the Nansen LEGACY

Annual report 2021

The Nansen Legacy Report Series 31/2022

The Nansen Legacy

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Statement from the Board

The Nansen Legacy project has entered the second half of the project period. With over 230 researchers, including 70 early career scientists at present, the project is in many ways an experiment challenging the framework of what a research project is and can be.

The Nansen Legacy project initiative was inspired by evaluations of the bio- and geoscience research communities in Norway in 2011 concluding that strong communities were fragmented. A similar conclusion was raised by the Polar research evaluation in 2017. The planned Nansen Legacy initiative was therefore viewed as a tool for increased collaboration.

The international evaluation panel responsible for the midway evaluation of the Nansen Legacy project was "extremely satisfied with the progress and expected impacts". The project has so far proved to be very successful by delivering high quality research, underpinned by a successful organisation and a large number of early career scientists representing a new generation of Polar scientists.

In 2021, the Nansen Legacy team completed all fieldwork that had been delayed by the COVID-19 pandemic, with eight cruises and 128 days at sea. After the field intensive first phase of the project, the second phase will change character with increased focus on data interpretation, integration of results and synthesis of knowledge across the different disciplines. Another important task will be to strengthen user involvement and make sure that data and knowledge is both findable and useable.

The collaborative spirit that has characterised the first half of the Nansen Legacy has demonstrated the full capacity in the Norwegian marine research community when its competence, logistics, and resources are directed towards a common goal. The shared knowledge and helping-hands across institutions and disciplines that has been demonstrated in the field to ensure that everyone succeeded with their plans, is the best demonstration of how to overcome fragmentation to strengthen the research for everyone. ■

Photo: Malte Müller

All hands on deck

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

Half-way through the Nansen Legacy project, 2021 was a year to take stock and to catch up. It was time for the midway evaluation, time to complete COVID-delayed fieldwork, time for our Arctic Basin expedition, time to fully harvest results into publications, and finally, time to meet again in person.

Our field observations provide empirical evidence of ongoing change. They are also essential to evaluate performance of and improve processes in the large number of numerical models used in the project to zoom out in time and space. To bridge the gap between observations and simulations, a ship-based PhD course to the Polar Front allowed hands-on field experience for several early career scientists (ECS) that use models or satellite-based data as their primary tool.

Earth system models provided predictions of a Barents Sea without winter sea ice by the end of this century. A combination of satellite observations, wave-ice measurements, and numerical modelling improved the accuracy of strong wind and wave forecasts. Ecosystem models explored how the energy flow through the food web responds to different environmental conditions.

Our researchers spent 128 days with *RV Kronprins Haakon* out at sea in 2021. Winter conditions were investigated in February to understand ocean currents and processes impacting the northern Polar Front. The seasonal investigations - systematically linking physical, chemical, and biological processes - focused on sea ice in March, and on the spring bloom in May. Helicopters extended the observational capacity in March, while underwater robotics with various sensors complemented diver-based data collection to explore the bloom under the sea ice in spring.

The extended expedition into the deep Arctic Basin in September highlighted key differences and similarities between the Barents Sea shelf and the deep basin. This expedition was also part of the pan-Arctic research initiative of the Synoptic Arctic Survey. We succeeded in deploying a modified pelagic trawl in ice covered waters to sample fish in the Central Arctic Ocean. Data from several mooring stations were collected in November to obtain full-year observations of oceanographic conditions, nutrients, and bloom dynamics.

The Nansen Legacy set out to train a new generation of 50 polar scientists. By now the total number of ECS involved has overshot 90, including an increasing group of affiliated members. This new generation of scientists is an essential part of the Nansen Legacy, driving cross-disciplinary and cross-institutional collaboration. The project supports its younger scientists by creating fora for joint discussion and learning.

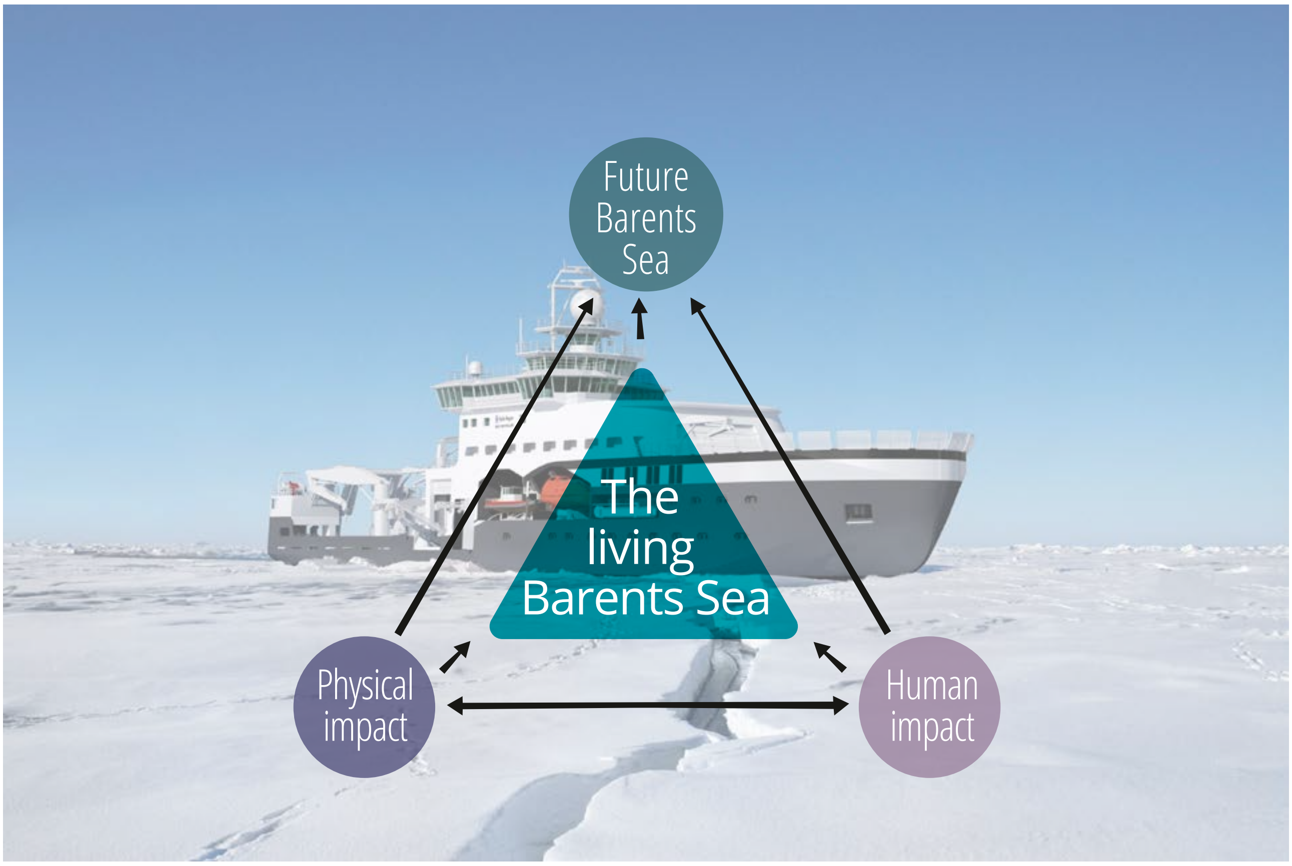
In 2021, an international expert panel evaluated the progress and performance of the project's first three years on behalf of the Research Council of Norway. The panel was extremely satisfied with the progress, recruitment and research output, and acknowledged an efficient and much-appreciated project administration. The panel strongly recommended to continue the good work throughout the project's second phase, including increased focus on user involvement and research dissemination to assure that project results contribute to sustainable future management of the region.

Nansen Legacy researchers contribute to several national and international management- and status reports, including the 6th Assessment Report cycle of the IPCC, a new assessment of Particularly Valuable and Vulnerable Areas (SVOs) in Norwegian seas, and the Copernicus Marine Service Ocean State Report.

The successful in-person annual project meeting in Trondheim facilitated fruitful and inspiring discussions framing the bigger picture and outlining new or extended collaborations.

Our joint effort is on a good track, ready to integrate our results into system knowledge, and to follow the recommendations of stronger user involvement. We look forward to provide new knowledge accessible for stakeholders and the public in the years to come. ■

Vision and objectives

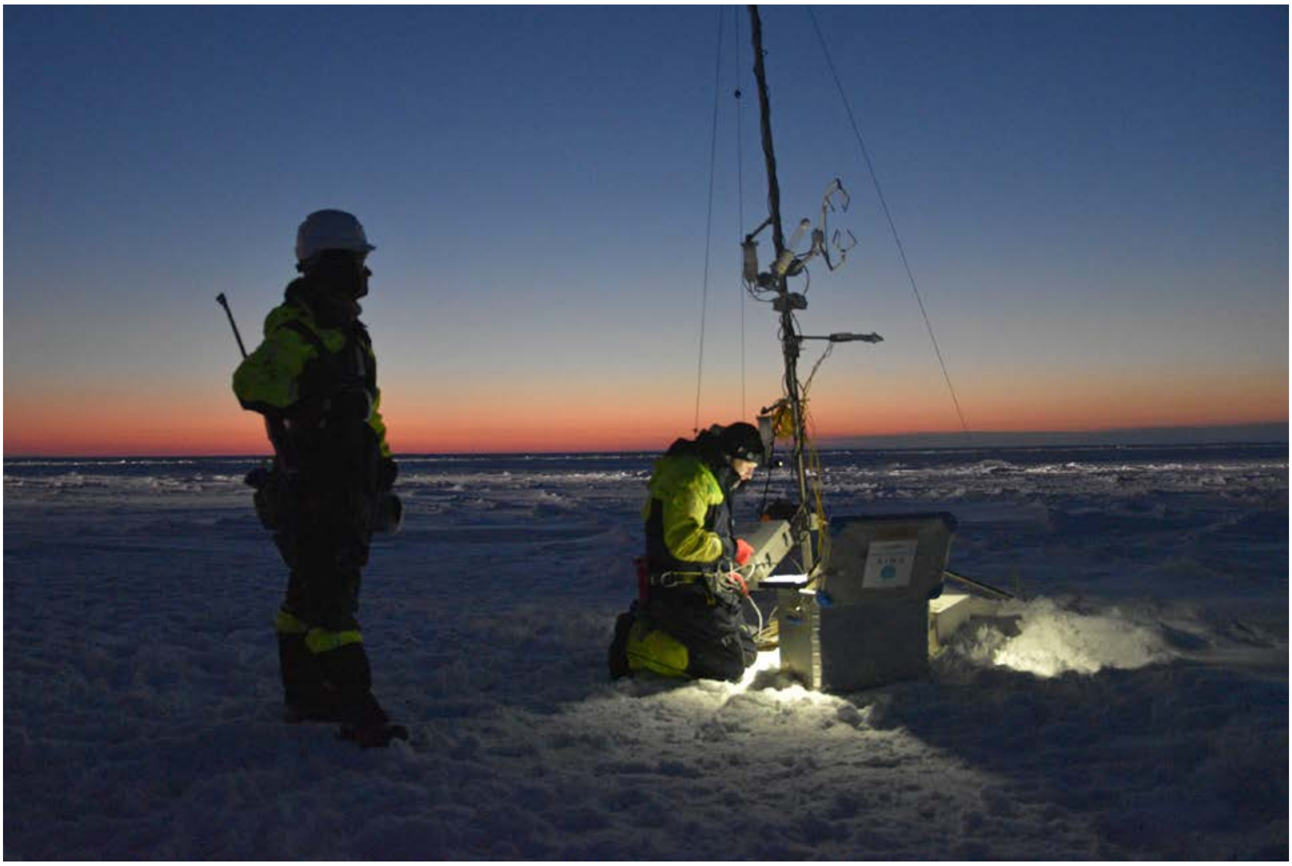


The four research foci of the Nansen Legacy. Physical and human impacts on the living Barents Sea will determine the state of the future Barents Sea.
Illustration: Tor Eldevik, Rudi Caeyers

The Nansen Legacy is a novel and holistic Arctic research project. It provides 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 has 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

Table of contents



Setup of a meteorological station to measure the surface energy budget on an ice floe during the Nansen Legacy Winter Process Cruise in February 2021.
Photo: Malte Müller

2021 in brief

Winter process study. The cruise focused on air-ice-ocean interactions with concurrent measurements in the ocean, the atmosphere, and the sea ice, and it was used to test recently developed robot technology and self-propelled crafts in both ocean and atmosphere.

Seasonal study 1. quarter. This interdisciplinary cruise was part of the seasonal survey, and focused on comparing the physical, chemical, and biological conditions along the Nansen Legacy main transect. Special emphasis was put on investigating sea ice and snow thickness at different scales, including regional scales surveyed from helicopter.

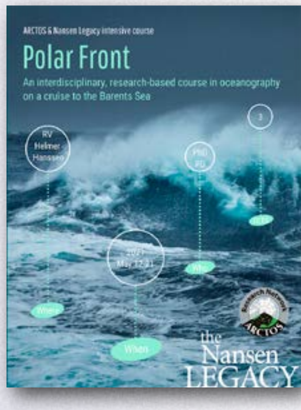
Seasonal study 2. quarter. The last of the four seasonal surveys was conducted in May, repeating physical, chemical, and biological measurements along the Nansen Legacy main transect. Use of divers and remotely operated technology facilitated increased under-ice studies.

Joint summer cruise. This cruise was the project's third late-summer survey mapping inter-annual variability in the environmental conditions along the Nansen Legacy transect.

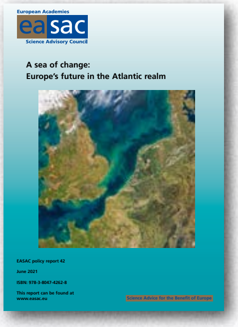
January

Workshop. Besides sharing raw data, exchanging analytical tools promotes scientific cooperation. Nansen Legacy early career scientists organized a workshop and reached both goals: they learned effective use of R and GitHub and strengthened their collaboration.

Science webinars. The Nansen Legacy continued organizing webinars to discuss and highlight topics of interest either within the project or with relevant international partners.



Summer school at sea. The ARCTOS research network and the Nansen Legacy joined forces and conducted an intensive PhD course at sea, focusing on the Polar Front. During the cruise, 15 young scientists were introduced to interdisciplinary marine research.



Contributing to major assessment reports. Fifteen Nansen Legacy researchers were involved in a new assessment of Particularly Valuable and Vulnerable Areas (SVO), which is part of the national management plan for Norwegian marine areas. Nansen Legacy scientists were also contributing to two major marine assessment reports for the European Union

COVID-19 related infection measures imposed hotel isolation and testing of all research personnel before working at sea.

International travel restrictions prohibited scientists from outside Norway to join Nansen Legacy research cruises.

International travel restrictions limited the mobility of Nansen Legacy early career scientists and reduced international integration.

Virtual conferences and limited in-person meetings hampered effective networking and international collaboration.

Arctic Ocean expedition as part of the Synoptic Arctic Survey. To place the Barents Sea in the pan-Arctic system, the Nansen Legacy extended its field surveys into the Nansen and Amundsen Basin of the Central Arctic Ocean. The expedition led close to the North Pole and was a Norwegian contribution to the international Synoptic Arctic Survey.

Polar Pint of Science. The project's early career scientists joined forces and organized popular science evenings at pubs in Oslo, Bergen, Tromsø, and Longyearbyen. Several hundred people enjoyed fun science presentations, quizzes, and hands-on activities about Nansen Legacy research.

Recruit Forum. Fifty Nansen Legacy early career scientists met in person for a joint reflection on career development and writing habits.

NOAA Arctic report card. Nansen Legacy scientists contributed to the sea ice chapter of the NOAA Arctic Report Card 2021, with an update about changes in Arctic sea ice extent, age, thickness, and volume. Results from Nansen Legacy observations were among the inputs to this report card chapter.

December

IPCC AR6 and COP26. Nansen Legacy scientists contributed as lead and contributing authors to the first part of the Sixth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC). Nansen Legacy scientists were also invited speakers at COP26 side events.

Data management goes YouTube. How to get scientists to publish data sets? You start a YouTube channel with weekly teaching videos on data publishing. Start watching, you too!

Nansen exhibition. On the occasion of Fridtjof Nansen's 160 birthday, the University Museum in Bergen set up an exhibition of Nansen's time and work in Bergen. The exhibition also portrays six young Nansen Legacy scientists from Bergen.

Annual project meeting. After over a year of virtual meetings, the long awaited physical annual meeting became a stimulating and productive platform to exchange new findings and ideas among the 150 participants.

Mooring service cruise. The Nansen Legacy and the A-TWAIN projects joined forces for the recovery and re-deployment of oceanographic moorings on the shelf and the slope north of Svalbard as well as in the northern and central Barents Sea.

The global silicon chip shortage delayed hardware research and development of projects such as remote sensing payload development.

Photo:RudiCaeyers - UiT

Could sea ice persist in the Barents Sea in a warmer-than-present world?

Arctic sea ice plays a pivotal role in the Earth's climate system and its loss may accelerate the rise of global temperatures. Understanding the future state of sea ice is therefore a prerequisite for evaluating the development of the World's climate. Nansen Legacy scientists have looked into both the past and the future to unravel the question of future sea-ice state in the Arctic.

An ice-free Barents Sea by the end of the century?

Since the start of satellite observations in 1979, Arctic sea ice cover has retreated on average with 13 percent per decade. Averages like this hide, however, the vast differences in sea ice loss between Arctic regions. To investigate regional differences in the evolution of Arctic sea ice loss until the end of this century, Nansen Legacy researchers have analyzed projections from the latest generation of global climate models. The analysis shows that, unlike today, sea ice loss will take place in all Arctic regions and all seasons. The transition to ice-free conditions spreads through the Atlantic and Pacific regions, with changes starting in the Barents Sea and Chuckchi Sea. Even under low CO_2 emissions, all Arctic shelf seas will become ice-free in summer before the end of the century. According to the models, the Barents Sea will even turn ice-free during winter, and hence become the first year round ice-free region in the Arctic before the end of the century.

