Polhavet Arctic Ocean 2050

Science Plan



Front page photo: Institute for Marine Research/ Michael Poltermann

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Polhavet
Arctic Ocean
2050

A 10-year programme for Arctic Ocean research

Science Plan (2026-2035)

Vision: Science for a sustainably managed Arctic Ocean

Mission: *Arctic Ocean 2050* unites Norwegian and international scientific expertise in a 10-year programme to understand the present and guide the future of the Arctic Ocean. Through interdisciplinary research and innovation and international collaboration, the programme will deliver knowledge and tools for sustainable use, conservation, and geopolitical resilience in a changing Arctic.

Arctic Ocean 2050 will pursue its mission through the following overarching research questions:

- What are the mechanisms, trajectories, and impacts of changes in the Arctic Ocean?
- How can scientific and technological breakthrough developed within *Arctic Ocean 2050* contribute to innovative monitoring strategies and next-generation predictive capacities?
- What are the best practices for engagement at all levels and forms of governance to increase awareness and mitigation of risks?

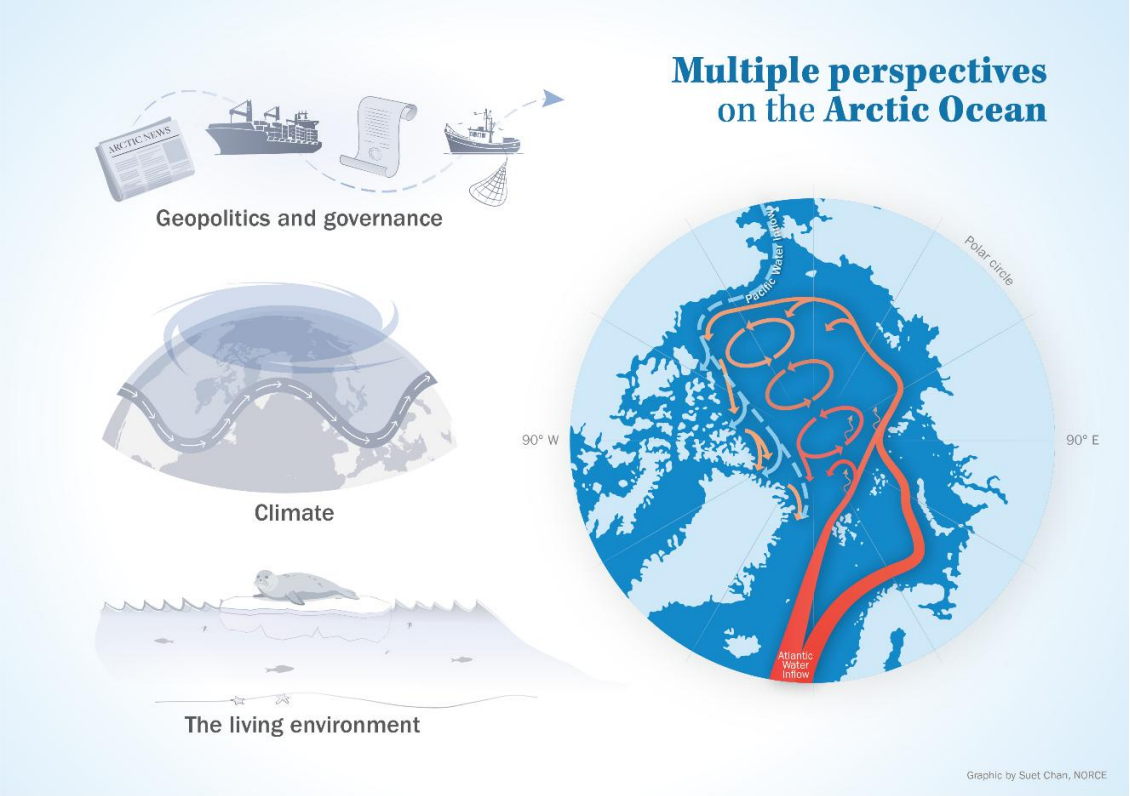


Figure 1: The multiple perspectives of *Arctic Ocean 2050*.

Box 1 | Purpose and Scope of *Arctic Ocean 2050*.

Arctic Ocean 2050 brings together the disciplinary breadth and extensive expertise of the Norwegian research community in a joint interdisciplinary research programme. *Arctic Ocean 2050* will deliver both fundamental and applied knowledge, along with urgently needed forecasts of what the Arctic Ocean will look like toward 2050 and beyond, by conducting novel and integrative research based on the best available current understanding. This 10-year programme will facilitate the development and implementation of science-based management of the new blue Arctic Ocean. This national research programme will demonstrate and strengthen Norway's presence in the Arctic and enhance our international position as a key provider of knowledge and technology. It will also help fulfil Norway's commitments to manage and protect this unique environment. *Arctic Ocean 2050* will leverage Svalbard as a natural springboard for research activity in the Arctic Ocean, thereby contributing to increased activity on Svalbard. *Arctic Ocean 2050* is a Norwegian research programme but will also serve as a natural platform for an internationally coordinated research effort in the Arctic in connection with the upcoming 5th International Polar Year 2032–2033.

Geographical scope: *Arctic Ocean 2050* will focus on processes *within* the Central Arctic Ocean, its interactions with adjacent seas, and how it is part of

larger climatological and political systems. "*Within* the Arctic Ocean", is here defined as the Amerasian and Eurasian basins and the surrounding continental slopes as focus area. As the state of the Arctic Ocean is heavily shaped by extra-regional processes, the scope of *Arctic Ocean 2050* also includes interactions with its marginal seas, such as the Barents and Kara Seas, exchanges with surrounding land and ice masses, and influences from larger political and climatological systems outside the Arctic. The Eurasian Basin, between Fram Strait and the North Pole, and the continental slopes north of Svalbard will be focus areas for field work based both on Norway's regional priorities and logistical reasons related to available ship time and its efficient use. Pan-Arctic perspectives and Pacific-Atlantic connections will be explored by remote sensing and modelling products that cover the entire Arctic Ocean and neighbouring seas, and through broad international collaboration.

Temporal scope*: Arctic Ocean 2050* will investigate past, present, and future changes within the Arctic Ocean on a wide range of time scales. The past includes recent decades when direct observations of environmental change (in-situ and satellite) are available, and the more distant past reconstructed from paleoclimate proxies. Studies of the present conditions will address seasonal, interannual, and decadal variability in state variables and processes in the region. The future time horizon covers both seasonal to decadal predictions and long-term projections toward 2050 and 2100.

The 10-year lifetime of the *Arctic Ocean 2050* programme will allow us to build solid knowledge of the present Arctic Ocean – much needed for addressing potential future changes. The 10-year horizon also allows for the development of new built-for-purpose observational platforms and new modelling tools and provides sufficient time to build relationships with transdisciplinary groups. A 10-year programme is also highly beneficial for the retention of early career researchers by ensuring that funding and career development opportunities extend beyond initial projects.

Disciplinary scope: *Arctic Ocean 2050* will cover physical sciences (from crust to seabed, ocean, sea ice, and atmosphere), biogeochemistry (carbon, ocean acidification, nutrients), the living environment (from biodiversity, food web dynamics to human use), and social sciences (from legal regimes to political, economic, social and security drivers, policies and trends; Figure 1). The interconnections between these disciplines are key to *Arctic Ocean 2050*. It is in these disciplines that consortium partners have built particularly extensive expertise in the Arctic over the past decades, providing ample potential for an impactful programme that integrates the team's comprehensive foundational datasets, knowledge and actions.

To achieve its interdisciplinary objectives, *Arctic Ocean 2050* will make use of data from satellites, planes, drones, ships (including R/V *Kronprins Haakon*), autonomous platforms and sensors, and moored installations. In addition to well-established technologies, new and novel tools will be

developed. *Arctic Ocean 2050* will also make use of recent advancements in numerical modelling and emerging methods in machine learning.

Arctic Ocean 2050 will be actively engaged in developing and implementing transdisciplinary approaches. One of our six research themes (RT6) is dedicated to continuous co-production of knowledge and transformative, extended peer community conversations, between researchers, Indigenous rightsholders, stakeholders and policymakers. These Research Theme 6-led activities cut across all research themes within the programme and take place throughout the programme to shape further research within the ten-year duration of the programme and in policy more generally.

Box 2 | History of *Arctic Ocean 2050*.

The *Arctic Ocean 2050* programme was established by the 18 partner institutions (Table 1) in early summer 2024 merging the ongoing project *GoNorth* with the initiative *Framtidens Polhav/Future Arctic Ocean*. Building on recent efforts including N-ICE2015, the Nansen Legacy, Synoptic Arctic Survey-I, MOSAiC, GoNorth, SUDARCO, the pan-Arctic Distributed Biological Observatory, the ICARP assessment processes, work in the Arctic Council working groups etc., this consortium was extremely well positioned to develop *Arctic Ocean 2050*. A working group (Table 2) tasked with developing the Science Plan for *Arctic Ocean 2050* was appointed by the board (Table 3) in autumn 2024, consisting of at least one member from each of the 18 partner institutions in *Arctic Ocean 2050*, and with complementary expertise across the range of disciplines needed to tackle the scientific challenges in the Arctic Ocean. This working group adopted the Research Theme structure developed for the *Future Arctic Ocean* initiative and developed a draft science plan by February 2025. This was circulated in open hearing round at all 18 partner institutions and thereafter revised based on invaluable feedback from more than 90 researchers across all institutions and many related disciplines. The revised plan was circulated at all partner institutions and with the International Advisory Board (Table 4) over summer 2025, leading to a second round of revisions, which resulted in the version submitted to the Research Council of Norway in December 2025. This final version of May 2026 includes much appreciated suggestions by both the international evaluation panel invited by the Research Council of Norway and, again, the programme 's International Advisory Board.

This 10-year science plan defines the scientific goals and structure for *Arctic Ocean 2050* and describes planned activities at an overarching level. Detailed planning of, e.g., fieldwork, model experiments, specific timing of activities, project organization, and budget allocations are outlined in the accompanying

Implementation Plan. The initial Implementation Plan covers the first three years of the programme (2026-2028). An Implementation Plan extending beyond 2028 will be developed during the initial phase of the program.

Table 1. Consortium of *Arctic Ocean 2050*. Partner institutions listed in alphabetical order.

Akvaplan-niva	APN
Fridtjof Nansen Institute	FNI
Geological Survey of Norway	NGU
Institute of Marine Research	IMR
Nansen Environmental and Remote Sensing Center	NERSC
Norwegian Defence Research Establishment	FFI
Norwegian Institute for Nature Research	NINA
Norwegian Institute of International Affairs	NUPI
Norwegian Meteorological Institute	MET
Norwegian Polar Institute	NPI
NORCE Research	NORCE
Norwegian University of Science and Technology	NTNU
SINTEF AS	SINTEF
Stiftelsen NORSAR	NORSAR
UiT The Arctic University of Norway	UiT
University Centre in Svalbard	UNIS
University of Bergen	UiB
University of Oslo	UiO

Table 2. *Arctic Ocean 2050* – Working Group who prepared this Science Plan and the 2026-2028 Implementation Plan. For organization abbreviations see Table 1. Persons marked with * are Programme co-leaders in the first programme phase.

Chair			**Co-chair**		
Are Olsen (UiB)			Marius Árthun (UiB)		
Research Theme – leaders					
RT1	**RT2**	**RT3**	**RT4**	**RT5**	**RT6**
Marius Årthun (UiB)	Paul Dodd (NPI)	Sissel Jentoft (UiO)	Paul Renaud (APN)	Malte Müller (MET)	Dorothy Dankel (SINTEF)
Research Theme – working group members					
Kari E. Ellingsen (NINA, co-lead)	*Bodil Bluhm** (UiT, co-lead)	Janne Søreide (UNIS, co-lead)	Priscilla Mooney (NORCE, co-lead)	Laurent Bertino (NERSC, co-lead)	Geir Hønneland (FNI, co-lead, after A. Østhagen)
Are Olsen (UiB)	Terje Thorsnes (NGU)	Randi Ingvaldsen (IMR)	Katrine Husum (NPI)	Asgeir Sørensen* (NTNU)	Marius Pedersen (FFI)
*Elana W. Rowe** (NUPI)	Jerry Tjiputra (NORCE)	Steffen L. Jørgensen (UiB)	*Helene Langehaug** (NERSC)	Volker Oye (NORSAR)	Lis L. Jørgensen (IMR)
Trude Storelvmo (UiO)		Vito De Lucia (UiT)	Knut Einar Skodvin (UiB)		
		Ida B. Øverjordet (SINTEF)			
		Øystein Jensen (FNI)			



Table 3. *Arctic Ocean 2050* Board members during the first programme phase.

Jørgen Berge	Chair	UiT
Tore Furevik	Deputy Chair	NERSC
Tor Eldevik	Member	UiB
Maria Fossheim	Member	IMR
Øyvind Paasche	Member	NORCE
Harald Steen*	Member	NPI
Davor Vidas	Member	FNI

*earlier Arild Sundfjord, now programme -co-lead

Table 4. *Arctic Ocean 2050* International Advisory Board members during the first programme phase.

Henry Burgess	NERC Arctic Office	United Kingdom (UK)
Heidi Dierssen	University of Connecticut	USA
Klaus Dodds	Middlesex University	UK
Thomas Funck	Geological Survey of Denmark and Greenland	Kingdom of Denmark
Maria Grigoratou	European Polar Board	Sweden
Martin Jakobsson	Stockholm University	Sweden
Maribeth Murray	Arctic Institute of North America, Univ. of Calgary	Canada
Shigeto Nishino	National Institute of Polar Research	Japan
Rolf Rødven	Arctic Monitoring and Assessment Program	Arctic Council
Marlene S. Hegelund	Greenland Institute of Natural Resources	Kingdom of Denmark
Sarah Strand	Association of Polar Early Career Scientists	-
Jens Terhaar	University of Bern	Switzerland
David N. Thomas	University of Helsinki	Finland
Abbie Thingstad	US Coast Guard Academy	USA
Jeremy Wilkinson	British Antarctic Survey	UK
Eun-Jin Yang	Korea Polar Research Institute	Korea

1. Introduction

1.1 A new Arctic Ocean and the need for integrated research

The Arctic Ocean is the smallest of the world's oceans, yet it plays a critical role in climate, environmental, and political systems. The waters of the Arctic Ocean are vital for global ocean circulation, Arctic ocean-atmosphere heat exchange influences global weather patterns, and its sea ice cover helps to regulate Earth's temperature (Timmermanns and Marshall, 2020, Nicolaus et al. 2022, Rabe et al. 2022, Shupe et al. 2022). The Arctic Ocean is also home to diverse marine species and unique, but fragile, ecosystems (Bluhm et al. 2015, Fong et al. 2024, Jørgensen 2025, Ramirez-Llodra et al. 2024). Because of its strategic location between North America and Eurasia, abundant natural resources, and emerging shipping routes, the Arctic Ocean is significant for security politics and global governance, in changing, intensifying and interlinked ways (De Lucia 2022, Dodds et al. 2025, Jacobsen and Wilson Rowe, 2026).

It is undisputed that the Arctic is the region on the planet that is experiencing the largest temperature rise (Rantanen et al. 2022). Since the industrial revolution Arctic air temperatures have warmed by 4°C. This is three times the global average and most of this warming has occurred during the last four decades. The loss of summer sea ice since the 1980s is one of the most striking results of Arctic warming. In the coming decades the sea ice will continue to retreat, and sea ice-free summers before 2050 seem inevitable for most of the Arctic Ocean (Figure 2). Amid this transition, we are now witnessing significant impacts on the functioning of Arctic Ocean ecosystems, on the accessibility of exploitable resources, and on the broader climate system (Figure 3).

Climate change will continue to alter all aspects of the Arctic Ocean, including its physical, biogeochemical and living systems (Polyakov et al. 2020, Husson et al. 2024, Årthun et al. 2025). The consequences of such changes go far beyond scientific interest, and there is a surge in strategic attention to Arctic issues and opportunities from governments and industries, both within and from outside the Arctic region. The ongoing and anticipated rise in use of Arctic shipping routes and the security and environmental risks that such heightened activity brings to a 'new' Arctic Ocean illustrate the interplay between physical and political, security-related and economic drivers (Østhagen and Rottem 2023).

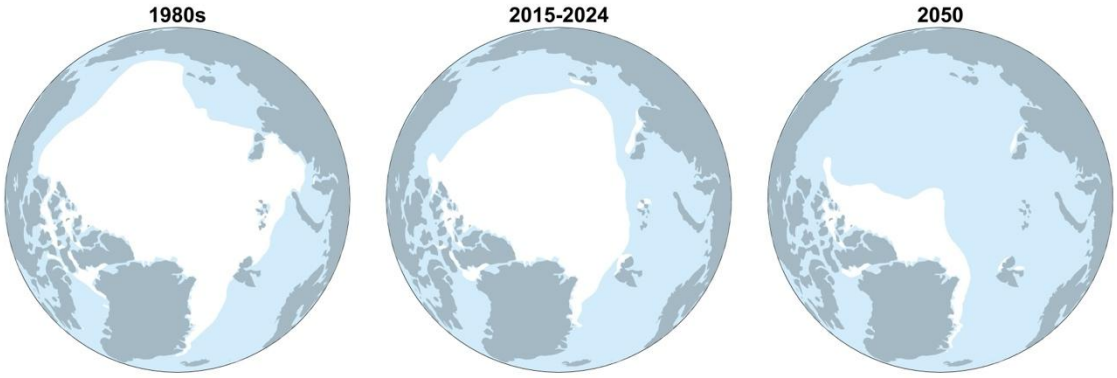


Figure 2: From a white to a blue Arctic Ocean. Arctic Ocean sea ice extent in September defined as regions with sea ice concentration of more than 15%, for a situation typical for the 1980s (5.5 million km^2), the last decade (3.3 million km^2), and for a practically sea ice-free Arctic Ocean (<1 million km^2), which is expected to occur before 2050. The sea ice lost since the 1980s is more than 5 times larger than the area of mainland Norway. An ice-free Arctic Ocean would mean that sea ice corresponding to an area about half the size of Europe is lost. Figure based on data from Jahn et al. (2024).

