The Nansen Legacy

Scientific exploration and sustainable management beyond the ice edge

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The *Nansen Legacy*

Scientific exploration
and sustainable management
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– scientific exploration and sustainable management beyond the ice edge

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Vision: *The* Nansen Legacy *is a novel and holistic Arctic research project that provides the integrated scientific knowledge base required for the sustainable management through the 21st century of the environment and marine resources of the Barents Sea and adjacent Arctic Basin.*

Motivation

An ice-free Arctic is gradually emerging. Wintertime sea ice retreat is to date most pronounced in the Barents Sea, the Atlantic gateway to the Arctic. The knowledge basis for sustainable management of this changing environment and the associated resources is an urgent scientific challenge. As sea-ice retreats and technology and infrastructure improve, it is imperative for the Norwegian research community to rise to the scientific and exploratory legacy of Fridtjof Nansen and move poleward through the Barents Sea.

The *Nansen Legacy* will pursue its vision by addressing the following overarching 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 operation of the changing Barents Sea ecosystems – 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.

Fridtjof Nansen overcame scientific and physical boundaries by challenging conventions, being unconstrained in his approach to science and to exploring nature in the field, and making full use of available human and logistical resources. The *Nansen Legacy* is the Norwegian Arctic research community's joint, concrete, and ambitious plan to follow Nansen's example and fundamentally contribute to future marine resource management at Norway's gateway to the Arctic (cf. Fig. 1, Tab. 1, and the "roadmap" of Fact Box 1). The *Nansen Legacy* constitutes an integrated Arctic perspective on climate and ecosystem change—from physical processes to living resources and from understanding the past to predicting the future. The *Nansen Legacy* will result in an unprecedented scientific basis for long-term, holistic, and sustainable management of marine ecosystems and human presence in the emerging oceans of the high Arctic.

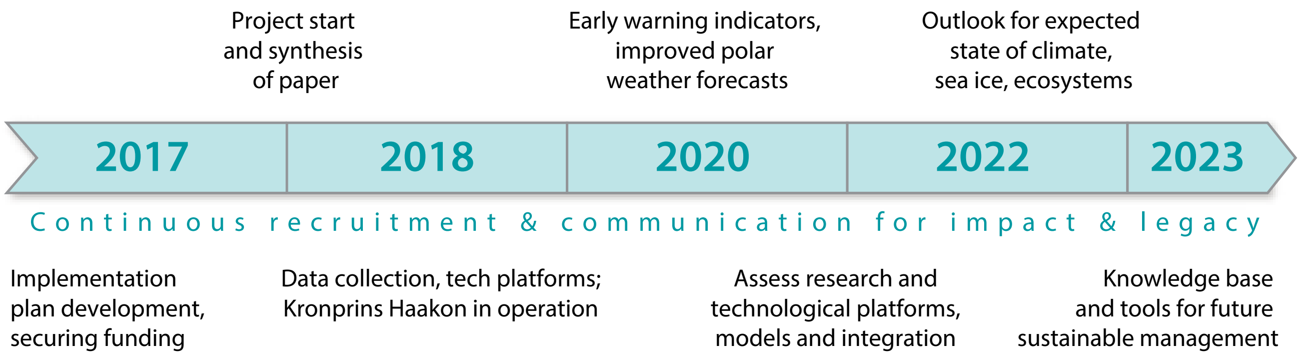

Figure 1. Overall timeline for the *Nansen Legacy* project

Table 1. The eight Norwegian governmental and two private research institutions comprising the *Nansen Legacy* consortium, in alphabetical order.

The *Nansen Legacy* team partners	
Akvaplan-Niva (APN)	The Norwegian Meteorological Institute (MET)
Institute of Marine Research (IMR)	The University Centre in Svalbard (UNIS)
Nansen Environmental and Remote Sensing Center (NERSC)	UiT The Arctic University of Norway (UiT)
Norwegian Polar Institute (NPI)	University of Bergen (UiB)
Norwegian University of Science and Technology (NTNU)	University of Oslo (UiO)

The scientific investigation of a rapidly changing northern environment leads to research questions of such intellectual, empirical and logistical complexity—and of such importance to the management of national resources and associated international obligations—that they can only be addressed properly through **national and prioritized cooperation, with the highest scientific standards.**

A dedicated Norwegian national team of research excellence has accordingly been assembled for the purpose of a 6-year long project, The *Nansen Legacy* (Fig.1). The team reflects the complimentary scientific and logistic capabilities of all eight universities and governmental institutions dedicated to Arctic research (Table 1), and research in the Barents Sea region in particular. Through this concept where the institutions **collaborate**, **assign** and **specialize** (Norwegian government's **SAK** concept; **S**amarbeid–Collaborate; **A**rbeidsdeling–Assign; **K**onsentrasjon–Specialize, NOU 2008:3. All in all. New structure in higher education), the resulting synergy will enable building the necessary integrated knowledge base for a future adaptive and sustainable management. In addition to the governmental institutions, two private research companies have recently been added to include relevant and complementary expertise.

The *Nansen Legacy* consortium was particularly established to meet knowledge gaps, by realizing the SAK potential in Norwegian Arctic marine research, and the precondition for the present proposal was the consortium's *Nansen Legacy* science plan (Eldevik et al. 2014a). The original *Nansen Legacy* Science plan was further developed into a proposal to the Ministry of Science and Education and evaluated by an international evaluation panel (lead by members of the National Academy of Sciences) in early 2016. Excellent reviews and recommendations[1] motivated the commitment from all involved institutions to provide a 50% in-kind contribution, and a pre-project to prepare the realization of the project including the development of this extended proposal was funded by the Research Council of Norway in 2017. With the new ice-going research vessel *Kronprins Haakon*, operational from 2018, Norway will have research vessels with the capability to carry out logistically challenging and important fieldwork. This will allow synoptic collection of data related to climate and ecosystems throughout the Barents Sea and into the Arctic Basin, both in summer and in the poorly investigated winter (Fig. 2).

The *Nansen Legacy* project will collaborate with relevant national and international research projects and initiatives to utilize complementary knowledge, share infrastructure, increase the scientific outcome and strengthen science networks (see Letters of Collaboration). It is accordingly now both timely and possible to move north.

The *Nansen Legacy* will produce the following *scientific, societal, and end-user impacts and legacy*: establish a holistic "ground truth" for the environment and ecosystem in the northern Barents Sea and adjacent Arctic Ocean; provide a 2020–2100 outlook for the expected state of climate, sea ice, and ecosystem, including near-term pre-

1 The *Nansen Legacy* evaluation report is accessible for download at the *Nansen Legacy* web page (About/download) at site.uit.no/nansenlegacy

dictions; to evaluate sensitivity and functionality of early-warning indicators used to detect change in marine resources and their vulnerability to exploitation; allow reliable polar weather forecasts for the safety of people and commercial operations. Another core legacy will be the recruitment and training of the next generation of trained cross-disciplinary researchers, with a unique national and international network. The *Nansen Legacy* will improve, secure and operationalize national data archives and ensure open data availability in accordance with national and international standards. Overall, the legacy and societal impact will be the scientific knowledge base needed for sustainable resource management in the transitional Barents Sea and adjacent Arctic Basin.

FACT BOX 1: The *Nansen Legacy* proposal – *a roadmap*

The present document is admittedly an extremely compact – but hopefully also consistent – description of an equally ambitious and resource-demanding six-year national research effort. A roadmap is therefore maybe useful to guide the reader with respect to content and intentions. The proposal is organized as follows.

The introduction offers the project vision and overarching objectives on the background of a general motivation and the urgency of a changing Arctic, but also importantly contextualization of the proposal in the realm of Norwegian research priorities and cooperative potential, and how the consortium and present proposal have been realised through consistent and collaborative national effort since 2012.

Section 1 offers justification for a dedicated, large-scale research effort in the Barents Sea and neighbouring Arctic domain. It describes state-of-the-art scientific understanding of the region, and from this outlines the novelty of what is proposed herein, including the latter's strategic foundation in Norwegian and international white papers, research priorities, and the practical, economical, and societal challenges associated with sustainable management of a changing Arctic, a compliance that is further detailed in Section 5.

The specific outline and description of the scientific programme accordingly spanned out by the four research foci (RFs; Section 1.5) are followed by the consequent organization of the RFs and crosscutting research activities (RAs) into an actual project (Section 2), resonating with the overall project structure visualized in Fig. 5. A broad timeline for the project period 2017–2023 is provided initially (Fig. 1), whereas more detailed timing is presented in Section 2.4, including completion of overall RF and RA deliverables, and the timeline for project fieldwork and distribution of ship time (Fig. 7).

Project organization – including leadership, partners, internal and external means of cooperation, and the scientific advisory board – is described in Section 3. Section 4 provides a summary of the funding framework and proposed total budget (provided + in-kind).

Project impact and legacy are the content of RA-D (Section 2.3.4), and further elaborated in Section 5 and the Communication plan (Appendix iv).

Means of reassessment or taking corrective actions will be evaluated throughout the project period (in project leadership 3.1.3).

Please note that further information concerning infrastructure overview and model inventories are found in Appendices i and ii, respectively. Key milestones and timetable is given in the on-line application form, and the data management is outlined and specified in RA-B and the Data Management Plan (Appendix iii)). An overarching budget is given in the on-line application form, while more specified budgets and costs distributions are given in Appendix v.

1. The *Nansen Legacy* research – Challenges, strategies and research foci

1.1 The need for pioneering research to allow for knowledge-based Arctic Ocean management

Global warming is arguably most pronounced in the Arctic (AMAP 2017). The Barents Sea is at the heart of this change (Fig. 2 and Fact Box 2; Wassmann et al. 2011; Smedsrud et al. 2013; Hollowed and Sundby 2014), and 92% of the year-to-year variance in the entire Arctic sea ice extent in winter is essentially explained by how far the ice extends into the Barents Sea (Onarheim et al. 2015). Directly related to this change is an expected increase in human presence and commercial exploitation in the region. The Barents Sea hosts Norway's richest commercial fisheries and contains unexplored petroleum and mineral resources. These issues have spurred much recent scientific and political discussions of broad societal relevance, including a) the potential extension of commercial fisheries deeper into the Arctic Ocean (Cheung et al. 2010; Ingvaldsen et al. 2015; Haug et al. 2017), b) where the Norwegian government's regulatory definition of the Barents Sea ice edge (and limit for hydrocarbon exploration) should be (Steinberg and Kristoffersen 2017), and c) the actual predictability of northern climate (e.g., Årthun et al. 2017) and Barents Sea ice extent (e.g., Nakanowatari et al. 2014; Onarheim et al. 2015).

FACT BOX 2: The Barents Sea region – a brief overview

The Barents Sea is one of the two inflow shelf seas of the Arctic Basin (Carmack and Wassmann 2006; the other being the more shallow Chukchi Shelf on the Pacific side), located between 72-81°N and 15-60°E. It has an average depth of 230 m. The border between Norway and Russia separates the Barents Sea into an eastern Russian and western Norwegian sector. The Atlantic Water (AW) inflow from the south and the fresher Arctic Water (ArW) and sea ice entering the Barents Sea from the Nansen Basin in the north, are separated by the Polar Front, and give rise to the dual bio-physical nature of the southern and northern Barents Sea (Nansen 1920; Loeng 1991; Reigstad et al. 2002; Haug et al. 2017; Fig. 2). Being located in this transition zone between the sub-Arctic and the Arctic, the Barents Sea represents the ultimate site for investigating the impact of climate change on the marine ecosystem, e.g., using transects through the climatically diverse region as a space-for time-approach (Hurlbert et al. 1984). The southern Barents Sea environment and ecosystem is quite well known, a systematic knowledge that was pioneered by the Pro Mare research program of the 1980s (Sakshaug et al. 1992). The northern and winter-ice covered region is far less investigated and understood, and is at present also experiencing the greatest changes, for example in increase in days with open water and presence of fall blooms (Ardyna et al. 2014; Arrigo and van Dijken 2015).

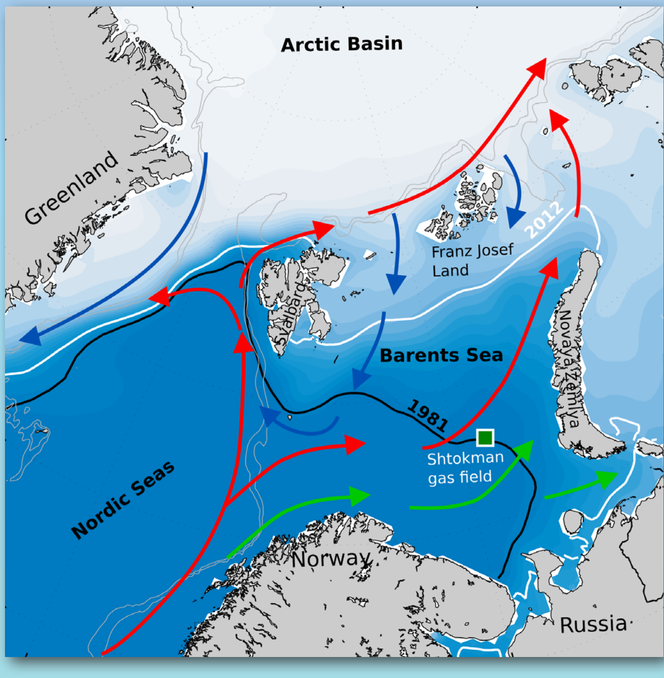

Figure 2. The two biophysical regions of the Barents Sea characterized by a dynamic winter sea ice cover in north, and open water in the south-west. The variable ice distribution is exemplified with the 1981 (black line) and 2012 (white line) extent, based on wintertime average (Nov-April) of satellite observations. The color shading indicates sea ice concentration climatology. The ice distribution is to a large degree determined by the Atlantic Water inflow (Onarheim et al. 2015) and topographically steered currents, with Atlantic Water (AW) entering the Barents Sea from the Nordic Seas in south-west (**red arrows**), and the Arctic Water (ArW) entering the Barents Sea shelf from the Arctic Basin in the north (**blue arrows**). The Norwegian Coastal Current (NCC, **green arrows**) transports freshwater to the Barents Sea and further into the Kara Sea. (Illustration M. Årthun, UiB).

The Barents Sea experiences strong seasonality with winter sea ice cover in the north and the Polar night lasting for several months. During parts of the spring and summer, the midnight sun provides light and productive conditions 24 hours a day. One branch of the North Atlantic Current goes into, and follows the topography within and partly through the Barents Sea. It is a main region for transformation AW subsequently entering the Arctic Ocean (Rudels 2015, and refs therein). On its way through the Barents Sea, a branch of the AW subducts below the fresher ArW entering from north. This results in a complex hydrography in the northern Barents Sea, with an insolating ArW layer separating a warm AW layer from the sea ice (Lind et al. 2016). Water mass transformation from heat loss, change in salinity from local ice formation or mixture with less saline coastal water, greatly affects hydrography. Advection of carbon and organic matter from the productive shelf to the deep Arctic Basin has great impact on the biogeochemical supply to the Arctic Basin (Fransson et al. 2000; Smedsrud et al. 2013).

At present, an "atlantification" of the European Arctic regions (Wassmann 2004; Polyakov et al. 2017) opens for changes along multiple scales in this dual biophysical region. A pioneering holistic approach to establish the status of and identify the potential responses to these multiple changes is therefore required in this region.

Among the Arctic coastal state governments, Norway pioneers the development of integrated, ecosystem-based management regimes (i.e. Management plan for Lofoten and the Barents Sea 2006, with updates 2010/11, and 2017 in prep). Such management plans are used for all Norwegian maritime areas, and a corner stone to meet international agreements. Knowledge-based management is an important principle, and with the Scientific Forum (In Norwegian: Faglig forum) identifying and keeping inventory of knowledge gaps.

Management plans need to be implemented and followed up systematically and flexibly on the basis of, e.g., new knowledge, changes in activity levels, and environmental change. The *Nansen Legacy* will address central knowledge gaps identified and given priority by the updated Management plan 2010 (Scientific Forum report Chapter 9.9 Priority of knowledge gaps). The Barents Sea Surveillance group (responsible for The Norwegian and Barents Sea Management plans) and Scientific Forum (responsible for knowledge status and gaps) are advisory groups under different governmental directorates. By including them in the *Nansen Legacy* User and Stakeholder group, with mandate to advise to the project board and leader group, a dialogue is facilitated that can give the very basis for decision making from new knowledge on present state and future trends in the northern Barents Sea and the Arctic Basin beyond. A close connection to Arctic Council, ICES and IPCC based working groups (see details in Section 3.5.7) also ensures dissemination to international bodies.

The joint Norwegian-Russian knowledge-based fisheries management in the Barents Sea has been successful in supporting sustainable fisheries. Active management and climate may both accommodate the future exploitation of high latitude marine resources (Kjesbu et al. 2014). Observations of species' response to changing environmental conditions, both on the species and community levels, are increasing (Wassmann et al. 2011; Kortsch et al. 2015), including harvestable species that spread northward (Mueter et al. 2009; Logerwell et al.; 2015; Haug et al. 2017). The expanding habitat of established species like the North Atlantic cod, and the arrival of new harvestable species like the invasive snow crab change the ecosystem in the northern Barents Sea (Fossheim et al. 2015; ICES WGIBAR 2016; Hvingel et al. 2017). Our knowledge of how they in combination with environmental changes will impact the productivity, pelagic, and benthic ecosystem functions, the species interactions and biogeochemical cycling, is nevertheless poor. **The need to understand these multifaceted and entangled responses calls for pioneering work combining a multitude of disciplines, scales and approaches.**

More than 100 years ago, Helland-Hansen and Nansen (1909) envisioned a northern maritime climate and ecosystem that were predictable, both in terms of temperatures, extent of sea ice and catches of fish (e.g., from observing that air temperature and catchment during wintertime Lofoten fisheries appeared preconditioned from upstream ocean temperature in the Norwegian Sea the preceeding summer). The *Nansen Legacy* consortium is confident that now is the time to address the pressing scientific and practical questions that need to be answered in order to provide a robust scientific basis for the future ecosystem-based management and improved weather-to-climate predictions of the northern Barents Sea and emerging Arctic Ocean.

1.2 Status and challenges

Large-scale patterns of Arctic climate change and responses seen are to a large extent present, and even enhanced in the Barents Sea, being both an Atlantic Water gateway to the Arctic Basin and at the receiving end of sea ice export from the Arctic Ocean. Climate change is therefore ubiquitous in the *Nansen Legacy* target region (Fig. 2); increased heat transport with Atlantic Water has caused up to 50% reduction in sea ice cover in the 1998–2008 period (Årthun et al. 2012). However, variability in the properties of an insulating intermediate Arctic Water layer between sea ice and warm Atlantic water can vary the effect of Atlantic Water on regional sea ice evolution (cf. Fact Box 2; Lind et al. 2016). Recently, this effect explained as increased "atlantification" (Wassmann 2004) characterized by weaker stratification and more shallow distribution of the warmer Atlantic Water, is observed as far into the Arctic Basin as to the eastern Nansen Basin (Polyakov et al. 2017), with increased heat exchange and thinner and younger sea ice. This thinner ice accelerates the sea ice drift and transport, also into the northern Barents Sea (Rampal et al. 2011).

Changes in the physical environment transfer to the organisms and ecosystems, seen across the Arctic, reflected in changed distribution and composition of species and communities (Mueter and Litzov 2008; Li et al. 2009; Wassmann et al. 2011; Haug et al. 2017). How the interactions of environmental change, with human impact through fish harvesting and intrinsic ecosystem processes, affect marine resources and energy flow in the Arctic and Barents Sea food webs, particularly beyond the present ice edge, is still largely unknown (Drinkwater et al. 2010; Overland et al. 2010; Ortiz et al. 2016). Similarly, it is poorly understood how ecological effects of pollutants, e.g., from petroleum activities, respond with respect to bioaccumulation and food web transfer in combination with change in climate (UNEP/AMAP 2011; AMAP 2016).

