Funded by the European Union

Monitoring Arctic Sea Ice

Earth observation value chain case study

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Characterised by vast expanses of tundra and sea ice, the Arctic region plays a crucial role in regulating the Earth's climate. However, climate change has had a significant impact on the region. The Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC) reports that over the past 50 years, it is very likely that the Arctic has warmed twice the global rate, though more recent research suggests that the Arctic has warmed four times faster than the rest of the globe. Since 1979, extreme heat events and minimum air temperatures have also increased significantly. The Arctic Ocean itself is also changing. Global sea level is rising, the Arctic Ocean is becoming fresher, and its temperatures are also warming at rates above global averages. Sea ice is declining rapidly, such that the IPCC is predicting with high confidence that the region could experience a virtually ice-free summer by 2050. The loss of sea ice in the region is particularly problematic as it creates a feedback loop (e.g. the known positive albedo feedback loop) in which the region warms faster, increasing the loss of sea ice. These losses impact both the socioeconomics of the estimated four million people living in the region and amplify climate change on a global level. The United Nations (UN) has recognised the importance of the Arctic region and has included several Sustainable Development Goals (SDGs) that are relevant to the impacts of sea ice loss, including SDG 13 (Climate Action), SDG 14 (Life Below Water), and SDG 15 (Life on Land).

This case study demonstrates how Earth observations and derived services, tools and information are indispensable for understanding, monitoring and predicting changes in Arctic sea ice and broader marine ecosystem implications to inform action and protect this vulnerable yet critical region. The study also provides examples of Earth observation data portals, monitoring and forecasting services and research projects supported by the European Union (EU) towards better understanding and predicting changes in Arctic sea ice and the broader ecosystem implications.

Description & impacts of Arctic sea ice decline

Sea ice is frozen seawater that floats on the ocean surface. Formed in both the Arctic and the Antarctic in each hemisphere's winter, sea ice retreats to a minimum extent in the summer without completely disappearing. However, Arctic sea ice has been declining at alarming rates as shown by satellite observations of Arctic sea ice started in 1979. According to the Copernicus Marine Service, the annual minimum extent of Arctic sea ice in September, has declined by approximately 12.5% per decade from 1979 to 2021. Furthermore, between 1979 and 2022, Arctic sea ice extent saw a loss of approximately 3.5 million km2, the equivalent to about seven times the area of Spain (Copernicus Ocean State Report 7, 2023). On 12 September 2023, Arctic sea ice extent reached its annual minimum, reaching 3.9 million km2; 1.7 million km2 less compared to the long-term average (1993-2010) and ranking the sixth lowest observed since the beginning of the satellite records (Mercator Ocean International, 2023).

This drastic reduction of the Arctic sea ice extent over the past 45 years is glaring evidence of warming temperatures and poses significant challenges to the Arctic ecosystem with far-reaching global consequences. Most of the Arctic sea ice is becoming seasonal and does not last from year to year, meaning it grows in the winter and melts in the summer. The freezing and melting of sea ice impacts global climate regulation, influencing temperature patterns in the Arctic and beyond. The reflective surface of sea ice, known as the albedo effect, reflects up to 70% of the sunlight that reaches the ice's surface back into space, helping to regulate ocean temperatures and impacts climate systems worldwide.

