EARTH OBSERVATIONS FOR BALTIC AND ARCTIC SHIPPING
EO4BAS

Geoinformation requirements

23. October 2023

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EO FOR BALTIC AND ARTIC SHIPPING

D2.1 Report on current EO information products and their fit to purpose

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Objective: The objectives of the Earth Observations for Baltic and Arctic Shipping (EO4BAS) project are:

- To establish current information needs and best practices for the use of Earth Observation (EO) based products and services within the Arctic and Baltic shipping sectors,
- To create a roadmap to a best practice for the use of EO information products and services by the shipping sectors operating in these areas
- To identify and consolidate geoinformation needs that fit the requirements highlighted by the shipping stakeholders

These objectives aim to enhance the safety, efficiency, and environmental sustainability of maritime operations in the Arctic and Baltic regions by leveraging the capabilities of EO technologies.

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1 EXECUTIVE SUMMARY

The increasing maritime operations in the Arctic and Baltic regions pose unique challenges due to harsh operating conditions, including sea ice and hazardous weather, as well as limited infrastructure and communication services. To mitigate the risks associated with these challenges, the International Code for Shipping Operations in Polar Waters, also known as the Polar Code, was implemented in 2017 to enhance safety and environmental standards for shipping in polar regions.

In this context, Earth observation (EO) satellites play a crucial role in providing geospatial information and data products to support various aspects of the shipping sector, from ship design and construction to operation, certification, insurance, and end-of-life considerations. EO satellites can address geoinformation requirements, such as:

- Ship Design (SD) and Ship Construction (SC): EO satellites provide detailed geospatial information about the polar regions, including ice conditions and sea-ice movement**.** This data is essential for designing ice-strengthened ships and ensuring safe construction practices in polar waters. High-resolution satellite imagery can assist also in site selection for shipyards and construction monitoring.
- Ship Operation (SO): EO data provides real-time or near-real-time information on ice conditions, weather, and sea-state. This information is vital for safe navigation, route planning, and avoiding ice hazards. EO satellites can also track vessel positions, speeds, and routes, contributing to maritime situational awareness.
- Insurance (IN): Insurance companies can utilize EO data for risk assessment and underwriting policies. Information on ice conditions, weather patterns, and historical incident data can be used to assess the potential risks associated with shipping operations in polar regions.
- Ship Certification (SCE): For compliance with the Polar Code, ships must meet specific requirements related to design, equipment, and operational procedures. EO data can support certification by providing information on ice conditions, navigational hazards, and environmental factors that may affect the ship's operation and safety.
- End of Life (ELD): EO satellites can assist in monitoring the end-of-life phase of ships, especially in terms of disposal, recycling, and environmental impact assessment. This information is essential for ensuring responsible and environmentally sustainable ship decommissioning.

Data from government-operated satellites like those from NASA, ESA, and other space agencies are a valuable source of information for all the business processes, given the continue monitoring capability. Commercial EO satellite and EO data service providers offer tasking observing capability at very high-spatial resolution and data products/services potentially tailored to the specific needs of the shipping sector in polar regions. By utilizing these EO resources, stakeholders in the shipping industry can better manage the challenges associated with polar waters and enhance safety, environmental responsibility, and efficiency in their operations.

The EO4BAS project provides a framework aiming to:

1. provide a common understanding of the path for supporting the usage of EO in the shipping sector operating in the Artic and Baltic. The common understating is provided by underlining the shipping needs and the key questions needed to advance on the evaluation whether EO data is needed and desirable. This is achieved by:
   - providing a basic introduction to satellites, sensors, and data information processes,
   - developing a shared understanding of the components (processes, products, and providers) of EO data and services,
2. facilitate the exchange of knowledge across the satellite earth observation sector and all the relevant shipping sectors. This includes also defining and mapping key general and specialised terminology that will address overlaps and discrepancies within the sectors.

