Nordic Council of Ministers

NORDIC CRYOSPHERE DIGITAL TWIN

Digital Twin technologies to address the impact of climate change

Contents

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The Nordic Cryosphere Digital Twin (NOCOS DT)

The challenge

The Arctic area is one of the hot spots of climate change. The observed air temperature change is 3–4 times larger than the global average[1]. Atmospheric changes are associated with unprecedented shrinking and thinning of the seasonal sea ice especially in the coastal areas. This already affects the distribution of fish species, fishing activities, shipping routes, tourism, and the lives of indigenous peoples. The European Arctic area, including the coasts of Greenland and Svalbard as well as the Barents, has been heavily impacted by those climate changes triggering the need to establish some actions in the region.

The project

Funded by the Nordic Council of Ministers and leveraging the Nordic and Baltic expertise and competences in digital twin technologies, the Nordic Cryosphere Digital Twin[2] project (NOCOS DT) has piloted new models for climate information and impact sectors such as navigability, engineering and vessel design, fishing and shipping, and renewable energy.

1. https://www.nature.com/articles/s43247-022-00498-3
2. https://wiki.eduuni.fi/x/_p2hH

The tools developed by NOCOS DT improve climate-smart practices and assessment of climate-related risks making shipping in the Arctic and Baltic Seas safer and more efficient. Beyond the immediate benefits for industries such as coastal engineering, shipping, and fishing and harbor authorities, the longer-term societal and economic benefits of the applications in the region span from effectiveness in policymaking to improved innovation capabilities of companies and higher societal ability to adapt to the effects of climate change, including decision-making and measures in support of traditional hunting and fishing by indigenous peoples.

The project was coordinated by CSC – IT Center for Science (CSC). The other partners were Danish Meteorological Institute (DMI), Finnish Meteorological Institute (FMI), Norwegian Meteorological Institute (MetNo), Swedish Meteorological and Hydrological Institute (SMHI) and the Tallinn University of Technology, Department for Marine Systems (TalTech).

Climate Change Adaptation Digital Twin (Climate DT)

NOCOS DT piloted using data produced by the Destination Earth Climate Change DT[3] in its use cases. Climate DT is part of the European Commission's Destination Earth (DestinE) flagship initiative, which develops digital twins of the Earth to support decision-making. Climate DT utilizes Earth system models at a high resolution, producing simulations that provide insights into the future evolution of our climate. In addition, Climate DT integrates impact-sector applications with the climate models to produce information of the climate change impacts on hydrology, renewable energy production and wildfires.

Key outcomes of NOCOS DT

- Enhanced sea ice modelling, including breakup into drift ice and dynamic simulations using exascale computing
- Advanced tools for navigation risk, landfast and ridged ice, marginal ice zones, and marine spatial planning
- Integrated framework for input data, modelling methodologies, technical requirements, and output analysis
- Improved data quality, visualizations, and statistical output using Climate DT data and novel modelling techniques
- Demonstration of how the data produced by Climate DT can be used in practice, and important feedback for future development of both the digital twin and DestinE interfaces
- An open-source software package containing the code produced during the NOCOS DT project that will be useful for future users of Climate DT, enabling relevant user-oriented sea ice diagnostics tools in the Baltic and Arctic regions

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3. https://destine.ecmwf.int/climate-change-adaptation-digital-twin-climate-dt/

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Through NOCOS DT, the Nordic-Baltic region demonstrates the power of collaboration in turning knowledge into actionable results. By combining shared expertise, technologies, and evidence-based insights, the region contributes to Climate DT with new sea-ice use cases that make climate information more democratic, accessible, and directly usable for decision-making. This joint effort strengthens our ability to adapt to and mitigate climate change – showing that when the Nordic-Baltic countries work together, cooperation translates into tangible results, benefiting the region as a whole, but in particular the Arctic ecosystems and the people whose lives and livelihoods depend on them.

Dan Koivulaakso
Director – Growth & Climate
Nordic Council of Ministers

Janek Valdsalu / Unsplash

Six use cases supporting specific sea ice phenomena

NOCOS DT implemented six cryosphere-related use cases at the intersection of science and policy:

- The ship navigation risk indicator to improve information on navigability in varying ice conditions.
- An analysis tool diagnosing the period for landfast ice to inform people living in the cryosphere when and where it is safe to travel on ice, and a demonstration of an iceberg drift model.
- The provision of accurate and reliable data on ridged ice probability to improve winter navigation, increases safety at sea, and conduct efficient risk assessment for maritime operations, such as offshore construction.
- Regular monitoring and prediction of the marginal ice zone to increase understanding of the Nordic seas by providing locations, weekly evolution, and statistics.
- The marine spatial planning use case to pilot how the climate models' data can be utilized on planning platforms.
- Demonstration of an iceberg drift model.
- The development of a discrete element model-based sea ice model.

Ship navigation risk indicator

Ship navigability in ice-covered sea depends on sea ice concentration, ice thickness, fraction of pressure ridges and multi-year ice as well as ice speed and compression, but also importantly the ice class of the vessel.

The International Maritime Organisation (IMO) has introduced a Risk Index Outcome (RIO) method to provide ship-specific guidelines for safe navigation in ice-infested waters. Calculating RIO needs accurate, high-resolution sea ice information.

Goal

Improved information on navigability – develop a method to calculate a navigation risk indicator similar to RIO from model data and to estimate probabilities of sea ice extremes.

Users

Open-source code will be published on GitHub for scientific use, and the forecast of risk index can be provided to shipping companies.