Adding to these, ocean acidification represents an increasing major influence on Arctic ecosystems CO_2 levels rise (Mathis et al. 2015). As one of the high-productive Arctic shelf seas, the Barents Sea plays a large-scale role in Arctic biogeochemical cycling and carbon transport. As a carbon sink, and under-saturated in CO_2 year round for example, the Barents Sea's increasing uptake of CO_2 not only leads to ocean acidification, but also to the transport of CO_2 from the Barents Sea surface waters into greater depths of the Arctic Basin (Omar et al. 2007; Lischka et al. 2011). Processes within the sea ice are also likely to sustain CO_2 under-saturation in surface waters (Fransson et al. 2017). Through this and other exchange and feedback mechanisms, regional conditions in the Barents Sea (e.g., sea-ice thickness; King et al. 2017) can influence the large-scale climate system (Smedsrud et al. 2013), both within the Arctic and more globally (Bengtsson et al. 2004; Yang and Christensen 2012), possibly including mid-latitude weather (Francis and Vavrus 2012; Cohen et al. 2014; Sorokina et al. 2016).

The present climate and ecosystem of the productive southern Barents Sea is relatively well-surveyed and understood (Sakshaug et al. 2009). This understanding has been much elaborated recently, e.g., with respect to climate (Smedsrud et al. 2013), biomass and productivity (Dalpadado et al. 2014), ecosystem and carbon fluxes (Wassmann et al. 2006; 2015), and the impact of sea ice change on biology and human activity (Meier et al. 2014). The situation is different for the winter ice-covered northern Barents Sea shelf and adjacent Arctic Basin. Here, recent knowledge has only just begun to highlight the impact of changing physical conditions on the living Barents Sea, through, e.g., productivity, ecosystem function, and distribution of fish species (Reigstad et al. 2011; Kortsch et al. 2015; Haug et al. 2017). Most of this emerging knowledge is based on Norwegian-Russian autumn management surveys, with focus on biomass distribution and community composition of harvestable species and their main prey (Eriksen et al. 2017), but with major gaps in process measurements, community composition and food web transfer on lower trophic levels and non-harvestable species and in seasonal coverage.

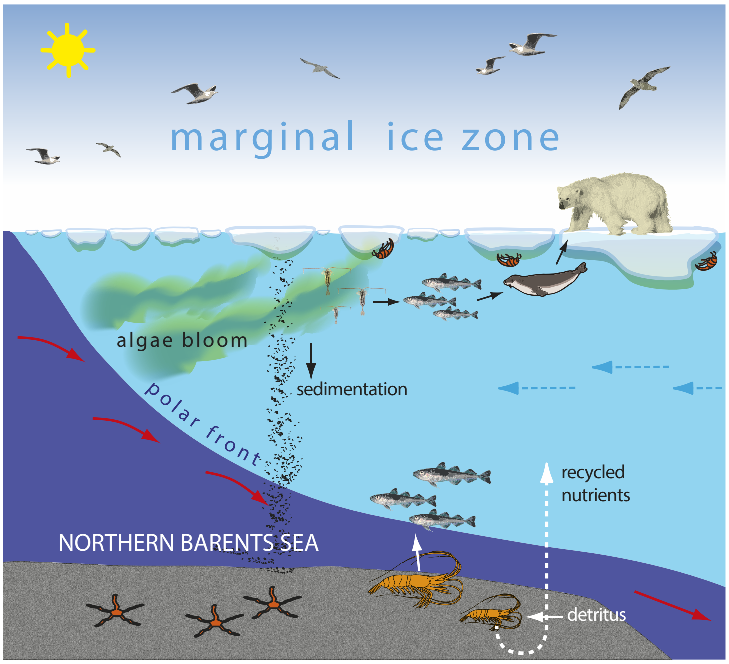

Figure 3. The Barents Sea ecosystem and marginal ice zone across the Polar Front from the temperate North Atlantic (left, red arrows) to the freezing Arctic Ocean (right, blue arrows), and from the shelf (left and center) to the basin (far right) (illustration M. Reigstad/R. Caeyers, UiT).

Several substantial changes have occurred at the base of the food web in this region (Fig. 3). The productive season has prolonged by 10-15 days (Arrigo and van Dijken 2015), early pelagic under-ice blooms have been observed (Assmy et al. 2017), and the presence of autumn blooms has increased by 70% in the last decade (Ardyna et al. 2014). The steepest increase in chlorophyll-*a* concentrations over the years 2003–2016 for the entire Arctic have occurred during May in localized areas of the Barents Sea, with an overall positive trend averaging ~0.79 mg m-3 yr-1 (Frey et al. 2017). Resource surveys show that boreal generalist fish species are replacing more specialized Arctic fishes in the north (Fossheim et al. 2015; Kortsch et al. 2015). Fundamental changes in biogeochemical cycling, metabolic rates and partitioning of productivity are expected in northern parts of the living Barents Sea as global warming continues (Reigstad et al. 2011; Holding et al. 2015; Tremblay et al. 2015; Mesa et al. 2017), but the responses of organisms and food webs, as well as the combined responses to multiple stressors, remain poorly known (Michel et al. 2013).

Recently, major advances have been made in the Barents Sea with respect to forecasting regional climate conditions on timescales from months to decades (cf. Årthun et al. 2017; Yeager and Robson 2017). Adding to this, more specific and realistic projections of future ecosystem scenarios are being developed, building on the emerging predictive capability for the relatively near future and the increasingly more detailed climate scenario projections spanning the 21st century (e.g., Planque et al. 2014; Skaret et al. 2014; Slagstad et al. 2015). Such advances need to be expanded to or improved within the region of interest, including the most practical and immediate concern for more reliable weather forecasts. Predicting future responses in the northern Barents Sea and adjacent Arctic Basin ecosystems requires more region-specific observations and knowledge of climate-organism response than available at present. The important addition of paleo-records from the northern Barents Sea region will provide necessary validation data for climate reconstruction models and show the variability and drivers throughout the Holocene, indicating a range of possible present and future changes (Slubowska-Woldengen 2008; Eldevik et al. 2014b). Another area of active research is investigating how much Arctic changes influence the rest of world, compared to the more well-known pathways by which the tropics and midlatitudes influence the Arctic (Overland et al. 2016, Shepherd et al. 2016).

Important issues to address include the identification of the major drivers and mechanisms regulating the physical environment, and how the biological communities and related processes in the ecosystem respond to these. A recent study in the Bering Sea identified wind stress and air temperature as major biophysical drivers (Hermann et al. 2016), while for the North Atlantic a multiple effect of mixed layer depth, light and macronutrients where main drivers for a Poleward shift of phytoplankton species (Barton et al. 2016). The combined effects of human activities, including fisheries, hydrocarbon exploration, and shipping, also need to be understood to provide a knowledge base for predictive capability.

The understanding of high-latitude climates and how their ecosystems are changing remains inadequate, and challenges the use of established tools for the sustainable ecosystem management of the Barents Sea. Advection from the subarctic into the northern Barents Sea and the Arctic Ocean form a lengthy contiguous domain (Wassmann et al. 2015) supporting large seasonal migrations of fish, marine mammals and seabirds (Haug et al. 2017). These organisms travel long distances to utilize the high food concentrations resulting from the seasonal ice zone algal production to feed, breed or build up energy stores (Sakshaug et al. 2009). These advective regimes seen at both the Barents and the Bering inflow shelves, fuel life in the Arctic Ocean (Bluhm et al. 2015; Wassmann et al. 2015; Hunt et al. 2016). In turn, the Arctic influences the physical, chemical and biological oceanography of adjacent subarctic waters through southward fluxes. The advective pathways or migration routes extend the regional influence to contiguous domains (Wassmann et al. 2015) beyond the region of present observations. **To understand the Pan-Arctic functions and connections, there is an urgent need for region-specific knowledge**.

On the Pacific side, the ongoing Synthesis Of Arctic Research (SOAR) established a "new normal" for the present biophysical conditions in the Pacific Arctic Chukchi and Beaufort Seas (Moore and Stabeno 2015) and the US national Bering Sea project (2007-2014) has conducted a comparatively large Arctic shelf ecosystem investigation which provided current knowledge on the Bering Sea (Deep Sea Research II special issues in 2012 - 2016). Such extensive efforts have not yet taken place in the northern Barents region, but through dedicated region-specific studies and by comparing systems across the Pan-Arctic domain, we aim to understand similarities and differences in physical drivers and ecosystem responses that will help us understand the heterogeneous Arctic marine region.

1.3 Strategic foundation

The *Nansen Legacy* assesses physical drivers, human impacts and resulting ecological responses. Our holistic scientific framework will lead to prognostic capabilities required for future sustainable management. The *Nansen Legacy* meets the needs and tasks of relevant national and international Arctic-focused strategic plans and identified knowledge gaps including better observations over time, integration across biological and physical spheres, use of coupled model systems, open data policy and link to international data sharing initiatives (Sustained Arctic Observation Network SAON via Svalbard Integrated Arctic Earth Observing System SIOS, and dedicated communication of science to policy makers and users; for specific national and international strategies, see Section 5).

The *Nansen Legacy* is designed to meet stakeholder needs – the Lloyd's report on *Arctic Opening; Opportunity and Risks in the High North* (2012) for example highlights the urgent need to close knowledge gaps on environmental changes and responses in order to prepare for risk assessments needed to safely increase human activities in the Arctic. Initiatives by the Arctic Council (e.g., *Circumpolar Biodiversity Monitoring Program* CBMP; follow up of the assessment *Snow, Water, Ice and Permafrost in the Arctic SWIPA, under AMAP 2017;* the reports by AMAP for Arctic Ocean Acidification, and Adaptation Actions for a Changing Arctic AACA, especially herein the part on the Barents region), also call for more observations and synthesis of regional and pan-Arctic ecosystems and the development of tools for adaptation to changes.

The *Nansen Legacy* thus resonates with strategic white papers nationally and internationally, builds on and extends exciting science capabilities, and is at the same time rooted in stakeholder needs. This unique mix distinguishes The *Nansen Legacy* from research traditionally supported by Norwegian funding agencies. Furthermore The *Nansen Legacy* will be *the* merging activity for Arctic marine research involving Norway's leading universities and institutes with expected positive effects for decades to come. Through the consortium's open data policy and close collaboration with SIOS the *Nansen Legacy* project will operationalize the data accessibility across disciplines and institutions.

1.4 Novelty

The *Nansen Legacy* will constitute the collective Norwegian **Arctic marine research platform** that unites national competence and provides a collaborative partner both nationally and internationally. **The holistic approach** will be achieved through the cooperation and the complementarity of the participating institutions combining scientific expertise, disciplines, approaches, perspectives and infrastructure to an unprecedented extent for the Norwegian research community.

The *Nansen Legacy* team is **purposefully interdisciplinary** including physical, chemical, and biological researchers from eight core Norwegian institutions, and two research institutes. The institutions include universities with basic research and educational expertise, management oriented institutions, the national weather service, and research institutes with close collaboration with industrial partners. The joint effort offers a human capacity of 3590 person months, corresponding to 50 full time positions of dedicated scientific or supportive man-power in a 6-year period.

Up-to-date infrastructure, instrumentation, analytical and experimental facilities from the majority of the Norwegian University- and marine research communities are included in the project, and will be utilized across institutions and RF/RAs where relevant.

Over 370 days of ship time, primarily using the new Norwegian ice-going research vessel *Kronprins Haakon* allow for collecting unique, synoptic and interdisciplinary seasonal and inter-annual time series data. Beyond-the-state-of-the-art features of this vessel include specialized laboratories with cooling and freezing laboratories for experimental work, a moon-pool for deployment of instruments at high sea or in close pack-ice, a helicopter platform, two sinking keels with the most updated acoustic instrumentation, facilities for sediment coring, trawling, and use of autonomous vehicles.

The *Nansen Legacy* field component will use a **combination of ship-based, moored, and autonomous technological platforms**. Development, testing and application of novel advanced technology and combinations of these in ice-covered regions, will allow high resolution observations to be a core activity that will increase future observational capabilities. The unique collaboration of project partner NTNU who is focused on development of cutting-edge technology with the Arctic-experienced partner institutions ensures that operational needs specific to high latitude applications feed directly into the development process.

The consortium's prognostic expertise in, e.g., **weather forecasts and climate projections, combined with paleo-oceanographic reconstructions** constraining environmental change through the Holocene, will allow collected data on present conditions to be placed in context with the past to explore the future, and will bring the *Nansen Legacy*'s environmental and ecosystem studies beyond both the present ice edge and state-of-the-art. The consortium will build on existing operational competence to improve in communication with stakeholders on future scenarios for the state of the Barents Sea and Arctic, associated uncertainties, and practical implications.

The *Nansen Legacy* coherently **brings together the national model capability** ranging from general circulation models (GCMs; from weather to climate) – via GCMs coupled with biogeochemistry or more dedicated biological models – to non-deterministic food-web models (Fact Box 3 Assessing the future Barents Sea, Section 2.2.4; and model inventory overview Appendix ii). **An ultimate goal is to realize the prognostic potential** skillfully and routinely in numerical models. This is particularly important given the general complexity of interactions in the separate and coupled physical and biological domains in a generically under-observed Arctic (that will remain so for the foreseeable future).

The use of **sharp environmental gradients** across the Barents Sea, from the Atlantic to the sea ice impacted Arctic influenced shelf, and into the deep Arctic Basin (Figs. 2, 6), allows studies of ecosystem responses on organism, community, and process levels under variable environmental and anthropogenic forcing conditions.

Multi-stressors represent the new challenging scenario in many Arctic regions, and the effect on the living Barents Sea will be investigated through for example combined effect of temperature, contaminants and ocean acidification.

The *Nansen Legacy* project builds on a **long tradition of Norwegian Arctic and Barents Sea research** including Nansen's *FRAM drift,* the *PRO* MARE program; Norway's contribution to the IPY 2007– 08, and links novel approaches in several aspects. In contrast to *ongoing national long-term monitoring efforts by e.g. NPI and IMR*, and shorter research projects, the *Nansen Legacy* has a six-year timeframe, with five years of intense interdisciplinary field investigations starting in 2018.

A new generation of scientists will experience a unique collaborative community and supervision across institutions and disciplines, and with practical integration in the field and through mobility resulting in national and international networks opening for new and innovative approaches, providing scientific and organizational foundation for future Arctic research leaders.

1.5 Research Foci (RF) – the scientific program

The *Nansen Legacy* will conduct a detailed end-to-end investigation – from physics to fisheries – along the climatic gradient from an Atlantic to an Arctic marine environment and ecosystem. With a research team capable of investigating characteristics and processes across time- and spatial scales, both disciplinary and interdisciplinary, the *Nansen Legacy* will reach a more holistic understanding of the northern Barents Sea and adjacent Arctic Basin atmosphere-ice-ocean physics and biological-biochemical-chemical system than what has been possible to date from more standard (yet high quality), but fragmented, research initiatives.

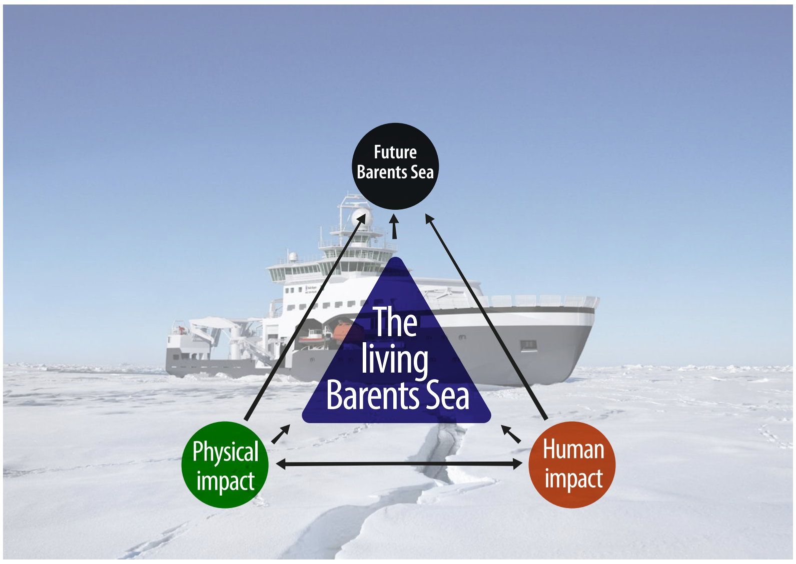

Figure 4. ***The Nansen Legacy* project structure** reflects a holistic perspective on how the living Barents Sea respond to the physical drivers and human impact, and the considerable changes seen at present – represented with the space for time approach along the Barents Sea climatic gradient. Based on Research Foci addressing the understanding of processes and mechanisms, potential and constraints for its future state can be outlined. The new ice going research vessel *Kronprins Haakon* (in the background) will be a core infrastructure allowing sampling in ice covered areas during winter and into the Arctic Basin.

To enable both disciplinary expertise and integrative focus, the project is organized and coordinated through four clearly defined Research Foci (RFs) which are conducted and integrated through four crosscutting Research Activities (RAs). The four RFs will provide observations, experiments and models for the Barents Sea to assess the physical state of the Barents Sea (RF1), determine specific human impacts (RF2), evaluate the ecosystem structure (RF3) and strengthen the predictive capabilities (RF4). This structure was chosen as *the living Barents Sea* evolves internally and under the combined influence of *physical drivers* and *human impacts*, and the assessment of these drivers and impact on the organisms, the biogeochemical cycling and the ecosystem in the *Living Barents Sea* must be combined to obtain the necessary data and knowledge base for estimating the *Future Barents Sea* (Fig. 4).

The scientific background with theoretical foundation and contribution to the research front for each of the four Research Foci is presented in Section 1.5, and is outlined below with overarching hypothesis and research questions. Further details regarding the approach, objectives, tasks and deliverables of each RF as well as the description, approach tasks and deliveries of the cross cutting Research Activities (RAs) are given in Section 2.3.

1.5.1 Physical drivers (RF1):
Hypothesis, research questions and background

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 (RF1 focus) is a fundamental building block for any sustainable management, and prognostic models for the Barents Sea and the adjacent Arctic.

Hypothesis: The state and variability of the Barents Sea is set by a competition between cold Arctic Water, and warm Atlantic Water, modulated by variability in sea ice cover and atmospheric forcing.
This will be investigated through the research questions:

Q1.1 What is the role of the large-scale atmospheric variability in forcing the Barents Sea ice-ocean system through its influence on ocean circulation and sea ice cover, and how important is this compared to the reverse influence of the Barents Sea on the large-scale circulation?
Q1.2 To what extent is the long-term trend of retreating sea ice cover dominated by the transport of AW into the northern Barents Sea, and how do internal air-sea-ice processes control the adjustment of the local system?
Q1.3 How will projected changes in sea ice cover, mixing, and stability alter physical properties of the system that control distribution of heat, nutrients, carbon, and other parameters?
Q1.4 How will projected changes in clouds, sea ice cover, and snow cover alter physical properties of the system relevant for the underwater light regime?
Q1.5 What is the range of natural, long-term variability in Barents Sea ice cover, ocean temperature, and paleoproductivity?

The Barents Sea ice cover differs from the neighboring regions (Fram Strait, Kara Sea, Arctic Basin) and has decreased considerably in the recent decades. Atmospheric circulation dominates the short-term variability of the ice cover (Walsh and Johnson 1979; Fang and Wallace 1994; Deser et al. 2000), while oceanic heat supply appears to explain much of the recent ice retreat (Årthun et al. 2012; Lien et al 2017), but the relative roles of atmospheric and oceanic influences on longer time scales are not clear (Polyakov et al. 2012). Internal regulating mechanisms and external forcings for the region, as well as possible feedbacks onto the larger-scale circulation, must be better understood to assess the future evolution of the ocean-ice system.

For example, the ocean heat budget and stratification are controlled by on-shelf transport of Atlantic Water, frontal stability, vertical mixing, and radiative transfer through the atmosphere-ice-ocean column; these processes exhibit geographic and temporal signatures (e.g., Sundfjord et al. 2007; Perovich et al. 2008), and it is unknown how these patterns will change under ongoing global warming. Looking further afield, the Barents Sea links the Atlantic to the Arctic domains, and is subject to external forcing from its side and top boundaries (Smedsrud et al. 2013). Atmospheric variability, which tends to occur in broad patterns over large geographic regions (Wallace and Gutzler 1981), can have a direct effect on surface fluxes of heat and momentum (Pavlova et al. 2014; Sorokina et al. 2016; Hermann et al. 2016) through its influence on e.g. the distribution of snow, leads and shear-driven vertical transports and mixing. Indirect effects arise from the influence of large-scale wind patterns on cyclone behaviour (Zhang et al. 2004), the amount and properties of inflowing Atlantic water (Furevik 2001), and sea ice import from the Arctic (Smedsrud et al. 2013), all of which also contribute to determining stratification and ice conditions.