Investigating the past to understand the future

While model simulations offer insight into potential future sea ice states in the Arctic, geological archives provide information on how sea ice has responded to climatic warming in the past, especially during periods characterized by warmer-than-present conditions. One of such periods took place after the last glaciation. At that time, the northern hemisphere warmed due to changes in the Earth's orbit that led to increased absorption of solar heat. This resulted in air temperatures above present day some 10 to 6 thousand years ago. Nansen Legacy paleo-oceanographers have now analyzed two marine sediment cores from the northernmost Barents Sea at about 80°N to evaluate if sea ice persisted in the region during that geological warm period. For that, the scientists took advantage of that the seafloor conserves chemical remains of microalgae and other single celled organisms over thousands of years. The remains of these organisms lie stacked in layers, which allow dating the layers back in time similar to when dating trees by their rings.

Sea ice persisted during a geological warm period

Analysis of 11.7 to 9.1 thousand years old marine sediment layers from the northernmost Barents Sea clearly showed chemical traces of sea ice algae - that means algae that only occur in marine regions where sea ice is present. Based on the amount of these ice algae traces, the researchers calculated that sea ice concentrations must have been about 55% in the region during spring even under warmer-than-present conditions. The scientists also found remains of single celled organisms, which only occur in relatively warm Atlantic water. This suggests that the hydrographic situation in the northern Barents Sea 11.7 to 9.1 thousand years ago was similar to what we see today, where relatively warm Atlantic water has an increasing influence on the northernmost Barents Sea, and is the main driver of sea ice decline in the region. Hence, the historical data are in keeping with model predictions placing the sea ice edge around the northern Barents Sea shelf break from the 2070s onwards. ■

> "While model simulations offer insight into potential future sea ice states, geological archives provide information on how sea ice responded to substantial climatic warming in the past."

Anna Pienkowski, NPI

References:

Årthun M, Onarheim IH, **Dörr J, Eldevik T** (2021) The seasonal and regional transition to an ice-free Arctic. *Geophysical Research Letters* 48: e2020GL090825

Pieńkowski AJ, Husum K, Belt ST, **Ninnemann U**, Köseoğlu D, **Divine DV**, Smik L, Knies J, Hogan K, Noormets R (2021) Seasonal sea ice persisted through the Holocene Thermal Maximum at 80°N. *Communications Earth & Environment* 2: 124

Photo:RudiCaeyers - UiT

Physical manifestations and ecological implications of Atlantification in the Barents Sea

Climate change does not only alter and displace ecosystems on land, but also in the oceans. In this context, Atlantification describes the ongoing transition of Arctic waters to a state more closely resembling the one of Atlantic waters, both physically and ecologically. As Atlantification has far-reaching consequences for the global climate system and socio-economic interests, Nansen Legacy scientists have synthesized existing knowledge in a Nature Reviews article.

Northeastwards expansion of the Atlantic-influenced waters

For at least 6000 years, the Barents Sea has been a region where relatively warm Atlantic water meets much colder water of Arctic origin. This setting has given rise to distinctly different ecosystems in the southern Atlantic-influenced and the northern Arctic-influenced Barents Sea. Since the 1980s, the Atlantic Water in the Barents Sea has experienced substantial warming. The heat content in these water masses was almost twice as high in 2016 compared to the 1980s, and the part of the Barents Sea dominated by Atlantic Water has substantially expanded northeastward. Concurringly, the warmer water has reduced the sea ice extent in the Barents Sea considerably, although extended winter sea ice still occurs in some years. In these instances, the ice is mainly imported by winds pressing ice from the central Arctic into the Barents Sea.

Increasing production in the wake of Atlantification?

Following the modifications in the physical environment, also the Arctic ecosystem in the northern Barents Sea is changing. A trend towards less and thinner sea ice allows more water mixing, which results in nutrient-rich surface waters. Time series data suggest that the increasingly ice-free surface waters allow a longer productive season, an increasing annual primary production, and a higher production throughout the food web. However, it is unclear if production will continue to increase in the future.

Organisms on the move

Warmer waters in the northern Barents Sea also support the successful establishment of boreal species in the region. Atlantic zooplankton species like krill and the copepod *Calanus finmarchicus* have increased in relative abundance, and boreal fish species including the Northeast Arctic cod (*Gadus morhua*) expanded their areal coverage in the Barents Sea. With these and other new boreal species, the biodiversity in the Barents Sea is currently increasing. However, as Atlantic species become more dominant in large parts of the Barents Sea, Arctic species lose their habitat and are exposed to increasing competition. This forces species adapted to living in cold, partly ice-covered waters - such as polar cod - to retreat northeastwards. The current increase in biodiversity may thus be only of short transitory phase, potentially followed by a decline driven by Arctic species loss and redistribution. In the long run, the expansion of the Atlantic-influenced domain may also lead to shifts in distribution of harvestable species to the northeast. Such shifts may result in redistribution of harvestable species from one national jurisdiction to another and international management agreements on how transboundary stocks are to be managed should therefore be developed. ■

> "Dedicated, multidisciplinary observations and advanced modelling experiments are urgently needed to get a comprehensive understanding of Atlantification"

Randi Ingvaldsen, IMR

Reference: Ingvaldsen RB, **Assmann KM**, **Primicerio R**, **Fossheim M**, Polyakov IV, Dolgov AV (2021) Physical manifestations and ecological implications of Arctic Atlantification. *Nature Reviews Earth & Environment*, 2(12): 874-889

Photo: Nathaniel Noir / Alamy Stock Photo

Minimal influence from Arctic sea ice on mid-latitude winter weather

An intensive blizzard slackened everyday life in London for days in early 2018. Flights were cancelled and public transport had to be temporarily stopped. Preceding this extraordinary winter had been an unusually low amount of sea ice in the Barents Sea the previous autumn. In a man's memory, this was not the first time that little Arctic sea ice in autumn had been followed by harsh winters in Europe. However, is there a causal link between Arctic sea ice extent and European winter weather?

Sea ice and winter temperatures have co-varied the last decades

Satellite observations from the last forty years give the impression that there is a connection between the sea ice extent in the Arctic and winter storm tracks over the North Atlantic. Little sea ice in the Barents and Kara Sea in autumn has been followed by winters when atmospheric low-pressure systems have tended to follow southerly tracks towards southern and central Europe, while the weather in northern Europe has been cold and clear for weeks at a time. Oppositely, autumns with more sea ice than normal have been followed by mild and wet winters. If this was always the case, it should be possible to use Arctic ice conditions in autumn to predict the coming European winter. Such a seasonal forecast of European winter weather could be useful for scaling various societal needs, from energy demands to snow clearance services.

Climate models tell another story

However, the fact that cold winters have followed autumns with little sea ice in the Arctic does not mean that the ice conditions have made the winters cold. To explore what goes on when separate climate phenomena interact – as in the case of sea ice and winter weather – climate models can be used. In the models, conditions in the ocean and the atmosphere develop according to the laws of physics, and can therefore be used to investigate mechanisms underlying observed phenomena. Curiously, the observed connection between sea ice and winter weather during the last forty years has been impossible to identify in climate models, which is why Nansen Legacy researchers have reevaluated the assumed link between Arctic sea ice and European winter weather in a recent study.

Forty years is not enough

In this study, the scientists investigated not only the last 40 years, but also used model runs and observations over the last 100 years. Seen over a century, neither observations nor models indicate a connection between Arctic sea ice in autumn and European winter weather. In these long data sets, sea ice and winter conditions vary largely independently of each other. As it turns out, the last forty years have been an exception in a highly variable and nonstationary system, giving rise to an incorrect interpretation of sea ice extent determining the following winter conditions. Yet, many of the mechanisms discussed for explaining the last forty years observations are still valid: Decreased sea ice extent opens up larger areas of ocean, increasing heat and moisture transfer to the atmosphere, which in turn can influence atmospheric processes. However, according to the new findings, these perturbations are not strong or systematic enough to influence mid-latitude weather many months later. What type of winter Europe will experience is therefore primarily driven by large-scale atmospheric variability rather than the autumn sea ice situation. Hence, seasonal weather forecasts and climate services cannot rely on Arctic sea ice extent for predicting the coming winter. ■

> «Everybody understands that one year is too little to say anything about climate. But it was thought that forty years would be enough.»

Camille Li, UiB

Reference:
Siew PYF, **Li C**, Ting M, Sobolowski SP, Wu Y, Chen X (2021) North Atlantic Oscillation in winter is largely insensitive to autumn Barents-Kara sea ice variability. *Science Advances* 7: eabg4893.

Photo: Andrea Taurisano - NPI

Sea ice retreat beyond the continental shelf – implications for wildlife?

In many Arctic regions, sea ice retreats northwards. This often moves the ice edge zone from relatively shallow waters on the continental shelf to several kilometre deep waters in the central Arctic Ocean. Implications of this displacement for organisms living at the ice edge are largely unknown. Nansen Legacy scientists have studied harp seals, which's icy habitat has retreated from shallower to deeper waters north of Svalbard over the last 30 years.

Poorer body condition than 30 years ago

Harp seals are iconic top predators in the Arctic. They are good swimmers and undertake long migrations in the northern most parts of the Atlantic but prefer to be near sea ice all year round. During summer, many of them gather at the ice edge north of Svalbard to hunt for food. The sea ice in this region has gradually retreated northwards in the last decades and is now often located over much deeper waters than previously. To investigate how the retreat of the ice edge has affected the harp seals foraging conditions, Nansen Legacy researchers have compared data from a survey in September 2016 with comparable data from the early 1990's.

The study shows that young seals (body length < 145 cm) now are slimmer than 30 years ago, suggesting that the overall body condition of young seals has declined. This finding is supported by earlier observations, but the experts struggle to give a definite explanation for the poorer body condition. Potentially, the currently large stock of Atlantic cod in the area is a strong competitor for prey, hence decreasing the amount of prey obtainable by young seals.

Harp seals' main prey has not changed

In contrast to the body condition, the main prey of harp seals has not changed. Both now and 30 years ago, the seals mostly prey on polar cod and the pelagic amphipod *Themisto libellula*, an up to 6 cm big shrimp-like crustacean. However, changes were detected in the seals' additional prey. While the seals preyed on bottom-associated prey, such as prawns and bottom-dwelling fish, 30 years ago, the seals now feed on pelagic fish, such as Atlantic cod and blue whiting. This shift may relate to the displacement of the ice edge from areas of 100 to 350 meter water depth 30 years ago, to areas of more than 500 meters of water depth today.

The study also sheds light on the food preference of harp seals. Though the researchers observed a lot of krill north of Svalbard in 2016, they found none in the seals' stomach. This suggests that either harp seals do not like krill during this time of the year, or that they prefer not to hunt below 100 m where most of the krill was. Amphipods, on the other hand, were found in similar percentage in the water column and in the seals' diet, suggesting that amphipods are a welcome prey but not harp seals' favourite. The seals' favourite prey remains polar cod.

The study illustrates the complexity in evaluating the ecological hconsequences of the displacement of the ice edge from the shallow shelf to the deep central Arctic Ocean. While some aspects of the foraging behaviour may stay the same, changes in prey availability and competition may lead to an overall new ecological setting. The consequences of such changes for single species and species communities are not yet understood. ■

> "Our results suggest that the body condition of harp seals was slightly but significantly lower in 2016 compared with seals sampled in the early 1990s."

Tore Haug, IMR

References::
Haug T, **Biuw M**, **Gjøsæter H**, Knutsen T, et al. (2021) Harp seal body condition and trophic interactions with prey in Norwegian high Arctic waters in early autumn. *Progress in Oceanography*, 191:102498.

Glimpses of the Nansen Legacy knowledge production

The Nansen Legacy team is generating a new and holistic understanding of the northern Barents Sea climate and ecosystem. Over the past years, the team has delivered many peer-reviewed articles in leading scientific journals. These studies are all pieces of the larger puzzle. Here we present glimpses of last year's knowledge production.

The living Barents Sea

• **No long-term changes in nutrient concentrations** (1980-2016) in the western Eurasian Basin of the Arctic Ocean, except for a trend of decreasing concentrations of silicic acid in Polar Surface Water. This trend is consistent with the reported increase in primary production in the region. Duarte et al. 2021

• Twenty-one years (2000-2020) of phytoplankton bloom phenology in the Barents, Norwegian, and North Seas show that **summer phytoplankton blooms are starting later**, ending later, and reach higher concentration. Silva et al. 2021

• High-throughput DNA barcoding shows that **most meroplankton species occur in late summer and autumn** in the Barents Sea. Meroplankton non-native to the region was also identified. Descôteaux et al. 2021

• The diet of 24 **Barents Sea zooplankton taxa** during late summer and winter revealed **little dependence on ice-associated carbon**, most likely due to the low availability and quality of ice algae despite relatively high sea ice presence. Kohlbach et al. 2021 a + b

• First abundance estimates of **planktic foraminifera and shelled pteropods** under the ice in the northern Barents Sea during the Polar Night. During late summer, pteropods dominated over foraminifera. Anglada-Ortiz et al. 2021; Zamelczyk et al. 2021

• Exploring 30 years of survey data (1986-2015) suggests that abiotic factors had a more pronounced effect than predation on the **population dynamics of polar cod**. Dupont et al. 2021

• West and north of Svalbard many **rorquals have trouble locating prey patches** of sufficient density to warrant feeding. An exception are minke whales, which showed a prey detection range of more than 10 km. Solvang et al. 2021

• The range of **possible configuration of the Barents Sea food-web** is much larger than what past observations (1988-2020) suggest. Trophic controls are fluctuating at interdecadal time-scales. These fluctuations can be interpreted as an emergent property of stochastic trophic interactions. Sivel et al. 2021

Hydrography and sea ice

• Large **year-to-year variations in sea ice** cover along the shelf break north of Svalbard between 2012 and 2019 were not a result of variations in ocean temperature, but were caused by unusual large-scale wind patterns. Depending on the wind, the transport of sea ice from other parts of the Arctic Ocean to the shelf break was strong or weak. Lundesgaard et al. 2021

• The variability in wind patterns controls the variability of the **West Spitsbergen Current** branches flowing over the Yermack Plateau. Increasing number of winter cyclones during years with anomalous atmospheric circulation patterns can increase the ocean volume transport and pulses of warm water to the shelf area north of Svalbard. Nilsen et al. 2021

• **Drivers of ocean mixing** north of Svalbard vary with water depth. Non-linear internal waves forced by diurnal tidal currents can develop, with the potential to mix the entire water column vertically. Koenig et al. 2021

• The variability in the **winter sea ice decline** is influenced by transport of oceanic heat, as well as atmospheric heat and moisture from the Atlantic and Pacific. Dörr et al. 2021

• The temporal variability of the **poleward ocean heat and volume transport** at the Iceland-Scotland Ridge and Barents Sea Opening is linked to wind forcing south of Iceland and along the Norwegian coast. Madonna & Sandø 2021

• The **propagation of fractures in sea ice** affects not only the patterns and the fraction of leads in sea ice but also the ocean-atmosphere heat flux through the leads. Ólason et al. 2021

• Poly- and perfluoroalkyl substances are synthetic chemicals used in many industrial and consumer applications. **Concentrations of these chemicals in the water underneath sea ice** in the northern Barents Sea was about 2-fold higher than measured in surface waters of the North Sea, though the latter is much closer to the industrial sources of these substances. Garnett et al. 2021

Atmosphere and CO_2

• **Seasonal anomalies in European precipitation and temperature** can be reconstructed based on the frequency of circulation patterns defined by the NAO index, atmospheric blocking, or the configuration of the North Atlantic jet stream. However, none of them provides a good reconstruction for both precipitation and temperature all across Europe. Madonna et al. 2021

• Increased tropical sea surface temperatures strengthen the **northward transport of water vapor** into the Arctic, irrespective if the warming pattern is zonally uniform or localized. Localized cooling of the tropical sea surface weakens the moisture transport more than zonally uniform cooling. Dunn-Sigouin et al. 2021

• The relationship between the February North Atlantic Oscillation and the surface **air temperature over the Tibetan Plateau** in March is unstable with time and regulated by the phase of the Atlantic Multidecadal Variability. Li et al. 2021

• The increase in **CO_2 fugacity was less pronounced in surface waters than in the atmosphere** in northern European coastal seas (incl. the Barents Sea) between 1998 and 2016. Concomitantly, the decrease in the ocean's pH was lower than expected from the increased atmospheric CO_2. Most northern European coastal seas were net sinks for CO_2. Becker et al. 2021

• **Rates of atmospheric CO_2 increase** inferred from natural variations of the land and ocean carbon sinks can be predictable at lead-time of two years. The predictability is limited by the predictability of the land carbon sink. Ilyina et al. 2021

Method development

• Successful development and application of **cost effective, shipborne wave loggers**. Comparison of wave heights measurements in the Barents Sea with spectral wave models found in general good agreement, but model forecasts overestimated wave heights in the marginal ice zone. Løken et al. 2021

• New algorithm to **examine the displacement of the sea ice edge**. The method expands on existing validation metrics and enables the assessment of the quality of ice edge forecasts on sub-seasonal timescales. Melsom 2021

• Seawater flooding of the snow-ice interface leads to underestimations of snow depth or overestimation of sea ice freeboard measured from radar altimetry. This can decrease the **accuracy of sea ice thickness estimates from airborne surveys** in the Atlantic sector of the Arctic where deep snow on thin ice has increased. Rösel et al. 2021

• Successful development and application of an autonomous robotic vehicle sampling an Arctic Ocean front based on **in situ data-driven autonomous path finding**. The measurements generated a high-resolution description of frontal features, substantially augmenting ship-based sampling. Fossum et al. 2021

• New all-sky camera system provides for the first time high temporal resolution **annual time series of biological relevant irradiance** at 79˚N, including the Polar Night. Johnsen et al. 2021

• Design and implementation of a **neural network model for improving chlorophyll estimates** from Sentinel-2 satellite measurements in the Barents Sea. Asim et al. 2021 a + b

• To facilitate studies of the **effects of petroleum related pollutants on polar cod**, the precision-cut liver slice culture protocol was adapted and successfully used on polar cod. Yadetie et al. 2021

• Successful development and implementation of a **system for labelling, tracking, and openly publishing metadata** from large research missions. Ellingsen et al. 2021 ■

Photo: Rudi Caeyers - UiT

Eight at one blow – The Nansen Legacy field campaigns in 2021

The Nansen Legacy disposes over 350 days of ship time to ensure high-resolution sampling of physical, chemical and biological parameters of the ecosystems of the northern Barents Sea and the adjacent Arctic Ocean. So far, the project has completed 17 research expeditions. Seven of them were conducted in 2021 alone. In addition to these seven research cruises, the Nansen Legacy and ARCTOS Research Network arranged a PhD summer school at sea in 2021. Hence, the project is looking back at a very busy and productive year in the field despite challenging logistics due to the COVID-19 pandemic.