Models and data

Copernicus, ECMWF and DMI HYCOM-CICE sea ice forecasting products have been used to develop the navigation risk indicator. The calculation method is implemented within the Destination Earth Climate Change Adaptation Digital Twin environment where the input data is streamed from the global high resolution Climate digital twin. Model outputs are validated by RIO in ice charts. In addition, an ice / no ice climatology and trend is derived.

Key innovations

The Risk Index Outcome is a new parameter in modeling, decided jointly by ice condition and ship class. Traditionally, the ice condition includes sea ice concentration and thickness. Salinity and age are introduced in the innovative RIO calculation algorithm developed by NOCOS DT as novel parameters, to better determine the POLARIS ice type, providing a more accurate RIO outcome.

Impact and legacy

- Daily updated RIO forecast derived from ECMWF S2S modeled ice data, including now-cast, +1, +2 and +3 days forecast, stored in FMI's internal FTP temporarily.

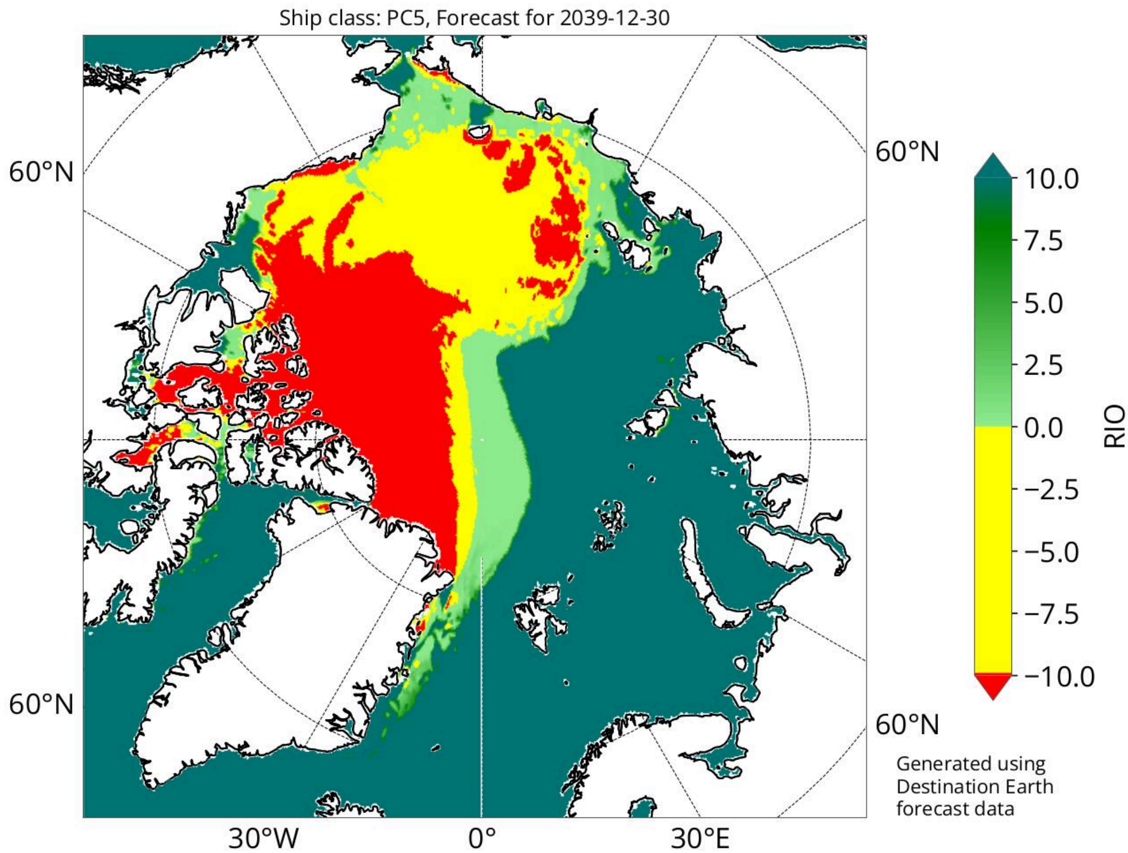

Figure 1 RIO distribution in the Arctic
© Finnish Meteorological Institute (FMI)