Finally, there is currently research going on and some debate in the scientific community about how the retreating Barents Sea ice cover may affect the large-scale atmospheric circulation, including the mid-latitude jet stream and ultimately weather at lower latitudes (Cohen et al. 2014; Barnes and Screen 2015; Overland et al. 2015).Some studies have identified pathways by which Barents Sea ice retreat can weaken the polar vortex and alter circulation patterns such as the NAO (e.g., Kim et al. 2014, Nakamura et al. 2016). Other studies argue that the atmosphere plays a critical role in controlling the interannual variability and trends within the Barents Sea (including those of sea ice) through moisture transport from the midlatitudes into the region (Woods et al. 2012, Park et al. 2015). An additional challenge is finding clear signs of a "response" in the midlatitude atmosphere, because this response is expected to project on modes of natural variability, which itself is very large (Shepherd et al. 2014, Wallace et al. 2014). A better understanding of atmosphere-ocean heat flux variability (e.g., Sorokina et al. 2014) and statistical methods designed to assess causal networks (e.g., Kretschmer et al. 2016) could help resolve the issue.

In the Barents Sea and adjoining seas, the early part of the current interglacial period was characterized by very high ocean temperatures, reduced sea-ice distribution and high paleoproductivity (e.g. Slubowska-Woldengen et al. 2007; Risebrobakken et al. 2011; Aagaard-Sørensen et al. 2014; Muller and Stein 2014) potentially making that period a relevant climate analog to present day warming. In order to investigate and understand the full range of variability in the climate-ocean system, longer time series beyond the instrumental record covering at best the last 150 years should be studied. Information beyond this period can be obtained using proxies, which record and enable quantitative reconstructions of past climate and environmental conditions, including the relative roles of Arctic Water and Atlantic Water in the Barents Sea. Such records also reveal the variability of sea ice cover and the degree to which oceanic heat supply has an important role determining the sea ice cover in the Barents Sea, but other drivers are also at play (e.g. Berben et al. 2014; Berben et al. 2017). New paleo-climate reconstructions from the northern Barents Sea will help establish natural base lines for the key features of climate state, which is so far only known in detail for the southern and western Barents Sea (e.g., Risebrobakken et al. 2010; Berben et al. 2014).

The trends and variability of this coupled system must be better understood to predict the evolution of the sea ice cover as well as the physical and geochemical setting for the marine ecosystem. **A novelty in the *Nansen Legacy*** includes a comprehensive, coordinated geophysics program spanning atmosphere, sea ice and ocean and pairing traditional field work with moored observatories, autonomous sensor platforms and numerical modeling tools in addition to coordinated paleoclimate data on ocean and sea ice that will provide a new level of knowledge of the interplay between external forcing and internal regulation of the Barents Sea environment. Furthermore, joint analysis of data from the *Nansen Legacy* and the NABOS program (see Section 5.3) will advance our understanding of how contemporary changes along the northern perimeter of the Barents Sea affect the ocean and sea ice conditions in the eastern Eurasian Basin (Polyakov et al. 2017) and how changes in the ice regime in the interior Arctic Ocean affect the transport of sea ice and melt water to the northern Barents Sea.

1.5.2 Human impacts (RF2): Hypothesis, research questions and background

Arctic areas are exposed to climate change as well as other human influences, such as ocean acidification, pollution and commercial fisheries.

Hypothesis: The multiple pressures of climate change, ocean acidification, pollution and fisheries will jointly and non-additively influence the ecosystem in the northern Barents Sea and the adjacent slope to the Arctic Basin. This hypothesis will be investigated through three interrelated research questions:

Q2.1 What are the current drivers of ocean acidification and how is ocean acidification affecting marine organisms and their adaptive capacity in the northern Barents Sea and adjacent Arctic Basin?

Q2.2 How are changes in species distribution, trophic interactions and energy allocation affecting toxic potency of contaminants in northern Barents Sea target organisms?

Q2.3 How may climate-driven changes in ecosystem structure and functioning lead to unanticipated effects of fisheries?

Effects of increasing atmospheric CO_2 on ocean acidification can only be understood by simultaneously considering climate-influenced drivers such as changes in sea ice, sea temperature and salinity, physical mixing and biological processes (Chierici et al. 2011; AMAP 2013). For example, progressing ocean acidification in the Arctic is linked to anthropogenic CO_2 uptake as well as increased freshening of surface waters (Chierici and Fransson 2009; Ericson et al. 2014; Qi et al. 2017). Furthermore, freezing of sea ice leads to brine formation, resulting in precipitation of solid $CaCO_3$(s) and production of CO_2, which thereby affects the CO_2 flux to the surrounding environment (Fransson et al. 2017). The progressing ocean acidification causes concern for fisheries (Mathis et al. 2015). Ocean acidification affects some calcifying organisms such as shellfish, echinoderms, and mollusks directly (e.g., Bednarsek et al. 2012), but may also affect ecosystem dynamics by influencing bio-availability of essential nutrients and metals (e.g. through complex binding with organic matter, Breitbarth et al. 2010). Whereas adult fish seem relatively robust for the projected CO_2 levels, fish larvae (Stiasny et al. 2016) and dominant prey such as pelagic snails, the pteropods *Limacina* sp. (e.g. Lischka and Riebesell, 2012), may be more sensitive. Other studies show a clear adaptation potential, but also that warming enhance negative effects of ocean acidification on organisms. Here, the use of paleoceanographic investigations using proxies for historical pH and saturation values give information on the ocean acidification state and the adaptation potential of the former ecosystem.

The Arctic is susceptible to local pollution from petroleum activities and shipping as well as long range transported persistent organic pollutants, metals, and emerging contaminants such as micro plastics that accumulate in polar regions. Climate change and ocean acidification result in changes in bioaccumulation and effects of contaminants in the food web in ice-associated, pelagic and benthic communities, by influencing environmental contaminant transport, distribution, and uptake, species distribution and properties, trophic interactions, and the carbon pump (Borgå et al. 2010; Kallenborn et al. 2011; AMAP 2016). In particular, lipid dynamics and energy allocation, which are strongly linked to climate and phenology (Søreide et al. 2010), are important for food web transfer of contaminants (AMAP 2016) and for mobilization of contaminants from storage fat to other organs (Bustnes et al. 2012). However, the combined effects of multiple stressors such as pollutants, warming, food limitation and ocean acidification, need further attention (Bustnes et al. 2015; Hylland et al. 2017).

Finally, climate-driven changes in the food web have implications for harvestable resources and multi-species management. Changes in ocean temperature and sea ice influence ocean productivity and the spatial and temporal distribution of organisms in the northern Barents Sea (Pinsky et al. 2013; Fossheim et al. 2015). Climate impacts the populations directly through abiotic effects as well as indirectly through altered species interactions, with the indirect effects probably being most important especially at high trophic levels (Ockendon et al. 2014), but also being highly uncertain (Hollowed et al. 2013). This uncertainty translates into uncertainty about how much biomass of different species can be sustainably harvested as climate changes. It is also uncertain to what degree fishing influences the ability of fish populations to adapt to climate change, which in turn depends on spatial population structure, local adaptations, and genetic connectivity within populations.

The novelty in the *Nansen Legacy* approach lies in the cumulative pressure concept. The planned research will leave a legacy by quantifying how the multiple pressures of climate change, ocean acidification, pollution, and fishing jointly affect Arctic marine ecosystems. Exploring these effects has relevance far beyond the Barents Sea: as ocean warming and acidification are expected to be most pronounced and rapid in the Polar Regions (IPCC 2013; AMAP 2013), the seasonal ice zone of the northern Barents Sea can provide early warning of global change.

1.5.3 The living Barents Sea (RF3): Hypothesis, research questions and background

Biodiversity, ecosystem functioning and environmental forcing are inherently and intricately linked in any ecosystem, with their relationships shaped by region, habitat and temporal dynamic.

Hypothesis: The ecosystems of the northern Arctic-influenced Barents Sea and adjacent basin areas function fundamentally differently from the advective Atlantic-influenced regions in the southern Barents Sea.
The main research questions of this research focus are:

Q3.1 What are unique traits of the marine life in the marginal ice zone of the northern Barents Sea and adjacent basin, compared to the much better understood southern Barents Sea?
Q3.2 How do environmental conditions impact the timing of biological processes in sympagic, pelagic and benthic realms?
Q3.3 What is the magnitude and variability in primary production, and secondary production of select groups?

Q3.4 How and at what rate do carbon and nutrients cycle through the food web, and what determines the rate of the processes involved?

The northern Barents Sea and adjacent slope to the central basin has risen to one of the most debated areas of the Arctic Ocean because of its observed and predicted rapid climatic change and tightly linked biological consequences (Haug et al. 2017). Yet the knowledge base of the living resources in this area is strikingly unequal compared to the adjacent, regularly surveyed southern Barents Sea. Given the drastic regional differences between physical forcing in north and south (see RF1) and environmental conditions driving regional diversity-ecosystem functioning relationships (Loreau 2000), inherent differences in functioning of northern and southern food webs in the Barents Sea are logical and knowledge on the mechanisms begins to emerge (Kortsch et al. 2015; Eriksen et al. 2017). As in the southern Barents Sea, light and nutrients are critical resources for phytoplankton production in the north, which in turn fuels the entire food web from zooplankton grazers to fish and mammals (Søreide et al. 2006). Unlike the south, however, ice cover, melt water, greater seasonality in light, and lower temperatures critically modify how, where, when and which resources are made available to sympagic, pelagic and benthic ecosystems (Bluhm et al. 2015; Larsen et al. 2015; Marquardt et al. 2016; Randelhoff et al. 2016).

Ongoing climatic changes in the northern regions may result in significant changes in timing of production cycles (Ardyna et al. 2014; Dalpadado et al. 2014), and traits such as body size and species composition of biological communities (Renaud et al. 2015). These will affect primary production and respiration (Mesa et al. 2017) with subsequent consequences for energy transfer, and carbon export, and potentially substantial impacts on fisheries yields, biogeochemical cycling, and carbon sequestration (e.g., Wassmann et al. 2011; Haug et al. 2017). In the last decade, boreal species and communities, including commercial fishes, have been expanding northward in the Barents Sea and elsewhere in the Arctic Ocean, while Arctic species are pushed northwards and potentially out of their suitable habitats (e.g. Mueter and Litzow 2008; Fossheim et al. 2015). Cascading effects link the changing structure and function of microbial food webs and zooplankton grazers (e.g. Boyce et al. 2015), with direct and indirect consequences for harvestable resources and top predators (Kovacs et al. 2011; Kortsch et al. 2015). Consequences may involve altered partitioning of energy between pelagic and benthic food webs through the efficiency of the biological carbon pump (Reigstad et al. 2008; Grebmeier et al. 2015).

A novel, hypothesis-driven and cutting-edge evaluation of the current status of the living northern Barents Sea and adjacent regions is needed. **The novelty in the *Nansen Legacy* lies in** the explicitly integrated approach of quantifying ecosystem compartments from microbes to mammals, and processes and linkages on a seasonal scale, to enable projecting future states. To obtain suitable data for studying community structures, seasonality and biological processes, RF3 will utilize the south-to-north *Nansen Legacy* transect using a space-for-time approach. Furthermore, to put the *Nansen Legacy* activity into perspective in time and space, we will also use historical data, data from IMR annual ecosystem monitoring surveys of the Barents Sea, as well as other data sources. Given the drastic environmental gradients and variability in the region (Lind and Ingvaldsen 2012), strong influence of advection (Wassmann et al. 2015; Hunt et al. 2016), potential for intensifying Arctic shelf-basin interactions (Pickart et al. 2013), extreme seasonality in biological cycles (Berge et al. 2015a) and migrations (Haug et al. 2017), and potential for expansion of human activity (see RF2), both relevant environmental drivers (RF1) and human pressures (RF2) must be considered in the framework.

This RF will, therefore, focus on quantifying structure and function of the changing but mechanistically poorly described northern Barents Sea ecosystems including shelf-basin linkages and identify fundamental differences to the southern Barents Sea by contrasting these regional ecosystems. Anticipated findings will also give opportunities for comparisons between Pacific and Atlantic inflow-interior shelf ecosystems, which have been suggested as a very useful next step in the development of a pan-Arctic model focused on improved understanding of ecological processes in the Arctic Ocean (Moore et al. 2016).

1.5.4 The future Barents Sea (RF4): Hypothesis, research questions and background

The sustainable management of resources and environment is fundamentally about foresight. It depends critically on our capacity to observe, understand and eventually to predict the transitions between past, present and future states of weather, climate, and the marine ecosystem.

Hypothesis: There is substantial practical potential for the prognostic quantification of the physical environment and ecosystem of the Barents Sea and neighboring Arctic from days to decades into the future.
The main research questions of RF4 are:

Q4.1 How can the forecast skill of polar lows be extended beyond the present 48-hour horizon?
Q4.2 To what extent is the climatic state of the Barents region predictable, and how does it causally relate to larger-scale climate?
Q4.3 How far into the future can ecosystem properties be meaningfully projected, what are the principal constraints for predictability, and what are the main uncertainties?
Q4.4 What is the range of possible future ecosystem states when including the combined influences of natural drivers and human impact on the living Barents Sea?
Q4.5 What are robust "early-warning" indicators of ecosystem sustainability and change that are directly useful for decision makers and resource users?

Implicit in this is the meaningful quantification and better constraining of natural and methodological uncertainties. In other words, when considering the coupled physical-biological system, the *Nansen Legacy* and RF4 addresses the fundamental question under which conditions and to what extent change in the climate system translates into distinguishable response in the ecosystem (and under which conditions such a response cannot be identified).

For the most immediate future perspective, days to weeks, there is a societal need for accurate weather forecasts and related operational services, i.e., detailed sea ice forecasts (Eicken 2013). Importantly, it is not modeling capability *per se* that predominantly hampers the forecast of potentially harmful weather events such as polar lows. The main constraints remain an insufficient observational basis for the adverse weather conditions and the lack of an operational forecast model system tailored to Arctic conditions (Kristjánsson et al. 2011; Jung et al. 2016). However, for the representation of sea ice per se and its influence on other model fields, model innovation and improvement are still required (e.g., Rampal et al. 2016).

Climate prediction models, such as the Norwegian Climate Prediction Model (NorCPM; Counillon et al. 2014), are currently being developed to forecast regional climate, e.g., for the Arctic, with a forecast horizon of seasons to years and possibly decades (Blanchard-Wrigglesworth et al. 2011; Kirtman et al. 2013). To what extent climate is predictable remains uncertain, particularly in the Arctic region (Spengler et al. 2016) and with respect to model-model consistency (e.g., Langehaug et al. 2017) However, the emerging empirical and mechanistic evidence for skillful predictability is encouraging in this respect (Nakanowatari et al. 2014; Onarheim et al. 2015; Årthun and Eldevik 2016; Yeager and Robson 2017).

For the modeling of future climate, and particularly for centennial-scale scenario projections, model divergence in regions or processes remain largely unresolved. Ensemble model simulations is presently our main guide in identifying such divergence and relate it to, e.g., internal climate (model) variability spanning the possible states of the Arctic atmosphere (Deser et al. 2016) and the Barents Sea ice cover (Onarheim and Årthun 2017). For climate prediction, the lack of a sufficient observational basis to initialize ocean circulation is generally a challenge, and particularly so in the Arctic. Further conceptual and model system developments are also much needed (Meehl et al. 2014; Yeager and Robson 2017), including procedures for the most beneficial assimilation of available observations into climate prediction model simulations (e.g., Massonnet et al. 2015). There is nevertheless an emerging interest in capitalizing on present and future capability in seasonal-to-decadal numerical prediction of the physical environment also with respect to useful prognostics for the ecosystem and its management (e.g., Payne et al. 2017; ICES Working Group on Seasonal-to-Decadal Prediction of Marine Ecosystems).

Future changes in sea ice extent and volume, and generally warming conditions, are undoubtedly going to cause major changes within the whole Barents Sea food web, but the overall consequences remain uncertain. While the annual primary production and the potential area of distribution for the Boreal species are likely to increase (e.g., Skaret et al. 2014; Haug et al. 2017), ice-associated and Arctic species will experience marked habitat loss and will certainly undergo distributional changes and presumably also abundance reductions (Haug et al. 2017). To properly assess the implications of future climate change for the marine ecosystem along the

Nansen Legacy space-for-time transect, including both Arctic and Boreal species, the changes postulated by prediction and projection models (NorCPM/NorESM) must be converted into detailed regional information before used as forcing for ecosystem models (Sandø et al. 2014).

The ecosystem models can be process-based such as biophysical models (Wassmann et al. 2010; Tjiputra et al. 2013; Skaret et al. 2014) and whole-ecosystem models (Fulton et al. 2004), which all require detailed parameterizations and can provide detailed projections of future ecosystem states. They can also be data driven Bayesian state space models (e.g., Mutshinda et al. 2011), based on simpler process models and more tightly linked to data, can be used to make complementary projections of future ecosystem states. Non-deterministic ecosystem models (e.g., Planque et al. 2014), which rely on relatively few assumptions, can provide envelopes for the possible future states of ecosystems and the trajectories leading to these.

The novelty of the *Nansen legacy* approach lies in how the combination of model approaches e.g., of process-based and non-deterministic models constitute a framework for the projection of ecosystem states into the future. This will allow model comparisons, ensemble modeling, and the development of specific tools to evaluate model performance and predictability horizon (Petchey et al. 2015). The coupling of ocean, climate, and ecosystem models will serve to determine the extent to which skill gained in northern climate prediction can improve assessment of the future ecosystem, as well as give predictions and projections of annual primary and secondary production, biomass estimates of trophic levels and ecosystem state. One will further seek to advance the meaningful communication of progress in prognostic capabilities – and associated uncertainties – to stakeholders building on the multiple-perspective scenario method suggested by Planque et al. (2017).

2. The *Nansen Legacy* approach – Objectives, work plans and milestones

2.1 Project Research Foci and Research Activity organization

The four **Research Foci (RFs)** presented are facilitated through **crosscutting Research Activities (RAs)** as described in the **RF and RA work plans detailed below** (Section 2.2; Fig. 5). The crosscutting Research Activities are specified as *Data collection and infrastructure* (RA-A), *Data management and synthesis* (RA-B), *Technology and method development* (RA-C) and *Impact and legacy* (RA-D). The leaders and co-leaders of each focus and activity represent two different partner institutions and complementary disciplines to facilitate institutional and cross-disciplinary collaboration and integration both within and between the Research focus and activity. Leader and co-leaders are selected based on research expertise or expertise on the specific tasks (see CV´s). All RF/RA-leaders and co-leaders are members of the project leader team.

The outlined project management (described in more detail in Section 3) ensures that the leadership of, and communication and organization within the project is functional, and that project milestones (cf. on-line application form) and deliverables (Section 2.2) are met. The project management also administrates the recruitment program, reviews the progress made, and informs and connects to the science community, users and stakeholders, and the general public.