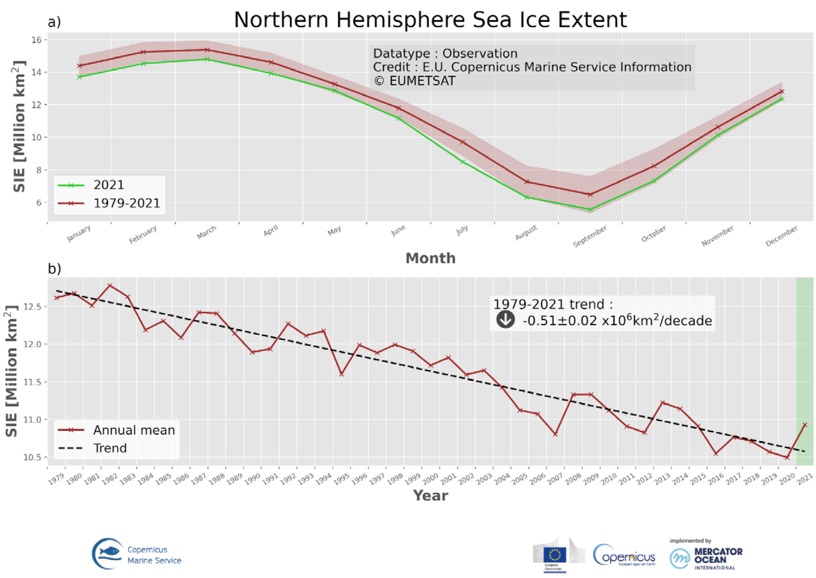

Figure 1: a) The seasonal cycle of Northern Hemisphere Sea ice extent expressed in millions of square metres (km2) averaged over the period 1979-2021 (red), shown together for the seasonal cycle in the year 2021 (green), and b) time series of yearly average Northern Hemisphere sea ice extent expressed in millions of km2. Time series are based on satellite observations (SMMR, SSM/I, SSMIS) by EUMETSAT OSI SAF with R&D input from ESA CCI. The change of sea ice extent over the period 1979-2021 is expressed as a trend in millions of km2 per decade and is plotted with a dashed line in panel b). Credit: Copernicus Marine Service.

Moreover, sea ice plays a multifaceted role in supporting biodiversity and maintaining ecological balance in the Arctic. Serving as a vital habitat for numerous organisms, sea ice fosters a complex food web that sustains various species, from phytoplankton and algae to large marine mammals and birds. Changes in sea ice can disrupt Arctic marine habitats, food sources, and breeding patterns, leading to population declines and changes in species distribution. This, in turn, can impact fisheries and food security, and threaten traditional cultural practices, while increasing sea levels may threaten some coastal communities.

These impacts, among others, all underscore the importance of monitoring and understanding this Arctic sea ice, and predicting its future state towards strengthening conservation efforts and informing mitigation and adaptation efforts in the Arctic.