3. facilitate a comprehensive and holistic evaluation of the relevant activities for the development of a roadmap for EO best practice.

The following document provides a mapping of EO information products fitting the shipping requirements.

2 CONCLUSIONS

Ships operating in the Artic need to follow the requirements described in the polar code, which include the development of a ship protocol to avoid hazardous sea-ice and weather conditions. An increasing number of ship operators need to take sea-ice and weather conditions into account in the risk assessments and voyage planning to follow the polar code regulations. The required practise from the polar code is to focus on hazardous conditions relates to sea-ice and temperature only and the use of climatological concepts to assess those conditions. The regulatory framework sets various requirements for safe operations, which operators need to meet, but it does not prescribe how these results should be achieved. The vessel operators' ability to avoid hazardous weather and sea-ice conditions critically depends on the accessibility, understanding, ability, usefulness, and reliability of environmental information in all voyage planning and execution stages.

Müller et al. (2023) states that there is a clear disconnection between the Polar Code guidelines for informed planning and the efficient use of weather and sea-ice information infrastructure that aims to support maritime navigation. The disconnection constrains the practical value of the Polar Code and arguably compounds operational risks. The continued high demands on weather and sea-ice information services are thus warranted and such services should form an essential element of the regulatory system. In this contest, we provide an overview of data information products combining AIS data and environmental data from satellite Earth observations to support the shipping industry.

3 INTRODUCTION

The EO4BAS project aims to consolidate a roadmap with guidelines for the shipping sector, operating in the Artic and Baltic marine areas, on how to use appropriately EO data for their purposes. In the report D1.2, we provided an overview of the shipping geoinformation needs. In this report, D2.1, we synthesize the current capability of EO-based information products in fitting the stakeholders needs.

The shipping industry, operating in the Artic and Baltic areas, relies on various geo requirements to ensure the safe and efficient transportation of goods across the world's oceans and waterways. Geospatial information and satellite technology play a crucial role in meeting these requirements. Here is provided a collection of geo-requirements for the shipping industry and an overview of the capabilities of satellites in meeting these needs. In summary:

1. Real-time Location Tracking: Satellites can provide real-time location tracking of vessels at sea, allowing ship operators and authorities to monitor their positions and movements.
2. Weather and Oceanographic Data: Access to weather forecasts, sea conditions, and oceanographic data is vital for route planning and avoiding adverse weather conditions that can affect vessel safety and fuel efficiency.
3. Marine Traffic Management: Satellites can assist in managing and optimizing marine traffic, helping to prevent collisions, congestion, and ensuring safe navigation in busy waterways.
4. Search and Rescue Operations: In the event of an emergency, satellites can assist in locating distressed vessels and transmitting distress signals to rescue authorities.
5. Navigational Aids: Satellite-based navigation systems like GPS and GLONASS are essential for precise navigation, both in open seas and coastal areas.
6. Environmental Monitoring: Satellites can provide information on environmental factors such as sea surface temperature, water quality, and pollution levels, helping the industry to comply with environmental regulations.
7. Ice and Iceberg Monitoring: For routes in polar regions, satellite data can be used to monitor ice conditions and the movement of icebergs, ensuring safe passage.
8. Port Operations and Traffic Management: Satellites help in optimizing port operations, monitoring traffic within ports, and managing cargo handling efficiently.
9. Regulatory Compliance: Geospatial data helps shipping companies comply with international regulations and safety standards, such as the International Maritime Organization (IMO) regulations.

Satellites, such as those in the Global Navigation Satellite System (GNSS) and Earth observation satellites, provide accurate positioning, real-time communication, and access to a wide range of environmental data, enabling the industry to operate safely, efficiently, and in compliance with international regulations. Additionally, satellite technology continues to advance, offering even more capabilities and potential applications for the shipping industry. An analysis gap and an overview of upcoming technology review will be provided in the following report D2.2.

