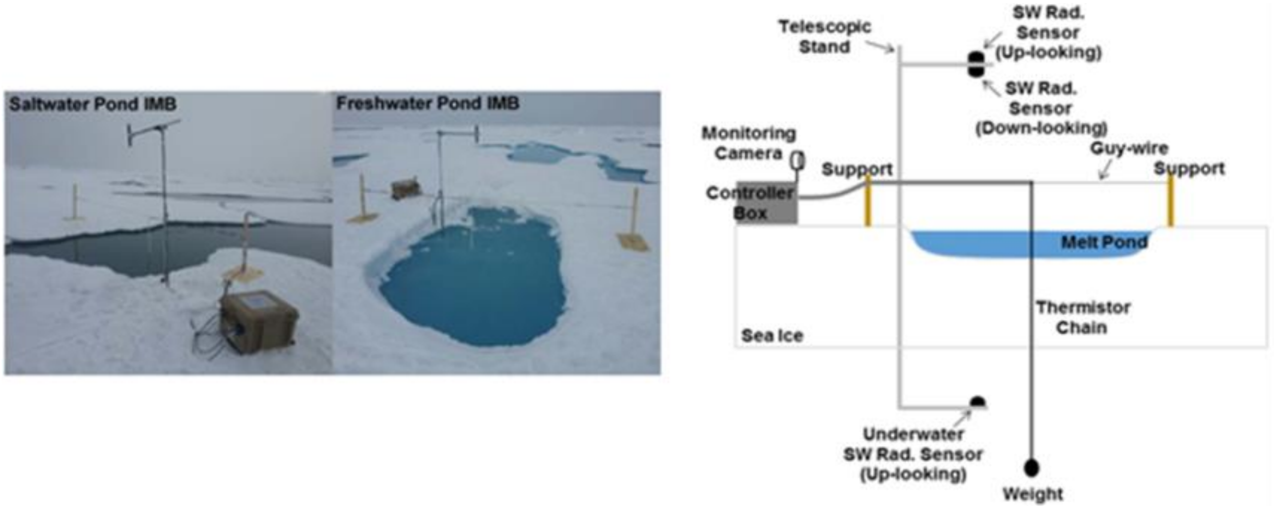


Figure 1.1. Photograph of two deployed IMB systems, one over a saline melt pond and another over freshwater meltpond, and (b) schematic of instrument deployment with sensors including a vertical thermistor chain through air, pond, ice and upper ocean, along with shortwave radiation sensors. Schematic by Joo-Hong Kim

Further technological developments include integration of a light-weight Lidar system on a long-range drone to map the surface topography of sea ice, and the use of autonomous underwater vehicles (AUVs) to map the underside of sea ice. Within ICE-ARC we were able to carry out two AUV missions to map under-ice topography in summer and winter with multi-beam sonar. We sought to determine how the underwater shape of pressure ridges, and the balance between under-formed and deformed ice, changes between the winter and summer months. In terms of ICE-ARC objectives, this helps us to understand the annual ice mass balance, the change in ice dynamics between winter and summer, and to investigate the way in which the extraordinarily rapid ice retreat observed in recent years manifests itself.

Task 1.2 - Ocean processes: ocean mixing and stratification, freshwater fluxes, wave propagation, and fjord processes

Task 1.2 covered a broad range of in situ ocean measurements, as well as novel remote sensing techniques. Partners developed and constructed ice-anchored robotic platforms known as SATICE and IAOOS, and collaborated in the deployment of several units in the Western and the Central Arctic Ocean. These systems sample the lower atmosphere, sea ice, and the upper ocean. The data contributed to an improved understanding of the present state of the changing Arctic marine environment. For example, the in situ data from SATICE, IAOOS along with data from CryoSat-2 satellite altimetry missions can be combined to examine changes in dynamic ocean topography in the Beaufort Gyre associated with temporal variations in freshwater storage.

Analyses of ocean data acquired by IAOOS (Ice Atmosphere Arctic Ocean Observing System) in the Eurasian Basin led to several publications. They confirm the existence of a seasonal Atlantic Water inflow over the Yermak Plateau in winter (the Yermak Pass Branch). Mercator model outputs (WP2) were compared to in situ observations which helped to put the in-situ data in a wider temporal and spatial context (fig 1.2).

In conjunction with WP3 this task also investigated fjord-based oceanographic processes by performing oceanographic observations in Inglefield Fjord, near the village of Qaanaaq, NW Greenland. This was achieved through the development of a participatory ocean climate monitoring program together with local Inuit hunters in the Qaanaaq region. The main driver of inter-annual change in the fjord was found to be the conditions in the North Water Polynya of the Northern Baffin Bay.

The task also refined the satellite-based SAR (Synthetic Aperture Radar) technique that allows one to determine the thickness of young ice (frazil, grease and pancake ice) through the change in the wave spectra as ocean waves propagate from the open ocean into these ice types. We developed a close-packing wave propagation model in frazil/grease/pancake ice (FGPI) to better describe the role of solid pancakes into the viscous frazil and grease ice mixture. Results are encouraging and compare well with in situ measurements of the thickness of FGPI made in the same region as the SAR images.

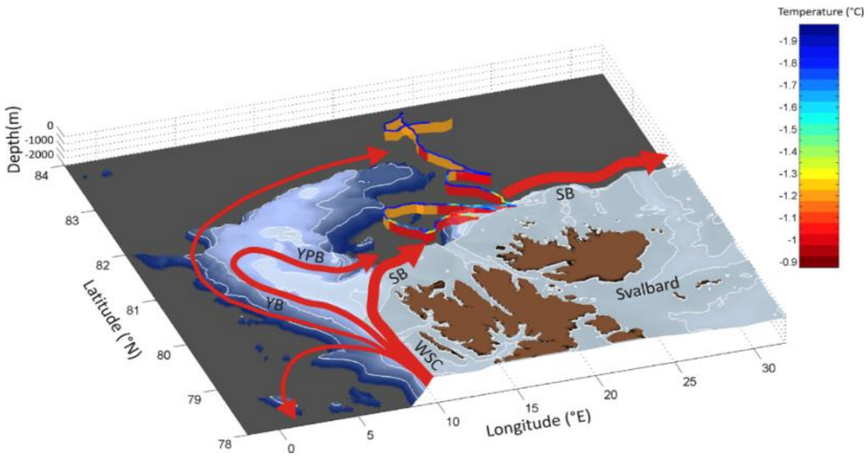


Figure 1.2. Summary of the in situ data results from Koenig et al. [2016] and Provost et al. [2017]. The background of the 3-D plot is the bathymetry. The red lines are the warm water paths. YB: Svalbard Branch. WSC: West Spitsbergen Current. YPB: Yermak Pass Branch. SB: Svalbard Branch. Summary of the warm water layer is the orange/red ruban: orange corresponds to Modified Atlantic Water and red to Atlantic Water. The overlaying data are the surface temperature obtained from the ice mass balance instrument (colour bar on the side).

Task 1.3 - Atmospheric processes: clouds, aerosols, trace gases (pollution), radiative budgets

The determination of dynamical and radiative properties of low-level clouds presently remains a challenge for large-scale models, due to a poor characterisation of critical atmospheric and surface parameters constraining boundary layer interaction processes. The IAOOS platform has been developed to provide more ocean, ice, and atmosphere observations over the central Arctic. In this task, an analysis was conducted of the first IAOOS atmospheric measurements performed in 2014 and 2015. These observations combined with satellite (CALIPSO) measurements show that low-level cloud occurrence may be very high and in excess of 90 % in the May-June period north of Svalbard, but such clouds may also extend over the whole Arctic. Our study further shows that such clouds may be linked to interactions with aerosols transported from the continent during this period (in particular from Siberia and Europe). Such clouds lead to a strong positive longwave (LW) radiative forcing (warming). Our study shows that the net monthly LW radiative forcing at the surface is underestimated in the ERA-I reanalyses with respect to values deduced from observations over May and June periods. This work highlights an important challenge for future observations to analyse in more detail the forcings linked to changes in surface properties.

Task 1.4 - Biogeochemistry processes, including marine acidification and CO_2

This task pushed forward our ability to remotely monitor the biogeochemistry of the Arctic marine environment. SAMI pCO_2 and pH sensors bought from Sunburst (USA) were interfaced onto a new surface unit developed in collaboration with LATMOS based on Raspberry controllers. The surface unit was installed onto a IAOOS buoy (Figure 1.4a), and the two sensors were deployed at the North Pole in April 2017 just below sea-ice next to another IAOOS platform equipped with a biogeochemistry sensing profiler (Figure 1.4b). More than 8 months of data were sent in quasi real time, decoded, calibrated, and validated.

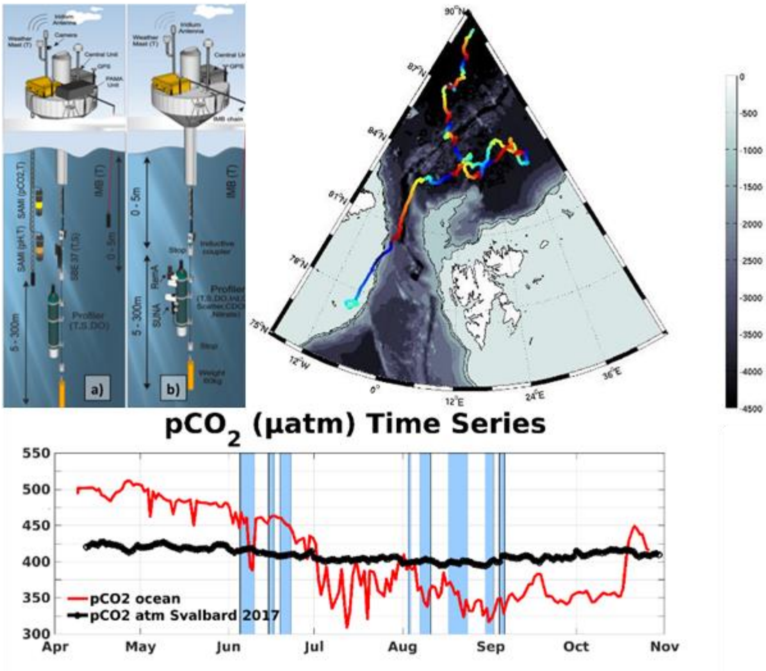


Figure 1.4: Top left: IAOOS platform with near surface pCO_2 and pH sensors and IAOOS platform with profiler equipped with biogeochemical parameters. Top Right: Drift of the platforms deployed at the North Pole in April 2017 (still on-going). Bottom: Under sea-ice pCO_2 from the drifting platform (red), atmospheric pCO_2 (black)

The first part of the drift shows oceanic pCO_2 well above atmospheric values: this is due to the export of corrosive water enriched by CO_2 originating from oxidation of eroded terrestrial carbon and Siberian rivers in the under ice cold and fresh waters. In the second part of the drift the primary production associated with the summer bloom reduces the oceanic pCO_2 to levels below atmospheric values. Short-term variations in oceanic pCO_2 are associated with opening leads and sea ice fragmentation.

Task 1.5 - Ecosystem dynamics

The integration of cutting-edge in situ sensors on to the IAOOS system continued within this task. An instrument package was installed on the IAOOS platform23 comprising of:

- OCR504 instrument measuring the downwelling irradiance at 412, 490 and 555 nm,
- Photosynthetically Active Radiation (PAR) and
- the ECO Triplet instrument measuring fluorescence from Chlorophyll-a and Coloured Dissolved Organic Matter (CDOM), and the Particle backscattering
- SUNA (Submersible Ultraviolet Nitrate Analyzer).

This IAOOS platform was deployed at the North Pole on April 12, 2017 (see Figure 1.5a for its trajectory). The 7 months long time series (as of November 2017) collected by the IAOOS platform 23 under sea-ice (Figure 1.5b, c, d) constitutes a *première* in this high Atlantic sector of the Arctic. Indeed, it enabled documenting for the first time in this high sector the existence of under-ice phytoplankton bloom growing beneath sea-ice, confirming earlier findings in the Pacific sector. Please note that algae blooms at the base of the sea-ice were not previously documented, as these under-ice blooms are invisible to ocean colour satellite sensors. This implies that previous estimates of annual net primary production in waters with occurrence of these blooms are largely underestimated. These blooms certainly represent an important component of the annual marine Arctic carbon cycle.