Substantial investments into infrastructure and human resources (estimated in person months, **pm**) are required, and provided in Section 4 on the *Nansen Legacy* Resources, and the specified budget and tables listing the available and requested infrastructure and model inventory as specified in the Proposal Appendixes (v - Specified budget, i- Infrastructure, ii- Model inventory). There is also a major

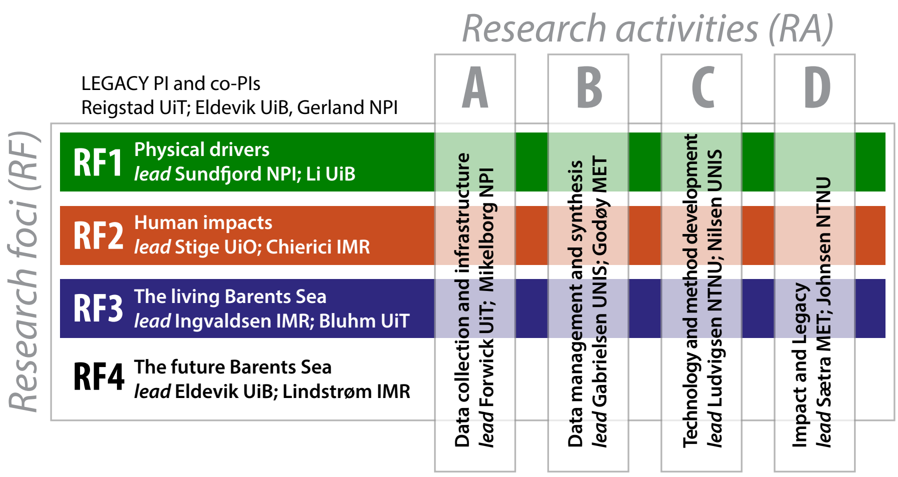

Figure 5. The *Nansen Legacy* organization. The Research Foci (RF1-4) represent "what" science the *Nansen Legacy* is investigating, and the Research Activities "how" (A–C), including impact and legacy in the public domain (D).

recruitment activity in the project with ~50 recruitment positions (PhD and post docs) being core to the research activities. Specified grants will facilitate and encourage national as well as international mobility to connect internationally as well as between involved institutions. Infrastructure in terms of equipment and analytical facilities provided by the participating institutions will be used across the project as indicated in Appendix i.

Key activities and milestones are shown in greater detail in the on-line application form.

2.2 Approach, objective and tasks of the Research Foci (RFs)
The work of the RFs will be carried out and delivered using the infrastructure, tools and initiatives in the crosscutting RAs. The specific workplans of all RFs (Section 2.2) and RAs (Section 2.3) are described in the text below, and specified with objectives, approach, tasks and deliverables. They also identify relevant cross RF/RA collaboration, supportive and innovative aspects. The open data policy is executed through RA-B. The outreach activities that carry important impact and legacy aspects of the RFs are coordinated by RA-D.

Leaders and co-leaders are explicitly identified for each RF and RA, and task leaders, all participating institutions and the human resources are listed with each specific task (**task leader**, institutions in alphabetical order, estimated **pm-effort** per task). The complementary deliverables as expected outcomes for each tasks, are specified with **month of delivery (M)**.

2.2.1 Approach to **Physical drivers (RF1)** *Lead:* Arild Sundfjord (NPI)**,** *co-lead:* Camille Li (UiB)
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.

Work plan: Elucidating how the physics of the Barents Sea region functions in today's climate and how this will change in the future requires observations, physical frameworks for understanding these observations, and numerical models to test this understanding. RF1 will focus on the processes that determine ocean conditions and sea ice cover of the Barents Sea through 1) the collection of new observational data sets to characterize local-scale interactions, 2) the analysis of observations with conceptual or idealized models to quantify the effect of these interactions, and 3) the use of reanalysis data and general circulation models to tie local changes to external forcing.

In-situ data will be collected through deployment of multidisciplinary sensor moorings and state-of-the-art autonomous vehicles at strategic locations in the northern Barents Sea, as well as survey cruises covering important gateways (Fig. 2). The new data will provide information on exchanges across boundaries, both external (e.g., inflowing Atlantic Water in the south-west and over the northern slope, inflowing Arctic Water and sea ice from the north, and atmosphere-ocean fluxes) and within the system (e.g., Polar Front in the central Barents Sea). The new data will also provide unprecedented synoptic-scale spatial coverage of the region through microstructure profiling by gliders and vertical profilers, irradiance measurements above and through the water column, aerial sea ice observations on regional scales (through EM-bird and stereo camera image analysis), and collection of other diagnostic data (wind, air-sea fluxes, hydrography, currents, systematic sea ice observations, satellite imagery, and autonomous drifting buoys). In addition, new seafloor sediment core samples will be collected to yield long records of sea ice cover, ocean temperatures, and paleo-productivity, thereby placing the recent period of instrumental data within a longer term perspective. One extended cruise into the central Arctic Ocean will exit through the Fram Strait to link observations north of the Barents Sea to the integrated Arctic Ocean signal leaving the Fram Strait.

To assess the importance of external forcing, we will combine existing data in upstream regions with new data from moorings, meteorological stations and drifters. These observations will be combined with global ocean/atmosphere re-analyses and idealized dynamical models to investigate physical mechanisms. Numerical models will be used to synthesize our understanding of the large-scale forcings, local processes, and their relative importance for the Barents Sea. Models to be used include NorESM for large-scale, long-term coupled atmosphere-ice-ocean simulations, ROMS coupled to CICE for studies of regional sea-ice cover on decadal time scales, neXtSIM for small-scale air-ice-ocean dynamics and CICE 1D for high-resolution ice and snow thermodynamics and radiation studies.

Fieldwork (process studies, mooring deployments, survey cruises) and data analysis will in part be carried out jointly with the other RFs and complemented by two targeted process studies carried out primarily by RF1 scientists. The *Nansen Legacy* RF1 will provide an improved, quantitative description of vertical mixing, including in the oceanic boundary layer, which enables quantification of fluxes of e.g. heat, nutrients and carbonate (RF2); better data, with respect to temporal and spatial resolution as well as with more precise sensors than in previous campaigns, on sea ice characteristics (including meltponds, ridges and floe size distribution), light conditions, wind forcing, vertical mixing and advection as regulators of nutrients, carbon and organisms (as the backbone for RF3); improved model parameterizations for key physical processes, better data including time series at key gateways previously not covered together with high spatial coverage during campaigns for model evaluation, and a better understanding of coupling with the adjacent atmospheric and oceanic environment, contributing to improved forecasts and regional climate projections (developed in RF4). Furthermore, an understanding of the local physical system together with advances in modern observation technology and strategy (from RA-C) will be used to extend the observations and plan a next-generation observing system to support the future weather forecasting system (developed in RF4) for the area.

RF1 overarching tasks (T) and deliverables (D)

T1-1 Measure and analyze fluxes of sea ice, water masses, momentum and heat into the northern Barents Sea and Fram Strait (lead Arild Sundfjord, **NPI**, IMR, MET, UiB, UiO, UNIS, 161 pm)

T1-2 Perform process studies to investigate the atmospheric, oceanographic, radiative and other physical controls on sea ice and stratification in the northern Barents Sea (lead Ilker Fer, **UiB**, IMR, MET, NPI, NTNU, UiO, UNIS, 229 pm)

T1-3 Produce high-resolution time series of sea ice and ocean climate properties in the northern Barents Sea and adjacent Arctic Ocean based on state-of-the-art organic, inorganic and biological proxy methods (lead Katrine Husum, **NPI,** UiB, UiO, UiT, 144 pm)

T1-4 Combine global and regional climate simulations, idealized sensitivity experiments, 1D modeling and analysis of long data series to quantify the relative influence of large-scale forcing factors and local processes on the ice-ocean-atmosphere system (lead Vidar Lien, **IMR,** NERSC, NPI, MET, UiB, UiO, 212 pm)

D1-1 Improved description of the external drivers at the side and top boundaries of the system. (M60)

D1-2 Quantitative description of key internal processes regulating air-ice-ocean fluxes, distribution of irradiance, vertical stability and frontal positions (M56)

D1-3 Characterization of the natural range and variability of the sea ice cover, Atlantic and Arctic Water through flow, as well as the physical and biogeochemical properties of the Barents Sea over the past 12 millennia. (M48)

D1-4 Assessment of how external and internal factors act in concert and understanding of how important model deficiencies and biases are for the Barents Sea. (M66)

2.2.2 Approach to **Human impacts (RF2)** *Lead* Leif Christian Stige (UiO), *co-lead* Melissa Chierici (IMR)

Objective: To improve our understanding of how human activities influence the northern Barents Sea ecosystem.

Work plan: RF2 takes a multidisciplinary approach to investigate human activities' impacts on the Barents Sea ecosystem in the past, present and future. The approach includes field observations, experimental work including combined effects, existing models and new innovative model development within and across the main impacts of ocean acidification, contaminations and effect of fisheries. Paleontological data will inform on the natural variability in the past (in terms of ocean geochemistry (RF2), physics (RF1) and biota (RF3), while new model tools developed in RF2 on climate-dependent effects of ocean acidification, pollution and fisheries will help to understand the present and, to project the future (RF4). The combined effects of increased atmospheric CO_2 and climate-related factors on ocean acidification, and their consequences for selected organisms and the ecosystem, will be quantified through a combination of field measurements from ice, water column, and sediments, and using incubation experiments, flux calculations, mass balance studies of the carbon system, and ecosystem modeling of food web effects.

Jointly with RF1, seasonal and targeted process studies along chemical and physical gradients, using measurements in the whole water column over a full year, will be used to investigate the major drivers of the observed changes in carbonate chemistry and ocean acidification state in contrasting regimes. The observation data as well as models (in RF4) will also be used to assess trends in CO_2 uptake and ocean acidification state. Continuous surface CO_2 measurements will provide new knowledge on the oceanic CO_2 sink, and sea-ice studies will result in increased information on different ice freeze and melt stages. These studies will help to understand the role of sea ice processes for the CO_2 transport to the deep parts of the Arctic Basin and the consequences of openings and leads in the sea ice for sea ice CO_2 flux and transport to underlying water (building on Fransson et al. 2017).

We will also study how pH and temperature influence the mobility of particulate and dissolved organic carbon, essential trace elements (micro nutrients) and heavy metals in the water column and on the surface sediment. The physiological and adaptive effects of ocean acidification on selected key multicellular organisms such as copepods and shell-bearing wing snails (pteropods) as well as unicellular calcifiers such as planktonic foraminifera will be quantified from studies along chemical gradients, sampled in different regimes in parallel to water sampling for acidification state (in RF2 and also linked to RF3). We will study possible adaptations to ocean acidification by measuring growth and metabolism in one-week incubations at different pH and saturation levels. Gene expression in zooplankton from contrasting acidification regimes will also be investigated. Fossilized calcifiers (pteropods and foraminifera and other paleo proxies) will be used to assess pre-industrial natural variability (linked to RF1).

Impacts of pollutants (e.g., organic contaminants, oil, microplastics) will be assessed by a combination of empirical field studies, controlled experiments, and statistical and mechanistic modeling (i.e. trophic transfer and food web biomagnification models), through which the combined ecosystem response to concomitant, cumulative factors is studied. Model predictions of climate change effects on food web accumulation of contaminants, include reduced accumulation due to expected reduction in lipid storage. Bioaccumulation changes due to altered dietary composition, are predicted to have less influence than the expected lower lipid content. These scenarios will be tested. A similar study of contaminant accumulation in the central Barents Sea pelagic food web was done in 1998, which allows a thorough comparison between the environmental states two decades apart.

Jointly with RF3, zooplankton and fish samples from climate gradients in different seasons will be analyzed in the state-of-the-art stable isotope lab being established at UiO, to study how changes in lipid, diet and energy allocation affect food web accumulation of pollutants. By analysis of seasonal lipid and pollutant dynamics in the pelagic (copepods, polar cod (*Boreogadus saida*) and kittiwakes) and the benthic (amphipods, bivalves and common eiders) parts of the ecosystem it will furthermore be investigated whether there are “critical periods of effects” when energy stores are depleted and pollutants are remobilized from lipids to blood and other body organs, which can lead to non-additive effects of climate and pollutants.

Effects of multiple stressors, i.e. temperature, ocean acidification and polycyclic aromatic hydrocarbons (PAHs), through incubation experiments with Arctic copepods will be investigated. A particular focus will be on oil and oil-related contaminants, for which exposure studies to identify sensitive species and life-stages of zooplankton and fish (*Calanus* spp., Atlantic cod, polar cod, capelin and long rough dab) will be conducted. The biological responses will be identified by using sub-lethal endpoints on physiology, such as respiration, biotransformation capacity and oxidative stress coupled with membrane integrity as well as by using genomic and proteomic analysis tools. For selected organisms (identified in collaboration with RF3), key life history traits such as development, growth, reproduction and survival will be targeted.

Effects of commercial fisheries will be investigated using complementary modeling approaches, both statistical (e.g., state-space multi-species time-series models) and mechanistic (e.g., the Atlantis ecosystem model (RF4; see further description below in this paragraph). To investigate how climate-driven changes in fish productivity and species interactions in the northern Barents Sea affect fisheries and ecosystem effects of fisheries, we will develop statistical models of multi-species dynamics under climate change (based on Patin et al. 2016, Langangen et al. 2017). This activity will be conducted in parallel with statistical modelling in RF3 on climate effects on phenology and multi-species dynamics and extended by investigating historical effects of fisheries under different climate states. Bayesian methods may be particularly suitable for integrating new knowledge from the *Nansen Legacy* cruises into the models, by using informed prior distributions for model parameters and/or by combining different data that inform on the same process (e.g., transect and time-series data).

We will furthermore investigate how the receding ice-edge influences the horizontal distributions of fish stocks, the benthic-pelagic coupling and the fisheries using the Nordic and Barents Sea Atlantis model (RF4, Hansen et al. 2016). This is a deterministic end-to-end model with 57 species and functional groups, including 4 ice-related groups, which will be further developed with focus on species-ice interactions and ecosystem effects of the melting sea ice. Furthermore, genomic data of Atlantic cod, polar cod and capelin will be collected and combined with samples from other investigations (e.g., from spawning grounds) to quantify population structure and identify signatures of directional selection, such as temperature adaptations. This work will build on high-quality genomes established for Atlantic cod (Star et al. 2011; Tørresen et al. 2017) and polar cod (planned to be finalized by the end of 2017). Moreover, we aim to develop a spatial population dynamics model based on the genomic information in order to assess implications of alternative fishery scenarios for stock dynamics and adaptability under climate change.

RF2 overarching tasks (T) and deliverables (D)

T2-1 Ocean acidification: Determine the current and past magnitude, variability and drivers of ocean acidification and its effect on bio-availability of essential nutrients and metals. Assess the consequences of ocean acidification for key ecosystem species and indicator species of ocean acidification effects (lead Melissa Chierici, **IMR**, NPI, NTNU, UiB, UiT, UNIS, 215 pm)

T2-2 Pollution: Determine the sensitive physical and biological drivers of food web biomagnification, and effects of contaminants in target species of the marine food web of the northern Barents Sea (lead Katrine Borgå, **UiO**, NPI, UiB, UiT, UNIS, 208 pm)

T2-3 Harvesting: Incorporate new knowledge about climate-driven ecological and genetic changes in fish communities, e.g. from observations during winter/spring in ice-covered areas, into population, multi-species, and ecosystem models that quantify the combined effects of climate and harvesting (lead Sissel Jentoft, **UiO**, IMR, UiT, 150 pm)

D2-1 New data and estimates on the variability and major drivers of sea-air CO_2 flux, ocean acidification state and trends. Improved understanding of calcification processes, physiological responses and adaptation of arctic key species and consequences for arctic marine ecosystems in future; (M63)

D2-2 Improved understanding and models of how pollutants accumulate in the northern Barents Sea food web, taking into account changes in species composition and energy allocation, and how arctic key species and the ecosystem respond to the effects of pollutants alone and in combination with, e.g., temperature, ocean acidification and altered food availability (M57)

D2-3 Description of how effects of fisheries may depend on climate state and relate to population structure and assessment of how continued sustainable management of the main commercial stocks can be achieved (M72)

2.2.3 Approach to **The living Barents Sea (RF3)** *Lead* Randi Ingvaldsen (IMR), *co-lead* Bodil Bluhm (UiT)

***Objective**:* To 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.

Work plan: RF3 will both synthesize existing data and extensively collect new data sets on key aspects of the northern Barents Sea and adjacent Arctic Basin ecosystems. RF3 focuses on structure, function and interactions within and between communities and food webs, as well as species biology and ecology. Unique to this effort and unprecedented for the region is the synoptic study across trophic levels (including pelagic and sympagic heterotrophic microbes and autotrophs, zooplankton, benthic invertebrates, fish, marine mammals and sea birds), and the all-seasons approach. In addition to quantifying biotic diversity, standing stock and distribution specific to life stages, seasons and environmental regimes, RF3 will study mechanisms structuring seasonal production and growth patterns under current and changing conditions. The results will be integrated to arrive at annual production estimates in the seasonal ice zone with hot and cold spot delineation that will cater to management structures. Detailed food web studies will provide the backbone of seasonal stock and production estimates through investigating the microbial loop and its interface with the traditional food web, as well as pelagic-benthic coupling through vertical flux, sediment community respiration rates, life cycles and trophic interactions. Results will be compared and contrasted with the better-known southern Barents Sea as well as with inflow shelf ecosystems in the Pacific Arctic.

To achieve its goals, RF3 will combine traditional tools (to facilitate appropriate comparison with southern Barents Sea data) with advanced state-of-the-art technology and analytical approaches. This approach will ensure high scientific standard, facilitate discovery and novelty, and train the new generation of scientists in cutting edge biological, ecological and oceanographic methods. Specifically RF3 will use: a) a field-based *space-for-time* approach using natural gradients in physical drivers; b) *seasonal* studies (a persisting challenge in Arctic areas) of selected species, communities, processes, interactions, ecosystems, and biogeochemical cycling; c) moorings for *year-round* observations of important biological and biogeochemical parameters; d) *experimental* work on adaptations, process rates, and food webs; e) *molecular tools* for studies of community composition and functions; f) *technological platforms* such as satellite observations, ice-tethered buoys and AUVs for extended observations in time and space, where practical; g) *models* to investigate energy flow and how changes in drivers may affect the ecosystem, including a coupled atmosphere-ice-ocean biogeochemical model, h) historical data, data from IMR annual ecosystem monitoring surveys of the Barents Sea, as well as other data sources to embed the *Nansen Legacy* into the larger regional framework. For each task, we will first synthesize existing knowledge to ensure that new field-work will fill gaps and not be redundant.

The field and subsequent sample and data analysis work will be carried out in cooperation and tightly coordinated with the other RFs and RAs. RF3 will concentrate its field-based efforts on the seasonal cruises conducted in 2019-2020 as well as the joint *Nansen Legacy* cruises (Fig. 7, RA-A). This also includes the extended cruise into the central Arctic Basin in 2021. The exit through the Fram Strait will include a limited, but adaptive biological sampling, where for instance the north and westward distributions of fish larvae advected from the Nordic Seas are checked. The planned research will strongly link with RF1 with regard to sea ice characteristics, light conditions, wind forcing, vertical mixing, stratification and other forcing factors, as these regulate the timing of processes and distribution of organisms. RF3 will provide data and model outputs to RF2 on ecological processes that are fundamental to evaluating how the impact of ocean acidification, pollution and fisheries on marine biota depends on environmental conditions. To ensure consistency and comparability with RF2, joint protocols for experimental designs and links of trophic structure and pollutants loads in plankton and benthos, for example, are currently in development. RF3 will provide data and knowledge to RF4 for model evaluation and improved model parameterizations of key processes, contributing to improved predictions and projections of the marine ecosystem of the northern Barents Sea and adjacent region. Models to be used and/or developed in RF3 in collaboration with RF4 include: i) lower trophic level communities and interactions (competition, predation); ii) energy allocation of key Arctic species and their impact on dominant marine mammal species; iii) fully coupled physical-biogeochemical dynamic models based on studies of the impact of physical drivers, including nutrient supplies, on the ecosystem; iv) statistical and dynamical multi-species, food web, and whole ecosystem models for effects on higher trophic levels. The synthesis of existing data takes place in cooperation with data rescue in RA-B. The extended observations using technological platforms, take place and will be further developed in collaboration with RA-C.