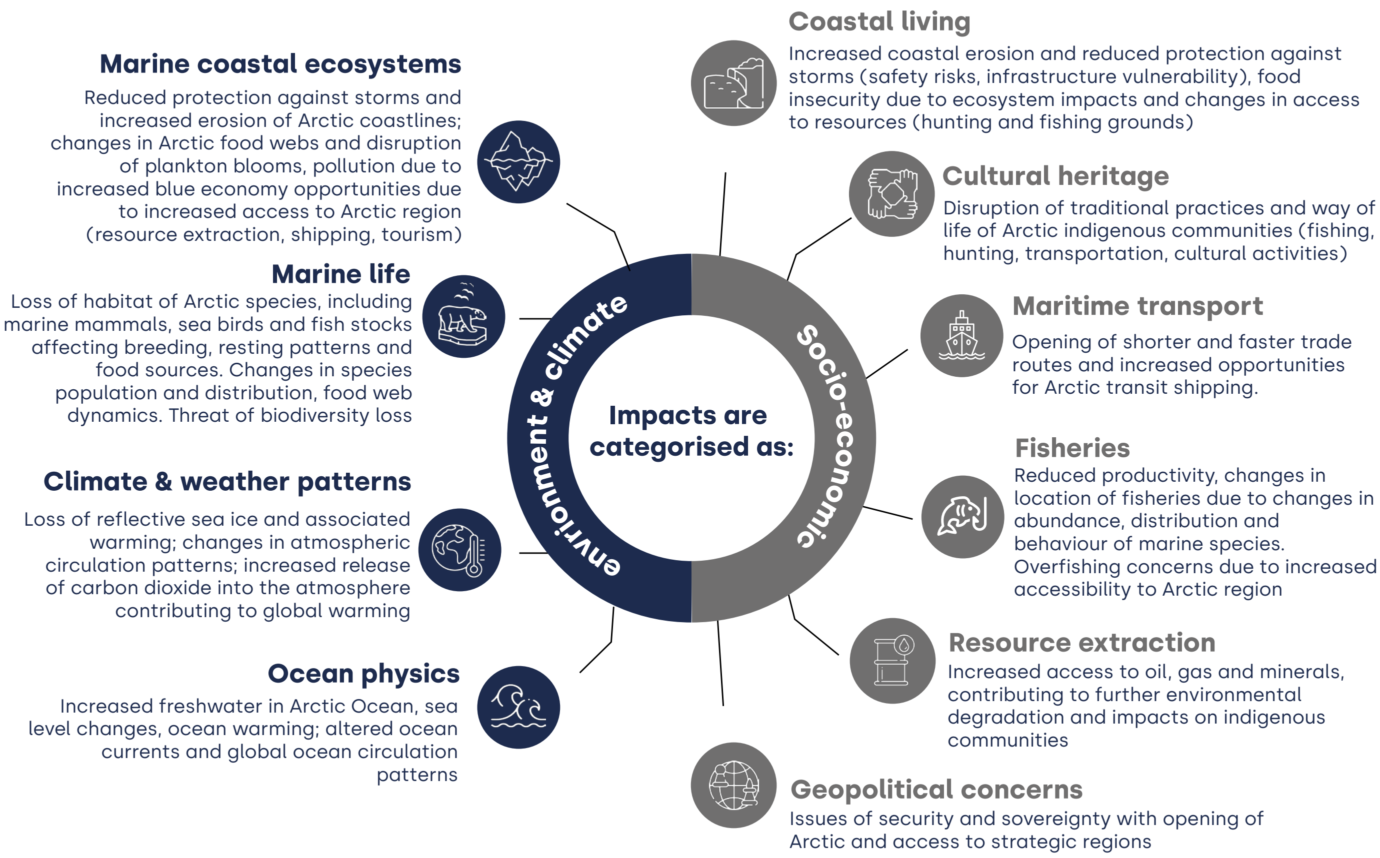

Figure 2: Environmental, climate and socio-economic impacts related to Arctic sea ice decline

EU commitment to the Arctic monitoring and preservation

The European Union (EU) is strongly committed to strengthening Arctic cooperation and safeguarding the Arctic environment. The updated EU Arctic Policy in 2021 reinforces this commitment seeking to slow the effects of climate change, tackle environmental threats, support Arctic community sustainable development, and ensure the Arctic remains a region of peaceful cooperation. These efforts include expanding Arctic monitoring and forecasting capacities, and supporting the integration of a fit-for-purpose Arctic Ocean observing system through various EU programmes, infrastructures, services and research projects.

Earth observations and derived tools to monitor and forecast Arctic sea ice

Various methods are used to detect, monitor and forecast Arctic sea ice. Critical data includes sea ice concentration (the percentage of an area covered by sea ice), extent, thickness, motion (the speed and direction sea ice travels), and age. Data on sea ice extent gives crucial information on the overall state of the Arctic ecosystem and the potential impact on global climate patterns. Sea ice thickness and age data are vital for assessing the ice's health and longevity, while sea ice motion is essential to predict future ice distribution.

In situ and airborne observations

In-situ and airborne instruments can provide localised high-resolution sea ice data for thickness and motion. The direct observation of sea ice provides ground truthing for sea ice extent estimations from satellites and models. Drifting profiling buoys and Ice Tethered Profilers (ICT) measure oceanic parameters associated with sea ice while surface sensors fixed to floes measure atmospheric conditions and sea ice motion. Upward-looking sonar instruments moored to the seabed also provide motion as well as thickness data. Moreover, airborne altimeters and inductance probes provide thickness data and direct observation. Less traditional platforms such as naval submarines and Voluntary Observing Ships (VOS) also contribute to invaluable long-term datasets. However, ship and airborne data collection can be limited by weather, availability of craft, and costs.

Satellite observations

Satellite remote sensing has provided coverage of the Arctic sea ice since 1979 through a range of instruments in several EU and international satellite missions, including:

- **Microwave radiometers** measuring sea ice concentration and motion (MIRAS onboard ESA Earth Explorer SMOS, SSM/I onboard the US DMSP satellites and AMRS-2 onboard the Japanese Space Agency GCOM-W1 satellite)
- **Scatterometers** measuring sea ice concentration, type and motion (ASCAT on board EUMETSAT's Metop-C satellite)
- **Synthetic Aperture Radars (SAR)** measuring sea ice concentration, type and thickness (C-SAR on board the EU Copernicus Sentinel-1 and North American RADARSAT satellites)
- **SAR altimeters** measuring sea ice thickness (SRAL and SIRAL respectively on board EU Copernicus Sentinel-3 and ESA Earth Explorer CyroSat-2 satellites)
- **Laser altimeters** measuring sea ice thickness (ATLAS on board the US ICESAT-2 satellite)

Although the data is often of a lower resolution than that collected by in situ or airborne instrumentation, satellite remote sensing provides regular coverage of the whole region in near real-time.