Winter Process Cruise 2021
Barents Sea Polar Front
Feb 9 – Mar 1

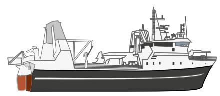
The Winter Process Cruise focused on air-ice-ocean interactions with concurrent measurements in the ocean, the atmosphere and in sea ice. Further, the cruise was used to develop advanced robot technology and self-propelled crafts in both ocean and atmosphere in order to study the Polar Front and air-ice-ocean interaction in more detail. Beside the Polar Front in the Barents Sea, Kvitøyarenna – a deep trench between Nordaustlandet and Kvitøya – was studied. Here, a sea ice camp was established allowing the collection of data in the atmosphere, in the sea ice and in the water column during a 36 hours drift.

Seasonal Cruise Q1
Barents Sea transect
Mar 2 - 24

The Seasonal Cruise Q1 (Q1: 1st quarter of the year) was part of the seasonal investigation of the northern Barents Sea and adjacent Arctic Basin. The survey focused on comparing the physical, chemical and biological conditions along the Nansen Legacy main transect in open waters and within the sea ice. Special emphasis was on the investigation of sea ice and snow thickness at different scales, from a few hundred meters of the ship to regional scale surveyed from helicopter.

Seasonal Cruise Q2
Barents Sea transect
Apr 27 – May 20

Also the Nansen Legacy cruise Q2 (Q2: 2nd quarter of the year) was part of the seasonal investigation of the northern Barents Sea and the adjacent Arctic Basin. The survey was conducted during the spring period – a biologically critical time window during which a large part of the annual primary production occurs. The expedition focused on comparing the physical, chemical and biological conditions along the Nansen Legacy main transect in open waters and within the sea ice. Use of divers and remotely operated technology complemented more conventional under-ice studies.



ARCTOS-Nansen Legacy Polar Front summer school cruise
Barents Sea Polar Front
May 14 - 22

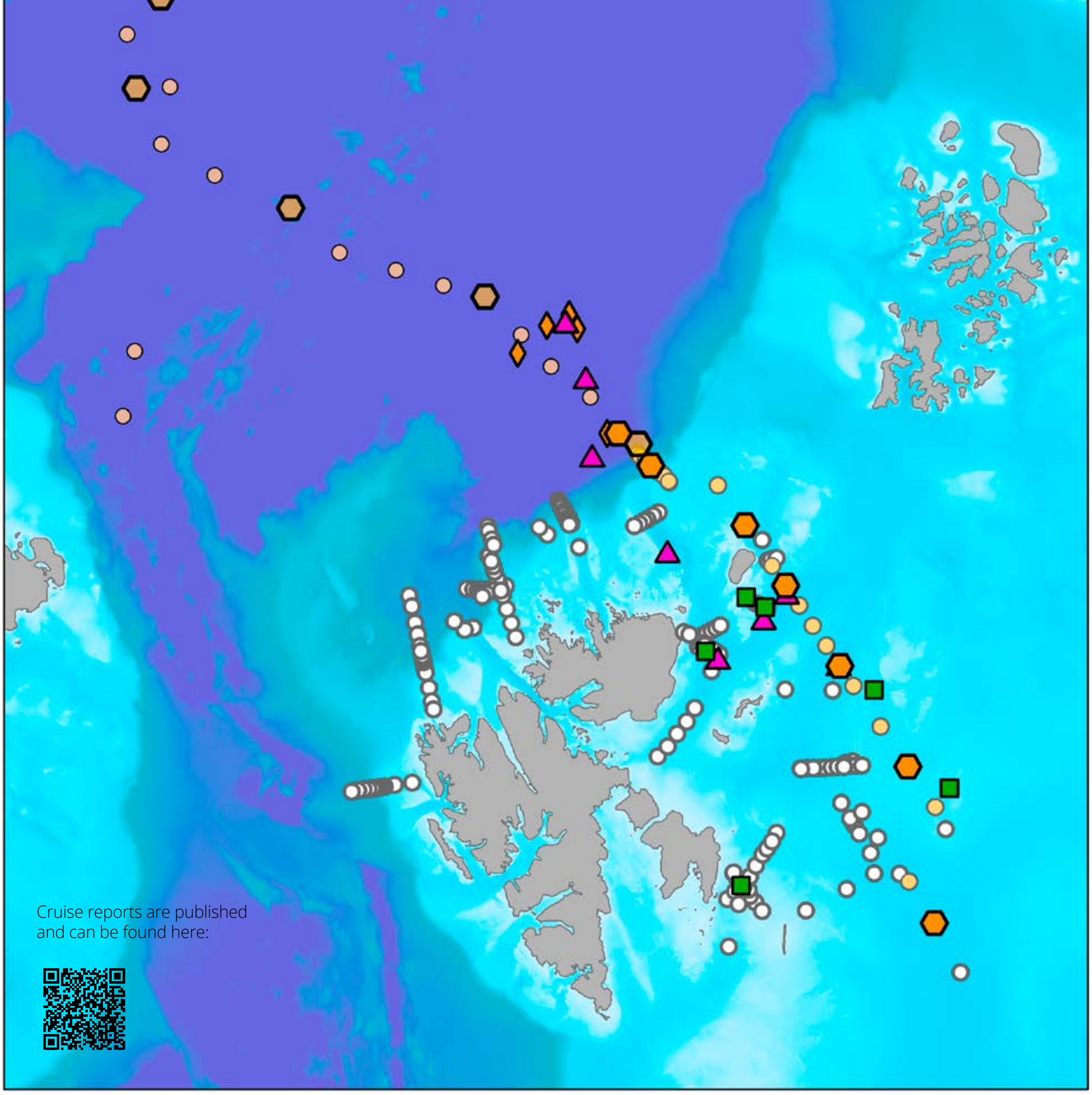
The ARCTOS-Nansen Legacy Polar Front cruise focused on the hydrography and biological processes in the Barents Sea Polar Front region during the highly productive phytoplankton spring-bloom period. The cruise was part of a PhD summer school, in which fifteen early career scientists with widely varying backgrounds and affiliations participated. For many of the course participants it was the first encounter with research work at sea. Read more about the field course on page 28.

Summer Joint Cruise 2-1
Barents Sea transect
Jul 12 - 26

This cruise was the project's third late-summer cruise - following Joint Cruise 1-2 in August 2018 and Seasonal Cruise Q3 in August 2019 - and allowed further investigation of inter-annual variability of the physical and biological environment along the Nansen Legacy transect. Tests and modification of equipment to operate pelagic trawls in ice-covered waters were conducted in preparation for the Arctic Basin expedition in August.

Arctic Basin Joint Cruise 2-2
Nansen & Amundsen Basin
Aug 24 – Sep 24

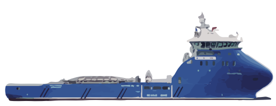
The main scientific goal of the Arctic Basin Joint Cruise 2-2 was to extend the research activities from the northern Barents Sea shelf into the central Arctic Ocean. The station plan covered a transect of 2330 km – from the Nansen Basin northeast of the Svalbard slope in the south, to the northern side of the Amundsen Basin in the north. A special goal of the cruise was to sample from the sea ice and the upper ocean, as well as to study the connectivity to the mid- and deep water column and underlying sediments. In addition, the expedition explored the role of transport of elements and organisms from the Siberian shelves to the Amundsen Basin through the Transpolar Drift. Read more about the expedition on page 18.



Through 17 surveys the Nansen Legacy has sampled a complex network of stations in the northern Barents Sea, along the shelf slope north of Svalbard, and into the Central Arctic Ocean. Many of the stations have been revisited over the years and sampled at different seasons of the year. Oceanographic moorings (green squares) continuously map the variation in hydrography and give important background information for measurements taken during ship-based surveys. Map legend: circles represent CTD stations, hexagons represent process stations with cross-disciplinary sampling, diamonds indicate large-scale sea ice stations, triangles show the position of paleo stations. Glider transects are not indicated on the map. Map: Ingeborg Reigstad

Nansen Legacy / A-TWAIN Mooring Cruise
Northern Barents Sea
Nov 6 - 16

The Nansen Legacy and the A-TWAIN project joined forces for this mooring cruise. The main goal was the service of the A-TWAIN moorings on the shelf and slope north of Svalbard and the Nansen Legacy moorings in the northern and central Barents Sea. In addition, transects for physical, chemical and biological measurements were done at key sites for long-term monitoring of the Atlantic Water boundary current north of Svalbard (A-TWAIN) and spatial context of the conditions at the mooring sites (Nansen Legacy).



Mooring Cruise - Second Part
Central Barents Sea
Dec 2 – 10

Reallocation of *RV Kronprins Haakon* for unforeseen assignments in Antarctica led to an earlier termination of the Nansen Legacy/A-TWAIN Mooring Cruise. This left several oceanographic moorings in open water unserviced. The Governor of Svalbard offered its vessel *MS Polarsyssel* for the retrieval of six Nansen Legacy moorings that had been deployed on the slopes of the Central Bank and Great Bank in the Barents Sea in October 2020. The project is grateful for the swift and generous support by the Governor of Svalbard.

Behind the scene

They ship containers full of research equipment, charter helicopters, struggle with custom clearance, publish sampling protocols, hold overview over hundreds of chemical safety sheets, manage databases to keep track of thousands of samples, book hotel rooms, and coordinate COVID-19 testing. Meet four key personnel without whose contribution the Nansen Legacy could not have conducted research out at sea.

Simon Sagelv Bjørvik
Operations & Logistics
UiT The Arctic University of Norway

- In 2021, the Nansen Legacy conducted seven research cruises. Do you know how many tons of equipment you loaded and unloaded from the research vessels?

The weight of equipment used on cruises can vary greatly and depends on the type of survey. An average cruise would bring roughly 7-8 tons of equipment. Geologists, taking cores from the sea floor, bring some of the heaviest equipment. However, I believe we set a record on the Arctic Basin Cruise in August 2021, for which we loaded 12 tons of research equipment.

- That is a lot of equipment! How many hours does it take to load the equipment for a research cruise? And what happens with all the stuff between the cruises?

The actual loading for a cruise takes about six hours from the time the first piece of equipment is driven to the ship to the last box is put in its respective location on board. In this, I must applaud the cruise participants on their efficiency in sorting through the equipment they receive on board. But the real preparation time is of course much longer – it is many hours of work from receiving the equipment, sorting and preparing it in containers until the actual loading. Equipment is usually shipped back to its owners between cruises. The equipment might be needed on other research vessels or back in the laboratories. Some equipment might also need to be repaired or recalibrated before the next use.

- Most of the Nansen Legacy surveys are outside of the Norwegian sovereign territory. Does that have consequences for the logistical work you are doing?

Certainly, whenever the research vessel ends or begins its cruise in Longyearbyen the amount of paperwork that follows the equipment is greatly increased. It also means a lot more planning for shipping between the mainland and Svalbard, as the transport ship only does a round-trip every 10 days.

Mona Isaksen
Accounting & Purchasing
UiT The Arctic University of Norway

- You are the accountant for the entire project. Among many things, you ensure that the scientists are reimbursed for their expenses and receive cruise allowance. How do you like working so closely together with researchers?

I think it is incredibly fun to gain insight into what is being researched on and how this is done in practice. I have gained an incredible amount of new knowledge after being in the position for one-and-a-half year. Both about copepods (which I did not know existed!) and all the other wildlife in the sea, as well as the interaction among these. I also gained a broader insight into the impact of climate change in the Arctic. Therefore, I really enjoy working closely together with scientists and not only looking at budgets and account numbers.

- In 2021, you suddenly became also a booking agent for isolation hotels and PCR tests before the Nansen Legacy research cruises. How many hotel nights did Nansen Legacy researchers spent in isolation in 2021?

Yes, in 2021 I have been responsible for finding sites for 1080 nights that our researchers had to spend in isolation before going at sea. We have used both hotels as well as camping ground cabins for isolation. In addition, our scientists have spent a total of 140 days in private isolation. Overall, COVID-19 forced Nansen Legacy researchers to spent 1220 days in isolation in 2021.

- After having tested different places for hotel isolation, what are the most important requirements for a somewhat pleasant isolation period?

Maybe not surprisingly, the most important thing for a somewhat pleasant isolation period is that one can maintain a close to normal everyday life. The best experience we have had is when we rented apartments that had a living room, full kitchen, bathroom with washing machine, bedroom and patio. Sitting in a hotel room for many days, as well as having food delivered to your door three times a day, is not optimal. It is also important to have good working conditions, as people were at work during the isolation periods.

“It is incredibly fun to gain insight into the different research topics and how research is done in practice.”

Mona Isaksen, UiT

Luke Marsden
Data management
The University Centre in Svalbard

- Nansen Legacy researchers returning from sea bring with them hundreds of small bottles, vials and zip-lock bags full of samples. They all carry a QR-code sticker. What is that for?

Fridges and freezers in research laboratories often contain samples that are difficult or impossible to identify. SIOS host a metadata catalogue that provides an electronic log of all the samples collected in the project. Anyone can scan the QR code to retrieve a universally unique ID for the sample. They can search for this ID in the metadata catalogue to find far more information about the sample than could possibly be included on a tiny label.

- Historically, a lot of research data have not been published. How do we go about changing this?

Publishing data takes time and effort. Data managers should make the process as quick and easy as possible. Education and good communication is key, on how, why and where. More and more, researchers are seeing the value in publishing their data, but now they need to put time aside in their calendars to prioritize it. We are getting there, and it is now quicker and easier than some researchers think.

- You have recently launched a Nansen Legacy data management YoutTube channel. What is the purpose of this?

Historically in academia, we have not managed our data very well. Now, we are seeing a lot of investment in data managers and data centres, but we also need to teach researchers how to manage their data. Many people use YouTube to learn about new things. Watching a video is less effort than reading a long document. I want my videos to be freely available and easy to find, so someone can go and watch them again if and when they need to. I am trying to focus on short 10 minutes videos that people can easily fit into their day. The uptake has been great!

Learn about data management on YouTube – you too!

Miriam Marquardt
Technical coordination & HMS
UiT The Arctic University of Norway

- You are the only research technician directly employed by the Nansen Legacy and serving the entire project. Among other things, you collect detailed descriptions of all sampling methods used out at sea. How many different sampling methods have been described and used so far?

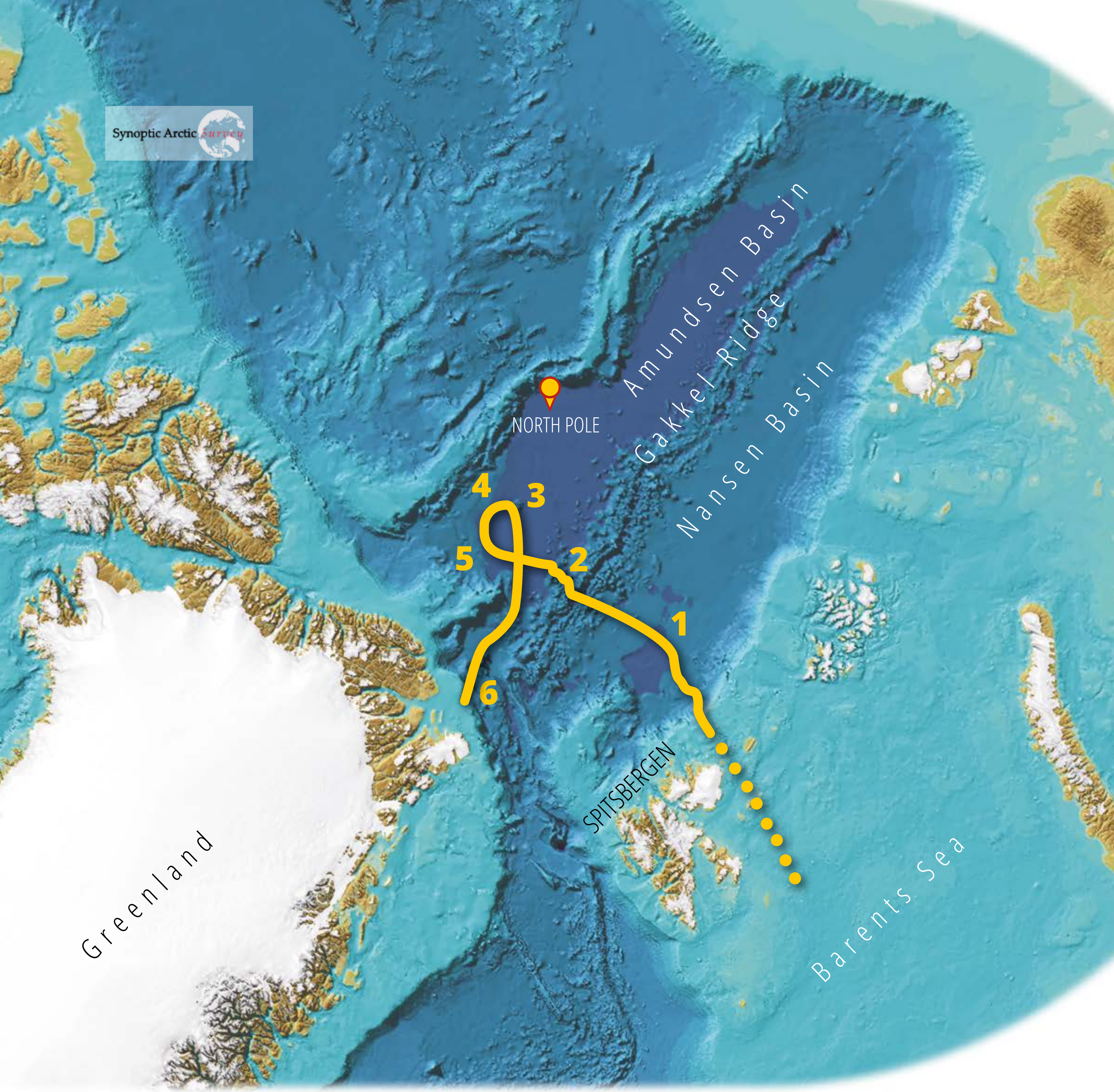
The protocol collection becomes longer and longer with each version. We are going towards version 10 now and it includes 16 chapters with about 120 different sampling methods and description of sampling equipment on over 300 pages.