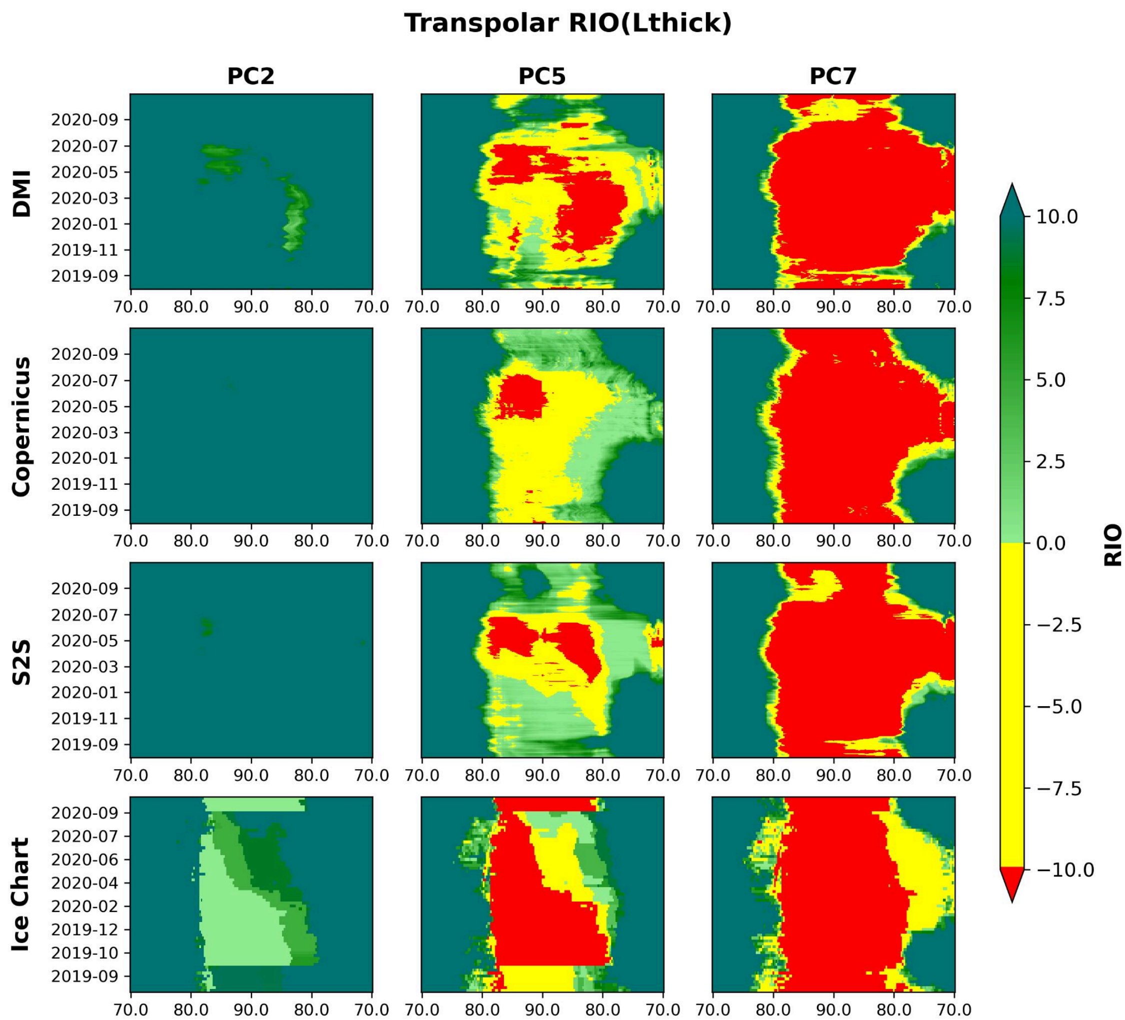

Figure 2 Arctic transpolar route RIO profile
© Finnish Meteorological Institute (FMI)

Landfast ice

Landfast sea ice refers to sea ice that is locked and does not move. This makes it a more stable and predictable area to work on when it is thick enough. Greenlandic people travel on the landfast sea ice and use it for hunting and fishing. This means that changes in landfast sea ice conditions will (and already do) affect their way of life. Landfast sea ice is also common in the Baltic in the winter, where it is used for winter roads and recreational activities such as skiing and ice fishing. Landfast ice starts to build up when ridges hit the sea floor or if icebergs or the coast locks the sea ice.

Goal

Create an analysis tool that diagnoses the period for landfast ice in present and future climate.

Users

- People travelling on sea ice
- Decision-makers who want to plan when it is feasible to travel on ice
- Decision-makers who want to install offshore constructions in ice-covered areas
- Cruises companies who want to know the length of the open water season.

Models and data

- DMI's ocean-sea-ice model for the Arctic
- Climate DT model output
- Ice charts (for validation)

Key innovations

- Demonstration of data access to Climate DT data.
- First high resolution landfast ice product with future projections.
- Demonstrations of landfast sea ice methods on reanalysis/forecast products from DMI.
- Landfast ice analysis is easily transferable to other sea ice data sets available through the DestinE Data Lake

Impact and legacy

- A toolbox for diagnostics of the landfast sea ice.
- The landfast sea ice analysis is easily transferable to other sea ice data sets available through the DestinE platform including the Data Lake and other sources.

Landfast sea ice is important for the Greenlandic and other Arctic societies as they use it for infrastructure, fisheries and hunting. Therefore it is important to predict the stability of the landfast in a changing climate.