These missions will be joined by the NASA-ISRO SAR (NISAR) mission in 2024, the EU Copernicus Polar Ice and Snow Topography Altimeter mission (CRISTAL) in 2027, and the Copernicus Imaging Microwave Radiometer (CIMR) - a polar-specific satellite which collects data on sea ice concentration, sea surface temperature, and other key variables for sea ice monitoring after 2028.

Sea ice models and reanalyses for monitoring and forecasting

Sea ice models are vital tools for understanding the behaviour of Arctic Sea ice. Models simulate sea ice behaviour and make analyses, reanalyses (reconstruction of past sea ice conditions) and forecasts about the future state of sea ice in the Arctic, including under different climate change scenarios. Both are used to evaluate the performance of climate models in simulating sea ice decline and global temperature change. Reanalysis data also help quantify the sensitivities of simulated Arctic Sea ice area and volume to perturbed atmospheric forcing. A key EU example is the dynamical/thermodynamical lagrangian sea ice model, neXtSIM (next generation Sea Ice Model), which simulates sea ice over a wide range of spatial and temporal scales providing information such as drift, thickness and albedo. Sea ice observations, satellites and in situ observations, have been instrumental in building these models and improving their accuracy and predictive capabilities, deepening knowledge of changing state of Arctic sea.

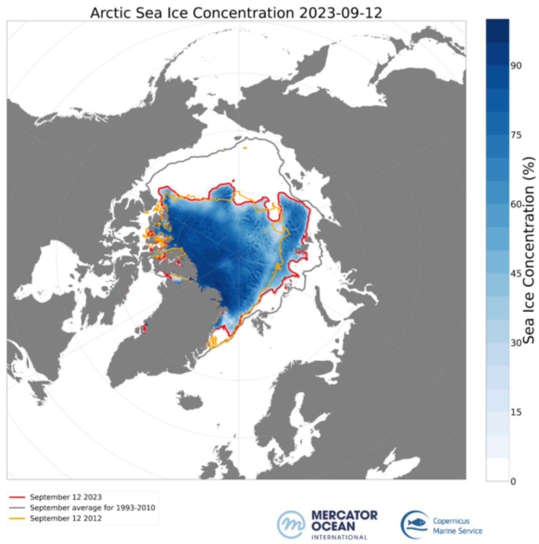

Figure 3: Arctic sea ice concentration for 12 September of 2023 (dark red), 2012 (orange), 2020 (light red) and for the climatology 1993-2010 (grey). September 12 is the annual Arctic Sea ice minimum for 2023. Global 1/12° forecasting (Lellouche, 2018) and reanalysis (Lellouche, 2022). Source: Mercator Ocean International, Copernicus Marine Service.

Arctic sea ice data, derived services and information points

The EU supports the following services, infrastructures and initiatives providing data and information access, monitoring and forecasting services on Arctic sea ice, and/or working to strengthen coordination and commitment to Arctic Ocean research and monitoring. This is essential to provide evidence and future projections of sea ice decline for various stakeholders. From indigenous and coastal Arctic communities to blue economy sectors, to policymakers, and local authorities developing and implementing climate change adaptation and mitigation plans and conservation strategies. This list is not exhaustive.