- Many of the samples taken out at sea have to be preserved and analyzed through addition of various chemicals that are hazardous for both humans and the environment. What are the safety measures around these chemicals?

All cruise participants have to write a risk assessment for any kind of work onboard or out on the ice before the cruise. In these protocols, they must include all chemicals to be used. In this way, they have to engage also in the safety measures around their chemicals. Further, participants inform about the volume of each chemical they bring, and provide the chemical’s safety sheet. This information is given to the bridge onboard. The chemicals are safely stored inside a chemical cabinet, and most of the labs have chemical fume hoods for working. For waste disposal we bring chemical waste canisters and waste bins. We also have to appoint a responsible person for the chemicals, which can be contacted in case something happens. So far, we always appointed one of the chemists onboard.

- The sampling protocols and detailed method descriptions are updated regularly and published in an own Nansen Legacy report series. Why is it important to collect and openly publish this information?

It is important to collect and make the sampling protocols available in a FAIR (Findable, Accessible, Interoperable, Reusable) way as part of the project’s data management. To publish new versions with updated protocols helps to link methodological information to published data sets. Hence, publishing the sampling protocols ensures transparency and reproducibility inside and outside the project. Find all of the project’s sampling protocols here:



1 – Nansen Basin
North of the Barents Sea shelf stretches the abyssal plain of the Nansen Basin with water depths of around 3000 m. Here, the signal of the warm Atlantic Water – which is so pronounced in the Barents Sea – is getting weaker as one moves away from the continental slope. Nansen Legacy researchers have sampled the heavily Atlantic-influenced southern Nansen Basin during multiple research cruises. The Arctic Basin expedition showed contrasts in water properties, biological communities, and rate measurements between the previously sampled southern station and the central part of the Nansen Basin.

2 – Gakkel Ridge
The Gakkel Ridge is a 1800 km long mid-oceanic ridge separating the Nansen and Amundsen Basins in the Central Arctic Ocean. Hydrothermal vents have recently been discovered along the ridge, but information on whether these vents or the shallower water depths make the area around the ridge more productive than the basins it separates is unknown. It is neither clear to what extent the ridge separates the biological communities of the Nansen and Amundsen Basin. Therefore, Nansen Legacy biologists eagerly mapped the biodiversity from viruses to fish during the entire expedition. Elaborate experiments were conducted to investigate food web structure and function in the different oceanic domains along the way.

Into the heart of the Arctic

The Arctic Ocean consists of vastly different marine regions, ranging from shallow shelf seas to four-kilometre deep oceanic basins. While the relatively shallow waters of the northern Barents Sea are the Nansen Legacy's main study area, the project acknowledges the need for understanding the Barents Sea as part of the pan-Arctic hydrographic and climatic system. Therefore, Nansen Legacy scientists headed northwards into the heart of the Arctic Ocean, to collect unique data, and to contribute to the international sampling effort of the Synoptic Arctic Survey.

Investigating two deep basins and one oceanic ridge

In August 2021, 34 Nansen Legacy scientists left Tromsø to embark on a five-week long expedition onboard *RV Kronprins Haakon,* during which they would cover a transect of 2330 km deep into the Central Arctic Ocean, taking them close to northeast Greenland and less than 300 km away from the North Pole.

Interdisciplinary team of scientists

The scientific team on board was highly interdisciplinary, consisting of physical and chemical oceanographers, ice physicists, ecotoxicologists, marine chemists and biologists as well as safety and helicopter teams. Sampling efforts focused on sea ice and the upper ocean as well as upper-ocean connectivity to the mid- and deep water column and underlying sediments. In addition, the role of transport of chemical elements and organisms from the Siberian shelves through the Transpolar Drift was investigated.

Contributing to the Synoptic Arctic Survey

The Synoptic Arctic Survey is a Norwegian-lead initiative aiming to provide a quasi-synchronistic status update of the Arctic marine system at a pan-Arctic scale. The Nansen Legacy expedition took place at the same time as the Swedish icebreaker *RV Oden* was on its Synoptic Arctic Survey voyage in the nearby region between Northeast Greenland and the North Pole.

The Nansen Legacy is proud to contribute to generating a comprehensive international dataset that allows for a more complete characterization of Arctic hydrography and circulation, carbon uptake and ocean acidification, tracer distribution and pollution, and organismal and ecosystem functioning and productivity. The data collected during the Nansen Legacy Arctic Basin cruise and within the Synoptic Arctic Survey will provide a unique status of the early 2020s, which will allow tracking climatic changes and their impact in the Arctic over the coming years, decades, and centuries. ■

3 – Amundsen Basin

The Amundsen Basin is the deepest of the Arctic Ocean basins with up to 4.4 km depth. Deep down in this basin, water masses are encountered that have not been in contact with the atmosphere for hundreds of years, carrying the chemical signature of the pre-industrial world. For the Nansen Legacy chemists on board, investigating these old water masses was like a travel in time. For example, seawater pCO_2 with the same values as reported for pre-industrial times were observed.

4 – Mesopelagic layer

In 2021, the agreement to prevent unregulated high seas fisheries in the Central Arctic Ocean came into force. Underlying is a need to close knowledge gaps on any potential fishes occurring in the area. The expedition, therefore, also undertook the challenging task to conduct pelagic trawling in an ice-covered ocean to provide biological material from the upper water column and mesopelagic layer that can help ground truth synchronously recorded acoustic fish signals. The trawl-experienced crew on *RV Kronprins Haakon* mastered this challenge with impressive skill. Very few fishes, however, were caught.

5 – The last of its kind

North of Greenland an almost lost type of sea ice is still encountered – several meters thick, multi-year sea ice. For the Nansen Legacy scientists this was a unique chance to study the physical and chemical structure of a type of ice that once had filled much of the Arctic Ocean. Detailed mapping of snow and ice thickness was conducted as well as thorough investigation of the ice as habitat for microscopic life. Special emphasis was placed on investigating the role of leads – areas of open water between ice floes – in the exchange of gasses, heat and moisture between the ocean and atmosphere.

6 – Transpolar Drift

The Transpolar Drift is a major ocean surface current in the Arctic Ocean, transporting sea ice, water and their properties from the Laptev Sea and the East Siberian Sea towards the Fram Strait. A weakening of this current with decreased sea ice export has been suggested. Hence Nansen Legacy scientists tracked the biogeochemical signs of the Transpolar Drift - such a carbon derived from Siberian rivers and melting permafrost - in the Amundsen Basin and northwestern part of Fram Strait to help record the vital signs of the Arctic hydrographic system.

The Nansen Legacy runs its own research blog on 'forskning.no' since 2018. In 2019, an English version on 'sciencenorway.no' followed. In 2021, Nansen Legacy scientist wrote over 50 blog posts about the research work out in the field and about how this work will aid our understanding of the Arctic climate and ecosystem. Here you have the chance to read one of the many blog posts once more.

Ephemeral landscapes

Written by Adam Steer, NPI

Have you ever watched the colors of the sunset over the sea – then suddenly the beautiful moment is gone, and darkness surrounds you. Arctic sea ice is like that – a temporary and beautiful landscape constantly presenting moments that are suddenly gone, if you dare to blink.

Sea ice is a lot of things. It gets made when the upper ocean becomes cooled enough (around -1.8 C for regular seawater) to freeze. In the right conditions, eventually vast regions of ocean become covered by a highly dynamic layer of ice. This thin layer affects how heat, light, momentum and gases are exchanged between the vast ocean and vast atmosphere – impacting the local environment of things which live here, and the earth system as a dynamic whole.

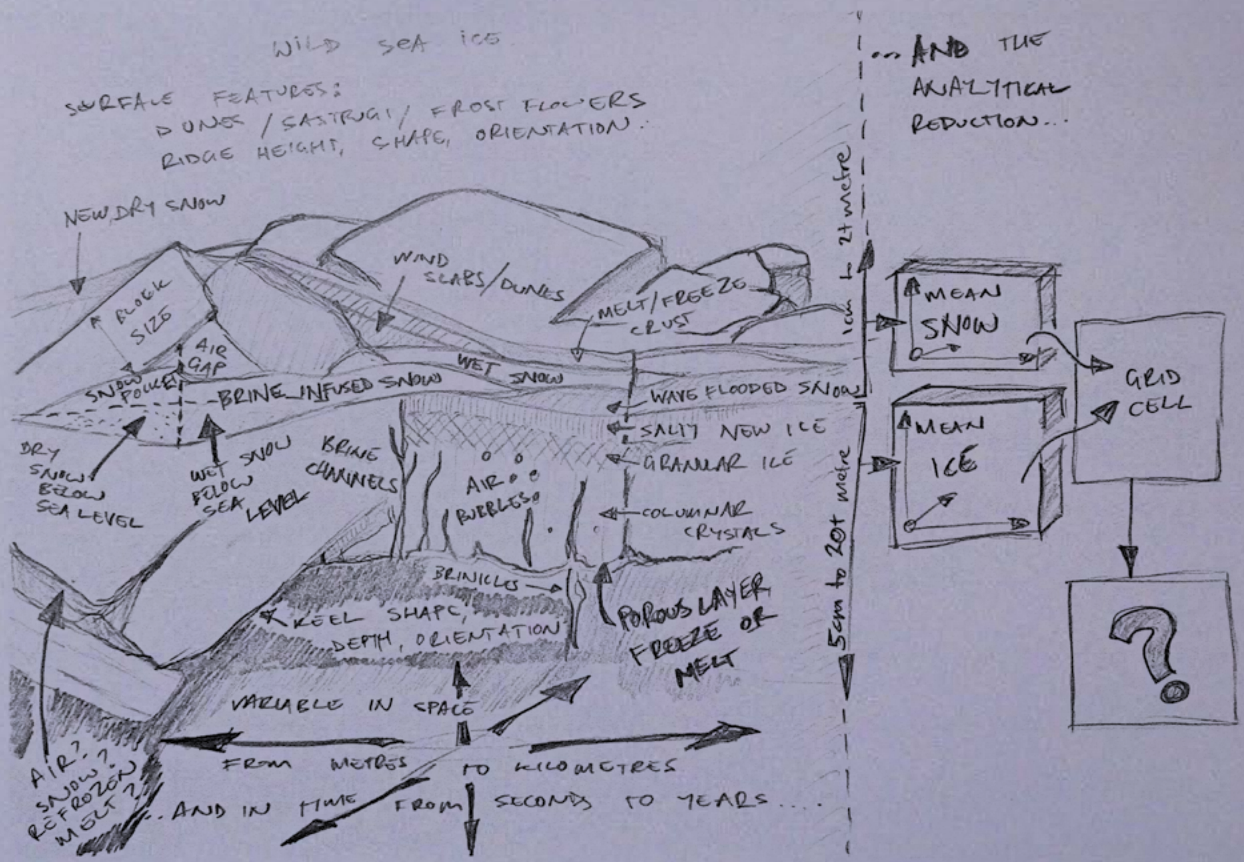
...but it doesn't stop there. Sea ice is itself a complex composite assembled from different types of ice at different stages of growth and decay; air gaps, water, slushy ice filling in voids; snow in complex layers of its own; and finally the living component – everything which makes sea ice its home, and the biological material they produce and leave behind.

Understanding how it looks – its shapes, how big or small things are, how they are assembled together – is like the microbiology of sea ice. To use ourselves as a metaphor, we can observe 'body' or 'organ' or even sometimes 'cell' size components of the sea ice system using remote sensing, usually satellites equipped with cameras (using light or radar) and altimeters (lasers and radars). In order to interpret those as well as possible, we need to go deeper – into the ice. What proteins are expressed? What's going on between synapses? How do the structural parts look and what are they made of? How do these small components affect the larger scale system?

Here in the Arctic Ocean aboard *RV Kronprins Haakon* we bring a range of approaches to this task. We are coordinating high resolution radar imagery from space, instrumented helicopter flights, smaller scale drone missions, person-towed instruments to measure fine scale sea ice properties, all the way to ice corers, drills and measuring tapes.

It is a lot – and difficult to find the mix of weather, light and wildlife encounters (polar bears, but then, we work in their house) to get a complete set of measurements, so we triage our approach and work from the basics up. The bare minimum we need to investigate is a few ice cores at the same place. From those we can discover whether the ice grew in calm or turbulent conditions by what kinds of ice crystals are present, whether it is still growing, and describe its physical properties generally.

This, however, is a single point in space and time. Broadening our scope, we use electromagnetic induction surveying tools, a simple semi-automated snow probe and a lot of walking or skiing to collect hundreds or thousands more observations about the snow and ice thickness on the ice floe we are sampling. From this, we can say something about whether the point sample can be generalized across an ice floe. We also aim to cover enough area to be, seen from space using near coincident radar imagers.



Sea ice is not a simple white layer but a complex composite as indicated in this cross-section through an ice floe. Sketch: Adam Steer

...and we still have gaps. We attempt to fill these with small drones, mapping the site with hundreds of overlapping images and then using computer vision and photogrammetry techniques to reconstruct the immediate area of our point sample.

Using modern geospatial tools, we can assemble these data in ways that were extremely difficult even a decade ago. We will overlay very high-resolution drone maps over satellite pictures, align walking tracks with towed instruments with both of those, and then add information about the state of ice at point sampling sites. In this way we can build a multi-scale picture of how sea ice looks, what makes it up, at a range of scales relevant to people taking samples on the ground as well as satellite imagery analysts working remotely. In turn, this level of detail can give a framework for asking questions like 'why does a thing live here in the sea ice but not there, just a few meters away?'

Sea ice is an ephemeral landscape, incredibly diverse and variable at scales from centimeters to hundreds of kilometers. When we take a snapshot of what is out here, when we walk around towing our tools of the trade to measure its properties, we are often the only humans who will ever see the places we have explored – a privilege which is granted to few on this planet of ours.

How we approach this place, and communicate about our experiences, often has more impact than the numbers and equations and dry facts we extract. It changes us forever, and that is multiplied when we relay our story to others. So it is also our task to bring back with us the sense of wonder we feel when we encounter, experience, immerse ourselves in these ephemeral landscapes. ■

Photo: Rudi Caeyers - UiT

"How does the Arctic sea ice affect us, and our internal world, is just as valid a question as 'how thick is the ice?'."

Adam Steer, NPI

Computer simulations of the real world for the real world

As computer games invite us into a constructed world, mathematical models represent compartments of the world we would like to explore and understand. Model types can be simple or complex and are designed to answer different questions. Alone or combined they help us to test how well we understand weather, climate, and ecosystems. Models can also provide possible future scenarios. In the Nansen Legacy a large variety of different models are used to improve forecasts and predictions, but also to understand the complex couplings and changes in the ecosystem. Some examples of the progress made in 2021 are given below.

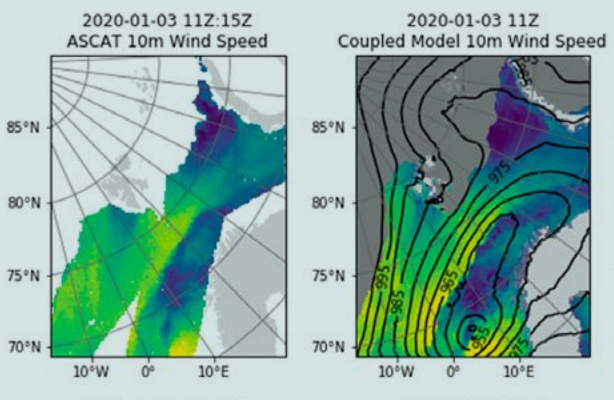
New individual-based models for Arctic key species

In a warming Arctic, where species composition in the food web is changing, models operating at species level are needed. Individual based models (IBMs) are based on the explicit representation of individual organisms, and the population dynamics are results from the sum of individuals. These models can answer questions where individual variability, local interactions, and adaptive behaviour are essential. The Norwegian Sea ecosystem end-to-end model NORWECOM.E2E couples the NORWECOM model for primary production and nutrient cycling to different individual-based models (IBMs) for zooplankton and fish. So far, NORWECOM.E2E contained an IBM for *Calanus finmarchicus*, a boreal key zooplankton species, while its Arctic siblings *Calanus glacialis* and *Calanus hyperboreus* were not represented. This hampered a meaningful application of NORWECOM.E2E to assess the northern Barents Sea ecosystem where the Arctic *Calanus* species are considered the dominant grazer. Nansen Legacy researchers at IMR have now developed individual-based models for *C. glacialis* and *C. hyperboreus* and incorporated the IBMs into NORWECOM.E2E. The work has demonstrated so far that these models can serve as a framework for integrating and testing existing knowledge, and disclose knowledge gaps and inconsistencies between independent studies and observational datasets.