Keld Qvistgaard
The Greenlandic ice service

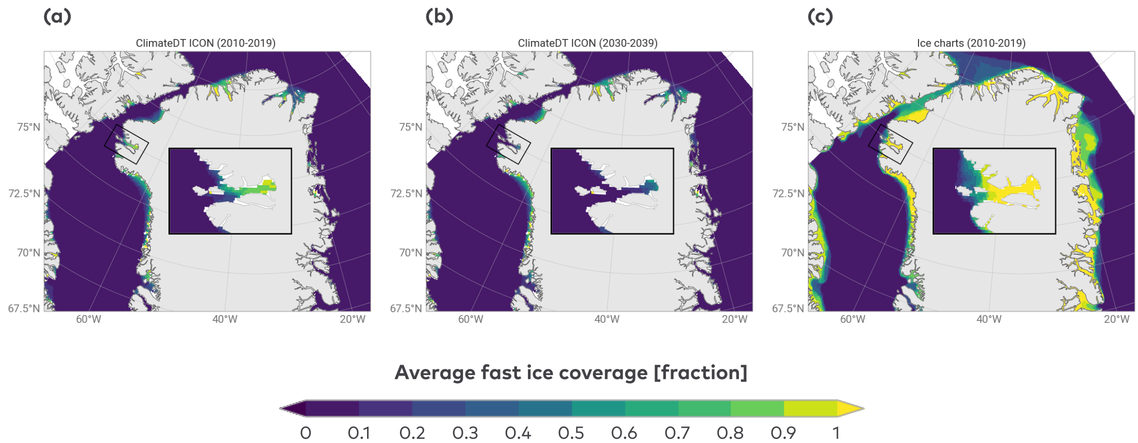

Figure 3 Landfast ice climatology for March. The color indicates how frequently in March the coast of Greenland is covered by landfast ice. The inlet shows a zoom on the Inglefield Bredning in Northwest Greenland. (a): Climate DT simulation (model ICON) for March 2010–2019; (b): Future projection of the Climate DT simulation (model ICON) for March 2030–2039; (c) for reference: Observed landfast ice coverage in March 2010–2019 based on ice charts.
© Danish Meteorological Institute (DMI)

Ridged ice

Ridged ice can be hazardous for offshore and coastal construction, and it limits the servicing and maintenance of offshore facilities. It is important to consider the ridged ice related risks during the design of constructions to assure optimal maintenance and servicing costs of each facility. Ridged ice occurs in areas of high ice dynamics and especially close to the coastal zone, which often coincides with the interest area of coastal developers (e.g., wind farms, aquafarms, Floating Storage Regasification Units). Drift of deformed ice formed around offshore wind farms can further affect local communities and ship traffic, increasing the relevance of detailed studies. Knowledge about the probability of ridged ice occurrence is also beneficial for safe winter navigation and ice breaking. Knowledge of expected changes in ridged ice has a considerable social impact as it helps to increase safety of wintertime navigation as well as to prevent ice-related hazards for coastal structures.

Goal

The goal of the application is to enhance and innovate the methods for computing the ridged ice probability index and to assess its impacts on offshore and coastal activities.

Users

Additional potentially interested parties besides wind farms, aquafarms and floating storage regasification units include:

- Maritime authorities: agencies in Baltic Sea countries are interested in ridged ice data for safe navigation, ice advisories and icebreaker management.
- Shipping companies: vessel operators require information on ridged ice for assessing risks, planning routes, and ensuring maritime operations' safety.
- Fishing and aquaculture industry: developers and operators rely on accurate ice information to assess impacts, plan operations, and ensure safety for fishermen and vessels.
- Insurance companies: industry requires ridged ice data to assess risks, underwrite policies and set premiums for maritime assets in cold regions.

Models and data

The regional configuration of the ice model, supplemented with Copernicus reanalysis, is used to establish a climatology of ridged ice. The application of Climate DT data provides a scenario model database at 5 km resolution, capturing basin-scale ice dynamics in the Baltic Sea.

Key innovations

Although ice ridging is not a common ice DT output parameter, the availability of reliable proxies for ridged ice can greatly enhance navigation and safety in marine activities.

Impact and legacy

- Climate DT data services and the NOCOS ridged-ice toolbox will remain accessible, supporting evidence-based policy, risk management, and sustainable planning for marine and coastal activities in the Baltic region

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The NOCOS case study on deformed sea-ice drift in the Gulf of Riga provided valuable input for the Saare-Liivi offshore wind farm environmental impact assessment, supporting evidence-based evaluation of ice-related risks.

Kristiina Nauts
Utilitas Wind

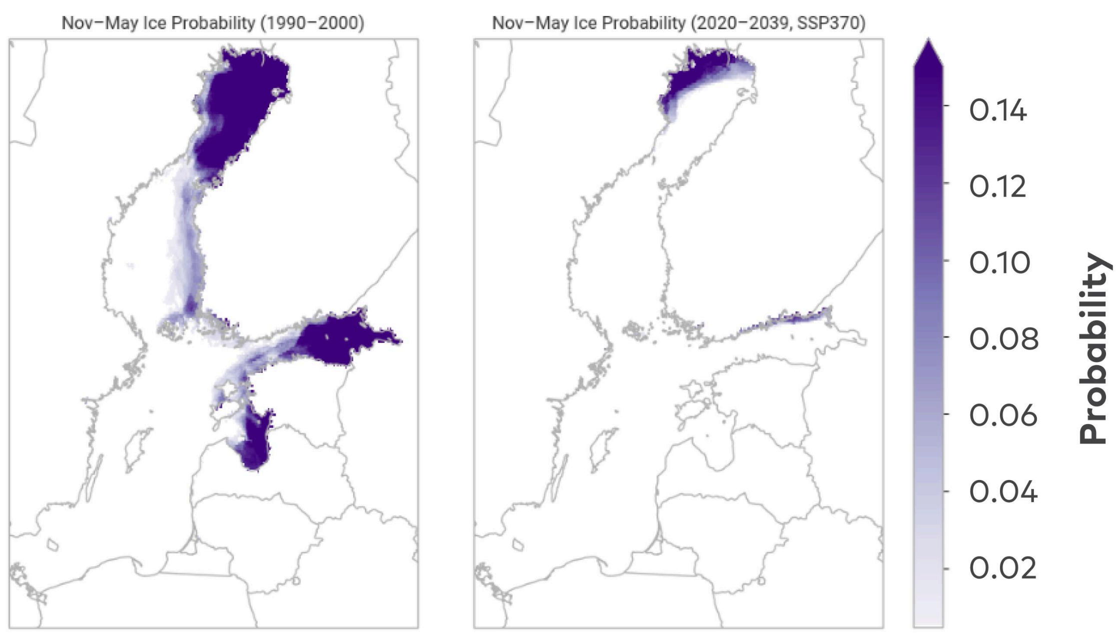

Figure 5 Ten-year climatology of average ridged ice probability from the Climate DT Phase 1 IFS-NEMO historical simulation for 1990–1999 (left), the SSP370 scenario for 2030–2039 (right) over the Baltic Sea.
© Tallinn University of Technology (TalTech)

