the Nansen Legacy

Final report

Statement from the Board

The Nansen Legacy project has been a great success and has delivered far beyond what was promised. We can look back on seven years of joint research effort from 10 leading national institutions and 300 scientists and early career researchers. Together we have established a unique and comprehensive knowledge base for the seasonally ice-covered northern Barents Sea and the adjacent Arctic Basin. In total, 18 PhD (and more to come), 35 MSc and 54 postdoc candidates have worked and finished their theses within the project. The publication record amounts to 270 publications, and many more will follow in the next few years. And not the least, a new Barents Sea textbook summarizing the research and knowledge created through the project period will be published in 2025.

The true legacy of the project goes far beyond the science, knowledge and degrees achieved during the last seven years. The Legacy of the project will continue with a new generation of polar researchers educated within the project, and their network with each other and everybody else that has participated or been affiliated during these years. The early career scientists are the mere diamonds of the project and the importance of them cannot be overstated, but they need to be taken care of, and their continuation secured. Through the Nansen Legacy project, Norway has created a funding mechanism that allows for partnerships and a joint national effort to secure and further enhance Norway's position as a leading polar research nation. In the build-up towards the fifth international polar year (IPY) in 2032-2033, the scientific and structural foundation developed through the Nansen Legacy will provide an excellent opportunity for Norway to be at the forefront of Arctic international research, including the IPY.

The Board thanks everyone that has been involved, from funders to participants, stakeholders and the public receivers. The project has been a huge success, well planned, well carried out and well concluded. Congratulations! ■

Photo: Peter Leopold

Foreword from the leaders: The Nansen Legacy - a proof of concept



From left to right: PI Marit Reigstad, co-PIs Tor Eldevik and Sebastian Gerland.
Photo: Magne Velle

After six years of planning and seven years in action, the Nansen Legacy has been realized. We are proud to conclude that such a large collaborative effort proved to be an excellent approach to the complex research challenges facing us. The bold idea and broad vision of the Nansen Legacy was:

1) to build knowledge about the rapidly changing and increasingly accessible northern Barents Sea – where a reduced sea-ice extent now is prominent even during winter – to ensure a knowledge-based and sustainable management;

2) to increase the national collaboration between research- and management-oriented institutions and optimize the use of expertise and infrastructure, including the new Norwegian research icebreaker RV *Kronprins Haakon*;

3) to educate a new generation of polar scientists with a broader system understanding complementing their disciplinary expertise.

It was not given that such a large collaborative effort – ten institutions and >300 scientists representing a multidisciplinary Arctic research community – would succeed. The *modus operandi* of competition between groups when normally applying for research funds was turned into one common goal of collaboration, trust, and respect. Looking back as the funding period now has come to its end, the following success factors stand out. The long planning phase resulted in a collective ownership – to the Legacy concept in general and to the research questions in particular. A strong project consortium and support team was built, based on trust and respect between researchers and institutions. The distribution of funding and responsibilities was also clear ahead of the project's start. Accordingly, we could from the offset focus on solving scientific and logistic challenges through collaboration and realise the huge potential in the complementary research lined up. This collaborative ability to solve challenges also included minimizing the consequences of the pandemics for planned fieldwork and other activities impacting the progress. A major success was the focus on early careers. From an initial funding for 50 early career scientists, we ended up with more than 90 actively involved – and also more than 30 master students. Their enthusiasm, competence, and dedication to the research and common goals really boosted the project. Most importantly, all the scientists and institutions involved took part with enthusiasm and a dedicated will to succeed.

The Nansen Legacy entrained collaborators, and added value well beyond its consortium. Through cooperation with national as well as international scientists, projects, institutions and organisations, the team grew as the project progressed. The many collaborations added value which further strengthened the research, networks, as well as the societal value. This joint effort has made the expertise and capacity of Norwegian Arctic marine research visible worldwide. We find that the Nansen Legacy proved the strength, quality and capacity of the Norwegian research communities when joining efforts for a common goal.

Along with the scientific findings, the richness of new data published, the new generation of polar scientists, and the collaboration, experience and joy, we hope a legacy of the Nansen Legacy is an organisational proof-of-concept for solving future grand challenges. ■


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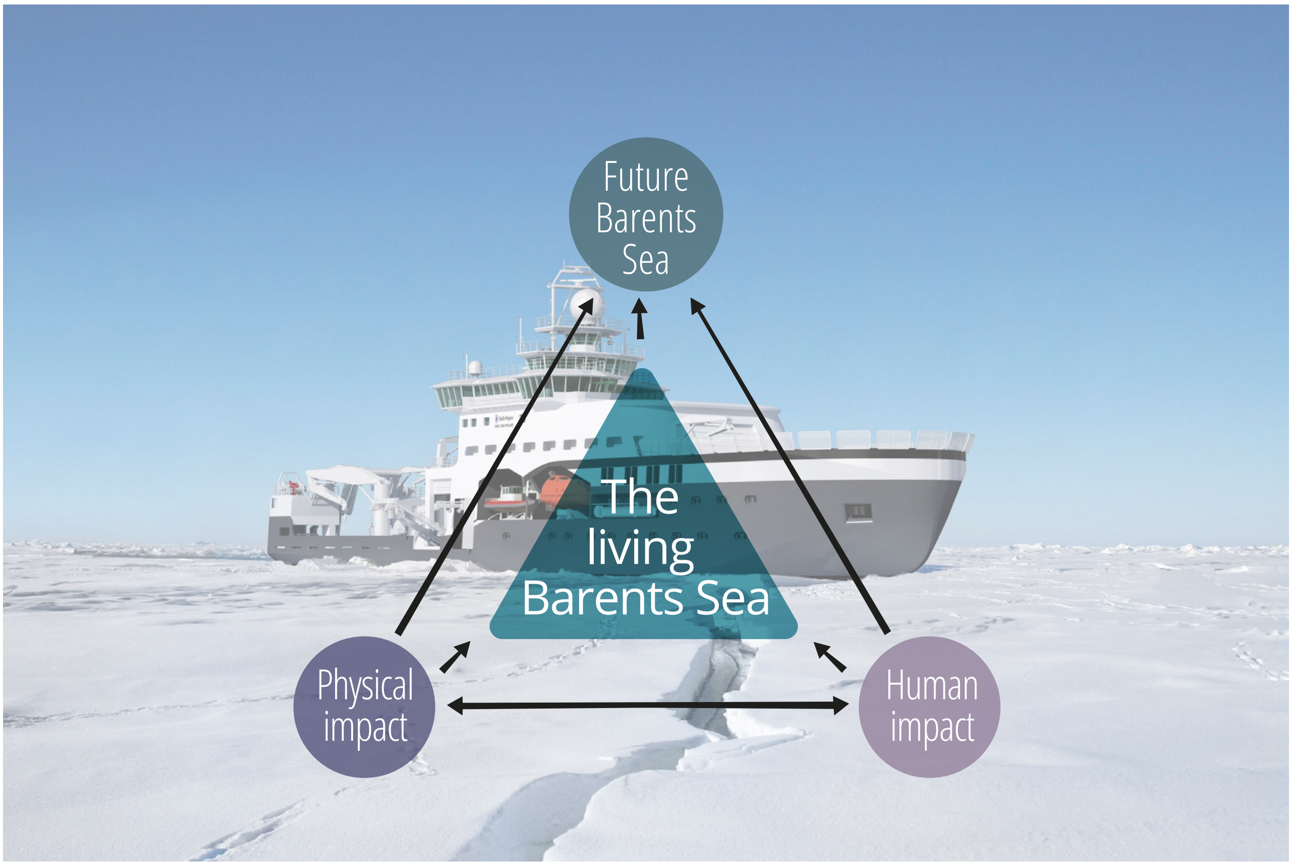
Photo: Christian Morel/christianmorel.net

Vision and objectives



The four research foci of the Nansen Legacy. Physical and human impacts on the living Barents Sea will determine the state of the future Barents Sea.
Illustration: Tor Eldevik, Rudi Caeyers

The Nansen Legacy was a novel and holistic Arctic research project. It has provided integrated scientific knowledge for sustainable management of the marine environment and resources of the Barents Sea and adjacent Arctic Basin through the 21th century. The Nansen Legacy had the following objectives:

1. Improve the scientific basis for sustainable management of natural resources beyond the present ice edge
2. Characterize the main human impacts, physical drivers, and intrinsic operations of the changing Barents Sea ecosystems in the past, present and future
3. Explore and exploit the prognostic mechanisms governing weather, climate and ecosystem, including predictive capabilities and constraining uncertainties
4. Optimize the use of emerging technologies, logistic capabilities, research recruitment and stakeholder interaction to explore and manage the emerging Arctic Ocean

Project take-home message

Having completed our journey, we take stock on the main objectives from the 2017 Nansen Legacy research proposal: The conclusion is "mission completed" for a very ambitious plan with a very ambitious and novel project concept. In-depth information can be found in this final report, the annual reports 2018–2023, and in our public outreach and research papers.

A scientific basis for sustainable management beyond the present ice edge in the Barents Sea is established. Data have been collected based on agreed methodologies and approaches to ensure complementary and consistent datasets. Scientific publications, assessment reports, synthesis articles and data are published. Relevance for management is identified as "high" for 65% of the publications and has been communicated through dialogue and information to relevant management bodies.

The main human impacts, physical drivers, and intrinsic operation of the changing Barents Sea ecosystems – past, present, and future – have been explored and characterised. The environment north of Svalbard has been impacted by both sea ice and Atlantic water the past 10 000 years. But even the winter sea ice is projected to disappear in the Barents Sea by the end of this century, given present day CO_2 emissions. Large-scale physical drivers like the Atlantic Current and the atmospheric jet regulate the Barents Sea's environmental conditions, with high seasonal and interannual variability. The ecosystem responded to warmer conditions with less sea ice with faster responses in the pelagic communities compared to the benthic. Boral species established further north with impact on community compositions and food webs. The living Barents Sea is impacted by human activities – local and remote. This includes fisheries, increasing sea temperature and ocean acidification and more new contaminants. The combination of all these impacts amplifies the responses of the individual impact and multiple stressors must be considered when making and evaluating impact assessments for environmental management.

Prognostic mechanisms governing weather, climate and ecosystems, including predictive capabilities and constraining uncertainties have been explored and exploited. Polar weather forecasts have been improved. Climate projections for 2050 and 2100 point to a warmer Barents Sea with increased ocean acidification and shift towards north-east for fish stocks. The longer greenhouse gas emissions remain according to a business-as-usual scenario, the more dramatic the impact for the Barents Sea by the end of the century. Strengths and weaknesses of ecosystem models provided guidelines for more optimal use with respect to downscaling, and similar for complex versus simpler or more conceptual models.

All annual reports

Peer-review publications

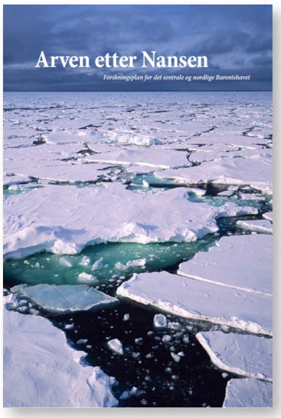
Fact sheets

By **optimizing the use of emerging technologies,** the observational capacity has increased in time and space. Combining observational approaches improved our 3D vision of physical and biological structures in the Arctic Ocean. The new research icebreaker RV *Kronprins Haakon* has facilitated new data from winter and extensively sea-ice covered area, and national **infrastructure** use is optimised. With a **new generation of Polar researchers** recruited and better interactions with the **stakeholder community,** the new integrated scientific knowledge base required for the future sustainable management is established. ■

"This national consortium already proves to be much stronger than the sum of its parts and will no doubt be a major legacy of the project for Norway."

Midway evaluation report summary (2021)

the Nansen Legacy

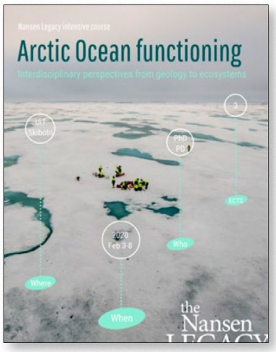


Research plan ready March 2014

Kickoff March 2018

Start of Nansen **Legacy webinar series on transferable skills**, especially aiming at the many ECS* in the project. March 2019

Start of the **science webinar series**, bringing together different scientists and disciplines. Sept 2019



3 PhD intensive courses for inter-disciplinary science in 2020

Idea launched by the Norwegian Academy of Science and Letters in 2011

Green light for the project and budget. Dec 2017

Physical process cruise. Sept 2018

MOSAiC

Nansen Legacy scientists joined the **international** ice drift campaign. Dec 2019

In May 2020, the project posted a **blog post** which became very popular and got international attention

Pilot Project in the National Budget in 2017

ipcc
INTERGOVERNMENTAL PANEL ON climate change
WMO
UNEP

Nansen Legacy contributed to the **IPCC special report** on Ocean and Cryosphere in a changing climate. Sept 2019

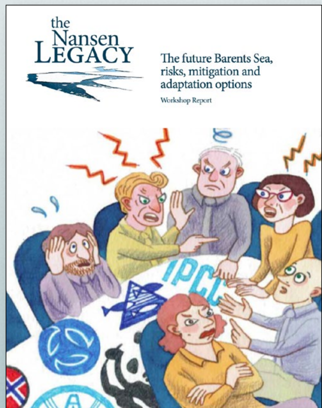
2011...

...2018

2019

2020

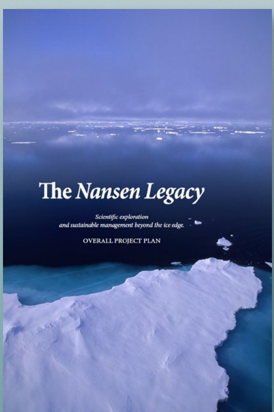
First joint cruise with the new *RV Kronprins Haakon.* Aug 2018



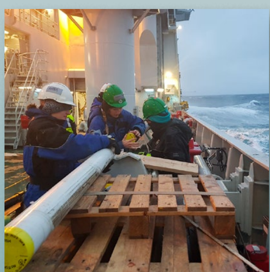
Dialogue meeting with the **reference group** and **stakeholder workshop.** Aug 2019

Many activities and cruises were reorganized due to the **COVID-19** pandemic. The annual meeting was held digitally in 2020

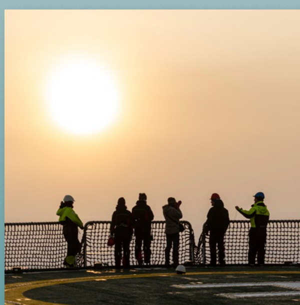
Research and fieldwork from **Nansen Legacy on TV** as part of NRK documentary series. Jan 2020



Project Applications 2015: evaluated by the National Academy of Science (USA); 2017: evaluated by the Research Council of Norway



Paleo cruise. Sept–Oct 2018



First of four seasonal cruises. August 2019 – May 2021

Workshops (online) on paleo-oceanographic findings and water mass definition in the Barents Sea, and **science for kids** events from the project members

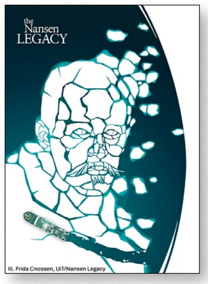
Polar Pint of Science. The project's ECS organized popular science evenings at pubs in Oslo, Bergen, Tromsø, and Longyearbyen. Oct 2021

NOAA ARCTIC REPORT CARD

NOAA Arctic report card. Nansen Legacy scientists contributed to the sea-ice chapter of the NOAA Arctic Report Card 2021

The **Winter Gap cruise** on the winter-spring transition. Feb–March 2022

Symposium Towards the New Arctic Ocean – Past, Present, Future: The Nansen Legacy hosted an international Arctic symposium in Tromsø, with >250 participants from all over the world. Nov 2023



The Nansen Legacy has landed - outreach event. Dec 2024

the Nansen LEGACY

Project end June 2024

Data management goes YouTube: Nansen Legacy data manager teaches data handling and FAIR publication.

Arctic Frontiers side event on "From Science to Policy" Jan 2022

MØT OSS PÅ ARENDALSUKA

The Nansen Legacy was involved in discussions with **politicians, stakeholders and industry** gathered at Arendalsuka and in Trondheim (Nor-fishing) in 2022

ARCTIC SCIENCE SUMMIT WEEK

Nansen Legacy members joined the **Arctic Science Summit Week.** Feb 2023

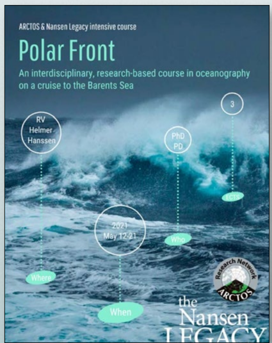
Ending the project with over **270 publications** and **thousands of shared data points**

2021

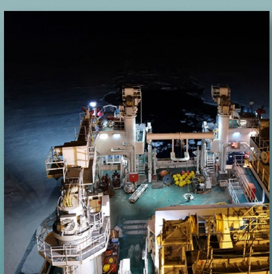
2022

2023

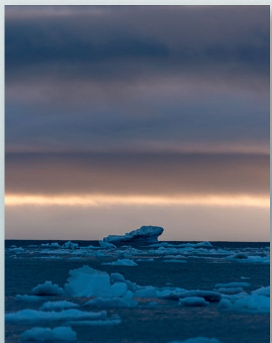
2024



Summer school at sea. The ARCTOS research network and the Nansen Legacy joined forces and conducted a PhD intensive course at sea. May 2021



Winter process cruise on air-ice-ocean interactions. Feb–March 2021



Arctic Basin joint cruise Aug–Sept 2021

PAME Protection of the Arctic Marine Environment

Nansen Legacy scientists contributed to the joint ICES-PAME-PICES **assessment of the Ecosystem in the Central Arctic Ocean.** Feb 2022

Annual Meeting and Recruit Forum. Sept 2022

Workshops in 2023 included synthesis work on Atlantic water inflow, annual production, the future Barents Sea, publishing data, hyperspectral imaging, and benthic communities in the central Arctic Ocean

ASLO

Nansen Legacy ECS and seniors were well represented at the **ASLO Aquatic Sciences Meeting** in June 2023

Annual meeting in Oslo June 2023

Reporting and concluding the project. Dec 2024

Photo: Èric Jordà Molina

Photo: Vårin Eilertsen

Learning from the past to prepare for the future

The climate on Earth is warming due to anthropogenic greenhouse gas emissions, but this is not the first time global warming has occurred in the history of the Earth. Between 10 and 6 thousand years ago, our planet went through a period called The Holocene Thermal Maximum, when it was warmer on Earth than it is today. Nansen Legacy scientists have reconstructed the northernmost Barents Sea climate during this warmer-than-present period to identify similarities and differences between then and now.

Persistent seasonal sea ice in a warmer-than-present northern Barents Sea

Climate change in the Arctic is particularly noticeable due to the visible sea-ice decline. Using climate model projections, Nansen Legacy scientists identified the Barents Sea to be the first Arctic shelf sea to be ice-free year-round by the end of the century, given 'business as usual' CO_2 emissions (see also highlight on "*The future Barents Sea*", page 42-43). Reconstructions of the past provide more insights into the complexity of interactions related to seasonal sea ice and global warming.

The tilt of the Earth's axis and the shape of the Earth's orbit around the sun change over time. This modifies how much sunlight and heat reaches the Earth. Due to these changes air- and ocean temperatures were higher during The Holocene Thermal Maximum (HTM), 10 – 6 thousand years ago, than they are today. Surprisingly, sea-ice biomarkers in sediment cores demonstrate that seasonal sea ice persisted in the northern Barents Sea through this period. At the same time, oxygen isotope analyses from the shells of planktonic foraminifers preserved in sediments indicate the inflow of warm Atlantic Water from the south. The persistence of sea ice in the past suggests efficient stratification separating the subsurface Atlantic Water and the colder and fresher Arctic-derived water at the surface. This layering likely protected the sea ice from the warmer Atlantic Water below, similar to the Central Arctic Ocean today. Phytoplankton biomarkers in sediment cores further suggest that during the HTM, the Marginal Ice Zone where melting of sea ice allows light to penetrate the dark ocean underneath which results in intense phytoplankton blooms, was productive also then.

Although the cause of global warming during the HTM is different from today, reconstructions of the northern Barents Sea suggest that seasonal sea ice may have persisted under a warming climate as long as the warm Atlantic Water layer stayed separated from a colder and fresher surface layer. To maintain this stratification, however, a freshwater supply, such as the import of sea ice from the Arctic Ocean, was required. Today, the Atlantification of the Eurasian Arctic is characterised by an erosion of this insulating arctic water layer, allowing a warmer surface layer to reduce or melt the sea ice.

An accurate reconstruction from the past requires an accurate marine-terrestrial offset.

Radiocarbon (^{14}C) is an isotope commonly used by palaeontologists to reconstruct the past in both marine and terrestrial environments. The uptake of ^{14}C from the atmosphere in the ocean, however, lags behind the uptake on land due to the slow global marine circulation. To convert marine radiocarbon dates to calendar-equivalent years, a global marine-terrestrial offset of ~400-600 years needs to be incorporated, meaning that radiocarbon in marine sediment samples is about 400-600 years older than terrestrial radiocarbon. The conversion is done using marine radiocarbon curves.

However, the exchange of carbon between the atmosphere and the ocean varies regionally depending on sea-ice cover, freshwater inflow, and upwelling. Therefore, the global marine-terrestrial offset needs to be complemented by a regional offset to correct the age of marine samples depending on the sampling location. Nansen Legacy scientists revised the regional marine-terrestrial offset in molluscs in different parts of the Barents Sea and found a variation of more than 350 years depending on the location in the Barents Sea. In Franz Josef Land for example, the recommended offset is -277 ^{14}C years, while in western Svalbard the recommended offset is +94 ^{14}C years. These new values make it possible to compare ^{14}C dates from marine calcium carbonate across different regions in the Barents Sea, which allows for better reconstructions of the Arctic through the Holocene.

The use of foraminifers as natural marine archives for fossil reconstructions

The use of foraminifers as natural archives for ^{14}C-analyses in sediment samples is possible due to their calcium carbonate ($CaCO_3$)-containing shells. Recent data from the project, however, indicate that the suitability to use foraminifers might depend on the location of the sediment sample. At a core site in the northern Barents Sea, planktonic foraminifers were present in the water column, but absent in the sediment core, down to depths dating back to 1300 CE. This mismatch suggests $CaCO_3$ dissolution in the sediment due to the decomposition of organic matter. Interestingly, this mismatch between the foraminifers in the water column and sediment was not observed at a core site in the southern Barents Sea. These data suggest that in addition to the sediment, the water column should be studied for foraminifers to assess if these organisms can serve as a natural archive to reconstruct the past at a specific location.

By reconstructing the climate during the Holocene Thermal Maximum and comparing it to today's conditions, we gain crucial insights into Earth's climate dynamics. The persistence of sea ice during past warming periods, in contrast to today's rapid decline, highlights the complex interplay between ocean currents and atmospheric conditions. These historical comparisons not only reveal similarities in climate responses but also emphasize the unique challenges posed by modern anthropogenic influences. This understanding is vital for predicting future climate trends and formulating effective climate management strategies. ■

"We conclude that seasonal sea ice persisted in the northern Barents Sea during the Holocene Thermal Maximum, despite warmer-than present conditions and Atlantic water inflow".

Anna J. Pieńkowski, NPI

References

Sediment cores: a long term archive of climate change

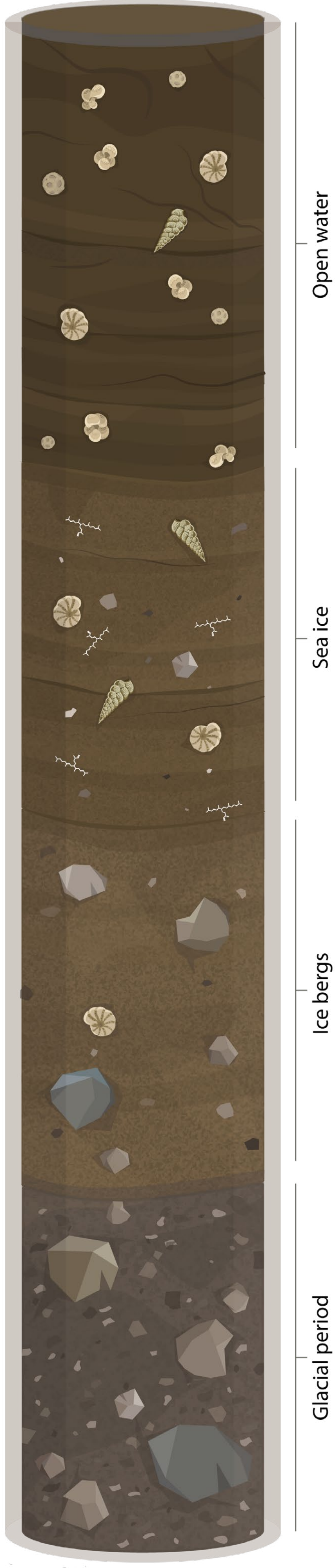


Illustration: Frida Cnossen

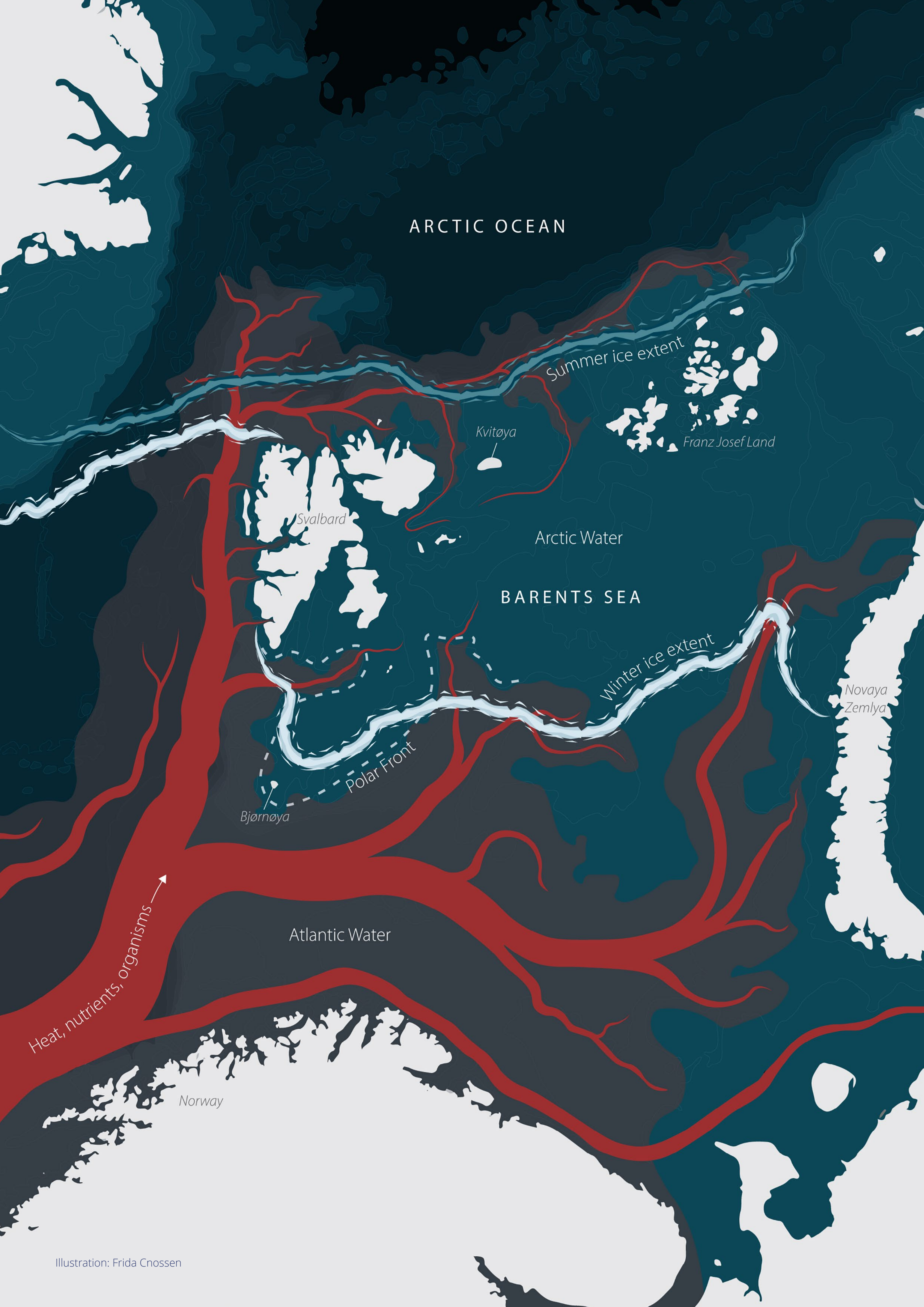


Illustration: Frida Cnossen

The physical Barents Sea

The Barents Sea is a place where the Atlantic Water and seasonal sea ice dominate the processes of the physical and living ocean. To further disentangle the puzzle of the processes in this region, the Nansen Legacy has collected and analysed a lot of new oceanographic, sea-ice related and atmospheric observations in the northern Barents Sea, spanning all seasons and several years. This includes measurements from moored installations, ships, and autonomous platforms. The data provides insights into regional Atlantic Water inflow routes and seasonality, distribution processes, and related factors like vertical mixing, light conditions, and sea-ice dynamics.

The Barents Sea – the beating heart of the Arctic

The Barents Sea is like a beating heart in the Arctic. The sea-ice cover pulses with the seasons, expanding in winter and contracting in summer, and the relatively warm and saline Atlantic water (AW) is its lifeblood – bringing in heat, oxygen, nutrients and living organisms. The AW flows into the Barents Sea from the North Atlantic Current, often thought of as an extension of the Gulf Stream. As it travels around and across the Barents Sea, it cools and is transformed by sea ice and colder and less salty Polar Water. In the central Barents Sea, these two water masses meet, and the AW leaves the surface and is submerged beneath the Polar Water, creating a thermohaline front known as the Polar Front. The Polar Front boundary is also where cold, dry air meets warm, moist air, which can create polar lows and outbreaks of cold air. The seasonal sea ice is found north of the Polar Front, while the Atlantic-origin waters in the south remain ice-free. The exact location of the Polar Front can vary, especially further east in the region where it has generally moved northwards in recent years.

The unique Barents Sea

The Barents Sea is a hotspot for global climate change, its atmosphere having warmed five to seven times faster than the global average and having lost the most winter sea ice of all the Arctic. The Barents Sea is different to other Arctic shelf seas. Apart from the strong inflow of AW at approximately 2.3 million $m^3 s^{-1}$, it is deeper than the other shelf seas with an average of 230 m, and no large rivers drain into it. Processes in the Barents Sea impact the large-scale ocean circulation. When AW cools as it travels north, it becomes denser and sinks to great depths in the Arctic Ocean. Oxygen, CO_2 and nutrients are brought along in the circulation around the Arctic Ocean. On other Arctic shelves, the addition of freshwater from rivers does not facilitate such dense water formation. Of the whole Arctic, the Barents Sea contributes most to the trend in increasing ocean heat transfer into the atmosphere due to large areas of open waters which used to be seasonally sea-ice covered. For these reasons, the Barents Sea is often referred to as a "cooling machine" that sucks heat out of its waters and into the atmosphere.

Inter-annual variations and decadal trends

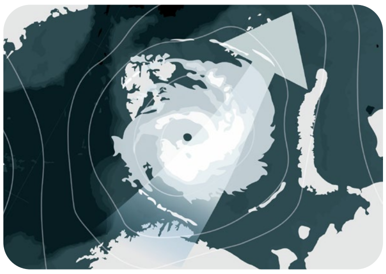
The AW inflow and sea-ice cover fluctuate seasonally, inter-annually, and over decades, influenced by local weather patterns, such as storms, but also by larger-scale oceanic and atmospheric processes. The atmospheric Arctic Dipole, which is created by the anticyclonic winds over North America and cyclonic winds over Eurasia, can regulate the inflow of Atlantic water into this region of the Arctic. Decadal trends show an enhanced and shallower inflow of warm and salty AW to high latitudes, driving an "Atlantification". This results in weaker stratification, enhanced heat fluxes, and reduced sea ice. However, in recent years, the Arctic Dipole seems to have switched gear to an alternative phase, which has led to weakened AW inflows and episodes of enhanced sea-ice import into the Barents Sea from north and east. Furthermore, although Arctic sea-ice extent and thickness have decreased dramatically over the last few decades, recent findings show that the sea ice in winter has become thicker over the last decade in parts of the northwestern Barents Sea. Still, the region has much thinner sea ice now than in the 1980s and the long-term projections are a continued decline, modified by natural variability.

"I am really impressed and happy with all the new observations and insights the team has produced during the project. From details on the processes governing sub-surface mixing to the regional dynamics controlling the inflow of Atlantic Water, sea ice and air masses to the northern Barents Sea. We now have a much better understanding of the physical part of the coupled Barents Sea system, which is key to understand both the ongoing changes and what the future Barents Sea might look like."

Arild Sundfjord, NPI

References

Important findings from the physical Barents Sea



1. Cyclone dynamics in the Barents Sea

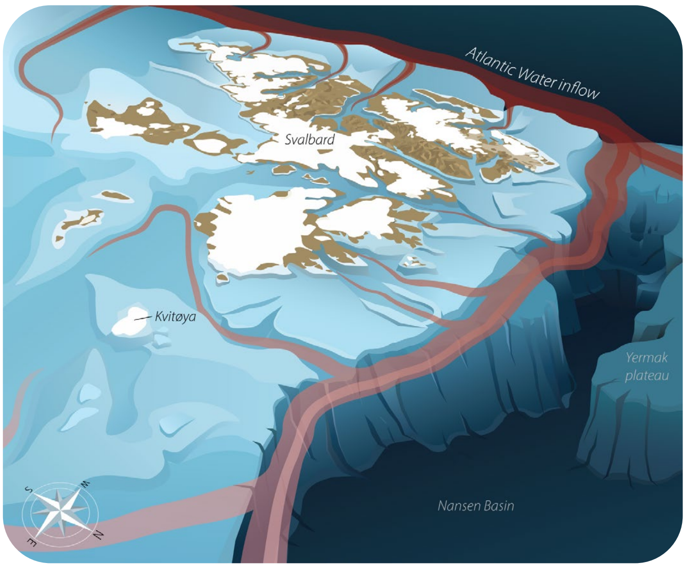
Cyclones in the Barents region vary widely in temperature and moisture, ranging from warm, moist ones like those from the North Atlantic to colder, drier types even chillier than typical Barents conditions. These differences arise from the surrounding atmospheric conditions at the time of their formation, leading to distinct development mechanisms: warm/moist cyclones have weak, deep circulation linked to the North Atlantic, while cold/dry cyclones exhibit strong, shallow circulation driven by the sea-ice edge.

2. Freshwater input and glacier melt

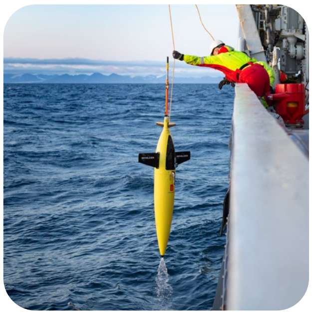
Freshwater fluxes from glaciers on Svalbard were studied using a model focused on glacier mass balance and seasonal snowmelt. Meltwater runoff increased significantly, which will likely impact fjord circulation and coastal marine production in the glacial fjords. The 31-year simulations were made publicly available on a daily and monthly resolution, which can be reused in a wide range of applications including studies on glacial runoff, ocean currents, and ecosystem response.

3. Large and warmer inflow of Atlantic water into the northern Barents Sea in autumn

Several years of mooring observations show that the strongest, warmest inflow of Atlantic Water enters the Barents Sea from the north, especially during late autumn and early winter. This can delay sea-ice formation and allow more wind-mixing and associated nutrient replenishment already during autumn (details page 22). A study of the Storfjordrenna trench indicates that this western pathway for warm Atlantic Water has become more active in the past two decades, due to increased temperatures and sectioning of water masses. It is further influenced by tides, winds, and changes in upstream currents.



4. New insights into Atlantic inflow to the Barents Sea



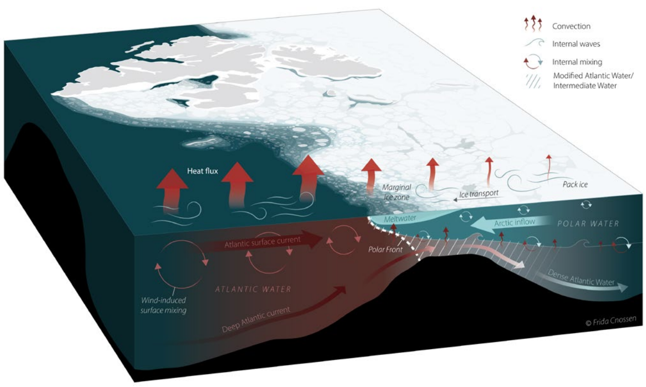
Measurements from the waters north of Svalbard in 2018-19 revealed that the Atlantic Water Boundary Current was 2.6 Sv in summer and can reach a peak transport of 3.0 Sv (= 3 000 000 m^3 s^{-1}) in October, with notable seasonal variability. It flows alongside a newly observed deep current. Observations also show significant seasonal heat loss from this current, ranging from 302 W m^{-2} in winter to 60 W m^{-2} in spring. Further south - in the central Barents Sea - density-driven currents direct warm Atlantic water into the Arctic-dominated north, underneath the Polar Front, though recent decades have seen a reduction in this flow (more details page 14).

5. Atlantic water entering from the north, melt glacier on Nord-Austlandet

Most of the Atlantic water entering the northern Barents Sea was previously believed to come from the south but recent findings show there is a large inflow of AW into the region from the north in the autumn and early winter when the AW is at its warmest. This inflow of warm AW from the north has a strong impact on the glaciers on Nord-Austlandet (in the Spitsbergen archipelago) where periods of warm AW lead to immediate and strong mass loss from the calving glaciers and a prolonged melting season for the glaciers.

6. Mixing across the Polar Front

Mixing studies in the northern Barents Sea revealed that vertical mixing during autumn wind events can



contribute up to a quarter of the nitrate replenishment in the mixed layer during winter, with both advective and turbulent fluxes playing equal roles (details on page 22). Comprehensive observations from cruises and autonomous platforms provided insights into the Polar Front's structure and variability, showing intense mixing in the surface boundary layer, significant mixing in the bottom layer due to tides, and notable water mass transformation through eddy-driven mixing.