As the eyes of industrial and geopolitical forces have sharpened their focus on the Arctic – including even the Central Arctic Ocean - for emerging opportunities, we are also becoming increasingly aware of the value and fragility of its marine ecosystems. Sustainability is a key watchword in ocean management in the Arctic and beyond (Steinberg and Kristoffersen 2018), and it is assessed at the levels of the environment, economy, and societies. The rapid convergence of these interests in the Arctic underscores the urgency and need for enhanced scientific exploration in this region's most poorly understood, remote parts where many unknowns remain. Apart from quite basic facts about warming and sea ice loss, knowledge of the drivers and consequences of Arctic Ocean change and how society should respond are woefully incomplete for our region of interest. These knowledge gaps inhibit our ability to define what practices are sustainable and where conservation needs are urgent. Situated in the midst of rapidly increasing geopolitical and economic pressures, time is of essence for building our understanding of how the Arctic system functions in this changing world and how especially the Central Arctic Ocean is shaped by and linked to the rest of the planet.

The Norwegian Arctic research community is now rising to this challenge through a decade-long endeavour in and about the Arctic Ocean; the *Arctic Ocean 2050* programme.

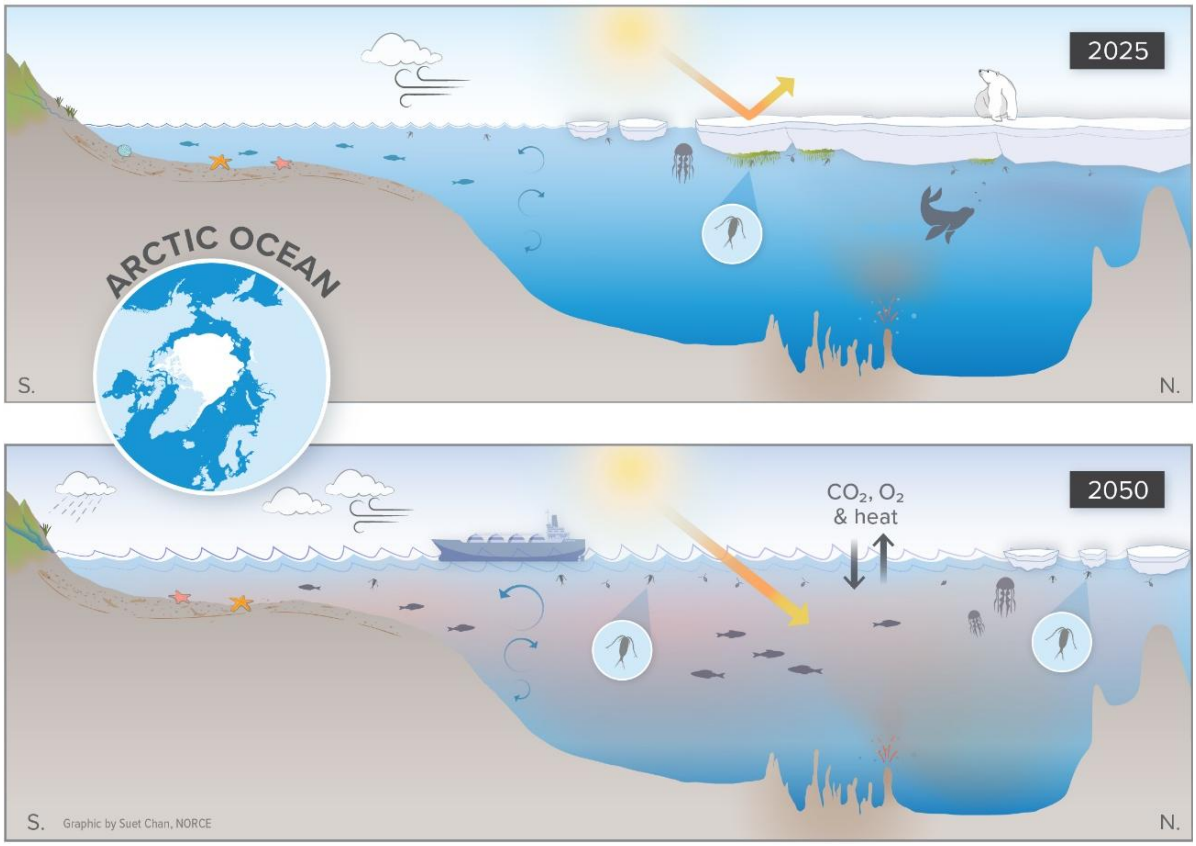


Figure 3: A changing Arctic Ocean. Idealized section across the Arctic Ocean from the shelf to the North Pole showing expected summer-time changes toward 2050, including a warmer, less ice-covered, and more productive ocean, with ecosystem components, including fish populations, and human activity moving northward (note that the schematics are not to scale).

1.2 *Arctic Ocean 2050* – timeliness

Since the first expedition led by Nansen more than a hundred years ago, we have gained much knowledge about the remote parts of the Arctic Ocean, yet many questions remain unanswered. This lack of knowledge is now made especially acute by the rapid changes occurring in the region and the need to improve the scientific basis for sustainable management. The need and urgency for new knowledge are well reflected in international processes, such as the United Nations' Ocean Decade, International Arctic Science Committee's (IASC) Fourth International Conference on Arctic Research Planning (ICARP IV) process, the 5th International Polar Year in 2032-2033, and the United Nations' Decade of Cryospheric Sciences (Figure 4). Norway is one of the internationally leading nations within Arctic research and in a position to fill major knowledge gaps due to our scientific expertise, geographic location, and scientific platforms. Alongside this heightened scientific engagement and concern for a rapidly changing environment, there are expanding, fast-changing and sometimes competing political, security, and economic interests from states and other actors, near and far.

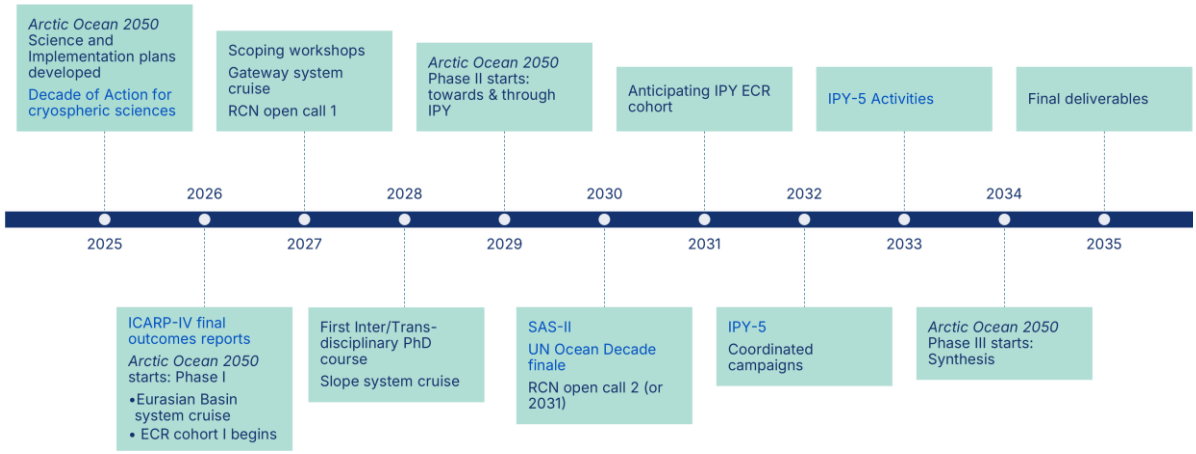


Figure 4: International Context. *Arctic Ocean 2050* in the context of relevant Arctic-focused international processes.

Rapid technological advancements coincide with these environmental and geopolitical changes and offer new and exciting opportunities for scientific research. *Arctic Ocean 2050* will seize the opportunities these advancements offer to accelerate scientific discovery in this uniquely challenging environment. New and emerging technologies include the latest advances in Autonomous Underwater Vehicles (AUVs), Unmanned Aerial Vehicles (UAVs), satellite remote sensing (e.g., CIMR, CRISTAL, ROSE-L), Internet of Things (IoT) & Edge Computing, improved communications infrastructure (e.g., Starlink, OneWeb) that enable remote control of instruments and live data streaming, next generation coupled atmosphere-ocean-sea ice modelling systems, biodiversity assessments using environmental DNA (eDNA), Artificial Intelligence & machine learning, open data platforms (e.g., SIOS, Arctic Data Center), and digital twins of Arctic systems. These advances will empower *Arctic Ocean 2050* to overcome past barriers to scientific exploration posed by the region's characteristic remoteness, extreme

conditions, and rapid environmental changes. Additionally, we aim at taking full advantage of state-of-the-art genomic tools to evaluate the vulnerability (i.e., the adaptive capacity/genomic diversity) and population structure(s) of key species inhabiting the Arctic Ocean, to further advance the development of sustainable management programs.

Arctic Ocean 2050 will position Norway as a central actor in these processes and provide leadership in the international arena. It will enable us to answer the IPY-5's call for global transdisciplinary coordination in the Arctic, essential for accelerating scientific discoveries that are needed to inform and develop sustainable and effective international, regional, and national strategies to mitigate and adapt to recent and future global changes.

As demonstrated by the highly successful *The Nansen Legacy* project, the Norwegian research community has the knowledge, infrastructure, and collaborative capabilities necessary to carry out a large national research initiative across multiple institutions. *Arctic Ocean 2050* will help retain much of the considerable expertise developed within Norwegian institutions, and in doing so, expand upon Norway's leading position in Arctic research.

1.3 Arctic Ocean 2050 – ambition

Arctic Ocean 2050 unifies a Norwegian team of excellence to ensure that:

- ✓ Norwegian Arctic research is bold, novel, and at the forefront of international research in the Arctic Ocean.
- ✓ The sensitivity of the Arctic Ocean to climate change and other external drivers is thoroughly assessed, and we have a quantified understanding of how changes in the Arctic Ocean feedback on regional, hemispheric, and global environments.
- ✓ Ecosystem changes due to warming, sea ice loss, invasive and migrating species, as well as more indirect drivers associated with oceanic and atmospheric circulation and biogeochemical changes, are well understood and can be projected for a variety of future scenarios.
- ✓ Risks for abrupt and extreme events are thoroughly identified and assessed, resulting in high levels of preparedness for coming changes in the marine ecosystem, industrial activity, and geopolitical interactions.
- ✓ The effects of environmental changes in the Arctic Ocean on geopolitical interests and trends, on legal and governance regimes and institutions are understood.
- ✓ State-of-the-art observing and monitoring systems combined with cutting-edge digital-twin solutions provide comprehensive real time monitoring, predictions and projections of environmental change, pollutant levels, and ecosystem state in a sustainable and cost-efficient manner.
- ✓ Norway takes an active lead in educating the next generation of Arctic scientists, fostering inter-disciplinary and transdisciplinary skills and strengthening problem-solving abilities needed to tackle the complex and interconnected challenges of climate and environmental change, conservation, and governance.

- ✓ Collaboration to inform further research and identify science-based strategies for mitigating the risks facing the Arctic Ocean for Norway is pursued through iterative dialogues with policymakers, rightsholders, the public and other stakeholders.

1.4 Arctic Ocean 2050 – novelty

Arctic Ocean 2050 offers a novel and urgently needed interdisciplinary approach by directly linking environmental changes with governance frameworks in the rapidly transforming Arctic region. Our programme will not only study *what* is happening in the Arctic Ocean, but also *how* regional and international governance can and should respond to those changes.

Arctic Ocean 2050 will stand out by **combining disciplines** from natural and social sciences that are rarely integrated in a single effort. While each of these fields plays a vital role in understanding and managing the Arctic, they are seldom brought together in a cohesive research framework. This integration allows for a more holistic understanding of both the natural processes and the human decisions that shape the future of the region.

Past, present, and future environmental changes in the Arctic Ocean, including sea ice dynamics, ocean currents, hydrography, biogeochemistry, and associated ecosystem changes will be investigated using novel multi-disciplinary observing systems and simulations. These physical, biogeochemical, and ecological changes are happening at an accelerating pace and understanding them is critical for anticipating broader environmental and geopolitical shifts. In terms of social sciences, we will explore how security dynamics and global and regional legal regimes (such as UNCLOS and the Polar Code), state policies, and Arctic Council mechanisms respond—or fail to respond—to rapid environmental transformations in the region.

Arctic Ocean 2050 is designed to directly **engage with emerging issues** that have gained new urgency due to global environmental, geopolitical, and technological shifts. The Arctic has become a frontline for understanding and responding to some of the most pressing challenges of the 21st century. As climate change accelerates and global interests in the region expand, new research priorities are surfacing that demand novel, integrated approaches.

One major emerging issue our programme will address is the transformation of Arctic marine systems due to climate-driven changes in sea ice, temperature, and ocean circulation. These shifts open previously inaccessible waters to international shipping, extraction of living and non-living resources, and geopolitical competition. Our research will examine these changes not just as scientific phenomena, but as catalysts for new governance challenges and socio-political tensions.

Arctic Ocean 2050 will harness **innovative methods and technologies** (Figure 5) to better understand and address the complex changes unfolding in the region. Traditional fieldwork in the Central Arctic Ocean has been limited by harsh conditions, high costs, and seasonal access. We aim to overcome these barriers by integrating cutting-edge

tools and techniques that allow for broader, more continuous, and more precise data collection and analysis. Remote sensing technologies and satellite data will be combined with in-situ measurements to build a multi-layered understanding of, e.g., ocean-ice-atmosphere interactions and associated biological responses.

Arctic Ocean 2050 is designed to anticipate and respond to a range of **future scenarios**, recognizing that the region is undergoing unprecedented transformation due to global climate, environmental, and ecosystem change, shifting geopolitical interests, and evolving governance demands. Rather than focusing solely on current conditions, our work is forward-looking, aimed at co-producing knowledge, policy, and strategies with stakeholders, rightsholders and scientific and policy communities about what lies ahead.

By integrating climate projections, ocean circulation and biogeochemical models, sea ice forecasts, and ecosystem studies, we will explore how different warming pathways might reshape Arctic marine systems. Equally important, we will examine how global and regional governance systems and legal frameworks might respond to – or be challenged by – these climate, environmental, and ecological transformations. For example, we will assess the resilience of international legal instruments like UNCLOS, the Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ), and the Polar Code under scenarios involving expanded commercial shipping and increased natural resource development. Our work will identify potential gaps in governance capacity and propose adaptive strategies to address emerging risks.

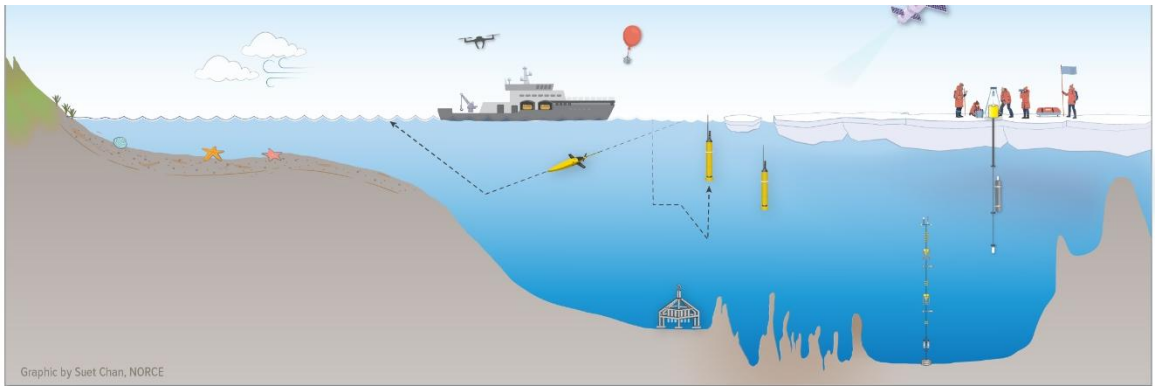


Figure 5: Arctic Ocean observations. *Arctic Ocean 2050* will make use of a wide range of observational techniques and technology, including research ships, autonomous platforms and sensors (e.g., gliders and buoys), moored installations (e.g., for biological sampling at the deep seafloor and for measuring ocean currents), and satellite remote sensing.

2. Relevance of Svalbard

Svalbard plays a central role in Norway's presence and stewardship of the Arctic Ocean. Strategically located at the gateway to the Arctic Ocean, with year-round ice-free harbours and airport access, it serves as an ideal logistical hub for assembling personnel and equipment for field operations aboard *R/V Kronprins Haakon*. Research and education are core activities in Svalbard and are set to be further strengthened in

the coming years, as outlined in the Svalbard White Paper by the Norwegian government in 2024. The University Centre in Svalbard (UNIS) in Longyearbyen is the world's northernmost higher education institution and an Arctic campus for Norwegian universities. Key supporting research and educational infrastructure, besides UNIS, includes the UNIS field station in Svea, one of few field stations worldwide with direct access to sea ice, and the Marine Laboratory in Ny-Ålesund at 79°N. These facilities will serve as important platforms for student training (as described under Section 4, "Cross cutting activities"), equipment testing, experimental research, and process studies. Other relevant infrastructure includes SVALSAT satellite facilities and the Svalbard Integrated Arctic Earth Observing System (SIOS), a collaborative, international effort to develop and maintain a regional observational system and data portal for long-term measurements in and around Svalbard.



Photo: Bodil Bluhm

3. Scientific programme

Arctic Ocean 2050 is a **10-year** concerted programme to provide the knowledge needed for effective management of the Arctic Ocean during the largest transformation of an ocean region ever recorded in human history. However, even if we achieve a perfect understanding of the physical, biogeochemical, and biological mechanisms that regulate the Arctic Ocean, a definite answer to what will meet us farther down the road will not be possible. The fact is that the future of the Arctic Ocean will be largely decided by societal actions, both in terms of climate change mitigation and the ways in which we choose to use, regulate, and protect this dynamic region. These decisions, again, will be influenced by how the Arctic Ocean is transforming, in terms of severity of impacts and the opportunities the changes may offer. Nothing can be seen in isolation. This calls for an integrated, multidisciplinary, iterative, and long-term approach. In response, and reflecting the overarching research questions listed above, *Arctic Ocean 2050* is organized into **six research themes (RTs)** that collectively ensure both inter- and transdisciplinary perspectives (Box 3, Figure 6). The first four RTs focus on closing key knowledge gaps on the region's environmental conditions and influences, marine life, human use and governance, the fifth focuses on advancing technological solutions for better research and management, and the sixth will integrate the knowledge generated in close collaboration with stakeholders and knowledge holders. This integration will ensure that we provide actionable advice and allow us to continually reassess the key knowledge gaps, which will help guide priorities of the programme during its ten-year lifetime. All research themes run simultaneously throughout the 10-year duration of the program.