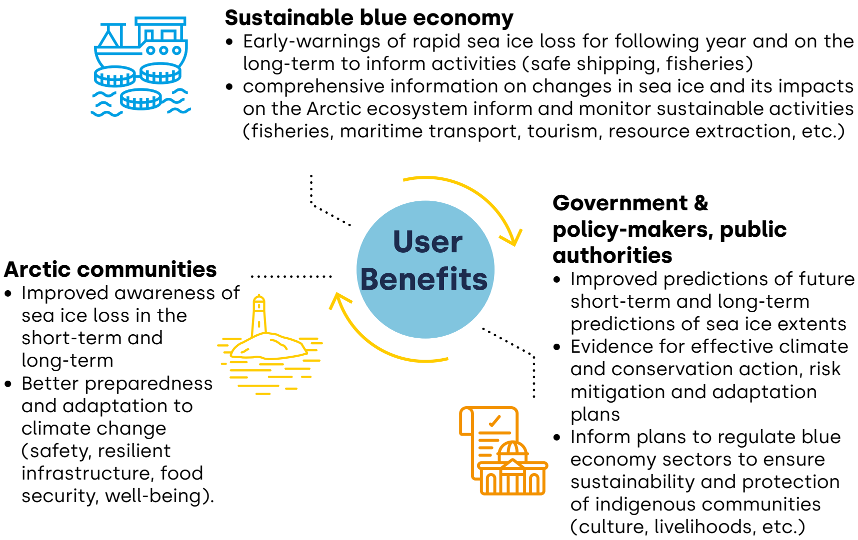

Figure 4. Examples of how Earth observation and derived monitoring and forecasting services, tools and information on Arctic sea ice decline respond to needs of various users and stakeholders

Data and information portals and monitoring and forecasting services

The Copernicus Arctic Hub (www.arctic.hub.copernicus.eu/) is a centralised portal that consolidates EU Copernicus data (land, sea, atmospheric) and provides a comprehensive resource for information on the Arctic and its changing environments. The Hub aims to assist different users to better visualise and understand the ongoing changes in the Arctic in a comprehensive manner, and describe complex land-sea continuum through a large set of variables, interactive maps, use cases and other tools.

The **EU's Copernicus Marine Service** (marine.copernicus.eu/) offers free and accessible data to the public that supports the EU Arctic Policy, research, and decision-making tools. The Service's Sea Ice Thematic Assembly Centre provides elaborated operation observational satellite-derived sea ice data for both the Arctic and Antarctic. This data is also used internally for assimilation into, and/or validation of, ocean analysis and forecasting systems in Copernicus Marine's Arctic Monitoring & Forecasting Centre (MFC). The Arctic MFC offers real-time forecasts for Arctic oceanic conditions, including sea ice and biological forecasts. Copernicus Marine also tracks and describes changes in Arctic sea ice extent through its Ocean Climate Portal and annual Ocean State Reports.

The **EUMETSAT Ocean and Sea Ice Satellite Application Facility - OSI SAF** (https://osi-saf.eumetsat.int/) develops, processes and distributes, in near real-time, products related to key parameters of the ocean-atmosphere interface, and offers climatological data records. Concerning Arctic sea ice, OSI SAF provides data on sea ice concentration, edge, type, emissivity, and drift.

European Marine Observation and Data Network (EMODnet) Arctic Data Portal (arctic.emodnet-physics.eu/) serves to improve the availability, quality, timeliness, and accessibility of essential marine in situ data from the Arctic region, including sea ice extent and type. The Portal incorporates in-situ data collections from various sources, including the International Arctic Buoy Cooperation Program, the Woods Hole Ice-Tethered Profiler Program, and icebreakers and research vessels operating in the Arctic area (ARICE).

Sustaining Arctic Observation Networks (SAON) data inventory (data.arcticobserving.org/) gives access to Arctic observational data and products. The information is harvested from the contributing institutions.