7. Marine heatwaves are increasing in the Barents Sea

Between 1982 and 2020, the Barents Sea experienced 72 marine heatwaves, with most occurring after 2003. The Barents Sea appears to be a heatwave hotspot, with an increase in frequency that is double the global increase. These heatwaves are now more frequent, intense, and longer-lasting, with the southern Barents Sea experiencing the longest and hottest events, such as in 2016 when a "strong" heatwave raised sea-surface temperatures more than 4°C above average for 63 days.

8. Warmer AW entering the Arctic Ocean and in larger volume

Model simulations show that atmospheric cooling of AW in the Barents Sea has lessened over the past 40 years, which in turn means that the water flowing into the Arctic Ocean's deep basins is warmer. Besides temperature, the volume of AW transported through the Barents Sea has increased, which together are highly correlated to the reduction in sea-ice area.

9. Increased importance of transported sea ice in the Barents Sea

Annual variations in heat transported with the AW into the Barents Sea have historically explained the extent of the sea-ice cover. In more recent years, the sea-ice cover has retreated northwards, so that AW no longer is the dominant factor determining interannual variations of the ice cover extent. In the area north and northeast of Svalbard, the interannual sea-ice variability was found not to be mainly driven by changes in ocean heat after 2000, when atmospheric circulation and ice advection from east and north became more important for the winter sea-ice extent.

10. Validating sea-ice algorithms for forecasts

Sea ice in the northern Barents Sea shows significant variability from year to year and throughout the winter season. It starts with thin, locally formed sea ice that is later replaced by and intermixed with thicker, older ice transported by large-scale atmospheric systems from east and north. New Nansen Legacy sea-ice measurements validated that recently developed sea-ice thickness algorithms for remote sensing effectively represented local conditions, and combining these data sources enhances understanding of both local and remote processes. ■

Illustrations: Frida Cnossen
Photos: Christian Morel / christianmorel.net, Andreas Wolden, Kay Jørgensen and Olaf Schneider

References

Photo: Kay Jørgensen

Natural variability and climate change

The Barents Sea is experiencing ongoing warming and Atlantification. Recent findings show this trend can have shorter disruptions with periods of a colder ocean and more sea ice. The field sampling of the Nansen Legacy occurred in such a cold disruption, giving unique opportunities to assess interannual variations in a warming Barents Sea.

Atlantification

The Barents Sea is influenced by the inflow of Atlantic Water, and climate change has intensified the influence of Atlantic Water since 2000. This has led to "Atlantification," where Arctic waters are transforming into a state that resembles that of the Atlantic more closely. Atlantification is driven by warmer Atlantic Water but is modified by atmospheric cooling and local processes like reduced freshwater input. In the climate system, processes are strongly coupled together. This means that if one process is changing, it often induces simultaneous variations in others, such as heat, sea ice, and stratification within the Arctic.

Natural cycles of cooling and sea-ice increase

In recent times, the general warming trend in the Barents Sea is disrupted by pulse-like events of abrupt warming and cooling. The inflow of Atlantic water from the northern North Atlantic became colder around the 2010s. However, due to reduced heat loss from the ocean in the Nordic and Barents Seas, the advected cooling was dampened as the Atlantic Water flowed northwards. Despite this modification, Barents Sea temperatures peaked in 2015-2016, resulting in a colder ocean during the Nansen Legacy sampling years compared to both before and after. Consistently, sea-ice extent and thickness increased, likely due to a combination of more freezing and the higher importance of sea-ice import from the north into the Barents Sea. The anthropogenic warming and sea-ice decline are superimposed by pronounced internal variability, resulting in shorter, colder periods during the long-term warming.

Atlantification will keep its influence on the ecosystems

Ecosystem responses to warming and sea-ice loss include increased production, northward expansion of boreal species (borealization), an increasingly connected food web, but also a gradual reduction of the ice-associated ecosystem compartment. These changes are anticipated to continue despite periods of cooling or sea-ice drift into the northern Barents Sea. ■

"But of more general interest are perhaps the annual variations in the currents ... and their relations to the variations in the climate of Norway, the variations in the fisheries, and also the variations in the harvests of Norway..."

Bjørn Helland-Hansen and Fridtjof Nansen,
The Norwegian Sea (1909)

References

Photo: Peter Leopold

Using optical sensors to understand ecosystem processes

Water has a unique feature: it is transparent and allows light transmission. Optical sensors, attached to satellites and deployed in the water, can determine light quantity and quality. Nansen Legacy scientists used these data to characterize different water types in the marginal ice zone and study the spatial and temporal changes in light regimes under drifting sea ice. New optical data further reveal details about organic carbon in the water column and its resuspension from the sea floor.

Satellite observations to characterize water types

Advanced optical satellite sensors monitor the surface ocean from space. The acquired raw data, however, requires comprehensive post-processing before detailed conclusions, such as on water turbidity, can be drawn. To tackle challenges linked to Arctic waters, like low sun angles, sea ice, and clouds, Nansen Legacy scientists applied a new machine-learning method to classify satellite images from the marginal ice zone. They characterized water types based on transparency and were able to distinguish algal-derived biomass from non-algal constituents.

New sensors assess the underwater light regime

Other project scientists have advanced underwater light measurements. With a newly developed chain of robust and highly sensitive light sensors, they overcame the challenges of collecting light measurements over time and at various depths in remote areas. As part of an autonomous ice observatory, the chain of light sensors recorded light down to several meters below an ice floe while it drifted in the Arctic Ocean for six months. The vertically, spatially, and temporally spaced data indicate that the light regime under sea ice is highly complex. Features like leads or melt ponds can significantly increase the underwater light beneath the sea ice, also affecting marine life.

Characterizing suspended particles in the water

When light penetrates the ocean, it is absorbed and scattered by suspended matter and water molecules, causing the light quality and quantity to change with depth. Measuring absorption and scattering enables scientists to deduce what substances are in the water. Nansen Legacy scientists identified phytoplankton as a major driver of optical variability in the central Barents Sea. However, the light absorption of phytoplankton deviates from globally observed relationships. The currently speculative explanation is that under-ice microalgae are adapted to low-light conditions and can absorb more light than low-latitude phytoplankton. If this holds true, the findings could improve how we represent underwater light in Arctic ecosystem models. Light measurements also revealed high concentrations of inorganic and organic matter up to 50 m above the ocean floor. These “dust clouds” are likely caused by resuspension events at the sea floor, initiated by tides or other water currents. They could influence the seafloor ecosystem by reducing visibility and replenishing nutrients in the water column. ■

“Understanding of factors controlling the optical properties are crucial for the development of more accurate regional bio-optical models.”

Tristan Petit, NPI

References

Biodiversity: A few supported by thousands

Do you know who lives in the Barents Sea? Even experienced Arctic researchers are still trying to figure it out. The Nansen Legacy project has contributed to mapping the diversity of marine organisms, especially focusing on the smallest and often most overlooked species. This knowledge is essential for assessing the ecosystem's status and health in the rapidly changing Arctic and strengthening the baseline for management plans.

System resilience needs biodiversity

Biodiversity is the variety of all living organisms. For a healthy, productive ecosystem that can support large predators and remain resilient to change, the diversity of organisms and their functions within the system needs to be high. As in other regions, Nansen Legacy researchers found that in the Barents Sea, the highest diversity was among the smallest organisms – the single-celled microbes. These tiny organisms are the engine of the ecosystems and contribute the most to biomass, forming a support system for the fewer, larger animals. Along the study transect alone, over 1500 types of microbes (excluding the massively diverse bacteria and archaea) were found in the sea ice, over 2500 in the water column, and more than 1000 in the sea floor sediments. A similar or even higher number of different bacteria and archaea likely inhabit the sea ice and water. Some of these were new to the Barents Sea, and some were likely new to science. Genetic analyses revealed microbial species that did not match any known species, with unknown ecosystem functions. For example, in the frost that forms flower-like structures on sea ice during very cold days, communities of bacteria and archaea were linked to nitrogen and sulphur cycling. Even among multi-cellular organisms, several were new to the region, such as the first-ever loriciferan (tiny sediment-dwelling animals) recorded in Norwegian waters, a *Rugiloricus* sp., found at 806 m depth north of Svalbard. Several other benthic meiofauna are also suspected to be new to science. Knowing what species are where, and their functions, will help assess and predict ecosystems' vulnerability and resilience in a changing environment, which is vital for management and conservation.

Who lives where and how is their distribution changing?

In the Arctic Ocean, organisms inhabit the sea floor and water column, but also the sea ice. The diverse habitats have promoted specialization. The proportion of endemic Arctic species (only occurring here) was found to be generally low for microalgae (<10%) but much higher for the largest species, including fish (26% in the whole Barents Sea), like the polar cod and the Leatherfin lumpsucker (*Eumicrotremus derjugini*), and marine mammals. Overall, our researchers confirm that Arctic species were mostly found north of the Polar Front, while in the southern Barents Sea, the communities were generally comparable to those found along the Norwegian mainland. Some endemic species inhabit the sea ice, such as specific amphipods and diatoms, while more widespread species, like juveniles of common benthic polychaetes, also take advantage of the sea ice. Boreal species are now venturing further north than before, as the Arctic warms. For instance, the jellyfish *Periphylla periphylla* was found further north in the central Arctic Ocean than previously recorded. Data from the Barents Sea on the open GBIF* portal, including Nansen Legacy data, revealed that community shifts of invertebrates have occurred since pre-1900 to present across warming and cooling periods. The most significant shifts occurred after 1980 in colder northern regions and around the 1950s in warmer areas, with many of these shifts involving northward range extensions in both benthic and pelagic communities.

Barents Sea biodiversity data – expanded across seasons and openly available

Through its seven-year project and over 300 days at sea, the Nansen Legacy has expanded the biodiversity data in the study region, especially improving knowledge of biodiversity across seasons. The biodiversity data are published in the international GBIF* database for global use. Furthermore, the Nansen Legacy samples have contributed to the Norwegian Culture Collection of Algae and the Arctic University Museum in Tromsø, and the vast genetic sequence datasets are archived and accessible. These data, in addition to being used in scientific publications, will be publicly available for anyone to use – allowing for model improvement and as baselines in future research. ■

** Global Biodiversity Information Facility*

"Take a closer look into the ice cracks, filter the water or sieve the mud to encounter thousands of living forms which sustain a unique, diverse and complex ecosystem such as the one found in the Barents Sea."

Èric Jordà Molina, Nord University

Photos: Joel Vikberg Wernström (left), Fredrik Broms/northernlightsphotography, (middle and right)

References

Number of species
at Nansen Legacy sites

ca. 150
ZOOPLANKTON

>500
SEAFLOOR SPECIES
(INVERTEBRATES)

>1500
SEA ICE MICROBES
(PROTISTS)

>2500
WATER COLUMN
MICROBES (PROTISTS)

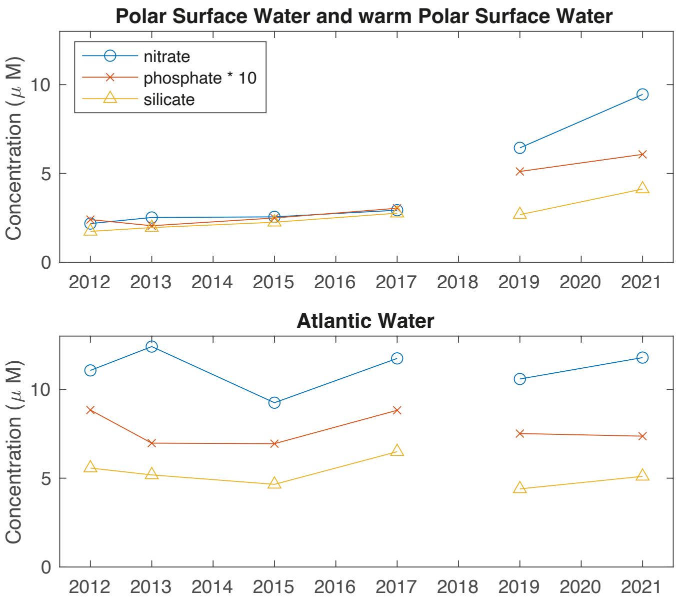
Illustration: Frida Cnossen

Pictures: Bente Edvardsen, Christine Gawinski, Èric Jordà-Molina, Fredrik Broms, Luka Supraha, and Wenche Eikrem

Photo: Rudi Caeyers

Physical processes fertilize the ocean's surface

Ocean physics mixes the water column and replenishes surface nutrient concentrations after a productive summer, like a farmer ploughing a field. Heavy sea-ice cover and water stratification can hamper this process, but Nansen Legacy scientists found that surface nutrients may already be replenished by autumn storms in a (partially) ice-free ocean. However, phytoplankton can take little advantage of the replenished nutrients for growth during autumn due to the fading daylight.



Nutrient concentrations (average per water mass) for Polar- and warm Polar Surface Water and for Atlantic Water at the shelf break north of Svalbard. Samples in 2012-17 is collected in summer, and 2019-2021 is collected in November.

Seasonality of the surface nutrient stock in Arctic seas

Nutrient concentrations in the surface layer of Arctic seas change considerably with the seasons. During late spring and summer, algae grow extensively in the illuminated upper tens of metres, depleting the nutrient stocks. In deeper waters, nutrient concentrations remain high, but due to strong water column stratification in summer, wind-induced vertical mixing is often too weak to replenish the surface nutrients. In autumn and winter, strong winds and cooling of the water surface induce overturning processes, restoring fresh nutrients to the surface. This preconditioning of the surface ocean is crucial for high algal production in the following year.

Sea ice hampers fertilization of the ocean surface

Interdisciplinary work by Nansen Legacy oceanographers, marine chemists, and biologists identified sea-ice cover as an important factor that hampers water mixing processes northeast of Svalbard and in the central Barents Sea during autumn. However, when sea-ice cover is weak or waters are open, autumn storms can often induce vertical mixing processes and replenish the surface nutrient stocks. Rough estimates suggest that 30 windy days in the central Barents Sea could restore approximately one-quarter of the fresh nutrients needed for annual algal production. Nevertheless, algae seem unable to extend their production into autumn due to rapidly declining day length and light intensity above 76°N.

Advection modifies local processes

The replenishment of the nutrient stock is also regulated by advective processes. On the one hand, nutrient-rich Atlantic-derived water is advected to the Barents Sea. Nutrients transported through the Barents Sea Opening between mainland Norway and Svalbard are mainly primarily utilised in the southern Barents Sea, but roughly 20% cross the Polar Front into the more Arctic-influenced northern Barents Sea. Wind, on the other hand, can advect sea ice from the central Arctic Ocean into the region north of Svalbard and the northern Barents Sea, where it can inhibit wind-induced vertical water mixing and the replenishment of surface nutrient stocks. Taken together, the rate at which fresh surface nutrients are replenished is determined by a complex interplay of both local and distant physical processes. ■

"Multidisciplinary observations provide insight into the interplay between physical, chemical, and biological drivers in the marine environment and are key to understanding ongoing and future changes."

Angelika H. H. Renner, IMR

References

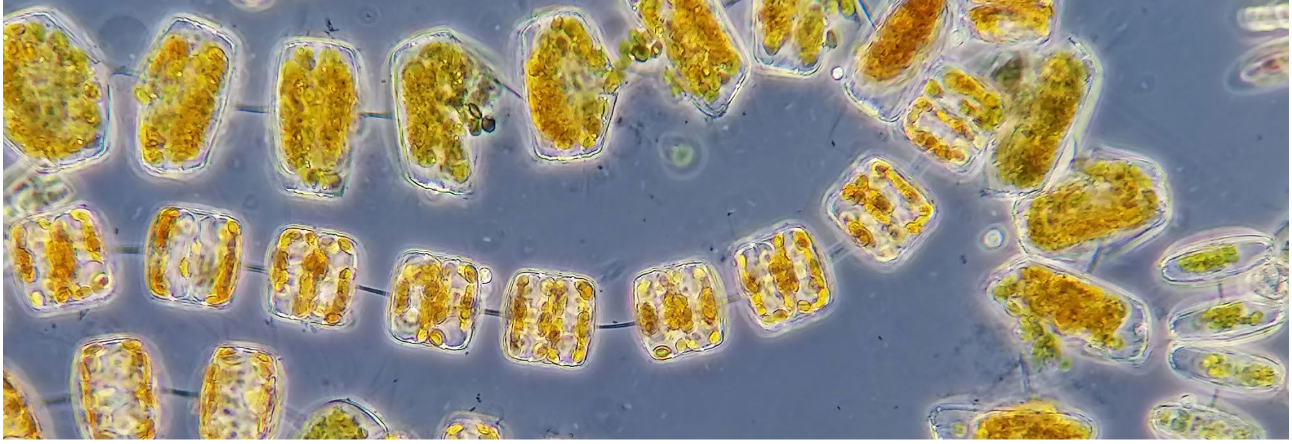


Photo: Christine Gawinski

Plankton production in open and sea-ice covered waters

Will more light in an ice-free Arctic Ocean increase plankton production? The answer is complex. Annual phytoplankton production in the Northwestern (NW) Barents Sea is higher in open waters than in seasonally ice-covered areas. In August, similar levels of daily production are maintained by plankton communities in both open and ice-covered waters; however, communities of contrasting size composition prevail, channelling energy differently through the food web. This has implications for harvestable species.

Phytoplankton production and why it matters

Phytoplankton and sea-ice algae production fuel the Arctic marine food web, including harvestable resources, but it remains unclear how their production changes as the Arctic warms. Nansen Legacy scientists used field data, satellite imagery, and model simulations to investigate annual phytoplankton production in the NW Barents Sea (1980-2021). They found that the Atlantic-influenced open waters of the NW Barents Sea (approximately 75-77 °N) had higher annual phytoplankton production compared to the seasonally ice-covered waters (approximately 77-84 °N). In-depth analyses of the modelling output suggest that a deep mixing layer, which is associated with nutrient replenishment in surface waters, is an important regulator of production in the Atlantic-influenced region. In the Arctic-influenced waters, increased light levels, which can result from less snow on sea ice or more ice-free waters, and higher nutrient concentrations in the surface waters seem to govern production. The key question remains: will phytoplankton production in the northern parts of the NW Barents Sea increase as sea ice continues to decline, and will harvestable species benefit from it?

Production of small and large plankton fuel different parts of the food web

Nansen Legacy field studies assessed phyto- and zooplankton production under contrasting sea-ice conditions in the NW Barents Sea in August 2018 and 2019. No significant differences in daily production were found in ice-free waters in 2018 and partly ice-covered waters in 2019, but the plankton size composition differed. In August 2018, small-sized phytoplankton, microzooplankton (single-celled grazers), and small copepods were key biomass producers in open waters. This community typically emerges several weeks after the sea-ice melt during summer. Conversely, in the partly sea-ice-covered waters in August 2019, a typical 'sea-ice melt' community of larger phytoplankton, particularly diatoms, and large zooplankton dominated and contributed most to production. The two contrasting communities channel energy differently through the food web. Large phyto- and zooplankton efficiently transfer energy towards large, harvestable fish, whereas the summer community, with its longer food chain of small phytoplankton, microzooplankton, and small zooplankton, 'loses' energy to physiological processes, leaving less energy for harvestable species. A future, warmer NW Barents Sea with less sea ice will likely experience earlier ice melt and a longer summer growth period. Still, nutrient-depleted surface waters may favour a food chain based on small algae and little effective energy transfer to harvestable species. These findings underscore the need to consider the prevailing phytoplankton (size) community when predicting production in the future Arctic because plankton crucially determines which parts of the higher food web levels are sustained with energy. ■

"We highlight the complexity of estimating annual and seasonal net primary production in the northwestern Barents Sea by combining different tools."

Laura Castro de la Guardia, NPI

References

Photo: Andreas Wolden

Times of dark and of cold: Winter's role in a sea of stark seasonality

From November to March the northern Barents Sea at 76–81°N is characterized by complete darkness, low temperatures and dense sea ice. Field studies during this time are logistically challenging but necessary to understand the complete annual cycle of physical, chemical and biological processes and life cycles of Arctic organisms. The icebreaker RV *Kronprins Haakon* enabled Nansen Legacy scientists to make important field observations that complement data collected by moorings and remote sensing.

Distinguishing between the polar night and the cold winter

A key objective of the Nansen Legacy was to deepen our understanding of the northern Barents Sea's seasonality, particularly during the less-studied winter months. In the Arctic, distinguishing between the polar night and winter is essential. The polar night, which lasts from November to February in our study region, is characterized by a lack of daylight, but it is not the coldest season. Multi-year mooring observations found the inflow of Atlantic Water to the northern Barents Sea to be the largest and warmest in this period, delaying sea-ice formation. Air temperatures drop to their lowest in March, coinciding with maximum sea-ice extent. As sunlight returns in March, large parts of the northern Barents Sea are covered by sea ice with a layer of snow on top. Previously, the sea ice made it challenging to access the area, but the completion of the Norwegian research icebreaker RV *Kronprins Haakon* in 2018 allowed the Nansen Legacy to explore the region also during the darkest and coldest times of the year.

Sea-ice formation and the annual cycles of CO_2 and mercury

New field observations enabled us to verify sea-ice model algorithms and satellite data. They could confirm that thin and uniform sea ice is formed locally already during the polar night, while older, thicker, and more deformed sea ice is imported from the north and east to the northern Barents Sea by large-scale atmospheric pressure systems in late winter and early spring.

Ocean chemists assessed the seasonally changing CO_2 concentration in the northern Barents Sea. Their data revealed that the area acts as an annual net ocean sink for human CO_2 emissions and that ice-covered waters in winter play an important role as a mediator for CO_2 exchange and ventilation. During ice freeze, CO_2 is transferred to deeper layers, while sea-ice melt and open areas in spring promote the exchange of CO_2 between the atmosphere and the water. Moreover, in the last two decades, the surface water CO_2 concentration increased at twice the global mean rate in the surface water and in the atmosphere. This fast increase was observed in areas with the largest ice loss, where more cold open waters allowed for more gas to dissolve. The increasing CO_2 concentration contributes to ocean acidification which has implications for the ecosystem (more details on page 31).

The new Nansen Legacy winter data also show that the ocean concentrations of the contaminant mercury vary with the seasons. Overall, the concentrations were well

Photo: Andreas Wolden

Photo: Alexander Eeg

Photo: Laura Kull

below levels of health risk, and lowest during winter. The scientists suggest that mercury may attach to sinking particles during this time of the year and settle to the sea floor.

Inhabitants of snow and sea ice

The new field observations made during winter also reveal that Arctic life is active all year round, not just during the better-known, illuminated summer months. Frost flowers, for example, form on top of sea ice and snow during the very cold winter months, and host unique communities of microorganisms. These include sulphur- and nitrogen-cycling bacteria among others.

Other small organisms inhabit the sea ice, which is not a solid ice block but a structure full of tiny channels and pockets. There, sea-ice meiofauna such as small copepods and worms thrive. Previously, it was known that meiofauna existed in sea ice during spring, but Nansen Legacy scientists have strengthened the understanding that many of these small organisms live active lives in sea ice throughout winter.

Zooplankton vertical migration during the polar night

During the polar night, the lack of light limits phytoplankton and ice algal production in the northern Barents Sea, and their contribution to the marine food web in this period is minor. Previously, it was assumed that due to lack of food other marine organisms would also be inactive during the dark and cold season. Acoustic mapping, however, showed a high abundance of large zooplankton north of Svalbard during winter. Specifically, these organisms accumulate in a thick layer in the core of the Atlantic inflow water (around 100 m depth) above the shelf break north of the Barents Sea. Some of the large zooplankton continue to perform daily vertical migrations in the water column during the polar night, a behaviour which was previously mainly observed during spring and autumn. Many zooplankton also actively avoid artificial light during the dark months. Even low light levels, such as those emitted by a research vessel, can alter zooplankton density in the upper water column.

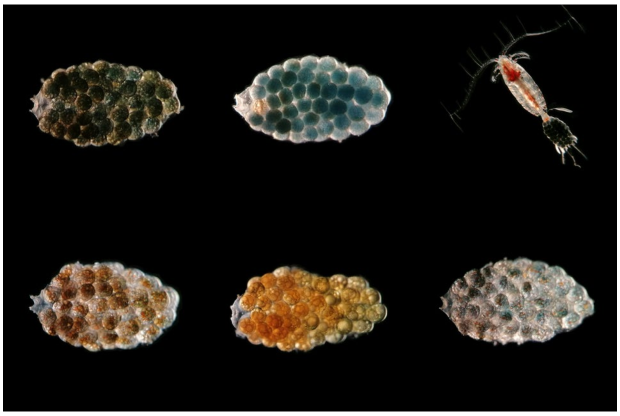


Photo: Christine Gawinski

Active life and reproduction in the dark and cold winter

Nansen Legacy scientists documented how production occurs even during winter when algae are inactive. While bacteria and other single-celled organisms (heterotrophic protists) produce less compared to phytoplankton, some can utilize naturally occurring sulphur as an energy source for production during the polar night. Additionally, winter-active zooplankton, such as the species *Metridia longa*, are opportunistic feeders with very flexible metabolic rates, allowing them to remain active throughout the polar night and utilize even scarce food sources. The large Arctic copepod *Calanus hyperboreus* reproduces during winter, with individuals producing over 300 eggs per female in December, leaving eggs to hatch and larvae to develop in winter. However, these animals likely rely mainly on fat reserves accumulated during the previous productive spring and summer to sustain themselves and their offspring.

These findings highlight important physical implications during the dark and cold winter months in the northern Barents Sea, for example on the uptake of CO_2. In addition, many organisms are well-adapted to the polar night and the cold temperatures. They live much more active lives during this period than previously thought. ■

"The emerging result is that there is generally more 'biological action' in the northern Barents Sea in winter than previously assumed. Perhaps that is not actually too surprising in a highly advective area, where tons of particulate carbon, nutrients and living organisms are being transported into the area with the Atlantic Water inflow from the south, and where that inflow is stronger in winter than summer."

Bodil Bluhm, UiT

Read more

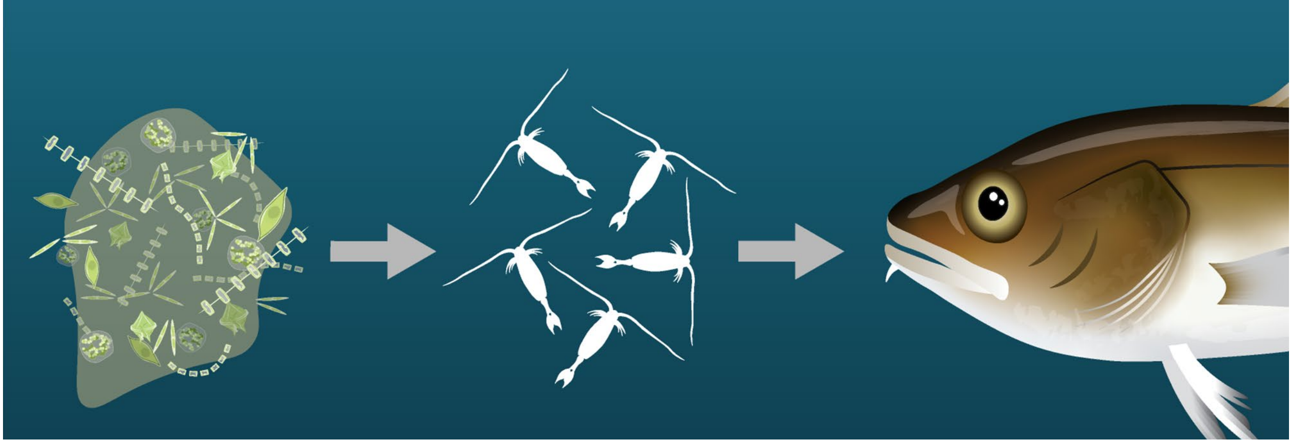


Illustration: Frida Cnossen

Disentangling the Barents Sea food web and the ripple effects of climate change

The reduced sea-ice cover in the northern Barents Sea reshapes the food web that supports a diverse range of marine life and commercially important species. Longer ice-free seasons, thinner, more dynamic sea ice, and increased Atlantification of the Barents Sea change the marine food web – resulting in smaller microbes, more inefficient energy transfer, and predators adapting their diets. Nansen Legacy researchers have increased our understanding of the food web, modelled fish stocks and attempted to disentangle the response to climate change in the Barents Sea.

Longer ice-free summers ripple through the food web

A food web is a complex network of interactions within an ecosystem. It illustrates who eats whom and the flow of energy and nutrients from one organism to another across different levels of the ecosystem. At the base of the food web are microbes and small phytoplankton. Typically, larger zooplankton, like the *Calanus* copepods, that feed on larger algae, such as diatoms, play a crucial role in spring by efficiently transferring energy up the food web to fish and other marine animals. Recent data from the Nansen Legacy indicate that with the earlier melting of sea ice, the summer season with less efficient energy transfer is extending. During this time, smaller phytoplankton, along with heterotrophic and mixotrophic single-celled organisms, dominate. This shift has implications, as smaller phytoplankton favor smaller copepods, which represent a reduced food package for larger fish or seabirds. The nutritional span from the larger Arctic *Calanus hyperboreus* to the smaller *Oithona similis* results in a reduction in carbon content per copepod, from roughly 200 µg to 1.5 µg. The dominance of smaller copepods introduces additional trophic levels in the food web, and with only 10-20% of the energy being transferred from one level to the next, this leads to less efficient energy transfer, impacting fish populations higher up in the food web. Moreover, a more prominent microbial community reworks and reduces the nutritional quality of organic matter sinking towards the seafloor. Such a scenario could alter benthic community structure and function, with consequences for nutrient recycling and other ecosystem services.

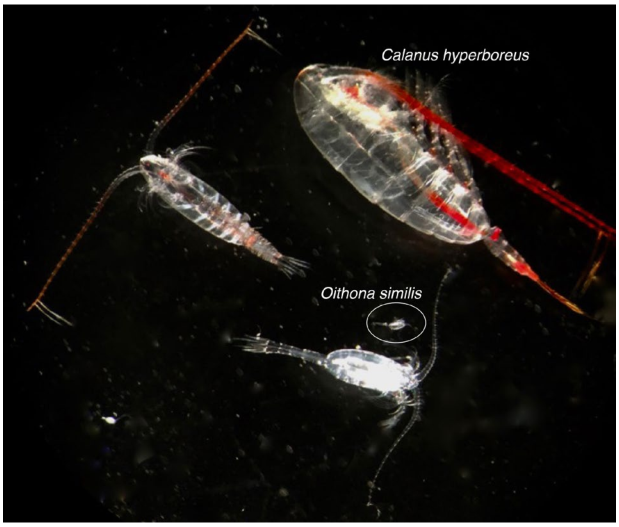


Photo: Camilla Svensen

In years with thinner and more dynamic sea ice, resulting shifts in the timing and location of phytoplankton blooms can have consequences for the entire food web. For example, in 2021 and 2022, exceedingly high phytoplankton (Chl a) concentrations were found in the Barents Sea, in both open and ice-covered waters. Simultaneously, low numbers of grazing zooplankton were observed across a wide area, leading to reduced feeding by capelin. This mismatch between producers and consumers left much of the fresh phytoplankton to sink uneaten towards the seafloor, resulting in low energy transfer to the pelagic food web and favoring the benthic system.

Larger animals adapt their diets in a warmer sea

Studies of fish stomachs indicate that the diets of Barents Sea fish are adapted to changing prey availability. Atlantification has caused capelin and polar cod, which traditionally feed on Arctic and sub-Arctic zooplankton, to consume less lipid-rich boreal zooplankton. Between 1990 and 2022, capelin predation was found to be a key factor controlling zooplankton biomass in the Barents Sea. Polar cod are more flexible, consuming both types of zooplankton as well as fish, which places them higher in the food web than capelin. Since polar cod are likely to decline with sea-ice loss and increased predation by Atlantic cod, capelin may exert greater pressure on the classic Arctic food web.

Marine mammals are also adjusting their feeding strategies. Minke whales have shown flexibility in their diet, switching from krill and capelin to larger fish depending on availability. Moving down to the sea floor reveals some surprises. Despite seasonally changing food quality, with up to a six-month lag after the spring bloom, the sea floor food web does not change with the seasons. Experiments with benthos have shown rapid adaptation to changes in food input, even for tiny organisms like foraminifera. This points toward resilient benthic food webs that might be capable of buffering some impacts of climate change.

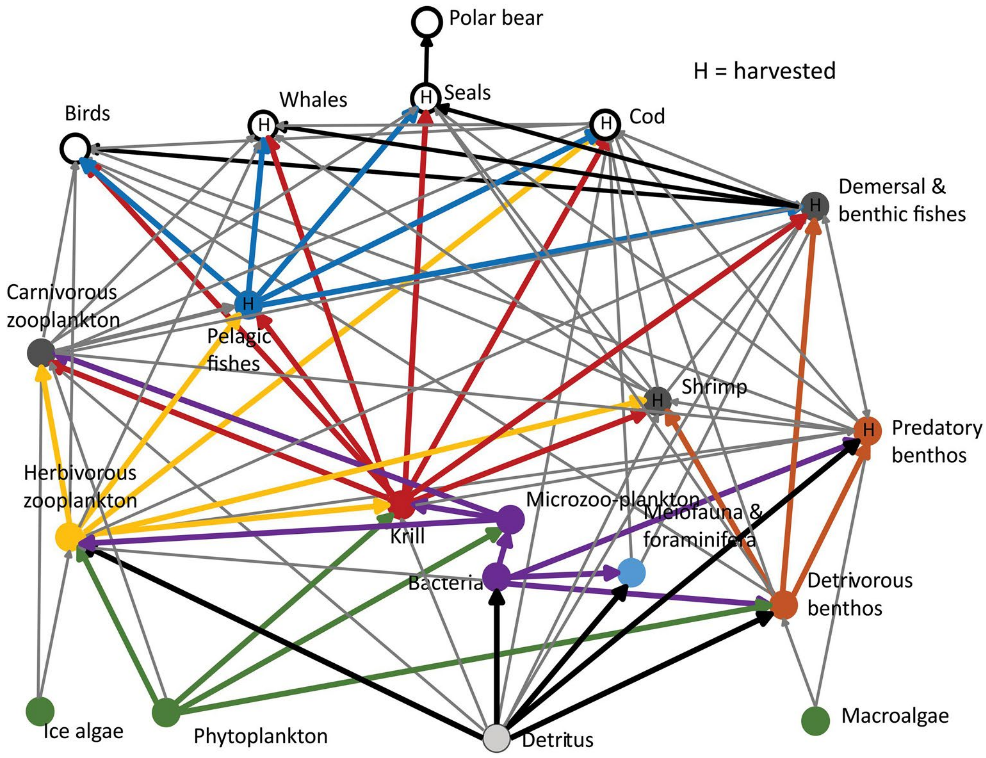
Modelling used to understand fish stocks

Fisheries and top predators compete for fish, but to what extent? A food web assessment that reconstructs the dynamics of marine mammals, fish, and fisheries for the Norwegian and Barents Sea, estimates that, on an annual basis, marine mammals consume an average of 11 million tons of fish, while fisheries capture 4.4 million tons. Predatory fish (like Atlantic cod) have themselves consumed an annual average of 9.5 million tons of forage species (like capelin) (for more, see page 61). Another study utilized a more detailed food web model ("Ecopath with Ecosim") to analyze the Barents Sea ecosystem and energy pathways from 1950 to 2013. It revealed that heavy fishing from 1970 to 1990 reduced the biomass of top predators, such as minke whales and adult Northeast Arctic Cod. A post-1990 reduction in fish harvest allowed the larger cod and whales to recover, likely aided by increased primary production due to warmer temperatures and reduced ice coverage. The model highlighted the significant role of krill in the food web (see figure above), supporting various levels, particularly after 2000, and the complex interactions between fisheries and the variability of lower food web organisms. These interactions differ between boreal and Arctic groups, which is important for informed ecosystem management.

Uncovering the previously unknown

Through extensive fieldwork since 2018, the Nansen Legacy has gained new insights into Barents Sea organisms and their food web functions. For instance, 12 species of larger zooplankton have been found to be more dependent on carbon from the water column rather than from the sea ice, which contrasts with earlier studies from the central Arctic Basin. Advances in genetic sequencing have uncovered the diets of tiny copepods, and rare winter data has revealed large amounts of organisms, from microbes to zooplankton, adapting their diets and reproducing during winter (for more, see pages 24-25). Additionally, stomach content analyses from over 27000 individual fish and 35 different species have revealed distinctions in diets between species and size classes. Fish that consume adult fish are typically planktivores (plankton-feeders) when young. Smaller species that are planktivores or benthivores (sea floor feeders) generally maintain similar diets throughout their lives. The role of snow crab in the ecosystem is relatively new, but it seems to have established itself in the Barents Sea and is unlikely to have a strong negative impact on the ecosystem.

The Barents Sea ecosystem continues to evolve under the influence of a warming climate, and it is crucial to understand these intricate food web dynamics. This understanding helps predict future changes and informs management and conservation strategies regarding the function and diversity of unique Arctic marine ecosystems. ■



Food web illustrating the many and complext interactions, from Pedersen et al. 2021, Frontiers in Marine Science.

"The ongoing changes in the northern Barents Sea are reshaping the food web that supports a diverse range of marine life and commercially important species."

Randi Ingvaldsen, IMR

References

Unravelling Fish Population Structure: Surprising Insights from Genomic Studies in the (Sub-) Arctic North Atlantic

Genomic analyses can give detailed insight into the population structure and differentiation within a species. This is important knowledge for sustainable fisheries management. Using state-of-the-art genomic tools, Nansen Legacy scientists have shed light on the population genomic structure, diversity, and connectivity of key fish species in the (sub-) Arctic North Atlantic.

Population genomics of capelin and polar cod

With the rapid development of genome resequencing technologies, it has become possible to gain an increasingly complete picture of the multifaceted variation that populations exhibit at the genomic level. To gain a comprehensive understanding of the population genomic structure of polar cod (*Boreogadus saida*) and capelin (*Mallotus villosus*) in the Barents Sea and surrounding areas, whole genome sequencing on a large number of specimens was performed. Estimates of genetic differences and similarities between individuals of the same species uncovered surprising and contrasting population structures for the two fish species.