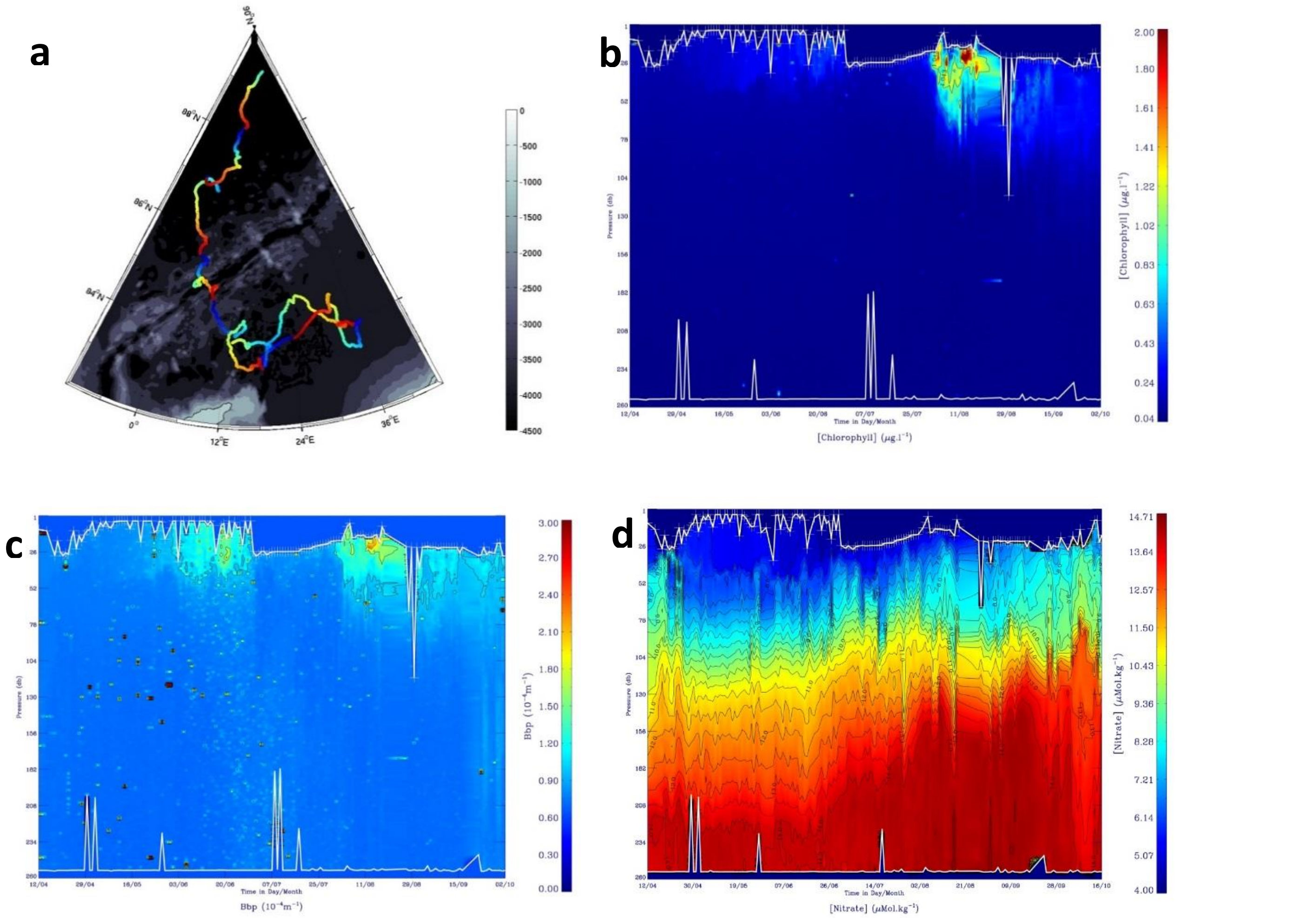


Figure 1.5: a) Trajectory of IAOOS platform 23 deployed in April 2017 from the Barneo Camp. The final position shown is the one on November 18th 2017, b) Chlorophyll a concentration time series obtained on this IAOOS platform, c) Backscattering coefficient time series obtained on IAOOS 23, and d) Nitrates concentrations time series obtained on IAOOS platform 23.

A large river input of dissolved organic matter (DOM) originating on land plays a significant role in marine aquatic ecosystems. This can directly affect the quantity and spectral quality of available light, thereby impacting both primary production and ultraviolet (UV) exposure in aquatic ecosystems.

Task 1.6 - Remote sensing: space-based ocean-cryosphere observations

From multisensory monitoring of sea ice a wide range of sea ice properties has been estimated. Assimilation of time series of satellite ice surface temperatures in WP2 models result in increased annual sea ice production and redistribution. From multisensory collocation with Ice Mass balance Buoys (Task 1.1) it was possible to construct the ice temperature profiles at independent IMB's. These data are essential input to sea ice models. Inter-comparison of Arctic Ocean large-scale, daily, sea ice drift products from passive microwave and SAR data with drifting buoys have provided estimates of robustness of the satellite ice drift estimates. From these sea ice displacement data and model wind data, the temporal and spatial characteristics of the surface wind relation to sea ice drift are estimated. These analyses indicate a general weakening of the Arctic sea ice strength. Finally, inter-comparison of snow depth in three ice models, reveal large differences in performance. DMI CICE model performs with the lowest bias in relation to operational snow estimates from NASA Ice Bridge.

During the three ICE-ARC airborne campaigns 2015-2017 (fig 1.6), a unique collection of combined LiDAR, radar and radiometer data has been collected. These data provide detailed information of sea ice surface topography and includes valuable information of lead/ridge distribution, penetration depths, and albedo. The efforts were coordinated with ground measurements during N-ICE2015 and CamBay SnowEx 2017, and offers evaluation data for various satellite missions, including altimetry missions CryoSat-2, Sentinel-3 and SARAL/AltiKa, but also sea ice classification using fully polarimetric SAR-images. Various public time-series of CryoSat-2 sea ice thickness products exist. These products usually compare reasonable well to validation data in the central Arctic. However, data obtained during N-ICE2015 show conditions where CryoSat-2 does not penetrate the snow in this particular region, even at cold spring temperatures (-15˚C), causing significant uncertainty in sea ice thickness retrievals from CryoSat-2. The campaign data completes a 20 year time series (1998-2017) of LiDAR data in the Wandel Sea, which show thinning of the sea ice, especially in the thick deformed sea ice classes.

Figure 1.6: BAS aircraft getting ready of airborne operations for ICE-ARC in the Arctic.

Key highlights of WP2: Improving modelling capabilities and reducing uncertainties

An extensive modelling effort has been carried out in WP2 with developing and running several model systems. A book-keeping system has been used to provide independent spatially and temporally distributed maps of estimated sea ice properties (age, sea ice deformation, wind drag and new ice production) that are very valuable for developing dynamical sea ice models. Improved sea ice parameterisations have been developed and implemented in both climate model systems and in high-resolution operational ocean-ice model systems in the Arctic. Different sea-ice model parameterisations have been assessed. Results showed that by including sub-grid scale representation of ice classes based on observations, the model predicted a more realistic sea ice volume and sea ice distribution. This improved parameterisation was implemented in the climate model system MPIESM and the IPCC climate scenarios RCP 2.6, 4.5 and 8.5 were rerun.

The effects of improved sea-ice representation became less as ice cover decreases, demonstrating the challenge of developing parameterisation that are also valid in a future Arctic ocean with less, thinner and more energetic ice cover. An ensemble of pan-Arctic coupled ocean-ice experiments driven by several different atmospheric reanalysis showed large sensitivity of model results to atmospheric processes, but independent biases were also identified. This ensemble of simulations also showed that, whatever the variables, the ensemble mean has better performance than individual members.

Simulated freshwater contents are shown to be sensitive to uncertainty in atmospheric forcing fields, but uncertainty is reduced with new sub-grid scale and dynamical sea ice parameterisation. Model results also indicate that internal variability impacting exchange across the Fram Strait and the Barents Sea has a large impact on freshwater distribution and its variability.

Continued decreases in sea-ice extent are expected to increase shipping in the Arctic along the Northern Sea Route. This leads to consequent increases in atmospheric pollutant emissions. Results from a regional chemical-aerosol model (WRF-Chem) show for instance significant local enhancements in ozone above background levels which could have impacts on human health.

Climate change may also have an impact on the ecosystems in the Arctic. Model results show that simulated marine primary production is sensitive to ice conditions, but also that strong stratification constrains nutrient fluxes and limits the growth of primary production in a seasonal ice-free Arctic Ocean. For terrestrial ecosystem, model results show a positive trend in net biome productivity over the last decades and that CO_2 fertilization was the main driver. Changes in climate were dominant for changes in phenology.

Task 2.1 - Evaluation and improvement of model parameterisations with respect to sea-ice processes

Changes in sea ice motion due to dynamically effective processes (surface and bottom drag, rheology, ice strength) generate spatial redistribution of ice mass, which in turn modifies the thermodynamical growth rate. These modifications usually occur on small spatial scales. Unless large-scale anomalies in the forcing generate a systematic preference for more or less open water areas, the Arctic wide ice volume (our target variable) is little affected. Dynamical processes, however, indirectly affect the total ice volume through the ice export from the Arctic. Thermodynamic processes and corresponding parameterisations on the other hand are likely to directly affect the total Arctic ice volume. Thus, we expect climate models to be more sensitive to parameterisations of thermodynamically effective processes such as the inclusion of sea-ice thickness classes based on recent observations and a corresponding snow thickness distribution (Fig 2.1). The altered heat flux calculations had a large and beneficial effect on the results of a forced ocean-sea ice model. We therefore implemented this modification for experiments with the selected Earth system model (T2.4, T2.5).

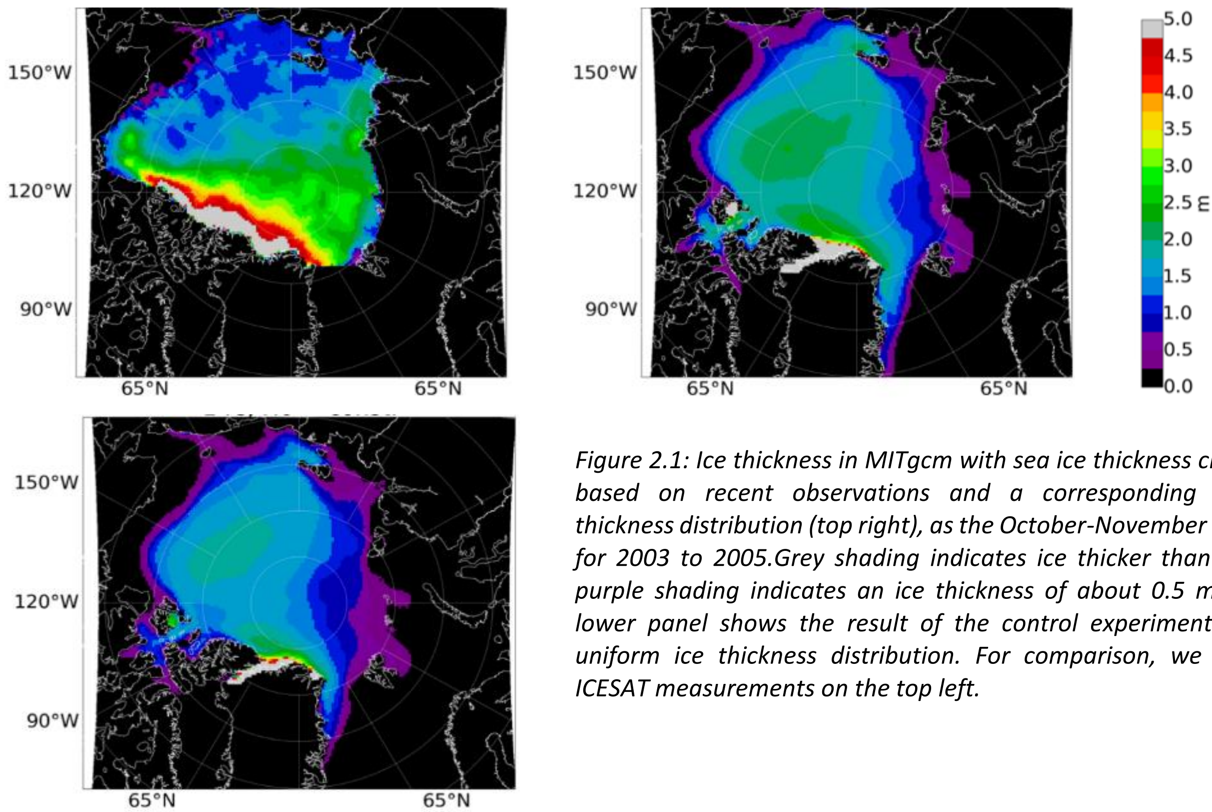


Figure 2.1: Ice thickness in MITgcm with sea ice thickness classes based on recent observations and a corresponding snow thickness distribution (top right), as the October-November mean for 2003 to 2005.Grey shading indicates ice thicker than 5 m, purple shading indicates an ice thickness of about 0.5 m. The lower panel shows the result of the control experiment with uniform ice thickness distribution. For comparison, we show ICESAT measurements on the top left.

Task 2.2 - Book-keeping model

Book-keeping of sea ice properties retrieved from satellite data is a useful method to systematically keep track of spatial and temporal variations of sea ice properties such as sea ice age and new ice production and it combines knowledge of past with recent processes/events. In addition, it can be used to provide a test bed for the first estimate in retrieval / inverse / assimilation methods using satellite data for deriving physical parameters on sea ice, e.g. snow cover and temperature.