New food web model with high resolution of trophic levels for the Barents Sea

To understand and explore the complex interactions in the food web and the efficient energy transfer to harvestable species, models can be used. Ecopath with Ecosim (EwE) is a modelling complex that is used to create mass-balanced models of marine ecosystems. In 2021, Nansen Legacy researchers at UiT improved an EwE model for the Barents Sea with high resolution of organism groups and trophic levels (Pedersen et al. 2021). The model is based on a comprehensive background material. The dynamic Ecosim model was calibrated using time-series for biomass and catches for the period 1950-2013. The Ecopath model showed that four major carbon pathways from lower to higher trophic levels exist in the Barents Sea.

Based on the newly improved EwE food web model, a spatial Ecospace model was developed to model effects of climate variability on the spatial distribution of functional groups in the Barents Sea. To evaluate the Ecospace model, predictions of the spatial distribution of organisms driven by changes in ice-coverage, primary production, and temperature were compared to the spatial distribution of organisms retrieved from survey data. First tests suggest that the model predictions generally match the survey distributions for both cold and warm years, making this new model a promising tool.



← Increasing human activity in Arctic seas calls for improved weather and sea state forecasts for these regions. Here, results from a newly developed high-resolution atmosphere-wave coupled forecasting system for the European Arctic are shown (Thomas et al. 2021). Verification of the wind forecasts of the coupled forecast system (right panel) with satellite wind measurements (left panel) showed that the coupling significantly improved the quality of short-term forecasts in the region.

Improving Arctic forecasts by implementing atmosphere-sea ice-wave interactions into operational models

Many users benefit from improved marine forecasts in the Arctic, such as shipping, fishing, and tourism. Accurate forecasting systems require simulation of the Earth system (atmosphere, sea ice, ocean, and waves) on a kilometre-scale resolution. In 2021, Nansen Legacy scientists at MET finalized a fully coupled atmosphere-wave forecasting system at a kilometer-scale resolution for the European Arctic. Verifications of the model results with satellite observations showed that the fully coupled wave-atmospheric forecasting system significantly improves the forecast accuracy of strong winds and large waves in the European Arctic (Thomas et al. 2021). The coupled forecast is currently tested in a pre-operational setup. At the same time, the development of the fully integrated forecasting system continues by coupling sea ice into the atmosphere-wave system. Wave-in-ice measurements from the Nansen Legacy Physical Process Cruise in February 2021 are used to test the new atmosphere-sea ice-wave forecasting system.

Understanding the impact of sea ice cover heterogeneity using a new coupled ice-ocean model

Sea ice is not simply a white homogeneous cover on the top of the ocean. It is full of cracks and leads, where intense heat and gas exchanges between the ocean and the atmosphere take place. While field campaigns can quantify these processes in a particular lead and at a particular moment in time, models can estimate the impact of leads over the whole Arctic and over many years, both in the past and the future. So far, sea ice models have not reproduced the ice cover heterogeneity very well, but the sea ice model, neXtSIM, developed at NERSC, considerably changed this. This new model uses a particular way of representing sea ice dynamics that reproduce leads very well, even at relatively low spatial resolution. The model has recently been coupled to the ocean model NEMO with the support from a French team in Brest, in order to better understand the impact of the sea ice heterogeneity on the sea ice itself and on the ocean underneath. After evaluating the model against remote sensing data, the first question the researchers addressed was how much leads contribute to winter ice production in the Arctic. The answer is that leads contribute to about 30% of winter ice production, and that this contribution has been increasing over the last 18 years.

New research tool for performing climate reanalyses and predictions

Climate predictions focus on forecasting the seasonal-to-decadal evolution of the ocean and the atmosphere. These predictions are initialized by simulations, called reanalyses, produced with Earth System models that assimilate observational data. Improving climate reanalyses is crucial to increase the skill of climate predictions, because they provide accurate information on ocean and sea ice conditions that influence the climate. In 2021, Nansen Legacy researchers at UiB contributed to the development and application of a new research tool – the Norwegian Climate Prediction Model version 1 (NorCPM1). The tool consists of a modern data assimilation scheme and the Norwegian Earth System model, which includes a state-of-the-art ocean biogeochemistry component. An improved climate reanalysis for the period 1950 to present was produced (Bethke et al. 2021) by assimilating oceanic observations and using a novel approach to update the sea ice conditions. Improvements in predicting conditions in the North Atlantic, Norwegian Seas, and Arctic on multi-annual timescales was demonstrated. The study is a contribution to the CMIP6 Decadal Climate Prediction Project (DCPP). The new model, NorCPM1, also participated in a multi-model intercomparison on carbon cycle reconstructions and predictability in 2021, and contributed to the WMO Global Annual to Decadal Climate Update for 2021–2025.

New high-resolution model for improved prediction of Barents Sea

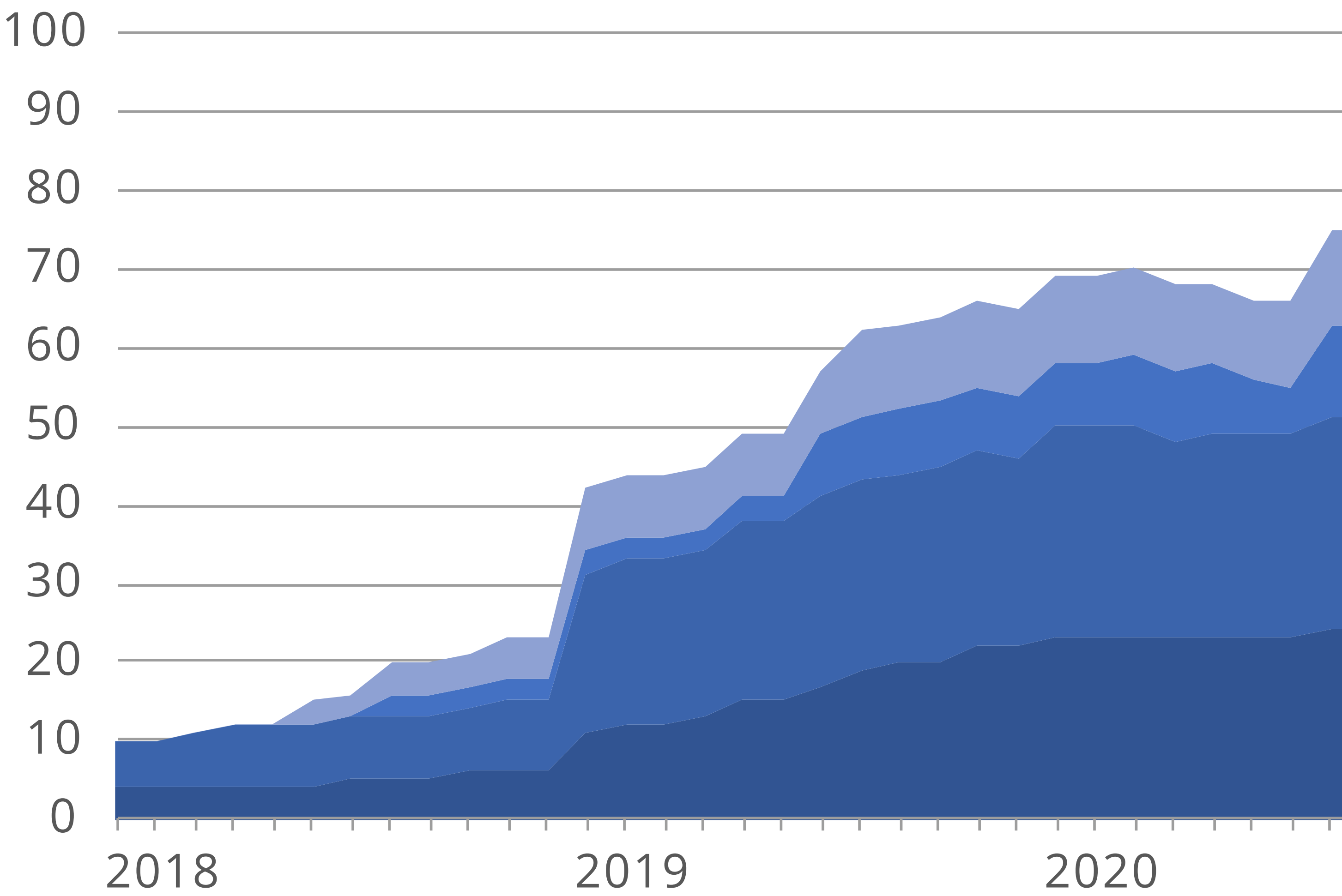
Models that can decently reproduce the heat transport towards the Arctic are an important tools to understand drivers of the Arctic sea ice conditions and responses in element cycling and biological production. The Norwegian Earth System Model (NorESM) is a global coupled model system for the physical climate system. The model includes interactions with biogeochemical processes in the earth system and simulates marine primary productivity. In 2021, Nansen Legacy researchers at UiB developed a high-resolution version of NorESM. This new version shows improved propagation of marine heat content, such as sea-surface temperature anomalies in the subpolar North Atlantic and Nordic Seas. A new computationally less expensive (data assimilation) technique to initiate predictions with this new model has also been developed. Ongoing analyses aim at understanding the consequences of sea ice changes on the Arctic and Northern Hemisphere climate. These developments are critical for predicting changes in the Barents Sea several years in advance.

The use of remotely operated vehicles under sea ice and in the marginal ice zone is challenging, but highly important for investigating the Arctic ecosystem. Therefore, the Nansen Legacy includes technological research to develop new observational methods. New concepts have been tested in the field in cross-disciplinary work during several of the Nansen Legacy research cruises in 2021, bridging physics (light, ice, oceanography), chemistry, biology, and technology by using Remotely Operated Vehicles (ROV). The ROV on the picture carried hyperspectral imagers and spectroradiometers and was used to survey the underside of sea ice for signs of algae living within and below the ice.
Photo: Helge Thomas Bryhni


DRONE-
PILOT

The Nansen Legacy as second home

The Nansen Legacy is home to over 70 early career scientists, including 14 affiliated PhD and postdoctoral fellows in 2021. In total, 24 affiliated young scientists have been part of the project. These affiliated early career scientists have their position funded from other sources, but are deeply involved in the scientific work of the Nansen Legacy. They add precious expertise to the project and help connecting the Nansen Legacy with other ongoing research efforts. The Nansen Legacy hopes to support its affiliates through inclusion into a large research community and increased research opportunities.

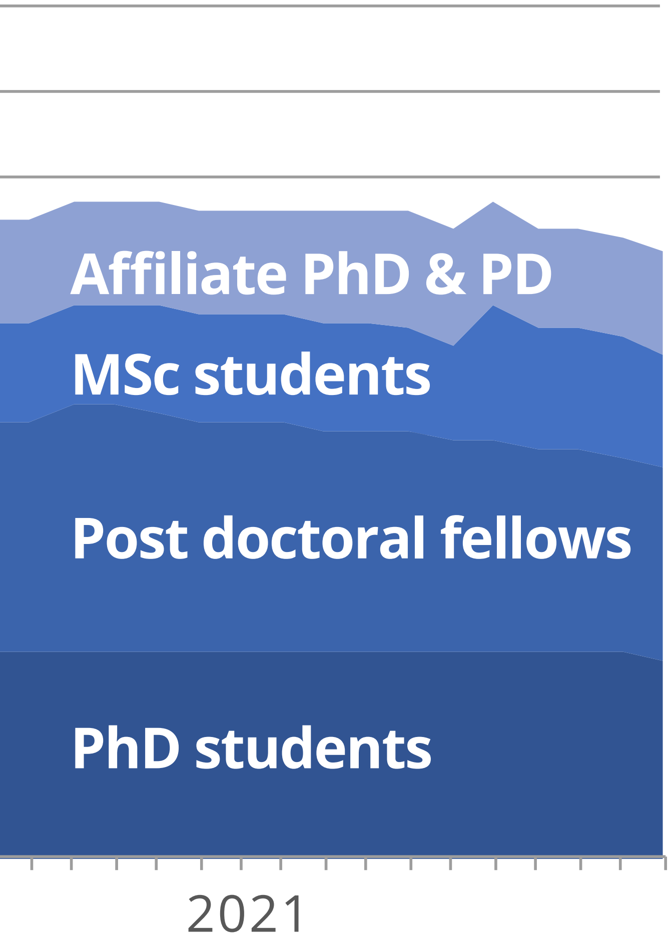


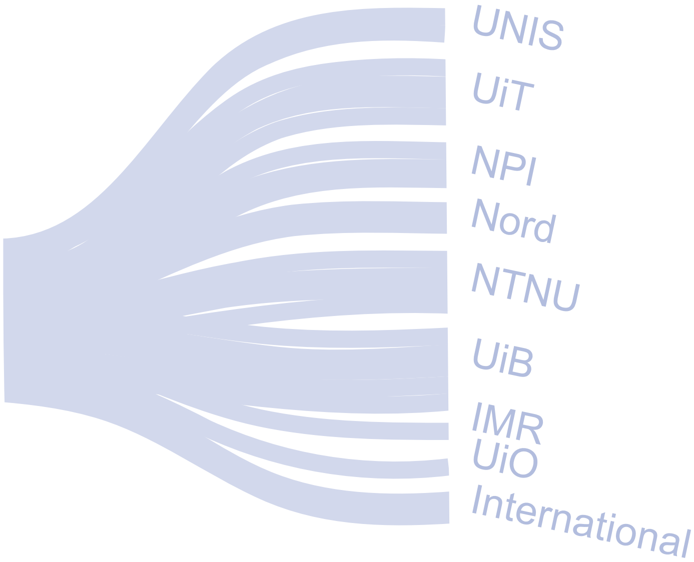
Stephen Kohler is a PhD student at NTNU investigating the biogeochemistry of mercury in the water column of the Arctic Ocean. He is interested in the seasonal and vertical distributions of mercury species within the northern Barents Sea and mercury's transport from sea ice to seawater to seafloor. He actively collaborates with the Marseille Marine Mercury research group in France. He has been affiliated with the Nansen Legacy project since the start of his PhD project in 2018, and has participated in four research cruises. Through affiliation, he has been able to form strong collaborations with other early career researchers within the project to broaden our understanding of seasonal cycling of mercury in Arctic fjords, marine sediments, and biota.

Emmelie Åström is a postdoctoral fellow at UiT funded by VISTA. Emmelie studies food webs in the Barents Sea and in areas of natural methane seepage, so called cold seeps. The focus of her study is to identify carbon sources to the benthic communities and whether chemosynthetic-based carbon from cold seeps is utilized by Barents Sea benthos. With her research, she brings new perspective on trophic relationship and food web patterns into the Nansen Legacy. Emmelie has participated in Nansen Legacy field work in 2018, as well as research cruises organized through the centers of ARCEx (The Research Centre for Arctic Petroleum Exploration) and CAGE (Centre for Arctic gas hydrate, environment and climate).

“Joining the Nansen Legacy gave me a broad research network in Norway, which I think helped in getting my current permanent position.”

Arunima Sen, UNIS





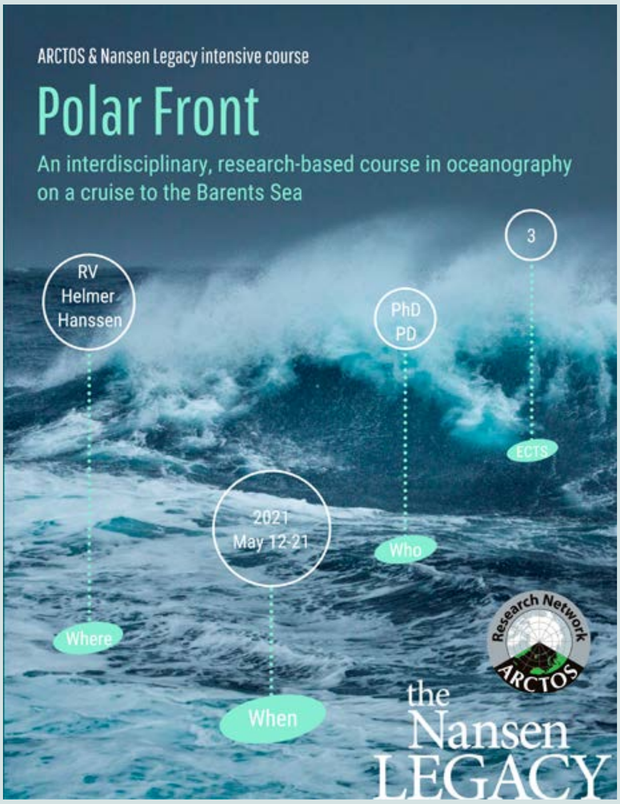
The number of early career scientist has grown vastly since the project’s start in 2018. Affiliated young scientists are an important asset. Their home institution is shown in the branch diagram. The branch thickness indicates the number of affiliated early career scientists who have that institution as their home.

Arunima Sen worked as a postdoctoral fellow at Nord University before she got a permanent position as associate professor at UNIS. Her research focuses on the ecology of benthic communities and their influence on carbon and nutrient cycling. Arunima joined the Nansen Legacy right from the start, and helped strengthening the benthic expertise in the project. She joined all four seasonal survey cruises as well as the Arctic Basin expedition. On board, Arunima run large-scale experiments with sediments retrieved from the seafloor in order to measure oxygen uptake rates and to quantify remineralization and carbon cycling. Affiliation to the Nansen Legacy helped Arunima establishing a larger research network in Norway, which she thinks was essential in getting her current position.