Capelin

In capelin, a key prey species for Atlantic cod (*Gadus morhua*), the whole genome population genomic analyses revealed three distinct genetic populations corresponding to fish stocks in Iceland, the Barents Sea, and East Greenland. Several chromosomal inversions were identified. They occur when a specific segment of the chromosome breaks and reconnects in opposite orientations, thereby reversing the gene order on that chromosome segment. Two inversions displayed unique frequencies for the East Greenland stock, confirming the distinct subpopulation in this region with limited connection to the other two stocks. Genomic analyses also showed genetic variations among the Icelandic and Barents Sea capelin, suggesting the potential use of different spawning grounds. Historical reconstruction over the last 100 years revealed that all three capelin stocks likely experienced periods of decreased population size during periods that coincided with intensified fisheries.

Polar cod

For polar cod, there was no evidence of population genomic structuring within the study area. This lack of structure could partly be due to polar cod's dependence on sea ice, which connects different regions of the Arctic. However, a large number of chromosomal inversions spanning hundreds of genes were detected. Although polar cod has a uniform population structure in the region, analysis of the frequencies of the inversion genotypes suggests some geographic sub-structuring among the specimens. This finding indicates that the inversions may underpin differentiation among cryptic subpopulations or ecotypes of polar cod in the study region.

Large-scale chromosomal rearrangements unveiled among codfishes

By generating and analysing chromosome-level reference genome assemblies for six codfish species in a comparative framework, the scientists uncovered that large-scale chromosomal rearrangements, such as chromosomal fusions and inversion events, can arise among closely related species over a relatively short evolutionary time. For the cold-water-adapted Arctic cod (*Arctogadus glacialis*) and polar cod, multiple species-specific rearrangements were identified. Such rearrangements may capture and promote lineage among advantageous genes and thus possibly underpin evolutionary functions, such as adaptation to environmental conditions, as well as initiation and maintenance of genetic barriers between species pairs.

The results highlight the importance of genomic re-arrangements and their potential ability to facilitate local adaptation to environmental conditions, particularly in marine species experiencing few barriers to gene flow and high levels of connectivity. They also underscore the relevance of implementing genomic information in the present and future of sustainable management of marine species, especially in the predicted rapidly changing environment of the (sub)Arctic and North Atlantic. ■

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Photos: Christian Morel/christianmorel.net

Photo: Christian Morel/christianmorel.net

Mercury levels in the Arctic are increasing and vary with season

Many people know mercury for its use in old-fashioned thermometers. These thermometers are now banned because mercury is toxic and may cause serious problems to human health. But mercury also occurs naturally in the earth's crust. It is released into the environment and the Arctic is particularly prone to mercury pollution. Nansen Legacy researchers were the first to measure mercury levels in Arctic Ocean waters during winter.

Routes into the Arctic environment

Mercury can enter the environment via volcanic eruptions, forest fires, river runoff, and many other processes. The environmental behavior of mercury is presently affected by climate change. In the Arctic, for example, mercury is released from thawing permafrost and melting glaciers. The main release of mercury, however, is due to human activities, such as coal burning for heating and cooking, waste incineration, and industrial processes. Although these human activities are scarce in the Arctic, most mercury emission at lower latitudes evaporates to the air where it can persist in the atmosphere for over a year. This evaporated mercury can be carried by the wind to the Arctic, and settles to the ground, ocean or sea ice with snow or rain. Due to this transport, mercury levels in the Arctic have increased by a factor of 10 in the last 150 years.

Bioaccumulation in the Arctic

Once in the environment, bacteria can transform inorganic mercury into the more toxic methylmercury. Methylmercury can be taken up by marine organisms via their diet and the contaminant biomagnifies in the food web. This means that lower concentrations are found in organisms at the base of the food web and higher concentrations found in top predators. Biomagnification happens because one large fish eats many contaminated small fish, and many large fish are eaten by one seal or whale. Although most species in the Arctic are at low risk for adverse health effects from mercury exposure, there are some geographic hotspots of high mercury exposure. Due to the transported mercury, the relatively long food web, and the fact that the indigenous people heavily rely on Arctic wildlife for their food supply, the people living in the Arctic are amongst the human populations with the highest mercury exposure on Earth. Monitoring mercury concentrations in this part of the world is therefore of great importance.

Seasonal mercury cycle in the Arctic

Stephen Kohler and his co-workers investigated the full seasonal cycle of both mercury and methylmercury in the Barents Sea. They found that the concentration of mercury was lower in winter than in summer, possibly because mercury sinks to the sea floor. The concentration of methylmercury, on the other hand, was lowest in spring and highest in autumn. Since the low concentration of methylmercury coincides with the spring bloom, a massive increase in phytoplankton abundance, the researchers speculated whether these two phenomena are linked. Potentially, phytoplankton could transform methylmercury back to the less toxic inorganic mercury. If this is true, phytoplankton would play an important role in decreasing the concentration of toxic methylmercury in spring, potentially reducing the accumulation in the food web and the exposure to humans. This is good news and helps our understanding of natural and seasonal variability in contaminants. ■

"The toxic pollutant mercury accumulates in marine food webs on a global scale, with consumption of seafood as the primary exposure pathway for humans."

Stephen Kohler, NTNU

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Photo: Christine Gawinski

The Barents Sea is a sink for CO_2 – at the cost of zooplankton

Human activities have contributed to increased levels of CO_2 in the atmosphere, and the ocean has so far absorbed about 30% of the anthropogenic CO_2 emissions. With decreased sea ice and a longer open water period, the surface CO_2 concentration in the Barents Sea has risen in recent years, leading to increased ocean acidification during late winter and spring. The Nansen Legacy found that organisms with calcium carbonate shells, which reproduce during this coldest time of the year, may be particularly exposed to ocean acidification.

The Barents Sea is a hotspot for ocean acidification

Ocean acidification, known as "the evil twin of climate change", is occurring in all the world's oceans, but the Arctic is particularly vulnerable. Its cold waters can absorb more atmospheric CO_2 than warmer waters, and the declining sea-ice cover allows for more gas exchange between air and water, further increasing the ocean CO_2, especially during the cold season and when the surface is not covered by sea ice. Nansen Legacy scientists have, for the first time, assessed the carbon cycle and the state of ocean acidification across seasons in the Barents Sea. They found that the region is an annual sink for CO_2 and that the most rapid increase in CO_2 uptake seems to occur in the northern Barents Sea, where sea ice is declining and thus no longer limits the CO_2 uptake into surface waters. Two studies emphasized a particular risk of ocean acidification in winter and early spring, when the water surface is coldest. The northern Barents Sea presently takes up CO_2 at a rate two to four times the rate of atmospheric CO_2 increase.

Organisms' response to ocean acidification

Ocean acidification is particularly harmful to marine organisms that form shells and outer structures of calcium carbonate. These substances dissolve faster due to changes in the carbonate chemistry of the ocean towards more acidic (less basic) conditions. Under ocean acidification, the organisms need more energy to form and maintain their shells, resulting in thinner shells that make them more vulnerable to predators. Nansen Legacy scientists found high numbers of the shell-forming pteropods *Limacina* spp. (zooplankton, winged snails called sea butterflies) in the cold surface waters of the northern Barents Sea in winter and early spring. Pteropods reproduce during this period, and with the intensified ocean acidification at this coinciding time, pteropods and their offspring are particularly exposed to the negative effects of acidification. Not only may the organisms be affected, but pteropods also play an important role in transporting carbon from the surface to the seafloor. In this way, the ocean's capacity to store CO_2 may be disturbed. Other organisms, like cold-water corals, may not be affected by today's ocean acidification, but model estimates imply that corals will be exposed to damaging levels of ocean acidification by the end of the century if human emissions remain high.

Dealing with the evil twins, climate change and ocean acidification

With the northern Barents Sea warming and taking up more CO_2, the "evil twins" – climate warming and ocean acidification – may reinforce each other. Their combined effect was illustrated by a recent Nansen Legacy study, which found that ocean acidification alone did not have a visible effect on the larvae of the important Arctic copepod *Calanus hyperboreus*. However, the larvae required more energy to survive when simultaneously exposed to acidification and higher temperatures. This emphasizes the importance of conducting multiple stressor experiments (see page 32) and highlights the need to assess the ecosystem consequences of higher temperatures and ocean acidification in combination. ■

"The seasonally ice-covered areas of the Barents Sea are an annual CO_2 sink and are at increased risk of ocean acidification with greater sea-ice loss."

Elizabeth Jones, IMR

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Photo: Christian Morel/christianmorel.net

Multiple stressors in the Barents Sea: the impact of climate change on marine life

Increased seawater temperatures, reduced sea-ice cover, increased ship traffic, ocean acidification, and changes in prey and predator abundances. These are all consequences of climate change and stressors to the organisms living in the Barents Sea. Nansen Legacy studied the combined effect of multiple stressors on copepod survival and the effect of individual stressors on the survival of polar cod at different life stages.

Climate change comes with multiple stressors

The Barents Sea is undergoing rapid environmental changes with the ongoing climate change, which may act as stressors for the sea-ice associated species. Stressors are, but are not limited to, increased temperature, change in food quality or abundance, and exposure to pollutants. The organisms' response may differ if exposed to one or two multiple stressors, randomly in space and time. When exposed to multiple stressors, these stressors can interact, and their combined effect, i.e. on survival, may become stronger than the sum of their individual effects, so that 1 + 1 is not 2 but rather 2.5. Also, the effect of a stressor may differ depending on the life stage of an organism. Young individuals may be susceptible to one stressor, while adult individuals may be impacted by another.

Simultaneous multiple stressors during the winter of *Calanus glacialis*

The effect of anthropogenic stressors can be enhanced during winter when it is cold and dark and organisms in the Barents Sea are already exposed to challenging environmental conditions. This is comparable to us humans who are more susceptible to the flu in winter compared to summer. The Nansen Legacy studied the effect of multiple stressors on *Calanus glacialis*, a key copepod species in the Arctic food web. Short-term winter experiments showed that exposure to pyrene (a compound of crude oil) reduced survival by 50%. Increased seawater temperature, reduced pH, or the presence of microplastics did not reduce survival. Combined with pyrene, however, each of these stressors increased the negative effect of the oil compound and further reduced survival to 33%. The presence of a recovery phase (a period free of any stressors) improved survival compared to a continuous presence of pyrene or multiple stressors. The experiments used seawater temperature and pH values corresponding to projected values for the future Barents Sea, microplastic sizes that are commonly found in cosmetics products, and pyrene concentrations that are found in areas affected by oil spills, exploitation, and high shipping activities.

Multiple stressors throughout the lifetime of polar cod

Using model simulations, the Nansen Legacy scientists found that the abundances of polar cod aged 0 and 1 year were associated with sea-ice cover and seawater temperatures, while the abundances in adult polar cod aged 3 and 4 years were mainly associated with predation pressure/level. Throughout its life cycle, the survival of polar cod appears to be affected by different stressors, which are projected to intensify according to current environmental trends related to climate change.

Environmental and anthropogenic changes impact the survival and fitness of organisms in the Barents Sea. Knowledge of the effects of individual and multiple stressors, either through simultaneous exposure or throughout an organism's lifetime, is key in predicting how these species will respond to the expected environmental change and increased human activities. ■

"Determining how multiple anthropogenic stressors may interact to affect the survival of Arctic life, is crucial for ecological risk assessments and management, but this topic is understudied, especially during the Polar Nights."

Khuong van Dinh, UiO

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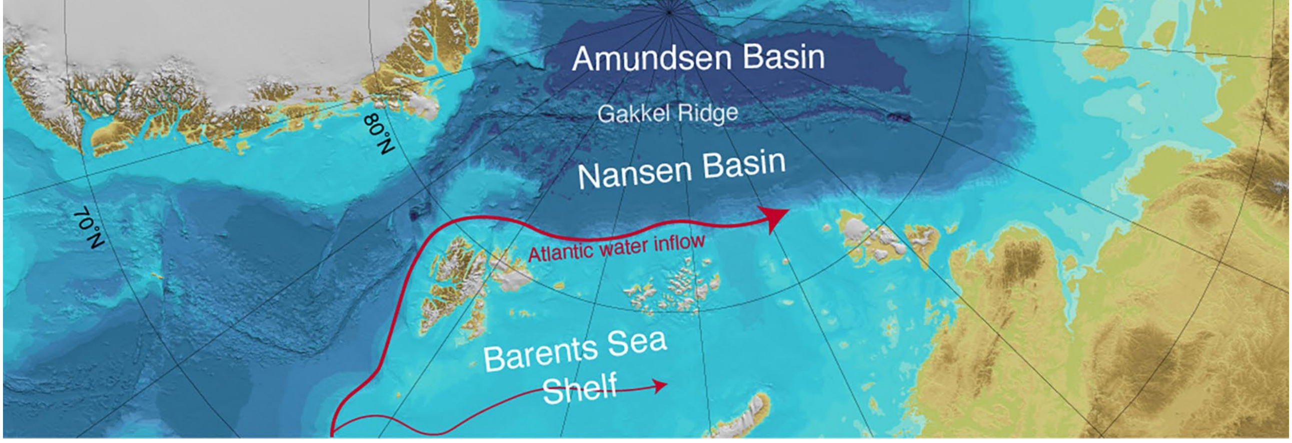

This map is edited from The International Bathymetric Chart of the Arctic Ocean (IBCAO)

A tale of two basins

When you venture north toward the pole, you leave the Arctic shelf seas behind and reach the deep waters of the central Arctic Ocean. In the dark, cold waters over 2000 m deep and covered by sea ice year-round, you might think that life is uniform. However, the Arctic Ocean is divided into different basins, and we found that the two on the Atlantic side, the Nansen and Amundsen Basins, differ not only in some features of their sea-ice characteristics and water masses but also in their ecosystems.

Two deep Arctic basins, distinct differences

The central Arctic Ocean, one of the last refuges of old and thick sea ice, has always been challenging to study. The Nansen Legacy organized a dedicated cruise to gather baseline data to support ecosystem monitoring and management. The Atlantic side of the Arctic Ocean, divided by the Gakkel Ridge, includes the ~3000 m deep Nansen Basin to the south and the ~5000 m deep Amundsen Basin to the north. The Nansen Basin, influenced by warmer and saltier Atlantic water, is relatively productive due to this inflow, which reduces sea-ice cover and introduces sub-Arctic species and additional nutrients. In contrast, primary production and numbers of organisms, including bacteria, decrease moving northward into the nutrient-poor, strongly stratified, and light-limited Amundsen Basin. Zooplankton communities differ significantly between these basins; krill are prevalent in the southern Nansen Basin but nearly absent in the Amundsen Basin, as these subarctic species can travel with the Atlantic water into the Nansen Basin. The researchers found, for the first time, Atlantic subarctic species as far north as 87˚N in the Amundsen Basin. Although very few organisms were found, ctenophores and amphipods were present in the water column, and harpacticoid copepods were most abundant on the sea floor.

Seven lonely fish

In 2021, the Nansen Legacy team covered a ~2330 km transect from the southern Nansen Basin to the northern Amundsen Basin, performing 12 trawl hauls for fish and larger zooplankton. These were the first-ever trawl hauls in the mesopelagic layer of Arctic basins. Only seven fish were found, representing three different species (pictured). Their prey, including larger zooplankton such as krill, amphipods, and copepods, were found in low densities. With the rapid loss of sea ice in the central Arctic Ocean opening new areas for potential fisheries, these findings provide valuable input to the international moratorium* and suggest that stocks of both economically and ecologically important fish and their prey in the Nansen and Amundsen Basins are extremely low.

Greenland halibut (larva) | Polar cod | Glacier lantern fish
Photos: Fredrik Broms

Important findings for management

The results highlight large differences in environmental conditions and ecosystem structures between the Nansen and Amundsen Basins. Also, compared to the northern Barents Sea, primary production is lower, and fewer, distinct species are present, some with slow growth, long lifespans, and unknown resilience to change. Tailored management strategies for different regions, in alignment with the proposed Biodiversity Beyond National Jurisdiction Agreement, are therefore needed. The relatively higher biological activity in the Atlantic-impacted near-shelf region of the Nansen Basin underscores that monitoring stations just north of Svalbard do not adequately represent the overall ecosystem status or responses to environmental changes across the entire Eurasian Basins. This reinforces that management assessments of changes in the marine system for the central Arctic Ocean cannot rely on the better-studied shelf slope alone and that the deep basins need to be assessed individually. ■

* The International Agreement to Prevent Unregulated Fishing in the High Seas of the Central Arctic Ocean

"We especially caution against using the area of strong Atlantic water inflow in the southern Nansen Basin as representative of the entire Nansen Basin, let alone the Amundsen Basin or the central Arctic Ocean in its entirety."

Doreen Kohlbach, UiT

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Photo: Yasemin Bodur

Photo: Sebastian Gerland

Leads – open windows in the sea ice

With thinner and more fragmented Arctic sea ice, leads and other small open water areas between ice floes are more common. They represent open windows for more exchange between the atmosphere and ocean and increase light penetration into the ocean, through the previously isolating snow and sea-ice cover. Leads can impact wind conditions several hundred kilometres away, as well as the timing of the phytoplankton blooms in the ice-covered ocean, and they are hotbeds for sea-ice production.

Heat loss impacts weather at long distances

A correct representation of the sea-ice conditions in models is very important for weather forecasts. The surface temperature difference between the cold sea ice and warmer ocean underneath is large, and with open water between the sea-ice floes, leads are found to be sites for great heat losses from the ocean to the atmosphere. This warms the air above the leads, impacting atmospheric dynamics. Traditional weather forecast models have operated with coarse sea-ice resolution and lacked finer-scale structures of leads. New model simulations represent leads more effectively, and it has been shown that wind conditions and surface temperatures were impacted as far as 500-1000 km from the ice edge.

New model tool for sea-ice fractures

A new way of describing sea ice in models (brittle rheology) has successfully reproduced sea-ice deformation and small-scale structures of sea ice, such as leads and ridges. The improved sea-ice model (neXtSIM) enables a realistic representation of sea-ice drift, transport, leads, and ridges, which are valuable for exploring the impact of such small-scale structures on large-scale characteristics and dynamics.

More winter sea-ice production in the leads

The new neXtSIM—NEMO model allowed Nansen Legacy researchers to delve deeper into the role of leads in the Arctic sea-ice mass balance. New studies of sea-ice mass balance for the central Arctic Ocean reveal that up to 25-30% of the winter sea-ice production (January–March) takes place in leads or coastal polynyas. The model results also show that the percentage has increased considerably in the period from 2000 to 2018.

Cracks and openings in the sea ice increase ocean acidification

Parallel with increased heat loss from open leads, the cooled surface water facilitates increased ocean CO2 uptake in winter when the isolating sea ice cracks and exposes open water to atmospheric CO2. Wind and mixing can also enhance the surface ocean CO2 uptake. The increased exposure of the surface ocean to the atmosphere caused by leads and reduced sea ice has increased the ocean CO_2 uptake in the northern Barents Sea two times the rate of global CO_2 levels, leading to enhanced ocean acidification.

Earlier Arctic Ocean spring with open windows

Leads, even when refrozen without snow, act as open windows in the Arctic Ocean in spring, because approximately two orders of magnitude more light reaches the underwater ecosystem here compared to adjacent sea ice. Sea ice and leads yield strong spatial variability close to the surface but average out at depth, meaning that a wide area underneath the leads receives more light. Given that low air temperature and the resulting convective mixing are not too strong, phytoplankton blooms can develop much earlier in spring below fragmented sea ice than in areas with a consolidated ice cover. ■

"Snow-covered sea ice transmits only about 1% of the incoming irradiance, meaning that the surface waters in the open lead receive about two orders of magnitude more light than waters under the adjacent sea ice."

Håkon Sandven, UiB

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Photo: Rudi Caeyers

Seasonal ice zones fuel pelagic and benthic life

The seasonal sea-ice retreat in the northern Barents Sea facilitates pulses of accumulating algal production – the ice edge bloom – attracting migrating organisms and feeding the local organisms. While the pelagic communities can follow the propagating productive pulses with the retreating sea ice, the rich supply of leftovers from the ice-edge bloom that sink to the bottom can serve the sessile benthic organisms for longer periods of the year. Nansen Legacy found that a changing sea-ice cover directly affects how tightly coupled the sea-covered waters are with the seafloor.

The attractive ice-edge bloom

Microalgae require light and nutrients to grow. Nutrients are remineralised at depth and brought back to the surface by ocean mixing during winter. At high latitudes, the light reaching the water is delayed in spring as it is still covered in sea ice and snow. Sea-ice break-up or melting allows the sun to illuminate the upper waters, creating perfect conditions for the algae to utilize winter accumulated nutrients and build large blooms until the nutrients are depleted. These high food concentrations attract migrating sea birds, marine mammals, fish and zooplankton, that can follow the retreating sea ice as it melts and exposes new areas of nutrient-rich surface waters to light. This period of sea-ice related blooms in the Arctic fuels the ecosystem with energy and is important for the productive areas in the seasonal ice zone – areas that are covered with sea ice parts of the year.

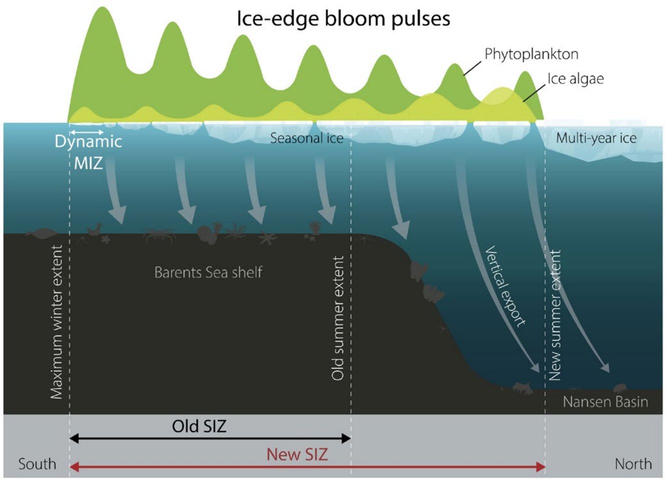

Illustration: Frida Cnossen

The sea-ice zone is expanding

While the geographic difference between the maximum and minimum annual sea-ice extent (known as the seasonal ice zone) used to cover the Arctic shelf sea areas only, the sea-ice reduction into the central Arctic Basin is now expanding. The coupling and supply of organic matter from algae and organisms in sea ice and the upper pelagic waters to the sea floor is relatively tight on the shallow shelves, where the Barents Sea is the deepest with 230 m average depth. A bloom following the seasonal ice zone into the central basin, will sink more than 3000 m to reach the benthic community. During the time this takes, much of the food is eaten or remineralised. The algal production can still be higher but will feed organisms living closer to the surface.

New findings from the Nansen Legacy

Nansen Legacy results documented that the benthic community in the northern Barents Sea receives a large part of their annual food supply from the ice zone blooms in spring. They will therefore represent an important part of the ice edge or sea-ice zone community despite being far south of the ice edge in summer. The repeated investigation of the Nansen Legacy transect resulted in data from two contrasting years in terms of sea-ice extension. While we were able to observe the ice edge bloom in the northern end of a still sea-ice covered Barents Sea in August 2019, the sea ice had retreated far into the central Arctic basin in August 2018. The extended open water period 2018, resulted in a pelagic system more dominated by microbial organisms and a stronger degradation of the material sinking to the sea floor.

The extended geographic stretch of the seasonal ice zone will therefore result in seasonal ice zone blooms that partly ends up in the deep central Basin, and partly prolong the open water and growth season, where a less efficient energy transfer to larger organisms dominates a larger period of the growth season. ■

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Data archives and public availability

Data sharing for increased use and public availability has become increasingly important. The FAIR-principles, introduced a decade ago, provide proper guidelines facilitating data sharing. With the huge data collection carried out within the Nansen Legacy, it has been a key focus to make data accessible and available for future use through proper data handling.

From office desks to global archives

The ocean is under-sampled. At the same time there is an increased need for updated information to monitor the ocean environment, map the marine ecosystems, and detect responses to climate change and the increased anthropogenic impact. This calls for a better use of the data that has been collected.

For a century, data has been shared as numbers or graphs in publications and stored in institutional data archives or personal notebooks and computers, but in this form data are not available for larger-scale integrations without considerable efforts and increased uncertainty. The Nansen Legacy did its uttermost to avoid this obstacle and made sure that collected and produced data are available for future use and new questions. With the multidisciplinary team, we had the opportunity to learn from the meteorological community, where data standards and sharing have a long tradition, and this was also beneficial for the scientists. As data publications with DOIs are citable, the data producer receives appropriate credit for data sharing, and updates of the datasets can be followed through separate versions.

The challenge of sharing data for use

The FAIR principles were developed to guide data sharing and facilitate a long data life and reuse in different contexts. The principles put a specific emphasis on the ability for machines to find and use data. The principles include Findability – data have a globally unique identifier, are published in a searchable resource and are associated with standardized metadata; Accessibility – the data can be easily retrieved through standardised communications protocols (e.g. HTTP, API); Interoperability – the data are in a formal, accessible, broadly applicable, and machine-readable language, using controlled vocabularies and including qualified references to other datasets; and Reusability – data are published with rich metadata meeting community standards, including a clear user license and details about the provenance of the dataset.

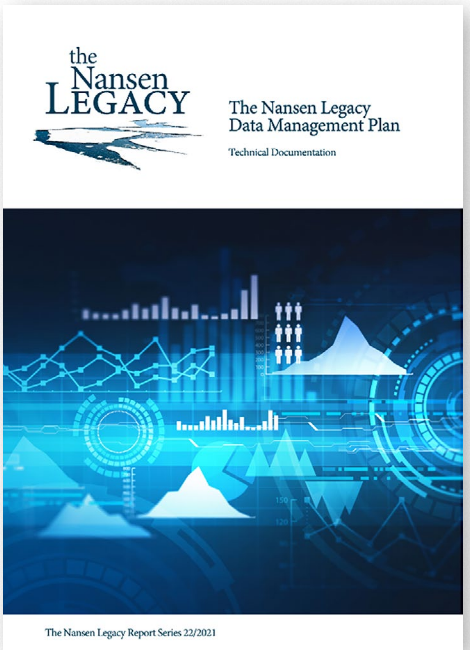
The Nansen Legacy made a major effort to implement these FAIR principles, to standardize sampling methods (see article on Implementation of a data sharing culture, page 65) and to develop tools for metadata registration during sampling or data production. Working with experts from, for example, the Global Biodiversity Information Facility (GBIF) ensured that data are formatted in adequate formats and meet the requirements of visibility and interoperability. A Nansen Legacy data portal in the Svalbard Integrated Arctic Earth Observing System (SIOS) facilitates access to data stored in institutional data centres. Through these efforts, the Nansen Legacy have successfully shared data in a FAIR manner.

Climate and nature crises call for open and accessible data

The climate and nature crises we are currently facing require data to build and update baseline information on species and environment as well as the rapid ongoing changes. The only way to solve this challenge is to join forces and share collected data openly and findable so that they can be used for further assessments. By respecting data producers and owners, and sharing what can be shared, the Nansen Legacy has contributed with much new data and datasets on the environment and ecosystem. This increases regional knowledge for management. It also contributes to a better understanding of the larger Arctic marine region. ■

"Data are the building blocks of knowledge, and the FAIR principles help us make the most of each one. Good data management shapes the future of science, ensuring today's data can contribute to tomorrow's discoveries."

Luke Marsden, UNIS/MET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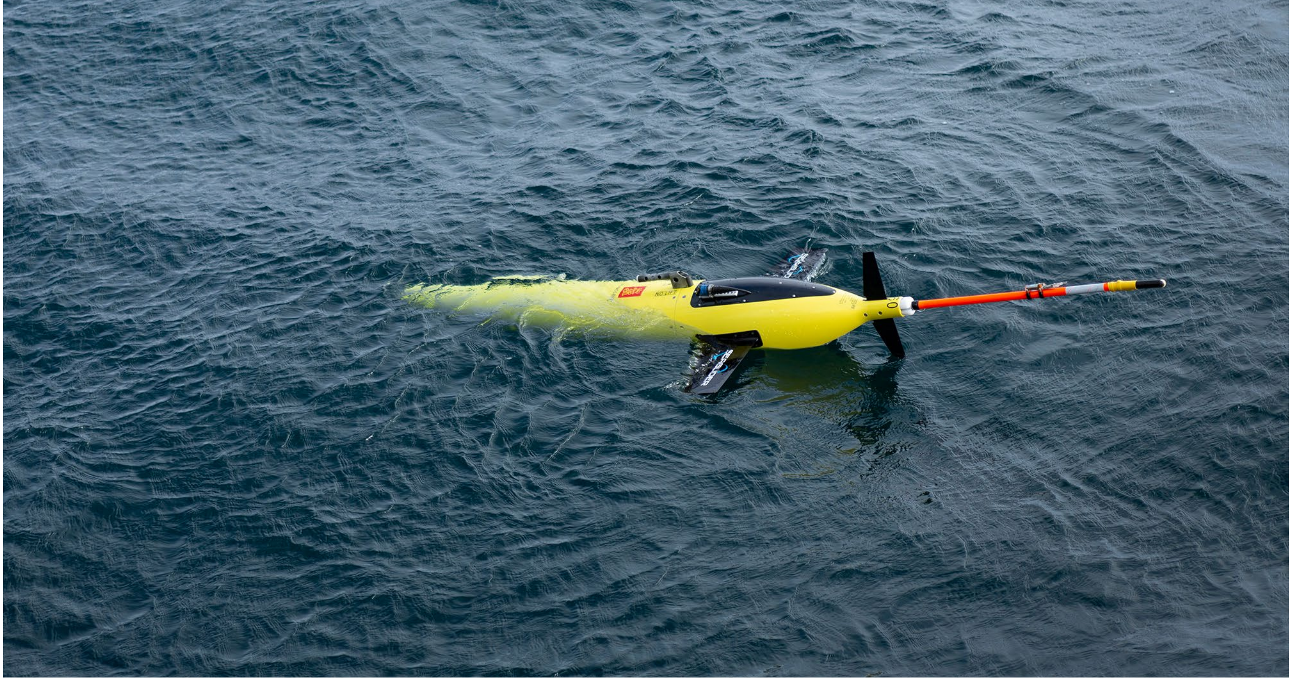

Photo: Christian Morel/christianmorel.net

Advancing technology for more cost-effective and integrated observations in the Arctic

Monitoring the rapidly changing Arctic seas is not easy. The vast area is characterized by harsh weather, winter darkness, and ever-changing sea ice. Observations by scientists are therefore infrequent and costly. Innovative developments and combinations of autonomous, cost-effective sensors, adaptive robotic sampling, and new data analyses in the Nansen Legacy enable a better spatially and temporally integrated understanding of the Arctic.

More observations with new cost-effective technologies

The infrequent scientific observations available from the Arctic hamper an integrated understanding of physical and biological processes, as well as validation of weather and climate simulations. To provide more observations, Nansen Legacy scientists have contributed to several cost-effective technological advancements.

In January 2022, the HYPSO-1 Cube Satellite was launched to monitor ocean colour in the Arctic. With a revisit time of 97 minutes in areas above 70 °N, this cost-effective satellite can provide time-series complementing fieldwork on the ground.

A limiting factor in the development of lightweight drones is building smaller sensors that provide the same data quality as larger ones. Nansen Legacy scientists have successfully equipped a low-cost, lightweight drone with a miniaturized sensor platform, including an upward-pointing spectrometer and a lightweight imaging spectrometer to acquire ocean surface data. This setup allowed for corrections for different light and atmospheric conditions without additional ground equipment. Additionally, a new method for direct georeferencing of drone images without ground control points was developed.

To measure waves in sea ice, a new cost-effective and robust sensor was attached to the front of the icebreaker RV *Kronprins Haakon*. It determined the ocean surface elevation inside and outside the marginal ice zone during a Nansen Legacy cruise, and wave attenuation in the marginal ice zone was shown to be frequency-dependent. Moreover, prototypes of the OpenMetBuoy-v2021 buoys were deployed during the cruises. These customizable, easy-to-build, and open-source instruments can monitor sea-ice drift and measure waves in open and sea-ice covered waters. The buoys are up to 10 times cheaper than the least expensive commercial alternative, and the data help to improve forecasts of ice drift and waves in sea ice.

Adaptive robotic sampling

Autonomous surface vessels can now help underwater vehicles with positioning aids that has been a challenge in such operations. A trajectory planning algorithm developed in the Nansen Legacy allows one surface vessel to aid both single and multiple underwater vehicles. Technological advances also allow autonomous underwater vehicles to adapt their sampling plan during a mission, which improves three-dimensional underwater observations. To identify, for example, where algal biomass is particularly high in the ocean, the vehicles can use their own measurements to identify relevant gradients and autonomously adjust their sampling path for higher resolution in areas where the algal concentration is high. Algorithms needed to coordinate several instruments in one sampling mission and to integrate observations with predictions by data simulations, satellite data, or ship-borne water samples are another advancement resulting from Nansen Legacy efforts.

Field-based validation data improve model performance

Nansen Legacy scientists not only collected new data but also integrated data in new ways. In one study, they combined atmospheric model simulations with field-based air temperatures collected on sea ice during the N-ICE2015 expedition and satellite data. This revealed that winter temperatures simulated by models were on average 4°C warmer than the ones measured on the sea ice. The poor representation of the snow layer on the sea ice was identified as the main reason for the too-high temperatures in the model simulations. These results are an updated Arctic weather forecasting system as well as improved Copernicus Climate Change Service's reanalyses.

Analysing data in a new way

Machine learning has advanced our observation analyses. Nansen Legacy scientists used this method to harmonize ocean colour images collected by two different satellite sensors. After the harmonization step, the ocean images collected by both sensors could be combined in the same analysis to achieve a better temporal resolution of observations. Combining and categorizing temperature and salinity observations by ships and autonomous instruments could also be done, providing a larger set of observations to test the accuracy of ocean simulations. Conventional methods helped to establish calibration coefficients, for example for two types of new underwater light sensors. Their calibrations will literally help to shed new light on bio-optical processes in the Arctic.

Risk analyses parallel with the development of technology

Developing new technologies involves various risks. New ways of assessing risk were therefore developed in the Nansen Legacy. This includes an online risk model, which uses autonomous marine systems under the sea ice as a case study. As few or no human operators are directly involved in the operation of the still expensive autonomous systems, it is critical to enhance the intelligence of the system by improving its situational awareness and decision-making. ■

"In-situ data are important ground observations necessary to calibrate satellite-derived algorithms used in remote sensing of the sea ice and to help further develop and calibrate fully coupled models."

Jean Rabault, MET

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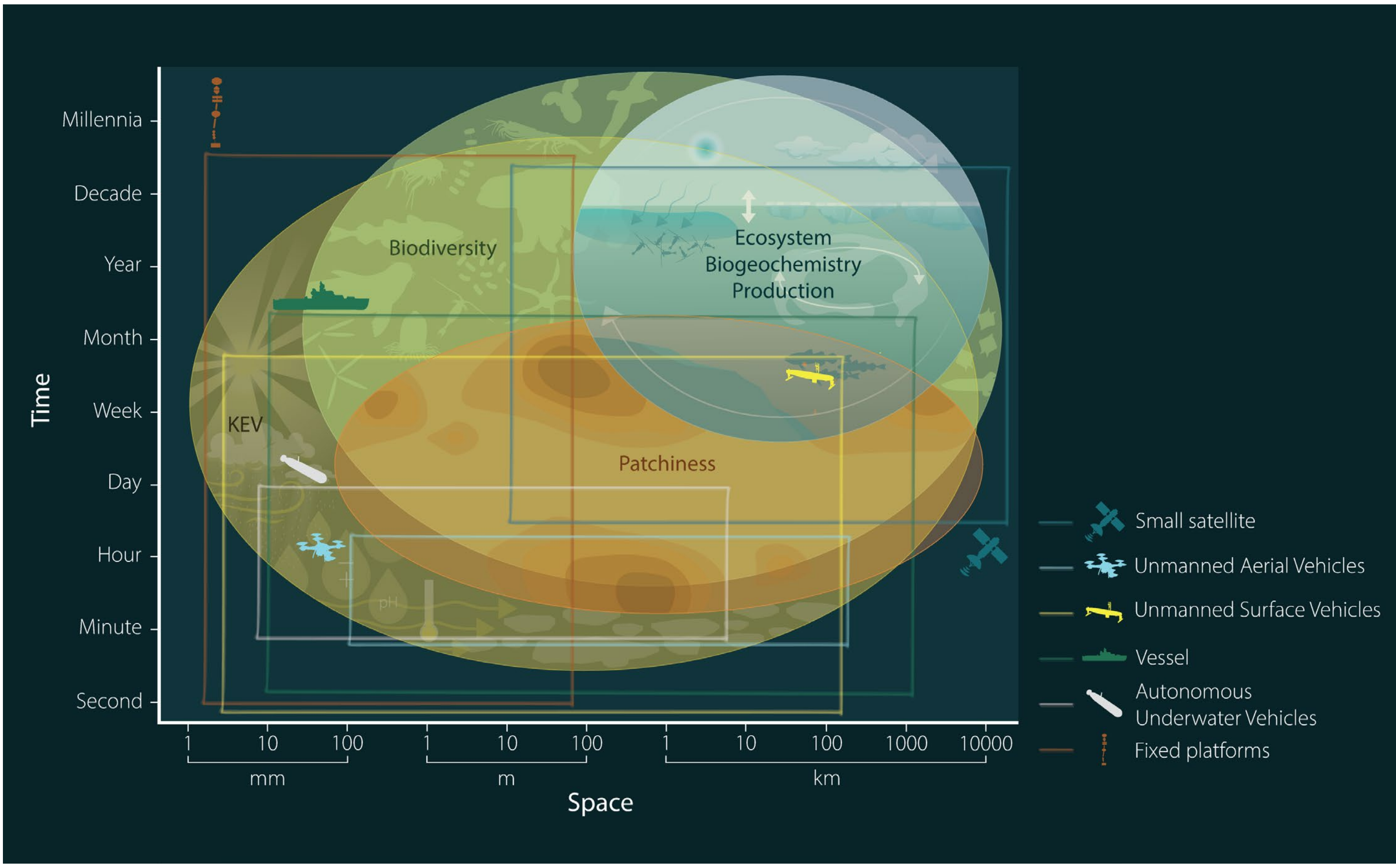

Illustration: Frida Cnossen

Photo: Kay Jørgensen

The future Barents Sea

In our everyday lives, we benefit from the weather forecasts for the upcoming days. Since the Norwegian physicist and meteorologist Vilhelm Bjerknes founded the modern school of meteorology > 100 years ago, our ability to understand the mechanisms involved in the climate system, the ocean-, and ecosystems has increased to a level where we now can say something about the more long-term future trends for the Barents Sea climate, the physical environment, and the ecosystem.