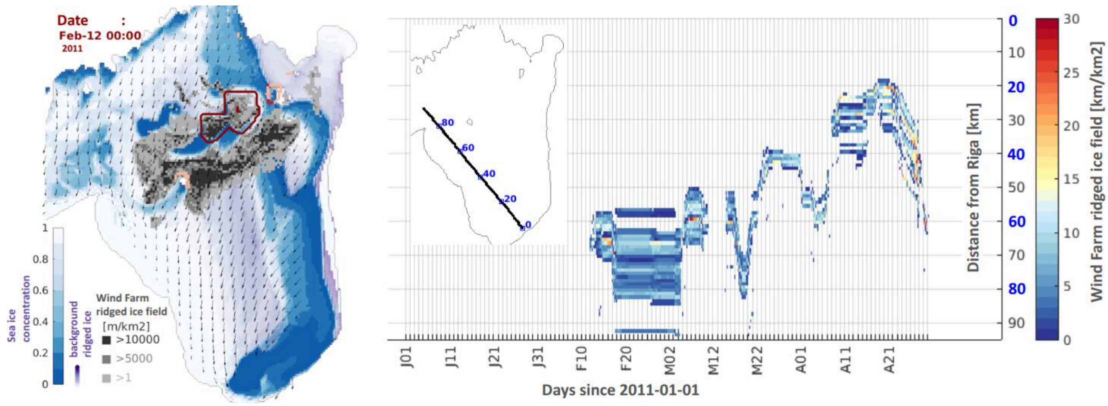

Figure 6 Deformed ice drift from the Saare wind farm development area during the severe winter of 2010/2011 on 12 February (left), and the distance–time plot of wind-farm ridge density along the main shipping route from Riga to the Irbe Strait (right).
© Tallinn University of Technology (TalTech)

Marginal ice zone

The marginal ice zone (MIZ) is defined as the region of an ice cover affected by waves and swell that penetrates into the sea ice from the open ocean. Typical MIZ conditions are found along the southern edges of the ice pack in the Bering Sea, Greenland Sea, and Barents Sea, in the Baffin Bay, and along the complete northern edge of the Antarctic ice cover. MIZ is a dynamic zone under strong interactions between the atmosphere, ocean, sea ice and waves, therefore playing a crucial role in the polar climate system. Due to the relatively low sea ice concentration and sea ice thickness, the MIZ is also an area much more navigable than the inner dense pack ice. Knowledge about the location and evolution of the MIZ is critically important for safe operations in the Nordic countries.

MIZ is a critical, dynamic region for polar ocean ecosystems. The extensive phytoplankton blooms form the base of the food web and provide a vital food source for a wide array of species. The MIZ is also a critical habitat for ice-dependent species, which use the patchy ice for hunting, breeding, and shelter. Due to the climate change, changes in the MIZ's extent and physical properties could significantly impact the ecosystems by altering food webs, affecting breeding and hunting grounds for marine mammals, and shifting species distributions.

Goal

Improved knowledge and regular monitoring and prediction of the MIZ in the Nordic seas, providing locations, weekly evolution, and statistics.

Users

- Fisheries, offshore oil and gas industry, shipping and marine tourism companies who operate close to the sea ice edge
- Research vessels for MIZ biological and ecological studies

Models and data

- CMEMS operational reanalysis and forecast products including NEMO, TOPAZ5 and neXtSIM
- Norwegian high-resolution pan-Arctic coupled model NorHAPS
- Climate DT models IFS-NEMO, ICON
- Definition of criteria for the MIZ, and development of methods to derive MIZ properties from standard variables
- Calculation of spatial distribution of MIZ from existing data sources (e.g., Copernicus, Climate DT)

Key innovations

MIZ is a new parameter from sea ice and climate models.

Impact and legacy

- The definitions for different MIZs and their formulation will be useful for future studies
- The toolbox for MIZ calculation is useful for determining MIZ for short-term forecasts for tactical purposes such as fishing and navigation, and for climate impact evaluations.