Sanna Majaneva worked as a postdoctoral fellow at NTNU before she got a permanent researcher position at the same university. Her research focuses on taxonomy and ecology of pelagic communities to unravel processes that structure the plankton populations and their interactions. She is especially interested in the taxonomic groups and interactions that have traditionally attracted little attention. Sanna has been affiliated with the Nansen Legacy project since 2019, and has contributed to developing the protocol for sampling and analyzing of all Nansen Legacy samples of understudied zooplankton groups, such as gelatinous zooplankton. Through affiliation and her research on gelatinous zooplankton, Sanna brings new perspective on biodiversity and species interactions on pelagic ecosystems into the Nansen Legacy.

Field school at the Polar Front

In May 2021, the ARCTOS research network and the Nansen Legacy project joined forces for a combined research and teaching cruise to the Barents Sea Polar Front with *RV Helmer Hanssen*. The field school - offered as a PhD level course through UiT - attracted 15 early career scientists from universities in Norway, the UK and the US.



The Polar Front - an ideal teaching case

The Polar Front is a prominent feature in the Barents Sea. It is here that relatively warm, saline water masses of Atlantic origin meet colder and fresher water masses of Arctic origin. Hence, the Polar Front marks an area of extensive changes also in the biogeochemical composition and the distribution of organisms. With these features, the Polar Front offers an ideal place for interdisciplinary studies of a complex marine system, and is inevitably an ideal place for teaching interdisciplinary marine survey techniques.

A complex system requires a complex survey

The scientific goal of the cruise was to examine linkages between physical, chemical, and biological properties at different scales across the Polar Front. For this purpose, a combination of remote sensing, traditional, and autonomous sampling platforms and techniques were used. The course participants were involved in all types of sampling and data acquisition - from glider deployment to microalgal activity measurements or the study of benthic macrofauna. In addition, they were welcome to take samples for their own work.

Getting landlubbers out at sea

Not all Nansen Legacy early career scientists work out at sea. Most climate scientists, statistical ecologists, and technologists normally have their feet safely planted on land. The teaching field campaign to the Polar Front offered an opportunity for these landlubbers to get out to sea. Read here how two of them reflect about their experience.

Jakob Dörr is a PhD candidate in climate dynamics at UiB. In his PhD project, Jakob uses a combination of climate models and observations to understand which large-scale drivers influence the winter sea ice in the Barents Sea and the rest of the Arctic Ocean, now and in the future.

- As a scientist studying sea ice dynamics using numerical models, how important do you think it is for you to have seen sea ice with your own eyes?

I do not believe that having seen sea ice is a prerequisite for my work, but the experience certainly influences my creative thinking and may help developing research questions and approaches to interpret my data.

- What was the most interesting aspect of the cruise to you?

Besides seeing sea ice in real life for the first time, for me it was most interesting to observe the biological sampling. I only knew water sampling from physical oceanographic cruises. There the sampling is quite limited and not much water is used at each station. During the Polar Front survey, there were so many different parameters sampled that a water budget had to be organized, because otherwise there would not be enough water for all samples. Often, we even needed to repeat the CTD cast just to get more water. That was very interesting and different from what I had experienced so far.

- How did you like the combination of a research cruise and a PhD summer school?

Overall, the cruise was a very good and intensive learning experience. The instructors made sure that everyone helped with each sampling. The target to understand the Polar Front embedded all the different sampling parameters inside a complete picture, so that it was easy to understand their relevance. I can only recommend such blended research and teaching cruises!

"The cruise was a very good and intensive learning experience. I can only recommend such blended research and teaching cruises."

Jakob Dörr, UiB

Muhammad Asim is a PhD candidate in remote sensing at UiT, interested in determining the distribution of phytoplankton from satellite-measured ocean color data. In addition, he is also interested in validating satellite-derived radiance against above-water radiometric measurements. Muhammad is an electrical engineer by training with specialization in signal processing and he has never been at sea before participating in the Polar Front cruise.

- You have investigated phytoplankton distribution in the Barents Sea based on satellite data for some time, while never having been at sea. Did the participation in the Polar Front cruise change your perspective on your work?

In my work, I am dependent on a large amount of in-situ data. During the course, I learned how challenging in-situ data collection is, especially precise measures of water-leaving radiance in the presence of other factors such as boat disturbances and glint during the measurement procedure. The knowledge I gained at sea is beneficial to me in future field surveys, especially in collecting radiometric data.

- Were you able to collect data for your PhD during the survey?

Yes. During the cruise, I collected water samples and filtered for in-situ substances such as phytoplankton pigments and color dissolved organic matter. In addition, I had mounted Trios-RAMSES radiometers on the reeling of the ship, which collected above-water hyperspectral radiometric data. These in-situ data I will use to calibrate and validate satellite-derived biogeochemical parameters and radiance data. ■

Creating own learning arenas

In 2021, Nansen Legacy early career scientists organized several meetings and learning arenas for themselves and others.

Reproducible data wrangling, visualization, and collaboration

Besides sharing raw data, exchanging analytical tools promotes scientific cooperation. Nansen Legacy early career scientists organized a workshop and reached both goals: they learned effective use of R and GitHub and strengthened their collaboration.

Workshops at Arctic Frontiers

Nansen Legacy early career scientists were in the organizing committee of all ARCTOS/ APECS workshops during the Arctic Frontiers conference in 2021. The workshops dealt with a variety of topics such as biomarkers, science communication, and Arctic seaweed farming, aiming at training the workshop participants' skills in communicating with stakeholders and product developers.

Nansen Legacy Recruit Forum

Fifty of the over 70 Nansen Legacy early career scientists met in person in Trondheim for the project's annual Recruit Forum. The forum is designed to give the younger researchers a meeting place to discuss topics of own interest. In 2021, career development was the main topic of the meeting. The idea of career design thinking was introduced as a way of reflecting on career choices. During the forum, participants also addressed their challenges with finding time and concentration for writing. They discussed how to implement good writing habits and agreed on creating writing groups to support each other's writing process. ■

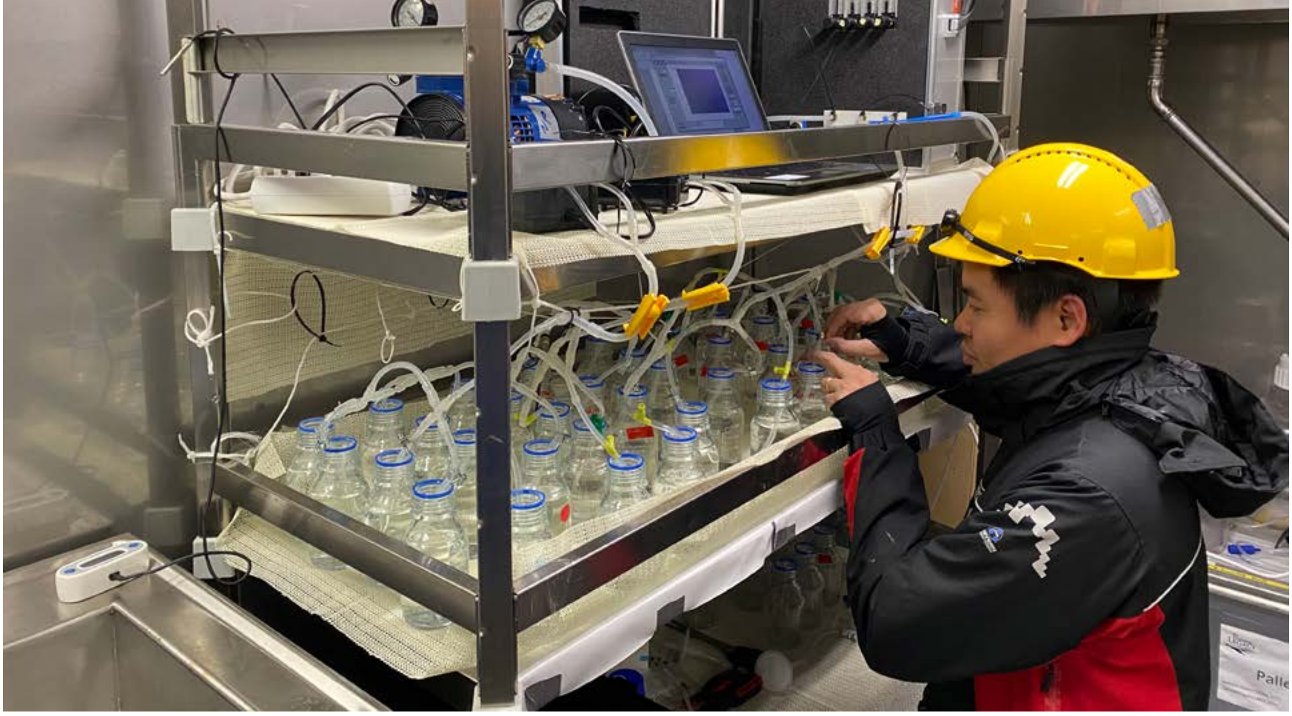


Photo: Amalie Marie B. Gravelle

The stress tester

In summer 2021, Nansen Legacy postdoctoral fellow Khuong V. Dinh from the University of Oslo received the highly competitive Young Research Talent (YRT) grant from the Research Council of Norway. In this interview, Khuong explains why we need to investigate the effects of cocktails of stressors on organisms.

- Congratulations with the grant! Your YRT project aims at investigating the response of boreal-arctic zooplankton to multiple stressors. What are stressors?
With stressors, we mean environmental factors that affect organisms, such as pollution, rising water temperatures or ocean acidification. If several stressors occur simultaneously, we speak of multiple stressors. In my YRT project, we will investigate the responses of boreal-arctic zooplankton to marine heatwaves and ocean acidification. Both are dominant stressors, which may substantially change the diversity, function, and ecological services of marine ecosystems worldwide.

- Why do you attempt to study several stressors simultaneously?
While marine heatwaves are typically short periods of extreme warming occurring randomly across space and time, ocean acidification is a long-term change. That means that marine organisms will have to cope with the effects of marine heatwaves and ocean acidification at the same time. That can make it much more difficult for zooplankton to cope with these two stressors than if they would occur each for themselves. Just think of us humans. Our body can cope to some extent with alcohol and to some extent with painkillers. However, taking both at the same time is no good idea! It is the same logic in the ocean. Many organisms can cope with one stressor but adding several stressors at the same time leads to interactive effects, which are typically much more severe than the simple sum of each stressor. Subsequently, the consequences for marine ecosystems simultaneously exposed to several stressors can be severe.

- How do you investigate the response of zooplankton to multiple stressors?
We expose Arctic copepods to simulated marine heatwaves, ocean acidification, and their combination in the laboratory. We track for immediate responses in the exposed organism, as well as delayed effects. A delayed effect can for example be that the animals show poorer survival over the winter or effects on their offspring born the following year.

- What are the greatest challenges in your work?
How multiple stressors may affect the overwintering of Arctic zooplankton is still a mystery, and it is challenging to detect such effects in field observations of zooplankton. Exploring the ecological consequences of multiple stressors across generations is neither an easy task. We generally say that “a perfect bird gives a perfect egg” - so we want to explore if stressed copepods produce stressed offspring.

- Why are you using copepods as study organisms?
Copepods are key organisms in marine food webs, efficiently transferring energy from phytoplankton to higher trophic organisms such as fish. Therefore, stressor-impacted copepods may have cascading effects on the entire marine food web.

- You are a postdoctoral fellow in the Nansen Legacy. Also here, you investigate multiple stressors. Does your work in the Nansen Legacy differ from the work you are planning in your new project?
In the last 10 years, I have studied multiple stressor effects on various species across ecosystem boundaries from the tropical, temperate to the Arctic regions. The work we are planning in the YRT project and our work in the Nansen Legacy complement each other. The projects share expertise and research facilities. Most importantly, both projects will help to provide different aspects to comprehensively assess how multiple stressors affect Arctic zooplankton. This is much needed for improving ecological risk assessment and Arctic monitoring programs. As a scientist, I devote all my effort to this purpose. ■

Master theses 2021

In 2021, five Nansen Legacy master students finished their degrees. Congratulation to all of them for successful work in the fields of oceanography, marine biology, and geology.

Allegra Alexandra Liltved successfully defended her master at UiB (supervisors: U.S. Ninnemann, N. Irvali, E. Jansen, all UiB). Allegra studied stable isotope records of pelagic and benthic foraminifera in a sediment core from the Kvitøya Trough. Her focus was here to determine the properties of Atlantic Water north of Svalbard during the Younger Dryas. Liltved concludes that an abrupt warming event (up to 5-8°C) of the intermediate Atlantic Water layer occurred in the Kvitøya Trough ca. 12500 to 12000 years ago.

Reference: Allegra Alexandra Liltved (2021) Abrupt deglacial changes in the properties of the Atlantic Water entering the Arctic. Master thesis, University of Bergen.

Malin Lunde successfully defended her master at UiB (supervisors: U.S. Ninnemann, P. Mørkved (both UiB) and A. Tessin, Kent State University). Malin studied carbon isotopes ($\delta^{13}C_{DIC}$), oxygen, pH and nitrate in the pore water in 11 sediment cores collected mostly on or close to the continental slope in the Nordic Seas. Lunde found that the studied sites were characterized by a higher carbon turnover rate than many other oceanic areas. This suggests that these regions may play a unique role in the global carbon cycle.

Reference: Malin Lunde (2021) The role of Arctic shelves in the global carbon cycling assessed using stable isotope geochemistry of Arctic and sub-Arctic pore waters. Master thesis, University of Bergen

Martin Skaugset finished his master at NTNU (supervisors: M. Ludvigsen, T.O. Fossum, both NTNU). Martin examined how a single autonomous underwater vehicle can make deliberate choices and plan an adaptive path of when and where to collect data. One of the central results in the thesis is that data collection using adaptive path planning gain better results than manually planned data collection missions do.

Reference: Martin Skaugset (2021) Using Monte Carlo simulations to evaluate adaptive sampling strategies in synthetic and real ocean models. Master thesis, Norwegian University of Science and Technology

Simon Hasselø Kline graduated from UiO (supervisors: L. Supraha, B. Edvardsen, T. Andersen, all UiO). Simon studied six strains of Arctic sympagic and pelagic diatoms mostly collected during Nansen Legacy cruises. He found that not all species were equally well identified with the 28S rRNA gene and that a combination of genetic sequencing and morphological analyses is most beneficial. Further, Kline showed through growth experiments that the pelagic diatom strains were more flexible in adjusting to changes in salinity, temperature and light than the sea ice species.

Reference: Simon Hasselø Kline (2021) A tale of six diatoms: an insight into the taxonomy of Arctic diatoms from different sea-ice communities and their physiological response to climate change. Master thesis, University of Oslo

Simon Pierre Lefèvere graduated from UiB (supervisors U.S. Ninnemann, UiB, N.Irvali, UiB, M. Forwick, UiT, H. Kleiven, UiB). Simon analyzed a sediment core to study the variability of the Atlantic Water inflow North of Svalbard during the last glaciation. He documented an inverse relationship between flow speed and temperature of Atlantic Water suggesting an important role for sea ice in modulating Atlantic Meridional Overturning Circulation during abrupt climate changes.

Reference: Simon Pierre Lefèvere (2021) Natural variability of the Atlantic Water inflow to the Arctic during the last deglaciation - Based on sediment grain size and foraminiferal stable isotope geochemistry. Master thesis, University of Bergen.

In 2021, the Nansen Legacy project became part of museum exhibitions in both Longyearbyen (shown here) and Bergen. In Longyearbyen, Nansen Legacy scientists and communication advisors from UNIS and NPI convey knowledge on marine microbes and sea ice through videos, texts, and exhibits, such as Nansen's water sampler. The display is now a part of the exhibition at Svalbard Museum, which has around 50 000 visitors annually. In Bergen, the University Museum set up an exhibition on Fridtjof Nansen's time and work in Bergen in connection with Nansen's 160 birthday. Six Nansen Legacy early career scientists currently working in Bergen are presented in this exhibition as a testimony of Nansen's legacy lives on in today's young researcher generation.
Photo: Eva Therese Jenssen

Outreach

Nansen Legacy scientists used the project's fourth year to communicate their work and new insights to a broad audience, ranging from preschool kids to international policy makers. Here is a taste of the various activities in 2021.

For and with kids

"Far to the north is an ocean with ice on top. Not ice like ice cream, and not ice like that we have in a glass of soda, but ice that tastes salty." This is how the story about the three brave stuffed animals Max, Diamanta and Ibjørn begins in a small booklet for children. The animals joined Nansen Legacy scientists on *RV Kronprins Haakon* to the Arctic. Back home, Max, Diamanta, and Ibjørn met preschool kids at the experience centre Polaria in Troms, and told about their Arctic adventures together with Nansen researcher Sigrid Lind (NPI).

Throughout 2021, Nansen Legacy scientists from UNIS, UiO, NPI, IMT, and UiT met children and teenagers to talk about their science and the Arctic natural environment, either virtually through platforms like "Skype a scientist", or in person at schools and at the political festival Arendalsuka. Pupils from Norway, Germany, UK, and USA were involved. Additionally, the Nansen Legacy collaborated with the Arctic Frontiers conference and the Science Centre of Northern Norway in the project "Science for kids". Here seventy 5-year-olds received a hands-on introduction on how to conduct own research.

Three stuffed animals joined the Nansen Legacy research cruise deep into the Arctic pack ice, where many adventures awaited them. Safely back home in Tromsø, they told their story to preschool kids.
Photo: Sigrid Lind/ Simon Hasselø Kline/ Andreas Wolden

For and with the public

Nansen Legacy researchers used a large variety of different platforms to convey their work and findings to a wider audience in 2021. Besides contributing to two exhibitions, scientists wrote over 50 popular science texts for the Nansen Legacy blogs on forskning.no and sciencenorway.no. Nansen Legacy was also represented in two articles in the ECO Magazine, an international trade publication reporting from the frontlines of ocean science, innovation, and exploration for over 40 000 readers worldwide. Expedition leaders Agneta Fransson (NPI) and Bodil Bluhm (UiT) reported on Norwegian radio and TV about the Nansen Legacy Arctic Ocean survey. Further, Nansen Legacy early career scientists arranged a vibrant popular science evening in four cities (see next page).