By forcing a sea-ice bookkeeping system with observed ice drift data, a number of sea ice parameters are derived. These parameters are normally not estimated directly from remote sensing. Many of the poorly constrained assumptions in sea ice models such as rheology and roughness are bypassed using the observed sea ice drift directly in the bookkeeping system. Therefore, the bookkeeping model provides an independent estimate of spatially and temporally distributed maps (Fig. 2.2) of sea ice age, total degree of sea ice deformation and wind drag on sea ice and total measure of new ice production for comparison with traditional sea ice models.

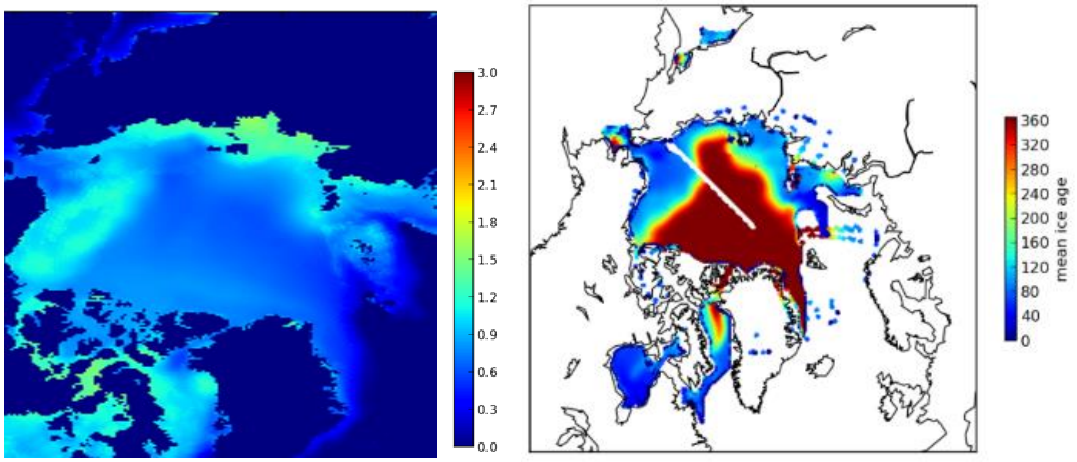


Figure 2.2: Results from bookkeeping model showing annual new ice production: 2017 to the left and mean ice age for 2017 to the right

Task 2.3 - Modelling and data analysis for operation and sustainable applications

We have developed a pan-Arctic numerical ocean- ice model system essentially dedicated to calibrate and evaluate hindcasts, nowcasts, and forecasts of Arctic marine products. Numerous studies have already highlighted the importance of the retroaction between atmosphere and sea ice/ocean in Polar Regions at climate scales, and their substantial and relative role in recent extreme events such as the 2007 and 2012 historical summer minimums. Given the importance of atmospheric processes and the relative errors found in state of the art atmospheric reanalysis in the Arctic Ocean, we performed 2007-2014 experiments driven by 6 state-of-the-art atmospheric reanalysis to assess their impact on Essential Ocean and Sea Ice variables. Large uncertainties in atmospheric reanalysis hydrological cycle induces a large spread in the simulated freshwater content (Fig. 2.3). Also, considering the methodology applied in these pan-Arctic experiments, atmospheric forcing represents about 56 % of the uncertainties in the freshwater sink of the Arctic Ocean. However, important biases seem relatively independent from atmospheric uncertainties. Parameterisation such as number of sea categories, rheology and ridging has been changed and a “New” ensemble of experiments has been performed. These proposed set of changed parameterisation and parameters improve largely the summer sea ice extent (Fig. 2.3) and sea ice thickness. Whatever the variables, the ensemble mean still shows better performance than individual member.

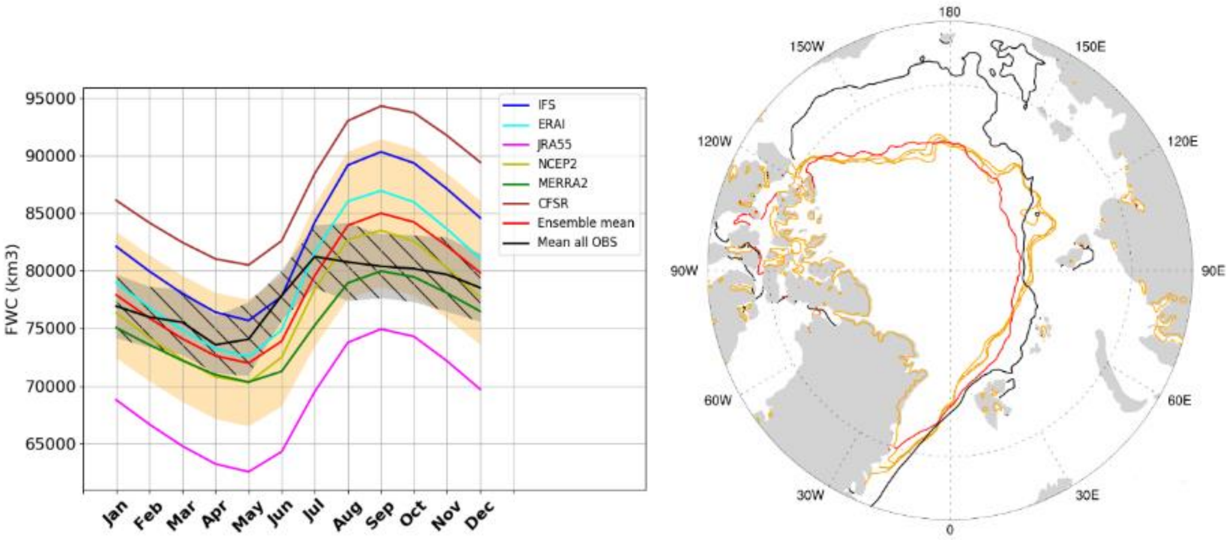


Figure 2.3: Left: Mean freshwater content (km^3) (solid line) and standard deviation (hatched areas) over the Arctic domain from the 6 experiments driven by the 6 different atmospheric forcing with the ensemble mean (red), and from the mean of 5 climatologies (black).

Right: Mean sea ice extent in September 2012 from 3 satellite data sets (orange), from mean ensemble "Old" experiments (black) and from mean ensemble "New" experiments (red) showing 15% ice fraction.

Task 2.4 - Freshwater pathways

Ensemble experiments with the MPI-ESM-LR coupled model were performed, investigating the impact of a new sub-gridscale parameterisation for sea-ice thickness distribution (ITD, see T2.1 and T2.5) on the Arctic Ocean freshwater, its pathways and its dynamics. The spatial pattern of the freshwater in the Arctic Ocean is similar between the standard ("STD") experiments and experiments with the new ITD. An overall lower freshwater level and in particular a lower freshwater content in the Eurasian Basin in the ITD experiment, is closer to observations and forced model results than in the control ("CTRL") experiment. The ensemble standard deviation of the freshwater distribution is less in experiment ITD when compared to experiment CTRL, translating into a small reduction of the model uncertainty. The ensemble standard deviation is largest in the Eurasian and not the Canadian Basin, where the larger fraction of the freshwater is located. This indicate that internal variability, that affects the exchanges across the gateways of the BSO and Fram Strait, has a larger impact on the freshwater distribution and its variability than locally driven changes in the more isolated Canadian Basin. The multi-decadal variability found in the detrended total freshwater exports as compared to the detrended intensity of the Atlantic Meridional Overturning Circulation AMOC in 1000 m depth at 26º N does indicate an effect of increasing exports on slowing down the AMOC, and vice versa. However, due to internal variability, this relationship is not identifiable with consistent intensity in all ensemble simulations.

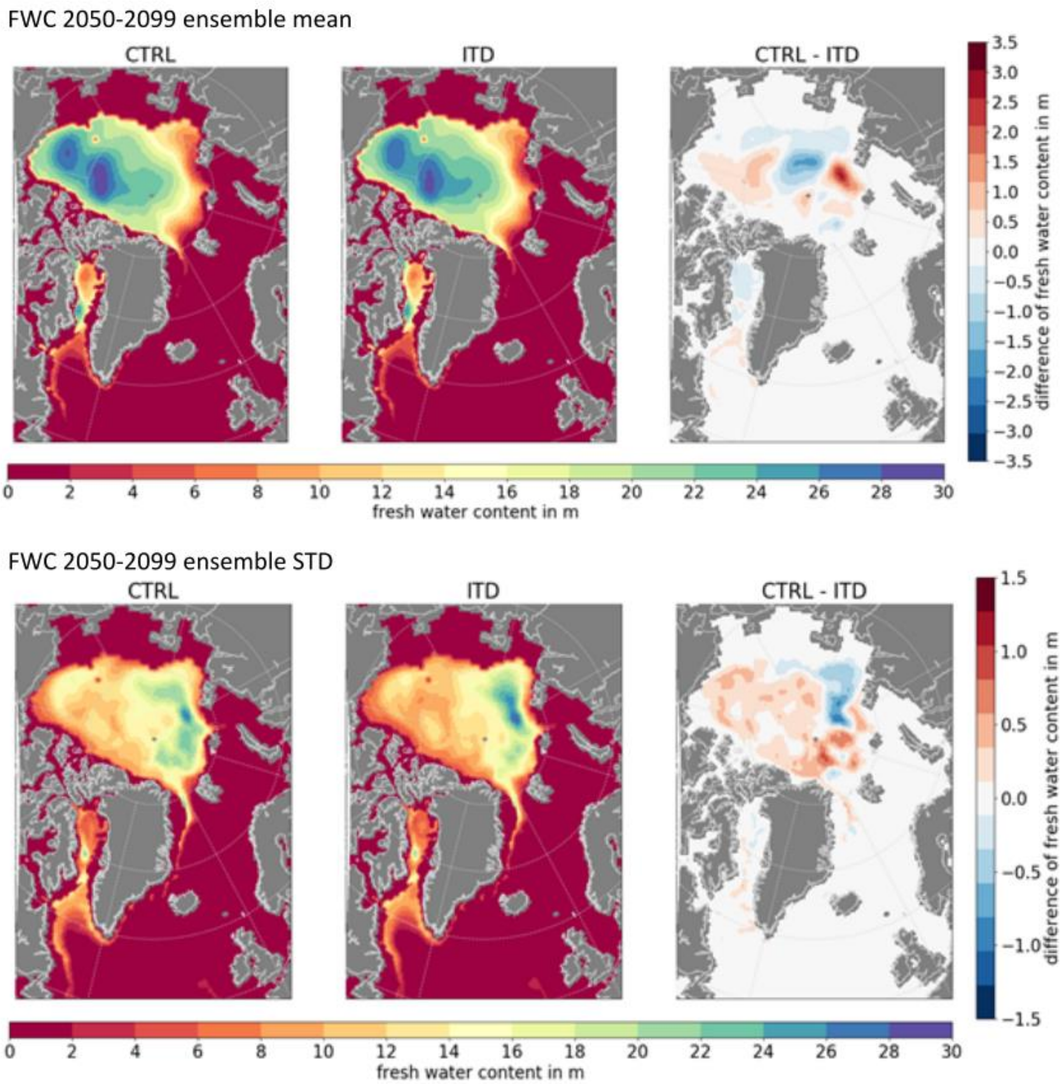


Figure 2.4: 2050-2099 ensemble mean (top) and ensemble STD (bottom) of the freshwater in the deep basins (> 500m bottom depth) for control experiments CTRL (left) and ITD – ice thickness distribution (middle) and the difference (right). Reference salinity is 35.

Task 2.5 - Incorporation of new parameterisations into the climate model system

We implemented a sub-grid sea ice thickness distribution in the MPI-ESM-LR model. In contrast to the original one-layer sea ice thickness approach used in the MPI-ESM-LR, here we use a 15-classes formulation (ITD), which is based on sea ice thickness measurements.

The Arctic sea ice extent remains similar in both model experiments with and without the ITD. However, the Arctic sea ice volume increases in the ITD model due to a thickening of sea ice. This effect is more pronounced in the historical experiments, less so in the RCP experiments, which could be understood as a consequence of the shape of the prescribed ITD, which is fixed in space and time. Overall, the sea ice volume is closer to observationally based estimates after the introduction of the ITD. The location of maximum sea ice thickness is shifted towards the coast of North Greenland and resembles better observations in the ITD model. Outside the Arctic, the ITD model simulated a near surface air temperature that is colder (warmer) by about 1°C over Siberia (China and Japan) during March and warmer northeast of the Black Sea during September by the end of the 21st century.