The Barents Sea – a preview of changes expected in the Arctic

The Barents Sea is a particularly well-suited spot to study the ongoing warming and responses in the Arctic Ocean. The effect of global warming is more pronounced in the Arctic than globally due to Arctic amplification, and the impact of the warm Atlantic current passing through the Barents Sea region makes this an early impacted site. Using a combination of historical data, field studies, experiments, and a toolbox of different models, we can project what the Barents Sea may look like in the future.

Researchers from the Nansen Legacy project have run and used different climate scenarios from IPCC models (Intergovernmental Panel for Climate Change) to predict how the Barents Sea will look in 2050 and 2100. The amount of anthropogenic greenhouse gasses in the atmosphere is an important variable in these models and scenarios based on both medium and high CO_2 emissions were used as input for other models and experiments.

2050 – a sealed fate

The climate models predict that the conditions in the Barents Sea in the year 2050 are more or less sealed. The expected changes in 2050 are the consequence of the greenhouse gases we have released in the past. Due to the slow but persistent response of the ocean to both warming and cooling, it takes time to reduce ongoing changes.

It is projected that air and seawater temperatures will rise, resulting in a reduced sea-ice cover. With less sea ice, more light reaches the surface waters earlier in spring, projecting a one-month earlier spring bloom. The potential consequences of an earlier onset of the spring bloom for the Arctic food web are further explained in the articles "Disentangling the Barents Sea food web and the ripple effects of climate change" (pages 26-27), and "Plankton production in open and sea-ice covered waters" (page 23). It is also projected that the pH of seawater will reduce, as less sea ice means more available sea surface to absorb the increasing atmospheric CO_2 concentrations. More on the consequences of ocean acidification can be read in the article "The Barents Sea is a sink for CO_2" (page 31). Due to rising seawater temperatures and reduced sea-ice cover, it is also projected that boreal fish species such as Atlantic cod will migrate and have their spawning grounds further north where they can interact and prey on Arctic fish species.

The major paradox is that these projected changes for the Barents Sea in 2050 occur regardless of whether we continue with high greenhouse gas emissions today or shift to a scenario with medium greenhouse gas emissions. The important message is that the response of a selected moderate emission pathway will become evident by the end of the century.

2100 – a response to today's decisions

The future of the Barents Sea in 2100 depends on the severity of human-driven climate change in the years to come. The changes projected for 2100 in the physical environment, ocean biogeochemistry, and ecology are all intensified changes compared to those projected for 2050. However, the amount of greenhouse gas emissions determines the intensity of the projected changes.

By 2050, air temperature in the northern Barents Sea is projected to rise by 6°C, no matter the emission scenario. For 2100, however, this temperature rise is projected to

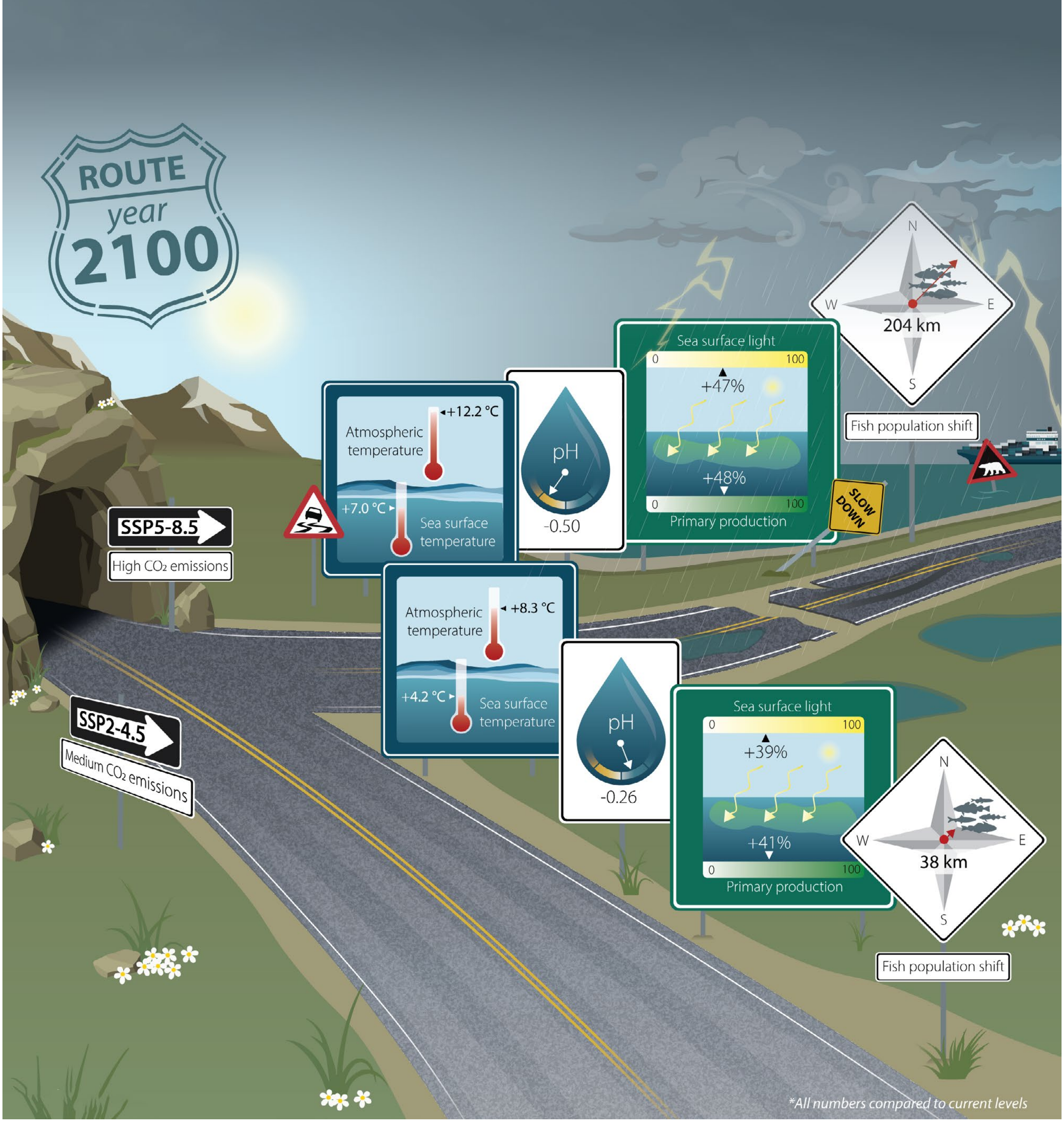

Illustration: Frida Cnossen

exceed 8°C with medium emissions, and over 12°C if we continue with high emissions. Sea surface temperatures in this part of the Barents Sea are projected to increase with over 4°C under medium emissions, and 7°C under high emissions in 2100. The northward expansion of boreal fish species also depends on future emissions. Under high emissions, a northeastern shift of 200 km is expected, compared to 38 km under medium emissions.

The uncertainty of model projection increases the further in the future the model projects. The year 2100 is outside the time horizon for the management of living marine resources, but the models can still be used to project the implications of our actions today for the more distant future. While an abrupt decline in greenhouse gas emissions will come too late to avoid the projected changes in the Barents Sea ecosystem in the year 2050, reducing greenhouse gas emissions today, could still weaken the impact in the year 2100. Although even with medium emissions, the projected changes for the Barents Sea 2100 are exacerbated changes compared to 2050. ■

"Whereas near-future (toward 2050) climate change impacts in the Barents Sea are more or less determined from the emissions we already have committed, we show that the severity of anthropogenically-driven climate change in the longer term is still not decided."

Marius Årthun, UiB

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Glimpses of the Nansen Legacy research

The Nansen Legacy science team has, in recent years, discovered so many new mechanisms in the Barents Sea system that it is not possible to compile all of them in this report. We, therefore, complement the scientific highlights with some glimpses of other new (and often unexpected) findings during the Nansen Legacy.

The living Barents Sea

- ➢ Model results based on 30 years of survey data showed that young polar cod survival is more sensitive to the presence of sea ice, while older/adult polar cod is more sensitive to predation from cod (**Dupont et al. 2020**)
- ➢ Krill and amphipods are important prey for larger marine animals, but their energy content varies with the season, and body size alone is therefore a poor predictor of their energetic content (**Nowicki et al. 2023**)
- ➢ The shells of foraminifera are often used in micropaleontology. A mismatch between high abundances of living foraminifers in the water and a lack of fossils in the sediment of the northern Barents Sea suggests that the shells dissolve in this region (**Anglada-Ortiz et al. 2023**)
- ➢ Bottom-living organisms in the Arctic have been shown to quickly react to increased input of carbon. This suggests that additional algae production in a warmer, less ice-covered Arctic may not necessarily be stored and sequestered at the seafloor but utilized and processed by benthos (**Sen et al. 2024**)
- ➢ Analyses of minke whale diet suggested that the whales have adjusted to the ongoing borealization of the Barents Sea. In the past, they consumed mainly small pelagic fishes, but now they seem to exploit more krill and demersal fish (**Haug et al. 2024**)
- ➢ A survey investigating the pelagic food web found extremely high chlorophyll *a* concentrations that were largely invisible to satellite remote sensing because of sea ice and clouds. This coincided with low concentrations of zooplankton and suggests a mismatch between prey and predator (**Renaud et al. 2024**)

Hydrography and sea ice

- ➢ Sea ice in the northern Barents Sea changes throughout the winter. In early winter, the ice is rather thin, homogenous, and locally formed, while in a later winter phase, the sea ice is thicker, deformed, and older because then sea-ice import from the central Arctic Basin and the Kara Sea prevails (**Lundesgaard et al. 2022, Efstathiou et al. 2022**)
- ➢ The development of a new brittle Bingham-Maxwell rheology model improved the sea-ice physics representation in the sea-ice model, neXtSIM, because it can simulate how sea ice reacts to wind and ocean currents (**Ólason et al. 2022**)
- ➢ Surface warming associated with Arctic cyclones depends not only on their strength, but most importantly, on their origin and the path they take toward the Arctic. Variability is large for all Arctic cyclones, but particularly for those with genesis at high latitudes (**Madonna et al. 2020, Tao et al., in revision**)
- ➢ North of Svalbard, tidal forcing seems to be the major source of turbulence in deep water layers and near the seabed (**Koenig et al. 2021**)
- ➢ Seawater flooding of the snow–ice interface on the sea ice can lead to underestimations of snow depth or overestimations of sea-ice freeboard. This impacts the accuracy of sea-ice thickness estimates from airborne snow radars (**Rösel et al. 2021**)
- ➢ A previously unknown deep current was discovered north of Svalbard at 1500-2000 m depth, flowing parallel, but deeper, to the well-known Atlantic Water Boundary Current at 75-500 m depth (**Kolås et al. 2020**)

Environmental stressors: pollution, warming and sea-ice loss

➢ Contrasting the rate of global atmospheric CO_2 increase (roughly 2 µatm yr^{-1}), the Arctic Ocean fCO_2 increases at 4.2 and 5.5±0.6–1.1 µatm yr^{-1}, accelerating Arctic Ocean acidification (**Ericson et al. 2023**)

➢ Previously it was assumed that mercury concentrations in the water column were conservative throughout the year. New results indicate seasonal changes driven by seasonal inputs and biological activity, with different seasonality of total mercury and the toxic form methylmercury (**Kohler et al. 2022**)

➢ Polar cod exposed to crude oil spawned earlier, which was unexpected because previous studies reported delays in reproductive development following crude oil exposure (**Strople et al. 2023**)

➢ Long-chain poly- and perfluoroalkyl substances (PFAAs) are bioaccumulative, synthetic chemicals, that can have toxic effects on humans and biota, but it was unclear how they enter the Arctic food web. They were now found in high concentrations in the uppermost sea-ice layer, likely deriving from rain or snow (**Garnett et al. 2021**)

➢ Pelagic organisms seem to avoid artificial light emitted from instruments lowered in the water column (including red light, 575–700 nm). The density of organisms decreased by up to 99% when exposed to artificial light, and the distance of avoidance varied from 23 to 94 m (**Geoffrey et al. 2021**)

Technology and Method Development

➢ Recent, unprecedented extreme precipitation events over Svalbard are becoming more likely in the future because the sea-ice decline along East Greenland directs more moist air towards Svalbard (**Müller et al. 2022**)

➢ Reanalysis of 54 fish stock collapses around the world showed that the stocks respond to environmental drivers differently after a collapse, so caution is needed when using pre-collapse knowledge to advise on population dynamics and management **(Durant et al. 2024)**

➢ A standard protocol was developed that allows for the evaluation of ecological models using the objective(s) of the modelling application, the ecological patterns of relevance, and the evaluation of the methodology proper (**Planque et al. 2022**)

➢ Methods, tools and results for efficiently collecting metadata and tracking samples collected in the field have been compiled and are available for other multidisciplinary projects (**Ellingsen et al. 2021**, **Marsden & Schneider, 2024**)

➢ By equipping an autonomous underwater vehicle with a microstructure sensor and an automated adaptive sampling, turbulence in the polar front could be measured at much finer horizontal spatial resolution than by traditional vertical profile measurements (**Mo-Bjørkelund et al. 2024)**

➢ New risk models were developed to inform the autonomous marine systems, like autonomous underwater vehicles (AUVs), about the risk level and to make risk-based decisions accordingly. This improved the AUVs' intelligence (**Yang et al. 2023**)

Photo: Peter Leopold

Fun facts

Some discoveries are just so surprising that even scientists scratch their heads. Here is a choice of the most extraordinary findings in the Nansen Legacy.

Far out over the Arctic Ocean, our scientists were surprised to find a piece of **green moss** in the sediment samples collected **at 4000 m depth in the Amundsen Basin**. Was this contamination, or was this moss from the Siberian tundra that was flushed by a river into the ocean, where it froze into the sea ice, drifted across the Arctic Ocean, and was then picked up by the Nansen Legacy scientists from the sea floor? (*Nansen Legacy Benthos team, personal communication*)

Genetic analyses revealed that many small copepods had grazed upon comparable large planktonic arrow worms. This was surprising because it is commonly assumed that arrow worms graze on copepods and not the other way around. (*Flo et al. 2024*)

Experiments showed that **females of the copepod *Calanus hyperboreus* produce hatched eggs** after more than **2 years in the laboratory** – even if they are incubated without mating males. This suggests that the females can either keep sperm for over 2 years or that their unfertilized eggs have the potential to hatch. (*Van Dinh et al. in prep*)

The **brittle star *Ophiopleura borealis*** is quite a small animal with a central disk of up to 4-5 cm. Its bands have age rings, like tree rings, and a master's thesis revealed that this small brittle star can be as **old as 39 years**! This is a new record for Arctic brittle stars! (*H. Dinevik*)

The Nansen Legacy team found an ear bone of a polar cod in the surface sediment of the Arctic basin at more than 4000 m depth. Age-dating showed that the **Polar cod ear bone was 4000-5000 years old**. Finding this on the surface of the sediment suggests two astonishing things: 1) Polar cod has apparently been **present in the central Arctic Ocean basin for a few thousand years**, and 2) **very little material seems to sink to the sea floor** in the central Arctic Ocean – otherwise, the ear bones would have been buried deep in the sediment. (*Nansen Legacy Benthos team, Kohlbach et al., in revision*)

Minke whale defecation has the potential to **stimulate 0.2 to 4% of the daily net primary production** in the small management area south and west of Svalbard (*Freitas et al. 2023*). Similarly, extremely nutrient-rich water draining from **seabird colonies seems to fertilize adjacent coastal waters** (*Finne et al. 2022*).

Five species of red, green, and brown **macroalgae were found to grow during the Polar Night**, and the species *Saccharina latissima* and *Alaria esculenta* grow up to **50 cm in length** during the three darkest months of the polar night (*Summers et al. 2023*)

During the Nansen Legacy cruise to the **central Arctic Ocean**, 12 pelagic trawl hauls were conducted between the ice floes. They showed that a lot of zooplankton is present there, but little fish: **Only seven individuals of three fish species** (*Boreogadus saida, Benthosema glaciale* and *Reinhardtius hippoglossoides)* were **caught** (*Ingvaldsen et al. 2023*). ■

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Photo: Andreas Wolden

Photo: Robin Hjertenes

Nansen Legacy field efforts and sampling approaches

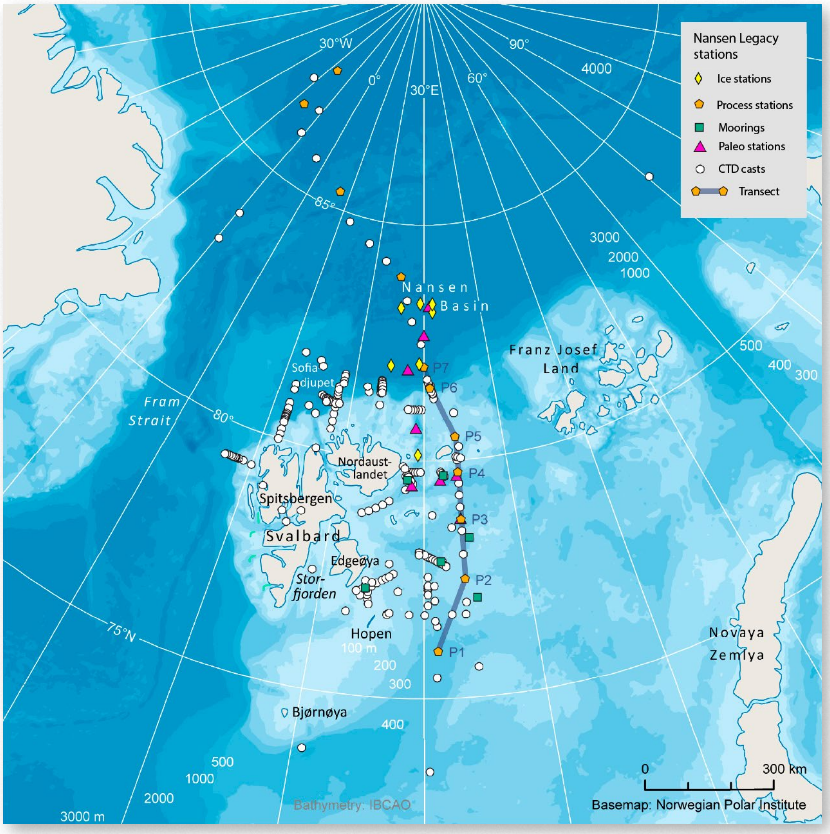
The Nansen Legacy has conducted a total of 21 research expeditions, summing up to over one year at sea – 386 days of ship time. About 300 of these were on the new ice-breaker RV *Kronprins Haakon*. These research cruises gathered high-resolution data at different seasons and across various physical, chemical, and biological parameters of the northern Barents Sea and the adjacent Arctic Ocean system. Developing technology to improve observational capacity in Arctic waters has also been a key focus of the project.

An important coordinating backbone was the Nansen Legacy transect prolonging the established time-series transect of IMR. The transect starts in open water south of the Polar Front, cuts through the seasonally ice-covered northern shelf, and ends just north of the continental slope in the deep Nansen basin. Stations for process studies were identified and investigated with seasonal and interannual coverage. A network of moorings was established at key sites to detect Atlantic water inflow and biogeochemical characteristics with year-round measurements.

The Nansen Legacy researchers have collected an abundance of samples and data to gain more knowledge about the Barents Sea and Arctic Ocean. Here we show an overview of the sampling stations and range of different methods that have been used within the project.

Illustrations: Frida Cnossen

In field sampling, covering both temporal and spatial scales is crucial for understanding variability and the interplay of different processes. The Nansen Legacy optimised observational capacity by combining logistics and expertise from partner institutions. Ship-based sampling captures processes and interactions from open water to the Arctic Basin, including the seasonally sea-ice covered shelf. Using a range of moorings equipped with sensors to monitor key variables year-round, complemented the ship-based sampling. Geological cores contribute to our understanding of long-term climate variability. At the same time, remote sensing, glider deployments and the use of helicopters and/or autonomous underwater vehicles (AUVs) enhance spatial coverage and improve data collection.



Joint sample collection and process studies

Interdisciplinary sampling of organisms ranging from viruses to fish to map biodiversity, measure production, or estimate food web connections was carried out on joint cruises. Sampling of the physical and chemical environment was conducted, including contaminant measurements and onboard experiments.

Helicopter with EM-bird

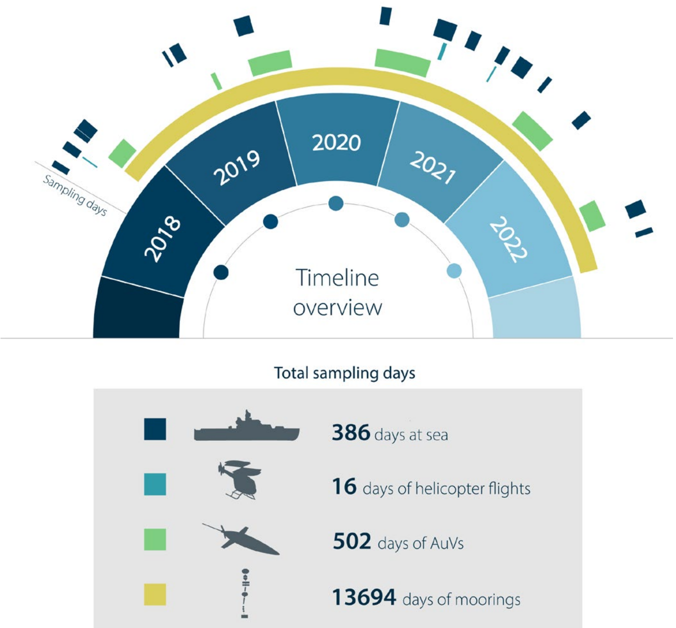
The electromagnetic (EM)-bird measures both sea ice and snow thickness. The use of an EM-bird is complementary to detailed studies by sea-ice physicists on the ice floes near the vessel, and satellite remote sensing. Weather permitting, the helicopter can cover larger areas and several ice floes and provides detailed observations that help map the spatial variations in sea-ice thickness within the study region.

AUVs

Several types of AUVs were used during our fieldwork, and gliders represent the most extensively used instrument. Gliders are deployed and retrieved by research vessels and can be operated for several months along pre-programmed transect lines, as well as being remotely controlled by pilots on land. The gliders have been an important supplement to moorings by extending our spatial measurements.

Moorings

Moorings, equipped with sensors at different depths, provide continuous observations over several years and serve as our longest-recorded datasets within the Nansen Legacy. Sensors can measure hydrographic, chemical, and biological characteristics, respectively. ■



"Dedicated work with logistics has been critical for the efficient use of available time on RV Kronprins Haakon*. Through my efforts, we have freed up time for researchers to focus on their research rather than worrying about unnecessary administrative and logistical challenges."*

Simon Sagelv Bjørvik, UiT

Modelling approaches in the Nansen Legacy

The Nansen Legacy researchers have used and combined a range of different models. The models are specialized to represent and explore different compartments relevant to the ocean and ecosystems. They help us to zoom in and out in time and space and integrate our often-fragmented understanding of specific processes or compartments.

Model approaches

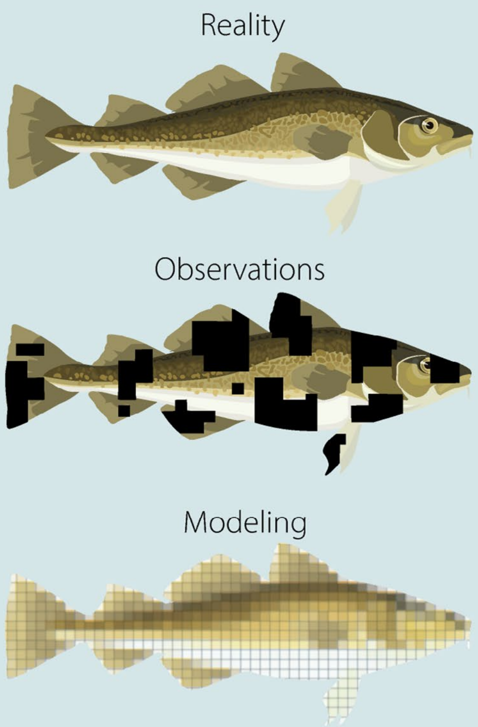
The >20 different models used by the Nansen Legacy community represent a complementary approach to field observations, focusing on different parts of nature and impacts of human activities. The models comprise a complementary and wide specter of tools that help us understand the complex processes in the ocean in better detail, either in combination or as a part of a larger global system. This can, for example, be how fractures in sea ice, on a small scale, can be translated to large scale impact on weather conditions, or how global features like climate warming act on regional scales like heat transport with ocean currents or sea-ice formation. Coupled physical-biological models can help us understand how increased ocean temperatures impact changes in growth or survival of specific species in the ecosystem, and the cascading impact on other species and the whole system. By understanding present global and local conditions, models can reconstruct the past, and forecast, predict, or project possible future scenarios on shorter or longer time scales.

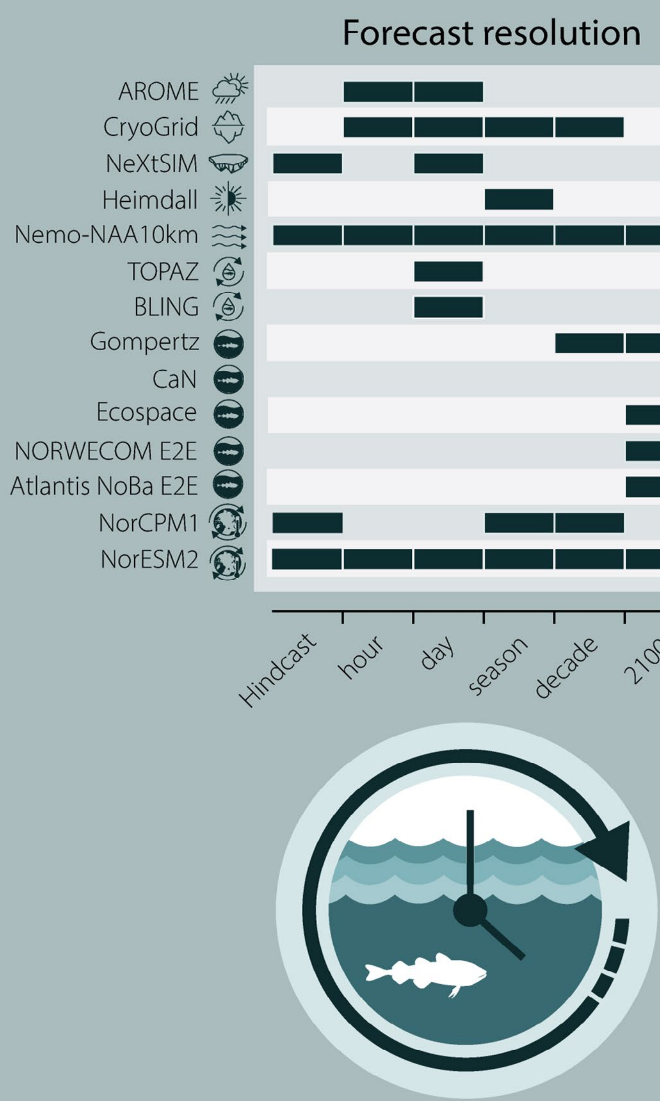
Different models address different scales and complexities

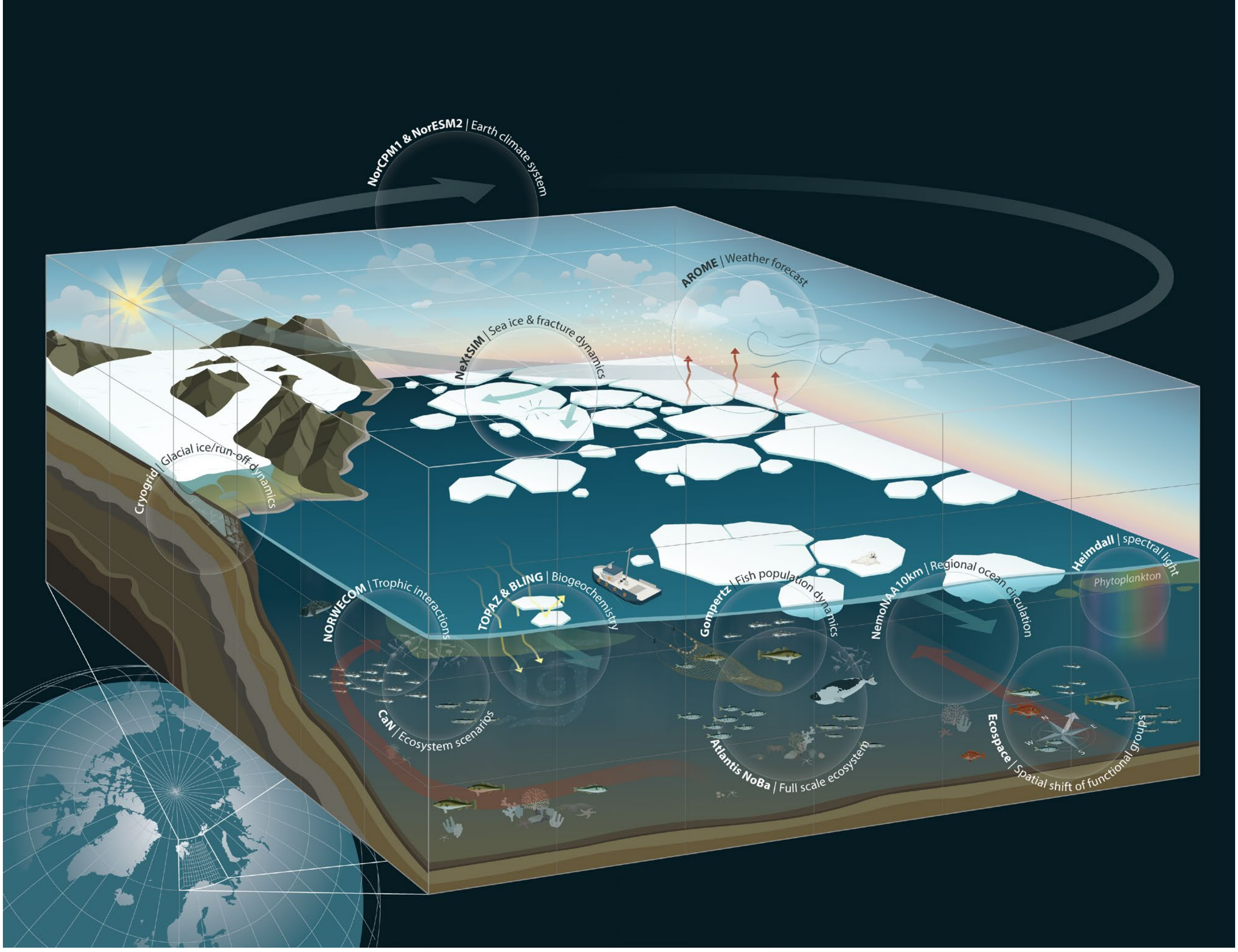
The cost of running a model depends on the complexity and resolution of the model. End-to-end (E2E) ecosystem models driven by physical models of intermediate spatial resolutions require huge amounts of computational time and storage space. Models that explore the possible outcomes of interactions among selected key ecosystem species on the other hand, are much simpler models. They can be run thousands of times to identify the specter of possible outcomes. Some models focus on smaller regions, and shorter time spans, like weather forecasts, while others include global processes and make projections for several decades in the future, like the NorESM model (Norwegian Earth System Model). None of the models can answer all questions, so it is therefore important to use the type of model that best represents the specific questions we ask. ■

What is a model?

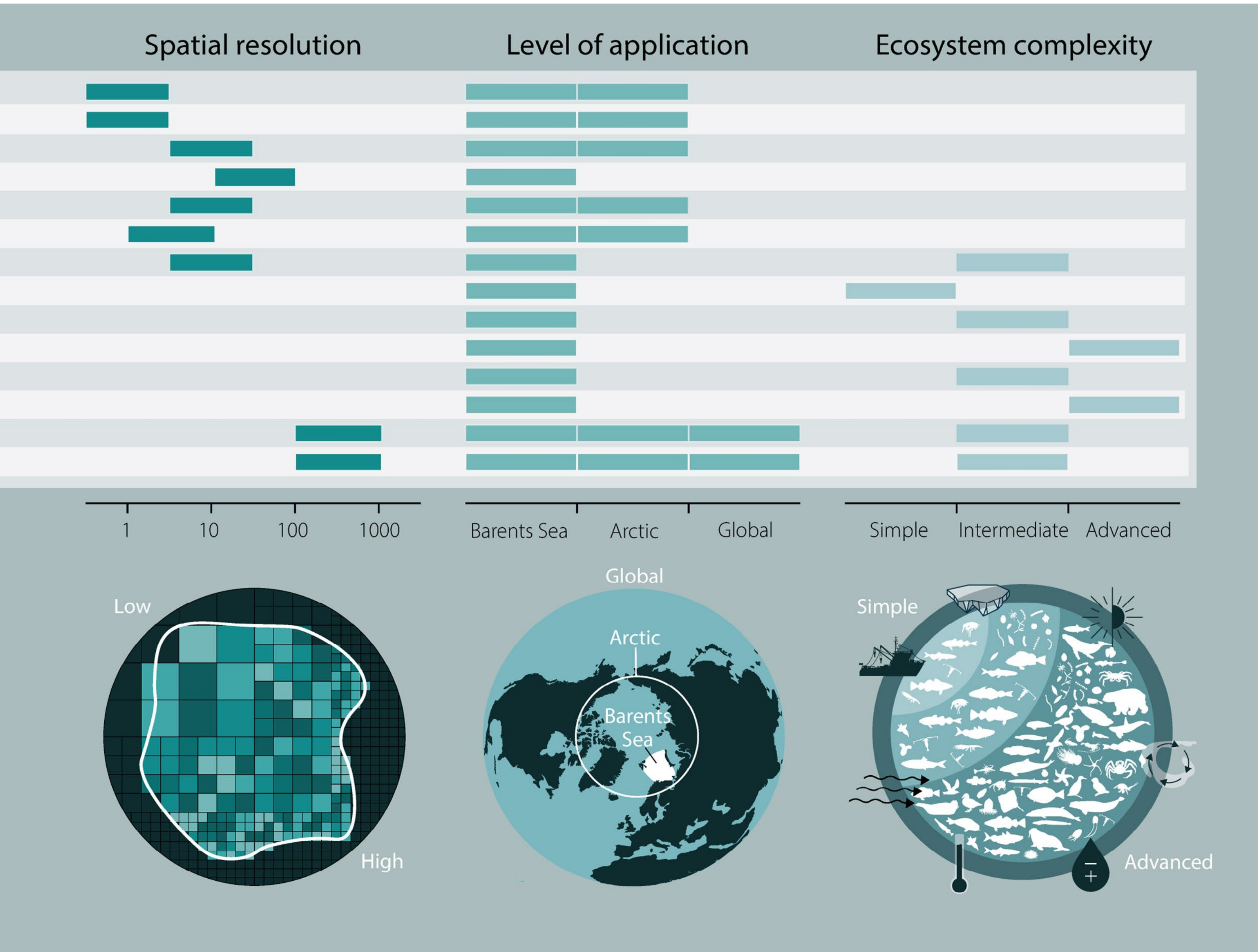
With fragmented pieces from field observation, experiments, and general knowledge, the models can help to zoom out to a larger picture and a longer time scale to provide a more complete understanding of a system like the Barents Sea.

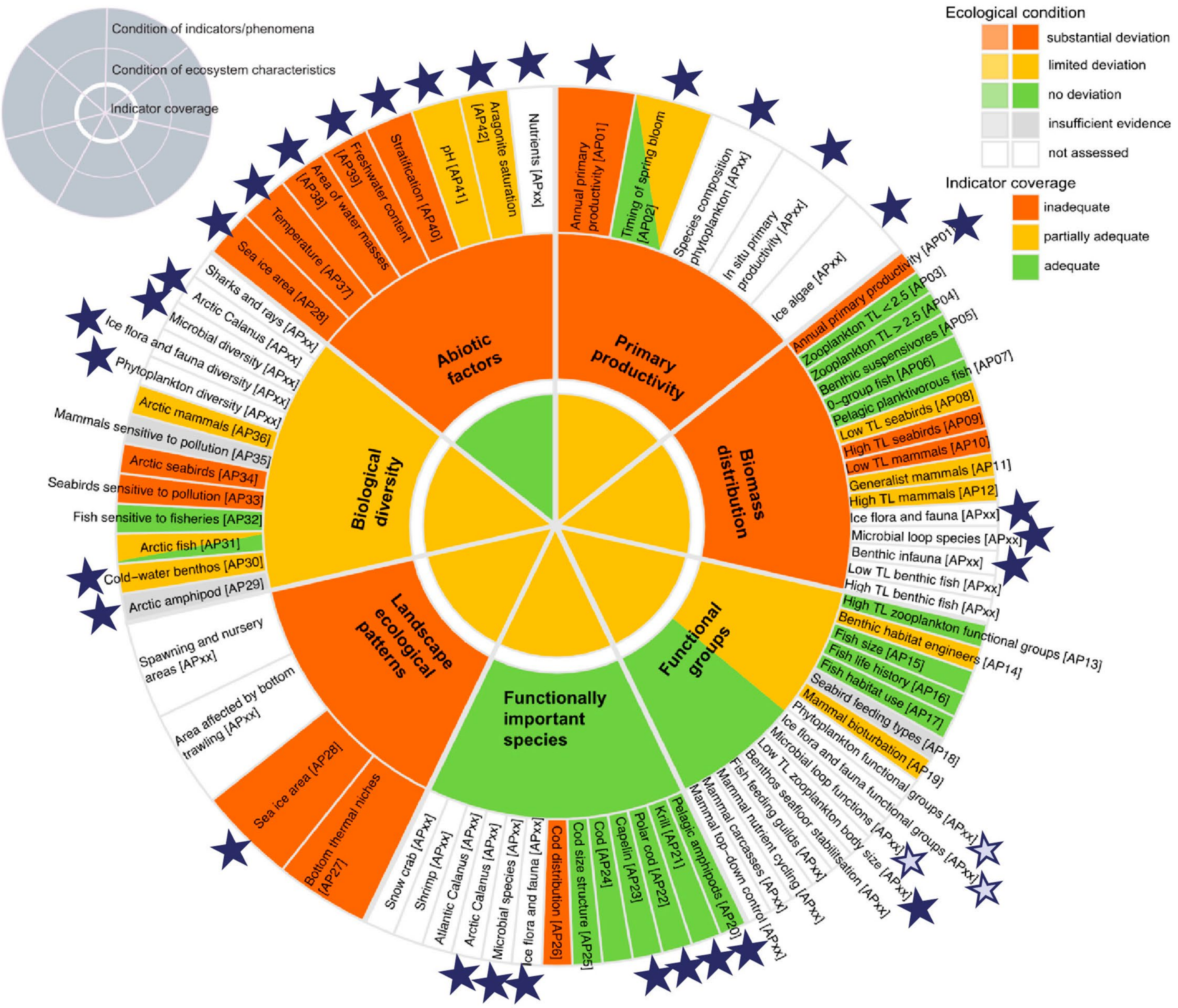






Illustrations: Frida Cnossen





Graphical summary of the assessment of the Arctic Norwegian sector of the Barents Sea (Figure 7.3.2.a in the report, see QR code). The outer circle represents the conditions of indicators/phenomena, and the inner circle the indicator coverage. In the middle circle, the condition of ecosystem characteristics is presented. Red and orange colours indicate substantial or limited deviation from the reference condition, defined as an ecosystem largely unimpacted by modern industrial anthropogenic activities. The stars specify the fields in which the Nansen Legacy contributed to minimizing knowledge gaps.