Box 3 | The six Research Themes of *Arctic Ocean 2050*

RT1: The Arctic Ocean in the World
- Zooming out

RT2: The Changing Arctic Ocean
- Zooming in

RT3: Human Impact and Sustainable Use
- Prospects and consequences

RT4: Abrupt and extreme events
- Preparing for surprises

RT5: Advances in Observing and Modelling
- Innovating for the future

RT6: Arctic Ocean Pathways
- Transdisciplinary connections and actionable knowledge

Research Themes 1 to 4 will explore the Arctic Ocean from four complementary perspectives. Combined, these provide the information that is needed to understand the Arctic Ocean, how our actions shape it, and what is needed to ensure a safe and sustainable future. In RT1, we take a large-scale perspective. This is necessitated by the global and hemispheric nature of the drivers of both change and variability impacting the Arctic Ocean, and of the impacts of Arctic Ocean changes on the rest of the world. In RT2, we focus on the Arctic Ocean itself. Here, we will close existing knowledge gaps on the state of the Arctic Ocean, determine its sensitivity to climate change in terms of the nature of impacts and rates of change, and evaluate how this challenges current regulatory frameworks and how these may be revised. In RT3, we turn to specific ongoing or likely forms of human activity in the future, the risks and benefits that will accompany such increased human activity, and how these activities can be monitored and managed. Finally, we acknowledge that hard-to-predict abrupt change and extreme events can define the evolution of natural, as well as societal systems, and evaluate the likelihood and impacts of the unanticipated in RT4.

While the research in RTs 1-4 will initially be based on well-established technologies, RT5 will improve our capability to observe and model the Arctic Ocean by designing and testing fit-for-purpose sensors and observing systems. We will develop techniques for AI-assisted integration of data into next-generation model systems for better reanalysis, predictions and projections of the Arctic Ocean, ultimately leading to improved Decision Support Systems such as digital twins that can be used to guide management decisions. These novel tools developed in RT5 will be increasingly adopted into the programme as it progresses.

Research Theme 6 focuses on co-producing actionable knowledge from research in *Arctic Ocean 2050* – and shaping the further direction of research in the programme through rigorous, transformative extended peer review conversations, which convene different forms of knowledge. To achieve this, RT6 will take advantage of the knowledge generated in RTs 1-4 and the Decision Support Systems developed in RT5 in a post-normal science framework involving rightsholders, stakeholders, and policymakers.

To reach the vision and mission of the program, *Arctic Ocean 2050* will take an iterative approach. This Science Plan outlines the research priorities as we understand them today but results and developments throughout the lifetime of *Arctic Ocean 2050* will highlight new topics and priorities that need to be addressed.

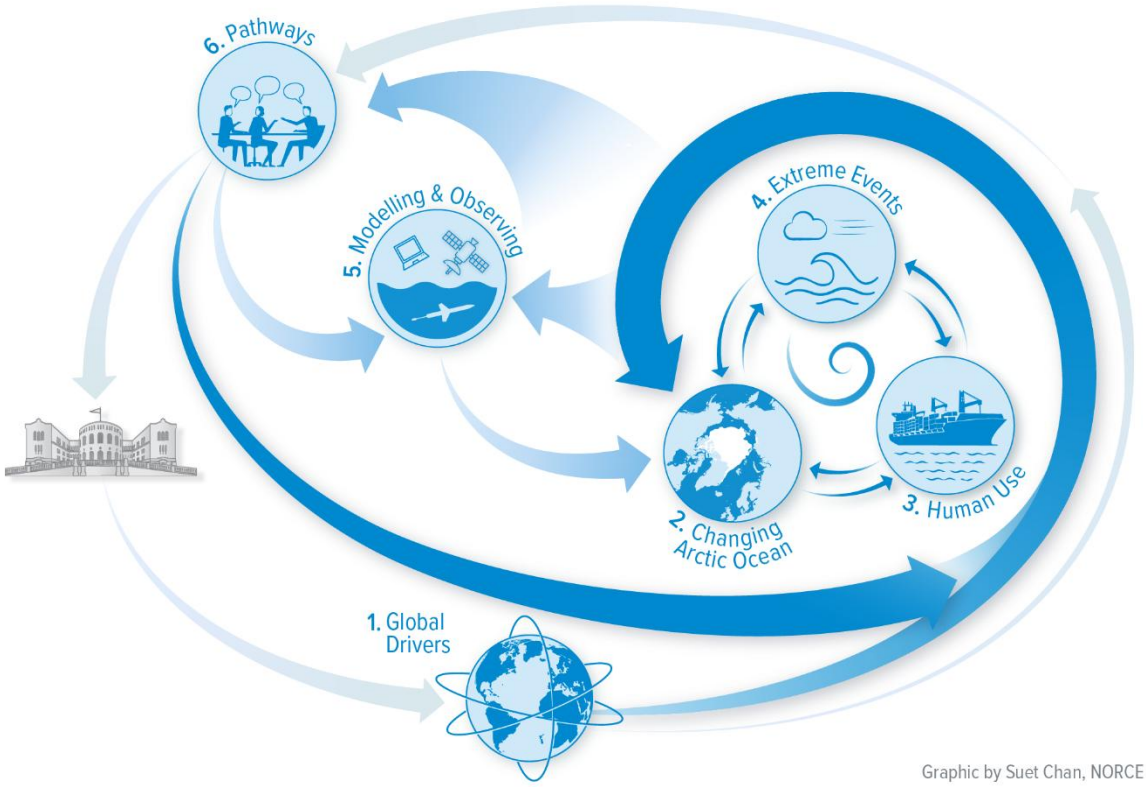
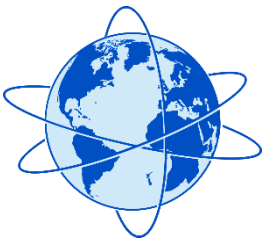


Figure 6: Structure of *Arctic Ocean 2050*. The *Arctic Ocean 2050* programme is organized into six research themes (RTs) that collectively ensure a transdisciplinary approach. The first four RTs focus on closing key knowledge gaps on the region's environmental conditions and influences, marine life, human use, and governance. The fifth RT focuses on advancing technological solutions for better research and management, and the sixth will integrate the knowledge generated in close collaboration with stakeholders.

Research Themes

RT1: The Arctic Ocean in the World

– zooming out



Relevance and Scope

The Arctic Ocean is an integral part of the Earth's natural and societal systems. Ultimately, the transformation of the Arctic Ocean depends largely on broader extra-regional drivers, including climate change and variability (Landrum & Holland 2020), northward expansions of species (Ingvaldsen et al. 2021), large-scale inflows to the region (Polyakov et al. 2020), and broader political, economic, and security-related interests (Friis et al. 2023, Jacobsen and Wilson Rowe 2026, Østhagen 2025). Several drivers influence the physical and biogeochemical properties of the Arctic Ocean, potentially affecting shifts in species distributions, biodiversity, and food-web structure in the region. In turn, Arctic Ocean changes will feed back on adjacent seas, continents and the global environment through impacts on atmospheric and oceanic circulation (Cohen et al. 2020, Årthun et al. 2025), ecosystem dynamics and global governance. The goal of this RT is to **understand the interplay between external processes and ongoing and potential future changes in the Arctic Ocean.**

This goal will be achieved through four priority topics (PT1.1-1.4) that answer the following key questions:

1.1 How are key global and extra-regional processes (political and environmental) driving changes in the Arctic Ocean - and how are and can they be governed?

1.2 To what extent are sub-seasonal to decadal changes in the physicochemical environment in the Arctic Ocean and associated changes in productivity and species distributions predictable?

1.3 How will climate drivers and feedbacks shape the evolution of the Arctic Ocean toward 2050 and beyond, and what are the impacts on species distributions and productivity?

1.4 How will changes in the Arctic Ocean influence environmental and governance systems outside the Arctic?

RT1 will provide an enhanced understanding of the global drivers shaping the Arctic Ocean, and of the external impacts of a changing Arctic Ocean. RT1 is the large-scale counterpart to RT2s regional focus, with both RTs aiming to improve the understanding of key processes governing Arctic Ocean change but at different scales and using different approaches. RT1 will also provide large-scale insights into future Arctic Ocean productivity, biodiversity, biogeochemical cycling, and food-web dynamics that will be investigated in more detail in RT2. RT1 will deliver new, improved predictions (up to 10 years) and projections (more than 10 years) of the Arctic Ocean using traditional and innovative methods, including machine-learning based prediction and downscaling

systems developed in RT5. These predictions and projections will be used throughout the other RTs. Sub-seasonal forecasts provide information at a timescale relevant for extreme events such as marine heat waves (RT4). At longer timescales, decadal predictions and future projections of, for example, sea ice conditions and species distributions, will inform this RT's work on global and regional security dynamics, as well as work on human activities in the Arctic in RT3, thus supporting future sustainable management of the Arctic Ocean (RT6). RT1 will also investigate how predictions and projections of the future Arctic Ocean are shaping broader geopolitical interests and governance aims in this rapidly changing part of the world. Finally, RT1 will assess the wider implications of Arctic changes, including impacts on the Atlantic Meridional Overturning Circulation (AMOC), whose cascading tipping elements in turn could introduce significant disruptions in the Arctic region (RT4).

Priority Topic 1.1: Political and environmental drivers originating outside the Arctic Ocean

Motivation and knowledge needs: This PT addresses critically important research needs about global and extra-regional processes – sociopolitical and environmental – that are driving changes in the Arctic Ocean. This broader focus is necessary as many of the factors shaping the environmental and security-political premises for the Arctic Ocean state and evolution originate and are governed outside the region (Woon and Dodds 2020; Hoogensen et al. 2020; Friis et al. 2023; Jacobsen and Wilson Rowe 2026; Østhagen 2025). Some of these drivers remain poorly understood or are undergoing rapid change, necessitating consistent analytical attention. Interplay across environmental and sociopolitical drivers remains understudied overall.

Objective: Enhance our understanding of the role and interplay of key political and environmental drivers originating outside the region with high impact (demonstrated or likely) on the state and evolution of the Arctic Ocean.

Activities: PT1.1 will identify the major external sociopolitical, climate, and environmental drivers that have or are likely to have a large influence on the Arctic Ocean. These include global efforts to govern a transforming planet from climate and biodiversity through pollution regulation to ocean governance, the dynamics and regional impacts of broader security-political concerns and rivalries, as well as the inflow of heat, moisture, carbon, nutrients and pollutants to the region, both by the large-scale oceanic and atmospheric circulation and by river runoff and land-ocean interactions.

PT1.1 will first examine external and global drivers shaping the environmental state of the Arctic Ocean by analysing historical and present-day observations and simulations to assess the long-range pathways and fluxes of heat, moisture, carbon, nutrients, and pollution into the Arctic Ocean from both the Atlantic and Pacific Ocean. This PT will also investigate emerging scenarios for global greenhouse gas and aerosol emissions, including Arctic Ocean-related implications and risks associated with potential large-scale climate intervention (with PT1.2 and PT1.3).

We will then turn to efforts at the global level to govern these drivers, particularly focusing on international processes and frameworks impacting directly on Arctic Ocean

governance and/or in which there is strong engagement by Arctic actors, from Indigenous organizations (Dahl et al. 2024; Lightfoot 2017) to states. Political and legal processes to be analysed include developments in ocean governance and law of the sea, pollution and greenhouse gas reduction efforts and frameworks, and biodiversity/conservation conventions and initiatives. We will also study how these regimes, constituting a fragmented and complex legal, political and governance puzzle, interact with each other, and seek to identify the key regulatory and institutional challenges and how they may impact the Arctic Ocean.

PT1.1 will also investigate security and foreign policy developments in and around the Arctic Ocean more broadly. This will include research into how the ongoing environmental changes in the Arctic Ocean and predictions and projections (with PT1.2 and 1.3) are shaping Arctic and non-Arctic states' and other actors' security-political concerns and policies (including within the NATO alliance). PT1.1 also directs analytical attention to how extra-regional conflict and security dynamics scope the prospects for Arctic Ocean governance and science cooperation.

Priority Topic 1.2: Near-term predictions of the Arctic Ocean climate and environment

Motivation and knowledge needs**:** Skilful predictions of near-term changes in the Arctic Ocean can potentially strongly support climate adaptation and sustainable management. However, to what extent the state of the Arctic Ocean is predictable remains uncertain. In PT1.2 we will therefore explore the sub-seasonal to decadal predictability of the physical climate, biogeochemical environment, biota, and productivity in the Arctic Ocean. Achieving skilful and useful predictions requires understanding of predictable dynamics and relationships in observations and models. This includes understanding how the Arctic Ocean environment is modulated by variable inflow of, for example, heat, salt, nutrients, and organisms from the Nordic Seas and the Atlantic (PT1.1; e.g., Fransner et al. 2023).

Objective: To explore and improve the predictability of the physical climate, biogeochemical processes, and biota in the Arctic Ocean, how it relates to extra-regional drivers, and how this information can improve Arctic Ocean management.

Activities: In PT1.2, we will examine the predictability of the Arctic Ocean at sub-seasonal to decadal timescales. We will distinguish predictability originating from outside (e.g., upstream changes in ocean circulation, with PT1.1) and within the Arctic Ocean (e.g., changes in sea ice thickness or atmospheric circulation, with RT2). Anthropogenic factors (e.g., greenhouse gases or aerosols) that can add predictive skill will also be considered. PT1.2 will cover observed and modelled present-day conditions, the reconstructed past, and the simulated future, to establish to what extent variability and predictability of the Arctic Ocean differ for different climate states.

Predictability will be assessed for physical, biogeochemical, and biological systems. For the physical environment and biogeochemistry (including e.g., sea ice cover, ocean temperature, nutrient availability, primary production, carbon uptake, and ocean acidification), predictability will be examined using the NorCPM (Norwegian Climate Prediction Model, based on the Norwegian Earth System Model; NorESM; Bethke et al.

2021) as well as output from model ensembles within the CMIP Decadal Prediction Project (DCPP). Coupled climate models, such as NorCPM, have large uncertainties within the Arctic Ocean, and predictable relationships and physical processes will also be assessed in observations and regional high-resolution ocean models and reanalyses (with RT2 and RT5).

We will also explore the predictability of climate-driven poleward redistributions of species, using different approaches depending on whether the species are passively transported, redistributed by migration, or introduced by human interventions. For passive transport of plankton, including fish larvae, we will use hydrodynamical models including sea ice. Whereas poleward transport may have always been the case, climate-related changes within the Arctic may lead to the establishment of populations of species that are transported into the region. To examine species distributions at higher trophic levels (fish, seabirds, marine mammals, benthos) we will evaluate existing modelling approaches (species distribution models; Isaac et al. 2020; Karp et al. 2025) and develop models suitable for high latitudes if needed (including phenology and light conditions). Species may establish permanent or temporary populations, or they may use the region during different life stages. Since the potential future migration of species into the Arctic Ocean will be from the adjacent regions, we will identify ongoing changes in these areas, using, e.g., environmental DNA metabarcoding/metagenomics to characterize biodiversity in water, and tracking and monitoring seabirds. Additionally, we will use the recent developments in high throughput sequencing technologies to characterize the sub-population structuring of key fish species in the pan-Arctic region and evaluate if some sub-units are more likely to contribute to the northward expansions than others (Theissinger et al. 2023, Bernatchez et al. 2024).

Priority Topic 1.3: Long-term projections of the Arctic Ocean climate and environment

Motivation and knowledge needs: Despite decades of research, the key drivers of long-term Arctic climate change remain poorly quantified, and the environmental implications are only partly understood (Fox-Kemper et al. 2021). To what extent is the amplified Arctic warming caused by changes in heat transport to the region (addressed in PT1.1), versus amplifying feedback mechanisms in the Arctic itself? And how are long-term climate projections shaping political, economic, and security planning around the Arctic? What are the relative contributions of climate-driven influx of species from neighbouring seas and environmental alteration (within the Arctic Ocean; RT2) to biodiversity changes in the Arctic Ocean? These are some of the questions that must be answered to improve long-term projections of the Arctic Ocean and assess implications across a range of disciplines.

Objective: To develop plausible storylines for the long-term (decade- to century-long) evolution of the climate and environment in the Arctic Ocean and project associated long-term species redistributions into the region.

Activities: In PT1.3, we will use Earth system models to investigate future changes on decadal to centennial timescales, complementing the shorter-term predictions in PT1.2. Identifying which changes are robust across model ensembles is important to this activity, and we will use both novel (e.g., machine learning) and established tools to

identify the most credible models based on observational constraints. Projections of the future Arctic Ocean will be compared with paleoclimate data contributing to the assessments and improvements of Earth System Models, including NorESM.

Arctic climate feedback mechanisms, for example involving sea ice, clouds, permafrost, or marine carbon uptake, must be better understood and constrained. Here, we will use in situ and satellite remote sensing data from the Arctic combined with machine learning (from RT5) to improve process understanding (with RT2) and parameterizations in Earth System Models, to ultimately improve long-term Arctic climate projections and identify any signs of nonlinearities or tipping point behaviour (with RT4).

The above activities rely heavily on Earth System Model ensembles, and NorESM in particular, so model assessment and improvements are central to this PT. For example, Earth System Models currently fail to predict the same extent of Arctic amplification as observed and disagree in projections of key properties like ocean stratification; are these symptoms of missing or misrepresented processes, or explainable by climate variability (PT1.2)? In the former case, we must identify which processes have to be improved (e.g., through sensitivity analyses), refine key process representations (e.g., through higher spatial resolution), and how machine learning can be used to leverage Arctic observations for the benefit of model improvement (with RT5). Paleoclimate records (e.g., from high-temporal-resolution sedimentary archives) can be particularly valuable in this regard, as they give insights into vastly different Arctic climate states against which models can be tested.

Once we have confirmed that the models are “fit-for-purpose", they can be used to generate long-term projections for the Arctic Ocean for different scenarios of, e.g., global governance and technological shifts. Relevant climate scenarios will also serve as input for species distribution modeling (building on PT1.2) to generate long-term projections of redistributions of both commercial and non-commercial species (e.g., fish, seabirds, benthos) into the Arctic Ocean. The long-term projections generated within PT1.3 will serve as crucial input to the other RTs.