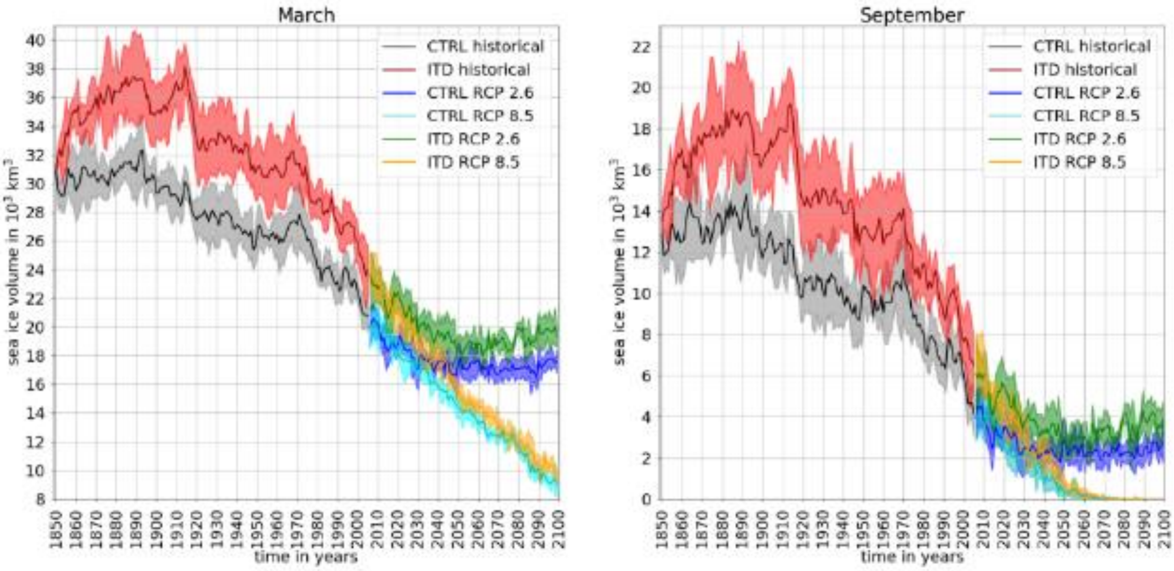


Figure 2.5: Arctic integrated sea ice volume simulated with the MPI-ESM-LR model for March and September. The thick lines show the ensemble mean over five members of each experiment. The shaded area indicates the ensemble spread. The historical simulation covers the years 1850-2005. Emissions scenario simulations RCP 8.5 and 2.6 are applied for the years 2006-2099. The ITD experiments use a sub-grid sea-ice thickness distribution while the CTRL experiment does not.

Task 2.6 - Atmospheric processes, pollution, and deposition

Continued decreases in sea-ice extent are expected to increase shipping in the Arctic along the Northern Sea Route. This leads to consequent increases in atmospheric pollutant emissions that may have adverse effects on marine ecosystems and biogeochemical cycling in the Arctic. A regional chemical-aerosol model (WRF-Chem) is used to examine the impacts of future shipping emissions on atmospheric composition and pollutant deposition in the Barents Sea. This region, including the Norwegian coastal region is already affected by present-day shipping emissions enhancing pollutants such as ozone and aerosols (nitrate, sulphate, black carbon). Model simulations show significant local enhancements in ozone above background which could have impacts on human health. Significant predicted increases in total nitrogen (nitrate aerosols plus gaseous nitrogen species like nitric acid) are estimated along shipping routes resulting in large local increases in total (wet and dry) deposition of total nitrogen as shown in Figure 2.6. These results indicate that deposition of acidic nitrogen compounds from shipping to marine ecosystems could be significant. The main contribution is coming from shipping diverted from southerly routes into the Arctic.

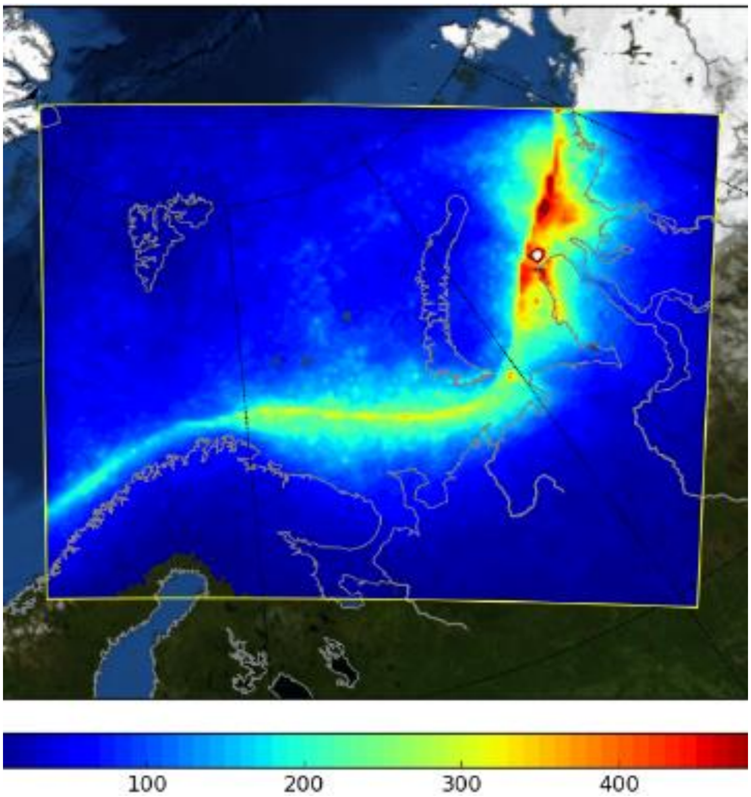


Figure 2.6: Simulated percentage increase in total nitrogen deposition in the Barents Sea in summer (July-August) due future shipping emissions in 2050 compared to the present-day (2012). The WRF-Chem model was run at 25km using present-day and future (high growth scenario) shipping emissions from Winther et al. (2014). The future scenario also included shipping diverted from southerly routes from Corbett et al. (2010).

Task 2.7 - Climate change effects on the Arctic marine ecosystem

Light is an important modulator of primary production in Arctic Seas due to seasonal changes in light conditions and ice coverage. Changes in ice conditions seems to have led to increased productivity over the last decade, but the magnitude of response varies from region to region. Previous studies using the coupled model system SINMOD indicate that different regions will have different response to climate change. To further assess sensitivity of simulated primary production to climate change, SINMOD have been run for several experiments with seasonal ice free AO, change in freshwater discharge, and with several RCP scenarios from two ESM models. Results show that productivity in general is very sensitive to changes in ice conditions, while changes in magnitude of river discharge have less impact. However, distribution of freshwater is important as strong stratification impacts vertical mixing of nutrients. Model results show that changes in sea ice conditions have limited effect on primary productivity in the region with the largest freshwater storage. Highest increase in production is projected for the shallower shelf seas; northern Barents Sea and along the Eurasian shelves. Nutrient availability for production depend on nutrient advection upwelling events, benthic-pelagic coupling and vertical mixing. SINMOD results also show that seasonality of production is very sensitive to change in ice condition and in particular to change in duration of the ice free period.

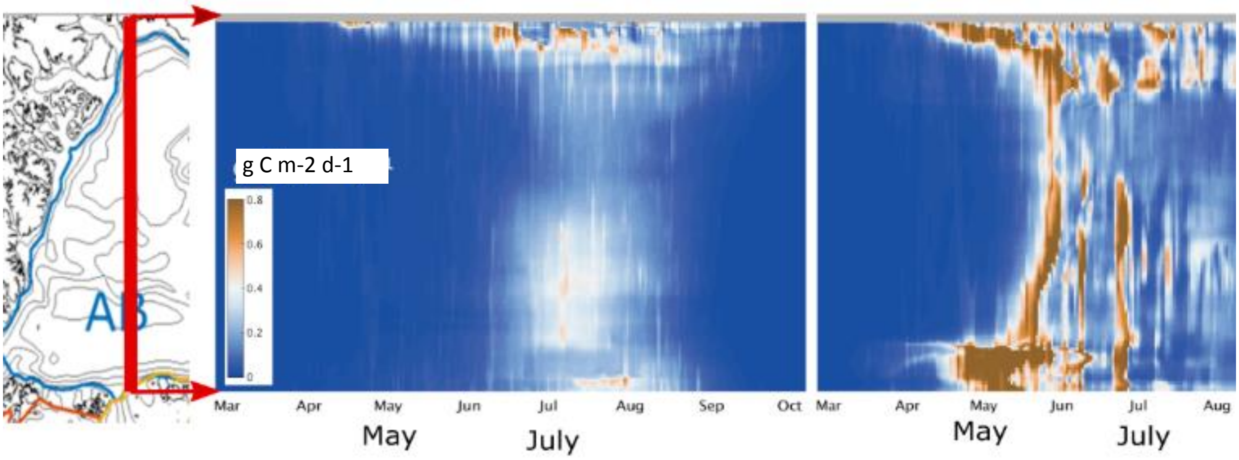


Figure 2.7 Temporal evolution of daily new production (g C m-2 d-1) over 1 year (2015) over a section (shown in red to the left) crossing the Arctic Basin for present day conditions and a future experiment with ice free summers in the AO.

Task 2.8 - Climate change impacts on Arctic and boreal terrestrial ecosystems

We investigated changes in Boreal and Arctic ecosystems with a combination of model simulations and Earth observations. We simulated the period 1980-2015 with the CLM4.5 model. Our simulations showed a positive trend in the Net Biome Productivity (NBP), and the magnitude of our simulated global trend is in agreement with the one derived from inverse modelling output. By conducting an attribution experiment to factorise the trend of Net Ecosystem Productivity (NEP), and therefore excluding stochastic disturbances from the analysis, we found that CO_2 fertilization is the dominant driver for productivity, whereas changes in climate are the dominant driver for changes in phenology. We identified positive trends of the integral Leaf Area Index (LAI) in two different satellite products, which were generally confirmed by our model simulations. We also simulated future trends of ecosystem productivity under the RCP2.6 scenario. Our findings show that in this scenario, although using relatively low atmospheric CO_2 concentrations, future changes in climate (higher temperatures in particular) can potentially become main drivers for productivity changes in periglacial, temperature-limited, ecosystems.

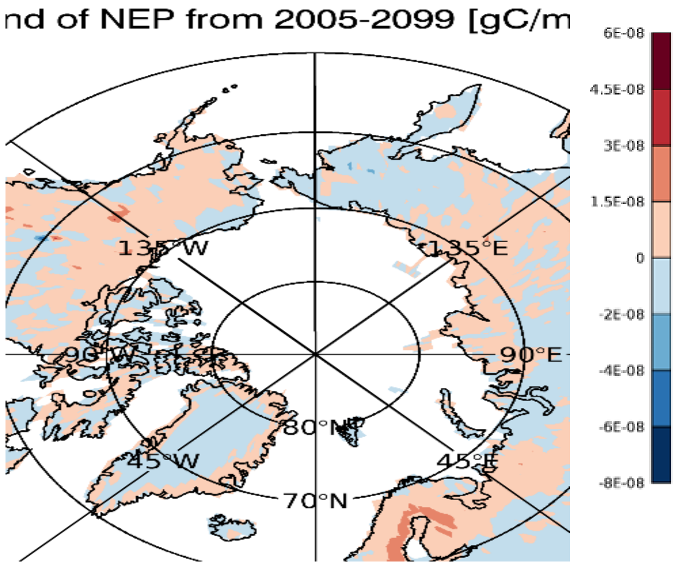


Figure 2.8: Trend of NEP for the simulated period under the RCP2.6 scenario. The periglacial ecosystems show a diffused weak positive trend in productivity, mainly and more uniformly over Alaska and Northern Canada. In Siberia, the trend is less.

Key highlights of WP3: Identifying socio-economic vulnerabilities within the Arctic region

Together with local communities, we examined the options for sustainable livelihoods; for example, future management of living resources (including the effectiveness of governance institutions and whether they can create additional opportunities to increase resilience, flexibility and the ability to deal with change), needs to proceed from a community-based perspective, incorporating local knowledge. We aim to return information and data to communities and are also contributing to building local research capacity through advising on the development of an educational programme at the school in Qaanaaq on changes in past and present climate and sea ice and the possible socio-economic impact of these changes.

As northern communities undergo social and economic transitions, households are changing and gender roles are transformed. This has implications for the generational transmission of knowledge. We are learning how women reflect upon these changes and how they participate in discussions about the future and the maintenance of sustainable livelihoods. Women's knowledge and experiences of sea ice, of hunting and fishing, of preparing the products of the hunt in the form of food or in the form of skins and furs for clothing give insight into changes in climate and weather. This broadens understanding of socio-economic contexts, how people have responded to such changes in the past, how they deal with changes experienced today, and how they anticipate the changes to come.

We have co-developed and executed a participatory ocean and sea-ice climate monitoring programme with local indigenous hunters. The programme builds on state-of-art scientific sensor- and platform technology for arctic monitoring, but is designed to be conducted using knowledge and support from the hunting community who are also trained to set-up, service and recover the systems.