References

Partnerships for a stronger societal impact

The Nansen Legacy is a collaboration among 10 partner institutions, spanning from Norwegian universities to research institutions with roles in management and public services, as well as private research institutes with stronger links to industry. All partners have contributed to the research conducted in the Nansen Legacy, and with their unique mandates and pipelines to society, they spread new knowledge to end users.

The different partners in the Nansen Legacy have complementary expertise and mandates.

Science for service

The Meteorological Institute (MET) provides weather forecasts to the wider public and specialized products for maritime activities, like sea-ice distribution and wave heights. In the Nansen Legacy, several of these tools and products could be enhanced using improved and more realistic models and data reanalyses. New sensors have been developed and tested, allowing for real-time data acquisition in the field. This ground data will further improve predictions.

Management

The Norwegian Polar Institute (NPI) and the Institute of Marine Research (IMR) combine surveys and time series with basic research and provide advice to the Norwegian state. While the NPI has key responsibility in the polar regions, including ice-covered oceans, the IMR provides advice on harvestable living resources in open water regions. The new scientific findings in the seasonally ice-covered northern Barents Sea and adjacent areas by the Nansen Legacy directly feed into the management advice of both institutions.

Education

The four universities, UiO, UiB, UiT and NTNU, along with UNIS on Svalbard, have mandates to conduct research and provide research-based education. In the Nansen Legacy, 35 master's students, 37 doctoral candidates, and 56 post-doctoral researchers were involved and developed specialized skill sets. Thus, a new generation of scientists was educated, which is beneficial for Norwegian society. Even though a high number is internationally recruited, most of the well-educated professionals continue working in Norway (details on pages 72-73).

Additional pipelines to society

Two private research institutions were also part of the Nansen Legacy. Akvaplan-niva (APN) conducts marine ecosystem and climate change research of specific relevance to industry and society. The independent foundation, the Nansen Environmental and Remote Sensing Center (NERSC), primarily focuses on understanding and forecasting changes in the marine environment and climate. Both institutions have valuable and unique contact points to national and international scientific networks and end users, providing additional pipelines for knowledge transfer to society.

Complementary partners for more social impact

With its complementary partners, the Nansen Legacy could take advantage of its experience in addressing relevant research questions and establishing channels for end users. This helps with effectively channelling new knowledge where it can be most useful for society. One example is the recent *Panel-based Assessment of Ecosystem Condition of Norwegian Barents Sea Shelf Ecosystems*, requested by the Environmental Directorate. The report revealed that the northern Barents Sea is considerably impacted by anthropogenic drivers. Several ecological conditions deviated substantially or to a limited degree from the reference condition, defined as an ecosystem largely unimpacted by modern industrial anthropogenic activities (figure to the left, red and orange fields in the outer and middle circles). Particularly affected characteristics were *Abiotic factors*, *Primary Productivity*, *Biomass distribution*, and *Landscape ecological patterns*. With a strong focus on the physical system and the lower levels of the food web, including the sea-ice system, the Nansen Legacy contributed to minimizing many of the identified knowledge gaps (indicated by stars). ■

the Nansen LEGACY

The Research Council of Norway

Norwegian Ministry of Education and Research

UNIS The University Centre in Svalbard

Norwegian Meteorological Institute

NTNU

NERSC Nansen Environmental and Remote Sensing Center

Akvaplan-niva

From science journals to assessment reports

The Nansen Legacy results are relevant for a wide range of professional users, from the international science community, consultants, industry to policy makers. However, translating from science results into useable knowledge is not straightforward. Nansen Legacy scientists have contributed to this process through science publications, synthesis papers on key themes, and by contributing to assessment reports dedicated to management and policy makers.

Scientific publications and synthesis provide quality-controlled science

The Nansen Legacy results have been published in more than 270 scientific articles in peer-reviewed journals with external quality control. More than 89% of these articles are not hidden behind any paywall and the data associated with the publications are freely available online for future use. Articles on the key topics *Seasonality and interannual variability* and *Food web structure, functions, drivers and dynamics* (see pages 26-27) were bundled in dedicated article collections (i.e., special issues) in the journal *Progress in Oceanography* for interested experts. Building on the detailed scientific articles, Nansen Legacy scientists have also condensed science on specific themes like the Barents Sea system, the future Barents Sea, and multiple stressors into comprehensive synthesis articles. These reviews provide a more overarching understanding of the topics and facilitate in-depth insights without the need to read a long list of specific publications.

National and international assessment reports

Assessment reports are compilations of scientific results and knowledge that address specific geographic regions or themes. These reports are useful for the industry, government, or other state institutions. The Arctic Council working groups, the Intergovernmental Panel on Climate Change (IPCC), or expert groups linked to recurring updates of the Norwegian management plans for marine areas exemplify organizations that coordinate such assessment reports. These groups invite specialized scientists to be part of the assessments, and many of the Nansen Legacy scientists accept their invitations and contributed to assessment reports (available through the QR code below). Thus, results and knowledge from the project were brought into documents that form the basis for national and international management and politics. Sebastian Gerland, a sea-ice physicist and Nansen Legacy co-PI, was, for example, a lead author of a chapter of the *IPCC's 6th assessment report* published in 2021. The holistic system approach used in the Nansen Legacy and the cross-disciplinary connections and processes identified by the project helped him a lot when writing for the IPCC assessment. Tor Eldevik, climate researcher and also co-PI, was the lead author of the policy report on *A Sea of Change* on behalf of the European Academy of Sciences (EASAC), and many Nansen Legacy scientists contributed to the *Panel-based Assessment of Ecosystem Condition of Norwegian Barents Sea Shelf Ecosystems*, a document related to the Norwegian Management Plan process. The whole process from scientific work to the publication of results in expert journals and their synthesis in national and international reports may be a long and winding road. However, it ensures that only high-quality science forms the basis of important decisions in society. ■

"The holistic system approach we did on a rather regional scale in The Nansen Legacy was very helpful when working with the IPCC assessment."

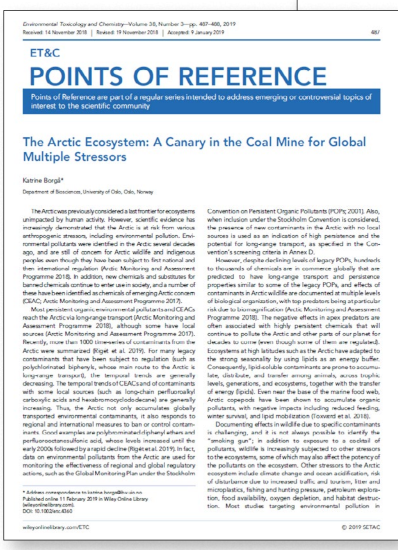
Sebastian Gerland, NPI

Science of the Total Environment

A risk assessment review of mercury exposure in Arctic marine and terrestrial mammals

Marine Environmental Research

Distribution and ecology of polar cod (*Boreogadus saida*) in the eastern Barents Sea: A review of historical literature



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POINTS OF REFERENCE

Points of Reference are part of a regular series intended to address emerging or controversial topics of interest to the scientific community

The Arctic Ecosystem: A Canary in the Coal Mine for Global Multiple Stressors

Katrine Borgå

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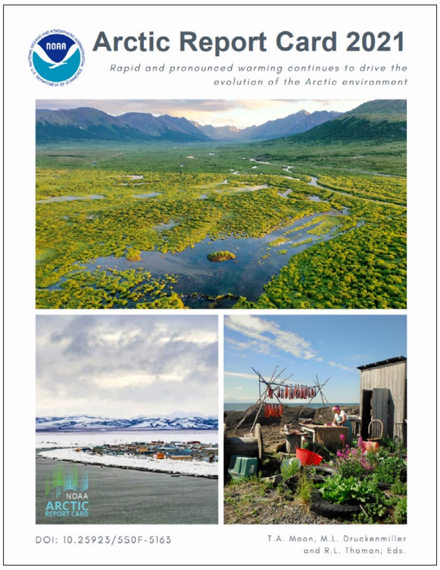
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PANEL-BASED ASSESSMENT OF ECOSYSTEM CONDITION OF NORWEGIAN BARENTS SEA SHELF ECOSYSTEMS
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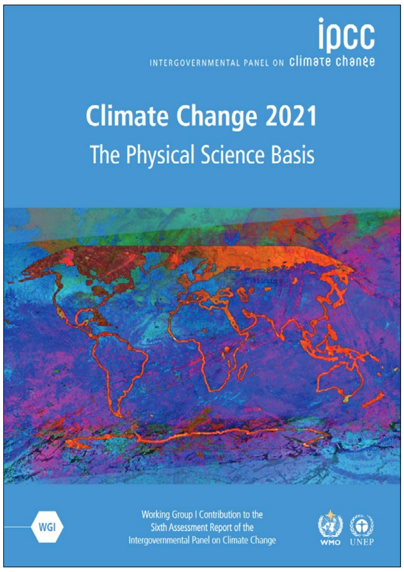
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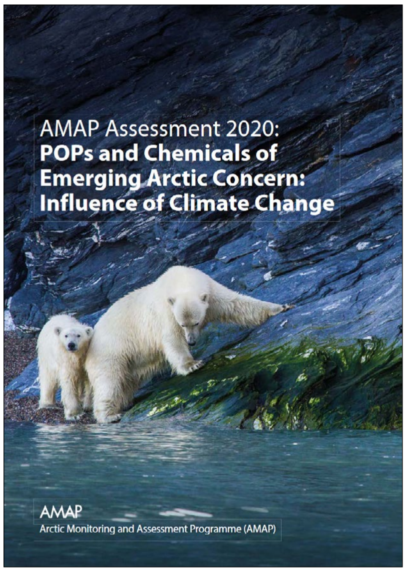
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WORLD METEOROLOGICAL ORGANIZATION
YEAR OF POLAR PREDICTION
ACHIEVEMENTS AND IMPACTS


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Volume 355 I July 2022
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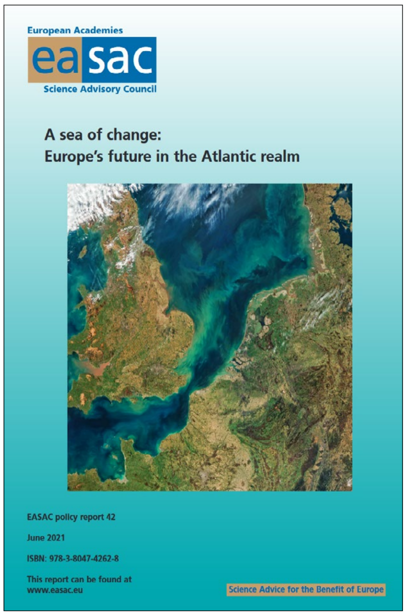

European Academies
easac
Science Advisory Council
A sea of change:
Europe's future in the Atlantic realm
EASAC policy report 42
June 2021
ISBN: 978-3-8047-4262-8
This report can be found at www.easac.eu
Science Advice for the Benefit of Europe

The Nansen Legacy fact sheets and a new book on the Barents Sea system

With the extensive and interdisciplinary research in the Nansen Legacy project, we have been able to update, expand, and integrate our understanding of the Barents Sea system. To integrate the results and make the updated knowledge more accessible, the Nansen Legacy produced thematic fact sheets with the most central findings and communicative illustrations. In addition, a new textbook providing an updated overview of the Barents Sea system, observational approaches, and management is underway.

Photo: Elin V. Jensen

"The Nansen Legacy Fact Sheets creatively and effectively distil a vast amount of research and information in an attractive and appealing format. They are a great introduction and reference for a broad audience."

Alan Haynie, General Secretary of the International Council for the Exploration of the Sea (ICES) and member of the Nansen Legacy reference group

The fact sheets

Key findings from ten overarching or important themes within the Nansen Legacy research have been compiled into double-sided A4 fact sheets to communicate the important findings in an appealing way. The sheets were produced in close collaboration between Nansen Legacy scientists and the science illustrator Frida Cnossen. They convey the key findings through informative illustrations and short, easily understandable texts, and were well received by various user groups, including schools, management, policy makers and science colleagues. The process of compiling and integrating results when making the fact sheets has also had positive ripple effects. The production challenged the Nansen Legacy scientists across disciplines to combine their knowledge, learn from each other, and closely collaborate to identify and formulate the main messages. In this way, knowledge was further synthesized, which was beneficial for other products of the project, like review articles and the book. The fact sheets have also inspired the international science community, who recognized them as a very effective way to communicate project results to user groups, and other science projects have started sharing their main findings in a similar way.

The Barents Sea system book

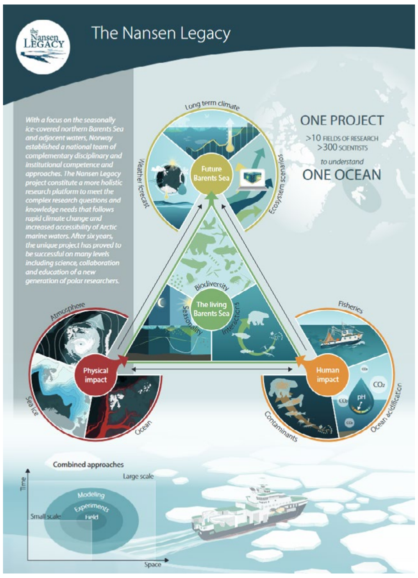
The updated knowledge on the Barents Sea from the Nansen Legacy research is also compiled in a new book, co-authored by a large number of the scientists in the project. The book is aimed at students, stakeholders, managers, and people with a general interest in the Barents Sea. It provides a general overview of the physical, chemical, and biological characteristics and processes, anthropogenic stressors on the ecosystem, up-to-date observational technologies, projections of the future, and insights into national and international management of the area. Besides informative text, illustrations, and pictures, detailed knowledge is presented in fact boxes, allowing readers to gain a comprehensive system understanding of the Barents Sea. ■

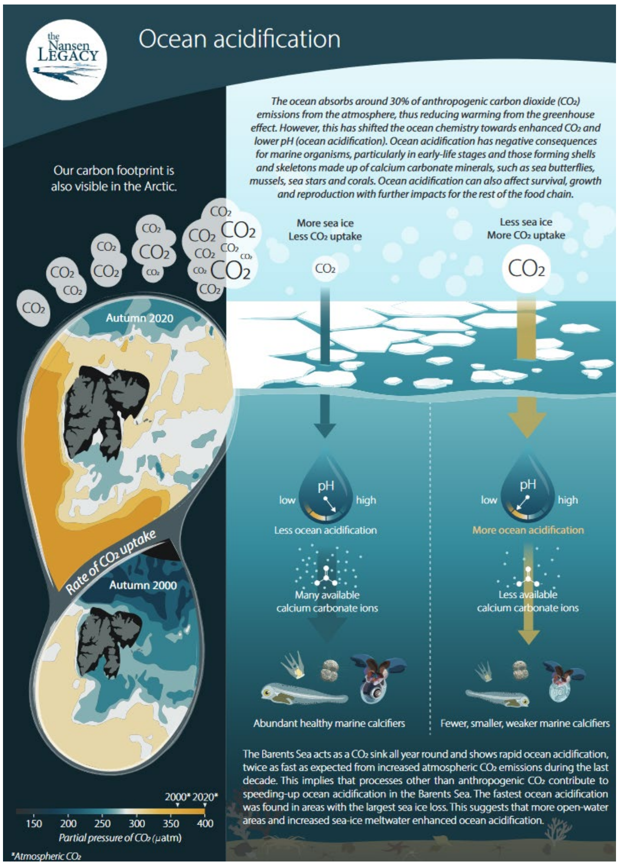
Photo: Bodil Bluhm

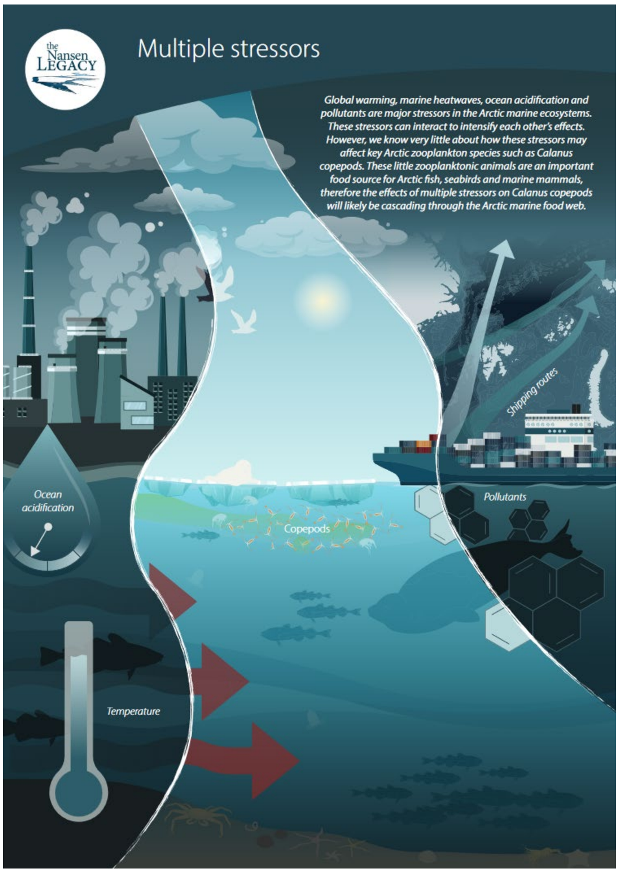
References

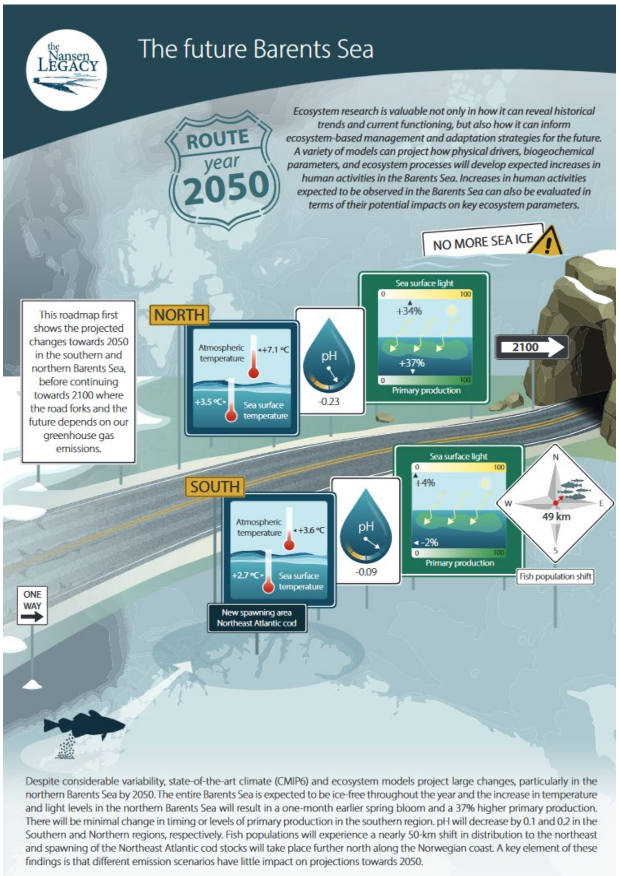
"The fact sheets are a prime example of informative and attractive science communication in condensed format. We will use them as a model for our own project outputs in the future."

Michael Karcher, Alfred-Wegener Institute, Germany, leader of the project Arctic PASSION and member of the Nansen Legacy advisory group









A scientific base for management

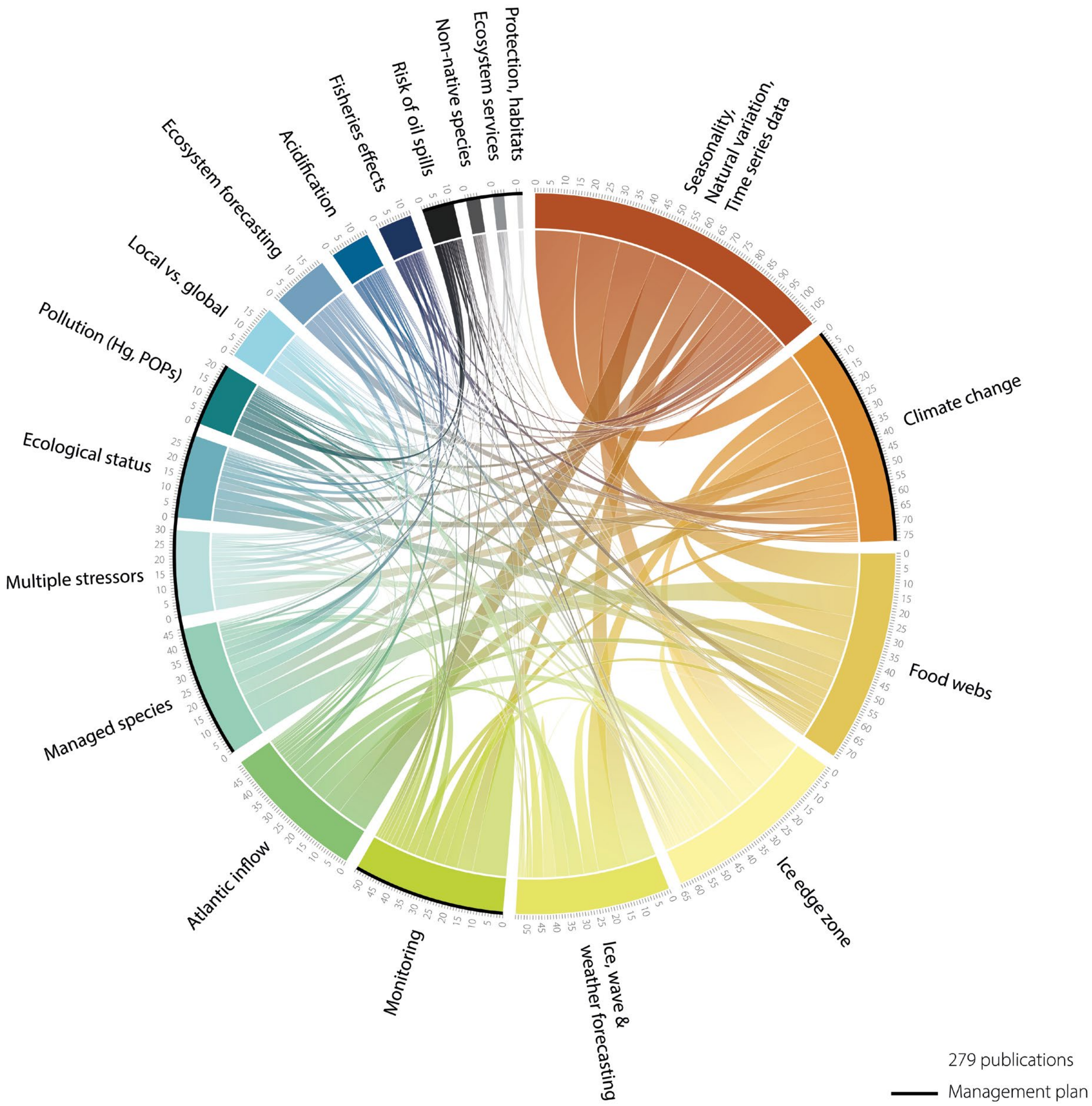
A meta-analysis demonstrates that themes of the scientific articles published by the Nansen Legacy align well with target areas identified by the Norwegian advisory bodies for ocean management. These figures visualise how science conducted by the Nansen Legacy provides knowledge that is useful for management, and at the same time can give a broader system understanding.

Topics identified by management advisory bodies align with Nansen Legacy research

The Forum for Integrated Ocean Management is led by the Norwegian Environment Agency and, in cooperation with the Advisory Group on Monitoring, the Forum synthesizes the knowledge base for Norway's integrated ocean management plans. For this work, particularly relevant themes have been defined, such as *Climate Change*, *Monitoring*, *Managed Species*, *Pollution*, *Multiple Stressors*, *Ecological Status*, *Risk of Oil Spills*, and *Non-native species* (marked in the figures associated with this text). A meta-analysis indicates that around 66% of more than 270 peer-reviewed and quality-controlled articles produced by the Nansen Legacy address these management-relevant themes. Thus, the Nansen Legacy provides an important knowledge base for the future development of the Norwegian management plans in times of a rapidly changing Arctic climate.

The need for a comprehensive system understanding

Investigations specifically focused on the *Risk of Oil Spills* and *Pollution* are highly relevant for management decisions because pollution can directly affect food security and value creation. However, the ecosystem, including its

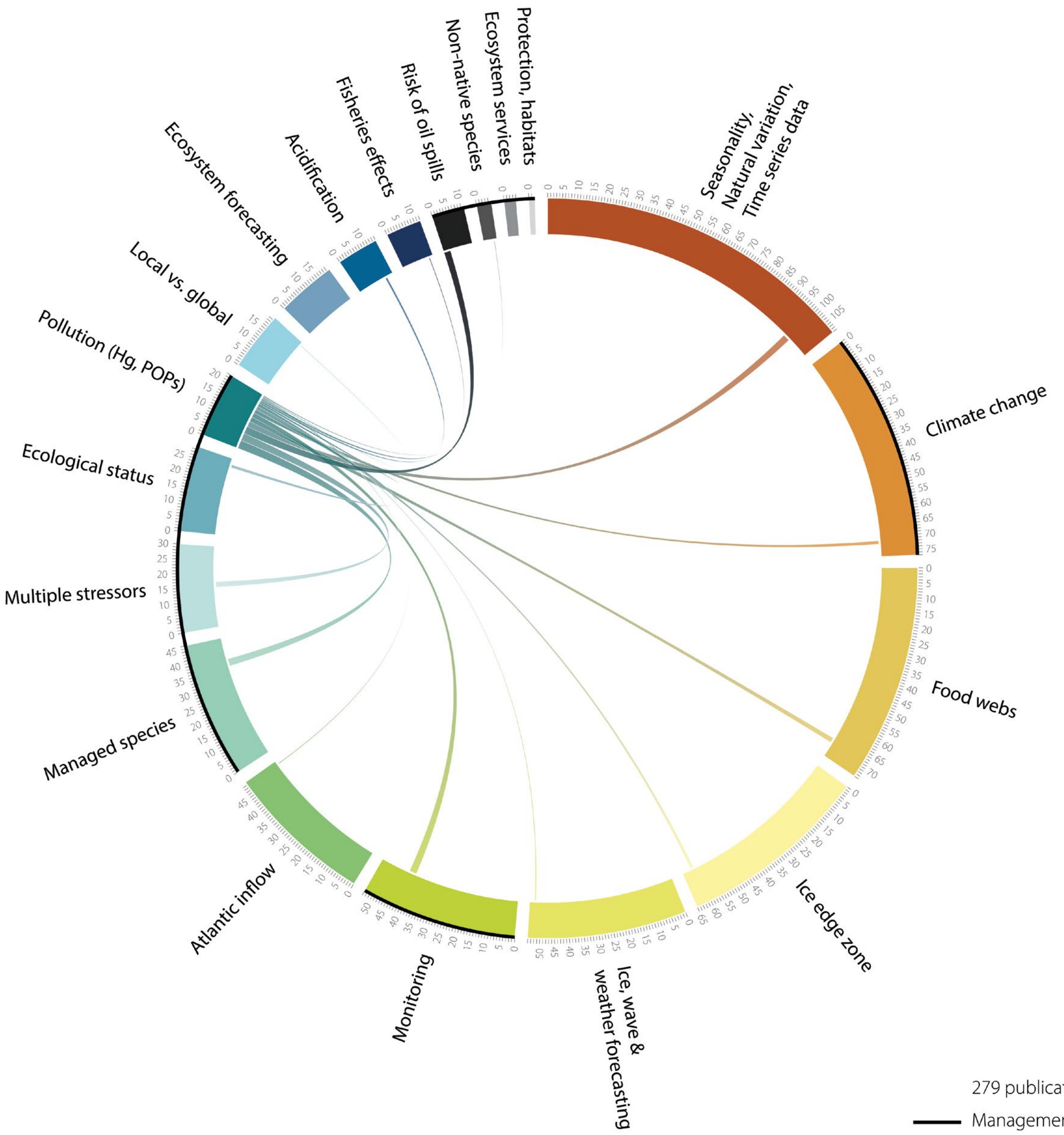


Version 24.10.2024 with 279 publications. Black lines at the outer margin indicate management relevant themes identified by the Forum for Integrated Ocean Management

commercially used species, is not only impacted by pollutants. It is also influenced by factors like sea-ice, pronounced seasonality, and the inflow of Atlantic water, ecosystem characteristics that are currently changing in the Barents Sea. To ensure a full understanding of the sum of impacts that need to be taken into account for sustainable management of human activities in the region, a broader understanding of the entire ecosystem and its present stressors is required. Our meta-analysis shows that the Nansen Legacy publications serve both needs. For example, more than 80% of the articles focusing on the target theme of *Pollution* also co-focused on other system drivers (see figure, page 59), and thus contributing to both a more detailed and a more comprehensive understanding of pollution in the complex marine system of the Barents Sea. ■

"This exercise reveals how the Nansen Legacy research addresses issues of high relevance to ecosystem management, and that a good understanding of these issues requires a multidisciplinary approach."

Paul Renaud, APN



279 publications
Management plan

Illustrations: Frida Cnossen

Photo: Èric Jordà Molina

Understanding drivers of fish stocks

Rich fish stocks in the Barents Sea provide food and are of great commercial value to the Norwegian society. However, many details about what regulates these fish stocks are still unknown. Nansen Legacy scientists have utilised historical data and existing time series to develop and improve data simulation tools to gain more insight into factors such as the competition between marine mammals, fish, and fisheries, or how warmer waters influence the spatial distribution of fish.

Using existing data to better understand the impact of physical drivers

The Nansen Legacy is a 6.5-year-long research project, but it is still too short to properly study how (commercially important) fish stocks react to human-induced system changes in the Barents Sea. Therefore, the project utilised existing historical and long-term data series, including the surveys by the project partner IMR. These were also used to evaluate new and improved model simulations, including the benefits of downscaled physical forcing compared to global forcing for an ecosystem model. Many larger organisms at the top of the food web were not particularly impacted by using the coarser global physical forcing. Cod, however, was an exception, as it is sensitive to too low temperatures in its spawning areas, and prediction of spawning success requires more precise temperatures than coarse grid models provide. This highlights the need for more high-resolution models for species that are sensitive to the physical regime.

Fish on the move

The Barents Sea is divided into the Norwegian and the Russian Exclusive Economic Zones, and the spatial distribution of commercially important fish is crucial for negotiations of quotas and utilisation of the valuable fish stocks. It is thus of societal relevance to understand how lucrative fishing grounds may change in the warming Barents Sea. Based on field observations and model simulations, the Nansen Legacy found that the centre of distribution for many fish species was more than 41 km further to the northeast in the warm year 2013 compared to the cold year 2004. Feeding the model with future climate scenarios (see Future Barents Sea, pages 42-43), a high CO_2 emission scenario projects even a 204 km displacement compared to 38 km with a moderate CO_2 emission pathway.

Predation and fisheries affect fish stocks, and previous collapses

A central aspect of sustainable stock management is to avoid the collapse of fish stocks, but this still happens. A Nansen Legacy study investigated how harvesting, fish recruitment, and climate variability affect a fish stock before and after a collapse. Analysing 54 population collapses around the world identified two relevant aspects for stock management in the Barents Sea: First, fish stocks seem to react differently to environmental drivers before and after a stock collapse, and second, the reaction appears to be stock-specific.

A long-standing debate concerns the competition between marine mammals, fish, and fisheries. Using a chance and necessity modelling framework, which recognises uncertainties in expert knowledge, data, and input parameters, the dynamics of plankton, fish, and marine mammals in combination with fisheries from 1988 to 2021 were quantified. Despite considerable inter-annual variation, fisheries catch accounted on average for 18% of the total fish removal, marine mammals accounted for 44%, and fish predating on other fish (and 'recycling' it into new fish biomass) for 38%. This new modelling framework has been developed in dialogue with the ICES working group and is highly relevant for management. ■

"Solid ecosystem-based knowledge collected over time is essential for identifying the drivers of fish stock development in the Barents Sea. Understanding the drivers helps to foresee changes in fish stocks and to adapt management plans to environmental and ecological changes, ensuring long-term resource sustainability."

Elena Eriksen, IMR

Gro van der Meeren, IMR

References

How can research improve the safety of maritime activities and the ecosystem?

Maritime activities in the Arctic are increasing as the sea ice retreats. To reduce the risk of accidents in remote regions, Nansen Legacy scientists have contributed to improved weather-, wave-, and sea-ice forecasts through (real-time) observations and better algorithms. Also, the effect on Arctic species of crude oil, alone and in combination with climate-related stressors, has been assessed to contribute to risk mitigation.

Improving weather, wave, and sea-ice forecasts

Maritime activities in the Arctic can be dangerous, and reliable weather, wave, and sea-ice forecasts are crucial for the safe operations of fishing trawlers, cruise- and cargo ships, and vessels conducting oil and gas exploration or research. The forecasts currently available for the northern Barents Sea often have a poorer precision than forecasts for the Norwegian mainland coast, due to lack of sufficient real-time data. Scientists in the Nansen Legacy have used a two-fold approach to advance and improve the forecasts. On the one hand, more observations were collected during ship-based expeditions with the ice breaker RV *Kronprins Haakon*, and through international collaborations like the German-led *MOSAIC* project. Additionally, more cost-effective sensors have been developed that autonomously monitor the sea-ice drift and waves and provide real-time data via satellite transmission. The collected data are accurate references in weather models used by the Nansen Legacy, and data were also shared with international initiatives like the Year of Polar Prediction (YOPP), aiming to improve operational weather forecasting systems. On the other hand, Nansen Legacy scientists have advanced weather, sea ice, and wave predictions in the northwestern Barents Sea by refining the algorithms of computer models. The new algorithms allow for example more realistic modelling of sea-ice deformation and the snow layer on sea ice, correcting the modelled surface temperature by 5-10°C. Thus, the simulation of physical processes in and linked to sea ice is more realistic and a better weather forecast is achieved.

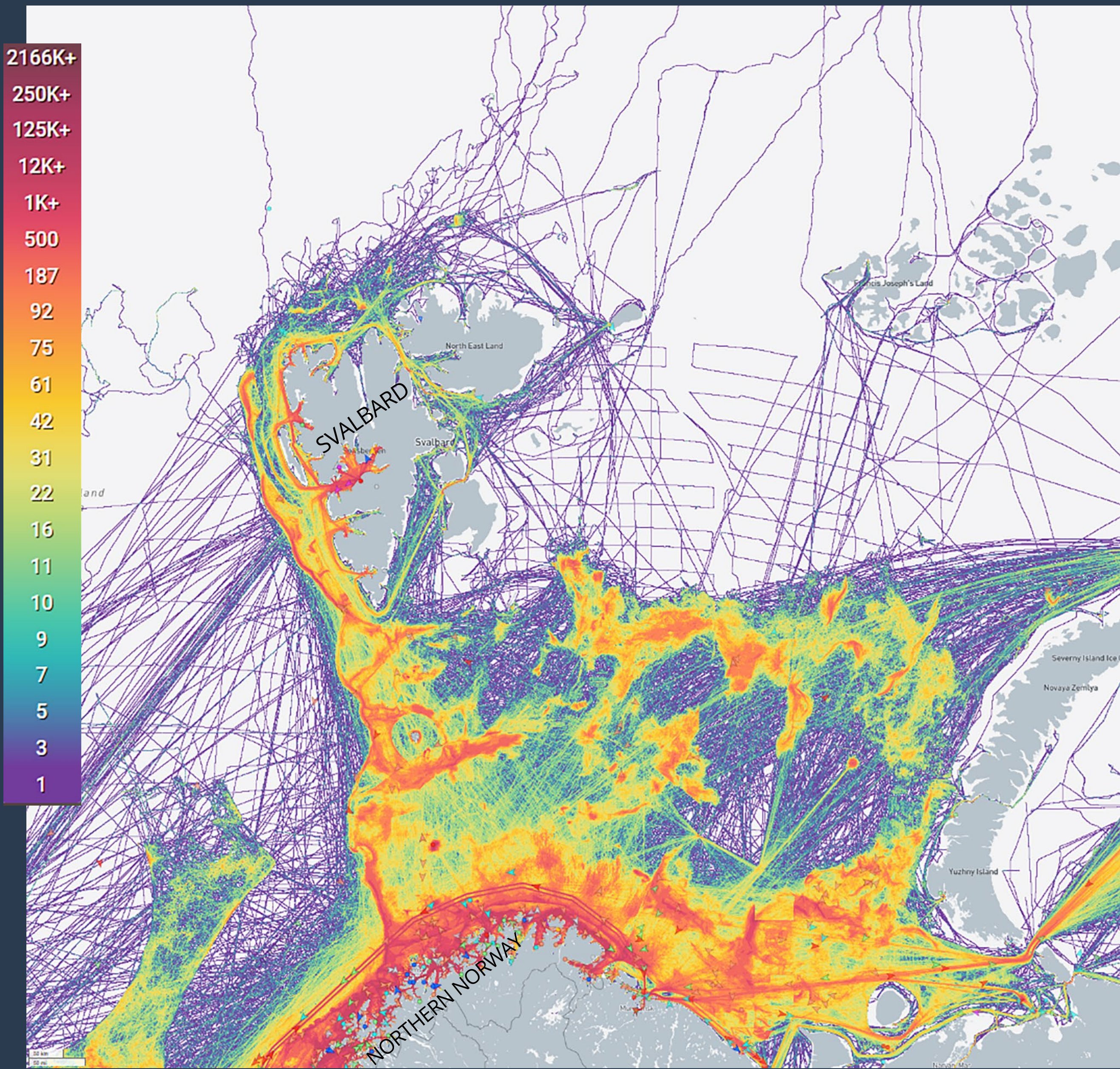
Providing a knowledge base to mitigate potential risks for the Barents Sea ecosystem

Besides improving forecasts, mitigating the consequences of potential accidents helps to protect the ecosystem in the northern Barents Sea. Satellite observations are useful tools to monitor remote areas, but it has been difficult to distinguish oil slicks from newly formed sea ice. The Nansen Legacy has contributed to a new approach that improves the detection of harmful oil slicks in the marginal ice zone. Early observation is important, as experimental studies conducted by the Nansen Legacy have shown that oil spills may be especially harmful when they occur in combination with other stressors (details page 32) and during vulnerable life periods of the organisms' life cycles.