Priority Topic 1.4: External impacts of a changing Arctic Ocean

Motivation and knowledge needs: “What happens in the Arctic, does not stay in the Arctic” was noted by Vidar Helgesen, former Norwegian Minister of Climate and Environment, at a NATO Parliamentary Assembly meeting in 2017. Although a major focus in RT1 will be on the global drivers shaping the Arctic Ocean, the melting of the sea ice and transformation of the Arctic Ocean may also have large-scale consequences with important extra-regional, hemispheric and global impacts. Arctic Ocean changes may affect external regions both via the atmosphere and the ocean. Arctic countries, peoples and communities (e.g. Saami Council 2023, p. 38-40) and a broader global audience thus need better knowledge about the potential impacts of a changing Arctic Ocean on adjacent regions and the rest of the world.

Objective: To investigate the external impacts of a changing Arctic Ocean with a transdisciplinary approach, ranging from physical, biogeochemical, and biotic changes in neighbouring seas and up to global climate, environmental, and governance systems.

Activities: In PT1.4, we will investigate the effects of ongoing and future sea ice retreat on ocean-atmosphere heat fluxes and atmospheric structures such as the positions and intensities of the polar vortex and the jet stream. The implications of these changes for atmospheric circulation and weather across the northern hemisphere will also be examined.

We will examine how Arctic Ocean changes impact neighbouring seas in the Atlantic sector (Barents Sea, Nordic Seas, Irminger/Labrador Seas), focusing on changes in freshwater and nutrient exports from the Arctic Ocean to these regions and how this will impact mixing, deep water formation and carbon uptake, and primary production, in conjunction with other drivers such as the freshwater input from the declining Greenland ice sheet. We will assess the wider implications of changes in Arctic deep-water formation, including impacts on the AMOC and associated carbon sequestration. AMOC is a hypothesized tipping element in the climate system that is believed to be sensitive to high-latitude freshwater fluxes (Dijkstra and van Westen 2025). A collapse or slow-down would have dramatic consequences for the climate of not just the Arctic Ocean but the entire planet (with RT4).

The potential ecological implications of a changing Arctic Ocean on neighbouring seas, such as the ecologically and economically important Barents Sea, will be evaluated using new knowledge on exports of heat, freshwater, nutrients, carbon, etc. from the Arctic Ocean. Changes in abundance and distribution of species living adjacent to the Arctic Ocean (benthos, fish, seabirds, marine mammals) and potential for redistribution between non-adjacent regional seas (i.e., via the central Arctic Ocean) will be estimated using statistical and trait-based models based on existing survey data (e.g., north of Svalbard, northern Barents Sea). The ramifications for the ecosystem services in these adjacent regions, e.g., food production and carbon storage, will be assessed on the basis of the model predictions.

Finally, we will evaluate the eventual global normative and policy repercussions of potential Arctic specific climate interventions, e.g., technologies to refreeze the Arctic Ocean sea ice, and address environmental, safety, governance, and legal concerns (Chitty et al. 2025, Siegert et al. 2025). The work will also include simulations of broader scale climate consequences of such interventions, with emphasis on assessments of the associated risks and needs for precautionary governance.



RT2: The Changing Arctic Ocean

– zooming in



Relevance and Scope

The ongoing sea ice retreat is a visible manifestation of a changing Arctic Ocean (e.g., Onarheim et al. 2018). However, the sea ice that characterizes the Arctic also greatly hinders both in-situ and remote observations. Our understanding of processes within the ice, in the atmosphere above and in the ocean and seabed below is extremely limited, in particular in the deep central basins. Compared with other oceans, we have a poor understanding of the system from which to construct and validate regional models. This strongly limits our capacity to both qualitatively and quantitatively determine how the Arctic Ocean will respond to the ongoing changes we do observe. The goal of RT2 is to **understand the atmosphere, sea ice, water column, and seabed within the central Arctic Ocean** particularly the least-explored slope and deep basin areas**.** RT2 will work within the Arctic Ocean itself, to map the ecosystem and to understand how key processes, such as primary production, will respond to ongoing sea ice retreat and changing inputs from adjacent regions (RT1) in a warming world.

Our in-situ observational focus is constrained by geological settings and geopolitical boundaries, and the distance Norwegian vessels can travel through the sea ice during a typical research cruise. Autonomous instruments will be important for understanding seasonal changes, while international collaboration and vessels of opportunity will be key to obtaining in-situ observations beyond this focus region. Pan-Arctic, kilometer-scale regional models and remote sensing work are less constrained and will focus on a larger area to include exchanges through the major gateways and with the peripheral shelves.

RT2 includes five priority topics addressing the atmosphere, sea ice, water column, and seabed:

2.1 How will increased poleward transport of heat, momentum, salt/moisture in the ocean and atmosphere affect the sea ice cover, light environment, stratification, and water mass transformation and circulation inside the Arctic Ocean?

2.2 What are the physical properties of the seafloor and how quickly do the processes change? What do the paleoclimatic record and present biota tell us about the past and present functioning of the Arctic Ocean?

2.3 Which processes control the transformations and flows of carbon and nutrients through the Arctic Ocean today and how are these changing? Will the future Arctic Ocean be a carbon sink or source?

2.4 What spatial and temporal variability in biodiversity is found in sea ice, water column, and seafloor habitats? Which processes are steering that variability, and how will on-going environmental changes affect biodiversity and ecosystem functioning?

2.5 How are trophic interactions and resource competition shaped by resident, migrating, and advected species, and how may this change in the future?

RT2 complements the assessment of the Arctic Ocean's interaction with the global and extra-regional system made in RT1 by providing greater detail within the Arctic Ocean itself and focusing on regionally important physical, biogeochemical, and biological states and processes. RT2 will use new observations from vessels, satellite remote sensing, moorings, and state-of-the art autonomous platforms together with high-resolution regional models. In addition to providing an improved understanding of the central Arctic Ocean itself, RT2 will allow improved parameterizations in the next generation of high-resolution regional models developed in RT5 and contribute to the natural science basis for scenarios explored in RT6.

Natural baseline values derived from paleoclimatic data in PT2.2 will provide a perspective for work done in other parts of RT2 and put the ongoing rapid changes into a longer-term context.

Priority Topic 2.1: Physical Interactions between the Ocean, Sea Ice and Atmosphere

Motivation and knowledge needs: The future Arctic Ocean will feature a much larger area of open water in summer than it does today (Heuzé and Jahn 2024). The transition from year-round to seasonal ice cover will have profound implications for the ecosystem and for accessibility to human activity. We anticipate dramatic changes in the seasonal stratification of the upper ocean, which will be more directly connected to the atmosphere as the sea ice retreats. Concurrent changes in the inputs of heat (e.g., Dörr et al. 2024), salt, and freshwater from adjacent regions and changes in air-sea interaction are anticipated to affect both sea ice processes and water mass transformations. However, we lack a detailed understanding of the impact these changes will have on individual processes, how different processes interact, and what consequences the combined effects will have for the integrated system.

Objective: PT2.1 will determine how changes in the inputs of heat, salt, and fresh water via major currents, exchanges with shelf seas and the atmosphere, will affect the sea ice cover, light environment, and water mass structure, circulation, and transformation in the Arctic Ocean. We will investigate internal processes in the Arctic Ocean so that these can be better represented in models and so that we can assess their importance for climate, biogeochemistry, biodiversity, and navigability.

Activities: With a regional focus on the Arctic Ocean, PT2.1 will investigate the roles of oceanic and atmospheric properties in determining sea ice cover, including the roles of clouds, radiation, net precipitation minus evaporation, and local atmospheric systems such as the Beaufort High. In the ocean, exchanges with adjacent regions are highly relevant, especially changing inputs of run-off and brine from the peripheral shelves and inputs of heat and salt via major currents from the Atlantic and Pacific Ocean which provide a link to work in RT1. The updated understanding of the changing sea ice cover will enable us to address regulatory and infrastructure needs associated with increased accessibility, as well as the implications for the environment.

As the Arctic Ocean shifts from perennial to seasonal sea ice cover, the release of seasonal meltwater will affect the seasonal stratification. This PT will evaluate the collective impact that changes in ice-type, snow cover, and surface stratification will have for air-sea heat and gas exchange, propagation of sound and light, micro- and macronutrient availability for biota, exposure to physical and chemical stressors, and how these changes affect the niches in which key species can operate. This PT will further investigate key feedback mechanisms including albedo, the marine heat flux and radiation absorption, and how these will change.

PT2.1 will also investigate the Atlantic Water boundary current, where we will study both exchanges with the basins in the central Arctic Ocean, its properties and impacts on the Eurasian and Amerasian basins, and the potential for enhanced local dense water formation as air-sea interactions intensify under increasingly ice-free conditions.

To carry out these activities we need to collect new, year-round observations from the Arctic Ocean. Major observational gaps exist outside of the summer field season, particularly in the atmosphere and in the upper 25 m of the ocean, which is expected to receive the greatest amount of seasonal meltwater, but sea ice keels prevent the deployment of conventional moored instruments. PT2.1 will use a foundation of ship-based and moored observations including tracers, augmented with measurements from the latest autonomous platforms and remote sensing techniques taking advantage of developments in RT5. Process understanding gained in PT2.1 will directly contribute to the improvement of regional models in RT5. PT2.1 will use these models to investigate processes and interactions within the Arctic Ocean, understand how the Arctic Ocean is responding to global forcing, gain greater insight into links between different components of the climate system, and to explore future scenarios.

Priority Topic 2.2: Seafloor and geosphere interactions

Motivation and knowledge needs: Seafloor topography and the morphology of continental margins surrounding the Arctic Ocean impact ocean circulation and water mass pathways. Past and present tectonic, magmatic, and sedimentary processes form the topographic and underlying morphology, giving rise to resources and seabed habitats. Yet, more than 75% of the seafloor in the Arctic Ocean remains to be mapped in detail (Ramirez-Llodra et al. 2023, Gaina et al. 2025). Climate system dynamics are also influenced by interactions between seafloor morphology and ocean (e.g., Jakobsson et al. 2016). Past warmer-than-present climate states provide a crucial window into Arctic climate interactions under ice-free conditions. However, areas lacking essential morphological details and paleoclimatic records with large knowledge gaps during crucial climate transitions limit our ability to predict changes and refine future climate projections

Objective: To determine the nature of the seafloor and understand how the submarine landscape contributes to past and present ocean-climate evolution in addition to shaping seabed habitats. Understand how past and present processes (hydrothermal vents, cold gas seeps) affect the benthic ecosystems and oceanographic conditions.

Activities: In PT2.2, we will carry out high-resolution mapping of the seafloor within the Arctic Ocean including the use of geophysical methods and collect data on its composition. This will give new information about the topography of the seafloor and its stratigraphy/underlying morphology in addition to the composition of bedrock and sediments in the Arctic Ocean. This will help us develop continental margin models to advance understanding of processes forming the seafloor and continental margins of Arctic Ocean such as volcanism, hydrothermal venting, faulting, and gas seepage in addition to climate processes related to warmer-than-present and as-cold-as-the present conditions. The new models of the seabed will complement overall Arctic Ocean basin configuration models. Such models will be informed by and based on geophysical observations including fibreoptic seafloor cables and seismological observations. We will also assess how these processes define and determine the distribution of seafloor habitats and resources of the Arctic Ocean.

With new information of stratigraphy/underlying morphology we will also obtain marine records and paleoclimatic data using organic, inorganic, and biological paleoclimatic proxies, hence establishing new paleoclimatic records. Paleoclimatic records can be used to generate quantitative relationships between changes in the climate-ocean-cryosphere system and ecosystem responses. The new paleoclimatic records will be used to establish baseline values for ocean-sea ice fluctuations and improve the understanding of climate-ocean processes during different climate states, e.g., during an ice-free Arctic Ocean. New paleoclimatic records will also enable improved, empirically-informed Earth System Modelling.

Priority Topic 2.3: Biogeochemical cycles: baseline, pathways, responses, impacts, and feedbacks

Motivation and knowledge needs: The cycling of biogeochemical constituents, such as carbon, nutrients, and oxygen, in the Arctic Ocean is essential for regulating environmental states and habitats that the ecosystem relies on, and for the CO_2 uptake and storage in this important sink region, via both the biological and the solubility carbon pumps. The unprecedented environmental changes in the Arctic Ocean will transform the biogeochemical cycles with consequences for primary production and for carbon uptake (Juranek et al. 2022) In fact, the Arctic Ocean is the region that is currently experiencing the largest climate driven trend in carbon uptake (Yasunaka et al. 2023) and strongest ocean acidification (Qi et al. 2022). Yet, inadequate knowledge of the biogeochemical state and its dependence on physical drivers hinders our understanding of current changes and ability to predict future changes. An in-depth understanding of the biogeochemical dynamics in the Arctic Ocean across different regimes requires high resolution observational data sets covering key seasons and fit-for-purpose regional coupled models.

Objective: Improve our understanding of biogeochemical states and changes in the water column and sea ice in the underexplored central basins, elucidate the governing physical and biological processes, examine future changes, with a focus on the biological and solubility carbon pumps, ocean acidification, and availability of nutrients.

Activities: In PT2.3 we will collect new biogeochemical observations of inorganic carbon chemistry and ocean acidification, nutrients, and oxygen, over a full seasonal cycle throughout the sea ice and water column at targeted cruises in the Arctic Ocean.

We will utilize these and other observations (e.g., remotely sensed surface properties, sediments) and coupled regional models to establish the biogeochemical mean states, spatial variability, source-sink processes (air-sea gas exchange, riverine transport, primary production, remineralization, sedimentation, as well as horizontal and vertical transport) and budgets under present day climate. Together with RT1 we will examine how variations in lateral transports of nutrients, carbon, and other key biogeochemical tracers through the principal gateways and across the peripheral shelves shape Arctic Ocean states and variability. Together with PT2.1, 2.4 and 2.5 we will evaluate how biological and physical processes internal to the Arctic Ocean further drive horizontal and vertical gradients in biogeochemistry and how these in turn regulate nutrient availability and primary production, carbon uptake and ocean acidification, as well as oxygen availability at depth. Biological processes include organic and inorganic particle production, export and degradation in the water column, where we will evaluate both the magnitude and critical species or functional groups, as well as higher trophic level changes identified in PT2.5. Physical processes include warming, sea ice cover, stratification and vertical mixing, circulation patterns, ventilation. These physical processes can impact biogeochemical states both directly and indirectly, via biological processes such as mentioned above. A key aim of PT2.3 is to understand the role of the Arctic Ocean in regulating the pathways and the rates of long-term ocean carbon sequestration as we transition from year-round to seasonal ice cover.

Using near-term predictions and long-term projections of the future Arctic Ocean from RT1, PT2.3 will determine the biogeochemical transformation during and after sea ice disappearance, including interactions and feedback with processes such as primary production, marine aerosol emissions-induced cloud formation, and CO_2 fluxes. In collaboration with RT5, PT2.3 will improve the respective process parameterizations in the high-resolution regional models. Along the sea ice margins where changes in air-sea gas exchange, carbon and nutrient cycling, primary productivity, and ocean acidification are expected to be large and rapid, we will investigate potential future changes, predictability, and consequences under different mitigation scenarios.

Priority Topic 2.4: Biodiversity across habitats

Motivation and knowledge needs: Exploring and understanding the dynamic biodiversity and ecology of Arctic biota provides key knowledge for evaluating status and change of the Arctic Ocean system, required for effective management and conservation actions across Arctic and global communities. However, large knowledge gaps remain regarding biodiversity, distribution, abundance and biomass, and basic biology of all organism groups especially in the Central Arctic Ocean, from viruses, bacteria, microalgae and other microbes, invertebrates, to fish, seabirds, marine mammals and their parasites, in particular microbes (CAFF 2017). Also, their responses to climate and environmental gradients are poorly known in the current sea ice, water column, and seafloor habitats of the Arctic Ocean (Skjøldal 2022). These knowledge gaps severely limit our ability to

link biodiversity to ecosystem functioning and services, anticipate the future Arctic Ocean, and advise stakeholders dealing with the living Arctic Ocean.

Objective: To characterize biodiversity and ecological processes across diverse sea ice, ocean, and seafloor habitats; understand how these vary along and respond to physical, chemical, and temporal gradients, and identify potential feedback mechanisms.

Activities: In PT2.4 we will quantify taxonomic and functional biodiversity of all organism groups across Arctic Ocean habitats: microbes (viruses, bacteria, microalgae, etc.), invertebrates, vertebrates (fish, seabirds, marine mammals) and all group's parasites. We will achieve this objective by combining modern, integrated taxonomy (through morphological and molecular tools, advanced imaging, passive acoustics etc.), with biological and functional traits.

In PT2.4, we will then identify hot and cold spots of taxonomic and functional diversity. Associating hot/cold spots with specific habitats (characterized in PTs 2.1, 2.2) will be achieved using geospatial analysis, biologging, and other tools. This information will feed into RT3 that will evaluate the need for conservation, potential for harvesting, and the vulnerability (or resilience) to perturbations, including climate change, in hot-spot areas.

Important environmental drivers of biological communities will be identified across habitats to connect biodiversity knowledge to the habitats and conditions species and communities are adapted to. We include at the seafloor: ridges, sea mounts, hydrothermal vents, seeps, abyssal plains, continental slopes, canyons; in the water column: marginal ice zone, polar mixed layer, halocline, Atlantic layers, deep and benthic-boundary layers, water column above continental slopes; in and beneath different ice types: ice meltwater, bottom, interior and infiltration layers, snow-ice interface, melt ponds, ridges, leads and polynyas.

PT2.4 will also investigate basic biological characteristics of dominant taxa or functional groups of lower to higher trophic levels. These characteristics include growth rates, longevity, reproductive output, life cycles, and behavioural aspects including their seasonality. The results will feed into the evaluation of vulnerability and resilience capacity that will be conducted in RT3.

Priority Topic 2.5: Central Arctic Ocean food webs and ecosystem functioning

Motivation and knowledge needs: Knowledge on how the Arctic Ocean ecosystem's food web works today is currently lacking but is a prerequisite for establishing, and evaluating, conceptual and model scenarios for future functioning under reduced ice-cover, potential harvesting regimes, and other interventions. The structure, function, and controls of the Arctic Ocean food web must be characterized to anticipate responses to such perturbations. Sea ice decline, contaminants, toxic algal blooms, diseases, and parasites could potentially have detrimental impacts that spread through the ecosystem. Knowledge of species migrations and transports inside the central Arctic Ocean will further elucidate how strongly coupled ice-water-seafloor and basin-slope/shelf habitats are. None of these ecosystem functions and processes are

currently well constrained, in particular they are lacking for the Central Arctic Ocean (Wiedmann et al. 2020).