RF3 overarching tasks (T) and deliverables (D)

T3-1 Characterize biological communities in sympagic, pelagic and benthic realms in the seasonal ice zone of the northern Barents Sea and adjacent slope to the Arctic Basin in terms of biodiversity, abundance, biomass and distribution patterns in relation to environmental forcing, in particular sea ice (*lead* Bodil Bluhm **UiT**, APN, IMR, NPI, UiB, UiO, UNIS, 194 pm)

T3-2 Investigate the timing of critical biological processes including primary and secondary production, phenology of life cycles, and related processes and test how changing conditons may affect these seasonal patterns across several trophic levels (*lead* Tove Gabrielsen **UNIS**, IMR, NPI, UiB, UiO, UiT, 140 pm)

T3-3 Characterize the total annual production from microbes to fish along latitudinal and environmental gradients, identify production hot spots and how condition-specific variability in life history traits affect these (*lead* Randi Ingvaldsen **IMR,** NPI, NTNU, UiB, UiT, UNIS, 101 pm)

T3-4 Characterize lower trophic level food web structure and links to consumers including top predators, carbon cycling, and biological interactions, and investigate selected regulating factors (*lead* Gunnar Bratbak **UiB**, APN, IMR, NPI, NTNU, UiO, UiT, UNIS, 315 pm)

D3-1 Morphological and/or sequence-based taxon identifications; high-resolution acoustic data for zooplankton and fish; abundance, biomass, diversity, community composition by size fraction and/or taxon. Major environmental drivers identified for biological communities across trophic levels and habitats; characterization of ecosystem gradients from the open ocean to ice-covered waters; Productivity vs Irradiance (PI) and Production vs Temperature (PT) curves, nutrient update dynamics (M60)

D3-2 Seasonality of stage-specific community composition for ice-associated and pelagic organisms (from microbes to selected macrofauna) across seasons and production regimes; experimental data of population-level processes of key taxa from single-celled organisms to zooplankton: seasonal metatranscriptomics data for protist activity, primary production rates, temperature effects on size, and other factors on zooplankton production rates, etc. (M48)

D3-3 Annual production estimates from microbes to fish, related to the environmental regimes; hot spots identified (as areas of particularly high standing stocks and/or activity, export flux, diversity, food web structure) based on the *Nansen Legacy* surveys and historical regional data; evaluation of role of hotspot to annual production for entire northern Barents Sea; analyses of individual variability (in space and time) for selected traits of select taxa using life history modeling approach; age-distribution information of a dominant benthic taxon (M56)

D3-4 Data on pelagic and sea ice microbial food web structure, carbon flow and controls thereof; identify links of microbial to higher trophic levels in pelagic system and to benthic realms through vertical transport, sediment community respiration rates, and sedimentation; delineate regulatory processes of links and flux; diet/trophic marker data of key species via isotopic ratios and/or fatty-acid compositions; diet data for small benthos organisms based on molecular sequences; synthesis of how climate influences population and food web dynamics (M60)

2.2.4 Approach to **The future Barents Sea (RF4)** *Lead* Tor Eldevik (UiB), *co-lead* Ulf Lindstrøm (IMR)
Objective: To assess the state, predictability, and associated uncertainties of the Barents Sea weather, climate, and ecosystem.

Work plan: The *diagnosis of the present* Barents environment and *prognosis of its future* can be based on empirical, conceptual, statistical, or physical models (including hindcasts), or a combination thereof. RF4 will focus on what can be constrained from observations, including the *Nansen Legacy* fieldwork, and the synthesis of this empirical knowledge and related mechanistic understanding (RFs 1–3) into a holistic description of the past, present, and future state of the Barents Sea. A variety of numerical general circulation models (GCMs) will be used and improved from the range of weather and sea ice forecast models, to regional ice-ocean hindcast models, to fully coupled earth system models tailored for predicting (seasons to decades) or projecting (decades to centuries, including *what-if* scenarios) the future. Biophysical, mechanistic, and non-deterministic food web models will be used to investigate the likely impacts of expected future environmental changes. RF4 will deliver estimates of model performances for a range of ecological properties (e.g. biomass time series, biodiversity, primary production, ecosystem stability) and forecasting horizons, and will identify assumptions, scales and parameters to which individual model projections are most sensitive and, report range of likely and extreme possible future states and trajectories of the Barents Sea ecosystem. A comprehensive *Nansen Legacy* model inventory is provided in Appendix ii.

Data and knowledge from RFs 1–3 and RA-B will provide input for evaluation and realization of key processes in these models, thereby contributing to improved prognostic capabilities. Model use and evaluation will focus primarily on the Barents Sea and contiguous domains, but also on geographically or dynamically contagious domains of the Arctic and beyond. The prognostic use of statistical models and GCMs is largely complementary, and this complementarity will be used, together with the observational record, to develop confidence estimates on resulting inferences, including qualifying and quantifying uncertainties in hindcast and future state estimations.

FACT BOX 3: Assessing the future Barents Sea

The future is principally unknown, yet the future is what policies and management address. Quantitative assessment of the future, including what will be informed by *Nansen Legacy* fieldwork or otherwise, is generally realized by the use of prognostic or statistical models. The range of numerical models, and accordingly the *Nansen Legacy's* weather/climate-to-ecosystem modelling capability, have been compiled and aligned for the following purpose. Firstly, there is the required consistent flow of variables and information through the hierarchy (cf. Appendix ii) ranging from full climate models (e.g., NorESM) through to non-spatial, but highly specialized, ecosystem models (e.g., Ecopath). Secondly, there is both a cross-institutional and a general need for common case studies, benchmarking, and intercomparison of models and model output at the different range of climate and ecosystem complexities. Thirdly and most importantly, we will use a coherent suite of models – informed and evaluated by observations as part of the *Nansen Legacy* – as a comprehensive approach to assess the possible future states in the Barents Sea.

The "Future Barents Sea" model philosophy and hierarchy is outlined in *Nansen Legacy Fact Box 3*. Model alignment concerns both identifying model sensitivities to environmental change including, e.g., harvesting, and to the selection of input data to constrain the habitat(s), e.g., the temperature a given ecosystem model is operating within. Observations and GCMs provide important variables defining habitats; habitat characteristics are typically input to detailed ecosystem models. This leads directly to the scientific challenge at hand, *how changes in the different parts of the climate system translate into changes in the ecosystem.*

The ecological models in the *Nansen Legacy* project (cf. Model inventories Appendix ii, but see also Fact Box 3), which comprise ecosystem (NoBa Atlantis and EwE), bio-physical (NORWECOM.E2E), stochastic food web (NDND) and multispecies state-space (GOMPERTZ) models, are fully operational. However, further model developments are required to improve model performance, and hence, prediction and projection capabilities. The model development and evaluation will take place in close collaboration within RF4, and with RFs 1–3, and focus on, e.g., i) projected future ocean acidification and quantify how effects of pollution and fisheries depend on climate state (RF2), ii) explore lower trophic level community drivers and interactions (competition, predation); iii) explore energy allocation of key Arctic species (RF3); iv) explore impact of physical drivers on the ecosystem (RF1 and RF3); v) explore the performance of early warning indicators to detect systemic changes in ecosystems (RF4, T4–5). Model evaluation also importantly involves confrontation of model hindcasts with historical data.

The data required to run, develop and evaluate the models include physical (ocean currents, salinity, temperature, water level, ice, wind fields), chemical (carbon and nutrients) and biological (growth and consumption rates, production and biomass of each species/group, primary production, fisheries catches) data; these data will be exchanged between the different RF4-models, including fields for near-term prediction (months-to-decade) from NorCPM, or provided by RFs 1–3 and RA-B. Future projections (with 2050 as the reference point for communication with stakeholders; see also below) of the key ecosystem properties will rely on various climate, harvesting and ecological (invasion of new species) scenarios. A reference climate scenario will be IPCC's RCP4.5 implying gradual increase in atmospheric forcing agents to about 550 ppm CO_2-equivalents by 2060, a levelling off thereafter; including that simulated by NorESM.

Using downscaled prediction and projection fields (from NorCPM/NorESM), we will explore multiple climate driver-response relationships such as warming, leading to reduced sea ice cover and weakened stratification (see RF1), which will affect the seasonal and spatial dynamics in primary production and weaken the pelagic-benthic coupling, and hence, reduce benthic productivity. Additionally, we will explore how increasing water temperature affects food web structure and dynamics as a result of e.g. displacement of Arctic by boreal species, lower benthic production and loss of sympagic production. The harvesting scenario will be based upon today's fishery regulations and multispecies/ecosystem based harvest control rules and the ecological scenario will be based upon observed and hypothesized future movement of Atlantic species and snow crab into the Arctic. Model output, i.e. the selected ecosystem properties, from the five models will be combined into ensemble projections of the Barents Sea ecosystem states and trajectories, taking into account that the five models differ greatly in temporal, spatial and structural (who-eats-who) resolution.

Identifying credible ecosystem indicators that warn us prior to critical ecological transitions may have important implications for the management of resources. We will use the ecological models to evaluate the performance of "early warning indicators" by examining the sensitivity of indicators with respect to drivers and by examining how indicators perform on model simulations. Although the translation of research into meaningful stakeholder information is done routinely by *Nansen Legacy* partners (e.g., IMR, MET, NPI), it is no trivial task. The useful and continuously improved communication between scientists, managers, and stakeholders in the emerging field of predictability and future scenarios is a priority for the *Nansen Legacy*. We will accordingly scope a series of multiple-perspective workshops developing and discussing 2050-scenarios with key stakeholders through the project period to improve mutual benefit and communication.

RF4 overarching tasks (T) and deliverables (D)

T4-1 Tailor an ensemble weather–ice–ocean forecast model system to the Barents Sea and Polar region (*Lead* Malte Müller, **MET**, NERSC, NPI, UiB, 137 pm)

T4-2 Produce climate predictions and climate projection scenarios for the Barents Sea and regions influenced by it (*Lead* Marius Årthun, **UiB**, MET, NPI, 96 pm)

T4-3 Constrain biogeochemical variability, spatially and temporally (*Lead* Are Olsen, **UiB**, IMR, NPI, 48 pm)

T4-4 Develop and use dynamic ecosystem models to simulate key ecosystem properties of the present and future living Barents Sea, e.g., productivity, phenology, distribution (*Lead* Ulf Lindstrøm, **IMR**, UiB, UiO, UiT, 164 pm)

T4-5 Identify ecosystem indicators that might reveal early warning of significant systemic state change, and evaluate possible ecosystem indicators for their scientific, management, and communication potential (*Lead* Ingrid Schjølberg, **NTNU**, IMR, 24 pm)

T4-6 Scenario 2050 workshops (*Lead* Benjamin Planque, IMR, NTNU, UiB, UiT, 3 pm)

D4-1 Operational weather–ice–ocean ensemble forecast model (M42)

D4-2 Model analyses, predictions, and projections contributing to the *Coupled Model Intercomparison Project* (CMIP6; M36)

D4-3 Report on prognostic capability in assessing natural and anthropogenic change in biogeochemistry (M42)

D4-4 Report on performances and predictability horizon for food-web models and documentation of the range of likely and extreme possible future states and trajectories of the Barents Sea ecosystem (M70)

D4-5 Report on early warning indicators of significant ecosystem state changes in the Barents Sea (M36)

D4-6 Scenario 2050 workshop, Report and future recommendations (M18, M42, M66)

2.3 Approach, objective and tasks of the Research Activities (RAs)

The crosscutting Research Activities (RAs) realize and sustain the RFs, and explicitly take the *Nansen Legacy* into public domain. Also the RAs are organized across the consortium with leaders representing complementary expertise and institutions. The different RAs will have activities that align and synergize the Research Foci in different ways. *Data collection and infrastructure* (RA-A) will facilitate the operational logistics of arranging fieldwork and sampling from different platforms. *Data management and synthesis* (RA-B) will make sure that the data collected and produced within the project, and also some historical data, are delivered to agreed databases according to the open data policy and data management plan to enable visibility, accessibility through standard formats, and that they are secured for future use. *Technology and method development* (RA-C) will develop reliable and robust autonomous platform solutions to improve the observational capability within the project, but also to enhance and improve our future observational capability in ice covered waters. Through the research activity *Impact and legacy* (RA-D), the communicative expertise and capability of all the involved institutions, in addition to dedicated resources in the project administration, are merged 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.

The approach and workplan of the four RAs is described in Sections 2.3.1–2.3.4.

2.3.1 Approach to **Data collection and infrastructure (RA-A)** *Lead* Matthias Forwick (UiT), *co-lead*Øystein Mikelborg (NPI)

***Objective*:** To facilitate, coordinate and integrate the collection of new observational data, proxy data and modeling output across the *Nansen Legacy* project.

Work plan: The *Nansen Legacy* will carry out multi-disciplinary research using extensive ship-based field expeditions, remote sensing, moorings and UAV/ROV/AUV technology, to collect data and observations for a baseline description of the northern Barents Sea and adjacent Arctic Basin marine region. Another important goal is to develop the technological platforms for better and more coordinated use and obervations in ice covered waters. The fieldwork is based on a coordinated use of the Norwegian research vessels, particularly the new Norwegian ice-going research vessel *Kronprins Haakon* (in operation by 2018). The research vessels will also act as platforms for airborne activities and underwater robotics (Appendix i).

The approach to identify physical drivers and ecosystem responses includes a “space-for-time” strategy, e.g., the investigation of various environmental settings along physical gradients (i.e., transects shown in Fig. 6) within the limited time available during expeditions (timeline for fieldwork in Fig. 7). Along the main transect (black line through the boxes in Fig. 6), boxes indicate sites for process studies associated with regions of contrasting physical gradients. The transect includes the Atlantic influenced regions in the south, the Polar Front and Arctic influenced inner shelf, the Arctic and Atlantic influenced northern shelf, and the shelf break adjacent to the deep Arctic Basin (Figs. 2, 6). It will be investigated annually over five years for time-series studies. High spatial resolving transects will typically be made while going north. Process studies will be carried out during the returning south-going transect at key locations identified during the northward transect. In 2018 and 2021, the investigation region will be extended to include the Russian territories (through APN participation in synoptic cruises with parallel sampling activities as part of a Russian federal research project (MEMO-PRO), using Russian vessels). In 2021, the *Nansen Legacy* main transect will be extended deeper into the Arctic Basin, returning through the Fram Strait to extend the observational coverage (i.e., into the more central Nansen Basin domain and downstream of the Arctic Basin transpolar drift to include the integrated Arctic Ocean signal leaving the high Arctic with sea ice and water masses through the Fram Strait), providing a context to the observations north of the Barents Sea. Existing and new technologies will be tested and developed for improved future observation strategies. During one year (autumn 2019–summer 2020), a major effort will be made to cover all four seasons, including winter, which typically remains a main knowledge gap. This coincides and will be coordinated with the international MOSAiC trans-polar drift on regional intercomparison and interdisciplinary processes, and Arctic Amplification (AC)[3] on airborne campaigns. Ship-based data collections will be supplemented with time series provided by moorings (see RFs 1–3) at strategic locations (see Fig. 6), and with satellite observations obtained from Synthetic Aperture Radar- (SAR) and optical satellites (relevant

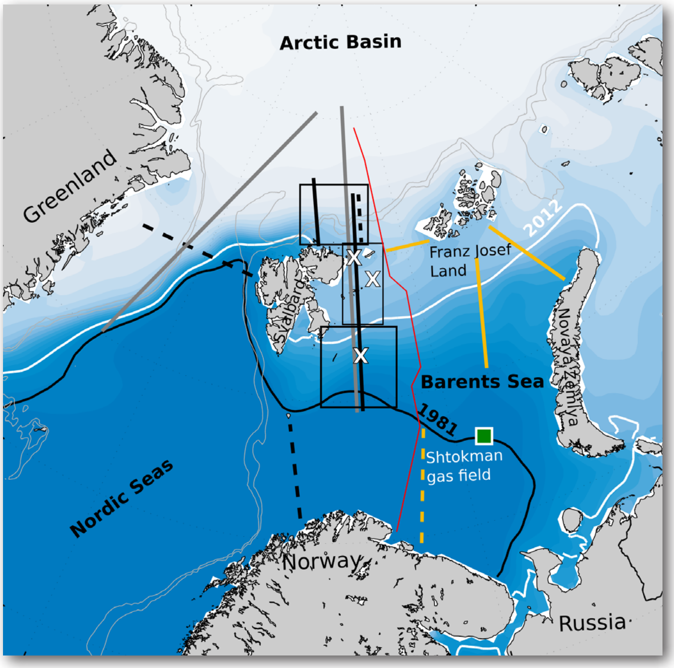

Figure 6. Realizing the *Nansen Legacy* in the field. The maximum wintertime sea ice extend situation observed from satellite, exemplified for 1981 and 2012 (where the ice-edge is defined as 15% ice concentration), and showing the location of the Shtokman gas field in what has become ice-free water. The color shading indicates sea-ice concentration climatology (mean between 1980-2012) scaled from 0-100% with 5% isolines (based on Årthun et al. 2012). Depth contours show the 500 m and 1000 m isobaths. Focus areas and sampling transects of the *Nansen Legacy* fieldwork are indicated. Transects run across gradients in the physical and biological environment, and across the main ocean currents connecting the Barents Sea with the Nordic Seas and the Arctic Basin (see Fig. 2). **Black solid lines**: transects sampled annually and in every season; **grey lines**: extended transect into the Arctic Basin with exit through the Fram Strait; **yellow lines**: proposed transects for Russian-Norwegian cooperation; **black boxes**: focus areas for process studies; **dashed lines**: existing transects covered annually by IMR and NPI as part of monitoring programs (mainly sampled in August); **white crosses**: moorings to be deployed during the *Nansen Legacy*. Ship-based and mooring-based observations are extended with technologies for multisensory and multidisciplinary field campaigns (Illustration M. Årthun, UiB).

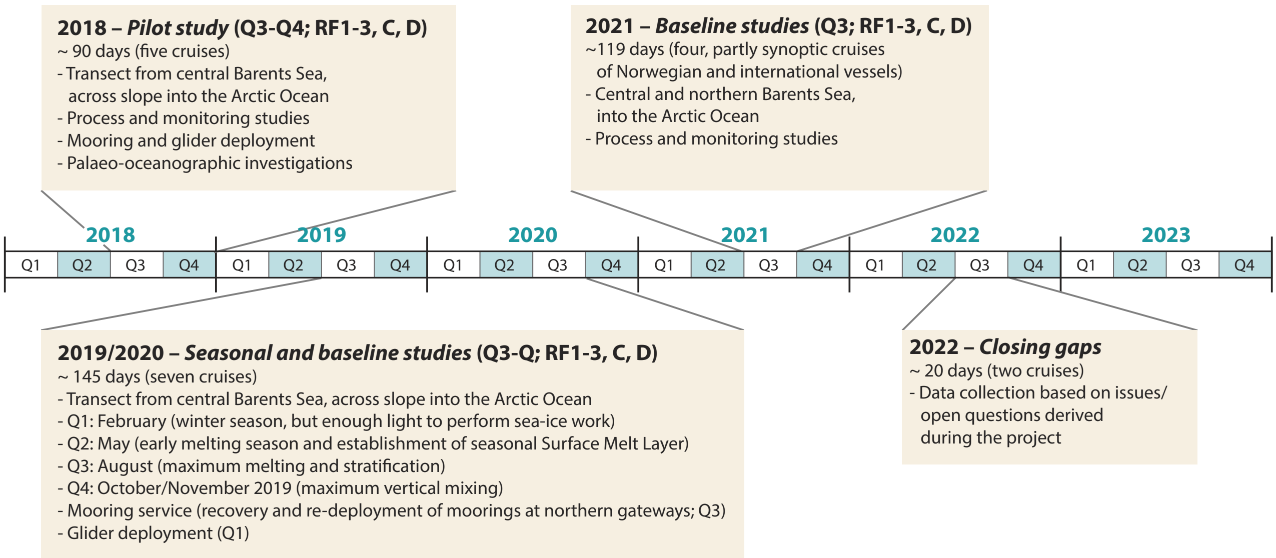

Figure 7. Timeline for fieldwork during the *Nansen Legacy* project.

satellites listed in Appendix i on infrastructure). The observational effort links to the broad group of modelers involved. They will link to each other and with the observationalists as described, e.g., in RFs 1 and 4, and summarized in the model inventory of Appendix ii. One cruise in 2018 will focus on investigations of the sea-floor and sub-seafloor for paleo-environmental reconstructions.