Sharing is caring – also in a data and knowledge context

The new understanding of sea-ice dynamics, advanced forecasts, and the effect of crude oil in combination with other stressors on marine organisms is highly relevant for various users of the Barents Sea. The Nansen Legacy shared most of their new findings in open-access scientific publications (<15% behind a paywall), reports, and an open data policy that allows users to access the raw data. Good dialogues with stakeholders identified challenges in the data format and the data platforms, that researchers use to publish their data and a need for a transition to the pipelines stakeholders use to access data. The heterogeneity in users further highlights the necessity for standards and the use of FAIR principles in data publication to better facilitate data identification, harvest, and the use of data across platforms.

Photo: Christian Morel/christianmorel.net



Right: Colour code for the number of vessels travelling a route Map showing the ship traffic in the Barents Sea and adjacent Seas, from MarineTraffic.com

Venues of dialogue between stakeholders and the Nansen Legacy included side events during the Arctic Frontiers conference and the international symposium organized by the Nansen Legacy, panel debates as well as several stakeholder seminars. These meetings brought together scientists across different disciplines and users in industry, management and non-governmental organizations, strengthening communication about knowledge, needs, challenges, and opportunities across users of the Barents Sea region. The discussions were fruitful for all sides. The stakeholders gained insights into the newest scientific findings and the researchers became aware of the knowledge gaps identified by users. ■

References

“The Nansen Legacy has provided new knowledge helping in planning and executing maritime operations. As the new knowledge finds its way into more models and datasets, it will improve risk assessments and governance of the Barents Sea region.”

Øyvind Rinaldo, The Norwegian Coastal Administration, and member of the Nansen Legacy Reference group

Implementing a data sharing culture

Scientists have been afraid that somebody will steal their data to publish them in a scientific journal and earn all the glory for costly, long, and hard work in the field or laboratory. In many heads, this fear is still present, even though a data sharing culture has many advantages for the scientific community, stakeholders, and society, which funds many scientists. The Nansen Legacy worked hard to create a data sharing culture within the project and beyond.

Data citations acknowledge the data producer

Prior to the Nansen Legacy, a system where datasets can be published and cited with Digital Object Identifier (DOI) was established. This important step towards more sharing made it obvious to cite a used dataset as a publication in the same way as scientific papers or assessment reports. This acknowledges the data producer and recognizes the value of a dataset. That way, a dataset can have a longer life and be more cited than a publication as generations of scientists integrate these data in new analyses.

The Nansen Legacy Template Generator

For data providers, it is essential that data are published or stored in standardised machine-readable structures like CF-NetCDF or Darwin Core Archives. A crucial step towards proper data publication is sufficient and appropriate information on how and where data were collected. Application of standardised terminologies ensures a common understanding of the concepts used. To avoid many individual solutions and ease the registration in the field, the Nansen Legacy data managers Pål Ellingsen and Luke Marsden developed a template generator. An Excel sheet is generated, providing the hierarchic links to the cruise and gear used as well as a unique identifier to each sample. A selection of drop-down menus makes sure that 1) all necessary information is provided, and 2) information is registered the same way. The generator is freely available for the science community online on NorDataNet as well as via the Nansen Legacy and SIOS web pages.

The metadata were published in the SIOS data portal within a short time after each cruise. This system makes the datasets meaningful because they contain information on where, when, and with which protocol the data were collected, and this is essential information for later comparison, and to plan complementary sampling.

Harmonised solutions across institutions and disciplines

Prior to the first Nansen Legacy research cruise in 2018, a sampling protocol of all methods to be used onboard was collectively developed to ensure that data collected throughout the project was comparable and independent of the researcher, institution or vessel that had collected the samples. The protocol was updated with new methods or modifications to version 10 and is published for open and free use. The protocol development helped to harmonise methodologies used in the different institutions and to secure comparable data.

Workshops have trained the scientists and helped them to publish the data. Videos published in the Luke Data Manager YouTube channel guide the different steps in the process, and the accessibility to data managing support has been invaluable in solving smaller and larger challenges.

The comprehensive efforts to standardize data and publish data in a FAIR way did not only change the way how many Nansen Legacy scientists regard data publication. They shared these principles and the great YouTube tutorials with colleagues and students outside the project, also internationally, leaving a Legacy and considerable footprint in the community. ■

Nansen Legacy Sampling Protocols	
Nansen Legacy Data Policy	
Nansen Legacy Data Management Plan	
Other references and portals	
LukeDataManager YouTube channel	

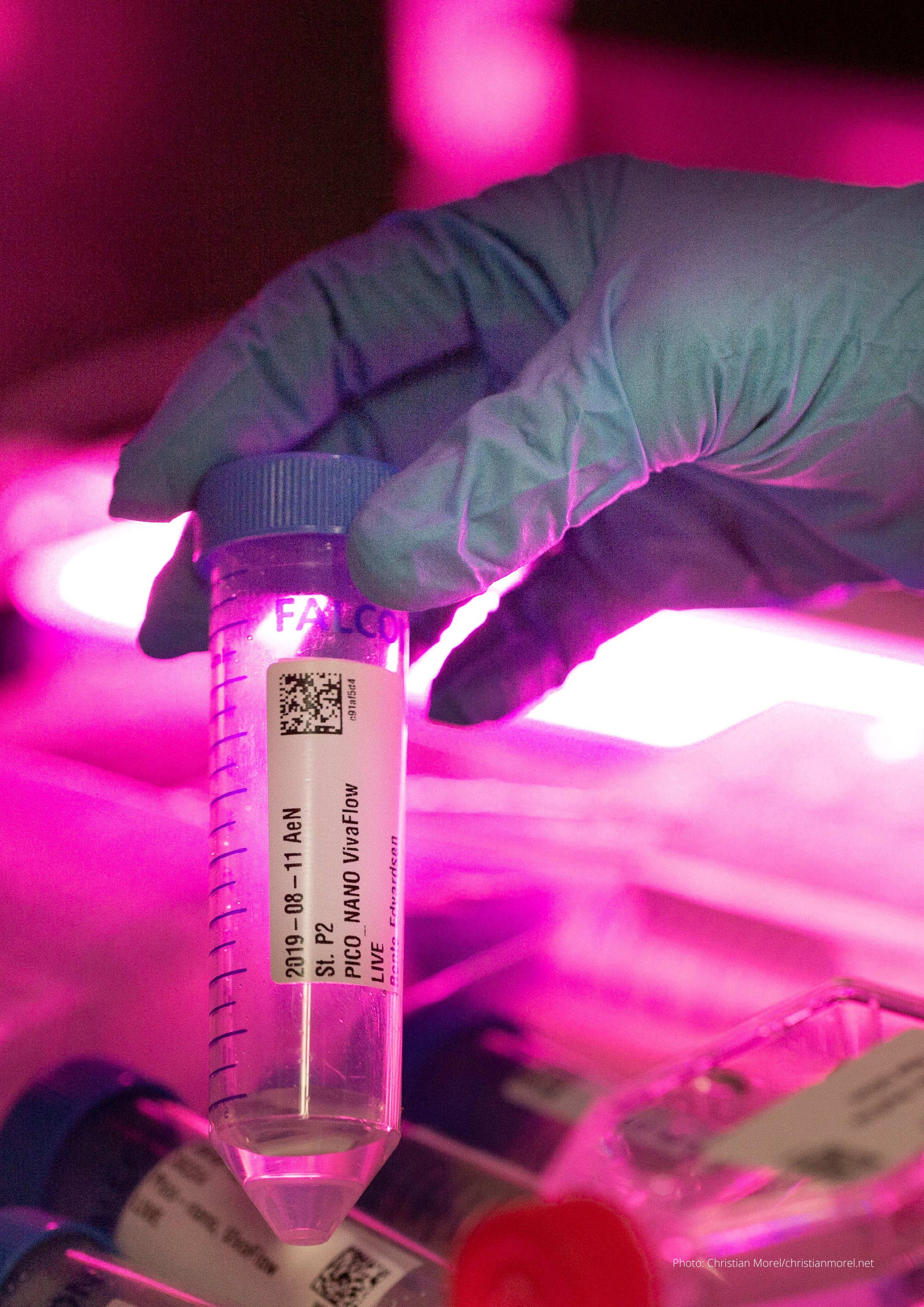
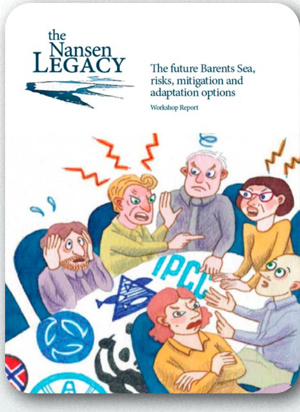


Photo: Christian Morel/christianmorel.net

Interactions with user groups

The overarching goal of the Nansen Legacy is to provide a better scientific basis for the sustainable management of the northern Barents Sea and the adjacent Arctic Ocean. The acquired knowledge and relevant questions were therefore shared and discussed with relevant user groups on many occasions. Examples of such interactions, dialogue meetings, and events are presented in the timeline below.

2018: Representatives from the Nansen Legacy leader team, members of the board, and scientists joined the 2nd Arctic Science Ministerial. During a side event, the new Nansen Legacy project was presented.



2019: Nansen Legacy organized a stakeholder workshop on risks, mitigation, and adaptation options in the future Barents Sea.

2021: During the annual political festival Arendalsuka, political and business leaders, entrepreneurs, non-governmental organisations meet the public. Nansen Legacy scientists and early careers explained the role of the Arctic Ocean on the Earth's climate system and potential consequences of a warming climate.

2018

2019

2020

2021


the Nansen LEGACY NEWSLETTER
June 2019

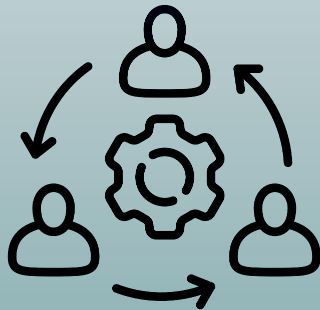
SCIENCE NEWS
Technology test cruise
Nansen Legacy data infrastructure
Reference group meeting
Nansen Legacy workshops
Planned webinar series

PROJECT INFORMATION
Registration annual meeting 2019
Overview affiliated members
Travel reimbursement
Annual report is sent out

LATEST PUBLICATIONS
Reduction in Arctic sea ice cover affect marine food webs through a multitude of direct and indirect effects

Whole project period: Regular newsletters update the user groups on the latest scientific findings in the Nansen Legacy, project internals, and recent publications

2020: In the side event "What does it take to manage fisheries sustainably?" the Nansen Legacy gathered international experts and discussed critical elements of modern fisheries and the importance of a science-based understanding and monitoring of marine systems.



2020/2021: To strengthen the dialogue between the Nansen Legacy and interested user groups, individual dialogue meetings were conducted, including the representative of AMAP, the Coastal Administration, the energy sector, and the Norwegian Environmental Agency.

2023: Project leader Marit Reigstad and work package leader Kai Håkon Christensen provided updates on key results of the Nansen Legacy and discussed mechanisms of knowledge transfer with the Forum for Integrated Ocean Management at two meetings. The Forum is an important body in drawing up the scientific and knowledge basis for Norwegian management plans for the marine system.

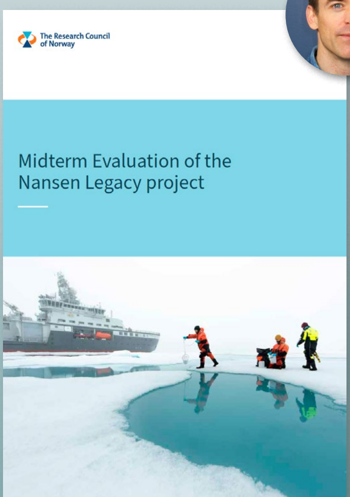
2022: The Nansen Legacy organized the side event "From Science to Policy to Impact in the Arctic" at the Arctic Frontiers Conference in Tromsø. Project members like post doctorate Alun Jones (right in the picture) joined the panel together with Espen Barth Eide (Norway's Minister for Climate and Environment).

2024: The stakeholder seminar entitled "The Nansen Legacy and the use of new knowledge in ocean management" focused on relevant project results and the needs of the energy industry in the North to reduce risks.

2024

2022

2023

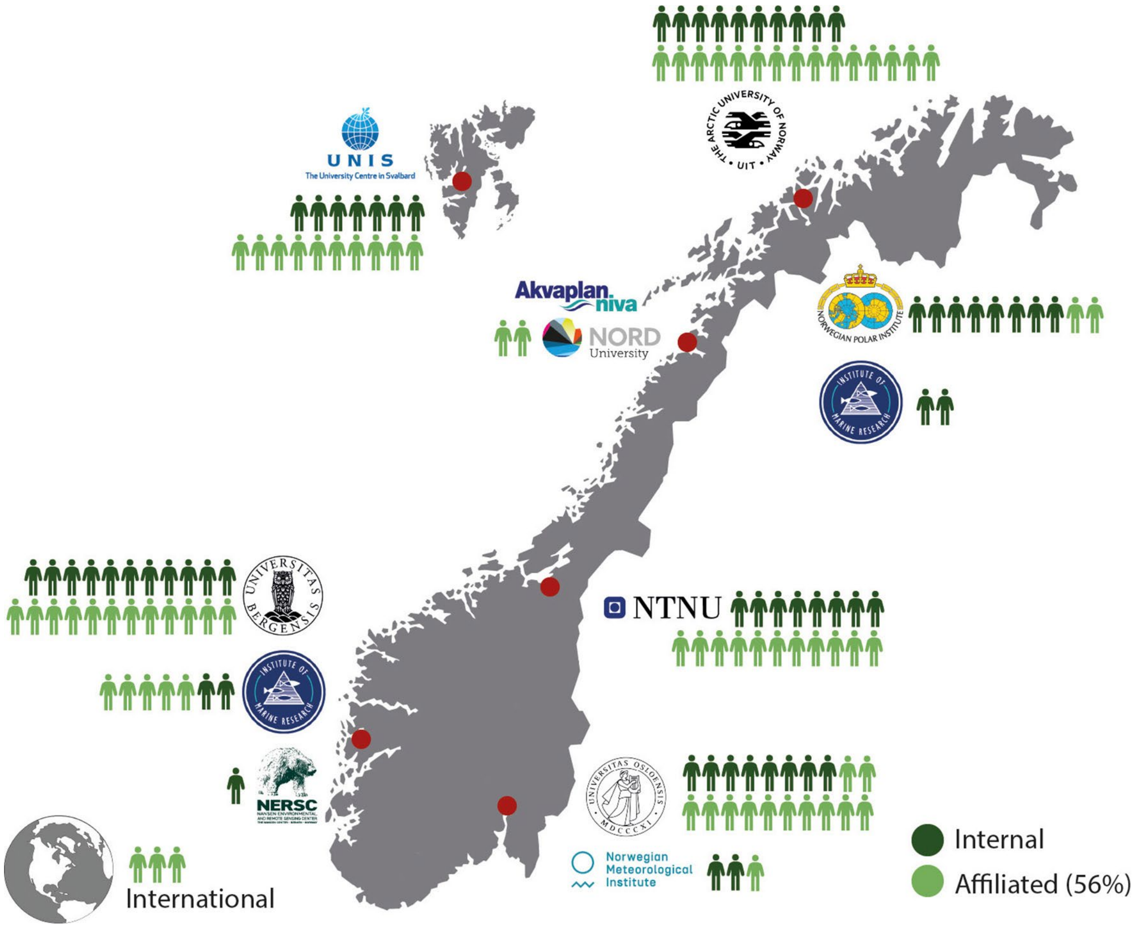


2022: Following recommendations from the Midterm Evaluation, Paul Renaud (APN) joined the project administration to further strengthen the contact with the user groups.

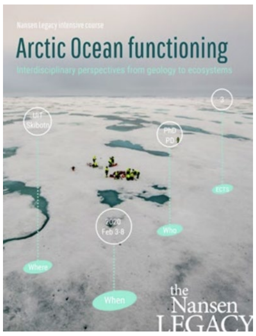
2023: The international symposium "Towards the New Arctic Ocean – Past, Present, Future" organized by the Nansen Legacy included a session entitled "From observation to adaptation" to focus on possibilities and user needs. In addition, the fact sheets were launched, presenting key findings in an easily understandable way.

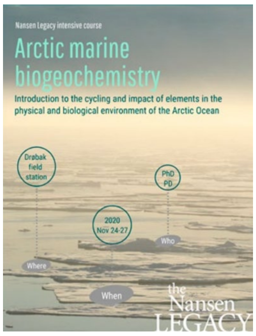
Early Career Scientists – recruiting a new generation of Arctic researchers

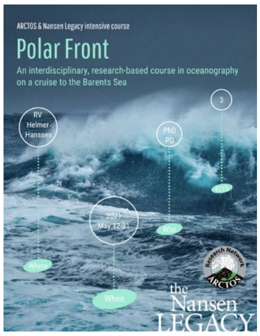
One of the key achievements of the Nansen Legacy project is the involvement of early career scientists. They have collaborated across disciplines and institutions. Initially, the project aimed to recruit 50 PhD's and postdocs, but by the project's conclusion, 128 had joined, of these 93 PhD's and postdocs. 60% of these were women. This group included 56 postdoctoral scientists, 37 PhD students, and 35 master's students. As much as 56% of the early career scientists group represented growth as they became actively affiliated with the project, enhancing its expertise, workforce, and overall results.

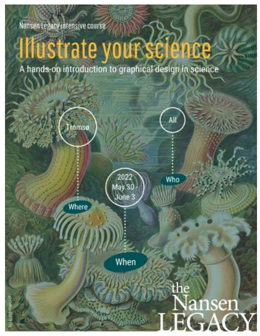


The Nansen Legacy supported early-career scientists in building a strong and supportive community. The Recruit Forum organized back-to-back meetings to the annual project meetings and represented a meeting place, allowing the recruits to set their own agenda and to invite resources to discuss important topics and receive additional training on relevant subjects. To further promote interdisciplinarity and connection, the project also facilitated intensive PhD courses relevant to a multidisciplinary group with invited expert lecturers from various fields and perspectives on science. Some examples of these courses are detailed below. ■









Reflections on Growth: Revisiting Elevator Pitches from Early Career Scientists in the Nansen Legacy

In 2020, thirteen Nansen Legacy early career scientists made a 1-minute elevator pitch video on their PhD or postdoctoral project. What has happened in the last four years? We asked four of these early career scientists how they reflect on their videos.

Johanna Myrseth Aarflot (IMR) was a postdoctoral fellow who used model simulation to predict how climate change will affect arctic zooplankton species

"Working on the elevator pitch and other outreach activities has made me become more aware of the target audience I'm addressing through my research communication. What level of background knowledge can I expect that they have, are they scientists from my own research field, scientists from a different field, or not scientists at all? This affects how I present my work. I believe that reflecting upon who the target audience is for different settings is key for efficient science communication, written and oral, to both scientific and non-scientific audiences."

Elliot Sivel (IMR) was a PhD student who developed a model to study who eats whom in the marine ecosystem.

"Working within the Nansen Legacy project, I got a global view of how research on completely different topics can interact, which is not always the case in smaller research projects. The Nansen Legacy also highlights the importance of developing transdisciplinary skills which are key to present and future research. Now that my PhD is done, my elevator pitch would probably be much different from the initial one. I would have been more specific about the objectives of my project, such as using the model to run scenarios of human activities to identify their potential effects in the Barents Sea ecosystem in the future."

Robynne Nowicki (UNIS) is a PhD student who studies how krill in the Barents Sea cope with stress.

"The number one thing I think when I look back and watch my elevator pitch video is quite simply how much I have learned since then! I think the most unexpected aspect of my PhD work, and the part I am particularly grateful for, is just how much I have learned from the Nansen Legacy research cruises. Of course there were many setbacks along the way, and I think I was very naïve when I see my younger self in this video! However, I can confidently say that in the end it all worked out, and I'd like to think I have come a long way since those early days of PhD"

Oliver Müller (UiB) was a postdoctoral who explored the role of bacteria in the Arctic ecosystem

"Having the opportunity to take a step back and think about my research in a larger context for the elevator pitch video was very helpful for conducting the field sampling. It highlighted the opportunities of working with microorganisms in terms of higher sampling throughput and lower analysis costs, which in turn opened new research collaborations and links to other disciplines and researchers within Nansen Legacy. In the end, that led to many more collaborative research papers than I could have imagined when I started and enabled more holistic assessments of the Barents Sea ecosystem under a changing climate" ■

Videos

Photo: Charlotte Stark

Meet our early career scientist representatives – Chrissie and Khuong

The Nansen Legacy Board was extended and strengthened halfway through the project, following recommendations from the midway evaluation. The PhD student – Christine (Chrissie) Gawinski (UiT), and the postdoctoral fellow – Khuong van Dinh (UiO) took on the role as early career representatives and became valuable assets to the project. They also joined the project leader team with the PIs and the work package leaders in monthly meetings. Their involvement strengthened the connection between early career and senior researchers and brought other viewpoints to the leadership discussions. Let's hear how Chrissie and Khuong reflect on their time as ESC representatives.

Reflections on the journey as ECS representatives

"Taking on the role of an ECS representative gave me a new perspective on the project's interconnectedness. It allowed Khuong and me to gain insights into the behind-the-scenes processes and appreciate the collective output of the initiative. Over time, we learned how to use our voices effectively and provide constructive feedback on behalf of the ECS community. Working as a pair of representatives was especially valuable, as we supported and learned from each other throughout the experience. Looking back, I believe having such roles established from the start, or involving an ECS advisor during the planning phase of the project, would have been highly beneficial—something I strongly recommend for future projects." – Chrissie

"My overall experience with the project as both an ECS and ECS representative has been incredible. I have never been part of a project of this scale, both in terms of the sheer volume and quality of scientific work, as well as the number of researchers involved. Although I didn't initially plan to take on the role of ECS representative, I have never regretted doing it. Over the past three years, I have been deeply connected with a network of highly skilled ECSs. This network has empowered representatives to serve as a bridge, linking them with senior scientists and project leaders." – Khuong

Challenges and triumphs

"I am truly happy and grateful to have been part of such a supportive network of ECS, where we worked together to foster and maintain strong connections. I hope these connections will endure and continue to grow in the future. While I faced challenges during my time as a PhD student in a large project—particularly with deliverables being designed before I joined—it was reassuring that the concerns raised by me and other ECS members were always met with understanding and openness to discussion." – Chrissie

"I have faced several challenges including managing time effectively across different tasks and balancing the demands of conducting quality science while fostering connections within the ECS community. Additionally, ECS members were spread across 10 different institutions in cities along the country, making it difficult to organize events that included everyone. The greatest reward for me has been being part of this ECS network, surrounded by diverse competencies of both ECS and senior scientists that will be invaluable for my future collaborations, especially in multidisciplinary research in the Arctic." – Khuong

What's next for you?

"The Nansen Legacy has given me a broad perspective, showing how my PhD is just one small piece of a much larger puzzle. This experience has helped me recognize that my skills and passions might be better suited to organizing and communicating science to policymakers, working with NGOs, or engaging in societally applied research. While I am not entirely ruling out an academic path, I feel more drawn to explore a direction that aligns more closely with these interests." – Chrissie

"As a representative of ECS, I have had numerous opportunities to learn from project team leaders to manage research activities across various groups and disciplines and communicate with a wide range of stakeholders and user groups. These experiences have enhanced my scientific leadership and communication skills, enabling me to effectively manage my Young Research Talent grant team with more than 10 ECS. In the future, I want to build on the extensive network established through the Nansen Legacy and my own projects, and I aim to advance the Arctic multiple stressor research to a new level." – Khuong ■

Insights across generations: reflections from a Nansen Legacy's senior and an early career scientist

A core aspect of the Nansen Legacy project was to train a new generation of polar experts. Now that the project is finished, we asked one early career scientist (ECS) and one senior scientist how they experienced being part of this large interdisciplinary project, how it has impacted their careers, and how the Nansen Legacy compared to other projects they participated in.

Geir Wing Gabrielsen is a senior scientist at NPI who has studied ecotoxicology in free-living seabirds for the past 40 years. As an ECS, Geir studied the feeding ecology and energetics of seabirds as part of the large collaborative PRO MARE project, a project that has had a big impact on his career today. In the mid-1980s, few studies focused on free-living seabirds and how they were adapted to life in the Arctic, but PRO MARE inspired him to pursue a career in this direction and to lead seabird projects in his later career. Geir believes and hopes that the Nansen Legacy ECS have had similar experiences as he did at the start of his career:

"Being an ECS in the Nansen Legacy project should be a good starting point for a future career in marine science or working with management-related topics".

Geir explains that interdisciplinary work was an important part of the PRO MARE program and, as a PhD student employed at NPI, he collaborated with scientists of different disciplines like oceanographers, glacier and sea-ice researchers, and fish- and marine mammal scientists. These connections resulted in good, long-lasting collaborations with several scientists. Reflecting on how the Nansen Legacy differed from his earlier experience, Geir says that previous research projects he was involved in had a big focus on higher trophic levels, including seabirds and marine mammals. The Nansen Legacy project mainly focused on the lower and intermediate trophic levels like phytoplankton, zooplankton, and fish, and the physical aspects in the ocean east of Svalbard. This was important since this area is experiencing significant changes related to climate change. Geir believes that the biological and physical knowledge obtained in the Nansen Legacy project will be of great importance for better management of the ecosystems in the northern part of the Barents Sea.

Griselda Anglada Ortiz was a Nansen Legacy PhD student at UiT. She studied the effects of ocean acidification on living marine organisms and the oceanic paleo-environment from the last 12 000 years in the Barents Sea. Griselda says that being an early career scientist in the project has impacted her career positively for several reasons. First, having the support of the administrative team made her life a lot easier. Also, the annual meetings provided connections outside her specific working group and offered a space to present and discuss her work. The Recruit Forum for all the early career scientists in the project also opened for discussions on other topics related to their journeys. The opportunity to go on cruises was precious to her since she had never been on a cruise before she started her PhD. Working in an interdisciplinary project was another valuable opportunity for Griselda:

"I learned something from everyone in the project. In the future, I would like to continue working in interdisciplinary projects and try to include other perspectives, such as social sciences and humanities, as well as the local communities."

Griselda states that having early career representatives who connected the project leader team, and the PhD and postdocs was one of the most valuable aspects of the project. Another valuable aspect was the structure of the project. Despite the more disciplinary tasks, there was plenty of room to create new collaborations. That is reflected in all the small projects that have been developed over the last few years. That will be something to implement in the future as well. ■

Photo: Snorre Flo

The Nansen Legacy Early Career Scientists – where do they come from and where do they go?

The Nansen Legacy has been a large research project, with over 300 scientists working together. Almost half (128) of these researchers were early career scientists (ECS). Where did they come from and where did they go? The project hosted people from all over the world and most of them continued their career in research and stayed in Norway.

The Nansen Legacy has been one of the largest projects funded by the Norwegian Research Council, but it is by no means a project solely run by Norwegian scientists. On the contrary, scientists from 34 nationalities from all over the world contributed. Particularly among ECS, more than 70% were not from Norway. The majority came from European countries, with Germany, UK and France on top, but Asia and North America were also well represented at all ECS levels. Our early careers moved to Norway to work in the Nansen Legacy and seem to thrive. As more than 68% of the international ECS who found a new job stayed in Norway when their work in the project ended, Norway retains and gains valuable expertise and capacity.

The collaborative research initiative of the Nansen Legacy involved ten different universities and research institutions. After their time with the project, most ECS continued their careers in research, taking on roles as scientists, advisors, or analysts at government agencies, private companies, institutions, or universities. 19% of our ECS continued from a Master's degree to a PhD, to a Postdoc, or a new Postdoc, and 18% found other temporary positions in academic-, institute- or management sectors. Of all the ECS who found a new job after their time with the project, 61% now have a permanent position. About two-thirds of these ECS with a permanent position were Postdocs with the project and have continued with scientific research. The other one-third were mainly former Master's and PhD students who started working in the private or governmental sector. Three early-career scientists started their own companies with consultancy services or with a business specialising in autonomous robotic systems for the marine environment. ■


Photo: Inger Lise Næss

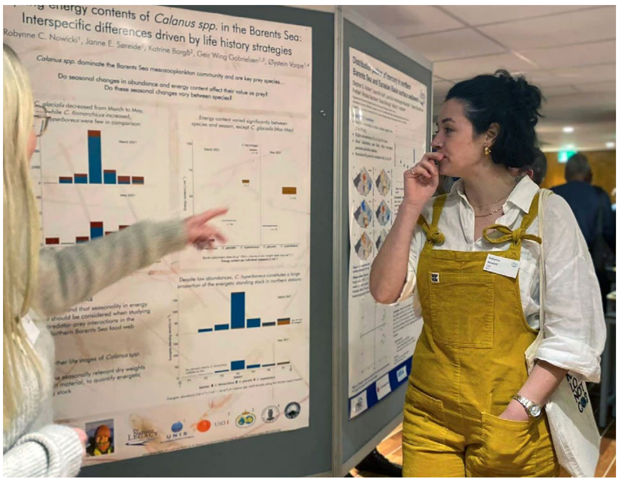
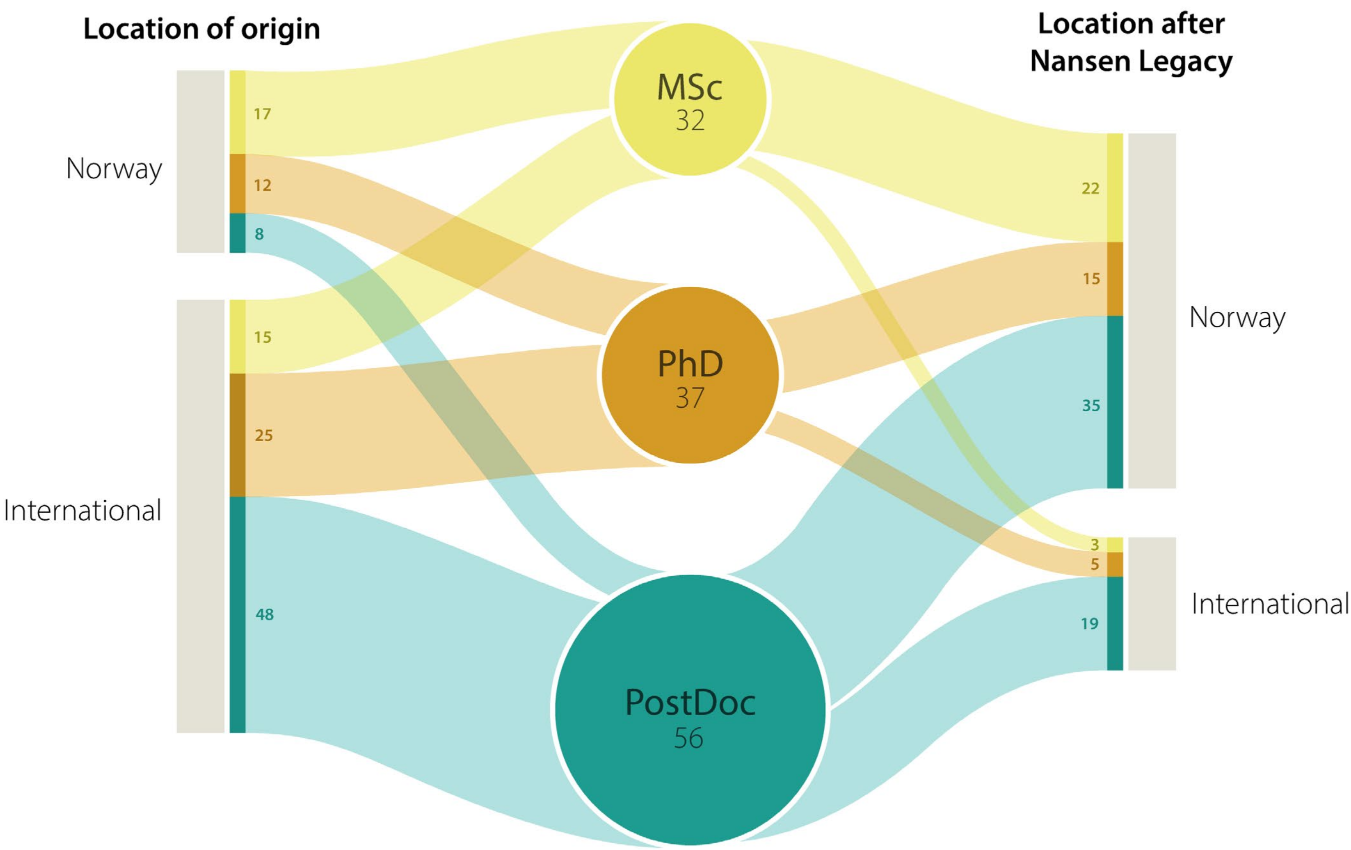
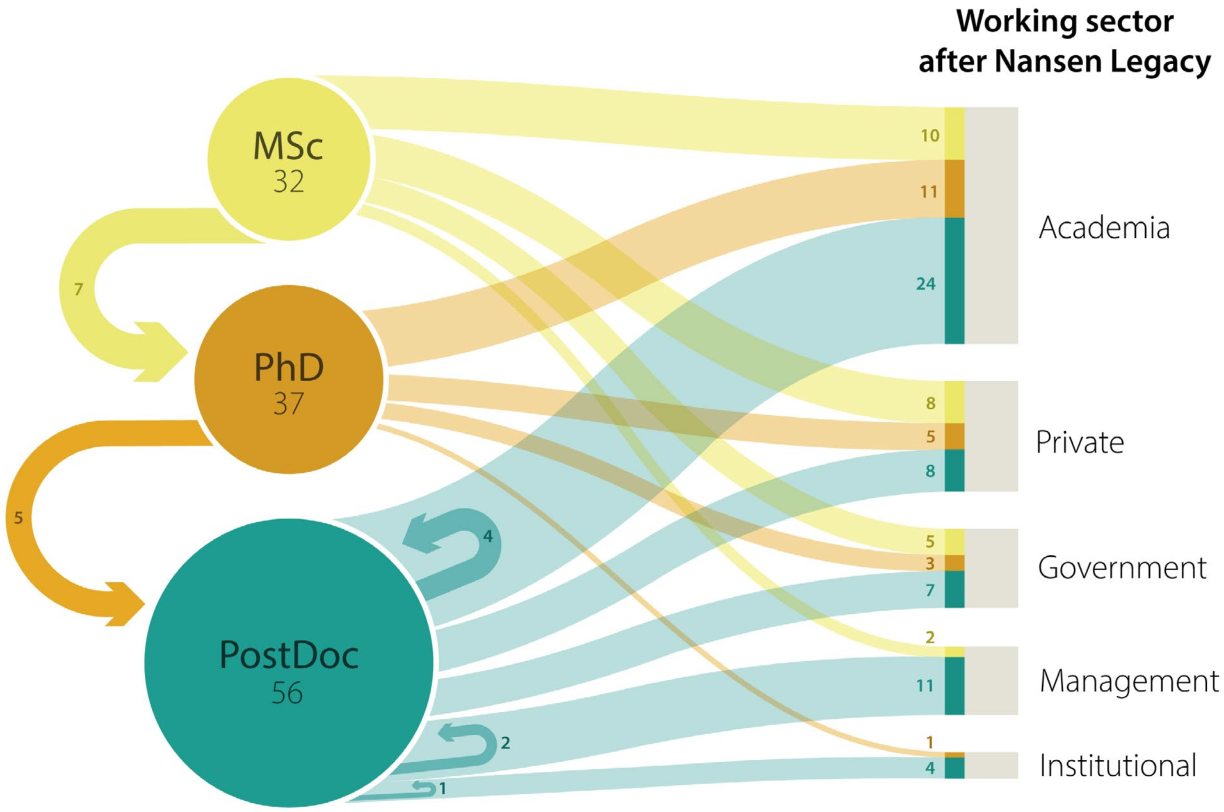


Photo: Charlotte Stark





The numbers indicate the number of Master's students, PhD candidates or Postdocs coming from Norway or abroad (top), and the number of these early career scientists who found a new job in or outside Norway in one of five different sectors (bottom). The private sector indicates those who work with private companies, some of which do consulting or research. The arrow's thickness indicates the relative percentage of the early careers coming and going, and circular arrows indicate they stayed within an early career scientist position. The candidate numbers used are from October 2024.

International collaborations and mobilities

The Nansen Legacy had a wide and strong connection to the national and international Arctic marine research communities and analytical experts, through collaborations with researchers, projects, and institutions. The early career scientists of the project completed over 40 shorter mobilities, both within Norway and abroad. Project members travelled, had mobility and shorter travel stays abroad, hosted international colleagues at home, as well as shared data and samples. Joint publications with international colleagues on 57% of the 270 publications reflect the level of collaboration. Here is an overview with examples of the many international collaborative efforts of the project.

ARCTIC

Several Nansen Legacy members took part in planning and joined the **international MOSAiC field campaign**, through joint scientific- and data publications.

The Nansen Legacy Arctic Ocean expedition in 2021 was a contribution to the international research effort of the **Synoptic Arctic Survey.**

RUSSIA

In 2021, Nansen Legacy and Russian scientists from the Murmansk Marine Biological Institute, the Murmansk State Technical University, the Russian Federal Research Institute of Fisheries, and the Toms State University Oceanography published a **review article of historical Russian data on polar cod in the eastern Barents Sea**, making important datasets available for the broader research community. A field campaign in 2019 provided samples from the eastern Barents Sea.