Objective: To establish food web structure from microbes, invertebrates to fish, seabirds, marine mammals, and including parasites. To be achieved through understanding and quantifying resource competition at the base of the food web, identifying trophic pathways, measuring process rates and amount of secondary (consumer) production and consumption, and by establishing how organisms connect food webs from surface to seafloor and between basins and slopes/shelves.

Activities: In PT2.5, one activity focuses on resolving mechanisms at the base of the food web, namely what controls the balance of phytoplankton-bacteria competition for mineral nutrients. This balance contributes to determining the magnitude of primary production and pathway of organic material to higher trophic levels. Results from experimental approaches will form the basis for conceptual models.

We will then establish structure and trophic pathways of microbial and classical food webs in sea ice, water column, and seafloor communities. This requires determining types and proportions of carbon sources used; trophic redundancy and flexibility; quantifying who eats whom and to what extent; constraining what controls these pathways such as resource competition; and identifying what alternative pathways are likely in future food webs. Approaches will include traditional diet studies, grazing experiments, trophic markers, molecular tools, and process-based predator-prey and migration models.

PT2.5 will also generate estimates of secondary production and its controls, covering open ocean to perennial sea ice regions, and including consumers in ice, water, and at the seafloor. These estimates will be generated using a combination of approaches, such as in-situ experiments, age/size-based and other model estimates.

PT2.5 will characterize additional system connectivity mediated through migration and transport of small-to-large organisms within the Arctic Ocean (while RT1 focuses on external connectivity). Mechanisms include horizontal connectivity (e.g., sea ice as vector; dispersal among disparate Arctic Ocean habitats) and vertical connectivity (via vertical migrations or diving behaviour). Approaches will include direct measurements (e.g., underwater visual profilers, tags), particle tracking models, and individual-based and mechanistic migration models.

RT3: Human Impact and Sustainable Use

– prospects and consequences



Relevance and Scope

The ongoing global warming which is accompanied with changes in the physicochemical environment, including decreasing seawater pH (Findlay et al. 2025), together with the potential of increased exposure to pollutants (Bergmann et al. 2022, Townhall et al. 2022, Spataro et al. 2025), in addition to altered species distributions (i.e., northwards expansions, e.g., Fossheim et al. 2015, Fauchald et al. 2021, Brandt et al. 2023, Calvet et al. 2024), is dramatically affecting the Arctic marine ecosystem by significant transformations, likely affecting its resilience, services and functioning (Doney et al. 2012, Renaud et al. 2011, Pinsky et al. 2013). Additionally, the reduction in sea ice extent opens new areas of the Arctic Ocean, including regions under Norwegian jurisdiction, to human activity (Haug et al. 2017, Müller et al. 2023, Reiersen et al. 2024, Jørgensen 2025). Some see this region as a future arena for shipping, fisheries, energy production, bioprospecting, deep-sea mining, tourism, and military operations. Others, however, call for strict protection of the Arctic Ocean, recognizing that the combined effects of climate change and human activity will place increasing pressure on these, until now, relatively pristine ecosystems. These developments strain established Arctic governance instruments, institutions, and multilateral bodies, while also driving significant geopolitical shifts centred on national security and defence. The overarching goal of this RT is to **evaluate the prospects and consequences of future human activity in the Arctic Ocean, to ensure sustainable governance and management of this region at both Norwegian and regional levels.**

This goal will be achieved through three priority topics (PT3.1-3.3) addressing the following key questions:

3.1 What are the prospects for sustainable activities and resource exploitation in the Arctic Ocean in the next and coming decades?

3.2 What are the synergistic effects, cumulative consequences and risks of increased human-induced pressures in the Arctic Ocean, and adjacent ecosystems and societies

3.3 What future national and regional governance and regulatory mechanisms will be required to ensure sustainable human activity while safeguarding vulnerable biota in the Arctic Ocean and its adjacent seas and societies

This RT will build extensively on the insights and findings from RT1 and RT2 to address how increased human activity, and thus, human induced pressures affect the ecosystems and governance of the Arctic Ocean. Understanding the synergistic effects of these pressures is essential for ensuring sustainable management of the Arctic Ocean and its surrounding seas and societies (Jørgensen 2025). Such knowledge may necessitate development of targeted action plans to reduce environmental risks and

hazards, ensuring protection of particularly vulnerable areas (i.e., EBSA; Ecologically or Biologically Significant Marine Areas), populations, as well as entire ecosystems.

The knowledge gained in RT3 will in turn be valuable input to RT4 with the aim of the evaluation and investigation of potential abrupt changes, including societal shifts. Furthermore, RT3 will provide information on baseline and threshold values for a multitude of contaminants as well as other important environmental variables, which is needed to enable sustainable management and protection of the Arctic Ocean. Finally, RT3 will actively collaborate with RT6 to monitor and inform current and emerging human interests in the Arctic Ocean.

Priority Topic 3.1: Scientific foundation for sustainable use of the Arctic Ocean

Motivation and knowledge needs: As the Arctic Ocean becomes more accessible, an in-depth evaluation is needed to assess stakeholder's and industries' potential interest for utilizing this area, in terms of e.g., emerging shipping routes for commercial vessels (cargo and tourism) and fisheries versus conservation, and how this increased activity can be managed in a sustainable manner (Jørgensen 2025). The main focus will be on how the ecosystems in the region will be affected by e.g., chemical pollution, increased underwater noise, changing lightscapes, expansion of fishing grounds due to altered species distribution (e.g., movements/migratory routes), as well as exploitation of other economically important marine resources, e.g., bioactive compounds, seafloor minerals, and fossil/wind/wave energy.

Objective: Identify the likelihood and possibilities for intensified human use of this region, including establishment of new shipping routes for commercial vessels (cargo and tourism), increased fisheries, and use of other economically important marine resources in the Norwegian sector of the Arctic Ocean, e.g., such as commercial exploration and/or exploitation of seafloor and subseafloor resources.

Activities: First, we will investigate the interest in future use as well as exploitation of the Arctic Ocean among industries in collaboration with RT6. This will encompass the main actors (industries, companies, institutions, NGOs) currently operating in the neighbouring seas (e.g., the Norwegian Sea and the Barents Sea), including commercial vessels (cargo and tourism) and fisheries, as well as emerging industries such as bioprospecting and mineral extraction that are expected to expand into the Arctic Ocean. We will, together with the industries and stakeholders, identify the challenges as well as potential opportunities, based on short- and long-term perspectives, i.e., sub-seasonal/decadal predictions vs. long-term climate projections, for the physical and biological systems in the Arctic Ocean (with input from RT1 and RT2).

Second, we will evaluate the prospects for increased use of marine fishery resources based on input from RT1 (potential northward expansions of species) and RT2 by addressing abundance, density, and distribution of known commercial species. We will investigate if there is enough bioenergy in the system, i.e., by evaluating energy budgets/carrying capacities, to support fisheries of resident species in the Arctic Ocean, for the present and for a representative set of future scenarios. Additionally, food-web structure (e.g., its modularity and feeding links) will be used as an indicator

of sensitivity. Furthermore, simulations integrating food web models with ecosystem-based fisheries management concepts will be used to evaluate how changes in food supply affect trophic interactions and energy transfer within the ecosystem (Pikitch et al. 2004).

We will also take advantage of the genomic information generated in RT1 from different key commercial fish species (and sub-populations) that are likely to establish themselves permanently or seasonally in the Arctic Ocean combined with ecosystem modelling to evaluate their response to such a transition and thus further infer their harvesting potential. This will include in-depth investigation into two of the well-known sub-Arctic and Arctic pelagic fish species capelin and polar cod as well as mesopelagic species, including lanternfish species and northern shrimp species (*Pandalus borealis*).

Lastly, based on the mapping of the seafloor and subseafloor (in RT2) we will identify potential areas for other increased human activities. Likely areas include environments in and along spreading ridge systems and on the slopes of seamounts where mineral deposits are formed (Pedersen et al. 2021). In addition, bioresources suitable for commercial use are typically found in areas that host extreme life, such as hydrothermal systems also found at or near spreading ridge systems (Stokke et al. 2020).

Priority Topic 3.2: Consequences and risk assessment of increased human activity

Motivation and knowledge needs: An extensive knowledge base and novel analytical tools for risk assessment are urgently needed to determine how cumulative anthropogenic pressures under global warming, impact key species as well as the food-web dynamics in the Arctic Ocean (Jørgensen 2025). An improved understanding of how different stressors impact different components of the Arctic marine ecosystems, i.e., the living biota and their interplay, and thus the overall ecosystems functions, is essential to fuel predictive models, prioritize future monitoring, and understand bioaccumulation processes (e.g., for seafood safety). Such knowledge will truly aid in determining the effect thresholds (Scheffer et al. 2015) and further identify possible future scenarios of the highly complex and fragile Arctic ecosystems.

Objective: By using a comprehensive and multidisciplinary approach combining cutting edge genomic and omics tools, with ecological knowledge, geochemical profiles, field surveys-, and monitoring (including screening of chemical marine pollution), multi-stressor experiments and modelling, we aim at defining species sensitivity and vulnerability at the individual, population, and ecosystem level. We will perform integrated assessments to determine the potential response as well as risks for adverse negative impact to increased human activities such as intensified human exploitation, e.g., via fisheries/trawling, deep sea mining and subseafloor exploration, as well as other disturbances such as changing chemical-, noise-, and light conditions. We will establish how such perturbations combined could generate additive, antagonistic, or synergistic effects on the overall ecosystem functioning and health.

Activities: First, we will obtain a reference baseline for how the Arctic Ocean and its ecosystems are impacted by pollution (in terms of regional and global sources as well as lifetime and transformation). We will perform comprehensive targeted, non-target

and suspect screening of chemical marine pollution in various compartments of the environment in the Arctic Ocean using agnostic methods and state-of-the-art analytical tools, including high-resolution mass spectrometry that can be used for future data mining and retrospective analyses to identify and quantify contaminants that are not yet recognized. Other disturbances including underwater noise and changing light conditions will be assessed using state of the art in situ observational technology, with gathered data serving as input for footprint models.

Second, we aim at determining the effect thresholds, for relevant single stressors (including contaminants/pollution, ocean warming, ocean acidification, oxygen content and changes in carbon flux) as well as the cumulative impacts of these stressors in key species, including top-predators, and meso-pelagic fish species as well as sympagic (i.e., ice associated), pelagic, and benthic components of the food web through controlled multi-stressor experiments. This will be investigated *ex situ* using laboratories and mesocosms as well as *in situ* by establishing test sites on the seafloor as part of this program. These sites will also be used to evaluate the consequences and resilience of the seafloor and subseafloor ecosystem to perturbations caused by human activity e.g., seafloor mining and bottom trawling in the Arctic Ocean.

We will further evaluate the vulnerability of the key fish species (identified in RT1), that are likely to establish themselves in the Arctic Ocean at a temporal (e.g., seasonal) or more permanent scale. For instance, will such an alteration in distribution impact the genomic diversity (i.e. adaptive capacity) and/or the population structure of the species? Combining such genomic information with input from multi-stressor experiments will enable a deeper understanding of the genotype vs. phenotype variation of a species, and thus, their vulnerability and sensitivity to increased perturbations (e.g., intensified fisheries; Theissinger et al. 2023, Bernatchez et al. 2024).

Moreover, with the identification of response traits for key ecosystem components, we will further assess which biota and ecotypes are most vulnerable to increased human activity. This will aid in the establishment of approaches to predict and evaluate the individual and combined impact of both indirect and direct human-induced stressors to guide the development of sustainable management programs.

Finally, we aim at conducting systematic risk and impact assessments of human activities and exploitation of the Arctic Ocean based on data from this RT and RT2 (i.e., the biodiversity assessments and the development of improved ecosystem/food web models), and by such develop area-based risk maps of particular vulnerable habitats/ecosystems and associated resources providing management perspective on the impact of increased human activities and the subsequent alteration of the Arctic ecosystem services and functioning. For example, hot spots of taxonomic, habitat and functional diversity (RT2), as well as areas rich in metal and carbon storage, will be identified and linked to specific habitats, and thus, providing a scientific basis for targeted sustainable management efforts and conservation (i.e., establishment of Ecologically or Biologically Significant Marine Areas).

Priority Topic 3.3: Governance and Conservation needs

Motivation and knowledge needs: Increased human activity in the Arctic Ocean will put more pressure on national and international governance systems (Wu and Li 2025), as well as Indigenous governance practices and usages at the interface of land and sea (Saami Council 2023). Sustainable regulatory and management frameworks must be developed based on anticipated activities and their ecological impacts (assessed in PT3.1, PT3.2). Although cooperative Arctic regimes have supported political order and shared management approaches (De Lucia 2022, Wilson Rowe 2025, Stokke and Hønneland 2007), current geopolitical tensions involving Russia, China, and the United States complicate multilateral cooperation and challenge assumptions of "Arctic exceptionalism" (Bertelsen 2024). Understanding whether existing cooperation models remain adequate—and what alternatives may be needed—is essential (Khorrami 2025). The CAOFA demonstrates that such cooperation is still possible.

Objective: This priority topic will assess the governance, legal, and regulatory developments in light of shifting geopolitical dynamics. We will further evaluate the capacity of existing institutions – such as the Arctic Council and interacting regimes (De Lucia 2024) – to address emerging issues, resource frontiers, and conservation needs. Conservation assessments will integrate knowledge gained from PT3.2 on e.g., the potential cumulative impacts on Arctic biota coupled to area/location and extent of human exploration/operations. The results will support scenario evaluations in RT6 and feedback from the co-production of these scenarios in RT6 will further inform research in this task.

Activities: First, based on the work done in PT3.1, we will examine how global political, legal, and economic trends may influence Arctic human activities. This includes scenario development for a range of potential future activities, including possible shipping routes for commercial vessels (cargo and tourism) and the likely expansion or displacement of fisheries

Second, we will assess the impacts and risks associated with increased human activity in terms of human health and infrastructures, with the goal of securing the safety of people operating in the Arctic. For instance, increased human activities in the Arctic Ocean are likely to require facilitating infrastructure in Svalbard, which is located at the doorstep to the Arctic Ocean. Svalbard offers ice-free harbours year-round, an airport, and logistical support, making waters under Norwegian jurisdiction more accessible than other regions in the high-Arctic. How these prospects combine with broader external factors such as global political, legal, and economic trends will be investigated.

Third, based on the work done in PT3.2 we will identify conservation needs using risk maps of vulnerable ecosystems and evaluate Norway's ability to contribute to processes under CBD, CAOFA, BBNJ, OSPAR, NEAFC, and others. We will further explore whether new conservation measures (e.g., dynamic management approaches and/or based on the area-based risk maps of vulnerable habitats/ecosystems, including establishment of MPAs) are needed and whether existing frameworks (e.g., UNCLOS) can accommodate them, particularly for species spanning EEZs and areas beyond national jurisdiction. We will assess the effectiveness of bilateral and regional agreements,

including the potential need for a future regional fisheries agreement post-CAOFA, and evaluate sectoral frameworks for ensuring safe, sustainable operations. Recommendations will support ecosystem-level governance and consider impacts for peoples and communities.. We will also assess institutional adequacy under heightened geopolitical competition and explore alternative cooperation models.

Finally, we will examine governance needs related to local Arctic pollution and disturbances (e.g., contaminants, shipping-related spills, cargo releases, waste as well as noise and the possible changing light conditions). Key questions include whether instruments such as the Polar Code and the Ballast Water Management Convention require amendment or complementing to better control local pollution and disturbances in the Arctic Ocean.



Photo: Norwegian Polar Institute / Philipp Assmy



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RT4: Abrupt and extreme events
– preparing for surprises



Relevance and scope

Abrupt and extreme events can define the evolution of natural systems as well as human societies (McKay et al. 2022). Extreme events are defined statistically as being rare for a given location and time period and are of a relatively short time scale. Marine heat waves, catastrophic pollution events, or fishing moratoria are examples where impacts may be reversible (Gou et al. 2025, Pecuchet et al. 2025). As defined by the IPCC, an abrupt event is a large-scale rapid shift occurring over decades or less resulting in persistent structural changes in the system and the services it provides (Field et al. 2012). Collapse of the AMOC and rapid loss of Arctic sea ice are examples. Both abrupt and extreme events can cause significant disruption, positive or negative, to socio-ecological systems over different time scales.

Complex adaptive systems, such as ecosystems or human societies, are characterized by emergent properties, characteristics that would not be predictable from analysing the sum of the parts. These properties are responsible for the products and services provided but may also confer resilience to some types of perturbation. A fundamental challenge is our lack of mechanistic understanding of the Arctic Ocean system, making abrupt and extreme events and their consequences notoriously hard to predict. The goal of this RT is to **assess the nature and potential consequences of disruptive events by improving our skill in their prediction, characterizing their impact, and providing insight into system resilience.**

This goal will be achieved through four priority topics that answer the following key questions:

4.1 How do we identify disruptive events, their drivers over different scales of time and space, and their consequences for physical, biogeochemical, ecological, and geopolitical systems?

4.2 What are the risks/benefits associated with different disruptive events?

4.3 What are the potential consequences of different low likelihood, high-impact events, and how can we be prepared for these events?

4.4 How can we develop prevention, mitigation, and adaptation strategies for managing abrupt and extreme events?

This RT will exploit existing and new data from observations, experiments, and models from *Arctic Ocean 2050* and international initiatives. We will explore past, modern, and projected extremes in natural, political, and economic systems; identify the drivers of changes in these extremes; and use results of experimental studies conducted within RT2 and RT3 to assess potential resilience to change. Global and downscaled models used and developed in RT1 and RT5 will be critical for identifying driver thresholds and

the uncertainties around them. We recognize that driver-response mechanisms previously documented in observational or experimental studies may not be valid under new physical, biogeochemical, ecological, economic, and political system states. Despite this, RT4 can provide important insight into when projected threshold values will be passed, the system response to exceeding these values, and where systems may be resilient to change. RT4 will also investigate potential risk factors associated with future scenarios developed in RT6. This work will help scientists, managers, businesses, and politicians prepare for a variety of abrupt changes likely to confront the Arctic Ocean socio-ecological system (RT6).