A total of about 370 days of ship time, starting in 2018, is planned with a total of 12 000 days of personnel at sea. In addition to scientists and relevant technical staff, personnel from RA-C (Technology and method development) and RA-D (Impact and Legacy) will participate in the cruises, and the data collected will be made accessible through data bases as described in RA-B (Data management and synthesis) and the *Nansen Legacy* Data management plan (Appendix iii). Some berths on each cruise will be made available for international and national colleagues to participate in the fieldwork. This will be coordinated with appropriate international and national initiatives to facilitate synergy and synoptic sampling. Ship time is owned by the participating institutions, and will be provided based on applications to the local and national vessel organizing committee. Both RA-A leaders are members of the *Kronprins Haakon* vessel organizing committee, and will ensure a close contact with the operating organization at IMR. The *Nansen Legacy* project will have priority as part of the institutional support.

The fieldwork is complemented by using models, ranging from conceptual via statistical to full Earth system models (cf. RFs 1–4 and Table 2 on model tools). Sufficient observations are necessary for the evaluation and "training" of models. Models provide a framework for assessing mechanisms and quantitative links indicated by the observational record or more generally hypothesized in RFs 1–4, and observations can be guided by model output. Prognoses and, more specifically, predictions of the future are generically model based, with weather forecasts and climate model projections being most pertinent examples. The use and improvement of adequate models are cornerstones for the convergence of RFs 1–3 findings into the synthesis and future outlook of RF 4, and this outlook's manifestation in RA-D Impact and Legacy.

RA-A overarching tasks (T)

TA-1 ***Cruise-plan development:*** Coordinate and integrate the plans for collection of observational and modeling data by all RFs and RAs within *Nansen Legacy* (*Lead* Matthias Forwick, **UiT**, NPI**,** 2 pm)

TA-2 ***Cruise-plan follow-up:*** Coordinate and develop detailed cruise plans across all RFs. Follow up cruise application to the respective local cruise planning committees. Develop logistic support plan. Follow up necessary notifications, permits and registrations. Contracts with external service providers (*Lead Øystein Mikelborg,* **NPI**, UiT, 20 pm)

TA-3 ***Operational/logistic support:*** Logistic support. Ensure the functioning of necessary equipment, packing and shipping to/from ports of departure. Liaison with external service providers (helicopter operators, ports etc.) (*Lead Øystein Mikelborg,* **NPI**, APN, IMR, UiT, 143 pm)

The deliverables for RA-A are materialized in the other RF/RA through the data collection, and the different types of field cruises (pilot, seasonal, baseline, closing gaps) are specified as mile-stones in on-line form. The main risk in the data collection and infrastructure lies in the use of a new research vessel. We evaluate this risk to be small, and not critical. The first 6 months after delivery is dedicated to extensive testing of all planned operations and use of gear, to minimize problems during ordinary cruises. Given delays or problems, the *Nansen Legacy* has planned 4 cruises in a 4 month period, and will have the possibility to transfer critical activities to one of the later cruises. Support has also been offered from UK projects planning synoptic cruises in 2018. In case of long term problems, UiT holds an ice-enforced vessel, RV *Helmer Hanssen*, that can be used in 2019 to catch up on eventual delays. For the Russian cruises, they are organized by Russians as part of a Russian federal project, and do not depend on admissions to western ships or projects. Participants from Akvaplan-Niva are invited to participate based on a collaborative history since 1980s.

2.3.2 Approach to **Data management and synthesis (RA-B)** *Lead* Tove Margrethe Gabrielsen (UNIS)*, co-lead* Øystein Godøy (MET)
Objective: To ensure long term 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.

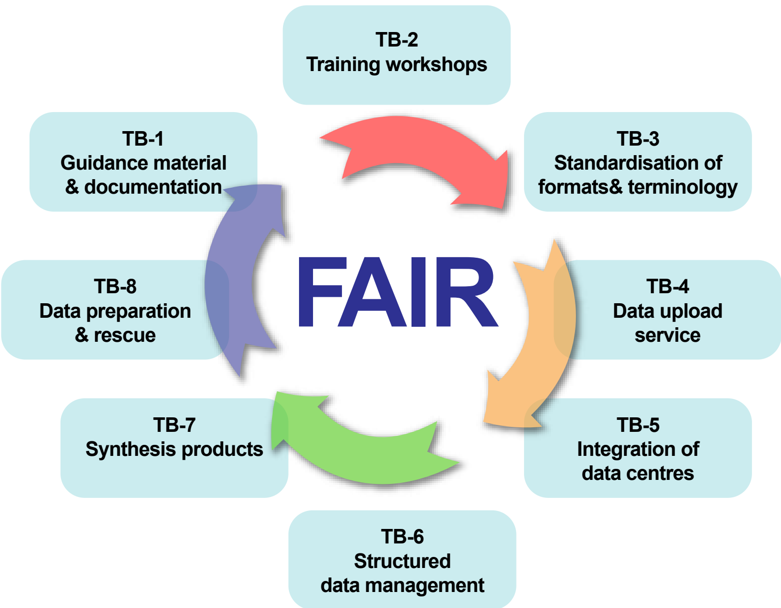

Figure 8. All tasks are connected to the FAIR principles of Findable, Accessible, Interoperable and Re-useable.

Work plan: The work principle of RA-B is FAIR, *Findable, Accessible, Interoperable and Reuseable* (Fig. 8). 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. Structured data management is based on standardized documentation of and interfaces to data, and well-defined procedures for data preservation and governance. This simplifies the process of finding, using, and preserving data. The basic principles for the *Nansen Legacy* data management are a distributed data management system where all datasets are documented with standardised discovery metadata and use metadata (exceptions may occur for some data), governance of data within mandated data centers, but discoverable and accessible through a central hub. This ensures interoperability with national and international systems and frameworks, including WMO's systems, Year of Polar Prediction (YOPP), and many national and international Arctic and marine data centers. Coordination of the *Nansen Legacy* data management is done within the context of the Svalbard Integrated Arctic Earth Observing System's (SIOS). *Nansen Legacy* will address training of scientists in data documentation, sharing of data and integration of data available on-line, long-term data preservation, and data rescue (data at risk or not digitised). Details are provided in the Data Management Plan, which is based on the Digital Curation Centre outline for such plans.

RA-B overarching tasks (T) and deliverables (D):

TB-1 Development of discipline specific guidance material, creation of templates for dataset documentation and documents, references to external best practises etc. This task also includes development of a Data Policy (based on the SIOS Data Policy; *Lead* Helge Sagen, **IMR**, APN, MET, NERSC, NPI, NTNU, UiB, UiO, UiT, UNIS, 4 pm)

TB-2 Training of scientists in general and technicians at KPH through a number of best practise oriented workshops. The objective is to introduce scientists to best practise procedures and show the benefit of structured data management, not only for data publication and preservation, but also for the individual scientific process. This integrates training material developed in SIOS and NorDataNet as well as material developed by the Research Data Alliance (RDA) and the International Council for Science (ICSU) (*Lead* Øystein Godøy, **MET**, IMR, NPI, UiB, UNIS, 4.5 pm)

- TB-3 In order to improve the interoperability of datasets collected and to benefit from the huge scientific effort in the project, a nationally coordinated effort focusing on standardisation within the project and identification of gaps in existing standards is required. The main effort is attributed to encoding and terminology (*Lead* Øystein Godøy, **MET**, APN, IMR, NERSC, NPI, NTNU, UiB, UiO, UiT, UNIS, 3.5 pm)
- TB-4 Implementation of an ad hoc data upload service which routes submitted datasets to contributing data centers for publication and preservation (*Lead* Øystein Godøy, **MET**, IMR, NPI, 2.5 pm)
- TB-5 Adaptation of interoperability interfaces at the central node (SIOS KC). This requires harmonisation of interfaces at contributing data centers linked to a common data model (*Lead* Øystein Godøy, **MET**, IMR, NPI, UiB, 3 pm)
- TB-6 Provide structured data management focusing on long term preservation, accessibility and usability, including the development of a long term data preservation plan incorporating the NorStore and mandated institution archives. This includes conformance checks of data submitted for curation (*Lead* Stein Tronstad, **NPI**, IMR, MET, UiB, 36 pm)
- TB-7 Develop synthesis products and services that provide combinations of data targeted at specific user communities and needs, such as a regional climatology for the Barents Sea and adjacent areas (*Lead* Benjamin Pfeil, **UiB**, IMR, MET, NPI, UiB, 26 pm)
- TB-8 Documentation and preparation of data for sharing and long-term preservation. Rescue of datasets at risk or not digitised data and preparation of these to a form suitable for *Nansen Legacy* (*Lead* Tove Gabrielsen, **UNIS**, APN, IMR, MET, NERSC, NPI, NTNU, UiB, UiO, UiT, 130.5 pm)

- DB-1 Documentation package for scientists and technicians prior to the first field campaign. *Nansen Legacy* Data Policy based on the SIOS Data Policy (M04)
- DB-2 Training workshop for project participants (will be ongoing through the field campaign period) (M01-42)
- DB-3 First discipline specific gap report on data management practise within the community. Initial set of recommendations for the project. This activity is aligned with DB-1 (M11)
- DB-4 First version of project specific ad hoc data upload (M13-M25)
- DB-5 Harmonisation of interfaces at the contributing data centers. Priorities are given to metadata interoperability, for data interoperability, selected datasets will be supported (M30)
- DB-6 A unified overview of the datasets collected, responsible data center and availability (M66)
- DB-7 Provide regional oceanographic climatology for the Barents Sea and adjacent areas using Russian data. Russian meteorological data integrated with Norwegian data from the region (M60)
- DB-8 Documentation and preparation of data for sharing and long-term preservation. Rescue of relevant data sets (M72)

The distribution of pm in RA-B is motivated by the need to involve all partners or institutional data centers in the preparatory work for data management. The main effort is allocated to TB-8 and the documentation and preparation of data for submission to ensure the FAIR principle.

2.3.3 Approach to **Technology and method development (RA-C)** *Lead* Martin Ludvigsen (NTNU)*, co-lead* Frank Nilsen (UNIS)
Objective: To 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.

Work plan: 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 (Utne and Schjølberg 2014; Berge et al. 2015b). To obtain a holistic understanding, a coordinated effort is needed to map climate- and ecosystem drivers over larger spatial and temporal scales, including under ice measurements, by combining high-resolution data and time series of the Barents Sea. For larger temporal and spatial spans, remote sensing is superior for the surface ocean, whereas in-situ instruments carried by the vessels, underwater moorings and vehicles will conduct measurements and samples not obtainable from remote sensing. Especially ice-covered areas suffer from lack of satellite-based remote sensing data on ocean features. To increase the quality of the earth observation system, in situ measurements like sea ice thickness and characteristics, sea surface temperature, Chlorophyll *a* (Chl *a*) and ocean colour will be used to calibrate the obtained remote sensing data, while the remote sensing data can be used as a priori information for vessel based and robotic mapping operations. An overview of satellites that will provide data to the project, is given in Appendix i Infrastructure. The systems and data will be utilized in RFs 1–3 using bio-physical-chemical data from AUV (Autonomous Underwater Vehicles) equipped with sensors including CTD, oxygen optodes, the IOP (inherent optical properties) concentration of Chl *a*, cDOM (coloured dissolved organic matter) and TSM (total suspended matter), ADCP (Acoustic Doppler Current Profiler) for estimation of current velocity profiles and zooplankton biomass, and turbulence parameters in open water and under ice boundary layers (new development in close collaboration with RF-1).

Nutrients and light are important ecosystem drivers (Palter 2015; Rumyantseva et al. 2015), which in turn depend on physical and chemical variables, such as currents, oxygen, salinity, and pH (Sakshaug et al. 2009). Remote sensing data from satellites will be applied for oceanic front detection, in combination with in-situ instruments carried by the vessels and AUVs and gliders, in order to perform air-ice-ocean process studies and to investigate the atmospheric, oceanographic and other physical controls on the distribution of sea ice and stratification in the northern Barents Sea. Moreover, using satellite based remote sensing data (for overview of satellites, see Infrastructure overview, Appendix i), the project will investigate the correlation between estimated Chl-*a* and the characteristic properties of sea ice and the Marginal Ice Zone (MIZ). An important goal is to improve sea ice mapping systems with near real time data assimilations through improvement of automatic sea ice mapping (mainly from Sentinel) and multisensory sea ice analysis (SAR optical, passive microwave) combined with in-situ observations. The *Nansen Legacy* will also contribute to improve the MET Norway's operational sea ice products to local conditions in the northern Barents Sea.

Acoustic data will be the basis for studies of vertical distribution and migration of fish and zooplankton. Data will be obtained from hull-mounted acoustic equipment onboard *Kronprins Haakon,* TS-probes on stations, as well as acoustic equipment mounted on unmanned vehicles. Engineering research is required to develop technologies to increase the platforms' capabilities, e.g., related to acoustic sampling (Handegård et al. 2013). To locate sea-ice and different water masses with the aim of investigating the water mass momentum and heat flux into the northern Barents Sea, gliders and AUVs will also be fitted with direct turbulence sensors in close collaboration with the process studies in RF1. Water sampling by samplers developed from the project will enable the first ever year-round dissolved Fe (DFe), other bioactive trace metals and if needed, macronutrient concentration data from polar waters. This information can also be used in combination with AUV data looking at horizontal and vertical distribution of the variables detected by its sensors.

Autonomous systems have made observations of ocean processes more efficient at varying spatio-temporal scales. A number of systems have been proposed (Faria et al. 2014; Ludvigsen et al. 2016), but these must be further developed for integrated Arctic operations across fronts and under sea ice in order to serve the multi-disciplinary fieldwork in RFs 1–3. New autonomous observational strategies and technology will therefore be developed in order to improve the understanding of bio-physical-chemical processes in RFs 1–3, with a focus on front detection and cross-gradient surveys (temperature, salinity, ocean currents, turbidity, oxygen and zooplankton biomass), vertical and horizontal mixing processes (gradients in temperature, salinity and ocean currents shear), and spectral irradiance and optical properties of sea ice and the water column. There is a need for combined use of robust and reliable autonomous sensor platforms that are able to communicate with each other and adjust their observational strategies, such as airborne drones (UAV), underwater vehicles (ROV, AUVs; AMOS 2015), buoys, moorings, and gliders for Arctic conditions. Autonomous and collaborating unmanned systems in this environment must hence be able to do initial data controls and processing to determine the information that should be transmitted to other nodes in the network, or to the operators (Py et al. 2016).

To accommodate better data collection from the MIZ, under ice robotic operations will be addressed. Under-ice operation in the drift ice is currently beyond state of the art for AUV and glider operation – but technology for such operation will be developed and tested in this RA to enable measurements of nutrients and light together with physical and chemical variables.

To reduce risk related to AUV operation and missions in the high north, risk and reliability studies during the design phase are important. Still, several hazardous events may occur during a mission that can lead to aborted mission, loss of vehicle, and damage to surrounding vehicles or critical equipment. Hence, risk monitoring and risk control during an operation is decisive for efficient risk management and decision support for the human operator. Currently, such monitoring is limited due to the available means for communication between the operator and the vehicle. It is expected, however, that technological development will improve the autonomous functionality of the systems and enable more efficient communication between the vehicle and the operator. This will allow for on-line risk monitoring and risk control of the autonomous vehicles, i.e., improved situation awareness and early warning of deviations and potentially hazardous events during operation. The goal is to reduce the number of serious incidents, and to improve mission success. Input from RF1-3 on environmental parameters important for reliable and risk reduced operations AUVs will be crucial, and forecast models developed in RF-4 will be included in the risk analysis for the AUV missions. The outcome of the work may also be useful for other types of applications and other industries, such as offshore aquaculture.

RA-C will be realized in close cooperation with RFs 1–3 and RA-D (Impact and Legacy). Moreover, the leader and co-leader of RA-C is closely linked to RFs 1–3 (RF1 in particular) with supervision of PhD fellows combining process studies with technology development, and will be participating on most of the planned cruises.

RA-C overarching tasks (T) and deliverables (D)

TC-1 Environmental variables: Identify and implement reliable and robust sensor carrying platforms for autonomous detection of important variables (RFs 1–3) in the Barents Sea, and develop area-tailored methodologies for integrated environmental monitoring using SAR and optical satellite sensors (*Lead* Martin Ludvigsen **NTNU**, IMR, NPI, MET, UiB, UiT, UNIS, 205 PM)

TC-2 Autonomous systems for measurement of key biogeochemical, physical and biological variables: Combine technological concepts with scientific a priori understanding of the processes in the Barents Sea to develop methods and algorithms to measure and analyze biogeochemical physical processes and relate data, including structure and functionality of plankton (primary productivity measurements), biologically mediated carbon uptake and sequestration, and the use of acoustics and optics to estimate key ecosystem parameters. Developing automated detection systems of biogeochemistry and ecosystem structure and functions to provide better measurements and observation for RFs 1–3 in open water and under ice, using unmanned vehicles underwater, on the surface and in the air (*Lead* Frank Nilsen, **UNIS,** NTNU, IMR, MET, UiB, UiT, 144 PM)

TC-3 Next generation observation systems: Study and develop systems (based on TC-1 and 2) for autonomous detection of couplings between forcing, the climate, and ecosystems, and provide an integrated process and observation strategy for managing and reducing operational risks related to the use of the autonomous sensor platforms in TC-1 and TC-2 (*Lead* Ingrid B Utne **NTNU,** UNIS, IMR, MET, UiB, UiT 42 PM)

DC-1 In situ measurements and sampling. Glider and AUV procedures and operations providing data characterise and quantify biota from the different parts of the ecosystem. Under-ice technology development. Under ice operation of AUVs using adaptive mission management providing measurements of salinity, temperature, Chl-*a,* oxygen and turbulence. Autonomous water sampling. Long-term water sampling, System design and water sampling. Satellite based remote sensing. Models for the relationship between Chl-*a* and the characteristic properties of sea ice and sea ice forecast models (M36-54)

DC-2 On-line data processing. Data collection campaigns providing data for RF 1-4 using autonomous systems with automated data processing for adaptive route planning. Adaptive and collaborative strategies. Data collection campaigns providing data for RF 1-4 using multiple and collaborative autonomous vehicles. Instrumentation – UHI. Hyperspectral imaging characterizing the Arctic light climate and conditions for primary production (M48)

DC-3 Risk modelling system. Collaboration with RA-D for innovation and realization. Description of safe states and safety envelopes for the autonomous underwater systems improving robustness and efficiency in Arctic scientific data collection operations (M54)

2.3.4 Approach to **Impact and Legacy (RA-D)** *Lead:* Øyvind Sætra (MET), *co-lead*: Geir Johnsen (NTNU) Please note that the specific *Communication plan* also very much part of RA-D, is provided separately in Appendix iv.

***Objective*:** To 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.

Work plan: The first part of this RA (TD-1 and TD-2) focus on Impact. The vision on communication is to promote interest for and increase the general knowledge about Arctic marine systems, their specific nature and changes, and how they connect across disciplines, latitudes, across the Arctic, and to the society. The project aims to communicate with the general public, the scientific community, actual and potential users, and to decision makers, both nationally and internationally.

A detailed plan for communication with the different groups is given in the Communication Plan (Appendix iv). A new home page aim to reach and connect to both society and research, to provide a knowledge platform, to communicate research, and to connect to the history and spirit of Nansen. The communication plans include a suite of additional platforms like social media, popularized science platforms for different groups and generations, learning resources to schools, an Arctic field course for media, media- and communication training for researchers and students, and a dedicated *Nansen Legacy Year* in 2021, to celebrate the 125 year anniversary of the return of Nansen and Fram from the Arctic Ocean drift expedition. A dedicated communication team from all institutions, holds a broad and complementary expertize (see CV's, Appendix xiii) and will together with the researchers ensure that the communication of project activities, results and relevant themes are in front.

To maximize the impact of the *Nansen Legacy*, the new knowledge and information will be made available to, discussed, and further developed through interaction with users and stakeholders, such as policymakers, environmental agencies, and representatives from the offshore, shipping, and fishing industries, as well as with the scientific community. Dedicated workshops on specific topics will be arranged as part of the Arctic Frontiers conference throughout the project period, and RF4 adresses focus on human impact and development of future scenatios in collaboration with users and stakeholders. The user and stakeholder reference group (see further details in Communication Plan, Appendix iv), will be in close contact with the relevant researchers, the project PIs, and report annually to the Board.