During this work package we reconstructed seasonal sea ice and primary productivity dynamics spanning the past ca. 4,000 years in the region, using a multiproxy approach from ICE-ARC obtained sediment cores. We have identified periods of reduced sea-ice cover coeval with warming episodes during the Holocene, whereas neo-glacial cooling after ca. 2000 year BP resulted in unstable ice/ocean conditions, with a negative impact on the primary productivity of the North Water Polynya (Pikialasorsuaq). This information has been combined with detailed historical sea ice reconstruction of the past ca. 150 years in Inglefield Bredning (Kangerlussuaq). Local observations indicate that sea ice is of a different texture and consistency and tends to form later and break up earlier than many people have known it during their lifetimes. Hunters report that the period of travel by dog sledge on good, solid sea ice is now only around three months during winter and spring, with decent, but somewhat fluctuating conditions for another month or so. At the same time, the longer open water period in the region opens up new possibilities in terms of hunting from boats and kayaks. In some seasons the open water period near the fjord mouth may be almost doubled in length for hunters from Qaanaaq. Around Kullorsuaq, hunters have, in recent years, been hunting by boat during some periods when there is open water during winter and spring. Even if adapting to an ever-changing sea ice environment is inherent in Inuit culture, the implications are many. Climate change is rapidly altering the physical environment. This is leading to constant gradual changes in seasonal hunting practices and mobility, with social, economic and ultimately political consequences. Adaptive strategies include exploring new fishing grounds, seeking alternative sources of income, and greater reliance on boats, rather than dogsleds, during the increasingly ice-free water periods in winter.

Task 3.1 - Sea ice, resources and livelihoods in Northwest Greenland

Local observations and experiences indicate that sea ice in the Upernavik and Qaanaaq areas of Northwest Greenland tends to form later and break up earlier than many people have known it during their lifetimes. The ice edge near Qaanaaq, for instance, is a place of constant shifts and movement, uncertainty and increasing risk for travel, hunting and fishing in winter and spring. Local adaptive strategies include exploring new fishing grounds, seeking alternative sources of income, and increased reliance on boats during the increasingly ice-free water periods in winter. Climate change and shifting sea ice mean economic opportunities for Qaanaaq in the form of a new fishery for Greenland halibut, while at the same time having an impact on the traditional hunting culture. With a changing climate and economic transitions, households are changing and gender roles are transformed with implications for the generational transmission of knowledge. Our work contributes to understanding the nature of community vulnerability and resilience to climate change in Northwest Greenland. Our research provides insight into local experiences of how change affects local livelihoods and communities and how climate change and socio-economic change influences, shapes or hinders local adaptive capacities (as well as the ways communities are proactive in responding to change), as well as reducing or increasing vulnerability and resilience.

Figure 3.1: Matilde B. Kreiner (DMI) discussing the most recent developments in sea-ice conditions with the local community in Qaanaaq and highlighting the importance of the participatory monitoring program executed as part of ICE-ARC WP3. The two-way dialogue is important in order to co-develop the services with the community and to integrate traditional knowledge. December 19th 2017, Qaanaaq community house (photo by Steffen M. Olsen)

Task 3.2 - Community engagement

Within ICE-ARC, we have built a unique Arctic monitoring capacity and data record on the interplay between sea-ice and oceanographic conditions in NW Greenland. This has been achieved by engaging the local Inuit community in the design, planning, and completion of the programme, which has been ongoing throughout the project. The community in the town of Qaanaaq relies on the ability to travel and hunt on the winter sea-ice and people there have a strong interest in the observations; for their daily planning of hunting trips and journeys on the ice, and for understanding the nature and implications of the climate changes they are witnessing in their surroundings. Experiences from this engagement of the community have been valuable in order to reach an integrated understanding across social, natural, and anthropological sciences of sea-ice, resources, and livelihoods in Northwest Greenland. Through this collaboration, scientists have also obtained easy and safe access to high arctic marine environments, which has accelerated the development of new novel systems for arctic monitoring applications including proving them fit-for-purpose as components in future community-based climate observatories or participatory monitoring programmes.

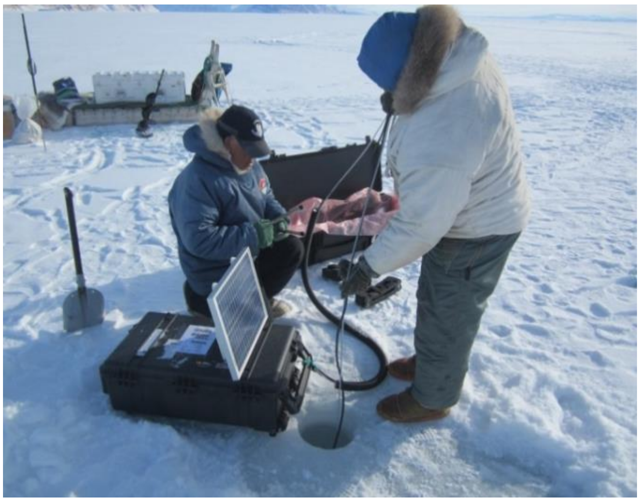


Figure 3.2: Local hunters Ramus Avike (right) and Lars Jeremiassen (left) from the Qaanaaq region engaged in installing components of the ocean and sea-ice monitoring program (Photo by Steffen M. Olsen).

Task 3 - Past transitions and responses: 4500 years of human migration and sustainability in NW Greenland

Seasonal sea ice and primary productivity dynamics spanning the past ca. 4,500 years has been reconstructed in the North Water region applying state-of-the-art paleoceanographic tools to a unique high-resolution sediment core collected from a carefully selected site to represent the NOW mid-to late Holocene development a multiproxy approach to marine sediment cores. Periods of reduced sea-ice cover have been identified to be coeval with warming episodes during the Holocene, whereas neoglacial cooling after ca. 2000 year BP resulted in unstable ocean conditions, with a negative impact on the primary productivity of the North Water Polynya.

Figure 3.3: John Boserup, GEUS, is discussing results from the marine geological investigations in the Inglefield Bredning with the local hunter Toku Oshima, Qaanaaq

By analysing a series of sediment core-top samples collected in the Inglefield Bredning-NOW region in terms of their organic matter composition, biomarker and microfossil contents, we have generated a new modern dataset that provides a baseline for reconstructing past climate and environmental changes in the region. A transect of sediment core records from the Inglefield Bredning was analysed together with historical and satellite data, to reconstruct sea ice extent in the fjord during the past 150 years.

Key highlights of WP4: Modelling socio-economic vulnerabilities and assessing management options arising from Arctic marine

To assess the global cost of Arctic change, we combined ICE-ARC results along with the latest sea ice and permafrost simulations from state-of-the-art climate models with current environmental and socio-economic information to produce a more accurate integrated assessment model (IAM) for estimating the cost of climate change: PAGE-ICE.

Arctic feedbacks associated with the decline in sea ice and land permafrost will accelerate climate change and could jeopardise mitigation efforts. Running PAGE-ICE under a wide range of climate scenarios, including those from the Paris Agreement, revealed how these feedbacks are going to affect the global climate and economy over the next 300 years.

The cost of net additional warming from the Arctic feedbacks is significant. The effect is the greatest if we carry on as usual, amounting to around $130 trillion in extra losses globally over the next three centuries, but is reduced over ten times to under $10 trillion if we achieve the Paris Agreement target of 1.5°C. Following current intended national pledges (INDCs) will lead to extra $90 trillion worth of losses from the Arctic feedbacks. If the ambitious climate target of 1.5°C and 2°C are to be met, adequate financing is needed, for example a carbon tax that covers the additional cost associated with Arctic change, which has been calculated by PAGE-ICE. Under the INDCs scenario, for example, the estimated optimal carbon tax raises from around $175 to $200 per ton of CO_2 due to the two Arctic feedbacks.

We also developed a specialised tool for predicting trade volumes along the Northern Sea Route (NSR) and estimating the resulting economic gains and changes in emissions. The net climate feedback associated with the NSR has been translated into additional economic losses globally using a specialised version of PAGE-ICE.

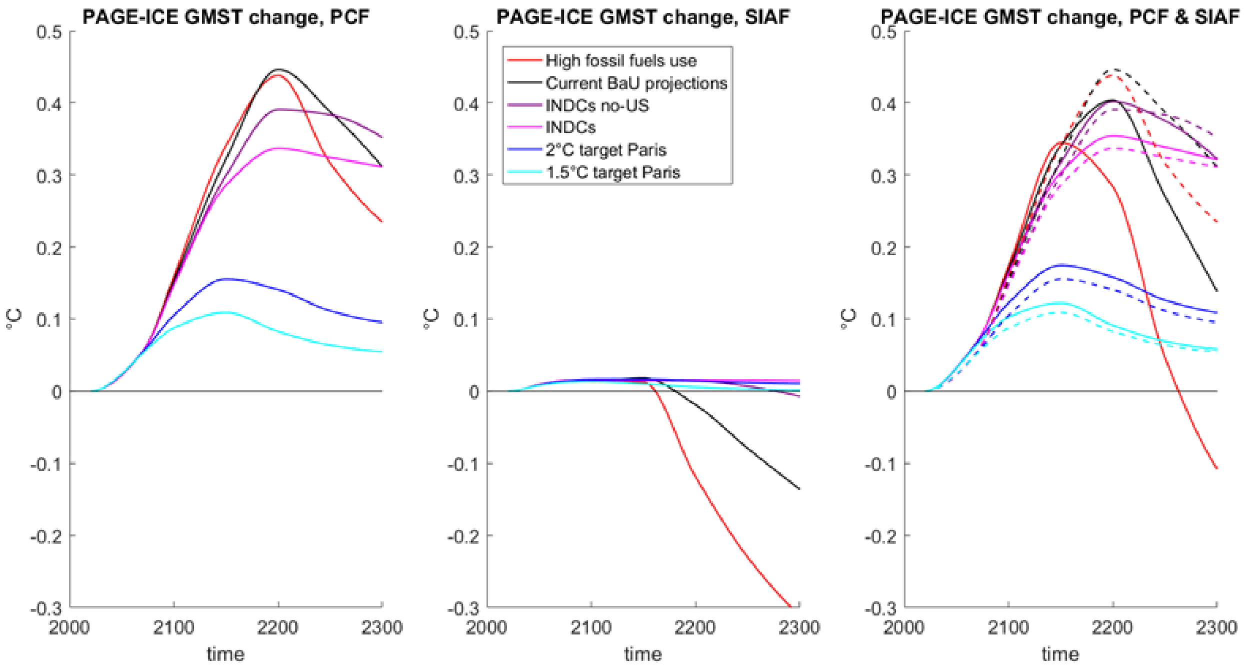
The losses could offset up to a third of the gains in Europe and East Asia from the enhanced trade via the NSR, and will be incurred mostly by the poorer regions such as India and Africa.

In addition, we used simulations from climate models and crop models to investigate correlations between the climate-driven loss of Arctic sea ice and an increase in global food security risk. The possible future worlds with mean annual sea ice cover reduced by 30% and 70% relative to historic observations will be characterised by climatic conditions detrimental to crop yields in most world regions.

Task 4.1 - Development of PAGE-ICE to include a better physical representation of the Arctic region

This task focused on developing the flagship version of PAGE-ICE IAM, which includes nonlinear dynamic emulators of the permafrost carbon feedback (PCF) and sea ice albedo feedback (SIAF), along with a number of updates to the science and economics in line with the latest literature. The emulators are simple statistical representations of output from much more complicated physical models.

The PAGE-ICE model represents a major advance in probabilistic simulations of the nonlinear PCF and SIAF dynamically in an IAM consistent with results from state-of-the-art climate and biosphere models. It accounts for multiple nonlinear transitions in the intensity of the two feedbacks that have not been explored in the literature. PAGE-ICE allows one to perform fully-coupled runs of both feedbacks combined, where PCF emissions influence the SIAF and *vice versa*, and also allows one to quantify the effect of CO_2 ocean uptake on the PCF strength. The Figure below illustrates the projected changes in the global mean surface temperature (GMST) over the next three centuries separately from the PCF and SIAF, and from the PCF & SIAF combined.



We also modelled the dynamics of sub-sea permafrost and methane hydrates on East Siberian Arctic Shelf (ESAS) throughout Holocene. The model allows one to track the shifts in the boundaries of methane hydrate stability and permafrost permeability to gaseous methane inside the sediments column. These shifts are responsible for methane emissions and are dependent on several location-specific parameters such as geothermal heat flux and time of inundation following the end of the last glacial minimum. Introducing probabilistic modelling of these parameters and performing Monte-Carlo simulations provided a representation of most areas of the shelf, which made it possible to identify hotspots for methane emissions and estimate methane fluxes for the entire shelf throughout Holocene.