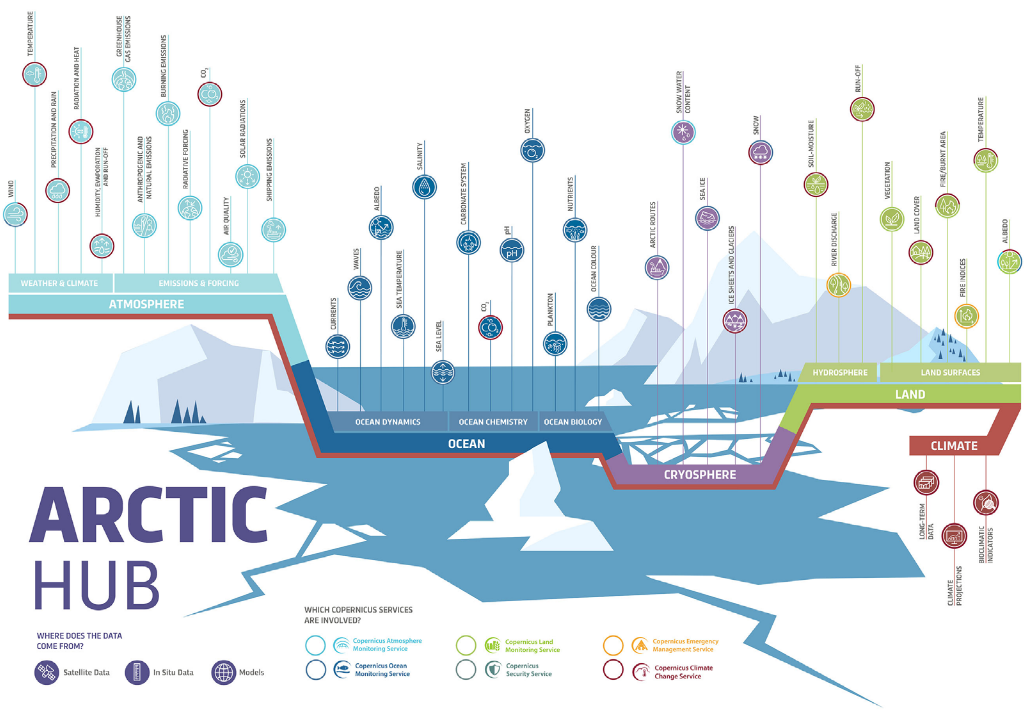

Figure 5. The Copernicus Arctic Hub provides fit-for-purpose open and free Earth Observation data in the Arctic region from the Copernicus Sentinel satellites and all Copernicus Services (marine, land, atmosphere, climate, emergency). This includes air, sea and land products and information that describes the Arctic environment in the context of climate change.

Coordination networks and programmes strengthening Arctic Ocean and sea ice monitoring

The **EU Polar Cluster** (www.polarcluster.eu) is a network of collaborative polar projects, which are funded by the EU, and four permanent members: the European Polar Board, the Association of Polar Early Career Scientists, the Svalbard Integrated Arctic Earth Observing System, and the European component of the Global Ocean Observing System (EuroGOOS). The cluster thus merges a broad spectrum of research and coordination activities – ranging from the most up-to-date findings on permafrost and sea ice, from enhancing observation to improving predictions, and from networking research stations to coordinating access to icebreakers.

The **Polar Task Force** is a group of polar experts coordinated by EC JRC and DEFIS. The group works to further elaborate and facilitate coordination of the polar activities carried out by the various Copernicus Services and stake out the direction for the polar dimension in Copernicus, including the recent establishment of a Copernicus Arctic Thematic Hub as a one-stop shop for all polar-relevant services and products. Activities include taking into consideration results and ensuring information flows from projects such as KEPLER which ended in 2021, ARCOS and Arctic Passion, among others in the EU Arctic monitoring landscape).

The **Arctic Regional Ocean Observing System (Arctic ROOS)** (arctic.eurogoos.eu) is a is an open forum for national agencies, research institutes, universities as well as commercial bodies to inform, share and develop an Arctic Ocean observing system. A regional node under EuroGOOS, Arctic ROOS serves to integrate and strengthen European oceanographic and sea ice monitoring activities in the Arctic. This includes, fostering the development of real-time observations, enhancing dissemination of data via the FAIR principles and promoting open-source community oceanographic, wave and sea-ice models.

EU-PolarNet 2 (eu-polarnet.eu) is the world's largest consortium of polar research expertise and infrastructures, involving 25 partners representing all European Member States and Associated Countries with well-established Polar Programmes. Funded by the EU, the network seeks to establish a sustainable and inclusive platform to co-develop and advance European Polar research actions and to give evidence-based advice to policy-making processes. This platform will further develop the coordination of Polar research actions in Europe and with overseas partners.

The **European Polar Board (EPB)** (www.europeanpolarboard.org) is an independent organisation focused on major strategic priorities in the Arctic and Antarctic. EPB members include research institutes, logistics operators, funding agencies, scientific academies and government ministries from across Europe.

The **ESA Polar Cluster** (link) is a collaborative group of projects funded by ESA that focus on Earth observation satellite and in-situ data, citizen science, advanced modelling capabilities, and interdisciplinary research in polar science. Projects include ArcticSummIT, which seeks to deliver a summer sea ice thickness product based on data collected by the ESA Cryosat-2 satellite.

The **Arctic Council** (arctic-council.org) is the leading intergovernmental forum promoting cooperation, coordination and interaction among the Arctic States (including EU states Finland, Sweden, Denmark), Arctic Indigenous peoples, and other inhabitants on common Arctic issues. Formally established in 1996, the Council focuses on issues of sustainable development and environmental protection in the Arctic. The Arctic Council includes several working groups, such as the Protection of the Arctic Marine Environment (PAME), which uses sea ice data to guide decisions on shipping routes and other activities in the Arctic.