The *Nansen Legacy* will have an important and direct impact on the national research community through recruitment and education of a new generation of scientists and technologists in the Recruitment program. Dedicated interdisciplinary summer schools and intensive courses will be organized to strengthen national and international cooperation and integration of students. Resources for a mobility program (see Budget specifications, Appendix v) will ensure national and international exchange. The use of mobile exhibitions informing about *Nansen Legacy* findings in the project partners' cities will be a powerful way to communicate the overall take-home-messages and to invite and inform the public, politicians, media, and other stakeholders about the *Nansen Legacy*. Communication must reach people with the information they need and in a form they can use. To achieve this, the new knowledge and findings need to be discussed with the users of the information.

The second part of this RA (TD-3 and 4) deals with the Legacy of the project. The *Nansen Legacy* will bring the understanding of the seasonally ice covered parts of the Barents Sea and adjacent seas within the Arctic system to a new level, and in various sectors, the project will result in enhanced knowledge and services for the next generations, through education, mapping, monitoring, and the use of enabling technology and methodology to improve nature management and enhance sound decision making. Usability is a function of how knowledge and information is produced and how it is needed in different decision contexts. To achieve useful information, there should be an iterative dialogue (i.e., co-production) where researchers provide scientific knowledge and end users contribute local knowledge and understanding of the specific problem to be solved.

The *Nansen Legacy* has the ambition to stimulate innovation activities through bringing in new technology ideas and pilot versions into marine science. This will be done in collaboration with RA-C. The gathering of observations in the harsh climate of the Arctic puts special demands on the maintenance and operability of platforms and instruments designed for data gathering at different temporal and spatial scales, and on the *Nansen Legacy* in order to fulfill its ambitions to explore the ice-free areas that emerge due to global warming.

Academic entrepreneurship involves enabling technology and business activities that transform commercially promising research-based ideas into successful innovation. This result will be ensured through a close cooperation between researchers and equipment suppliers, through field-testing and continuous improvement of measurement systems and instrument carrying platforms. NTNU Entrepreneurship School will be actively involved to strengthen the focus on entrepreneurship. RA-D personnel will also work across all work packages in the *Nansen Legacy* to bridge science development. One task here will be to provide review regarding the evolving methods and insights in relevant marine sciences since the ProMare project (1984-1990) to the conclusion of the *Nansen Legacy,* including the use of enabling technology to provide knowledge of the marine ecosystem in the Barents Sea.

The innovation potential in *Nansen Legacy* and future applications to provide better ecosystem management and decision making in the Barents Sea will be evaluated. So will the potential for spin-off activities. Two important deliverables are 1) "Proceedings from the *Nansen Legacy* project" in form of special issues in peer-reviewed international journals, and 2) the new Barents Sea book – The *Nansen Legacy* book. These will be managed in collaboration with the project administration, and developed in collaboration with the project participants.

RA-D overarching tasks (T) and deliverables (D)

TD-1 Impact of the *Nansen Legacy* through outreach and communication. Manage the communication of information to the public through a *Nansen Legacy* web site. Active use of scientific and popular-science publications; TV, social media, newspapers and invite media to join cruises. Arrange *Nansen Legacy* multi-media exhibitions at museums, institutions and science centers with take-home-messages for the public (all age classes), educators, politicians, government managers, and research councils. The next generation scientists and research communicators will be especially important as a target group, and therefore we need to find innovative ways to create interest in the project. This will also be important to reach a younger audience in the public. Details for the communication strategy and plans are outlined in a separate document: External and internal communication plan for the *Nansen Legacy* project (*Lead* Karine Nigar Aarskog **UiT,** IMR, NTNU, NPI, MET, UiB, UiO, UNIS 43 pm)

TD-2 The *Nansen Legacy* impact on international scientists, managers, and policy makers: Produce high quality scientific publications, including special issues in high-ranked peer-reviewed journals. Communicate activity and results to international scientific networks, such as IASC (International Arctic Science Committee) and AMAP (Arctic Monitoring and Assessment Programme). For the sake of recruitment and mobility, a recruitment program matching a PhD school is outlined. *Nansen Legacy* researchers will arrange intensive PhD courses open for national and international students, and facilitate use of existing PhD schools and intensive cources, organize symposiums – including one Pan-Arctic, and sessions at conferences, synthesize the *Nansen Legacy* results for use within the Norwegian Barents Sea management plan, establish user groups and discuss research plans and results with stakeholders and policy makers in dedicated workshops. National and international stakeholders will be involved from the start of the project to ensure involvement and important input to the project, like identifying knowledge gaps. See Communication Plan, Users and stakeholders (*Lead* JoLynn Carroll **APN**, IMR, MET, NPI, NTNU, UiB, UiO, UiT, UNIS, 54 pm)

TD-3 From impact to legacy—lasting effects of the *Nansen Legacy:* Make results from the project accessible to the wider community; implement recommendations from the *Nansen Legacy* in long-term monitoring and knowledge-based management, and provide results and competence to IPCC (Intergovernmental Panel on Climate Change) and other policy processes; recruit the next generation of scientists, technologists and emerging leaders. Assess work, tools and platforms based on the first project period (*Lead* Øyvind Sætra **MET**, IMR, NPI, NTNU, UiB, UiO, UiT, UNIS, 36 pm)

TD-4 The legacy of the *Nansen Legacy*: RA-D will be the main channel for project outreach and its use of enabling technology for marine science in all work packages. This includes support and encourage scientists to transfer technology and application ideas to business development, and arrange innovation seminars and patent courses to promote the commercial potential of new ideas related to instruments designed for Arctic conditions; perform a study of how policies set requirements for technology development for Arctic areas (*Lead* Geir Johnsen **NTNU**, IMR, MET, NPI, UiB, UiO, UiT, UNIS, 36 pm)

DD-1 Develop and manage a new *Nansen legacy* web site, dissemination of *Nansen Legacy* activities and results in media and popular science journals to reach a broad public. *Nansen Legacy* exhibition with take home messages to the overall community (M72).
DD-2 Communicate *Nansen Legacy* information to international scientists, managers, and policy makers through scientific journals, networks, conferences, courses, workshops. Recruitment program. Provide knowledge to stakeholders and users, including managers of the Barents Sea region (M72)
DD-3 Provide *Nansen Legacy* results and knowledge to the overall community with special emphasis on national and international nature management and decision making bodies. Recruitment of next generation of scientists, technologists and leaders (M72)
DD-4 Technology systems and innovation potential for future observations. Proceedings of the *Nansen Legacy* (special issues in a scientific journal) (M72). New book of the Barents Sea (tentative outline by end of 2021, establish an editorial team, final book in 2023)(M72)

2.4 Time line of the *Nansen Legacy* project

The *Nansen Legacy* initiative was taken in 2011, and received a two-year governmental support to develop the consortium and science plan, built on the SAK-perspective (see Section Motivation, page 2; Eldevik et al. 2014a). Following the *Nansen Legacy* Science Plan in 2014, the evaluated proposal to the Ministry of Science and Education in 2015/16 and the funding of a pre-project to develop the present extended proposal, the full project is planned to start in January 2018, coinciding with the delivery of the new Norwegian ice-going research vessel, *Kronprins Haakon*. The pre-project includes a synthesis paper that will corroborate, extend and further update the overarching scientific basis (cf. Section 1; Eldevik et al. 2014a), as well as other necessary preparations for the first planned field season in summer and autumn 2018. As detailed above, important deliverables along the planned project period (Fig. 9) include present characteristics of the northern Barents Sea in both the Norwegian and Russian sector, variability in physical properties in the region the past 12000 years, integrated observations from the next generation observational platforms, as well as ecosystem responses to multiple stressors and general prognostic capabilities, ranging from weather via climate to ecosystem. An important delivery is the recruitment of at least 50 new polar researchers, and forecasts and an outlook to provide the knowledge base needed for an adaptive and sustainable future management. The justification for new data and a need for a holistic understanding of the region includes 1) limited and fragmented existing knowledge from the northern Barents Sea, 2) lack of seasonal coverage, 3) present changes in environmental conditions and ecosystem responses is considerable, 4) the region is of great interest for the Norwegian economy and the society, and 5) the research will provide an important regional contribution from a region experiencing considerable changes to the Pan-Arctic understanding of climate responses. A detailed description of the milestones and timing of activities is given in the on-line application form.

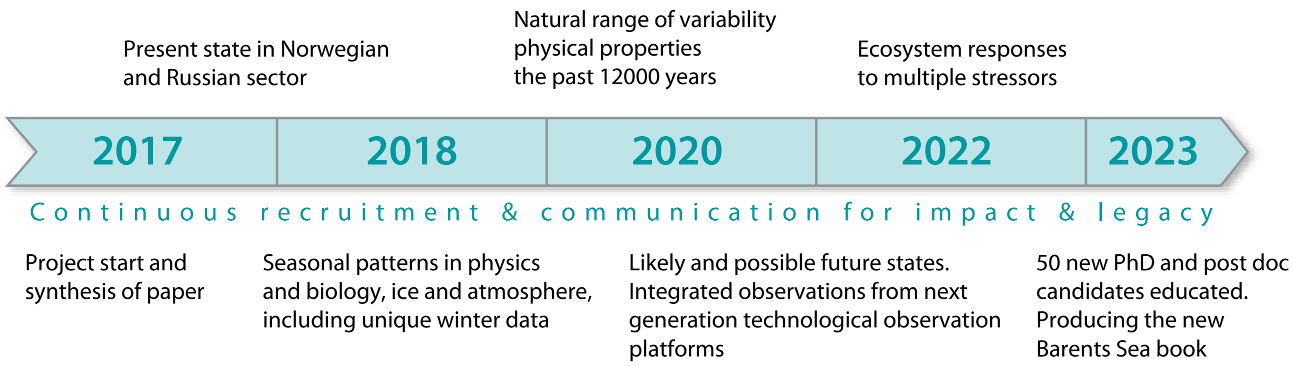

Figure 9. Timeline with important deliverables and expected outcomes and deliveries from the *Nansen Legacy.*

3. The *Nansen Legacy* - project management, organization, and cooperation

3.1 Project management

3.1.1 Principle investigators (PIs, see CV's for details)

The PI, Prof. *Marit Reigstad* (UiT), is a marine biologist, and has extensive experience in research project organization, administration and leadership, international science organizations and planning (ICARP II, IASC marine working group), governmental white paper development (Climate 21), and in supervision of Master and PhD students and post docs. She has been chief scientist on several expeditions in the Arctic. Her science combines primary productivity, vertical export and the role of physical drivers for these processes. She has been leading the *Nansen Legacy* project initiative since June 2015. Prof. *Tor Eldevik* (UiB) is a climate dynamicist originally trained as a mathematician, and a highly experienced research leader, supervisor and public communicator, and presently the Deputy Director of the Bjerknes Centre for Climate Research. His research combines observations and models, and is mainly concerned with the role of the northern seas in climate, ranging from paleo climate via biogeochemistry to present predictability. Dr. *Sebastian Gerland* (NPI) is a sea ice geophysicist and Section leader (Oceans and Sea Ice) at the Norwegian Polar Institute. He has lengthy experience with applied sea ice studies, leading projects and fieldwork, participation in assessments (e.g. contributing author to IPCC AR5 WG1 in 2013, coordinating lead author in Arctic Council/AMAP SWIPA in 2011 and 2017), and in supervising PhD students and postdocs.

3.1.2 Project partners

The project partners include all eight national research institutions with expertise in Arctic marine sciences. Their governmental tasks and competence are complementary, including education and/or management, and their combined expertise, infrastructure, and size provide a unique consortium that will strengthen national collaboration and provide potential for ground-breaking research in Arctic marine science. In addition are two private research institutes with highly relevant expertise in Arctic marine science included. The consortium includes the four largest Norwegian universities; The Norwegian University of Science and Technology (NTNU), University of Bergen (UiB), University of Oslo (UiO) and UiT The Arctic University of Norway (UiT), plus the cross-institutional University Center in Svalbard (UNIS), as well as the management-oriented governmental institutions Institute of Marine Research (IMR), the Norwegian Meteorological Institute (MET), and the Norwegian Polar Institute (NPI). The two recently included PI/coPIs private research institutes are Akvaplan-niva (APN), and the Nansen Environmental and Remote sensing Center (NERSC).

3.1.3 Project leadership

The *Nansen Legacy* is a large and complex project requiring a leadership enabling both a realization of the scientific potential in the group and sufficient discipline to meet the ambitions and reach the specific and overarching goals (e.g., Fig. 9). Important tools are the milestones and activity plan (on-line application form) of the project. They reflect the tasks and deliverables outlined in the proposal. Background documents (not included), in form of RF/RA specific workplans, provide further details to ensure a sufficiently detailed description of activities (sub tasks with sub task leaders), measurements and specification of recruitment positions (timing, theme and supervision responsibilities) to plan and coordinate all aspects of the work within and across RF/RAs. Together, they.will be used actively to visualize common goals, plan the process and to measure progress. These workplans will be updated along the project period. The project leaders will take part in the science activities, and keep a good dialogue with scientists, students and technicians involved to be informed and use the competence in the team to succeed. The PI/co-PIs are mid-career scientists, with complementary scientific specialization and institutional background. This strengthens the ability to lead a multidisciplinary project like the *Nansen Legacy*. The PI/co-PIs have worked together on the *Nansen Legacy* project development since 2012, filling different roles, and are well teamed.

PI Reigstad will be the scientific leader of the project, and coordinate the project activities. An executive manager will handle the administrative leadership and partner relations of the project. One administrative and one scientific advisor, also involved in science communication will provide support on scientific coordination, activities, reporting and development of end products, and be responsible for budget, follow up on financial progress and reports, and support on administrative coordination. A communication advisor (50%) coordinates and facilitates internal and external communication. For logistic organisation, one person is dedicated to infrastructure and field administration and coordination, in collaboration with RA-A leaders. A full position is also dedicated facilitating the data management in collaboration with RA-B leaders and data managers at all involved institutions, and located at UNIS, in association with SIOS. The project administration has responsibility to follow up and coordinate the scientific, administrative and economical project plan, but also an overarching role including a strong involvement in the communication of project results in collaboration with RA-D and the communication team from all involved institutions. The PI functions as secretary for the *Nansen Legacy* Board (see Section 3.1.4). The scientific project leadership also includes the two co-PIs. The co-PIs take part in the scientific strategic decisions, administration and planning, ensuring progress and coordination across

RFs/RAs, and project activities including national and international collaboration, impact and legacy. The RF/RA leaders are responsible for biannual progress reports, to evaluate the progress, present scientific findings and plan the coming period. The Project leader team (PIs and RF/RA leaders/co-leaders) has developed this project together since 2012, and has established a well functioning team, as well as common understanding of overarching project goals and the coordination of the tasks within and across the RFs/RAs. The project leader team will meet physically at least twice per year, and use videoconferences for monthly team meetings.

Assessment of research platforms, analytical and integrative tools, and models for prognosis, will be carried out half way in the project to ensure adjustment and optimizations.

Mechanisms for successful functional and timely communication within RFs/RAs, but also between the groups will include joint advising of students and mentoring of post-docs, student mobility, joint contributions to publications and outreach (RA-D) and encouraging researcher mobility.

3.1.4 Project organization, administration, coordination and internal communication

For further details on project coordination, internal communication and platforms, please refer to the Communication Plan (Appendix iv).

The Project Owners with the directors or rectors of the project partners constitute the top decision level in the *Nansen Legacy project* (Fig. 10), and meet annually. A Project Board with appointed members from all institutions, with the member from UiT (coordinating partner) as leader, will govern the project's strategic plans and issues of relevance for the consortium with board meetings when necessary, and at least twice a year. As 50% of the project budget is allocated by the partners as in-kind, the investment from the partners in the project is considerable. The Board will meet the User and stakeholder reference group, and the Scientific Advisory Board annually, and both will report to the Board to ensure involvement and to impact decisions. The PI is secretary for the Project Board, to ensure good communication between the Project Board, the project administration and the project leader team. If problems or conflicts arise within the project that cannot be solved by the project administration or leader team, the board will take part in finding appropriate solutions.

The *Nansen Legacy* project includes about 130 scientists from ten different institutions. In addition will about 50 recruitment positions be part of the research project and the core activities in close collaboration with senior scientists and supervising teams**.** All project participants will meet at least once a year during the *Nansen Legacy Annual Meeting*, where scientists, Project Board, Project Owners, Scientific Advisory Board, Users and stakeholders meet. In addition to the project team, representatives of collaborating projects will be invited to the annual meetings for scientific communication, dialogue, planning, integration and team building. In addition to annual meetings, workshops will be organized to address specific topics or groups, and to ensure involvement and dialog with users, stakeholders, industry, international research communities, early career driven activities, or others. For scientists participating in fieldwork, cruises will be an important integrating platform.

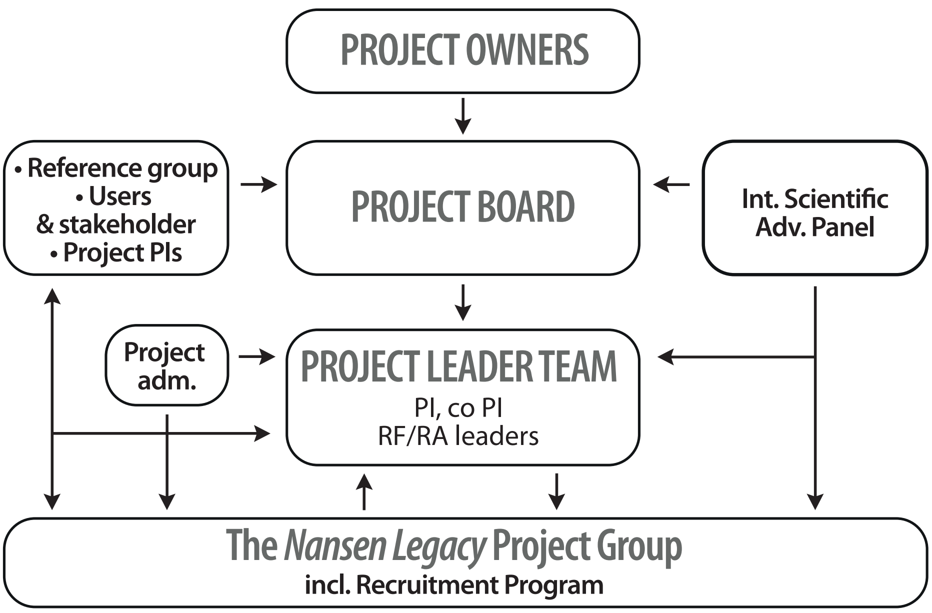

Figure 10. The *Nansen Legacy* organizational structure

Day-to-day project coordination will be carried out by the PI, an executive manager, the two co-PIs, the administrative and scientific advisor, the communication advisor, the logistics responsible and data manager. Project activities are planned, coordinated, carried out and evaluated in close communication with all RF/RA leaders and co-leaders, who together comprise the Project Leader team. The PI and administrative team (except data manager) is co-located at UiT. Videoconference will be used for weekly contact with the co-PIs. The Project leader team will meet at least twice a year, but members will in general interact continuously if more informally.

An international Science Advisory Board is established both to provide scientific advice and to link the *Nansen Legacy* to international activities, securing synergy and coordinated international efforts (for further details, see Section 3.1.5). All work in the project is organized in thematic Research Foci (RFs 1–4) and crosscutting Research Activities (RAs A–D; Fig. 5). Each RF and RA has a leader and a co-leader, representing different institutions and science disciplines to ensure an integrative perspective and cooperation within and across RFs and RAs. Each governmental consortium institution leads one RF or RA.