JAPAN

Nansen Legacy scientists **collaborated on several occasions with Japanese scientists from JAMSTEC**, including on calcium carbonate shell analyses, stable isotope analyses on foraminifera, and X-ray Microfocus CT analyses. In 2021 a scoping webinar for enhancing joint work was organized and in 2023, members organized sessions with JAMSTEC at the Arctic Science Summit Week.

POLAND

Throughout the project, members have had a strong collaboration with researchers from the **Institute of Oceanology of the Polish Academy of Sciences (IO PAN) on plankton and benthos analysis for biodiversity mapping**, and joint supervision of a PhD student.

HUNGARY

A postdoc from the Nansen Legacy spent time at the **Balaton Limnological Research Institute in Hungary for a 1-year sampling campaign**, where they developed a machine learning algorithm to capture high special and temporal ocean optical variability using satellite data.

DENMARK

A Nansen Legacy PhD student **had joint supervision with and research stays at DTU Aqua in Denmark**, facilitating work trait-based ecology of copepods. Nansen Legacy also had ties with **Aarhus University**, including analysis of samples on dissolved organic matter, and being home to a member of our Scientific Advisory Board.

GERMANY

Nansen Legacy had several fruitful collaborations with researchers and teams in Germany, including the **German Weather Station on improved forecasts, the German Aerospace Center and the German Research Centre for Geosciences** on using global navigation satellite systems for sea-ice monitoring, as well as with the **University of Hamburg, Senckenberg Research Institute Hamburg and Max Planck Institute of Meteorology.**

Several collaborations were established with the **Alfred Wegener Institute Helmholtz Center for Polar and Marine Research**, including the joint supervision of a PhD student, chemical analyses and investigations on gelatinous zooplankton, and expert advice from two of its researchers on our Scientific Advisory Board.

FRANCE

Early career members collaborated with the **Mediterranean Institute of Oceanography in France** to analyse mercury and to study microbes. Researchers at **Université de la Rochelle** collaborated on compound-specific stable isotope analyses for a joint publication. Collaborations were also established with **Ifremer (the French national institute for ocean science and technology) and École Normale Supérieure** to work on multiple stressors and cyclones, respectively.

UK

Nansen Legacy members initiated collaborations with UK scientists at **Oxford University for modelling future scenarios and work on multiple stressors, and at the University of Plymouth to analyse sea-ice biomarkers and work on paleoclimatic reconstructions** (also with collaborators at the University of Leeds). There were also collaborations with scientists from the **Arctic PRIZE, ARISE, and ChAOS projects, as part of the Changing Arctic Ocean program** to combine samples for a more comprehensive understanding of the northern Barents Sea food web.

A PhD student studying seafloor food webs at the **Scottish Association of Marine Science (SAMS)** was affiliated with the project, and another PhD student spent time at the **National Oceanographic Centre in Southampton** for detailed analysis of phytoplankton cell traits.

USA

The Nansen Legacy had many collaborations across the USA, including on long-term Arctic sea-ice variability and marine robotics at the **California Institute of Technology**, on ocean-glacier interactions at **Oregon State University**, on future fisheries at **NOAA and the University of Washington**, on genetic analysis of copepods at the **University of California (Berkeley)**, on sea-ice thickness changes at the **Polar Science Centre**, and on data from mooring sensors and autonomous underwater vehicles at the **University of Florida, University of Washington and Brown University**. Two **Fullbright scholars** spent time with Nansen Legacy members in Tromsø to work on sea-ice meiofauna. USA had a researcher on **our Scientific Advisory Board**.

CANADA

Nansen Legacy members had several connections across Canada, including work on phytoplankton phenology, satellite-derived primary production estimates, and modelling of physical and biological Barents Sea components – with the **University of British Columbia, University of Rimouski and the University of Alberta**, respectively. One early career scientist also spent time in **Cambridge Bay to complete a course on sea ice**. The Nansen Legacy also had two Canadian researchers on **our Scientific Advisory Board**. ■

National and international collaborations

The Nansen Legacy project has been a major player at the forefront of Arctic research, with contributions to international and Arctic collaborations and knowledge-sharing during the project period. This includes initiatives led by international organisations, as well as larger research initiatives.

Nansen Legacy researchers contributed actively to assessments or status reports by key international groups, such as the 2021 IPCC report, integrated ecosystem assessments from the ICES/PICES/PAME working groups, the IASC state of the Arctic report, and the Circumpolar Biodiversity Monitoring Program (CAFF-Arctic Council) reports under the Arctic Council.

Contributions to larger international science initiatives included the Arctic Distributed Biological Observatory (DBO) through support in initiating the Atlantic-Arctic DBO, together with Arctic Passion. As part of the British-led Changing Arctic Ocean Program, the projects shared sedimentary materials and geochemical analyses along the Nansen Legacy transect, as well as mooring data and supervisors for students. The Nansen Legacy 2021 Arctic Basin cruise was a Norwegian contribution to the Synoptic Arctic Survey, and we had joint activities with Japan's Agency for Marine-Earth Science and Technology. Increased frequency of weather balloon launches on RV *Kronprins Haakon* supported the Year of Polar Prediction and the Arctic Amplification Project (AC)^3. EU project collaborations included Arctic Passion, Blue Action, TriAtlas, and EU Marine Robots. Project members participated in the international MOSAiC field campaign, aligning sampling methods and enhancing the collective understanding of the Arctic Ocean system.

Outreach activities were strategically targeted at international scientists and stakeholders, coinciding with Norway's chairing of the Arctic Council, the ICES and AMAP executive secretaries being part of the Reference Group, and Rolf Rødven representing users in the Nansen Legacy Board. Nansen Legacy's data management team contributed to developing the WMO Unified Data Policy, expanding the SIOS portal, linking to SAON and promoting FAIR data. Additionally, project members chaired Arctic hubs within the Global Ocean Acidification Observational Network (GOA-ON), further solidifying their role in global Arctic science networks. Nansen Legacy biodiversity data has also been published in the Global Biodiversity Information Facility, GBIF and the Norwegian Artsdatabanken.

Being part of these partnerships and more, the Nansen Legacy fostered international collaboration and knowledge transfer, ensuring comprehensive and integrative insights into the Barents Sea and wider Arctic Ocean systems. ■

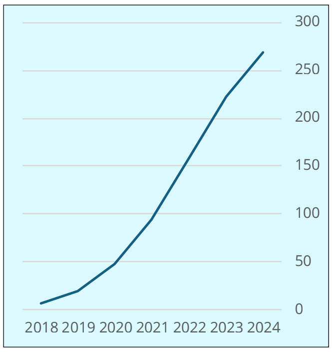

Photo: Rudi Caeyers

Publication statistics

The number of scientific publications is a prime measure for evaluating science projects. With more than 270 publications in over 90 different scientific journals, the Nansen Legacy undoubtedly has a significant output. The statistics also reveal that collaborations between national research institutions and international cooperation were strengthened compared to the Norwegian average.

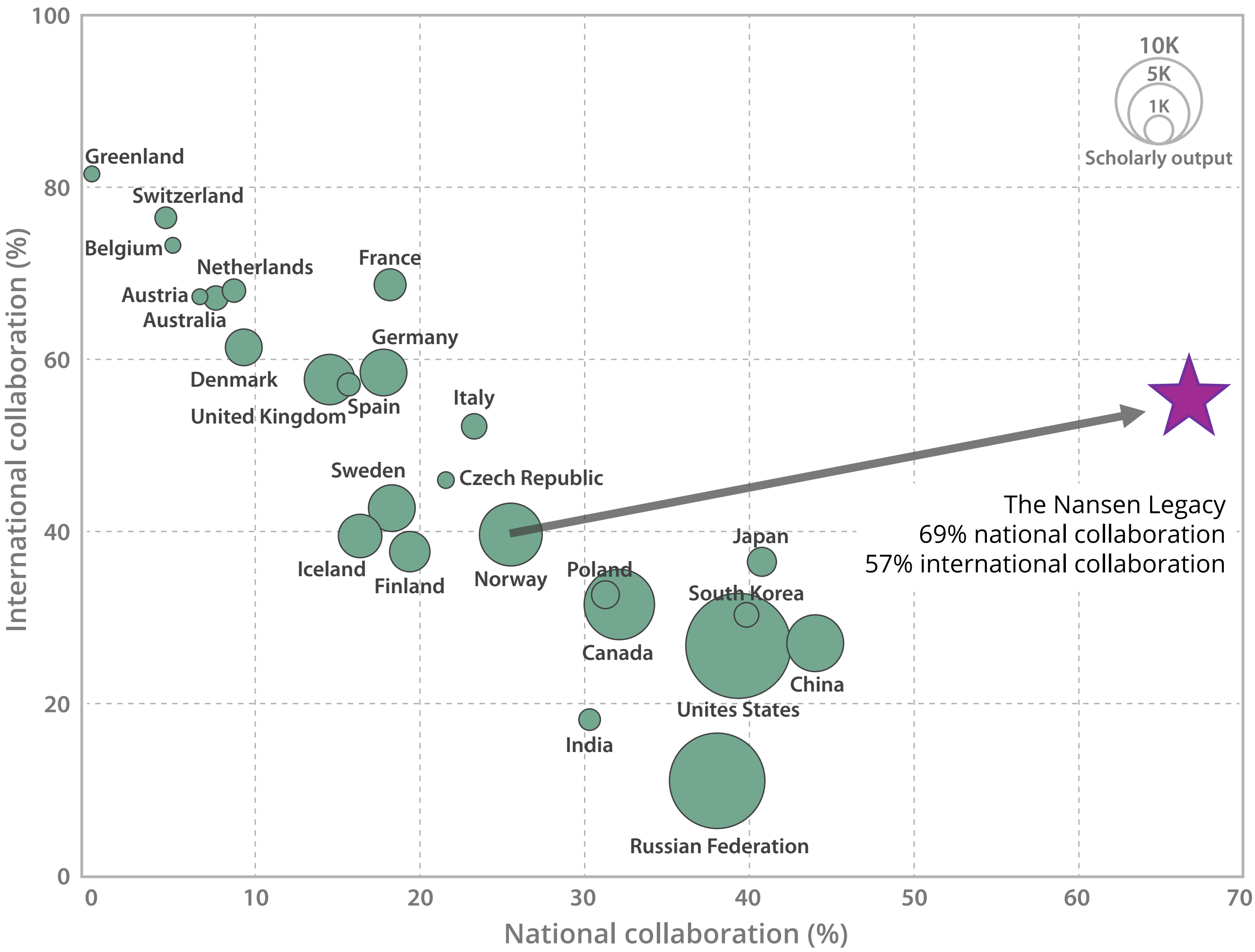
In the past 7 years, Nansen Legacy scientists have published more than 270 scientific publications in over 90 expert journals. Several manuscripts are still in the pipeline and will further increase the number. A look into the statistics (as of 6 December 2024) illustrates that most articles were published in *Progress in Oceanography*, where Nansen Legacy scientists led two special issues. Approximately 90% of the articles are openly accessible, and about 37% of the articles were published in fully open-access journals.

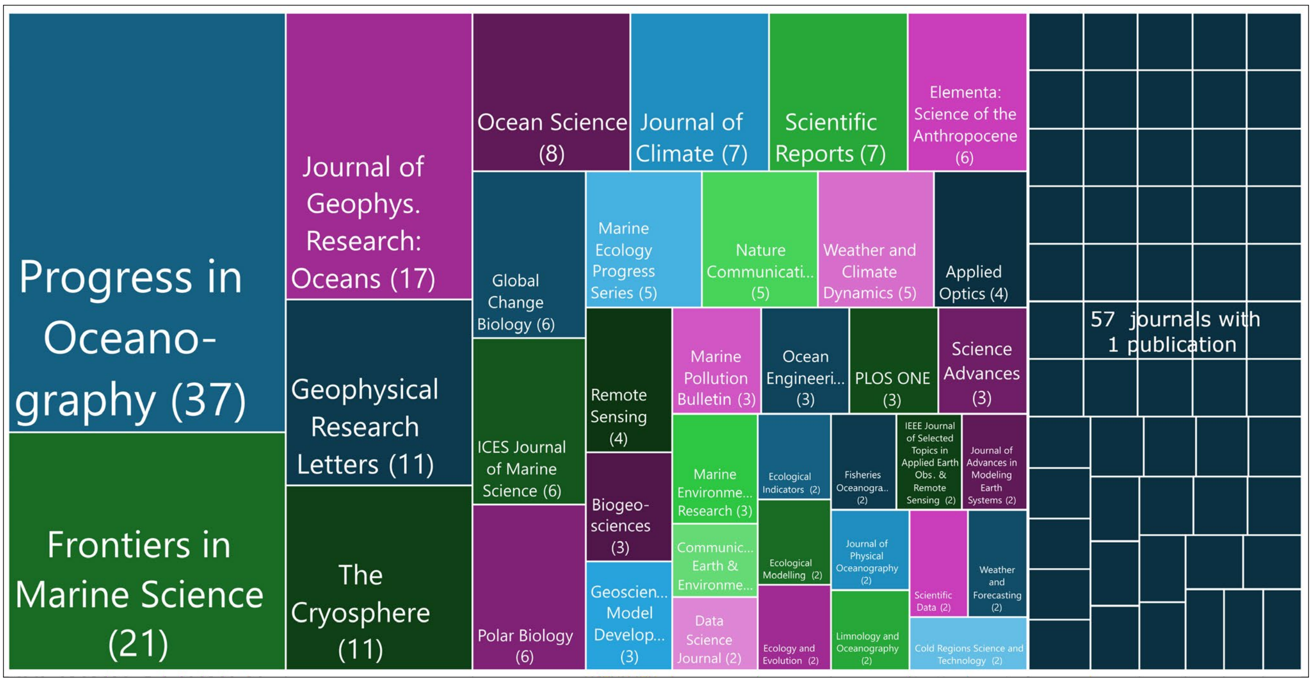
The statistics also illustrate that roughly 20% of the Nansen Legacy articles were produced in cooperation with 25 national institutions outside the consortium. Among those, NORCE, SINTEF, NINA, and NIVA were the most important partners. On the international level, publications were produced together with scientists from 33 different countries, but the main collaborators, in terms of co-authored articles, were the USA, the UK, Canada, Germany, and France.



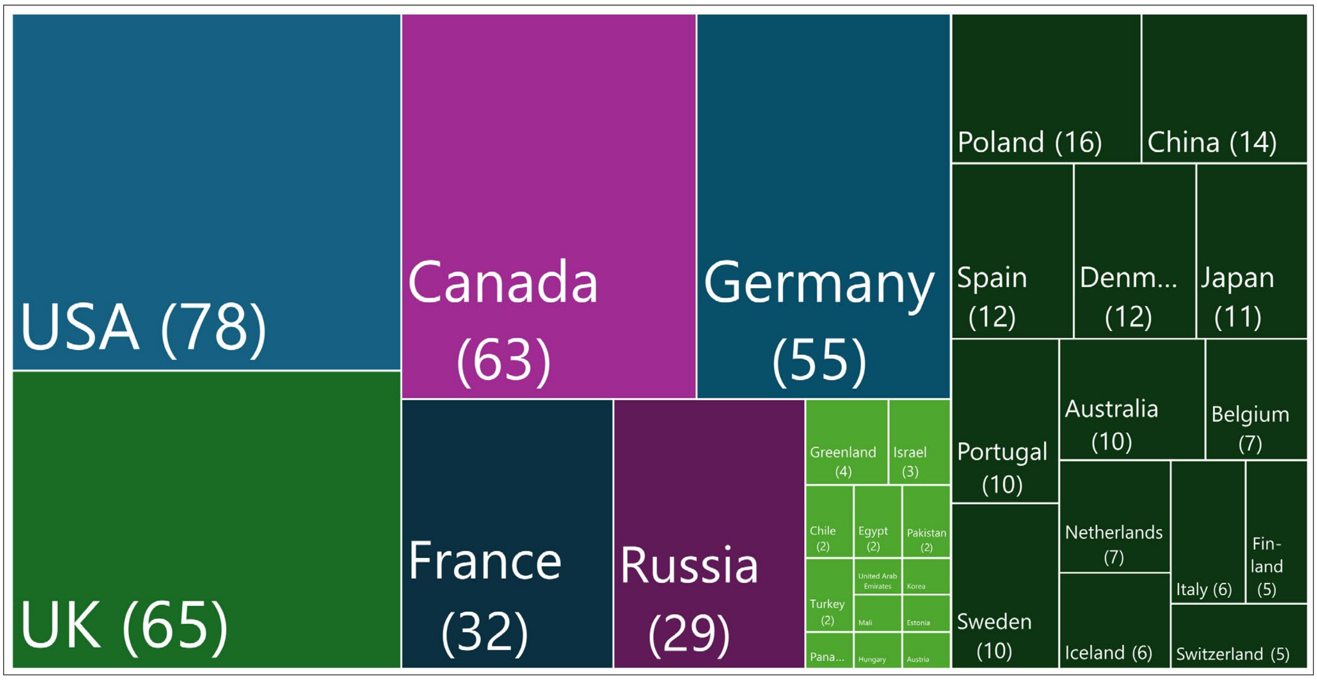
Accumulated peer-reviewed publications during the Nansen Legacy project period (as of 6 December 2024, and thus likely underestimating the total number of publications for 2024).

In terms of total numbers, a single research project like the Nansen Legacy cannot, of course, be compared to the scholarly output of entire nations. However, using relative numbers, it is evident that the project had a slightly higher level of international collaboration than the Norwegian publications on Arctic science average and considerably larger collaboration on a national level compared to national statistics. This demonstrates how the Nansen Legacy has succeeded in strengthening the collaboration between research communities at Norwegian research institutions with Arctic marine science expertise. ■





The 269 articles that were available as of 6.12.2024 were published in 94 different journals. Most of them were published in *Progress in Oceanography* (37 publications), but there was also a large number of scientific expert journals where only one article was published. This illustrates how many fields were covered by the Nansen Legacy.



The 269 Nansen Legacy articles available as of 6.12.2024 were co-authored by partners from 33 different countries. The most prominent collaborators, in terms of co-authorships, were the USA (78 co-authorships), followed by the UK, Canada, and Germany.

← In the Nansen Legacy, the production of articles co-authored by national collaboration partners was considerably higher compared to the Norwegian average. Figure modified from Aksnes et al. (2023) https://doi.org/10.5281/zenodo.7961982

Photo: Christian Morel/christianmorel.net

Annual meetings, workshops and an international science symposium – ways to build interdisciplinarity and collaboration

More than 300 scientists from 10 institutions distributed all over Norway collaborated in the interdisciplinary Nansen Legacy project. Regular meetings were key in building professional networks and personal relationships between the scientists and in bringing together all the pieces needed for an understanding of the comprehensive Barents Sea system. The final symposium placed the new findings in a pan-Arctic context.

Annual meetings as an important meeting arena

The Nansen Legacy had demanding project logistics: More than 300 scientists were employed at 10 institutions, located more than 2000 km apart, and the Covid-19 pandemic hit in the middle of the project period. Nevertheless, the project members cooperated closely, and the annual meetings were a driving force keeping the project together. During the three-day meetings, early career and senior scientists, the communication team, and members of the advisory and reference group met. Research approaches and recent findings were shared, stimulating collaborations and a comprehensive understanding of the Barents Sea system. As a byproduct, the participants also learned to communicate science effectively to experts from other fields.

Workshops as a forum for training and discussions

The Nansen Legacy supported workshops for early career scientists. During the *Recruit Forum* - a half-day event ahead of each annual meeting - the next generation of polar scientists learned about soft skill topics like *Communication with policy makers*. Two 1-week PhD courses on *Arctic Marine Biogeochemistry* and *Arctic Ocean Functioning* were also organised, as well as a field school on the polar front in cooperation with the research network ARCTOS. Senior project members organised workshops on specific themes and received funding through the Nansen Legacy. In this way, many expert discussions and advanced trainings were generated, such as a workshop on *Multi-factor experiments in marine science* (organized with SCOR), on *Arctic microalgae taxonomy*, on time-calibration of geological sediment cores, on *Best practices for ecological modelling*, and on *data publishing*. During the second phase of the Nansen Legacy, separate annual leader team meetings identified pathways for synthesis and science integration. These meetings resulted, for example, in the creation of the task force groups, which generated many science-integrating products like synthesis articles and fact sheets.

An international research symposium stretching from observation to adaptation

In 2023, the Nansen Legacy invited the international research community to Tromsø for a three-day international symposium entitled "Towards the new Arctic Ocean – past, present, future". It integrated scientific findings from the Nansen Legacy with the current understanding of climate and ecosystem functioning in other arctic regions. International keynote speakers and Nansen Legacy experts gave keynote talks on central pan-Arctic topics, balanced by expert sessions where many early career scientists presented their findings. The natural science program was complemented by a half-day side event entitled *From Observation to Adaptation*, organised with the EU project Arctic Passion, and supported by the Norwegian Arctic Council chairship. This event shed light on how effective coordination of different observing systems in the Arctic can provide strategies and solutions to local coastal communities and international resource management, facilitating adaptation to the new, seasonally ice-free Arctic. ■

Photo: Gudrun Sylte

Outreach

It was a genuine wish of the Nansen Legacy to widely share its activities and recently obtained understanding of the Barents Sea and the adjacent Arctic Ocean. The project aimed to inspire public interest, promote an updated understanding of a changing system, and ensure that the findings contribute to society beyond the academic community. The knowledge was communicated to anyone interested, from 5-year-old kindergarten children to His Majesty King Harald V.

A taste of the many outreach activities can be read below.

Photo: UiT Norges arktiske universitet

Photo: UiT Norges arktiske universitet

For and with kids

A variety of outreach activities focused on translating knowledge about the Arctic to children, the potential next generation of scientists. During the annual Norwegian Research Days, Nansen Legacy members demonstrated how contaminants reach Arctic organisms and how food produced at the surface reaches animals living on the sea floor. An imaginary research expedition to the North Pole for 5-year-old kindergarten children at a Science Centre explored biodiversity to show how polar scientists work. The team also met with kids through platforms like "Skype a scientist" and "Meet a Marine Biologist Monday". Additionally, one of the oceanographers, Sigrid Lind (NPI), wrote a children's book where three brave stuffed animals - Max, Diamanta, and Ibjørn - went on an adventure with the Nansen Legacy to the Arctic Ocean.

For and with youth

To reach out to youths with a future in ocean-related work life, Lena Seuthe (UiT *School Lab*) visited three high schools with a marine specialization in Northern Norway.

Photo: UiT Norges arktiske universitet

In collaboration with the Nansen Legacy, Lena and the students discussed ongoing ocean changes and built and tested wave sensors using technology developed by the MET scientists in the project. In this way, Norway's next generation of fishermen and fisherwomen gained hands-on experience with the ocean and their future working environment, and an understanding of how research and new technology can help with safety at sea.

For and with the king

Marit Reigstad was invited to give the 2023 Nansen Lecture, an annual event organized by the Norwegian Academy of Science and Letters. In her lecture, entitled *"From Fram to Kronprins Haakon – the Nansen Legacy meets a changing polar ocean"*, Reigstad discussed how the Nansen Legacy

Photo: Thomas B. Eckhoff

Photo: ecomagazine.com

project aims to obtain a better understanding of the Barents Sea system. She explained the physical drivers behind the observed climate and environmental changes, the ecosystem's response, the traces human activities leave behind, and what the Barents Sea might look like in the year 2100. The event was attended by His Majesty King Harald V.

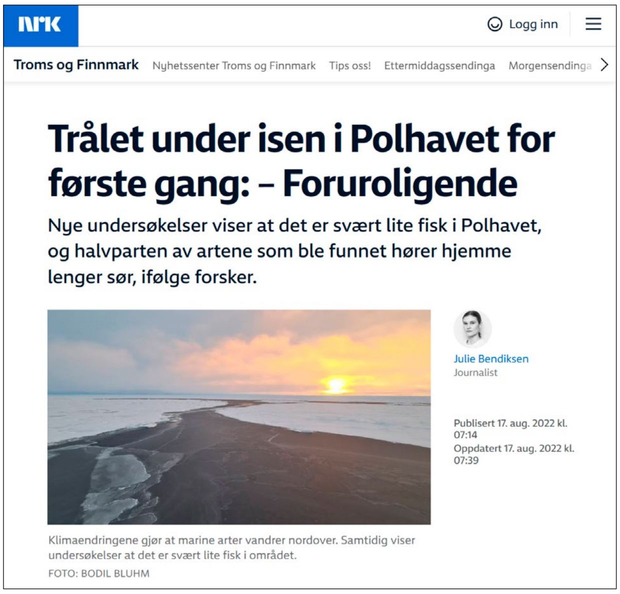
For and with scientists

Just in the last years, despite the COVID-19 pandemic, Nansen Legacy scientists have contributed to more than 95 conferences, with over 270 oral and poster presentations. Many of these were presented at large international conferences, such as the Ocean Science Meeting, the Arctic Science Summit Week, the ASLO meeting, the Gordon Research Conferences, the EGU meeting, and meetings organized by ICES. Additionally, the Nansen Legacy organized an international symposium in Tromsø in November 2023, which was attended by 250 participants.

For and with public

Nansen Legacy researchers used a wide variety of platforms to convey their work and findings to a broader audience. Besides numerous popular science talks and some pod casts, scientists wrote over 125 popular science texts for the Nansen Legacy blogs on forskning.no/ sciencenorway.no and developed the story map "En reise til den arktiske vinteren" ("A journey to the Arctic winter"), which takes the reader on an online cruise to the Arctic. The blog, written by Nansen Legacy's seafloor ecologist Bodil Bluhm (UiT), titled "Do you think we know whom we share this planet with? Then you are mistaken."

Photo: UiT Norges arktiske universitet


NRK
Logg inn
Troms og Finnmark | Nyhetssenter Troms og Finnmark | Tips oss! | Ettermiddagssendinga | Morgensendinga

Trålet under isen i Polhavet for første gang: – Foruroligende

Nye undersøkelser viser at det er svært lite fisk i Polhavet, og halvparten av artene som ble funnet hører hjemme lenger sør, ifølge forsker.

Julie Bendiksen
Journalist

Publisert 17. aug. 2022 kl. 07:14
Oppdatert 17. aug. 2022 kl. 07:39

Klimaendringene gjør at marine arter vandrer nordover. Samtidig viser undersøkelser at det er svært lite fisk i området.
FOTO: BODIL BLUHM

Photo: NRK

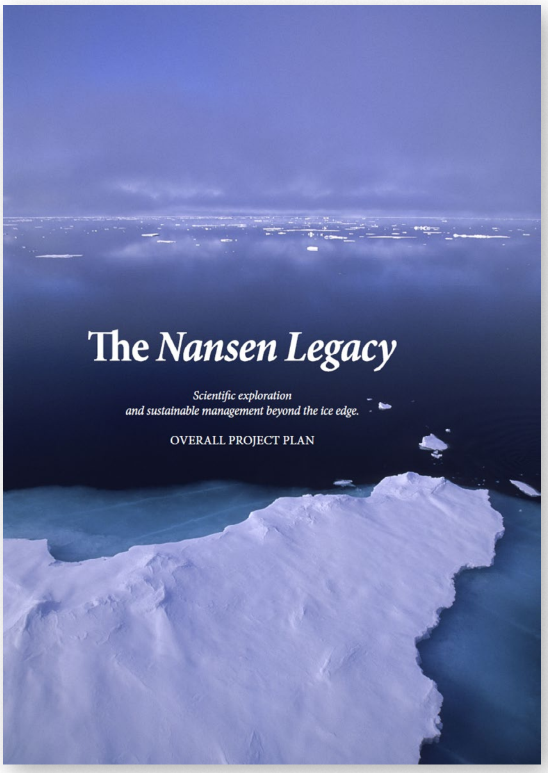
was among the most-read blog posts on sciencenorway.no in 2020. Nansen Legacy early career scientists organized vibrant popular science pub evenings in four cities in Norway as part of the "Pint of Science" event. An exhibition at the Svalbard Museum informed visitors about the project and research. In addition, the project was represented in national and international media. In national media, the expedition leaders Agneta Fransson (NPI) and Bodil Bluhm (UiT) were interviewed right after the Nansen Legacy Arctic Ocean survey by the Norwegian radio and TV program Helgemorgen. Ocean acidification was also discussed in Helgemorgen by Nansen Legacy researcher Melissa Chierici (IMR) in 2024. Nansen Legacy researchers shared their knowledge with Norwegian journalists, resulting in several articles by the Norwegian Broadcasting Corporation (NRK) and other print media, such as Aftenposten Viten, Nordlys, Klassekampen, and Svalbardposten. In international media, the Nansen Legacy was mentioned in for example the newspaper Wormser Zeitung, and the English edition of the South Korean daily newspaper JoongAng Ilbo, and a documentary by PhoenixTV, Hong Kong. ■

Media coverage *Blog posts*

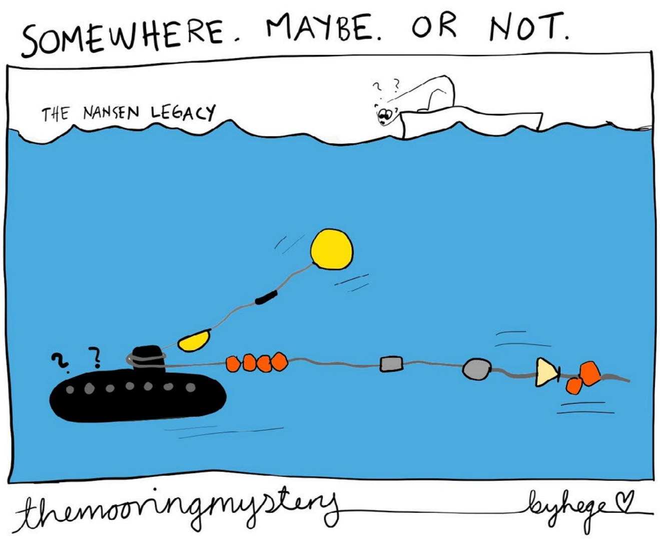
Artists and the graphic team complement the Nansen Legacy consortium

The Nansen Legacy focuses on natural sciences. To facilitate a non-scientific perspective on the Arctic, several artists and graphic designers complemented the science teams. An artistic perspective reaches beyond the scientific papers and brings life to the science stories. Annual reports, fact sheets, and the new Barents Sea book were given a professional graphic design. We are thankful for the eyes that captured and communicated Arctic moments in pictures, illustrations, and words.

Rudi Caeyers is a photographer and graphic designer at UiT, with an art background. He joined the Nansen Legacy already in the first hours. The Nansen Legacy logo, photography and the stringent graphic style resulted from his creative mind and branded the layout of project proposals, annual- and final reports, the symposium book of abstracts, and much more.

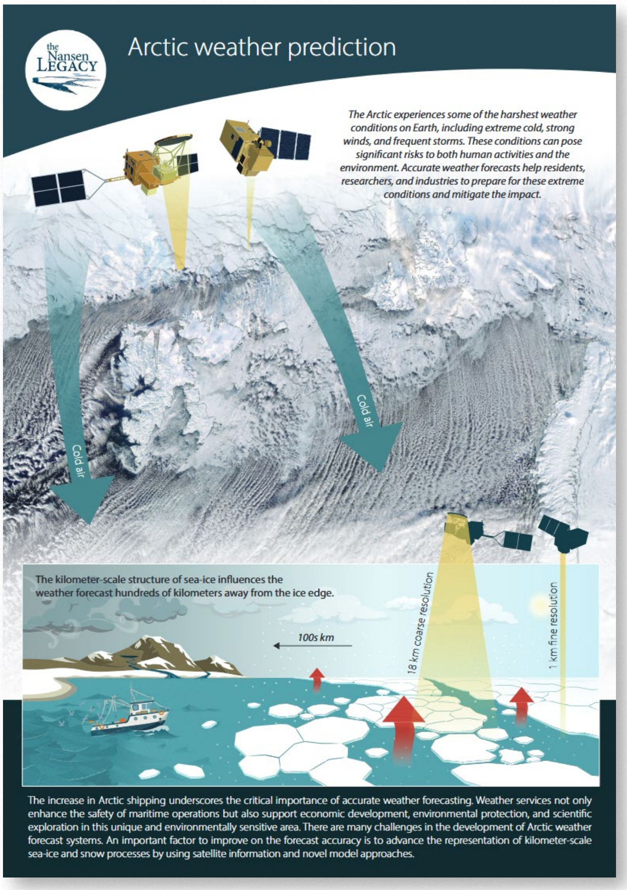


Hege Holen Paulsrud is a North Norwegian artist who joined a Nansen Legacy cruise in 2019 and documented the scientific work in her very own way. With a twinkle in her eye, she captured the joys and frustrations of scientific field work and provided some alternative explanations for why instrumentation was lost.



Lena Gudd is an artist with an interest in how humans entangle with the Arctic. She also joined a research cruise and communicated her impressions through a story map.

Christian Morel is a professional photographer with an extensive Arctic record. He joined one of the Nansen Legacy cruises, and his Arctic landscape pictures and detailed working scenes provide authentic insights into scientific work in the field. During the Nansen Legacy symposium, his pictures were exhibited and brought a flavor of the field to the meeting venue.



Frida Cnossen has been working as a scientific illustrator in the Nansen Legacy administration for the past two years. With a science background herself, Frida quickly captures scientific processes, and her creative mind comes up with easily understandable illustrations of complex processes. Among others, she designed the fact sheets, many illustrations in the Barents Sea book and publications, and the Nansen Legacy stamp, which was released in Norway in October 2024. ■

Project motivation and realization

Research evaluations calling for increased national collaboration, a new research icebreaker, and decreasing sea ice revealing a knowledge gap in the Barents Sea, were the main motivating arguments for initiating the Nansen Legacy project. The idea was born in the Norwegian Academy of Science and Letters in 2011. The opportunity to educate a new generation of polar researchers strengthened the case.

Excellent but fragmented Norwegian research communities

The evaluation of the Norwegian bio- and geoscience communities in 2011 and the Norwegian Polar Research evaluation in 2017 concluded that Norway had many excellent yet fragmented research communities. Meanwhile, global warming started to show in the Arctic, with winter sea-ice decline being most prominent in the seasonally sea-ice covered northern Barents Sea. The open water region of the southern Barents Sea is of high value for Norway due to its fisheries and petroleum resources. It also serves as an important gateway to the Arctic Ocean, marked by increasing maritime traffic and shared with Russia. Thus, a knowledge- and ecosystem-based management of activities is essential.

A new research icebreaker

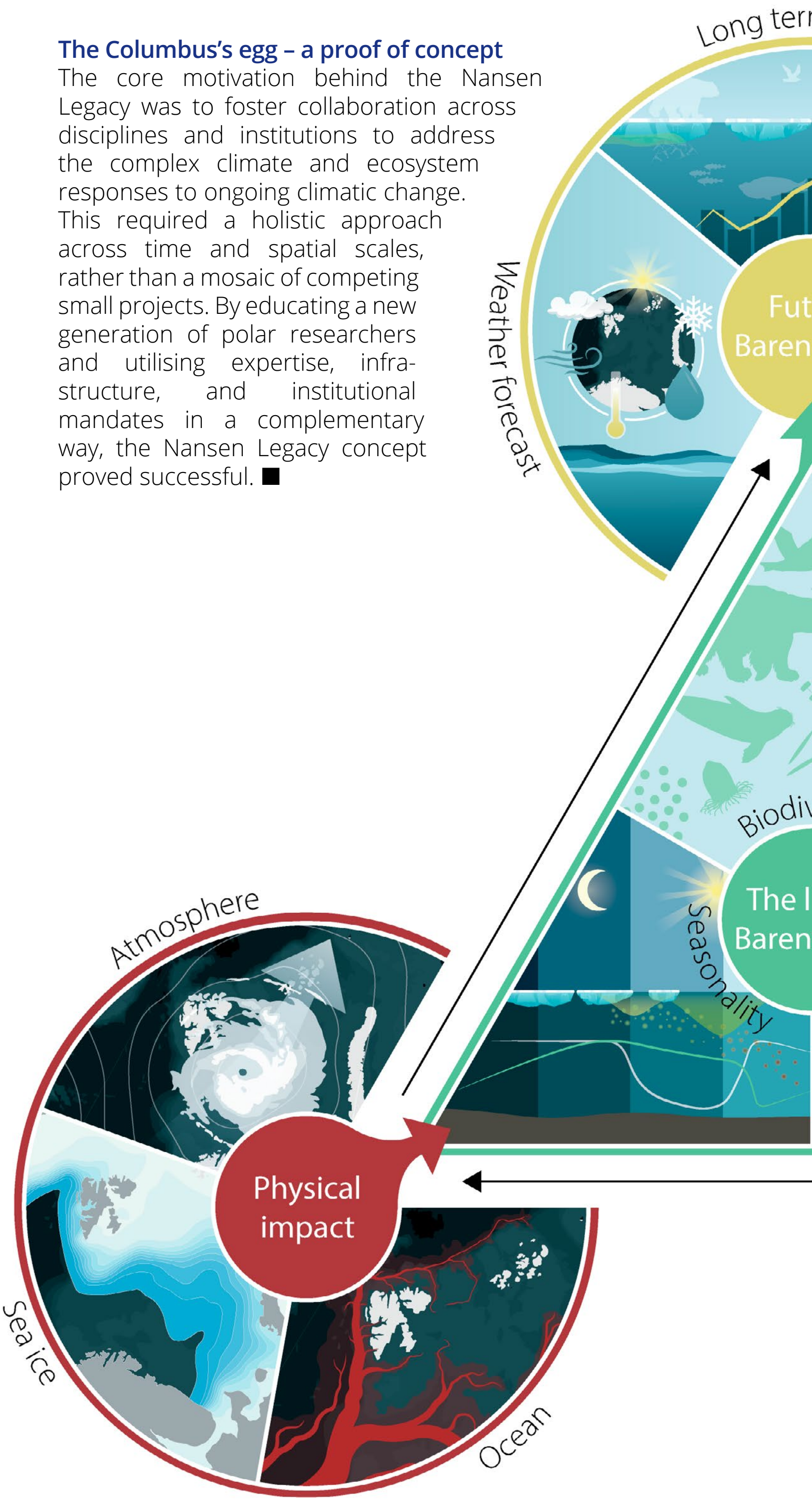
In 2012, Norway decided to build the new research icebreaker RV *Kronprins Haakon*. With the improved technology and infrastructure, it was imperative for the Norwegian research community to uphold the scientific and exploratory legacy of Fridtjof Nansen by moving poleward through the sea-ice covered Barents Sea. This was an opportunity for the Norwegian research community to build a national Arctic marine research team, the Nansen Legacy. If successful, this could be a Columbus's egg. In August 2018, the Nansen Legacy had the honor of taking the new Norwegian research icebreaker RV *Kronprins Haakon* on its first scientific mission and more than 20 Nansen Legacy cruises followed in the subsequent years.