Priority Topic 4.1: Identifying drivers and consequences of disruptive events

Motivation and knowledge needs: Abrupt and extreme events have different characteristic time scales. Over geological time scales, the Arctic Ocean has gone from ice-free to ice-covered conditions (Sluijs et al. 2006, Kaufman et al. 2021). On shorter time scales we see ongoing climatic, ecological, and geopolitical changes (e.g., altered phenology and biological community composition, and increases in military activity) that suggest that presumed driver thresholds have been passed (Kortsch et al. 2012). In most cases, however, the driver thresholds, either singly or in combination with other drivers, are not known (Zscheischler et al. 2020). Understanding the drivers of disruptive events over different scales of time and space, and their consequences, is, therefore, critical to developing better prediction, mitigation, and prevention strategies.

Objective: We will identify driver threshold values that, once surpassed, have significant consequences for physical, biogeochemical, ecological, and geopolitical systems of the Arctic Ocean.

Activities: Empirical and modelling data collected throughout the *Arctic Ocean 2050* programme will be critical for defining extremes and identifying thresholds. For example, paleoclimatic, geological, and ecological data from RT2 and experimental results from RT2 and RT3 will provide important information about the variability in both driver state and system response. Large ensemble models assessed in RT1 and run in RT5 will provide some of the more extensive data regarding the range and variation in driver values. We will use extreme-value statistical tools to identify driver levels that, when surpassed, have led to a state-change in the system. We will investigate responses to gradual changes in driver values and variation around changing baselines, possible non-linear dynamics, and effects of simultaneous changes in multiple drivers.

Events such as marine heat waves or rapid drainage of the fresh surface water of the Beaufort Gyre have been documented to have ecosystem consequences locally and well into the sub-Arctic and boreal regions. With the stroke of a pen, treaties may be signed or broken, with positive or negative consequences for ecological status and politics in the region. We will investigate how tightly linked Arctic geopolitical decisions/agreements are with both the ecological systems in the region and international relations within and beyond the Arctic.

Many expected thresholds may already have been surpassed in the rapidly changing Arctic, but we have not often observed clear changes in ecosystem structure or

function, or in governance or international agreements. It is possible that resilience built into the ecological and societal systems associated with the Arctic can buffer some extreme events and limit their impacts. We will investigate the *lack of abrupt changes* associated with documented extreme events or surpassing identified thresholds in the hope of better managing for resilience.

Priority Topic 4.2: Assessing the risk associated with abrupt and extreme events

Motivation and knowledge needs: Risk assessment is a key element of planning for surprises associated with abrupt or extreme events (Scheffer et al. 2012). It combines a quantification of the likelihood of surpassing expected thresholds in environmental drivers, human activities, and geopolitical events with an understanding of the consequences for the system. For the near- future, we can rely on climate predictions and projections of change in key environmental drivers (e.g., storm tracks and altered precipitation patterns, Atlantic Water inflow, freshwater fluxes, sea ice loss, ocean acidification, and non-native species; Shu et al. 2022, Polyakov et al. 2023, Stern et al. 2025). But each model has its own assumptions and uncertainties that must be considered when drawing any conclusions (Haines et al. 2025).

Objective: We will assess the likelihood of surpassing identified thresholds and the system changes associated with these disruptive events.

Activities: Models and empirical studies conducted in PT4.1 identifying scales of variability, sensitivity to changes in environmental drivers, and potential consequences of change, will form the basis for the work conducted here. For example, understanding the patterns and drivers of sea ice melt and ocean circulation can improve projections of future ecological change. Predictions of climate and weather extremes for the near-term future (the next 1-10 years), climate projections for the next 50 to 100 years, ecological consequences of accelerating ocean acidification, and changing species distributions produced in RT1 and RT2 will also help us reach this objective.

Data on the likelihood of acute pollution events from shipping/industrial accidents can be extracted from insurance-industry risk assessments. Both the risks associated with local and external (spillover effects) geopolitical pressures and their consequences will be evaluated to address what may impact the Arctic and how.

Finally, we will also explore the chances of easing political tensions, expanded entrance into force of international treaties, and strong cuts in CO_2 emissions, and what may spark these positive actions.

Priority Topic 4.3: Low likelihood, high-impact events

Motivation and knowledge needs: Low likelihood, high impact (LLHI) events can profoundly affect ecosystems and human societies at regional or global levels, but are challenging to model or even conceptualize for effective planning or mitigation (Kemp et al. 2022, Sundh et al. 2024). Surpassing a global warming of 1.5°C can trigger multiple significant climate-related tipping points. Some of these are predictable and, thus, the foundation for selecting climate targets. Less predictable is the human element, e.g., the nature, speed, and magnitude of societal and geopolitical responses. Whereas abrupt



or extreme events can be modelled and have quantifiable likelihood and impacts, LLHI events are deeply uncertain and occur outside the range of normal variability, making it especially difficult to determine both their triggers and their consequences. Thus, LLHI events require different methods for their investigation, assessment, and planning. Additionally, many LLHI events may not be linked with climate change. Recent history (COVID-19 pandemic, invasion of Ukraine) clearly shows the global impacts of such events, with consequences extending well into the Arctic.

Objective: We will explore potential triggers and consequences of LLHI events to build an early warning system for managers, businesses, and policy makers.

Activities: There are multiple thought experiments that can be carried out through both formal and informal 'horizon scan' type activities. Some LLHI events have been investigated previously, and together with ongoing national/international projects they will be reviewed. Examples of such events as relevant for the Arctic Ocean include the collapse of the Greenland Ice Sheet, continental margin failure/submarine landslides, volcanic eruptions, abrupt changes in ocean circulation, collapse of marine food-webs, revolutions in technology and computing capacity, and open military conflict in the Arctic. Positive LLHI events could include large-scale conservation of the Arctic Ocean, signing of peace treaties, and decisions to stop burning fossil fuels.

Once an initial list is constructed, LLHI events can be categorized in terms of their causes, multi-disciplinary impacts, and potential solutions. Discussions with stakeholder groups and the scientific community as well as scenario-testing activities within RT6 will be critical for this step, but also for suggesting how preparedness levels can be raised. A key objective here is to identify what may lead to such events, the probability or early-warning indicators of events, and how these events can be mitigated, essentially reducing the level of surprise LLHI events present. Marine digital-twin systems developed in PT5.4 can be helpful in some of these analyses.

Priority Topic 4.4: Planning for abrupt change and extreme events

Motivation and knowledge needs: Understanding the risks, uncertainties, thresholds, and consequences of abrupt change and extreme events is key to developing strategies for managing the physical, biogeochemical, ecological, and geopolitical elements of the Arctic Ocean. We need to avoid surpassing identified thresholds where negative consequences are expected to result wherever possible. We also need to use management tools to enhance the natural resilience of both environmental and socioecological systems. Key to achieving this objective is embedding natural science knowledge within the societal context that drives broader understanding and action. Minimizing negative consequences and maximizing positive outcomes must be integral elements of mitigation and adaptation strategies in the region.

Objective: We will develop the knowledge and tools for decision-makers to make informed choices in order to prevent, mitigate, or adapt to abrupt changes and extreme events.

Activities: Communicating the threats and both positive and negative consequences of extreme and abrupt events will be a key component of raising the issues within the scientific, political, and public audiences. *Arctic Ocean 2050* partners will be integrated into and contribute to advisory bodies such as IPCC, IPBES, and the Arctic Council in their reporting to national and international governance and management organizations. The focus will be on providing concrete, knowledge-based, and implementable strategies to minimize risk of surpassing thresholds; providing safe operational boundaries for future human activities; maintaining and enhancing resilience; leveraging political alliances; and planning for adaptation to change. Digital-twin systems developed in RT5 and pathways to action co-produced in RT6 are key tools for testing scenarios developed here.

For example, it is generally recognized that high species and functional diversity lead to ecological systems being more resilient. On the other hand, expansion of boreal species into the Arctic and the concurrent increase in biodiversity may not be desirable for maintaining ecosystems in their historical state. Therefore, identifying critical aspects of biodiversity needing protection and encouraging governance policies to prevent degradation of habitats subsidizing these biodiversity components will be important proactive elements of a management and adaptation plan.

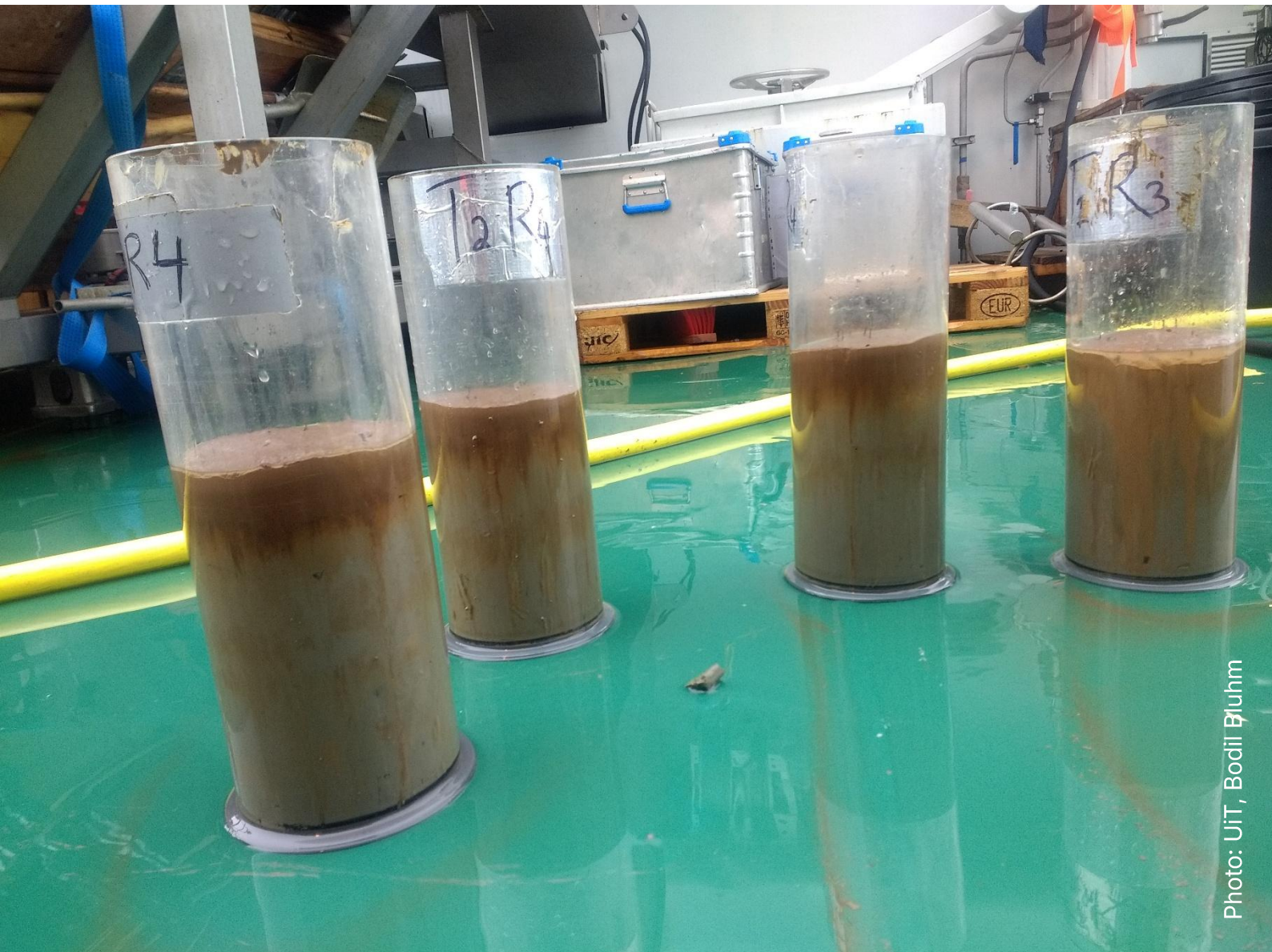

Photo: UiT, Bodil Bluhm

RT5: Advances in Observing and Modelling
– innovating for the future



Relevance and Scope

The latest advances in technology offer powerful new ways to observe and predict the ocean environment. Vast amounts of data are now being collected from satellites, research cruises, and autonomous platforms operating in space, air, on ground, seafloor, sea surface, and underwater. However, the integration of these data into modelling and prediction systems remains limited, and holistic approaches that combine data across disciplines are rare (Tzachor et al. 2023). In addition, large parts of the Arctic Ocean remain unobserved and navigation and positioning under sea ice is a major challenge which needs to be addressed and solved. Novel observation technologies and data- and physics-driven models are needed to fill these gaps (Lee et al. 2022). The latest hardware and software solutions, including new computing technologies and Artificial Intelligence methods, offer new tools to assist the development of next-generation autonomous platforms and sensors, to advance our monitoring and predictive capabilities, and to efficiently integrate data for science and decision-making (Bracco et al. 2025, Hazeleger et al. 2024). Ultimately, bridging research to operations will enhance system understanding and facilitate marine digital twin solutions for user-specific applications (Miedtank et al. 2024).

The main goal of this RT is to **make optimal use of emerging technologies, numerical models, machine learning methods, and data assimilation techniques** to fill observational gaps and enhance our ability to predict and understand the interconnected physical, geophysical, biogeochemical, biological, and societal processes in the rapidly changing Arctic Ocean.

This goal will be achieved through four Priority Topics that answer the key questions:

5.1 How can autonomous and modular sensor platforms, in situ sampling technology, and remote sensing products, be advanced and integrated in real time to enhance Arctic environmental monitoring and modelling?

5.2 How can a hierarchical, flexible numerical model framework be developed to efficiently downscale global climate model outputs into high-resolution regional simulations that improve representation of Arctic physical and biogeochemical processes?

5.3 How can machine learning models that integrate multi-source data be developed and validated to efficiently downscale Arctic climate scenarios, improve forecasting, and reduce uncertainties in extreme event predictions?

5.4 How can user-centred marine digital twins be co-developed to integrate multi-source data, provide interactive scenario-testing capabilities, and support informed decision-making for sustainable Arctic environmental management?

RT5 will design transversal methodologies that can help address research questions in RT1 to RT4, develop next-generation observing systems and model prototypes, and provide digital services that enable cross-disciplinary work between these RTs and RT6. Existing models and observing systems will be used from Day 1 by the various RTs and serve as a starting point for the new developments.

Priority Topic 5.1: Modular and Interoperable Observing Systems

Motivation and knowledge needs: Arctic Ocean observing systems must evolve to integrate space, aerial, and in situ data into a seamless and interoperable network able to answer a broad range of research questions and societal needs (Sørensen 2021, Alvares Fanjul 2024). New technologies are rapidly advancing our ability to integrate and assess large amounts of remote sensing data, while on the other hand they also provide us with new opportunities to develop autonomous, adaptive, and resilient sensor-carrying platforms capable of long-term operations, and that can navigate under ice and withstand the challenging Arctic environmental conditions.

Objective: To develop modular and interoperable sensors and sampling platforms that function autonomously in Arctic conditions, as well as advanced algorithms that seamlessly integrate data ranging from remote sensing to in situ data. The data should be ready to be analysed and fed to models for calibration or assimilation.

Activities: We will design and deploy autonomous sensor platforms as well as develop novel methodologies to integrate satellite- and ground-based observations, to advance our capabilities to provide *year-round* observations and assessments of the ocean, sea ice, and seabed, and their biological components in the perennial as well as seasonally ice-covered parts of the Arctic Ocean.

Observation platforms will be remotely controlled from shore and research vessels and will utilize next-generation communication networks, including low-cost, low-power satellite-based systems for real-time data transmission. Developing systems that can operate under ice or are tailored to the dynamic conditions in the marginal ice zone will be a central activity. To the greatest extent possible, sensing platforms will conduct on-board processing of data streams such that interpretable data are available in near-real-time. To maximize efficiency and impact, we will build upon existing autonomous platforms and infrastructure where possible, such as novel buoy and mooring networks, existing fibreoptic seafloor cables, and automated samplers for biological and chemical properties. We will also advance the set of sensors that are installed on research vessels during field campaigns. Based on projections of climate and environmental change made in RT1 and RT2, we will develop optimal observing strategies that can support robust detection, understanding, and decision making also in the likely future Arctic Ocean.

We will develop methodologies to advance the uptake of current and planned polar mission satellite data (next-generation Sentinels, CIMR, CRISTAL, ROSE-L) in research activities and their integration into operational systems. Underutilized observing system components, such as from historical satellite, in situ, and social sensing datasets, will be leveraged using, for example, machine learning techniques to extract new insights into the Arctic Ocean's physical-, biogeochemical-, and ecological systems. In addition, selected output from this mass collation of data will then be used in the training of machine learning based models and for assimilation of data into operational forecast and reanalysis model systems.

Priority Topic 5.2: A hierarchical numerical model framework for global model downscaling

Motivation and knowledge needs: Global climate models provide essential large-scale information, but their coarse resolution limits their ability to capture regional and local processes with sufficient detail, particularly in the Arctic Ocean that is characterized by complex sea ice physics, small scales of motion, and highly variable air-ice-sea fluxes (Fox-Kemper et al. 2021). These tightly coupled physical processes occur in – and influence – a unique ecosystem adapted to extreme cold and prolonged low-light conditions. This presents a critical challenge for applications that require high-resolution insights, such as the high-latitude ocean eddying circulation, atmosphere-ice–ocean interactions, physical-biogeochemical-biological coupling, and regional extreme events (Shu et al. 2025). A systematic and hierarchical framework is needed to efficiently downscale climate model predictions and projections (Gutowski et al. 2020). It needs to be based on well-evaluated and established model systems that are used for forecasting and reanalysis, as well as novel model frameworks that incorporate more flexible system realizations and couplings.

Objective: To develop a hierarchical and flexible downscaling data- and physics-driven framework that translates global climate model outputs into regional and relevant high-resolution information.

Activities: A range of model systems, developed and applied within the Norwegian research community and within national and international frameworks exist already. These models provide a valuable foundation that will be organized into a coherent hierarchical framework for downscaling, spanning from pan-Arctic to regional scales with km-scale resolution, and covering physical, biogeochemical, and ecosystem components. It will be complemented by more experimental and novel models and coupling solutions.