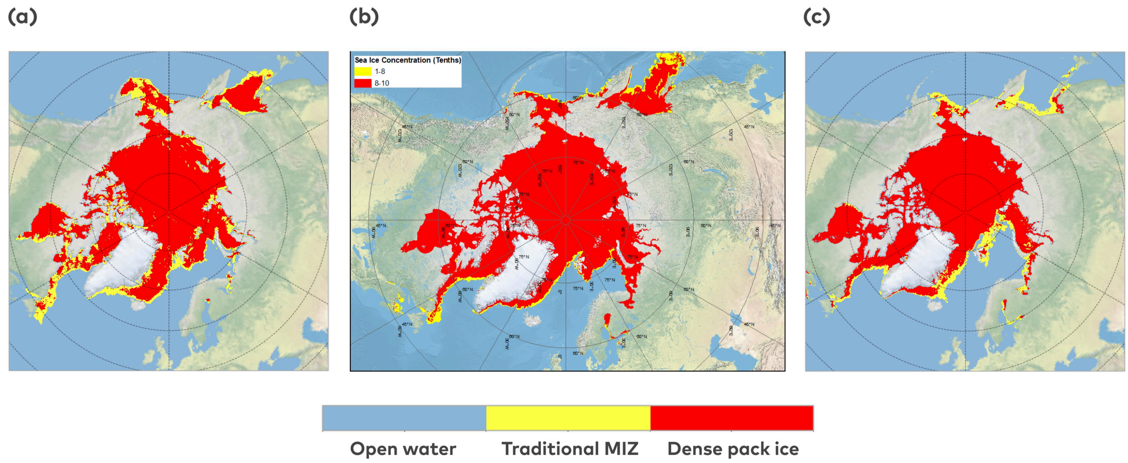

Figure 7 Traditional MIZs on 15 March 2021: (a) simulated by ICON, (b) observations by US National Ice Center, and (c) simulated by IFS-NEMO. The figure shows an example of the traditional MIZs on 15 March 2021. The simulated MIZs are calculated from Climate DT simulations ICON (a) and IFS-NEMO (c) and are compared with the US National Ice Center sea ice chart (b). On the whole, the ICON MIZ significantly overestimates the sea ice extent, whereas the IFS-NENO generally has a much closer agreement with the observation. Due to the large difference in the sea ice extent, the location of MIZ is of large bias, particularly in the ICON simulation. Despite the relatively closer agreement of the sea ice extent between the IFS-NEMO simulation and the observation, the simulated MIZ also has marked differences with the observation. New simulations are currently being carried out in the Climate DT with optimizations, and further improvements are highly expected.
© Keguang Wang (MetNo)

Marine spatial planning

Traditionally, Marine Spatial Planning (MSP) databases and platforms include only static information on the seabed, marine infrastructures, habitats, and other environmental parameters. Climate change causes quickly changing environmental conditions that should be taken into account in MSP since they have large direct influence on cumulative ecosystem impacts (e.g., Wåhlström et al, 2022) as well as on new potential activities and pressures that become possible, e.g., when sea-ice conditions change. In order to provide information on ocean and sea changes for decision making, new high-resolution ocean and sea-ice model projections need to be made available in formats that can be integrated into MSP platforms.

Goal

Pilot how the climate models' data can be utilized in the MSP platforms.

Users

- Marine spatial planners and managers
- Policy and decision makers

Models and data

- Focus has been on data from climate projections with the Nemo – SCOBI model.
- There are existing CMIP 5 projections for the Gulf of Bothnia from the SmartSea project, and new CMIP 5 and CMIP 6 projections are presently being produced for the North Sea and the Baltic Sea

Key innovations

Climate data is very relevant to MSP, but yet not considered enough, and facilitating access to the data via the unprecedented capabilities of DestinE is a breakthrough into managing our seas better.

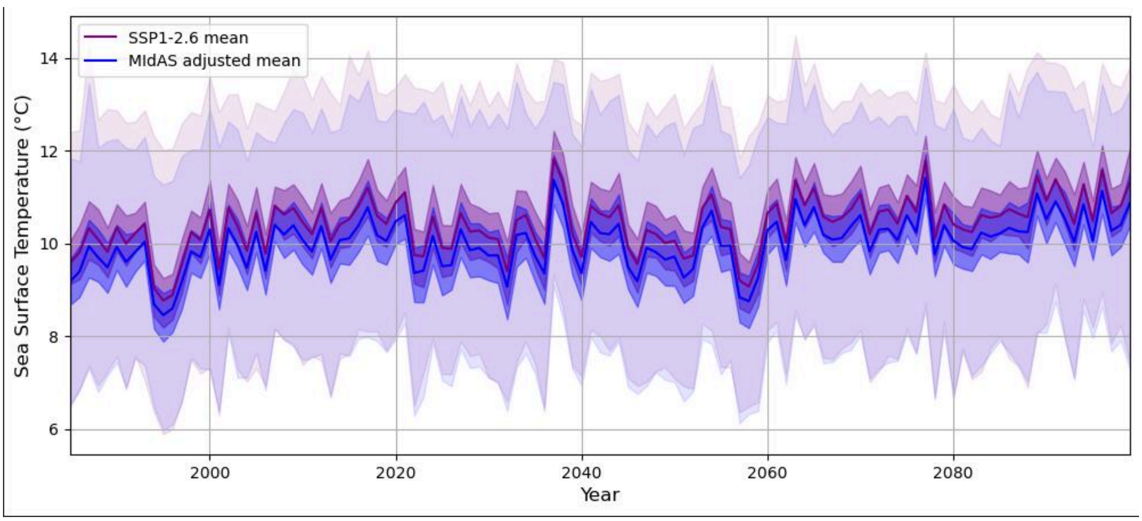

Figure 9 Example of bias adjusted and un-adjusted Baltic Sea mean temperatures for climate scenario SSP1-2.6.
© Swedish Meteorological and Hydrological Institute

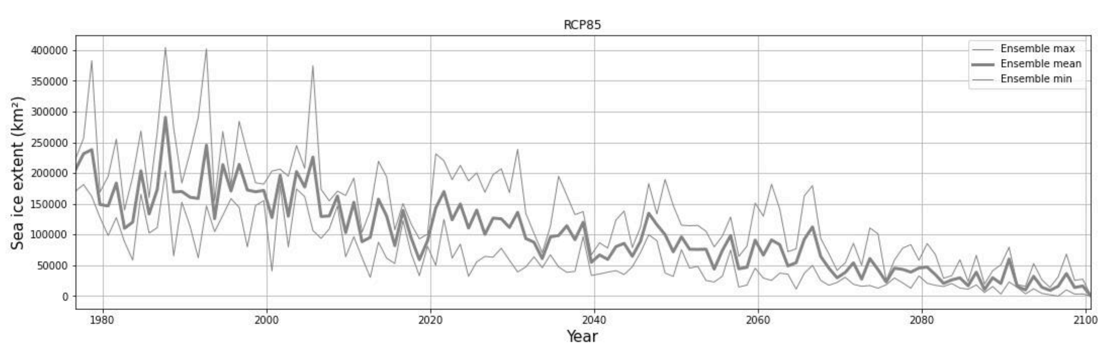

Figure 10 Time series of Baltic Sea sea ice extent for the CMIP5 RCP8.5 climate scenario.
© Swedish Meteorological and Hydrological Institute