The project was featured in the ECO Magazine, a magazine about the frontlines in ocean science.
Picture: ecomagazine.com

For and with scientists

Continued travel restrictions did not prohibit Nansen Legacy researchers from presenting their work at relevant international science conferences. In total, the project was present at 15 different conferences with 18 posters and 32 oral presentations.

For and with policy makers

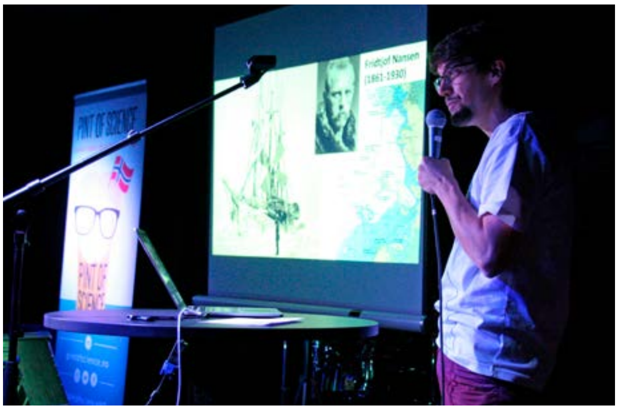
Several important status- and management reports were released during 2021, above all the first part of the Sixth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC). Nansen Legacy members actively contributed to this and other important reports (see page 41). In addition, the Nansen Legacy scientists contributed to the UN Climate Change Conference COP26 and the political festival week in Arendal (read more about both events on page 40). ■

Upon return of the Nansen Legacy Arctic Ocean cruise, the expedition leaders were invited to report about their experience and research on Norwegian radio and TV.
Picture: NRK

One night, four cities, 21 scientists, 260 people

Many of the early career scientists in the project burn for conveying their knowledge and research to a wider audience. They write blogs, talk to school kids, run an Instagram account, and much more. In October 2021, they joined forces with the science communication organization Pint of Science Norway. The result – a vibrant live evening in four Norwegian towns filled to the brink with excellent popularized sciences talks, quizzes, discussions and hands-on activities. Together, well over 250 people attended the Nansen Legacy Polar Pint of Science night!

Longyearbyen
In Longyearbyen, Robynne Nowicki, Cheshtaa Chitkara, Vanessa Pitusi and Victor Gonzalez Triginer (all UNIS) were on stage that night. Robynne, who had the general idea for the Nansen Legacy Polar Pint of Science night, said after the evening:
"It was a huge success! The audience was really engaged, and everyone seemed super happy, both speakers and participants alike! We had several people come up to us afterwards asking for more events like this, some even said they'd love to have it once a month!"



Bergen
In Bergen, Heather Cannaby (IMR), Elina Efstathiou, Stefan Thiele and Jakob Dörr (all UiB) surprised their audience with bringing boxes containing instruments with them. Jakob told after the night:
"The event in Bergen was great! We had around 80-90 people there, the bar was full, and the atmosphere was amazing! The bar manager told me that even the bar staff got interested in the science. There was a lot of interest and questions to our three speakers, and especially the pub quiz got people super engaged."

Tromsø
In Tromsø, Øyvind Lundesgaard and Nadjejda Espinel (both NPI), as well as Christine Gawinski, Griselda Anglada-Ortiz, Yasemin Bodur, Amanda Ziegler and Marti Amargant-Arumi (all UiT) had the stage. Nadjejda really enjoyed talking about her field of research to a wider audience and said:
"It was a great evening in Tromsø! I loved talking Arctic Ocean acidification with a live audience after all the online events these past months!"

Oslo
In Oslo, Louise Steffensen Schmidt, Simon Hasselø Kline, Karoline Saubrekka, Nicolas Dupont, Julia Giebichenstein and Thaise Ricardo de Freitas (all UiO) had set up for a night in the name of Arctic science. The audience was actively participating. Thibaud Freyd, leader of Pint of Science Norway, reported on Twitter:
"Questions from the audience on the impact of the researchers on the Arctic ecosystem. Really good discussion from the panel of speakers as they have been asking the same question themselves; followed by the impact of tourism in the Arctic, should we ban it?"

A polar bear in a pint glass - the logo of the Nansen Legacy Polar Pint of Science night! Drawing: Karoline Saubrekka

International collaboration and mobility

The Nansen Legacy is tightly connected to the international Arctic marine research arena through collaboration with researchers, projects, and institutions outside the project. Despite the COVID-19 related travel restrictions throughout most of 2021, Nansen Legacy scientists continued their international collaboration and mobility. A flavor of the different collaborative efforts is given here.

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

Several Nansen Legacy early career scientists have joined the international **MOSAiC field campaign** and are now putting together data from both the Nansen Legacy and MOSAiC investigations.

Nansen Legacy researchers have initiated collaboration with scientists at the **University of Washington** and the **California Institute of Technology** on decadal Arctic sea ice variability using a new method to identify and analyze low frequency (e.g. decadal to multidecadal) variability.

Nansen Legacy scientists initiated a **collaboration with UK scientists from the Arctic PRIZE project** to process and analyze complimentary nutrient time series data from the Barents Sea from both projects.

Early career scientists from the Nansen Legacy and the **UK's Changing Arctic Ocean program** combine samples from both programs for a comprehensive analyses of the northern Barents Sea food web.

Nansen Legacy PhD student Natalie Summers spent time at the **National Oceanographic Center in Southampton** to analyze water samples using the CytoSense instrument enabling her to look at trait variability of phytoplankton cells.

Nansen Legacy researchers collaborate with the **Mediterranean Institute of Oceanography in France** on analyses of mercury, and Nansen Legacy PhD student Stephen Kohler visited the lab in Marseille in 2021.

Compound-specific stable isotopes were analyzed in collaboration with researchers at **Université de La Rochelle in France**, and a joint publication is initiated.

Nansen Legacy researchers collaborate with scientists in many different countries, as indicated by the red lines on the map.

In 2021, Nansen Legacy and **Russian scientists from the Murmansk Marine Biological Institute**, **the Russian Federal Research Institute of Fisheries and Oceanography**, **the Murmansk State Technical University**, and **the Tomsk State University** published a review article of historical Russian data of polar cod in the eastern Barents Sea. The publication was co-financed by Equinor, and made important data sets available for the not Russian-speaking research community.

During several Nansen Legacy cruises in 2021, radiosonde weather balloons were launched in **close collaboration with the German Weather Service**. These observations contributed to improved weather forecasting and constitute valuable information for atmosphere research.

Nansen Legacy scientists **collaborate actively with the German Aerospace Center and German Research Centre for Geosciences** on investigating the potential use of global navigation satellite system signals for sea ice monitoring from ships.

Nansen Legacy postdoctoral researcher Doreen Kohlbach started a one-year stay at the **Alfred Wegener Institute Helmholtz Center for Polar and Marine Research** to conduct chemical analyses of organism samples.

Nansen Legacy scientists **collaborate with Japanese scientists from JAMSTEC** on calcium carbonate shell analyses, X-ray Microfocus CT (XMCT) analyses, and exchange of data and knowledge. A scoping webinar for expanding joint work was held together with JAMSTEC in 2021.

Nansen Legacy scientists continue **collaborating with researchers from the Institute of Oceanology of the Polish Academy of Sciences** on biodiversity samples as well as joint PhD student advisory committees.

Nansen Legacy postdoctoral researcher Katalin Blix spent large parts of 2021 at the **Balaton Limnological Research Institute** in Tihany, Hungary, for a 1-year data collection campaign. The campaign will enable machine learning algorithm development to capture high spatial and temporal variability of optically complex waters by using satellite technology.


Photo: Peter Leopold

Reviewing historical Russian data of the Arctic key species polar cod

A skinny polar bear on a melting ice floe – this picture vividly illustrates climate change in the Arctic. Yet, not only animals living on the ice lose their home by sea ice decline, also those under the ice may share their fate, like polar cod. This small fish is the most common fish species in the Arctic Ocean and a vital prey for sea birds, seals, larger fish, and whales. It is, however, unclear how declining sea ice cover and increasing anthropogenic activity will affect its future stock size.

Synthesis of 69 historical datasets

With antifreeze proteins in its blood, the up to 40 cm long polar cod is well adapted to icy waters. While polar cod feeds on zooplankton, it is itself an important prey for larger animals, indigenous people, and has even been commercially exploited. Hence, polar cod forms a crucial trophic link in Arctic marine food webs, and its stock size determines how much prey is available for top predators. The Barents Sea hosts one of the largest stocks of polar cod, located mainly in the seasonally ice-covered areas of the northern, northeastern, and eastern Barents Sea. As most of these waters are under Russian jurisdiction, much of the scientific literature about polar cod, its life stages, and its migration patterns has so far only been available in Russian. To overcome the language barrier, Equinor and the Nansen Legacy co-financed a Norwegian-Russian research initiative. In this initiative, Norwegian scientists collaborated closely with their Russian colleagues from the Murmansk Marine Biological Institute and the Russian Federal Research Institute of Fisheries and Oceanography. Together they digitalized and synthesized 69 separate historical (1935-2020) datasets on polar cod ecology, including maturation, fertility, feeding intensity, diet, lipid content, length-weight relationships, and seasonal variation in larval size.

Identifying knowledge gaps

The synthesis identified several knowledge gaps. Among others, researchers only have a rough idea of the migration patterns of polar cod larvae, young fish, and adults throughout the year. In addition, it is unclear to which degree polar cod depends on sea ice. It has commonly been assumed that polar cod spawns under sea ice or close to the ice edge, but Russian literature indicates that polar cod may also spawn in ice-free waters in warm years. However, it is unclear how many eggs successfully develop into adult fish in ice-free waters, because offspring may starve in open waters, or is more exposed to predators such as sea birds.

Why care about a small Arctic fish?

The Barents Sea is experiencing a vast reduction in sea ice as well as increasing water temperatures and human activities. However, the Barents Sea is also home to animals uniquely adapted to the Arctic environment. Sound and sustainable environmental management of the Barents Sea therefore requires in-depth knowledge of the biology and sensitivity of key species, such as polar cod. So far, researchers still know little about the migration patterns of polar cod and its dependency on sea ice, which are central knowledge gaps. Inaccurate assumptions on spawning areas and periods in impact assessment models may result in potentially improper protection measures in relation to hazardous human activities. The synthesis of historical Russian datasets on polar cod and identification of knowledge gaps is therefore an important contribution for knowledge-based management of the marine resources of the region.■

"The review documents knowledge gaps necessary to fill for effective management of ecosystems where polar cod plays an important role."

Magnus Aune, APN

Reference:
Aune M, Raskhozheva E, Andrade H, Augustine S, Bambulyak A, Camus L, **Carroll J**, Dolgov AV, **Hop H**, Moiseev D, **Renaud PE, Varpe Ø** (2021) Distribution and ecology of polar cod (*Boreogadus saida*) in the eastern Barents Sea: A review of historical literature. *Marine Environmental Research* 166: 105262.

During several of the Nansen Legacy cruises in 2021, radiosonde weather balloons were launched in close collaboration with the German Weather Service. These observations both contribute to improved weather forecasting and basic atmosphere research in the Nansen Legacy project. Another set of observations regularly conducted at all Nansen Legacy cruises were standardized sea ice observations from the observation deck above the bridge of *RV Kronprins Haakon*, including pictures of the ice situation. Several data collected during cruises in 2021 are available on Ice Watch.

Photo: Elizabeth Jones

Interactions with society

The Nansen Legacy is first and foremost a research project. However, the full value of a successful research project depends on its overall impact on society on shorter and longer time scales. To what extent can new knowledge help society to overcome the challenges posed by a rapidly changing climate and consecutive responses in the ecosystem? The Nansen Legacy interacts with society in several ways, and works towards synthesizing and communicating knowledge and results in a way that facilitates dialog with users also outside the science community.

Nansen Legacy scientists at COP26

The UN Climate Change Conference is the most important annual climate summit, bringing together all international parties to accelerate action towards the goals of the Paris Agreement and the UN Framework Convention on Climate Change. During the COP26 in Glasgow in 2021, Nansen Legacy scientists participated in different sessions. Nansen Legacy scientists Noel Keenlyside (UiB) and project leader Marit Reigstad (UiT) were part of the virtual panel debate "Ocean connections from the Arctic across the globe" in the Nordic Pavilion. Further, Nansen Legacy scientists Agneta Fransson (NPI) and Melissa Chierici (IMR) joined COP26 as experts on ocean acidification. Agneta presented aims and activities of the «Arctic hub», which is a part of the Global Ocean Acidification Observing Network. Melissa was a member of the discussion panel on ocean acidification in the northeast Atlantic, Arctic, and Baltic.

Nansen Legacy researchers joined two panel debates during the political festival in Arendal.
Photo: Stig Mathisen / NPI

Nansen Legacy scientists as ambassadors for the UN Decade of Ocean Science

Sustainable development is impossible without a healthy ocean. That is why the United Nations has proclaimed 2021-2030 the Decade of Ocean Science for Sustainable Development. Aiming at generating new scientific knowledge to improve the management of the oceans and coasts. Three Nansen Legacy researchers were appointed members of the Norwegian Ocean Decade committee, among them Nansen Legacy PhD student Julia Giebichenstein (UiO). The task of the committee is to ensure that Norway achieves the goal of the Ocean Decade. The committee provides advice, and is a strong ambassador for the Decade participating in various activities. The Nansen Legacy project is pleased to see that its scientists, and especially one of the many early career scientist, were invited to contribute and engage in this important mission.

The Norwegian Ocean Decade committee with Nansen Legacy PhD student Julia Giebichenstein to the upper left.
Photo: The Research Council of Norway

Arendalsuka

During the annual Norwegian political festival, Arendalsuka, political leaders, business leaders, entrepreneurs, and non-governmental organizations meet the wider society for an open debate, and in 2021 also scientists from Nansen Legacy were on board. Nansen Legacy scientists Sigrid Lind (NPI) and Johanna M. Aarflot (IMR) attended the Arendalsuka as experts in two panel debates arranged by the Norwegian Polar Institute. During these events, Sigrid and Johanna shared their understanding of the role of the Arctic Ocean in the Earth's climate system and the potential consequences for the ecosystem in a warmer Arctic with interested citizens. One of the events was focused on teenagers and thus the two Nansen Legacy scientists could discuss their most recent findings with the upcoming generation.

Science-to-policy workshop

Many researchers are increasingly motivated to engage with policy more directly to ensure that their research findings reach decision makers in a timely and policy-friendly form. However, identifying where, when, how, and at what level engagement is possible, and how research findings can find a way into policy priorities, can be challenging. Nansen Legacy postdoctoral fellow, Alun Jones (NTNU), joined forces with the CEO of the Arctic Monitoring and Assessment Program (AMAP), Rolf Rødven, and organized a workshop to address some of these challenges by identifying methods, approaches, barriers, and needs for effective science-policy engagement and impact. The workshop was held in connection with the Nansen Legacy's annual meeting in Trondheim and was well attended by researchers at all career stages, as well as members of the project's reference group. ■

Contributing to major status- and management reports

Nansen Legacy scientists - especially those working in management institutions - have contributed to several national and international status- and management reports on the ocean and climate state in 2021. This ensures a direct transfer of knowledge generated by the Nansen Legacy project into assessment reports used for management and policy making in Norway and worldwide.

Assessment of Particularly Valuable and Vulnerable Areas (SVO) in Norwegian seas
Fifteen Nansen Legacy researchers from five consortium institutions were involved in a new assessment of Particularly Valuable and Vulnerable Areas (SVO) in Norwegian seas. SVOs are areas of significant importance for biological diversity and production in the sea. Therefore, SVOs are part of the national management plan for Norwegian marine areas, and an important tool in the sustainable management and protection of marine resources. The Nansen Legacy researcher Elena Eriksen, Institute of Marine Research, led the report's editorial group.

EASAC report 'A sea of change: Europe's future in the Atlantic realm'
In June 2021, EASAC - the European Academies Science Advisory Council - published a report that synthesizes the underlying processes and trends of change in the Atlantic, and assesses how these changes affect Europe's climate, marine environment, and resources. The expert group behind the report was led by Nansen Legacy co-PI Tor Eldevik (UiB). EASAC is a collaboration of national science academies of the EU member states, Norway, Switzerland, and United Kingdom that provides independent science advice to European policy-makers.

Intergovernmental Panel on Climate Change (IPCC) Report AR6
In August 2021, the first part of the Sixth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) was released. It addresses the most up-to-date physical understanding of the climate system and climate change, bringing together the latest advances in climate science and combining multiple lines of evidence from paleoclimate, observations, process understanding, and global and regional climate simulations. Nansen Legacy members Sebastian Mernild (NERSC) and Sebastian Gerland (NPI) were lead authors in the Atlas and chapter 2, respectively, while Nansen Legacy early PhD student Jakob Dörr (UiB) was contributing author in chapter 9. Nansen Legacy scientists also contributed by reviewing draft versions of the report. Several publications produced by the Nansen Legacy are cited in the report.

CMEMS Ocean State Report
The Copernicus Marine Service Ocean State (CMEMS) Report is a reference report of the European Union. It provides a comprehensive and state-of-the art assessment of the state of the global ocean and European regional seas for the ocean scientific community as well as for policy and decision-makers. Nansen Legacy researcher Sigrid Lind (NPI) contributed to chapter 4 of the fifth Ocean State Report released in September 2021. The contribution states that despite low sea ice extent in the Arctic Ocean in 2019, the sea ice extent and ocean conditions were surprisingly normal in the Svalbard-Barents Sea region. This is explained by persistent northerly winds that caused an exceptionally large sea ice transport from the Arctic Ocean to the Barents Sea in 2019.