We will use ocean and sea ice models on pan-Arctic and regional scales, as well as wave models, atmosphere models, and ecosystem models, alongside flexible coupling frameworks. This model framework will be evaluated with satellite data and process-based observations from dedicated campaigns that provide representative spatial and temporal scale data for model validation.

A central goal is to provide downscaled global climate simulations of selected climate models and scenarios (RT1) generating valuable information to support central research

questions (RT2, RT3, and RT4) as well as in the context of decision making (RT6). In addition, these downscaled datasets will be leveraged as training data for machine learning based downscaling techniques (PT5.3), enabling the downscaling of a large number of model simulations and thus providing more useful information with reduced uncertainties.

Priority Topic 5.3: Machine learning based prediction and downscaling systems

Motivation and knowledge needs: Machine learning based models offer a pathway to improve the efficiency and accuracy of predictive systems and downscaling approaches for climate model projections (Nipen et al. 2024, Allen et al. 2025). Utilizing such methods will enable us to provide more versatile prediction systems and to be able to downscale large ensembles of climate model scenarios (Hess 2025). The underexplored Arctic Ocean makes physics-informed machine learning a promising tool (Karniadakis et al. 2021).

Objective: Design AI models that integrate data from multiple sources to downscale climate scenarios and enhance the predictive capabilities of Arctic environmental forecasting systems.

Activities: We will develop machine learning models that can integrate in situ and satellite observations, as well as numerical model outputs, to improve Arctic forecasting and climate model downscaling capabilities. This includes the development of advanced data assimilation and fusion techniques to dynamically integrate in situ data and low-level satellite products, as well as downscaling approaches. These models will use novel techniques, including physics-informed machine learning that are able to focus on regional aspects while still embedding large-scale information in the training data.

The regional climate model downscaling approaches will be trained on high-resolution dynamics-based (numerical) model simulations of different complexity in terms of resolution, process representation, system couplings, and regional extent (PT5.2). The machine learning based regional downscaling models will be based on generative AI methods that can produce a very large set of ensemble predictions and projections and are able to downscale multiple climate scenarios in a highly efficient way. This strongly supports the reduction of uncertainties in extreme event assessments (RT4) and more robust quantification of uncertainty (RT6). A detailed evaluation of these new methodologies will be conducted to build trust in machine learning approaches for climate model downscaling, ensuring their reliability and relevance for climate impact assessments and decision making.

We will develop machine learning based emulators of existing numerical models. These emulators can be used for testing new data assimilation techniques, as well as for efficient Observing System Simulation Experiments to optimize the use and development of different observing networks. In addition, climate model emulators will be explored to better understand their reliability and potential use for climate predictions and projections.

Complementary machine learning efforts will focus on the observation, modelling, and prediction of land–ocean interactions, such as variations in glacial calving patterns, through the combined use of seismic data and remote satellite sensing (e.g., Köhler et al. 2022; Baird et al. 2025). For example, freshwater fluxes from glacial calving in many regions surrounding the Arctic Ocean remain poorly constrained. Integrating these complementary data sources will help improve the quantification and temporal characterization of these fluxes.

All these developments will be embedded into key European infrastructure projects, including Copernicus, EU-Digital Twin Ocean, ECMWF-Anemoi, Destination Earth, and EPOS.

Priority Topic 5.4: User-centered Arctic decision support systems – Digital Twins

Motivation and knowledge needs: Digital twin technologies are transforming decision-making by creating virtual representations of real-world systems and creating a feedback loop between digital and real-world systems (Hazeleger et al. 2024). Digital twins for the Arctic Ocean offer powerful tools for advanced scenario testing, enabling stakeholders to anticipate and mitigate environmental risks while supporting operational and policy-related decisions (Miedtank et al. 2024). By integrating observational data, modelling outputs, and AI-driven analytics, digital twins will be able to provide a comprehensive understanding of Arctic system interrelations. These capabilities will allow the developed digital twins to efficiently synthesize program-generated knowledge, ensuring that scientific insights translate into actionable strategies, planning and decision making for stakeholders (Tzachor et al. 2023, Jeuring et al. 2024).

Objective: To engage with stakeholders in a co-development process of marine digital twins for the Arctic Ocean that can serve as holistic and interactive decision-support tools by integrating real-time and historical multi-source data for Arctic environmental management.

Activities: We will develop marine digital twins for the Arctic Ocean that integrate model outputs, satellite data, in situ observations, and social sensing data to provide comprehensive environmental insights. A key challenge will be to leverage existing infrastructure when configuring and deploying local marine digital twins, such as linking large-scale observing system components (e.g., satellites, reanalyses, model predictions/projections) with local sensor networks and ensure interoperability and scalability.

Marine digital twin development will be conducted in interaction with the other RTs by drawing on advanced process understanding, scientific insights, cross-domain model integration (e.g., physical, biogeochemical, and biological models), and multi-source observations. This will support a consistent and holistic digital representation of user-relevant Arctic system challenges. Stakeholder engagement will be prioritized throughout the development process and happen in close collaboration with RT6, ensuring that these tools address real-world challenges and support informed decision-making in marine pollution, safety, resource management, and climate change mitigation and adaptation.

Advanced scenario-testing capabilities will be implemented to allow stakeholders to analyse and evaluate ecosystem information under varying conditions. This will give *Arctic Ocean 2050*, and in particular RT6, an important tool to assess climate impacts, optimize resource management strategies, and inform governance decisions. Ultimately, these digital twins will have the potential to ensure a seamless link between scientific advancements and real-world applications, improving Arctic resilience and sustainability.



Photo: Colourbox.com

Photo: Norwegian Meteorological Institute / Pernille Amdahl

RT6: Arctic Ocean Pathways

– Transdisciplinary connections and actionable knowledge



Relevance and Scope

RT6 is a central, cross-cutting stream of work within the programme that runs throughout its entire duration. RT6 facilitates across-RT engagement within the programme and research co-production with the wider peer community. The aim of RT6 is to facilitate transdisciplinary engagement and transformative conversations with Indigenous rightsholders, policymakers, stakeholders and researchers in order to co-produce new directions within the research programme and to identify actionable policy pathways in conditions of uncertainty. By fostering systematic interdisciplinary and transdisciplinary interactions, RT6 will draw upon the leading edge of Arctic assessment knowledge and practices for extending peer communities and co-producing Arctic research (IASC 2026) and the transformative leadership framework approach (IPBES 2024, Sharma 2017, Leichenko and O'Brien 2024, O'Brien et al. 2023). The aim is to bring various forms of knowledge into conversation to co-produce actionable policy pathways and inform further research in *Arctic Ocean 2050*. RT6 engages in co-production/transdisciplinary conversation that reflects the social composition and economic dynamics of the Norwegian Arctic, while seeking to reach a broader circumpolar and international setting through cooperation with extant and future projects associated with the International Polar Year and similar.

RT6 will also strengthen internal cohesion among programme partners and support the co-development of policy-, community-, and industry-relevant knowledge and skills for working in transdisciplinary contexts. Through being a platform for regular engagement between RT leaders as well as with community, policymakers, rightsholders, and other stakeholders, RT6 will generate iterative project-specific scenarios that are scientifically robust, credible, and grounded in realistic conditions, while incorporating a broad range of knowledge systems. This cross-pollination of interdisciplinary insights (RT1-4) will also underpin the development of implementation strategies, such as the Digital Twins of the Ocean (RT5) and other platforms used by decision-makers to evaluate trade-offs and assess nature-related risks.

In addition, RT6 will align pan-Arctic knowledge (Skjøldal 2022, IPBES 2024, Jørgensen 2024) through targeted outreach and alignment with representatives of previous and ongoing projects, both Norwegian and beyond, ensuring knowledge exchange and fostering consilience beyond the project partnership.

The overarching objective of RT6 is thus to catalyse a consilience of knowledge within *Arctic Ocean 2050*, and to deliver a strong foundation, rooted in transdisciplinary engagement and co-production of policy pathways, for strategic decision-making in the face of complexity and uncertainty. By examining the coupled interactions among climate and environmental change, human activity, and geopolitical dynamics, RT6 will **advance an integrated pan-Arctic understanding of how industrial and sectoral development is mediated by physical, biogeochemical, and biological processes,**

climate-related risks, changing geopolitics and shifting legal and policy regimes. This knowledge will, in turn, inform pathways that support societal transformations toward more equitable, sustainable, and adaptive futures. This will be achieved through four Priority Topics that answer the following questions:

6.1 How can inter- and transdisciplinary collaboration within Arctic Ocean 2050 ensure that RT1–RT5 jointly identify and address the most urgent research questions related to the Arctic Ocean?

6.2 How can transdisciplinary co-production across diverse knowledge and value systems generate knowledge that is both credible and usable by policymakers, industry, and communities?

6.3 How can co-created scenarios of Arctic Ocean futures inform actionable pathways, policy roadmaps, and Digital Twin outputs that guide Norwegian decision-making, as well as providing actionable input beyond Norway?

6.4 How can transdisciplinary/co-produced knowledge from Arctic Ocean 2050 be aligned with external research projects and programs to build a coherent pan-Arctic understanding that supports just, sustainable, and adaptive futures?

By fostering cross-disciplinary collaboration among RT1–RT5, RT6 integrates outputs from climate science, social-ecological research, socioeconomics, infrastructure studies, and legal frameworks into a coherent foundation for actionable knowledge. This synthesis will support ministries, public agencies, industry, and communities in climate change mitigation and adaptation, conservation planning, and Arctic safety and policymaking. Through structured transdisciplinary work and in alignment with co-production with rightsholders, RT6 ensures that knowledge generated in *Arctic Ocean 2050* is presented in a manner that is credible, relevant, and usable. Co-created scenarios built on co-produced drivers of systems change are translated into policy roadmaps, implementation pathways, and Digital Twin outputs that can guide both Norwegian and pan-Arctic authorities. By aligning *Arctic Ocean 2050* outcomes with external projects and initiatives, RT6 also strengthens pan-Arctic knowledge coherence and contributes to just, sustainable, and adaptive futures.

Priority Topic 6.1: Foster internal cohesion across research themes

Motivation and knowledge needs: *Arctic Ocean 2050* operates in a period of deep environmental and geopolitical uncertainty, contested values, and urgent needs for decision-making — hallmarks of post-normal science (Funtowicz and Ravetz 1993). To ensure the consortium consistently addresses the Arctic's most pressing research questions and exemplifies interdisciplinary priorities, internal cohesion and co-creation of knowledge are essential (Sharma 2017, Funtowicz and Ravetz 1990, 1994). This requires that RT1–RT5 engage in active dialogue, jointly reflect on knowledge gaps and uncertainties, and explore their implications for governance and policy. Rather than treating synthesis as a purely technical exercise, this priority topic emphasizes facilitated, interpretive, and reflexive integration of insights across disciplines (Dankel et al. 2012, 2020, Sharma 2017, Funtowicz and Ravetz 1993).

Objective: To enable a shared, cross-disciplinary understanding of how to respond to urgent Arctic research needs in a comprehensive way, PT6.1 will ensure the consortium continually aligns around the most important questions by fostering internal cohesion, reflexivity, and joint sense-making, while supporting more pluralistic, transparent, and adaptive science-policy dialogues.

Activities: To foster internal cohesion and cross-disciplinary integration within *Arctic Ocean 2050*, Priority Topic 6.1 will cultivate a shared understanding of post-normal science principles (Funtowicz and Ravetz, 1990, 1993, 1994) and strengthen collaboration across all research themes. This will be operationalized through bi-monthly cross-RT coordination meetings and annual workshops aligned with public conferences or consortium gatherings, emphasizing reflexivity, extended peer communities, and the co-production of knowledge. These structured engagements will enable RT1–RT5 to jointly identify and address the Arctic's most pressing interdisciplinary research questions. A cross-thematic driver-mapping exercise will further support this process by synthesizing inputs from all RTs to identify critical drivers shaping Arctic research priorities. These drivers will be tested and calibrated in workshops to ensure alignment with governance and policy realities, thereby informing PT6.2. Systems thinking methodologies (Clifford et al. 2022, Dankel et al. 2020), combined with conceptual mapping, fuzzy quantitative data, and qualitative insights, will guide this integrative effort, supported by tools such as MentalModeler and Vensim for collaborative scenario development. Through this iterative and participatory process, PT6.1 will establish a dynamic forum for interdisciplinary dialogue and knowledge integration.

In parallel, RT6 will actively contribute to international science-policy dialogues by positioning *Arctic Ocean 2050* as a leading voice on Arctic research uncertainties and priorities. This will involve engagement with global conferences and policy forums to communicate evolving insights and foster mutual learning across regions and disciplines. Furthermore, RT leads and the cross-RT coordination group will systematically reflect on knowledge uptake by tracking how synthesized outputs are received, interpreted, and utilized – or not – within governance contexts. This process will identify key enablers and barriers to meaningful policy impact, ensuring that the knowledge generated is both actionable and relevant.

Priority Topic 6.2: Extending and engaging the Peer Community

Motivation and knowledge needs: This PT focuses on engaging a diverse group of rightsholders, stakeholders and policymakers in transdisciplinary conversation and co-production of scenarios, foresighting, and actionable pathways for policy and further research in *Arctic Ocean 2050* (Ravetz 1999, Blackstock 2023, Dankel et al. 2012, 2020, IASC 2026).

Objectives: Define and engage across Research themes, with stakeholder and rightsholder organizations, and relevant policy makers to establish an extended peer community for co-production of knowledge (IASC 2026) and a post-normal and participatory science framework (Funtowicz and Ravetz 1994, O'Brien 2018).

Activities: Identification of participants, mapping, and engagement will be conducted to ensure comprehensive representation. Scenarios will be discussed with the International Advisory Board (Table 4) and international science organizations, including the Arctic Council, EU Arctic Forum and the Indigenous Peoples' Dialogue, WGICA (ICES, PICES, PAME) to gather expert insights. Early outreach to key Norwegian/Nordic Arctic organizations to ensure that research in *Arctic Ocean 2050* is informed by an ongoing transdisciplinary conversation as well as knowledge and perspectives from pan-Arctic relevant projects and programs.

Priority Topic 6.3: Co-produce Scenarios

Motivation and knowledge needs: This topic aims to develop scenarios informed by multiple forms of knowledge to explore the social-ecological, economic, and political consequences of a changing Central Arctic Ocean. Such scenarios include environmental conservation, shifts in fishery distributions, policy positions of Indigenous governance mechanisms and organizations, policies and practices, changes in maritime accessibility, and emerging governance challenges of sustainable societal transformations (IPBES 2024). The goal is to provide a robust, transdisciplinary foundation for future decision-making and policy development (Clifford et al. 2022, Dankel et al. 2020), that continues also to inform research within the consortium.

Objectives: Co-create science-based scenarios to leverage stakeholder engagement and dialogue for actionable knowledge and science diplomacy.

Activities: *Arctic Ocean 2050* will first identify methodologies for participatory approaches and co-production of relevant multi-disciplinary and cross-sectorial knowledge for policy-relevant scenarios of future ecosystem and industry decision-making in the Arctic Ocean, resulting from the activities in PT6.1. Subsequently, interactive workshops with defined Extended peer communities from PT6.2 will be organized to facilitate collaborative scenario development. Finally, the programme will focus on the co-production of scenarios using the identified methodologies, with the specific methods to be determined as part of the program. This involves synthesizing existing results across 3–4 key thematic areas – such as marine ecosystem integrity, resource availability, local livelihoods, and governance resilience – to support scenario development, and the identification of ongoing knowledge gaps.

Priority Topic 6.4: Actionizing Scenarios into Transformative Pathways and Roadmaps

Motivation and knowledge needs: This topic aims to transform scenarios into concrete policy recommendations and action plans, responding to the urgent need for strategies that both anticipate possible futures and guide actionable steps toward sustainable ocean governance and a resilient blue economy (Blackstock et al. 2023, Stenseth et al. 2020, O'Brien 2018, Leichenko and O'Brien 2024, O'Brien et al. 2023, Stenseth et al. 2020).

Objectives: The overall objective is to translate research-based scenarios into actionable pathways and roadmaps for Norwegian policymakers, regional authorities, business leaders, and other relevant groups ensuring that outcomes are practical,

implementable, and aligned with stakeholder needs. A supporting objective will be the involvement of extended peer communities, drawing on the perspectives of policymakers, businesses, local communities, and civil society to build the proposed pathways. The work on scenarios draws inspiration from research that has shown the importance of storytelling and recovering/reclaiming Indigenous framings of land and sea that challenge and call for rethinking dominant framings based in colonial mindsets and practices (Kramvig and Salmela 2026).

Activities: Close collaboration with international initiatives, particularly the legacy of the EU Mission Restore our Oceans and Waters and supporting European research on the Digital Twin of the Ocean, will ensure methodological alignment, shared use of data, and mutual validation of transformative strategies, allowing Norwegian perspectives to both contribute to and benefit from European-level ocean and climate action and circumpolar governance. Furthermore, the integration of related science–industry projects will reinforce the innovation and implementation dimension of the roadmaps, ensuring that recommendations directly inform sectoral practices in areas such as environmental conservation, shipping, fisheries, offshore energy, and coastal resilience.

To ensure impact, targeted policy roadmaps and information briefs will be produced to safeguard Norwegian and global interests in climate-resilient oceans and sustainable blue growth. PT6.4 will also provide politicians, Indigenous leaders, ministers, and state secretaries with a strategic platform to prepare evidence-based contributions for international arenas such as in circumpolar governance efforts and the UN processes, Arctic Frontiers, and the Arctic Circle Assembly, ensuring Norwegian perspectives are both well-informed and influential. Finally, annual validation and calibration workshops will be conducted with funders, user groups, and international partners, to assess progress, refine recommendations, and ensure the ongoing relevance and effectiveness of the developed strategies.

4. Cross-cutting activities

4.1 Education and capacity building

Norway's leading role in Arctic research and governance requires highly educated people with skills and experience relevant to Norway's Arctic region. The next generation of researchers must acquire inter-disciplinary knowledge and diverse skill sets, be able to apply this competence to current and upcoming management and governance issues, and to communicate clearly across national and sectoral entities. Early career researchers (ECRs) will be an integral part of the science of *Arctic Ocean 2050*, significantly contributing new knowledge while developing research design, analytical, critical thinking skills in an interdisciplinary and multi-institutional environment.

Arctic Ocean 2050 will develop an ECR community of learning whereby ECRs work together across institutions to develop competence in a wide variety of communication and presentation skills and have the opportunity to explore non-academic career paths through co-supervision within the partner network and participation in stakeholder activities.