Task 4.2 - Determining Impact Sector Inputs

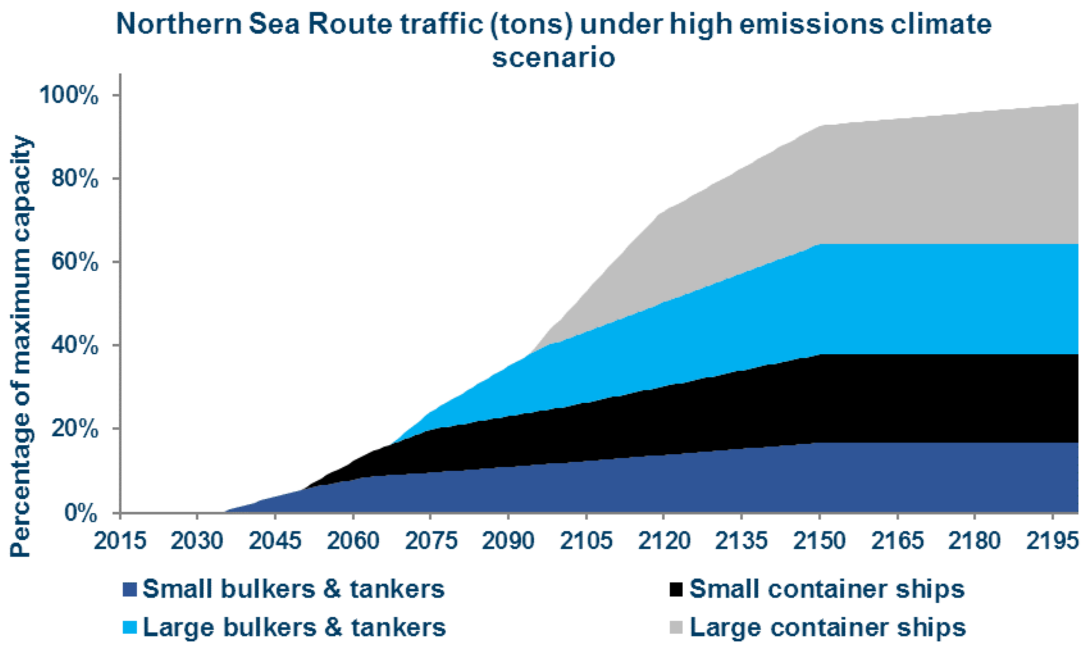
Industry sector vulnerabilities, risks, and opportunities have been explored in three case studies:

(i) Arctic shipping,

(ii) global agriculture and

(iii) Alaskan economy.

The case study on Arctic shipping provided detailed projections for the possible future growth of commercial shipping along the NSR under sea ice projections from the 5th IPCC report, coupled with the global economic drivers and business restrictions for shipping operators from the latest literature. Large-scale commercial shipping through NSR is unlikely going to be possible until mid-2030s for bulk carriers and around 2050 for container ships of small to medium size. The NSR use projections under the high fossil fuels use scenario (RCP8.5) are illustrated in the Figure below. The growth in NSR shipping results in large scale re-routing of emissions short-lived aerosols to the Arctic, including black carbon, which causes additional climatic and economic impacts globally (Task 4.3).

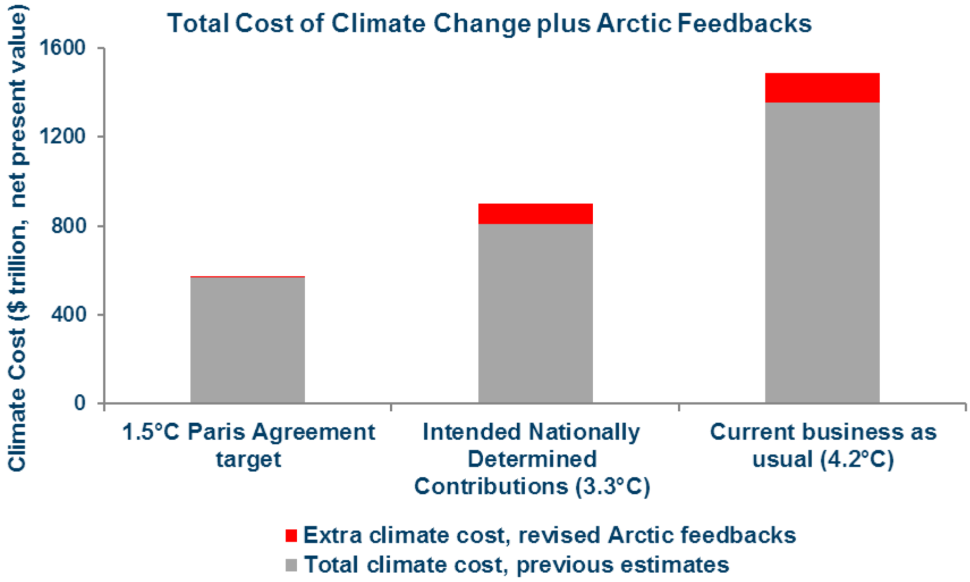


To estimate the correlations between the loss of Arctic sea ice and changes in wheat and maize yields globally, we adapted a specialised model for the crop yields to wheat and maize growing areas in six major producing countries on five different continents. In order to evaluate the impacts of the changing climatic conditions on gross primary production (GPP) that are correlated with the sea ice melt in the Arctic, a number of parameters such maximum and minimum surface temperature, precipitation, vapour pressure deficit and surface solar radiation, were derived from the CMIP5 database.

Along with the case studies on Arctic shipping and global agriculture we have been working on modelling economic consequences of climate change to a substantial Arctic economy. Given the assess to the appropriate datasets, the extent and the pace of climate change in the Arctic region, a complete lack of interlinked studies of Arctic economies, as well as the current push back on climate policies at the US's federal level, the Alaska case study is very timely. The motivation behind these efforts was to come up with a robust and statistically sound technique that would allow one to calibrate impact functions for each sector of the Alaskan economy for which the individual impact studies exist. Having such functions would make it possible to run multiple Monte-Carlo simulations for the Alaskan economy to explore a likely range of its vulnerabilities to changing climate under contrasting RCP-SSP scenario pairs.

Task 4.3 - Determining Impact Sector Impacts & Assessing Policy Options

When the permafrost and sea ice climate feedbacks are combined, the total influence is always that of warming. The resulting economic losses are as high as $130tr over the next three centuries under the current business as usual scenario, while the biggest relative increase in the losses due to the two feedbacks amounts to 12% and is set to occur under the scenario consistent with the US's withdrawal from the Paris Agreement. The poorer regions such as India and Africa, which are less likely to benefit from the economic opportunities associated with a warmer Arctic, are set to bear a higher share of these additional Arctic-driven costs. Meeting the 2°C and 1.5°C targets will reduce the global impacts of the Arctic feedbacks, respectively, to $14 and $8 trillion. The results are summarised in the Figure below.



In addition to the complex climate effects of emissions of short-lived aerosols and CO_2 directly from the re-routing of cargo shipping through the NSR, the additional economic growth in multiple countries enabled by the NSR is set to increase their CO_2 and non-CO_2 emissions. Our results suggest that the net climate effect of the NSR is that of warming. This feedback could add up to $2 trillion to the expected total negative impacts of climate change globally over the next two centuries under the high fossil fuels use scenario (RCP8.5) characterised by complete disappearance of Arctic sea ice by the middle of the next century. These climatic costs are going to offset around a third of the expected global gross economic gains associated with the NSR over the same period. The gains will mostly occur in Northern Europe and East Asia, and these regions will likely face relatively small climate losses from the additional emissions. The negative economic impacts of the emissions from NSR shipping, on the other hand, are expected to follow the commonly accepted scenario for climate-induced losses, with poorer regions such as Africa and India set to bear as much as two thirds of the global costs.

Global mean surface temperature (GMST) strongly correlates both with Arctic sea ice loss and the climatic conditions experienced in maize and wheat growing regions. This means that future yields for maize and wheat in the six countries considered are correlated with the decline in Arctic sea ice extent, supporting the idea that the Arctic ice can act as barometer of crop yield risks due to climate change. Out of all the crop and country combinations, only maize yields in India and wheat yields in China and France are set to grow due to climate change, while all other yields decline. The bigger the loss in the mean annual sea ice cover relative to the observation period between 1980 and 2008, the bigger the corresponding declines in the crop yields in most regions are projected to be.

Key highlights of WP5: Dissemination of results: An impact strategy for developing policy and management options

Industry, academia, policy makers, and society must understand the impact of change in the Arctic marine environment in greater detail. Especially if they are to appreciate and more accurately understand how the Arctic system functions, and how it is associated with global weather systems, global marine resources, and global trade. A changing Arctic has socio-economical, environmental, and geopolitical consequences for the region, Europe and the rest of the world. Understanding Arctic change and its socio-economic impact are priorities for us all.

Given the importance of the Arctic system disseminating knowledge of Arctic change has been prioritised by ICE-ARC. Within WP5 we enhanced our current capabilities in communication by building trust between the diverse range of Arctic stakeholders. The co-production and exchange of knowledge, involving collaborative exchanges with local communities, industry, policy makers and the general public, were of the up most importance to ICE-ARC. It is from this inclusive approach more effective policy and management options for societal responses to Arctic change can be developed, along with improved EU and international policies aimed at protecting the marine environment and safeguarding it as a living resource for human communities. In the next section, entitled '*The Potential Impact*', we describe in more detail the outcome and highlight of this approach.

The potential impact

Introduction

The ICE-ARC programme sits under the European Commission's Framework 7 programme, and was supported under Theme 6 Environment (including Climate Change). The objective of this Theme is *'the sustainable management of the environment and its resources through advancing our knowledge of the interactions between the climate, biosphere, ecosystems and human activities, and developing new technologies, tools and services, in order to address in an integrated way global environmental issues.'*

It forms part of Challenge 6.1 Coping with climate change through ENV.2013.6.1-1 *Climate-related ocean processes and combined impacts of multiple stressors on the marine environment*. This topic not only contributes to this strategic agenda of the *Oceans of the future*, but it was explicitly stated that it would benefit from the inclusion of participants from socio-economic science disciplines. The Expected Impacts of topic ENV.2013.6.1-1 were two-fold:

(i) Improved climate predictions and more accurate quantification of climate change impacts on oceans, marine ecosystems and services through the reduction of uncertainties.
(ii) Improved EU and international policies aimed at protecting the marine environment and safeguarding it as a living resource for human communities, and more effective policy and management options for societal responses to climate change.

Like the objectives of the ICE-ARC programme the Expected Impacts of ENV.2013.6.1-1 cut across disciplines and sectors. Consequently ICE-ARC's Communication strategy had to go beyond the traditional impact with the science community, which we generally do best at. Our strategy was designed to have a broad potential impact with local communities, industry, policy makers and the general public. Below we expand on the impact of the knowledge gained within ICE-ARC to this broad range of stakeholder groups.

Scientific Community

At the time of writing, ICE-ARC members have published their results in leading scientific journals such as Nature, Geophysical Research Letters and Ocean Sciences, with over 40 manuscripts currently either about to be submitted to a journal or already in the peer-review process. ICE-ARC members have given over 100 oral presentations, and about two dozen posters presentations at recognised scientific conferences such as Arctic Circle, Arctic Science Summit Week (ASSW), American Geophysical Union (AGU) meetings, European Geosciences Union (EGU) and the European Marine Board Forum.

Within European scientific community ICE-ARC developed a close and deep relationship with EU-PolarNet as well as the Arctic Cluster programmes. We presented our findings to the European Climate Research Alliance, and were proactively involved in EU initiatives such as the tri-nation EU-US-Canada meetings, and a number of Arctic-focused workshops and events in Brussels.

Indigenous and local Communities

ICE-ARC worked across the social sciences and the natural and physical sciences to develop a community-based research programme with residents of north Greenlandic communities. We were tasked with understanding the nature, effects and impacts of current and future changes in Arctic sea ice and the broader environment in Northwest Greenland – both from changing atmospheric and oceanic conditions – and the social and economic consequences of these changes. The collaborative and participatory nature of our research makes it unique within the overall ICE-ARC project in terms of integrating scientific knowledge and local knowledge, as well as for its relevance for communities in Northwest Greenland.

This has involved ICE-ARC scientists not just working in communities, but with them, and by providing opportunities for local people to become research partners, building capacity for communities to engage in research. And with our local research partners we developed our research questions, defined our research tasks of importance to communities, and worked to co-produce knowledge. We travelled with hunters on the sea ice and on the open water and across the land, worked with local people to map the social, cultural and economic importance of ice and living resources, and discussed concerns and hopes for the future of northern livelihoods.

One example of this collaborative process has been the work we have done in co-developing and implementing a participatory ocean and sea-ice climate monitoring programme with local hunters. This programme builds on state-of-art scientific sensor- and platform technology for arctic monitoring, but is designed to be conducted using knowledge and support from the hunting community who are also trained to set-up, service and recover the systems.