NSIDC Arctic Sea Ice Analysis and News
The National Snow and Ice Data Centre (NSIDC) provides monthly scientific analysis on Arctic sea ice conditions. In the September update, Nansen Legacy researchers Dmitry Divine, Sebastian Gerland, Adam Steer, and Sigrid Lind (all NPI) provided a summary of the melt season progress and sea ice conditions in the northern Barents Sea based on a series of Nansen Legacy research cruises to the region in 2021.

NOAA Arctic Report Card 2021
Nansen Legacy scientists Dmitry Divine, Sebastian Gerland, and Adam Steer (all NPI) contributed to the sea ice chapter of the NOAA Arctic Report Card 2021, with an update about changes in Arctic sea ice extent, age, thickness and volume. Results from Nansen Legacy observations were among the inputs to this report card chapter. The Arctic Report Card is a peer-reviewed source for environmental information on the current state of different components of the Arctic environmental system relative to historical records. The Report Card is intended for a wide audience, including scientists, teachers, students, decision-makers, and the general public interested in the Arctic environment and science.

Societal impact

The overarching goal for the Nansen Legacy project is to provide a better scientific basis for the sustainable management of the northern Barents Sea and the adjacent Arctic Ocean. The examples below illustrate some of the advances the project has made with improved model and forecast tools, new methodologies and improved predictive capabilities during 2021.

Improving marine forecasts

Reliable marine forecasts are a prerequisite for safe shipping, fishing, and tourism in the Arctic. Accurate forecasting systems require simulation of the Earth system (atmosphere, sea ice, ocean, and waves) on a kilometre-scale resolution. Nansen Legacy scientists have finalized a fully coupled atmosphere-wave forecasting system, which significantly improves the forecast accuracy for strong winds and large waves in the European Arctic. The Nansen Legacy is also involved in the development and application of cost effective, shipborne wave loggers, which provide needed field measurements of wave heights in the marginal ice zone.

Determining when to expect a year-round ice-free Barents Sea

An increasingly ice-free central and northern Barents Sea attracts an increasing level of human activity. Understanding the future evolution of sea ice in the Barents Sea is a prerequisite for adapting and planning of safe human operations in the region. A detailed comparison of several models suggests that the Barents Sea will become year-round ice-free towards the end of the century (2070 and beyond) independently of CO_2 emission scenarios.

Assessing the quality of sea ice edge forecast

The position of the sea ice edge is constantly moving due to wind and hydrographic conditions. Forecasts for sea ice expansion on synoptic timescales provide information essential for open ocean operations in the Arctic. However, the value of this information depends on the quality of the forecasts. A recently developed method allows now to examine the quality of forecasted sea ice expansion on sub-seasonal timescales.

Examine the basis for European and North American winter weather forecasts

Seasonal weather forecasts may assist scaling societal needs, such as disposition of water reserves or snow clearance services. Earlier research suggested that autumn sea ice concentrations in the Barents Sea could be used to predict the following winter weather in northern Europe and North America. However, a detailed study shows that Barents Sea autumn ice conditions and winter weather are not coupled, and consequently cannot be used for reliable seasonal winter weather forecasts.

Determining different possible states of the Barents Sea ecosystem

All ecosystems show a natural variability in their structure and function. Understanding this variability is important when assessing the potential effects of ecosystem drivers, such as climate change and fishery pressure. Modelling results suggest that the range of possible biomass configurations and trophic pathways in the Barents Sea food-web extends beyond what has been observed during the last three decades. Trophic controls appear to fluctuate at interdecadal time-scales. These fluctuations can be interpreted as an emergent property of stochastic trophic interactions.

Digitalizing and synthesizing historical Russian data

Understanding the variability of ecosystems and their potential response to climatic alterations requires long time-series of essential drivers and players of the ecosystem. For Arctic marine ecosystems, only few of these time-series exist. Securing and making available all existing data on Arctic ecosystems and key species is therefore of utmost importance. In collaboration with Russian researchers, the Nansen Legacy and Equinor have translated, digitalized, and synthesized 69 historical Russian datasets on the Arctic key species, polar cod, providing valuable information on the species life in the eastern Barents Sea between 1935 and 2020.

Developing a new tool for petroleum effect studies on Arctic key species

Polar cod is a key species in Arctic marine ecosystems and vulnerable to effects of pollutants, particularly from petroleum related activities. To facilitate studies investigating the effects of those pollutants, Nansen Legacy scientists developed a new method using the polar cod liver. First applications of the new method suggest that crude oil components activate certain metabolic pathways that may lead to reproductive disturbances in polar cod.

Mapping mercury concentrations in Barents Sea fish

The Barents Sea supports one of the richest fisheries in the world, and reliable knowledge on the concentration of pollutants in fish is therefore a matter of food security. Mercury in Arctic animals is well studied, but data from the winter are largely missing. Nansen Legacy investigations on polar cod, Atlantic cod, and capelin from the north-western and north-eastern Barents Sea showed mercury concentrations to be well below the toxicity threshold for fish health and the EU-accepted threshold for human consumption also during winter. ■

Photo: Christian Morel/ christianmorel.net

Overexploitation, recovery, and warming of the Barents Sea ecosystem

The Barents Sea ecosystem has experienced large variability in ocean climate and fishing pressure over the past seventy years. Both climate and fisheries are known to largely affect the structure and flow of energy through food webs. Hence, understanding how climate and fisheries have interacted and shaped the Barents Sea ecosystem in the past may aid sustainable management and fisheries in a warming world.

Preservation of the ecosystem's basic structure despite overexploitation

In the Barents Sea, fishing efforts and catches increased rapidly after 1945. The Norwegian spring spawning herring was the first fish stock to collapse due to overfishing in the 1960's, followed by collapses of other fish stocks the following two decades. During the same decades, the Barents Sea ecosystem also experienced cold and warm periods. Despite severe overexploitation and changes in climate, a new Nansen Legacy modelling study now suggests that the basic structure of the Barents Sea ecosystem seems to have been preserved during the periods of overexploitation and recovery.

The cold climate aided the preservation of the ecosystem's basic structure

This does not mean that overexploitation did not have a major impact on the Barents Sea ecosystem. The preservation of the ecosystem's basic structure was likely the result of several factors acting stabilizing in concert. Firstly, the post-war fisheries in the Barents Sea targeted and exploited several top-predators, causing severe reductions in the biomasses of marine mammals, large gadoids (e.g. Atlantic cod, haddock, and saithe), and long-lived fish like redfish and Greenland halibut. Secondly, the period of overexploitation of fish stocks coincided with a climatic cold period in the Barents Sea between 1960 to 1995. The broad exploitation of several top-predators contributed most likely to the lack of replacement of heavy exploited species by less exploited species. For example, redfish and Greenland halibut could have replaced Atlantic cod as major fish-eating predator at a time when the cod stock was overexploited. However, as the stocks of redfish and Greenland halibut were also heavily reduced, these two species could not take over the cod's place in the food web, leaving the niche open for the cod to fill as its stock recovered. The cold climate most likely enhanced this preserving process even further by preventing boreal species from expanding their geographical distribution northwards, and filling the ecological niche in the wake of overexploited fish stocks in the Barents Sea.

A warming Barents Sea

From the 1990's, many of exploited fish stocks in the Barents Sea recovered due to active fisheries management, and most likely well aided by the onset of a warmer period in the Barents Sea that caused increases in primary- and secondary production supporting the recruitment of the formerly overexploited fish stocks. The warmer ocean climate also favored more warm-adapted boreal species to establish larger stocks in the Barents Sea. Especially after 2000, krill became increasingly abundant, parly altering how energy is channeled through the Barents Sea food web. An important question is therefore if the Barents Sea ecosystem will show a similar stability and robustness in conserving its basic structure under further warming. Nansen Legacy scientists are using different numerical models to explore this question and to evaluate potential synergetic effects of fishery pressure and warming on the ecosystem's stability. The present work provides in this context an important baseline for evaluation of future ecosystem changes under increased Atlantification. ■

> "Despite periods of heavy exploitation, the basic ecosystem structure seems to have been preserved in the Barents Sea after 1950."

Torstein Pedersen, UiT

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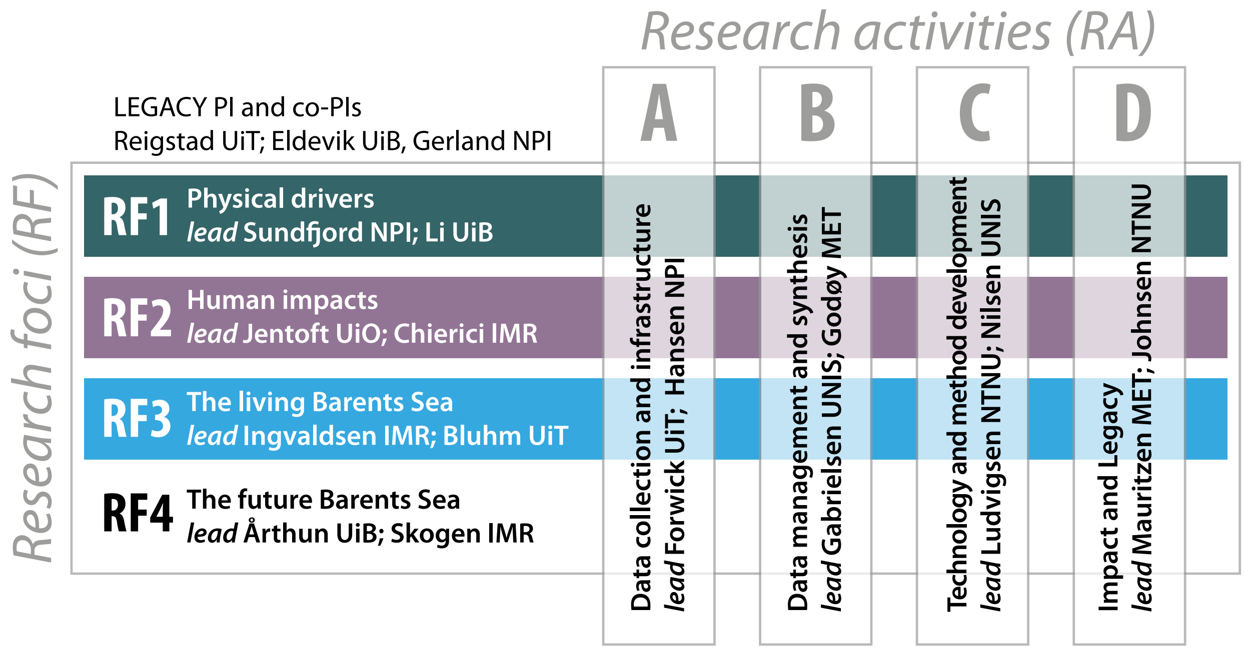
Pedersen T, Mikkelsen N, **Lindstrøm U**, **Renaud PE**, **Nascimento MC**, Blanchet M-A, Ellingsen IH, **Jørgensen LL**, Blanchet H (2021) Overexploitation, recovery, and warming of the Barents Sea ecosystem during 1950–2013. *Frontiers in Marine Science* 8: 732637

Leads are fractures of open water in areas otherwise covered by sea ice. Leads are hotspots in the exchange of heat and gases between the ocean and the atmosphere, as well as the formation of new sea ice. Therefore, dedicated measurements of ocean dynamics and gas exchange in leads were conducted during several Nansen Legacy research cruises. During the Arctic Basin expedition, Zoe Koenig (NPI) and Karen Assmann (IMR) used a kayak-catamaran to conduct measurements of the water column's properties in the middle of leads.
Photo: Agneta Fransson

Organisation

The Nansen Legacy is a collaboration between ten Norwegian research institutions, currently involving over 280 project members. Members include PhD 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).

RF1 Physical drivers

Arild Sundfjord, NPI

Camille Li, UiB

The Barents Sea is a significant gateway with inflow of Atlantic water to and Arctic water from the rapidly changing Arctic Ocean. A firm understanding of the physical climate system in this region is a fundamental building block for any sustainable management, and prognostic models for the Barents Sea and the adjacent Arctic. *Objective:* Determine contemporary and historical environmental conditions and internal regulation mechanisms, and based on this improve the understanding of physical system response to environmental changes.

RF2 Human impacts

Sissel Jentoft, UiO

Melissa Chierici, IMR

Arctic areas are exposed to climate change as well as other human influences, such as ocean acidification, pollution, and commercial fisheries. *Objective:* Improve our understanding of how human activities influence the northern Barents Sea ecosystem.

RF3 The living Barents Sea

Randi Ingvaldsen, IMR

Bodil Bluhm, UiT

Biodiversity, ecosystem functioning, and environmental forcing are inherently and intricately linked in any ecosystem, with their relationships shaped by region, habitat and temporal dynamic. *Objective:* Build critical understanding of how organisms in the northern Barents Sea ecosystem and adjacent slope respond to current and changing environmental conditions on the species and community levels by identifying characteristic communities, delineating the relevant environmental forcing factors that structure these communities across seasons and habitats, estimate their production and rate-limiting factors, and detail trophic and other ecosystem linkages.

RF4 The future Barents Sea

Marius Årthun, UiB

Morten Skogen, IMR

The sustainable management of resources and environment is fundamentally about foresight. It depends critically on our capacity to observe, understand and eventually predict the transitions between past, present and future states of weather, climate, and the marine ecosystem. *Objective:* Assess the state, predictability, and associated uncertainties of the Barents Sea weather, climate, and ecosystem.

RA-A Data collection and infrastructure


Matthias Forwick, UiT


Håvard Hansen, NPI

The Nansen Legacy carries out multi-disciplinary research using extensive ship-based field expeditions. This fieldwork is based on a coordinated use of the Norwegian research vessels, particularly the new Norwegian ice-going research vessel *RV Kronprins Haakon*. *Objective:* Facilitate, coordinate, and integrate the collection of new observational data, proxy data, and modeling output across the *Nansen Legacy* project.

RA-B Data management and synthesis


Tove Gabrielsen, UNIS/UiA


Øystein Godøy, MET

Structured data management is a pre-requisite for data exploitation; the act of exploration of the full potential of scientific data as individual datasets, in a discipline specific context, and in an interdisciplinary perspective. *Objective:* Ensure longterm preservation of all relevant data, with unified, open data access through services that provide for simplified data exchange and responsible data reuse, including proper attribution.

RA-C Technology and method development


Martin Ludvigsen, NTNU


Frank Nilsen, UNIS

Enabling technology for mapping and monitoring of extreme environments is essential for modern future management and sustainable utilization of the Barents Sea. Arctic conditions require a high degree of autonomy and integrated observation systems to reduce operation time and weather dependency, and to enable measurements in all seasons. *Objective:* Study and develop reliable and robust autonomous platform solutions for smarter measurements and sampling for detection and analysis, to improve modeling based on remote sensing with impacts on the ecosystem or human activity in the Barents Sea.

RA-D Impact and legacy


Cecilie Mauritzen, MET


Geir Johnsen, NTNU

A major task for the Nansen Legacy is to promote interest for and increase the general knowledge about Arctic marine systems. To accomplish this, it is necessary to reach out to the scientific community and the general public, to establish dialogue with users and stakeholders, to educate the next generation of scientists, and to enhance the focus on innovation as potential products of basic science. *Objective:* Ensure outstanding national and international impact from the research carried out, to ensure a lasting legacy of the project, and to enhance the benefit and relevance to society.

Nansen Legacy Annual meeting, October 2021. Photo: Maria Rossi

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5

Have you ever thought about how much you could find out about your neighbor by studying his garbage? Nansen Legacy researchers investigate the garbage of microalgae and zooplankton in the sea in order to learn more about the intricate pelagic food web and cycling of nutrients. As garbage bins for the pelagic trash the scientists use transparent cylinders that are deployed at different depths in the sea.
Photo: Christine Gawinski

Publications

By the end of 2021, the Nansen Legacy had published 89 peer-reviewed articles in renowned, high-ranking scientific journals, eight of them in Nature and Science journals. The majority of publications (83%) is available as open access. The cross-institutional spirit of the Nansen Legacy is reflected in the publications coming out from the project, with 60% of the articles having authors from two or more Nansen Legacy consortium partners. In addition to the 10 Nansen Legacy consortium institutions, the project's publications are co-authored by scientists from 13 Norwegian non-Nansen Legacy institutions. Additionally, 60% of the publications include international partners on the author list. These include scientists from 21 different countries and more than 60 different research institutions outside of Norway. Together, these numbers reflect the great collaborative spirit of the Nansen Legacy.

Peer-reviewed publications

2021

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Sea ice is a unique ecosystem, providing habitat to specialized ice-associated species. Many of these species live in channels and pockets within the ice, while others use the rough under-ice surface to feed and find shelter. Sampling the ice-associated fauna and flora from above the ice is challenging. Nansen Legacy used therefore underwater robots and divers to collect ice-associated organisms. On the picture, a diver uses a suction pump to catch crustaceans living at the underside of the ice during the Nansen Legacy Seasonal Cruise Q2 in May 2021.
Photo: Peter Leopold

The Nansen Legacy in numbers

7 years

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

280 people

Currently, there are about 230 researchers working with the Nansen Legacy, of which 73 are early career scientists. In addition, 50 persons are involved as technicians, project coordinators, communication advisers and board members.

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 institutions

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

>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.

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.

>350 days at sea

The Nansen Legacy has conducted 17 scientific cruises and spent more than 300 days in the northern Barents Sea and adjacent Arctic Ocean between 2018 and 2021. Most of these cruises were conducted on the new Norwegian research ice-breaker RV *Kronprins Haakon*.

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