A collective will to realise the Nansen Legacy

The National Academy of Science and Letters introduced the idea in 2011, and a SAK project from the Ministry of Education and Research supported the development of the first science plan, published in 2014. A dedicated group of individuals and institutions continued to develop the research project over the next three years. The project received funding for a six-year period starting in 2018, with a total budget of 740 million NOK. Half of this budget came from in-kind contributions by the ten partner institutions, while the Research Council of Norway and the Ministry of Education and Research provided the other half. The Nansen Legacy is the largest research project funded by the Norwegian Research Council. It is inspired by the Pro Mare project of the 1980s, which established a knowledge base for the southwestern Barents Sea following the collapse of several fish stocks.

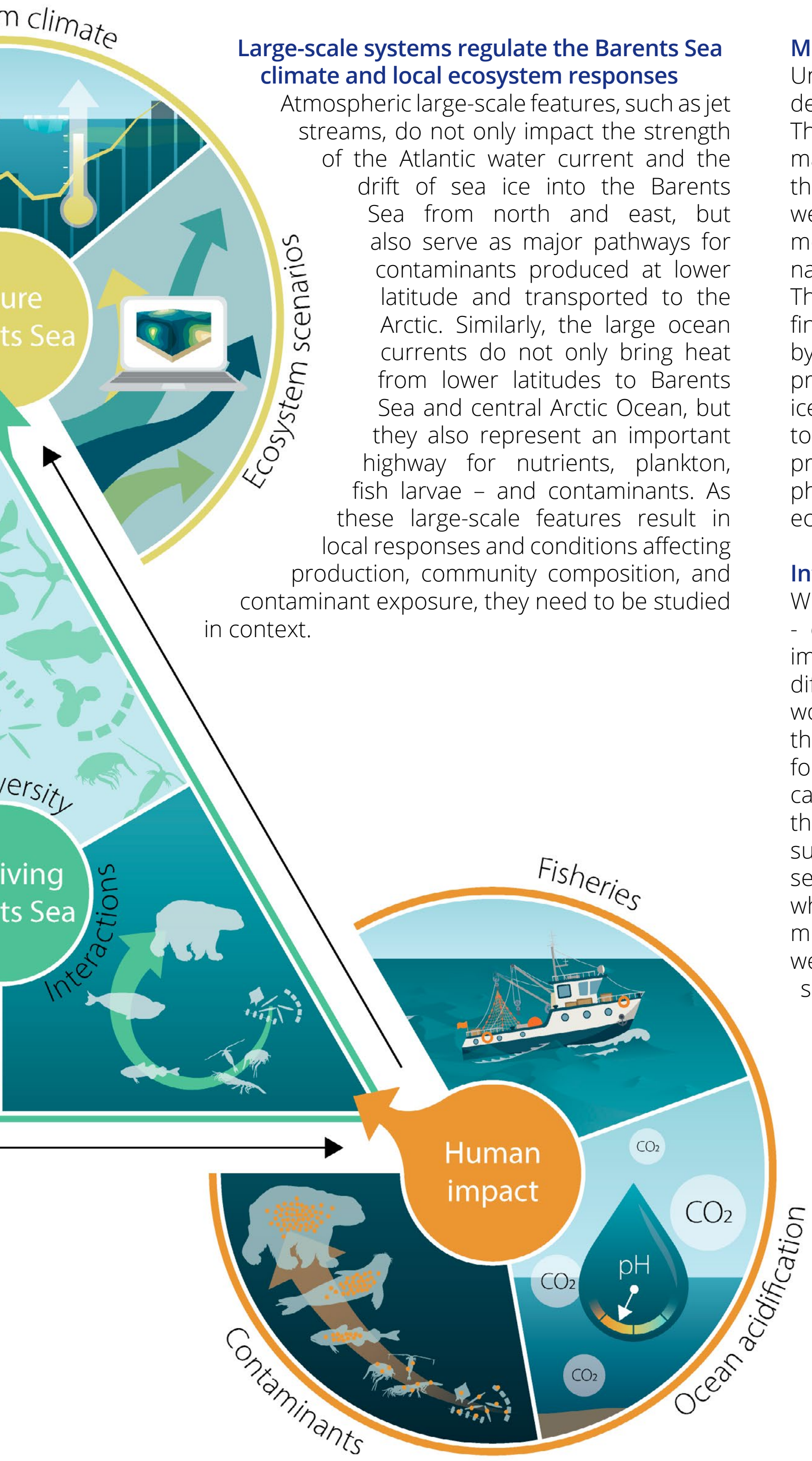
The Columbus's egg – a proof of concept

The core motivation behind the Nansen Legacy was to foster collaboration across disciplines and institutions to address the complex climate and ecosystem responses to ongoing climatic change. This required a holistic approach across time and spatial scales, rather than a mosaic of competing small projects. By educating a new generation of polar researchers and utilising expertise, infrastructure, and institutional mandates in a complementary way, the Nansen Legacy concept proved successful. ■



Understanding an ocean system

Climate change is particularly pronounced in the Arctic, with increased temperatures and reduced sea-ice cover. Warm Atlantic-derived water enters the Arctic through the Barents Sea, leading to early environment and ecosystem responses. With considerable Norwegian activity in the Barents Sea, knowledge on the larger system, including drivers and responses to change, is needed for a knowledge and ecosystem-based management.



Large-scale systems regulate the Barents Sea climate and local ecosystem responses

Atmospheric large-scale features, such as jet streams, do not only impact the strength of the Atlantic water current and the drift of sea ice into the Barents Sea from north and east, but also serve as major pathways for contaminants produced at lower latitude and transported to the Arctic. Similarly, the large ocean currents do not only bring heat from lower latitudes to Barents Sea and central Arctic Ocean, but they also represent an important highway for nutrients, plankton, fish larvae – and contaminants. As these large-scale features result in local responses and conditions affecting production, community composition, and contaminant exposure, they need to be studied in context.

Multidisciplinary exposure

Understanding a large, complex system requires dedication to both the large picture and the small pieces. The Nansen Legacy implementation plan identified the many pieces of the puzzle to be solved, but also placed the larger vision up-front. Annual project meetings were a crucial meeting place, facilitating exposure to more detailed results and showcasing the spectrum of natural science disciplines and approaches involved. These meetings also enabled the team members to find their role in the project and expand their network by starting cooperations with scientists who could provide complementary information. For example, sea-ice fauna researchers connected with meteorologists to trace sea-ice floe origins, while climate modelers projecting future Barents Sea scenarios connected with phytoplankton researchers, fish distribution experts, and ecotoxicologists.

Integration of multidisciplinary results

While the project's first phase focused on data collection - often through multidisciplinary cruises - and model improvements, its second phase needed to link the different puzzle pieces into a larger picture. To achieve this, work package leaders, early career representatives, and the project lead identified together ten key themes. Task force groups, open to all interested parties including early career scientists and user group members, addressed these themes. Each group produced relevant outputs such as synthesis papers, special issues, and conference sessions. Additionally, each group created a fact sheet, which turned out to be an effective tool for integrating multidisciplinary results into a broader context. Models were also employed to integrate knowledge on a larger scale, zoom in and out, explore future scenarios, or test responses to various pressures or conditions. This work led to a more holistic understanding of the Barents Sea system, including its drivers, components, and interactions across disciplinary processes. The derived knowledge and the developed tools are valuable and useful for future management. ■

Illustration: Frida Cnossen

The recipe for success

How did we get 300 scientists to collaborate across disciplines spanning from meteorology to past climate and from food webs to advanced robotics? The secret includes good planning with involvement, common visions on focus and goals, and ownership of the research and the project among both researchers and institutional leaders.

Planning phase securing involvement
The long planning phase of the Nansen Legacy project (2012-2017) allowed the scientists in the working group and the interim board, with representatives from the involved institutions, to develop ownership of the science lined up. The project development was anchored at the top of participating institutions to motivate funders and ministries to realize this new research project concept. The development of the project through a science plan, proposals, and an implementation plan included clarification of budgets and the role and contribution of each partner. This, in combination with sufficient funding for the planned activities, allowed a focus on collaboration and research, rather than competition and positioning when the project started.

A common financial pot for common activities
Each of the partners contributed in-kind as much as they received in external funding. A share of this external funding was directed to the common pool which funded, for example, the project administration, annual meetings, cruise logistics and allowances, outreach activities, publications, mobility and travel grants, PhD courses, and the Recruitment Forum - activities that contributed to the common good of the project. Transparent guidelines secured equal opportunities for all participants to join common activities and to apply for support for mobility, conference participation, or publication fees.

Integrating activities and products
The integration of results from the many activities into a larger and more holistic understanding was initiated through activities that looked at the results in a thematic or larger context. The team of work package leaders, early career representatives, and stakeholder contacts identified relevant themes and products. Several synthesis papers were written to summarize the state of thematic knowledge, and special thematic issues in science journals encouraged research papers to focus on integrative themes that are also relevant input for assessment reports. In addition, products relevant to stakeholders and the public were created, like the series of fact sheets, which present key messages visually and with short, informative text, and the nicely illustrated Barents Sea system textbook.

The collaborative will and enthusiasm of people at all levels involved – from institution leaders to early career scientists – have been the most important values and drivers for all activities in the Nansen Legacy. The joint trust and respect among the project members and partner institutions have provided the basis for this. ■

"The collaboration we have demonstrated in the Nansen Legacy shows the capacity and the results we are able to obtain as strong dedicated teams."

Marit Reigstad (UiT), Nansen Legacy project leader

Photo: Christian Morel/christianmorel.net

The communication team – a joint effort

The Nansen Legacy communication team included appointed members from the communication departments of all partner institutions. The different competencies and perspectives of their home institutions made it possible to share project activities and results through many suitable platforms and to reach a spectrum of target groups.

Collaborating on communication

The project's vision of communication was to increase the general knowledge about Arctic marine systems, their specific nature, changes, and how they connect to society. A dedicated team of communication advisors from all the partner institutions promoted the Nansen Legacy through coordinated communication and outreach. The group was led by Charlotte Stark (UiT, MET), who worked in close collaboration with the project lead and the project administration to stay up to date on ongoing and upcoming activities, plan outreach activities, and activate the communication team and relevant scientists. In addition, the communication experts joined the annual meetings to learn about the ongoing science of the entire project.

Target groups and communication channels

The Nansen Legacy aimed to communicate with the general public, the scientific community, as well as users and decision-makers, both nationally and internationally. Kids and youths were also important target groups, and several activities were dedicated to reaching them. The communication team produced articles, and moderated outreach on different social media platforms and the project's homepage. Further, they helped and encouraged scientists to reach out to different user groups through a variety of communication channels, including newspapers, TV, radio, blogs, science centres, social media, panel debates, and books. ■

Examples of different outreach activities are given in the *For and with* section on pages 82-83 and the project's web page.

The reference group – involvement of users

Building a knowledge foundation beyond the present-day ice edge to support sustainable and knowledge-based management requires that the new knowledge is relevant and reaches many different users. A reference group with representatives from key sectors was established at the start of the Nansen Legacy and followed the project to the end.

The Nansen Legacy Reference group included representatives from key sectors, including the maritime, petroleum, fishing-, and biomarine industries, as well as management organisations. Workshops and panel discussions at conference side events facilitated discussion and knowledge exchange throughout the entire project period. Based on feedback from the midway evaluation, the Nansen Legacy upscaled its capacity to enhance dialogue and involvement and to fulfil specific requests. For example, the reference group was given a seat on the Nansen Legacy Board, sessions addressing bottlenecks in knowledge focus and transfer were included in the annual meetings, and reference group members were involved in the production of the Fact Sheets to ensure that important results were conveyed in the appropriate manner.

During a final project debrief, representatives of the reference group praised the Nansen Legacy's implementation of the Midway evaluation as an excellent response and only recommended an earlier involvement of a user group in future projects. ■

Photos: Charlotte Stark

Photo: Algot Peterson

Data as a Legacy: Including data handling and management

There is an increasing focus on data management plans and data handling in research projects, institutions, and organisations. The Nansen Legacy project underscores, in this context, the value of a living Data Management Plan, broad involvement, and a sharing culture that is truly FAIR. By using data archives that follow data and metadata standards, can be harvested, and manage data well, data becomes a true project legacy.

Ambitions for data management in the Nansen Legacy

The ambitions in the Data Management Plan were formulated as "The Nansen Legacy will improve, secure, and operationalize national data archives and ensure data availability in accordance with national and international standards. A distributed data management system where physically distributed data repositories are forming a virtual data centre with seamless access to datasets regardless of physical location, will support the project by:

1. Unified data discovery through standardized discovery metadata indexed in the SIOS Data Management System

2. Online access to datasets

3. Visualisations of datasets

4. Aggregation of datasets

By bringing many types of observations together and asking questions about how these are influenced by each other, new insights on the region's role in the Earth system are created."

Data management from all institutions

The Data Management Plan was developed as part of the Nansen Legacy research proposal in 2017. It represents a common and living document for all researchers and institutions, with agreed-upon guiding principles for the handling of data. At the end of the project, version 19 was published on the project's web page. The Data Management Plan provides an overview of the steps, actions taken, and guidelines to facilitate FAIR data publishing. In addition, it offers insights into bottlenecks. By involving data managers from all partner institutions, the collaborative effort has been considerable, though the exchange of personnel impacted the involvement of some institutions. It is also clear that institutions with mandates involving data facilitation were more prepared in terms of resources and facilities.

The Data Management Plan has not only been useful for project partners. By being freely available on the web page, it has also been used as a template and guideline by large international research projects.

Data for the future and a wider use

The ambitions of FAIR data require that data can be harvested from data centres with a long-term mandate to ensure the preservation of their scientific legacy. Guidance on suitable data centres is presented in the updated Data Management Plan. Along with tools that ensure standardised formats and proper metadata, data is made accessible through portals like the Nansen Legacy Data access point in the Svalbard Integrated Arctic Earth Observing System (SIOS) and the Sustaining Arctic Observing Networks (SAON). ■

"The data will be used by many more and long after the scientific publications have lost interest. Data represent the true legacy of this project."

Øystein Godøy, MET

Models and their legacy

A wide range of models was used in the Nansen Legacy – from ocean models to ecosystem models and risk modelling of autonomous marine systems. All these are representations of the past or present-day processes or projections of a possible future. The model work, represented by new or improved models, identification of constraints, and the combined use of models, as well as the future scenarios for the Barents Sea, will serve as a legacy from the project.

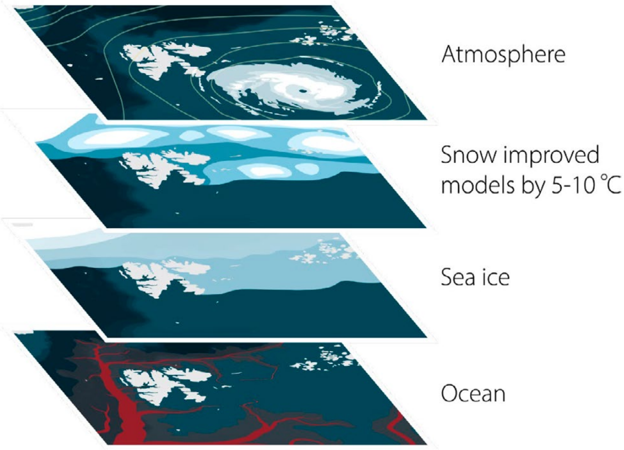


Illustration: Frida Cnossen

Combining models and optimised use

The Nansen Legacy model work has focused on improving of specific models through evaluation, for example, based on observational data, or by combining individual models. Through model stacking, we can gain an improved understanding of the ocean, sea ice and snow, waves, and the atmosphere. This advances the accuracy of weather, sea ice, and wave predictions. However, combining models is not a simple addition of specialized models. Instead, considerable effort is needed to be made to ensure that the integration maintains the quality of each model and, in addition, provides an integrated, reliable result that can be evaluated against observational data. Future work also includes the implementation of the new model with a more realistic representation of sea-ice dynamics.

The combination of models, where the output from one provides input for another, has also been very valuable. The Ecopath mass-balanced based food web model was used to gain important insight into the major pathways of energy flow through the Barents Sea food web. Extended with a spatial component and with input on future climate scenarios, potential spatial shifts in future fish distributions due to changing environmental and feeding conditions could be demonstrated. Identifying constraints for the different models is also important for an optimized use. Ecosystem models, for example, range from detailed end-to-end models, including environments, species, and interactions, to more conceptual or statistical models with a few key species and interactions. Model comparisons show that the different models are useful for different questions and purposes.

Evaluation of models

Bringing together the many different ecosystem models used, the Nansen Legacy ecosystem modelling team identified a gap in how to evaluate the performance of these models across different questions of scientific or societal relevance. Therefore, the team developed a general protocol with 25 questions designed to guide reporting and increase the transparency of model evaluation. The protocol can, for example, help modelers be more aware of evaluation at an early stage of model development.

Online risk modelling

The Nansen Legacy focused on technological development, including risk modelling for autonomous marine systems. The development of autonomous underwater vehicles (AUVs) has evolved quickly over the past years. AUVs are already used for unmanned and autonomous ocean monitoring and will likely play an important role in future ship traffic. Nansen Legacy scientists reviewed existing risk methods and models assessing operational safety and identified the main research challenges and gaps. They also investigated which hazards, or hazardous events, may affect the safe and reliable operations of autonomous marine systems, proposed a method for developing online risk models, and demonstrated the proposed methods by developing an online risk model to estimate the probability of AUV loss.

Results and approaches for combining models, a protocol to evaluate ecosystem models, and a risk model for newly developed autonomous marine technology are only a few examples of advances in modelling that will also be used in the future. The Nansen Legacy brought together scientists from different branches of the modelling community. The extended network developed will hopefully inspire further future steps. ■

"We suggest that it would be highly beneficial for modellers to consider the OPE (Observations, Patterns, Evaluation) protocol early in the modelling process, in addition to using it as a reporting tool and as a reviewing tool."

Benjamin Planque (IMR)

References

Future scenarios can help future management

Resource management, legislation and future investments depend on the best possible information on how the future will look like. The Nansen Legacy has developed scenarios for future climate, for future ecosystems, and through experiments – the response of organisms to impacts like warming, pollutants or increased ocean acidification separately as well as in combination. This information can help mitigation, adaptation and future management.

Short-term forecasts

The improved accuracy of weather forecasts in the north is an important societal legacy from the Nansen Legacy. With increased activities in this region, there is a greater need for reliable forecasts to evaluate the risks associated with expected storms, icing on vessels or a change in sea-ice distribution. The improvements in forecasting contribute to the safety of people as well as assets operating in the high north.

Long-term projections and scenarios

The long-term projections and scenarios come with larger uncertainties. At the same time, they provide information on the range of potential future realities we need to take into consideration when we prepare for activities, infrastructure, harvest or other kinds of resource utilisation that require considerable investments. With ongoing climate change and pressures on nature identified by the IPCC reports, the Paris agreement, and the Kunming-Montreal global biodiversity framework, the future outlooks provide important contexts for governance and management.

Future risks, mitigations and adaptation

A workshop on "*The future Barents Sea, mitigations and adaptation options*", arranged in collaboration with the Barents Risk project, brought scientists and stakeholders together to discuss risks, ecosystem services, futures for the Barents Sea, and how various risks may change under future scenarios. Science-based facts are valued, and dialogue between scientists and stakeholders can reduce risks. In the workshop discussions, global governance was often associated with increased risk, and it is therefore important to continue such dialogues to bring facts and risks to the table and find the best strategies for mitigation and adaptation. ■

References

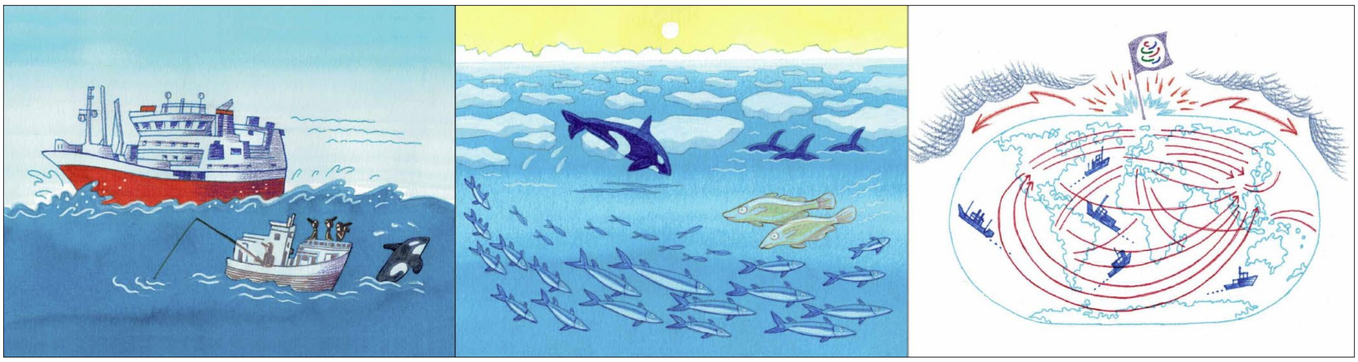


Illustration: Juliette Planque

A new generation of polar scientists

Fridtjof Nansen was in his early thirties when he led the Fram expedition to the unknown Arctic Ocean. The early career scientists in the Nansen Legacy have continued the exploration to understand the Barents Sea system in the light of ongoing change and will bring new knowledge, expertise and collaborative experience into the future.

A driving force and a glue

The 128 early career scientists who are and have been involved in the Nansen Legacy as Master's students, PhD candidates or postdocs represent a glue as well as a driving force for the project. Unlike many seniors, the early careers often had the opportunity to invest a full-time focus on the project's research questions. Several also had supervisors or mentors at more than one of the partner institutions. In this way, they linked expertise from different institutions to solve new challenges and kept the seniors actively involved and collaborating. Through teamwork and supporting each other in the field, through experiments and collaborative papers, this group of young and enthusiastic scientists has been essential for the success of the Nansen Legacy.

A new generation with wider perspectives

Many of the research questions and tasks addressed have had a disciplinary focus to allow the early careers to specialise. At the same time, they have been exposed to a multidisciplinary research community that also included societal aspects and discussions on how results best are made useful for a wide group of users. The annual meetings, recruit forums and joint cruises organised by the Nansen Legacy have strengthened the network and provided opportunities for collaboration, which in turn developed into new ideas and interdisciplinary collaborations. Their wider perspective of the marine ocean system research and interests in societal applications represents a competence and science outlook of this generation of polar scientists that is a true legacy for future research.

Competence and global networks to academia and society

The early career scientists represent a valuable resource that needs to be taken care of. The Nansen Legacy recruited candidates representing 28 nationalities that formed a truly international research community, bringing expertise and networks to the project. Many of these have moved on to new positions in Norway, and their competence has proved to be attractive for jobs both within the academic professions, but also for the governmental and private sectors (see pages 72–73). It would be of great value to secure that many of these researchers can be part of the foundation for the development of the Arctic, both as polar scientists but also as competent partners in the governmental and private sectors. The collaborative experience and competence combined with the wider perspectives is what the future Arctic needs. ■

References

Photo: Gudrun Sylte

Photo: Christian Morel/christianmorel.net

Observational legacy – technology and common protocols

The rapid changes in the Arctic marine environment and ecosystem call for continued observation to enable decision-making on updated information. The costly logistic challenges require smart technological solutions combined with better agreement on data protocols to integrate data across the institutions and projects collecting them.

Rapid change requires updated data

The Arctic marine environment is one of the most understudied ocean regions, but the response to the changing climate is amplified and natural variability is considerable. With challenging logistics for measurements and strong seasonal and interannual variations that impact the timing and magnitude of ecosystem characteristics, the ability to provide reliable projections and forecasts has been limited. Using multiple observational approaches combined with a suite of model tools for integration and outlooks, the Nansen Legacy project has strengthened the baseline knowledge for the seasonally sea-ice covered parts of the Barents Sea, and the understanding of important drivers of variability, involving large-scale systems. Still, we see that the combination of natural variability and ongoing climate changes requires continued observations that can be used broadly.

Data collection as a collaborative effort

To increase the observational capacity of the ocean, we need science communities to integrate information and data from satellites, long-term ocean moorings, autonomous vehicles and ship-based sampling and combine them with the understanding from research communities using models for short- or longer-term forecasts or projections. A prerequisite for this integration is that the research communities know about each other and the available expertise and projections. Moreover, comparable data are required.

In addition to the integration of data – multipurpose data use is important. The technological development is fast but remote and autonomous observations still require field-based observations for validation and further improvement. Data sharing that opens for multipurpose use will increase access and usability, as well as reduce societal and climate costs.

For this, the science network established by the Nansen Legacy, and the investments in data-sharing practices, competence building and supporting tools like the Nansen Legacy Template Generator (read more on implementing a data-sharing culture on page 64) are invaluable.

Common protocols facilitate the integration of data

Through the Nansen Legacy project, we have offered meeting places and utilised data collected by different platforms for different purposes, promoting synergies. Better sea-ice models and satellite data improved weather forecasts; measurements of the Atlantic Water inflow show how the warmer water reaches the Barents Sea from the north and speeds up glacial melt on Nordaustfonna; satellite-based observation of marine heatwaves was linked to responses in marine ecosystem time series; better estimates of annual primary production could be made by combining remote sensing, models and field measurements. In this way, the project demonstrates how a combination of different technologies and approaches can provide new knowledge. A very useful prerequisite for this success was the common protocols and the station map agreed upon at the project start. This agreement facilitated combinations of data that may not have been initially planned but helped us to build the larger picture of the Barents Sea system. ■

References


Photo: Andreas Wolden

Impact and Legacy

Science aims at making a difference. Not only can the outcome make a difference, so can also the organization of the research. The Nansen Legacy project team succeeded in realizing our potential for transforming the way we collaborate and address large complex research challenges. The Nansen Legacy integrated the involved researchers and research institutions for a common purpose, including the interaction with the larger research community and society.

Impact

The most obvious and direct impact of the Nansen Legacy is the extensive research and new knowledge established on the Barents Sea and larger-scale impacts. The extensive network the project represented, facilitated building and sharing existing and new knowledge and practices across generations, institutions and disciplines. The national pool of expertise and infrastructure was mobilized and used for the common good in exploring the collectively identified research challenges. This collectively increased insights and access to the competence of the involved scientists and to logistic capabilities will benefit future research, likely also beyond the arctic and marine domain. The immediate effect is the increased national collaboration manifested through joint publications. The international co-author contribution is also higher than the average for Arctic publications in Norway (read more on page 78). The extensive collaborations including mobility, both nationally and internationally, have also resulted in larger networks, improved models and methodology, harmonized sampling protocols, successful new research proposals with new collaborators and new positions for many of the early career scientists. The focus on outreach and useful science, resulted in dedicated products like fact sheets on important findings, synthesis papers and a new book on the Barents Sea system (read more on p. 56). Being available for national stakeholders, including government ministries, was a permanent priority.

Legacy

The Nansen Legacy offers a proof of concept for future national-scale research efforts – an organizational model and environment of trust for tackling the research challenges that require large-scale teamwork to succeed. The multi-disciplinarity and complementary approaches of this large network across institutions, provided extended context to the explorations of the individual scientists as well as the research questions, and thus the broader understanding of the Barents Sea system and dynamics. The focus on data sharing and training in the Nansen Legacy has increased the competence and improved practices of scientists and data management levels in all the involved institutions towards more FAIR data handling. The relevance for and involvement of management and other user groups increased the awareness, interest and competence in the scientific team as well as user group on both the importance and the challenges in making scientific results useful for the different user groups. The more than 130 early career scientists that have been involved is the new generation of Norwegian polar researchers. Their integration in the research community and expertise, use of infrastructure, and societal interaction will both guide and leave footprints in science and society in the decades to come. Trust and respect among the involved partners have been crucial for the collaboration. The projections on the future Barents Sea provide opportunities for policy makers and management to take informed decisions on future activities and important actions. ■

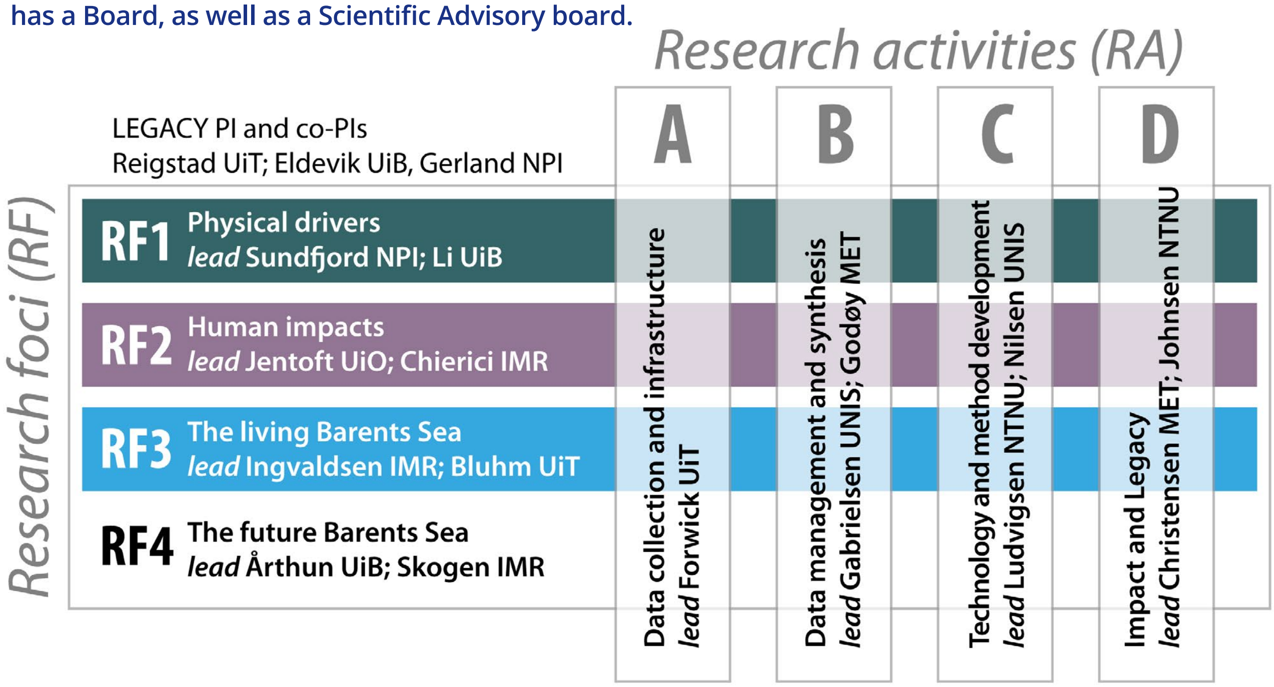
"Time, trust, and commitment. These were essential to the Nansen Legacy. By taking the time to build and mature the consortium and research concept, collegial and cross-institutional trust were in place when the operational part started. It succeeded in its execution because all involved remained committed to the end."

The Nansen Legacy PIs

Photo: Rudi Caeyers

Organisation

The Nansen Legacy is a collaboration between ten Norwegian research institutions, currently involving over 350 project members. Members include Ph.D. students, postdoctoral fellows, researchers, technicians, engineers and communication advisers. In addition to the scientific leadership, the project has a Board, as well as a Scientific Advisory board.



The Research Foci (RF1-4) represents "what" science the Nansen Legacy is investigating, and the Research Activities "how" (A-C), including impact and legacy in the public domain (D).

Project leaders

Marit Reigstad, UiT

Prof. Reigstad is the principal investigator (PI) of the Nansen Legacy. She is a marine ecologist interested in connectivity, including physics and biology, surface and deep waters, and regional connections. She has led several interdisciplinary projects and expeditions on Arctic marine ecosystems, and is active in science communication. Reigstad has been involved in international science planning since 2004, through ICARP and IASC. She serves on Liason- and evaluation panels and scientific advisory boards.

Tor Eldevik, UiB

Prof. Tor Eldevik is co-PI of the Nansen Legacy and the Head of Department of the Geophysical Institute, UiB. Eldevik generally explores the northern seas' role in past, present, and future climate, using a combination of theory, observations, and numerical models. The combination is also Eldevik's approach in communicating his research and other aspects of climate change to students and the general public. Present commissions of trust include contributing to the European Academies' Science Advisory Council (EASAC) and member of the Research Council of Norway's Portfolio Board for Climate and Polar Research.

Sebastian Gerland, NPI

Dr. Gerland is co-PI of the Nansen Legacy. He is currently working with sea-ice physics research and monitoring in the context of Arctic climate research. Beyond his involvement in the Nansen Legacy, he is leading and participating in other national and international projects, including the Norwegian Polar Institute's long-term Arctic sea-ice monitoring, and projects funded by the Research Council of Norway (e.g. HAVOC-MOSAiC and CIRFA SFI). Gerland is also active in climate assessments (currently IPCC's 6th assessment report and the NOAA Arctic report card).

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Stig Morten Knutsen	Norwegian Offshore Directorate

Photo: Maria Rossi

All science members

During its seven years of project time, the Nansen Legacy has been a joint research effort from 303 scientists and early career researchers, where 86 were affiliated (A) with the project from various national and international institutions. 45% of the researchers were female, and 42% were early career scientists. The scientists come from the ten Norwegian partner institutions: Akvaplan-niva (APN), the Institute of Marine Research (IMR), the Nansen Environmental and Remote Sensing Centre (NERSC), the Norwegian Meteorological Institute (MET), the Norwegian Polar Institute (NPI), the Norwegian University of Science and Technology (NTNU), the University of Bergen (UiB), The University Centre in Svalbard (UNIS), the University of Oslo (UiO), and UiT The Arctic University of Norway (UiT), and the national and international institutions of our affiliated scientists.

Name	Inst.	Position
Achim Randelhoff	APN	Researcher (A)
Adam Steer	NPI	Postdoc
Agneta Fransson	NPI	Researcher
Aleksander Dürr Libæk	UiB	MSc (A)
Alexei Bambulyak	APN	Researcher
Allegra Liltved	UiB	MSc (A)
Allison Bailey	NPI	Researcher (A)
Alun Jones	NTNU	Postdoc
Amalie Gravelle	UiO	MSc (A)
Amanda Ziegler	UiT	Postdoc
Ana Carrasso	MET	Researcher
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Andreas Lunde	UNIS	MSc (A)
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Important reports and sources

Nansen Legacy Team – All Project Members	
All Annual Reports	
Annual Report 2018	
Annual Report 2019	
Annual Report 2020	
Annual Report 2021	
Annual Report 2022	
Annual Report 2023	

Newsletters	
News Archive (of Nansen Legacy website)	
Media coverage	
Data management Plan	
Data Policy	
Cruise Reports	
Sampling Protocols	
Workshop Reports	
Experiments	
Collections	
Photographers & Picture Collections	

Publications, datasets, thesis and more

All Peer-Reviewed Publications	
Fact Sheets	
Published Data	
Master's and PhD Thesis	
Nansen Legacy Contributions to Assessment Reports	
Books and Conference Papers	
Blog Posts	
Highlights from Scientific Results	

Photos next pages 112-113, from top left to bottom right:
Èric Jordà Molina, Christian Morel/christianmorel.net, Èric Jordà Molina, Èric Jordà Molina, Christian Morel/christianmorel.net, Christine Gawinski
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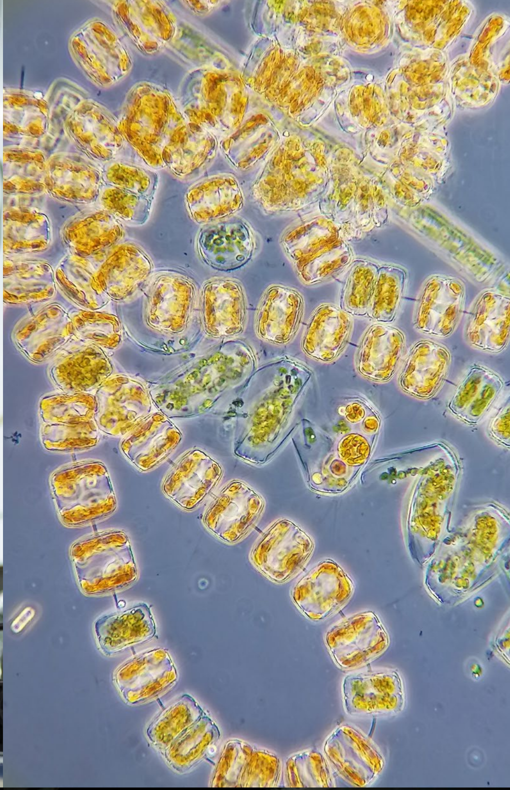
LUPINE




P2


KRONPRINS HAAKON

Photo: Christian Morel/christianmorel.net

The Nansen Legacy in numbers

7 years

The Nansen Legacy is a seven-year project, running from 2018 to 2024.

1 400 000 km² of sea

The Nansen Legacy investigates the physical and biological environment of the northern Barents Sea and adjacent Arctic Ocean.

>10 fields

The Nansen Legacy includes scientists from the fields of biology, chemistry, climate research, ecosystem modelling, ecotoxicology, geology, ice physics, meteorology, observational technology, and physical oceanography.

>350 days at sea

The Nansen Legacy has conducted 21 scientific cruises, equivalent to over one year at sea, in the northern Barents Sea and adjacent Arctic Ocean between 2018 and 2022. Most of these cruises were conducted on the new Norwegian research icebreaker RV *Kronprins Haakon*.

nansenlegacy.org

nansenlegacy

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350 people

In total there are over 300 researchers working with the Nansen Legacy, of which 128 are early career scientists. In addition, 50 persons are involved as technicians, project coordinators, communication advisers and board members.

10 institutions

The Nansen Legacy unites the complimentary scientific expertise of ten Norwegian institutions dedicated to Arctic research.

50/50 financing

The Nansen Legacy has a total budget of 740 million NOK. Half the budget comes from the consortiums' own funding, while the other half is provided by the Research Council of Norway and the Ministry of Education and Research.

Kunnskapsdepartementet

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