DEM-based sea ice model development

Current sea ice models used in short-term forecasting and climate research are typically based on finite difference (FD) methods due to the fact that some other numerical methods have been computationally too demanding for sea ice applications. The finest useful resolution for the FD models is typically 1–10 kilometers. An alternative to FD models is discrete element models (DEM) which resolve sea ice physics on the scale of about a meter. DEMs are computationally very demanding and have mainly been used for process studies. However, the advent of exascale computing facilities will allow utilization of DEMs for geophysical applications. Better forecasts for sea ice break-up, including the formation of leads, and sea ice drift, are of crucial importance for shipping and infrastructure in the sub-Arctic and Arctic regions, like the Baltic and the Barents Sea, as well as the entire Arctic Ocean. Furthermore, the understanding of long-term changes in the behavior of drift ice in a warming climate is highly important for the research related to Arctic biodiversity changes, conservation policies and support measures for traditional hunting and fishing by indigenous people.

Goal

DEM-based computer code suitable for HPC that can be applied to sea ice simulations. Peer-reviewed papers based on model computations.

Users

- Scientists
- Forecast providers as a service to the public

Models and data

The Discrete Element Model HiDEM is modified for sea ice simulations. The code adapts boundary conditions, driving forces, and bathymetry according to user-provided input data.

Key innovations

- The HiDEM code for sea ice.

Impact and legacy

- The HiDEM code for sea ice simulations is available for science and other communities.
- New insight into sea ice dynamics, glacier and sea-ice interaction, offshore wind farms in polar environments, etc. are currently being produced.

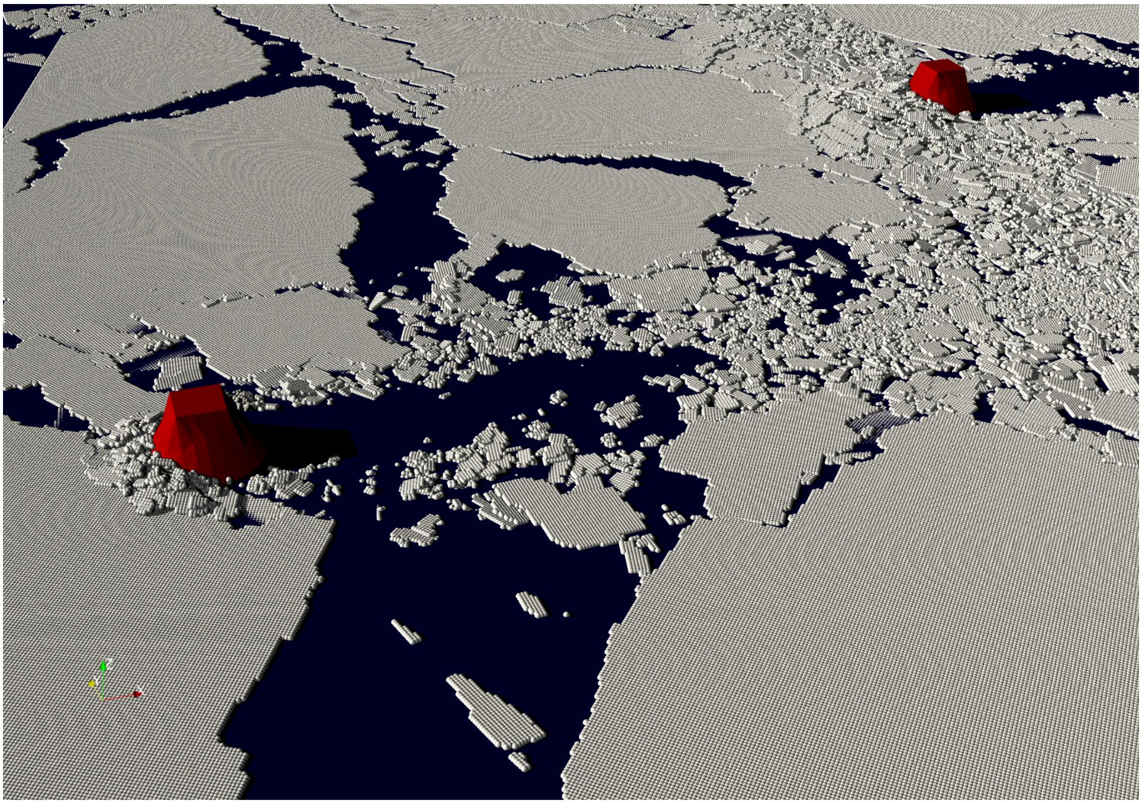

Figure 11 A HiDEM simulation, with 0.25 meter resolution, of drifting ice breaking around red-colored 10 meter diameter fixed pylons.
© Jan Åström (CSC)

© Andrea Gierisch, Danish Meteorological Institute

NOCOS DT and Destination Earth

NOCOS DT explored, defined, and piloted digital twin technologies to support key sea ice impact sectors across the Nordic, Arctic, and Baltic regions in close alignment with the European Commission's flagship initiative, Destination Earth (DestinE), and particularly its Climate Change Adaptation Digital Twin (Climate DT). In particular, NOCOS DT complements the digital twins that are currently being built under DestinE to achieve the overarching objective of developing a highly accurate digital model of the Earth – a digital twin of the Earth.