In Qaanaaq, we have established local partnerships and local networks that allow us to communicate efficiently the operational information on sea-ice conditions from the DMI Ice Service to the community and also, importantly, to adapt and time our information continuously to fit community needs and to engage in a dialogue on climate change and its impacts and effects. A key outcome of this dialogue is an increased focus on delivering interpreted satellite information in particular during the early winter period where the polar night combined with dynamic sea-ice conditions is challenging for start-up and safety of the Greenland halibut long line fishing activities on the winter ice which has become an important economic activity in the community in recent years. We are also contributing to building local research capacity through advising on the development of an educational programme at the school in Qaanaaq on changes in past and present climate and sea ice and the possible socio-economic impact of these changes.

Our methods are a contribution to new ways of doing research in Greenland and to developing community-based research and monitoring programmes. We have sought to disseminate our results to community and government levels in the country on the nature of community vulnerability and resilience to climate change in Northwest Greenland. Our research provides insight into local experiences of how change affects local livelihoods and communities and how climate change and socio-economic change influences, shapes or hinders local adaptive capacities (as well as the ways communities are proactive in responding to change), as well as reducing or increasing vulnerability and resilience.

Industry

Engagements between ICE-ARC and the industry sector were primarily through the World Economic Forum (see Policy section), as well as a series of dedicated roundtable discussion sessions. The events included:

Roundtable #1: **"Towards a balanced view of Arctic shipping"** organised by Lancaster University, and hosted by Ecorys in Brussels, was held on 15th September 2016. The roundtable brought together policy officers from the European Commission, representatives of the governments of Greenland, Netherlands and Finland, NGOs, representatives from the shipping industry, private maritime consultants, climate scientists and economists. There were a total number of 26 participants, including speakers and panellists, plus 7 virtual attendees via WebEx. Following opening presentations by WP4 researchers on possible futures of transit shipping through the Northern Sea Route (NSR) in the Arctic, and presentations from WP2, the panel-led discussion focused on policy measures to facilitate clean shipping in the Arctic.

Roundtable #2: breakout session **"The future of Arctic shipping under IPCC climate scenarios"** at the Arctic Circle Annual Assembly in October 2016. The session was organised jointly by ICE-ARC & EU-PolarNet, and featured presentations by several leading ICE-ARC researchers. The presentations covered the main themes from the WP4 paper "Towards a balanced view of Arctic shipping: estimating economic impacts of emissions from increased traffic on the Northern Sea Route", subsequently published in Climatic Change in June 2017. The breakout session attracted an audience of around 100 delegates, which was among the highest for breakout sessions at the Arctic Circle Assembly 2016, and facilitated a wide-ranging debate on multiple aspects surrounding the future of Arctic shipping.

Roundtable #3: **"Global risks and opportunities arising from Arctic change"** at the Arctic Circle Annual Assembly in October 2017, hosted in one of the officially allocated and promoted time slots for roundtable discussions at the Arctic Circle. The roundtable event was organised by Lancaster University. Its main aim was to increase global awareness of Arctic issues, and built on the latest expert knowledge from WP4 as well as from independent academic and industry experts to propose better solutions. The event was attended by approximately 30 delegates from different backgrounds, including NGOs, policymakers and scientists, and involved a panel-led open discussion with the audience.

Roundtable #4: This roundtable was not part of the original Description of Work for ICE-ARC but was added in 2017. We were able to take advantage of **"Sea-Ice Structure Interaction"** workshop at the Aurora Cambridge innovation centre (#AuroraCambridge) at the British Antarctic Survey, to run a fourth roundtable event that encompassed a broad range of stakeholders. The event was held in November 2017, and was organised in collaboration with the Turing Gateway to Mathematics. It brought together industry and academia from a broad range of sectors, including insurance, shipping, and engineering. This knowledge exchange event formed part of the Isaac Newton Institute Research Programme on the Mathematics of Sea Ice Phenomena. The day of talks and discussions on topics relevant to sea ice interaction with structures, such as ships and fixed platforms. The talks were from a broad range of experts, with the culmination of the day being a roundtable on 'Highlighting the Challenges and potential solutions for present and future operations in the Arctic marine environment'. The objective being open and free-flowing discussions, moderated Dmitry Yumashev, between all participants and the audience. Particular topics to be covered include overview of sea ice changes in Arctic and Antarctic, advances in technology for ice mechanics, remote sensing for ship routing, and ice forces on ship and structures.

Policy Makers

ICE-ARC have engaged with policy makers through several different fora, such as the World Economic Forum (WEF), the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties (COP), the Arctic Circle, White House Ministerial on the Arctic, interactions with the Greenlandic government, and more. Some highlights are included below:

Arctic Circle

In October 2016, Gail Whiteman (WP5 co-lead, WP 4 Lead) gave a keynote presentation to the fourth assembly of the Arctic Circle – the largest network of dialogue and cooperation on the future of the Arctic. The keynote presentation, entitled 'The Arctic as a Barometer of Global Risk' and delivered to an audience of around a 1000 people , opened a plenary session organised by the European Climate Foundation, with fellow ICE-ARC scientist Dmitry Yumashev also on the panel. The keynote described how Arctic change does not stay in the Arctic – there are global impacts. Drawing the analogy of how leaders and businesses all over the world use stock market indices to assess economic health, change trends and the associated risks, Professor Whiteman argued that the Arctic is also a true barometer of global risk through indicators such as summer sea-ice melt. Further high-level statements made during the keynote presentation illustrated how Arctic change accelerates global climate change cost.

In addition, CNRS (Kathy Law), BAS (Jeremy Wilkinson), and AWI (Katrin Riemann-Campe) presented at a session co-organised with EU-PolarNet on effects of Arctic change on shipping.

Figure: ICE-ARC partners Gail Whiteman (Panel Chair) and Dmitry Yumashev participate in a discussion at Arctic Circle in 2016 on The Arctic as a Barometer of Global Risk.

In October 2017, ICE-ARC, in collaboration with EU-PolarNet, convened a side session at Arctic Circle, entitled "Climate change, science, and safeguarding the Arctic environment". In their policy for the Arctic, the European Commission and High Representative declare that the European Union has a duty to protect the Arctic environment, strengthen ecosystem resilience, and promote sustainable development. This statement puts an obligation on the EU to work in partnership with Arctic countries, and to recognise the livelihoods, needs, interests, and rights of the indigenous peoples and local communities within it. Furthermore, EU funded science, like the ICE-ARC programme, has a central role to play in understanding Arctic change and safeguarding the Arctic environment. This session explained how we can utilise science diplomacy to smooth a particularly tricky political situation, and importantly how scientific knowledge can provide a conduit to ensure local communities, politicians and policy-makers, as well as industry leaders and the public, have the most up-to-date and robust information available. Easy access of this type of knowledge is exactly what is needed for effective decision making on sustainable development.

Within this session, experts provided a short overview of three climate change induced challenges for the Arctic environment. Additionally, we heard from six experts on their views on the responsibility of the space agencies to address these challenges, as well as the importance of the co-production of knowledge with local communities to ensure sustainable development within the Arctic and beyond. These six experts gave brief introductions to these topics and subsequently opened the floor for an interactive discussion focused around the following question: How can the complex scientific issues associated with Arctic change, with all its implications, be summarised to better inform policy makers and facilitate sustainable development of the Arctic. The session was moderated by Jeremy Wilkinson, ICE-ARC coordinator.

World Economic Forum

Central to the success and impact of ICE-ARC is broadening stakeholder knowledge of Arctic change (and its potential impacts), and positively influencing policy at the highest level. Building on the statements made at the Arctic Circle plenary in Autumn 2016, ICE-ARC research took centre stage at a very high-level science summit (Arctic Basecamp) convened in Davos during the World Economic Forum's (WEF) annual meeting in January 2017. Established in 1971, the forum engages the foremost political, business and other leaders of society to shape global, regional, and industrial development agendas.

Not just a science meeting, the ICE-ARC project literally took a physical symbol of Arctic science to the WEF 2017 gathering in Davos, and an Arctic Basecamp was constructed as a small exhibition and media centre-piece. The venue was co-organised and held at the Swiss Institute for Snow and Avalanche Research, also located in Davos.

From left: Gail Whiteman (Lancaster University; organiser) with keynote speaker Al Gore (former US Vice President) and co-organisers Koni Steffen (WSL) and Jeremy Wilkinson (British Antarctic Survey).

Joined by 80 business and civil society leaders, politicians, scientists and policy makers, the summit shared cutting-edge scientific knowledge and rousing keynotes from former US Vice President, Al Gore; former Executive Secretary of the United Nations Framework Convention on Climate Change (UNFCCC), Christiana Figueres; President/CEO of the World Business Council for Sustainable Development, Peter Bakker; and the former Finnish Prime Minister, Paavo Lipponen, amongst other dignitaries. A mixture of panel discussions, research presentations and speeches, the event showcased the latest Arctic science and was unequivocal in its call for action from global leaders and shapers to address the significant global risks posed by Arctic change – in line with the Paris Agreement.

The event had very successful media coverage and was live-streamed across the world - watched by nearly 5,000 people globally. It was covered by the BBC World Service and Reuters TV, and featured on 100 TV news outlets worldwide including US, UK, Germany, France, Spain, Italy and Switzerland. Christiana Figueres was interviewed at the Basecamp by the BBC featuring on the News at Six and the News at Ten. In addition, the Arctic Basecamp had strong print, radio and online coverage via the The Guardian, BBC Business Online, the World Economic Forum's Agenda, as well as German broadcaster Deutsche Welle and Swiss newspaper Südostschweiz.

The hashtag #ArcticMatters reached nearly 10 million people via social media and even engaged celebrities such as Jack Black. The Facebook live interview with BBC World Service had over 170,000 views. As a key part of the summary of this event, ICE-ARC has produced a 7-minute highlights film, which is available alongside this report. https://vimeo.com/220476586

Our Arctic Basecamp in Davos featured in the Nature Comment article as an example of best practice in using science to guide decisions and set targets. The article, co-signed by over sixty influential leaders, emerged after Christiana Figueres was the keynote at the Arctic Basecamp at Davos. https://www.nature.com/news/three-years-to-safeguard-our-climate-1.22201

Greenland

In February 2017, Mark Nuttall (WP3 Lead) presented the ICE-ARC project and the activities of WP3 to the Greenland Research Council in Nuuk. The Greenland Research Council comes under the Government of Greenland's Ministry of Education, Culture and Research. He was invited to brief the council on the methodologies used in WP3's community-based approach to research with communities in the Upernavik and Qaanaaq areas of Northwest Greenland. The presentation highlighted key research findings, and focused on effective and long-term monitoring and its contribution to policy-making. This was explored further in a presentation of WP3 to a conference in Ilulissat organised by the Government of Greenland's Greenland Reconciliation Commission in April 2017, where we reported on our contributions to the development of community-based methodologies for Greenland, to the development of interdisciplinary research on climate change, and understanding the changing sea ice in partnership with communities.

ICE-ARC researchers played a key role in the orgainastion and participation in the Greenlandic conference entitled *Ilulissat Climate Days*, a major Climate and Society-related conference in June 2015. The conference attracted more than 180 participants, including a large number of politicians and stakeholders from especially Greenland, but also several Nordic countries. A number of journalists/media people from Greenland, Denmark, Norway, Germany, and the US also took part in the meeting. A special ICE-ARC session on "Climate and Society" was prepared and convened by Mark Nutall and Lene Kielsen Holm from the Greenland Climate Research Centre, and Naja Mikkelsen from GEUS, Denmark. Jeremy Wilkinson, Jean Claude Gascard, Jimena Alvarez and Mark Nuttall also gave presentations on the ICE-ARC project during the conference, and Mark Nuttall, and Lene Kielsen Holm ran a discussion session on social effects of climate change, with participation from Toku Oshima from Qaanaaq and members of the Greenland government.