The **Voluntary Observing Ship (VOS) programme** (link) collects crucial data on Arctic sea ice changes. Crew members from ships worldwide observe weather and ocean conditions and send the data to national meteorological services. The programme involves Arctic Council member governments and provides valuable data from data-sparse areas. VOS reports can provide key observation data on sea ice and other factors influencing the Arctic climate and ocean.

Research and innovation projects enhancing monitoring and understanding of changes in Arctic sea ice and ecosystem implications

These projects are funded under the European Union's H2020 and Horizon Europe funding programmes

Arctic PASSION - Pan-Arctic observing System of Systems (arcticpassion.eu) is a H2020 project (2021-2025) aiming to co-create, develop and implement an integrated Arctic observing system. The project aims to overcome the present observing system's shortcomings, enhancing its operability, improving and extending Arctic scientific and community-based monitoring and the integration with indigenous and local knowledge. Following priorities established by Arctic Council, the Arctic Science Ministerials, and the Arctic Observing Summit, the project is developing pilot services, including the 'State of the Arctic Environment' and a 'Pan-Arctic requirements-driven Permafrost Service'.

ARICE - Arctic Research Icebreaker Consortium (arice-h2020.eu) is a H2020 project (2018-2022), which sought to improve European marine research in the Arctic Ocean by optimising the use of existing polar fleet. The Consortium shared and jointly funded operational ship time, facilitated access to European and international research icebreakers, and partnered with the maritime industry to develop a «ships and platforms of opportunity» programme. Although the project ended in Dec 2022, its legacy continues with ongoing partnerships to advance polar research. An example is the ARICE PONANT partnership, supporting research activities during polar expeditions on board le Charcot icebreaker.

ArcticWatch - Early warning of future rapid Arctic sea ice loss (cordis.europa.eu/project/id/101040858) is a Horizon Europe project (2023-2027) seeking to build an integrated early warning system that alerts on the possibility of rapid Arctic Sea ice loss for the following summer, up to 5 years. It will also provide evidence-based guidance regarding the design of the Arctic observing system for the next 30 years.

PolarRES - Polar Regions in the Earth System (polarres.eu) is a H2020 project (2021-2025) investigating key local-regional scale physical and chemical processes for atmosphere-ocean-ice interactions in the Arctic and Antarctic. By understanding these processes and interactions, PolarRES assesses how to make climate projections in the Polar Regions more reliable and what these projections means for society and the environment.

ARCTISTIC - Sedimentary ancient DNA for Arctic sea-ice reconstruction (cordis.europa.eu/project/id/101067156) is a Horizon Europe project (2023-2025) seeking to design innovative molecular tools to trace sea-ice-associated taxa in marine sediments, and validate them against established tools for sea-ice reconstruction and assess the impact of sea-ice changes on biodiversity.

HiAOOS - High Arctic Ocean Observation System (hiaoos.eu) is a Horizon Europe project (2023-2027) working to develop, implement and validate several ocean-observing technologies to improve data collection in the ice-covered Arctic Ocean. The technologies are based on a network of multipurpose moorings in the deep Nansen and Amundsen Basins. The HiAOOS network will provide point measurements of ocean and sea ice and active and passive acoustic data for several applications, including acoustic thermometry, geo-positioning of underwater floats, detection of marine mammals, geohazards and human-generated noise.

ACCIBERG - Arctic Cross-Copernicus forecast products for sea Ice and iceBERGs (acciberg.nersc.no) is a Horizon Europe project (2023-2026) aiming to develop a new iceberg forecast service using remote sensing algorithms, data assimilation and cloud computing, and consistently offer probabilistic sea ice and iceberg forecasts based on Copernicus data. The new forecasts will be automated and used by various groups navigating in the Arctic – from fisheries to cruise tourism.

ECOTIP - Ecological tipping cascades in the Arctic Seas (ecotip-arctic.eu) is a H2020 research project (2021-2024) focusing on understanding and predicting changes in Arctic marine ecosystem and the implications for fisheries production and carbon sequestration. Applying trait-based approaches and eDNA to understand Arctic biodiversity along with paleo-oceanography methods to understand historical stressors, the project will provide insights on the causes, consequences, and thresholds of the Arctic ecosystem tipping cascades, impacts on marine biodiversity, as well as make predictions about ecosystem vulnerability.