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The NOCOS DT project has been a trailblazer in harnessing the power of the Destination Earth Climate Change Adaptation DT – being one the first to explore how the climate digital twin data can be applied to real-world challenges. NOCOS DT not only demonstrated the use of Destination Earth's capabilities, but also showcased the value of collaboration across digital twin initiatives, paving the way for more integrated and impactful climate change adaptation solutions.

Irina Sandu
Director of Destination Earth
European Centre for Medium-Range Weather Forecasts

Most of NOCOS DT's models and applications were designed to use the data produced by Climate DT, making the project a trailblazer in cross-DT integration, and uniquely positioning it to push the boundaries of what digital twins can achieve for climate change adaptation. Destination Earth provided essential features that empowered the NOCOS DT, including high-resolution climate data that improved modeling of coastal and landfast sea ice processes, and tools for forecasting ship navigation risks. It enabled the derivation of ridged ice probabilities and detailed marginal ice zone statistics, while also supporting sea ice dynamics simulations. Additionally, the Climate DT's processing toolbox facilitated access to climate model data for marine spatial planning, helping to enhance ecosystem resilience and inform EU policymaking.

In turn, NOCOS DT significantly contributed to Destination Earth by providing advanced tools and data for understanding and forecasting sea ice conditions. Its achievements include improved navigation safety in ice-covered waters, future projections of landfast ice, detailed information on ridged and marginal ice zones, and the development of the HiDEM code for simulating sea ice interactions with infrastructure and forecasting ice motion.

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In addition to serving as a pilot case of an external project utilizing Climate Change Adaptation DT data, the NOCOS DT played a key role in bringing together Nordic and Baltic expertise. It also helped link topics of particular relevance to the Nordic region more closely with Destination Earth, thereby strengthening regional engagement and paving the way for future co-development.

Jenni Kontkanen
Development Manager in Digital Twin Technologies
CSC – IT Center for Science

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Contribution to Nordic and global policies

NOCOS DT supports the Nordic Council of Ministers' Vision 2030, which aims to make the Nordic Region the most sustainable and integrated region in the world. The project contributes to the Cooperation Programme for Nordic-Baltic Cooperation on Digitalisation 2025–2030 by:

- Strengthening regional collaboration through shared resources, expertise, and stakeholder networks.
- Expanding knowledge and innovation by increasing the relevance and reach of sea ice related solutions.
- Enhancing integration with the global climate change information ecosystem, maximizing the value of Destination Earth data and services.

NOCOS DT has contributed to the United Nations' Decade of Ocean Science for Sustainable Development (2021–2030) by advancing regional sea ice modelling and fostering collaboration among Nordic and Baltic stakeholders, aligning with the Decade's goals of inclusive, actionable ocean science. The project has also supported the European Green Deal by advancing climate change adaptation and carbon neutrality in key sectors such as shipping and renewable energy, while promoting digital innovation and data-driven decision-making through its integration with Destination Earth.

The project's global relevance has been highlighted by high-level interest towards its results. In 2024, NOCOS DT hosted a session[4] at the United Nations Climate Change Conference (COP29) in Baku, Azerbaijan, with the title *Global and Regional Approaches to Cryosphere and Related Climate Challenges: Digital Twin Technologies' Potential to Support Climate Change Adaptation*. In 2025, the NOCOS DT Programme Manager was invited as a speaker in session *Advancing Polar Research: From Field Data to Global Insights* of the Nordic Arctic Day[5] at the World Expo 2025 in Osaka, Japan.

4. https://pub.norden.org/cop29/
5. https://www.norden.org/en/event/expo-nordic-arctic-day

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What's next?

NOCOS DT developed sea ice research applications and models tailored to the unique conditions of the Nordic, Baltic and Arctic regions and contributed to the development of a global climate change information system. The modular and open nature of the project's software products contributes to their reusability by the target stakeholders in the region and globally. Further development leveraging NOCOS DT's achievements is already ongoing in projects such as the European Commission funded Digital Twin of the Earth System for Cryosphere, Land Surface and Related Interactions[23] (TerraDT).

The legacy of NOCOS DT is reflected in the open source suite of operational and research tools it leaves behind, which can be integrated into other initiatives and platforms. From the daily RIO forecasts supporting safer ship navigation to the landfast and ridged ice toolboxes aiding regional climate resilience and planning, these outputs are designed for long-term usability and adaptability. The marginal ice zone definitions and toolsets offer tactical and strategic value for fisheries and climate studies, while the marine spatial planning tools enable data-informed decision-making as the Climate DT datasets mature. Additionally, the open availability of the HiDEM sea ice model fosters continued scientific exploration into ice dynamics and their interactions with infrastructure and ecosystems. Together, these contributions ensure that NOCOS DT's impact will extend well beyond its project timeline, supporting both regional needs and global climate initiatives.

23. https://terradt.eu/

For more information

NOCOS DT website

wiki.eduuni.fi/x/_p2hH

NOCOS DT software package
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About this publication

NORDIC CRYOSPHERE DIGITAL TWIN

Digital Twin technologies to address the impact of climate change

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