White House Ministerial

Science Ministers, or their representatives, from 25 governments, the European Union, and representatives from Arctic Indigenous peoples' organisations gathered at the White House (USA), on September 28, 2016, to discuss Arctic research priorities. The outcome of the first-ever A*rctic Science Ministerial* was the signing of a Joint Statement on increased international collaboration on Arctic science and inclusion of Indigenous peoples in understanding and responding to changes in the Arctic. At this eminent gathering of dignitaries ICE-ARC was highlighted as one of the Major Arctic Research Initiatives of the EU. ICE-ARC statements can be found on page 73 and 76 of the summary document. See *United States Arctic Research Commission and Arctic Executive Steering Committee, eds. 2016. Supporting Arctic Science: A Summary of the White House Arctic Science Ministerial Meeting, September 28, 2016, Washington, DC. United States Arctic Research Commission, Arlington, VA, 78 pp*

UNFCCC COP

ICE-ARC, in collaboration with EU-PolarNet, the European Polar Board, and the German Development Agency co-organised a series of Arctic-oriented events at three consecutive COP meetings. The aim being to provide high-level decision-makers with a holistic overview of Arctic change and its multi-sector impacts. A summary the COP events are as follows:

COP21, Paris: Saturday 10th December 2015. Held in the EU Pavilion and hosted by ICE-ARC, EU-PolarNet and the European Polar Board. #ArcticCOP21

- This 90-minute briefing session was designed to provide high-level decision-makers and other interested parties with a holistic overview of Arctic change and its multi-sector impacts (climatic, societal, and economic) at local, regional and global levels.
- **Keynote presentations** were delivered by five leaders in their field on the multi-sector impacts of Arctic change. An open discussion gave audience members the opportunity to directly question high-level speakers working at the forefront of Arctic change issues. Speakers included: Peter Horvath (Directorate General for Research and Innovation, European Commission), Sir David King (Special Representative for Climate Change, Foreign and Commonwealth), Jean-Claude Gascard (ICE-ARC and Senior Scientist for the French Centre National de la Recherche Scientifique), Anthony Hobley, (Chief Executive The CarbonTracker), Sheila Watt-Cloutier (Former Chair of the Inuit Circumpolar Council) and Thorben Hoffmeister (Bundeswehr Geoinformation Center, Germany)

COP22, Marrakech: Friday 18th November 2016. Held in EU Pavilion and hosted by ICE-ARC, EU-PolarNet and the European Polar Board. #ArcticCOP22.

- The programme was introduced, chaired and discussion moderated by Maunel Pulgar-Vidal (Head of WWF's Climate and

Energy Practice, President of COP20 in Lima, former Peruvian Environment Minister).

- An opening statement on the importance of the Arctic and research into climate change was given by Andrea Tilche, (Head of Unit Climate Action and Earth Observation, Directorate General for Research and Innovation, European Commission).
- Presentations were given by ICE-ARC members Jeremy Wilkinson (Climate change in the Arctic), Dmitry Yumashev (Global economic risk and the Arctic), and Lene Kielsen Holm (Societal impacts of Arctic change – the indigenous perspective from Greenland).
- In addition, Petteri Taalas Secretary-general of the World Meteorological Organization also presented on connections between the Arctic and the rest of the world.

COP23, Bonn (hosted by Fiji): The COP23 of the UNFCCC was hosted by Fiji, but held in Bonn, Germany, 6th-17th November 2017. ICE-ARC co-organised three separate events (1) held in Fiji Pavilion, (2) at the GIZ headquarters (the German Development Agency) and (3) in the EU Pavilion. The first two events were hosted by ICE-ARC, EU-PolarNet and GIZ. The third event was hosted by the EU Arctic Cluster of which ICE-ARC is a founding Partner. #ArcticCOP23.

With a Small Island Developing State (SIDS), Fiji, hosting COP23, we felt this was an ideal opportunity to highlight the links between Arctic change, and these low-lying equatorial states. Links are through melting ice sheets and sea-level rise, but also, importantly to ICE-ARC, through people – there are many similarities and lessons to be learnt from the impacts of climate change on the people of north-west Greenland (our focus on ICE-ARC) and the SIDS inhabitants. The three events that ICE-ARC was involved in at the COP23 event were:

Event 1: Fiji Pavillion, COP23

- Very High-level panel event in the Fiji Pavilion of the Bonn Zone (accreditation to COP needed) –10th November. In collaboration with GIZ (the German Development Agency), EU-PolarNet, and AWI (Alfred Wegener Institute, the coordinators of EU-PolarNet). Speakers included: COP23 Climate champion Hon. Inia Seruiratu (Minister for Agriculture, Rural & Maritime Development, and National Disaster Management), Aqqaluk Lynge (Greenlandic author, former President of the Inuit Circumpolar Council, former Member of the United Nations Permanent Forum on Indigenous Issues), Deon E. Terblanche (Director of the Atmospheric Research and Environment WMO), Angelika Humbert (senior scientist AWI), Ulric Trotz (Caribbean Community Climate Change Centre), Manuel Pulgar-Vidal (Head of WWF's Climate and Energy Practice, President of COP20 in Lima, former Peruvian Environment Minister)

Event 2: GIZ headquarters

- In-depth briefing (half-day event) and discussion on the links from the Arctic to SIDS – hosted by GIZ – accreditation to COP not required. 11th November. Speakers included HE Anote Tong (former President of Kiribati, member of the Global Climate Action Leaders Network), Aqqaluk Lynge (Greenlandic author, former President of the Inuit Circumpolar Council, former Member of the United Nations Permanent Forum on Indigenous Issues), David Vaughan (British Antarctic Survey, Director of Science), Angelika Humbert (senior scientist AWI), Ulric Trotz (Caribbean Community Climate Change Centre), Manuel Pulgar-Vidal (Head of WWF's Climate and Energy Practice, President of COP20 in Lima, former Peruvian Environment Minister), Dmitry Yumashev (Lancaster University), Christoph Bals (Germanwatch) and Ricarda Winkelman (Potsdam Institute for Climate Impact Research).

Event 3: EU Pavilion, COP23

- EU Arctic Cluster event on Polar insights for climate action: Arctic science contributions to implementing the Paris Agreement. In the EU Pavilion in the Bonn Zone on 15th November. Speakers included: Jonathan Bamber (European Geosciences Union), Andrea Tilche (European Commission), Dirk Notz (MPI Hamburg), Jeremy Wilkinson (British Antarctic Survey), Sebastian

H. Mernild (Nansen Environmental & Remote Sensing Center), Margareta Johannsson (Lund University).

General Public and wider European Society

The ICE-ARC website, www.ice-arc.eu was set up for the start of the project. It contains descriptions of the various areas of the project, the goals, aims, and objectives, the personnel involved, and news items such as field campaigns and results. It is a portal for dissemination, collaboration, and data access. Links to the live data feeds from some of the ICE-ARC buoys are provided through these pages, or where we are working in collaboration with other systems, links to these sites are given to avoid having duplicated efforts. A link to other data sets is also available. News items are distributed on the project's social networking sites - Twitter (@ICEARCEU) and Facebookwww.facebook.com/IceClimateEconomics , in addition to other events of interest. The Twitter account, @ICEARCEU, has 1142 followers to date.

In addition to school talks, talks at science festivals, and media interviews we were able to facilitate the dissemination of the Arctic science to a significant section of the general public and European society through and our highly popular science blogs that were published by the World Economic Forum's online Agenda *(not peer reviewed). W*e published a total of seven blogs. These were:

1. World Economic Forum Agenda: "We set up an Arctic Basecamp at Davos 2017. Here are 5 reasons why." (Gail Whiteman, Lancs, Jeremy Wilkinson, BAS and Konrad Steffen, WSL)
2. World Economic Forum Agenda: "5 Reasons to Care about Arctic Ice Melt" (Gail Whiteman, Lancs and Jeremy Wilkinson, BAS)
3. World Economic Forum Agenda: "3 Industries that will be Hit by Arctic Change" (Gail Whiteman, Lancs, and Doug Crawford-Brown and Chris Hope, University of Cambridge)
4. World Economic Forum Agenda: "3 Ways You can Save the Arctic Ice" (Gail Whiteman and Jeremy Wilkinson, BAS).
5. World Economic Forum Agenda: "6 charts to help you become an Arctic expert" (Jean Claude Gascard, Jeremy Wilkinson and Michael Karcher) https://www.weforum.org/agenda/2015/09/6-charts-to-help-you-become-an-arctic-expert/
6. World Economic Forum Agenda: "The Arctic just had the warmest winter on record: The repercussions will be global" (Gail Whiteman, Lancs and Jeremy Wilkinson, BAS) https://www.weforum.org/agenda/2016/09/the-arctic-has-just-experienced-the-warmest-winter-on-record
7. World Economic Forum Agenda: "Greenland's ice sheets are disappearing faster than predicted: Here's why you should care" (Gail Whiteman, Lancs and Konrad Steffen, WSL) https://www.weforum.org/agenda/2016/09/greenland-s-ice-sheets-are-disappearing-faster-than-predicted-here-s-why-you-should-care**EU Arctic Cluster**

A new grouping of the Arctic projects funded by the EC, and coordinated by EU-PolarNet http://www.eu-polarnet.eu/eu-arctic-cluster/ was formed in the final years of ICE-ARC. This includes ICE-ARC, APPLICATE, ARICE, Blue Action, INTAROS, INTERACT II and NUNATARYUK. ICE-ARC have initiated the hashtag #EUArcticCluster, which now brings the projects together on social media. The other Cluster event at the Arctic Circle was a session on "Science as catalyst for international cooperation" – led by EU-PolarNet, the European Polar Board and INTERACT.

In addition, the EU Arctic Cluster created a booth (right) at the Arctic Circle – this was a popular port of call for many attendees, held in the main lunch area, and provided a focal point for the projects and an opportunity for people to discuss the projects. The booth was manned by the projects – ICE-ARC (Elaina Ford), EU-PolarNet (Kristina Baer and Nicole Biebow), EPB (Joseph Nolan), INTERACT (Margareta Johansson, Kisi Latola), and others. The first version of the ICE-ARC synthesis brochure was launched here – over 170 copies were distributed.

ICE-ARC synthesis brochure

One of the dilemmas the ICE-ARC Steering Committee were struggling with near the end of our programme was what is the best format for the broad range of information obtained within ICE-ARC to be disseminated to the widest audience. Should it be papers within a special issue, should it be an in-depth report, a shorter piece like an executive summary, or something else? We entered into discussion with our influential Advisory Board, and they agreed that a short synthesis report that contains the findings of ICE-ARC but in an easy to read format would be preferable to a lengthy in-depth scientific report. The report is supplemented by this report in addition to the scientific papers published in peer-reviewed journals. We have now completed the Synthesis Report and it has been published in English and Greenlandic.

International Community

ICE-ARC developed strong relationship with the international community. We are exceptionally grateful to very special relationship we developed with a number of non-European countries and scientific organisations. We hope that these collaborations developed between non-European countries on Arctic science will continue to strengthen in the years beyond ICE-ARC. These included:

Republic of Korea: ICE-ARC and the Korea Polar Research Institute (KOPRI) signed a Memorandum of Understanding to share data and knowledge. Through this relationship ICE-ARC researchers not only worked closely with KOPRI counterparts to analyse data and write joint scientific papers, but were able to deploy their observational systems (WP1) from KOPRI's ice strengthen research vessel *Araon* during the ICE-ARC programme (2014 to 2017).

Japan: Following an ICE-ARC presentation at a UNFCCC meeting in Bonn (7th June 2014) at the start of ICE-ARC, we built up a strong collaboration with Japanese colleagues within their new Arctic programme ArCS (Arctic Challenge for Sustainability Project). This collaboration involved MEXT – the Ministry for Science and Education, National Institute of Polar Research (NIPR), Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and Hokkaido University. Whilst developing their ArCS programme ICE-ARC representatives flew to Japan on a number of occasions, and we jointly organised an EU-Japan-US workshop at Arctic Science Summit Week in Toyama, Japan. The ICE-ARC coordinator sits on the international advisory board of ArCS. This small example shows the importance of highlighting and presenting EU programmes at high-level events. The take home message is that you do not know who may be in the audience, and how the approach or output of a presented EU programme will resonate with members of the audience.

China: We are extremely grateful to the Chinese Arctic Research Expedition (CHINARE) who in the summer of 2014 allowed ICE-ARC scientits to participate in the 6th Chinese Arctic Research Expedition (CHINARE 2014, 11/07/14-19/09/14) performed on board the Ice breaker “Xue long” (Snow Dragon). Participation to the cruise was also supported by the International France-China exchange program Cai Yuanpei (projet Campus France, ICAR 30481PM), the Polar Research Institute of China (PRIC) and the Second Institute of Oceanography (SOA-, Hangzhou City, China)

Canada: ICE-ARC were honoured to have two eminent Canadians on our Advisory Board: Eddy Carmack and David Hik. We were also able to establish relationships with a number of Canadian scientists and performed a 2017 Spring Campaign together based out of the new Canadian research station in Cambridge Bay, CHARS.

USA: ICE-ARC participants have a long track record of working with scientists from the US. In particular ICE-ARC established a strong collaboration with the US ONR funded Marginal Ice Zone and SODA projects. This enabled logistic and scientific resources to be shared.

Acknowledgements

The ICE-ARC community thank our many valued international collaborators for their cooperation, support, and substantial logistical commitment during the past four years. We are extremely grateful for the inspiration, insightful comments, and suggestions made by our Advisory Board, to whom we extend our deepest appreciation:

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- Eddy C. Carmack Emeritus, Institute of Ocean Sciences, Victoria, Canada
- HRH Prince Jaime de Bourbon de Parme Dutch Ambassador to the Holy See
- Bruce C. Forbes Leader of the Global Change Research Group, Arctic Centre, Finland
- David Hik University of Alberta, former President, International Arctic Science Committee
- Charles Kennel Former Director of Scripps Institution of Oceanography, now Visiting Research Fellow at the Cambridge Centre for Science and Policy
- Pam Pearson International Cryosphere Climate Initiative
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