During the duration of the *Arctic Ocean 2050* program, we will:

Establish an Early Career Researcher Forum. The *Arctic Ocean 2050* programme office will assign a dedicated staff member to run the ECR Forum. The forum will provide a communication platform, organize ECR meetings, training, and events (in person and online), point to career-relevant tools, and be a contact point for ECRs within *Arctic Ocean 2050.*

Support successful ECR journeys. *Arctic Ocean 2050* will educate a minimum of 100 PhD candidates, hundreds of master students, and dozens of post-docs in its decade-long lifetime. Furthermore, the 10-year duration of *Arctic Ocean 2050* will provide continuity and opportunities for student retention within the program, from MSc- to post-doc levels. Career advice and mentoring opportunities will be essential towards this goal. PhD committees will usually have members of several *Arctic Ocean 2050* partners to help integration and enculturation.

Build scientific knowledge. Scientific knowledge building is at the core of any PhD journey. *Arctic Ocean 2050* will periodically during the decade offer a signature course that focuses on disciplinary as well as inter- and trans-disciplinary insights and approaches related to our core themes: extra-regional drivers (RT1), characteristics of the Arctic Ocean (RT2), human impact, potential use and related governance (RT3), and extreme and abrupt events (RT4). A summer school will focus on experiential learning. Regular courses at partner institutions will be available and transferable to help tailor PhD academic training to meet academic needs and goals. The recently funded Research Council of Norway PhD school *Climate informed*, led by UiB, the existing ECR-focused northern Norwegian research network *ARCTOS* (Arctic Marine Ecosystem Research Network, including five *Arctic Ocean 2050* consortium partners), and a

research school proposal to be submitted related to the upcoming International Polar Year could be suitable vehicles. Coordination and interaction with the Association of Polar Early Career Scientists (APECS) is also critical. The *Arctic Ocean 2050* team has merited educators that will help ensure high standards and address national strategic education goals.

Build transferable skills. ECRs will be given ample opportunity to build relevant transferable skills inside *Arctic Ocean 2050,* such as on emerging scientific methodologies (RT5) and actionable knowledge generation (RT6). ECRs will also be encouraged and trained to lead science sessions in annual meetings, develop session proposals for international conferences, participate in panel discussions, engage in transdisciplinary work, participate in programme leadership meetings and help write new research proposals. In outreach settings, ECRs will be given opportunities to participate in workshops on diverse topics related to analysis and publishing of data, graphical presentation, writing for professional and lay audiences, effective public speaking, and other topics.

Network in peer and inter-sectoral communities. Enculturation into professional/academic life is a documented key to building a successful career. To help familiarize ECRs with their peer and broader stakeholder communities, *Arctic Ocean 2050* will establish a mobility programme supporting research visits with partner institutions and other (inter)national researchers, and experiential learning with non-academic partner institutions and relevant stakeholders.



Photo: Norwegian Polar Institute / Olaf Schneider

4.2 Communication, Outreach & transdisciplinary engagement

Arctic Ocean 2050 will implement a comprehensive communication and outreach strategy to support the overarching goals of the 10-year program, outlined in a separate Communication Plan. Effective communication and outreach are key to ensure the impact of the essential and applicable knowledge and skills that *Arctic Ocean 2050* will generate. The programme will facilitate and communicate the development and implementation of updated management principles in the new and blue Arctic Ocean.

The mission of the programme will serve as the guiding compass and the foundation for all outreach efforts. Once the strategic messages and their meanings have been defined, specific measures for how, when, and where the messages are presented will follow. The programme will work strategically to identify target audiences and develop content that resonates with them on relevant communication platforms. As part of the strategy, messages will be tailored to prioritized and other relevant audiences at three geographic levels, national (including both programme internal and external), Nordic and pan-Arctic, and global (see examples in Figure 7). Communication languages will be adapted to these levels.

The programme will adopt a policy of openness and inclusion, to ensure transparent communication of activities and results, as well as constructive extended peer community dialogue facilitated by RT6 activities. A transdisciplinary extended peer group, with representatives from e.g., Indigenous organizations, the private sector and government based in Norway, will be established early in the programme period as described above in RT6.

To reach the diverse target groups of the program, multilingual content will be produced in different formats and with relevant collaborators. To ensure that the programme has raw material to produce visual outreach, the budget will include provisions for dedicated communication resource(s) and persons to participate onboard, collecting and documenting – and producing outreach – aligned with the programme overarching mission. This material will be helpful not only for the program's own communication (to stakeholders, financing bodies, prospective partners), but for scientists' dissemination activities, and for increasing exposure to the media.

The programme will work proactively towards building a culture where researchers are oriented towards public communication (such as writing outreach articles and opinion pieces, engaging in hearing processes/statements, and giving popular science outreach lectures). The National Science Week, a research festival held once a year, conferences and events like Arctic Frontiers, Arendalsuka, and Arctic Circle Assembly are examples of natural arenas for the programme to participate in. A website for the program, as well as various social media platforms, will be important for regularly updating information about involved parties, funding sources, programme objectives, and research outcomes. The programme will also facilitate a platform for sharing photos and videos.

A dedicated communication advisor in the programme will be hired at the institution that leads the programme (UiT). This person will lead the work in a communication group with communication personnel from all partner institutions. programme scientists including ECRs will be engaged in popularizing findings and there will be a special effort on training their communication skills, e.g., engaging them in outreach activities when on field missions and research cruises.



Figure 7: Communication strategy. Examples of prioritized and other audiences for communication & outreach in *Arctic Ocean 2050* and related geographic scope. Fig. C. Stark MET.

The communication group will meet on a regular basis, both on Teams, and in-person at annual meetings. The group will be responsible for updating the communication plan with targets and annual task plans. This will ensure that the different activities and results in the programme are communicated to selected target groups, either by the leading communication officer or by communication personnel in the partner

institutions. The respective institutions will strengthen the dissemination work of the programme in their channels.

Engaging with local communities, including Indigenous, will be a priority, ensuring their voices are heard and respected in the research process. The programme will also focus on youth engagement, working with schools and youth organizations to encourage participation and translate materials into relevant Arctic Indigenous languages.

By maintaining a commitment to transparency and inclusive communication and outreach, *Arctic Ocean 2050* aims to effectively inform and influence international discussions on Arctic issues, in line with the overarching mission of *Arctic Ocean 2050*. Communication products will be tracked via specified performance indicators to assess impact.

4.3 Data management and Open Science

Arctic Ocean 2050 is committed to state-of-the-art data management and open science practices as outlined in the program's data management plan, *s*ubmitted with this updated Science Plan *T*he data management plan is considered a living document. The programme will follow the Research Council of Norway's policy on **Open Science** which specifies guidelines for research assessment (with reference to DORA), FAIR principles, ethically sound participatory approaches, open access to publications (with reference to Plan S), and crediting. **Performance metrics** tracking adherence to the policy will be used as available through the data centres used and the Norwegian Research Information repository; and complemented to indicators the programme will develop.

The International Polar Year (IPY) 2007/2008 was a turning point for scientific data management in the Polar regions. For many scientists, this was their first encounter with concepts like metadata, as well as structured and standardized data documentation. Data centres were tied together into a virtual data centre through the IPY Data and Information Service. Since then, this has been further developed through national e-infrastructures, The Nansen Legacy, and regional and global data management frameworks.

Structured data management is a prerequisite for efficient data exploitation, both within and between disciplines, as well as between research and management levels. It is also required for digital twins and machine learning. Structured data management is based on standardized documentation of data, standardized interfaces to data, and well-defined procedures for data publication, preservation, and governance.

The original purpose of the **FAIR** guiding principles (make data Findable, Accessible, Interoperable and Reuseable) was to achieve machine actionable information. This simplifies the process of finding and using data, but only if all four aspects of FAIR are properly addressed. Currently most data are now Findable and Accessible, but there are often issues with their Interoperability and Reusability. Improving this situation will be emphasized in *Arctic Ocean 2050*, such that we can ensure integration of data into

research and management workflows and value chains. FAIR is also a requirement for transparent and reproducible research and traceable decisions made based on data. Equally important is to adhere to **CARE** and **TRUST** principles as relevant and detailed in the data management plan.

Research is international, and integration of data into larger frameworks promotes collaboration through visibility. Reuse of existing data contributes to reducing both the financial cost and the climate footprint of research. To achieve this, system development and training must be undertaken in due course before researchers go into the field. If done appropriately, this would be a successful contribution to IPY 2032/2033 that builds on the previous IPY and extends into the future and supports emerging methodologies like machine learning and new observational techniques.

The Data Management Plan of *Arctic Ocean 2050* includes a strategy **for physical sample archival**, especially regarding biodiversity where the university museums will play a leading role. Museum collections have in recent decades undergone a revolution in digitalization, curation, and hence accessibility for the global community. With Arctic marine biodiversity at peril, archival efforts are important.

5. Organisation of *Arctic Ocean 2050*

5.1 programme organisation

Arctic Ocean 2050 is developed by a nationwide consortium consisting of 18 universities and research institutions, in response to ongoing climate change in the Arctic Ocean and its influence on environmental, industrial, and political development. The complexity of these challenges necessitates this large national initiative that goes beyond the time and funding framework of more traditional research projects. Unprecedently, *Arctic Ocean 2050* unifies not only environmental but also law/governance/security research across Norway in a concerted programme to understand the Arctic Ocean in all its aspects. The complementary skills and collective expertise of the consortium will enhance national collaboration and create opportunities for pioneering research in the Arctic Ocean.

The six **research themes** (RTs) of *Arctic Ocean 2050* collectively ensure transdisciplinary perspectives. In addition, RT6 will synthesize research results, knowledge, and insights from the other research themes (RT1-RT5) to support the co-development of policy-relevant scenarios for the Arctic Ocean. Each RT will have a leader and a co-leader, representing different institutions and science disciplines to ensure an integrative perspective and cooperation within and across the research themes. The **programme leadership** team consists of a leader and four co-leaders with complementary expertise and responsibilities and is supported **by administrative and financial staff** (Figure 8).

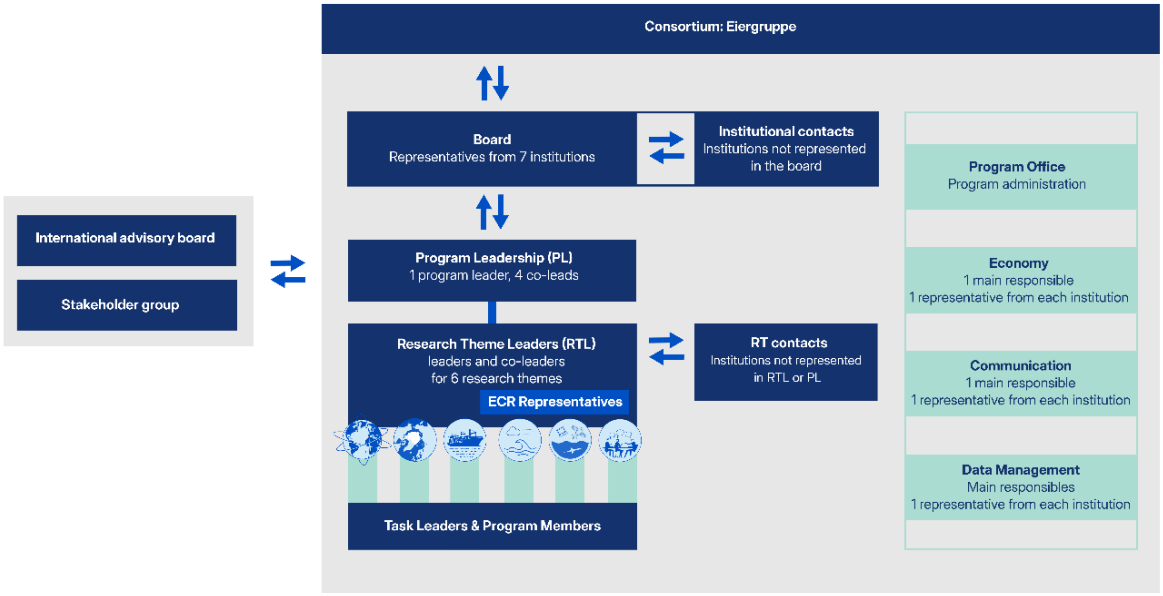

Figure 8: Organisation of *Arctic Ocean 2050*. Organigram representing the Board and institutional contacts, programme leader group, Research Theme Leader group and members, as well as the International Advisory Board, Transdisciplinary actors (in formation), Data management, Communication groups, programme office and economic support.

Arctic Ocean 2050 also has a **Programme Board** that will govern the program's strategic plans. Furthermore, the results, relevance and progress of the *Arctic Ocean 2050* programme will be overseen by an **International Advisory Board** of internationally recognized scientists (see Tables 2-4 for their composition in the first programme phase). **Communication** and **data management** teams are each lead by dedicated staff, supported by contact groups representing all consortium partners.

To further facilitate cooperation within and across research themes, everyone involved in the program, including scientists, the Board, International Advisory Board, communicators, data managers, financial and administrative staff, and transdisciplinary actors, will meet at least once a year for an *Arctic Ocean 2050* annual meeting. Dedicated workshops will also be organized to address specific topics that cut across several research topics. International collaborators and members of collaborating projects will be invited to *Arctic Ocean 2050* meetings.

5.2 Use of national infrastructure

Fieldwork: The state-of-the-art research vessel *Kronprins Haakon* is one of the world's most advanced platforms for scientific exploration and a vital asset in uncovering the future of the Arctic Ocean. As part of the *Arctic Ocean 2050* program, R/V *Kronprins Haakon* will be used to conduct ecosystem surveys, process studies, and measure hydrographic, biogeochemical and atmospheric conditions. Designed to operate in challenging ice conditions, it can break through ice up to one metre thick and is equipped with 15 laboratories supporting a wide range of research disciplines. The ship features advanced sonar for detailed seabed mapping, a remote-controlled submarine

capable of descending to 6,000 metres, a helicopter deck, and seismic and trawling equipment, making it exceptionally versatile for polar research. Additional platforms will be used for testing technology and achieving specific objectives for which icebreaker time is not required or appropriate.

Arctic Ocean 2050 will also take advantage of existing national infrastructure projects for ocean observations, such as NorArgo (The Norwegian Argo infrastructure), NorGliders (The Norwegian Facility for Ocean Gliders), and ICOS-Norway (Integrated Carbon Observation System - Norway), and of national technology core facilities such as the Norwegian Sequencing Centre. Arctic Ocean 2050 also plans to make use of the Deep-Sea Remotely Operated Vehicle Ægir, facilitated by The Norwegian Marine Robotics Facility (NORMAR). Furthermore, the international infrastructure SIOS (Svalbard Integrated Arctic Earth Observing System) will be used.

Modelling: *Arctic Ocean 2050* will make use of the national infrastructure Norwegian Earth System Modelling (INES2) for providing state-of-the-art global historical and future climate projections. These are key components for understanding large scale external drivers of Arctic Ocean changes as well as for downscaled modelling. Computing resources for model simulations and storage resources for storing data generated in *Arctic Ocean 2050* will be provided through the Norwegian Research Infrastructure Services (NRIS) with the National Infrastructure for Research Data (NIRD).

5.3 International Collaboration

The broad scope of *Arctic Ocean 2050*, as well as the fact that it will be a decade-long programme with long-term core funding, opens up for broad international cooperation with institutions, nations, and large international initiatives. Different regions of the Arctic are influenced by different physical drivers, have different ecological responses, are used by industry and Indigenous peoples and coastal communities differently, and operate under different jurisdictions. We also understand, however, that there is strong connectivity within the Arctic Ocean and with areas outside the Arctic, and trans-sectoral governance based on a deep knowledge base for all Arctic regions is important for informing strategies for conservation and responsible use. Thus, we rely on the strong research and infrastructure capacities of both Arctic nations themselves, and the many other nations with identified research focus in the Arctic Ocean. Strong international collaboration will provide *Arctic Ocean 2050* with complementary knowledge and perspectives across disciplines and foster a shared vision of a sustainably managed Arctic Ocean.

Arctic Ocean 2050 will be an important contribution to the International Polar Year (IPY) in the north, while also providing an international platform for pan-Arctic collaboration during the IPY. Scientific collaboration with international experts in Polar marine science will also be established and maintained through other highly relevant organizations such as the Arctic Council, the Association of Polar Early Career Scientists (APECS), the International Arctic Science Committee and its International Conference on Arctic Research Planning (IASC-ICARP), the Synoptic Arctic Survey (SAS), and Distributed Biological Observatories (DBOs). This interaction with other Arctic research projects and

programs will serve to counsel the *Arctic Ocean 2050* and its research strategies. International collaboration will also include research and data infrastructure (e.g., icebreaker support, shared use of ships, data and model development), and researcher mobility (e.g., student exchanges, research schools, summer schools).

Dialogue aiming to establish formal, long-term collaboration has been initiated between *Arctic Ocean 2050* and countries that have multi-year national Arctic research programs; Japan's ArCS-3 and Republic of Korea's new K-Arctic Ocean program, and it is our aim to establish formal and real collaboration with projects in different countries covering a variety of disciplines across the Pan-Arctic landscape. Discussions with relevant projects in other countries have also started – through contact with leaders of international projects, and in some cases based on suggestions from members of the International Advisory Board. *Arctic Ocean 2050* has established internal guidelines for establishment of formal collaboration with international programs and projects to ensure that we avoid duplication of work and to keep track of resources committed into collaborative efforts.

Upcoming (tentatively 2027 and 2030/31) open calls for project funding associated with *Arctic Ocean 2050* through the Research Council of Norway will enable funding of international collaborators. These calls may include funding from other countries' funding agencies, further extending the possibilities for jointly funded direct collaboration. An upcoming EU call for proposals explicitly mentions collaboration with *Arctic Ocean 2050*. We envision that other opportunities for solid, well-funded international collaboration will emerge in the coming years, e.g., through the Belmont Forum.

Arctic Ocean 2050 will make use of the Copernicus Marine and Climate Change Services providing free satellite data, ocean, sea ice, and biogeochemical forecasts in the Arctic. Copernicus Services also provide their Digital Twin infrastructures such as Destination Earth and EDITO. Conversely, *Arctic Ocean 2050* will provide ocean physical, biogeochemical, and sea ice observations to European data aggregators such as EMODNET and Copernicus.

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