3.1.5 International Science Advisory Board

To support the projects strong national integrative motivation, a Scientific Advisory Board with renowned international experts who are central in the development of their respective countries' research plans for the Arctic Ocean, will contribute advice to ensure the scientific quality and successful completion of the *Nansen Legacy*. This international Scientific Advisory Board will provide a top-level international network for the project's pan-Arctic integration. The Scientific Advisory Board will participate in annual meetings, and contribute to integrating the *Nansen Legacy* science within the international arena, adding to the established excellent international network of all members of the project leader group and consortium institutions. The members of the advisory board are appointed by the *Nansen Legacy* Board for 2 years, with possibilities for prolongation. They are selected based on their scientific expertize, research activities and their geographic distribution to provide scientific advice on a broad disciplinary and geographic basis, relevant for the *Nansen Legacy* and a Pan-Arctic integration. The following experts have accepted to serve on the internationally Science Advisory Board to represent a geographic and disciplinary complementary group; Prof. Jacqueline Grebmeier (USA; large multidisciplinary projects, ecosystem response to climate change), Dr. Michael Kärcher (Germany; modeling, oceanography, meteorology, remote sensing), Dr. CJ Mundy (Canada; physical and biological processes in sea ice covered environments), Prof. Søren Rysgaard (Canada/Greenland/ Denmark; structure and function of Arctic marine ecosystems, Biogeochemistry, atmosphere-ice-ocean linkages), Prof. Antje Boetius (Germany; Arctic Ocean deep sea, benthic microbial ecology, carbon cycle), Dr. Derek Muir (Canada; atmospheric transport, distribution, fate and bioaccumulation of contaminants, food web transfer), Prof. Julienne Stroeve (UK; remote sensing of snow and ice), Prof. Timo Wihma (Finland; atmosphere, meteorology, Arctic-mid-latitude linkages, atmosphere-ocean interactions, climate).

3.1.6 National cooperation

The *Nansen Legacy* will provide a core hub and facility for Arctic marine research in Norway in the coming decade by involving such a huge group of scientists representing a broad specter of the Norwegian research institutions working with Arctic marine systems. It will therefore be important to use the *Nansen Legacy* activities as a kernel that can provide and benefit from collaboration with other on-going and planned activities. An important facility that the *Nansen Legacy* can provide is access to ship-time through a number of berths that are reserved for collaboration on each cruise, and through data sharing from extended and/or complementary observations.

Collaboration on sharing of infrastructure has already been discussed with ongoing projects. These projects are lead by PI´s that are part of *Nansen Legacy*, or lead by institutions that are one of the *Nansen Legacy* partners. Collaboration is therefore facilitated. This includes the national infrastructure project *Arctic ABCD* that will deploy and test of ice-tethered technology for coordinated observations (PI J. Berge, UiT, NFR funded), Dynamics of Arctic-Mid-latitude Teleconnections (DynAMiTe) on atmospheric uncertainties (PI Camille, Li, UiB, NFR funded), Center for Integrated Remote Sensing and Forecasting for Arctic Operations (CIRFA) on remote sensing (PI Thorbjørn Eltoft, UiT, NFR), *SIOS* infrastructure on Svalbard on data management (PI OJ Lønne, UNIS, NFR funded), an international project with Norwegian coordination like *INTAROS* on potential use of *Nansen Legacy* cruise for mooring deployment and common interest in data management (PI Stein Sandven, NERSC, EU funded). For other national initiatives like MAREANO (PI Sten Rikard Birkely, IMR) to cooperate on sea floor mapping in the northern Barents Sea will be a common interest, and for the planned international initiative Synoptic Arctic Studies (SAS) (PI/contact person Are Olsen, UiB) for coordination of a *Nansen Legacy* cruise can be part of a larger synoptic study.

We have also been approached by social science initiatives, and the *Nansen Legacy* has agreed to contribute to two proposals submitted in May 2017: Aspects of science communication within the *Nansen Legacy* project in the project *Circles of Science Communication: A processual study of communication in a climate and environmental research project* (PI Benedicte Carlsen, Uni Research) and petroleum path dependency *Continuity and transformation in the Anthropocene* (PI Berit Kristoffersen, UiT) including participating on a *Nansen Legacy* cruise to the ice edge zone to map interdisciplinary science work in the ice covered ocean and interview scientists working on the subject of marine systems.

This indicates the potential for interesting and valuable national research collaboration, expanding the science field of the *Nansen Legacy* project. Collaborating projects and partners will be invited to annual meetings and relevant workshops. Collaboration through common scientific publications or outreach activities is also relevant.

3.1.7 International cooperation

The *Nansen Legacy* team brings a strong international network into the project through all the project members. The *Nansen Legacy* has been promoted internationally, and will link with relevant internationally planned Arctic initiatives in the project time frame. Dedicated agreements on collaboration have been signed with some of these already (see Appendix vii), while others have natural links through participants contributing to both projects. Some berths on each cruise will be reserved for relevant collaborating projects to increase the joint scientific output, and some funding is allocated for logistical support.

The *Nansen Legacy* has proposed a synoptic seasonal study during the one year MOSAiC Arctic drift study (in Oct 2019 to Sep 2020 with the German research vessel Polarstern) to make corresponding and consistent seasonal observations, measurements and sampling in the northern Barents Sea. This will enable regional intercomparison of the crucial climatic and ecosystem processes in the northern Barents Sea and adjacent slope with conditions in the high Arctic Basin and extend the larger geographical context for both projects. The *Nansen Legacy* project will also link to airborne campaigns, linked with MOSAiC, to strengthen and extend observations of boundary layers, radiative fluxes, clouds and aerosols, black carbon carried out by Arctic Amplification (AC)[3] to include also the *Nansen Legacy* main transect. The Nansen and Amundsen Basin Observational System (NABOS, 2002–), Year of Polar Prediction (YOPP, 2017–2019), Synoptic Arctic Survey (SAS, planned for 2020-2021), Distributed Biological Observatories (DBO, ongoing) provide regional and scientifically complementary Norwegian contributions. Cooperation with two new UK projects Arctic PRIZE (PI Finlo Cottier) and CHAOS (PI Christian März) addressing biophysical and benthic processes in the central Barents Sea will provide complementary observations and process studies and facilitate mutual added value. A new IASC endorsed Atlantic DBO initiative (Ingvaldsen and Reigstad) linking time series carried out by an international science community in the Svalbard and Barents Sea region (AWI, IOPAS, NPI, SAMS, UNIS, UiT) will include the *Nansen Legacy* transect and increase the observational frequency at each transect by passing vessels, and also connect the observations using the model of DBO on the Pacific side (Grebmeier et al. 2010). Coupling to the DBO provides a Pan-Arctic link. The ongoing cooperation between Russian and Norwegian management through NPI and IMR will, in addition to the APN collaboration and active participation in Russian Barents Sea research projects, provide a base for cooperation through the *Nansen Legacy*. The international integration will also take place through the international science organizations and activities in which *Nansen Legacy* participants are involved (e.g., ASOF International Steering Committee, Eldevik; IASC marine working group, Reigstad, Ingvaldsen; MOSAiC, Gerland, Gradinger; Arctic Council Circumpolar Biodiversity Monitoring Programme CBMP, Bluhm, Jørgensen; the climate models NorESM and NorCPM contributed by partners UiB and MET are part of the CMIP project under WCRP, the model basis for the IPCC reports; World Meteorological Organization WMO and Year of Polar Prediction YOPP, Godøy).

4. The *Nansen Legacy* resources

The *Nansen Legacy* resources include the intellectual capacity and expertise of the participating institutions, their infrastructure, and a dedicated commitment to provide a 50% in-kind to match the financial frames of 370 mill. NOK suggested from the Ministry of Science and Education and the Research Council of Norway.

A specified budget providing information on the different cost categories, distribution between partners, resources provided as in-kind and requested, and resource allocation to common costs, is included as Appendix v Budget Specifications, and briefly described below.

4.1 Financial framework
The total financial frame for the project is 740 mill NOK over 7 years (2017-2023).

The 2017 pre-project was funded with 10 mill NOK, and matched by the participating institutions to a total of 20 mill NOK.

For the main project (2018-2023) the financial frame of 360 mill NOK (6x30 mill NOK each from RCN and the government). The 50% own contribution that is provided by the consortium both reflects the SAK-perspective (cf. the initial Motivation) of realizing significant added value from bringing together separate governmental competence and resources, and manifests the partners' individual and common dedication to the science, region, and project at hand.

Budget specifications providing detailed information on costs distribution across activities, institutions, year and in-kind versus requested funding, are provided in the Budget specification (Appendix v). Information on the pre-project costs for 2017 is also provided here.

4.2 In-kind resources
The in-kind resources provide a core basis of the *Nansen Legacy* project. It secures the dedicated involvement from the partner institutions' top leadership, but also from the involved scientists and supporting staff. The types of in-kind provided varies between institutions, but is made up by 50% time for personnel, 25% as ship-time, 10% as other operating costs, and about 15% as equipment. This personnel include time from permanent scientific-, technical- and communication staff in addition to recruitment positions part of the universities' base funding from the Ministry of Education and Research. Ship-time is mainly on the new ice going vessel *Kronprins Haakon* but also includes other up-to date research vessels for work in open waters, primarily RV *G.O. Sars*. The partners provide infrastructure in terms of instrumentation, analytical platforms, models and high performance computation time.

4.3 Budget
The budget frame totals 740 mill NOK. Of this total, 50% is contributed as in-kind from the participating institutions, reflecting the unprecedented collaborative effort in this project needed to reach important national goals. The pm's requested will provide salaries for researchers, postdocs, and PhD students, the latter under supervision of senior personnel and their network; all institutions also contribute research time *in-kind*. In addition, universities contribute PhD positions. Ship-time is also provided as in-kind. To cover common costs in the budget, 15% of the total budget has been specified as common responsibility (Common pool). This budget is achieved through a surplus of in-kind from each of the governmental institutions, allocating the corresponding requested funds to the common costs. The costs are specified in Appendix v, and include project administration and coordination, workshops, outreach activities, internationalization, PhD courses, national and international mobility, and costs related to the field activity (i.e. Norwegian rules for cruise allowance, logistics, food onboard).

An extensive and field based research project in Arctic marine regions is expensive. Ship time and cruise allowance (required salary adjustment according to Norwegian regulation of field based research) make up 16% of the total budget. Above all, the proposed work requires intellectual and human resources, hence salaries making up 50% of the total budget. Only the collection of data, material and conducting the process studies in field require 12 000 person days. Analyses of collected material and data processing, non-field based work, publications and outreach activities add to this.

Resources corresponding to 2 pm x 6 years for all RFs and RA-C) and 1 pm x 6 years for RA-A,B and D) are allocated to RF/RA leaders to ensure their capacity to lead the groups. The differentiated resource allocation refers to different RF/RA sizes and expected workload.

The budget is detailed in the online form and with further specifications in Appendix v tables as: 1) Summary of institutional cost distribution to cost categories for the entire project period, 2) an overview of the 2017 pre-project costs (in-kind and requested), 3) distribution of payroll and indirect costs categories with annual resolution, cost distribution of different activities, human resources distributed on RF/RA and institutions, as well as detailed budgets for the Common pool, and all 10 partner institutions. The Budget specification will also provide information on priorities, reasoning of expenses, including high infrastructure costs, and how the project partners will share infrastructure, as outlined in Appendix iii.

5. Key perspectives, compliance with strategic documents and added value

The Arctic and the high north have high political priority and are equally important for organizations concerned with management and environmental issues. One of the key policy objectives of Norway´s High North policy is "to ensure an integrated, ecosystem-based management regime that safeguards biodiversity and provides a basis for sustainable use of resources". The *Nansen Legacy* is deeply rooted in these challenges and objectives.

The wealth of strategic documents calling for increased observations, more knowledge, identification of changes, and understanding responses underlines the importance of dedicated and concerted action to follow the ongoing changes in the north. Relevant Norwegian and international strategic documents include e.g. *Updated Management plan for the Barents Sea and marine regions outside Lofoten, with updated estimates of the ice edge* (Norwegian Parliament White paper 20; 2014-15); *Arctic Visions and strategies* (Norwegian Parliament white paper 7 (2011–2012)); *The high North, visions and strategies* (Norwegian Ministry of Foreign Affairs (2011); Norwegian strategic forum *Climate21* (2010); *Norwegian Strategy Ocean21* (2012); *Norwegian Governmental Action plan Marine Knowledge Boost* (2013); *Norwegian Polar Research policy* (Research Council of Norway, RCN, 2013); *IASC marine working group strategy plan* (2011); the European Union's *Arctic ECRA* collaborative program (2014); *Report on the Status of and Gaps in Knowledge regarding Research and Monitoring for Fish Stocks in the Arctic Ocean* (2015).); International Arctic Science Committee (IASC) ICARP III plan 2016; Germany, *Rapid Changes in the Arctic* 2011; US Interagency Arctic Research Policy Committee *Arctic Research Plan FY 2017–2021*; White House Arctic Ministry meeting 2016; *Norwegian Polar Research Policy 2014–2023*, 2013; *Norwegian Long Term Strategy for Research and Higher Education 2015–2023*; *Norwegian Governmental Marine Strategy*, 2017; *Norwegian Government High North Strategy*, 2017. All these documents emphasize the challenges posed by: 1) the limited amount of knowledge on which to base management of these marine areas; 2) the speed and diversity of ongoing change; 3) that causes and effects of these changes often involve broader regional—or even global—interactions; and 4) the lack of procedures for safe operations.

Furthermore, the *Follow-Up Plan for the Evaluation of Research in Geosciences* (2014), which is a response to RCN´s *Evaluation of Biological and Earth Sciences Evaluation of Biological and Earth Sciences* (2012) concluded that Norway has Arctic and marine research communities at top levels internationally, but also that the Geo- and Bioscience-communities rarely combine their strengths. The *Nansen Legacy* consortium meets this challenge as a large, integrated, national research initiative. This national integration links and builds on several former and present centers of excellence (AMOS on Technology; CEES on Ecology and Evolutionary Studies; Bjerknes on Climate Research), centers of research-based innovation (CIRFA on remote sensing and forecasting in the Arctic, UiT; SAMCoT on technology in the Arctic, NTNU) as well as PhD schools (CHESS on climate change and the Earth system, UiB; ARCTOS on arctic marine ecosystems, UiT). The *Nansen Legacy* thus provides added value and synergy between ongoing merited strategic activities.

5.1 Relevance and benefit to society

The ecosystem of the Barents Sea is the basis for Norway's richest fisheries and the majority of the undiscovered petroleum resources in Norway is expected to be found here. Substantial increase in the human presence in – and commercial exploration of – the seasonally ice-covered northern Barents Sea and adjacent Arctic Basin in the near future makes the sustainable management of the "Norwegian" Arctic a national priority and an international commitment. An immediate need with more recreational and commercial use of the Arctic, is more reliable forecasts of harsh weather conditions. Directly related to the longer time scales, are the prediction and projection of future climate and associated ecosystem change. A much debated and societally relevant research question presently is to what extent Arctic and lower-latitude weather and climate are "teleconnected", and whether a changing sea ice cover and the Barents Sea are particularly causal in this. Regarding the ecosystem, the marginal ice zone is associated with extreme environmental gradients. The relatively accessible Barents Sea offers a unique window to Arctic ecosystem change, and with that the challenge to disentangle what is representative of the Arctic and what is specific to the Barents Sea, providing regional knowledge to a Pan Arctic understanding. The new joint national effort of the *Nansen Legacy* will provide a novel and holistic research platform to establish a scientific basis that is urgently needed *before* exposing the northern Barents Sea and the Arctic Ocean to increased human exploration and commercial activity.

The relevance and importance of this scientific work for society is further emphasized through the user and stakeholder involvement described in Section 5.2, and the compliance with strategic documents and white papers both nationally and internationally described above.

5.2 Involvement of users and stakeholders

Users and stakeholders are of great importance for the *Nansen Legacy* project with aims to establish a knowledge base for future use. A chapter in the Communication Plan (Appendix iv, chapter 5) describes the involvement of this group in more detail. To facilitate involvement, a specific subtask i RA-D, and a task in RF4 is dedicated to activities and interactions between scientists and users and stakeholders. A panel of users and stakeholders including fisheries, oil and gas, tourist and other industries, NGO, AMAP, and management advising panels like the Norwegian and Barents Sea Surveilance Group, Scientific Forum and ICES will be established as part of the 2017 pre-project. The aim is to establish a dialogue with groups that have an interest in the results from the *Nansen Legacy* project, and that can contribute with relevant knowledge and perspectives, to improve the outcome of the *Nansen Legacy* activities or by additional complementary research, or use the results from the project. Workshops addressing relevant themes will be organized annually with participation from relevant scientists in the project, and members of the project leader team. This includes also development of potential future scenarios for the region, with multi-perspective input from scientists, users, stakeholders, management and others, to address preparedness from the different groups. The user and stakeholder group will also participate in the annual meetings, and report to the *Nansen Legacy* Board to inform and impact the decision-making. With a continuous dialogue we can get input of important relevant issues, and we can ensure early and efficient communication of results and main findings. The *Nansen Legacy* wishes to bridge science and society better through this interaction, and will also involve the new generation of researchers in these discussions.

5.3 Recruitment, national and international mobility

Nansen Legacy will secure the recruitment of the future Arctic marine research community by educating a minimum of 23 PhD students and 25 Post docs plus dozens of master students, and facilitate career development for early and mid-career scientists, with a special focus on promoting under-represented groups (see also Section 5.6). The *Nansen Legacy* will facilitate complementary activities in collaboration with industry and non-governmental research institutions, to achieve an enhanced synergy from the initiative.

A recruitment program, corresponding to a national PhD school is detailed and presented in the Communication Plan (Appendix iv, section 3.6). The students and recruits will be trained during field, lab and modeling efforts, where field participation will represent an important arena for integration and training across institutions, disciplines and nationalities. The *Nansen Legacy* project partners will develop interdisciplinary PhD courses, and also offer a broad range of relevant existing PhD courses. The educational component of the recruitment program will therefor develop intensive courses/ "summer schools" bridging disciplines, initiated and developed by the *Nansen Legacy* partners. The program will also select from existing platforms across institutions, including established PhD schools, university study catalogue, UNIS courses on Arctic themes. The educational program is organized as a sub-task in RA-D, task TD-2. Being part of the *Nansen Legacy* project will give the students a unique network including both national and international science collaboration, work in an interdisciplinary and inter-institutional community, involvement in relevant science activities and encouragement to participate as early career scientists in national and international science- and science policy arenas.

Resources have been allocated both to arrange workshops and PhD courses, but also to ensure national and international mobility of students, and through participation of meetings or travel to other institutions for research, analysis or realizing the potential in multi-institutional supervision. Visits to relevant institutions including users or stakeholders can also facilitate knowledge exchange and be a unique training opportunity for the *Nansen Legacy* students. This will also include student exchange across collaborating projects.

5.4 Environmental impact

It is expected that there will be a considerable positive environmental impact from the project, based on the overarching objective of providing a knowledge base for a future sustainable management of the region. No negative environmental impact is expected from the planned research.

5.5 Ethical perspectives

No ethical conflicts should arise from the planned research. Appropriate animal care procedures will be applied according to national regulations for organisms where this is required (decapods and vertebrates, but also including cephalopods).

5.6 Gender issues and career stage

The PI-team consists of one female (PI) and two male professors (33% female representation). The leader group including RF and RA leaders and co-leaders has 33% female representation, and this is also the representation at task leader level. For task leaders in the RFs, the female representation is 50%, while there is a need to increase the female representation in leading positions of the crosscutting RAs. This will be encouraged during employment of personnel for the project. The *Nansen Legacy* project is led by a mid-career generation of Arctic researchers. In Norway, PhD students and postdoc level early-career scientists have increased female representation, so an improved future balance of gender in higher-ranking positions is realistic, given the recruitment and training of early-career scientists through the six-year project period. The *Nansen Legacy* will contribute actively to an improved gender balance through good role models, mentoring, and special focus on early-career scientists and disciplines where the gender balance at present is weaker.

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Appendix overview

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The Nansen Legacy in numbers

6 years

The Nansen Legacy is a six-year project, running from 2018 to 2023.

1 400 000 km² of sea

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

>10 fields

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

>350 days at sea

The Nansen Legacy will conduct 15 scientific cruises and spend more than 350 days in the northern Barents Sea and adjacent Arctic Ocean between 2018 and 2022. Most of these cruises are conducted on the new Norwegian research icebreaker RV *Kronprins Haakon*.

280 people

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.

10 institutions

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

50/50 financing

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

Norwegian Ministry of Education and Research

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