NUNATARYUK - Permafrost thaw and the changing arctic coast (nunataryuk.org) is a H2020 project (2017-2023), which investigated the impacts of thawing coastal and subsea permafrost on the global climate, and developed targeted and co-designed adaptation and mitigation strategies for the Arctic coastal population.

SI3D - Arctic Summer Sea Ice in 3D (cordis.europa.eu/project/id/101077496) is a Horizon Europe project (2023-2028) harnessing deep machine learning, modelling of the radar altimeter response, and dedicated field campaigns, to produce the first 15+ year high-accuracy record of pan-Arctic sea ice thickness without interruptions in the summer. Integrating satellite data from multiple EU and US altimetry missions, the project seeks to close the Arctic sea ice volume budget, investigating drivers of seasonal decay and breakup of the ice pack and impacts on Arctic temperatures. Additionally, the project aims to upgrade seasonal sea ice forecasts from state-of-the-art modelling systems by assimilating summer ice thickness observations.

Figure 6: Earth observation-based monitoring and forecasting value chain for Arctic sea ice

EARTH OBSERVATION PLATFORM

EU satellites (e.g. Copernicus Sentinels, SMOS, CyroSat-2)

International satellites (e.g. RADARSAT/ Canada, SSM/I and IceSat2/ USA)

Improve calibration

NEED FOR AIRBORNE AND IN SITU OBSERVATIONS

- In situ: ships, buoys, moorings
- Airborne: airplanes, drones

DATA

Sea ice data products
(Extent, Concentration, Thickness, Type, Motion)

Other ocean data products
Sea surface temperature, sea surface salinity chlorophyll-a, sea level

Improve validation & accuracy of models

ANALYSIS

Reanalysis

Hindcast models

Forecast models

Climate models

INFORMATION

PRODUCTS / SERVICES

Sea ice characteristics
Near real-team sea ice extent map
Sea ice analysis, forecasts and hindcasts
Future sea ice extent predictions
Systematic sea ice reporting
Sea ice monitoring and forecasting systems
Iceberg monitoring and forecasting systems

END USER BENEFITS

Targets

Public & local authorities

Environmental Agencies

Research & Academia

Policymakers, government agencies

Blue economy actors (fisheries, maritime transport, tourism)

Arctic communities

Decision points

Risk mitigation and adaptation plans concerning sea ice changes and impacts

Inform Arctic conservation policies and strategies

Inform regulations to ensure sustainable blue economy activities

Inform shipping routes

Benefits

Improved predictions of future sea ice extents and concentrations, including early warnings of rapid decline

Increased understanding of climate change impacts on Arctic ecosystem and global scale

Protection of indigenous and other local Arctic communities

Sustainable blue economies

Safe-shipping

Gaps in monitoring and forecasting of Arctic sea ice

Despite all the significant progress made, there are gaps in monitoring and forecasting Arctic sea ice changes and associated impact. These include:

- Due to the remote, vast size, and often extreme and volatile conditions, the ocean observing system in polar regions is less advanced than in other ocean areas, hindering the reliability of ocean and sea ice forecasts and predictions. This impacts our understanding of sea ice dynamics in the region, including how they may change as the Arctic continues to warm, the impact of sea ice loss on the wider Arctic Ocean and marine life, and hinders the development of products that can ensure safe and sustainable use of the Arctic Ocean.
- Insufficient funding and resources pose significant challenges to sea ice research activities and developing effective management strategies. Improving financial support and enhancing coordination and collaboration among local, Indigenous, EU, and international stakeholders would bolster our understanding of sea ice dynamics, changes to the Arctic Ocean, and help support the socio-economic and cultural needs of Arctic communities.
- There is a need to improve the integration and assimilation of satellite remote sensing and in-situ data, and local and Indigenous knowledge into common databases. Common databases will contribute to an improved understanding of the interactions between sea ice, ocean processes, and climate, and support decision-making.
- There is a need for improved engagement with key stakeholders and decision-makers in affected sectors to ensure the provision of the most relevant and valuable information to support decision-making. This includes engagement with local and Indigenous communities who live in the Arctic region.

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