4 TECHNOLOGY OVERVIEW OF GOVERNMENT AND COMMERCIAL SATELLITES AND SENSORS

Satellite remote sensing involves the use of satellites to gather information about Earth's surface and atmosphere.

Traditionally, national government agencies, such as National Aeronautics and Space Administration (NASA in United States), European Space Agency (ESA), Indian Space Research Organisation (ISRO), Japan Aerospace Exploration Agency (JAXA), etc.., have been responsible for launching, operating, and monitoring Earth continuously and collecting various Earth's parameters (physical, chemical, geophysical, meteorological, other…). Nowadays, a new space infrastructure is upcoming, including national/international agencies and commercial operators, expanding existing businesses opportunities. The shift from a space ecosystem being primarily government owned to a mixture of commercial and government operators is driven by the reduction in satellite launch costs and the advancement in technologies (computing and manufacturing).

In principle, the government and commercially owned missions vary in the scope. Satellites from government agencies are designed to provide a long-term continuous coverage of various parameters, allowing therefore a comprehensive global situational awareness. Commercial operators design, build, launch, and operate satellites for a wide range of purposes, including Earth observation. Commercial operators often prioritize higher resolution imagery and specific applications, allowing them to respond rapidly to market demands, to the detriment of spatial-temporal continuity in the observation and data product information services.

The combination of continuous observations provided by government and "ad hoc" commercial satellite observations has greatly expanded the capabilities and applications of satellite remote sensing. This includes more accurate weather forecasting, improved disaster response, enhanced environmental monitoring, and increased accessibility to geospatial data for various industries.

4.1 Orbits

Satellites can be placed in several types of orbits around Earth, two common classes of orbits relevant for the Artic and Baltic region are low-Earth orbit (approximately 160 to 2,000 km above Earth), medium-Earth orbit (approximately 2,000 to 35,500 km above Earth).

Low-Earth orbit is a commonly used orbit since satellites can follow several orbital tracks around the planet. Polar-orbiting satellites, for example, are inclined nearly 90 degrees to the equatorial plane and travel from pole to pole as Earth rotates. This enables sensors aboard the satellite to acquire data for the entire globe rapidly, including the polar regions. Many polar-orbiting satellites are considered Sun-synchronous, meaning that the satellite passes over the same location at the same solar time each cycle.

A medium-Earth orbit satellite takes approximately 12 hours to complete an orbit. In 24-hours, the satellite crosses over the same two spots on the equator every day. This orbit is consistent and highly predictable. As a result, this is an orbit used by many telecommunications and GPS satellites. One example of a medium-Earth orbit satellite constellation is the European Space Agency's Galileo global navigation satellite system (GNSS), which orbits 23,222 km above Earth.

4.2 Electromagnetic spectrum

Electromagnetic energy, produced by the vibration of charged particles, travels in the form of waves through the atmosphere and the vacuum of space. These waves have different wavelengths (the distance from wave crest to wave crest) and frequencies; a shorter wavelength means a higher frequency. Some, like radio, microwave, and infrared waves, have a longer wavelength, while others, such as ultraviolet, x-rays, and gamma rays, have a much shorter wavelength. Visible light sits in the middle of that range of long to shortwave radiation. This small portion of energy is all that the human eye can detect. Instrumentation is needed to detect all other forms of electromagnetic energy.

4.3 Passive and active sensors on board of satellites

Satellite remote sensing can capture imageries using a variety of sensors and technologies. Sensors on board of satellites can be divided in passive and active sensors, and both technologies can provide types of data relevant for the stakeholders' requirements identified in WP1.

Passive sensors on board of satellites detect and measure the energy emitted or reflected by Earth's surface and atmosphere, relying on solar radiation or thermal emissions. The simplified schematic in

Figure 1 (on the left side) captures how the sun emits light (solar radiation), which passes through the atmosphere, and then a part of the solar radiation is reflected off Earth to a sensor orbiting Earth on board of a satellite.

Passive sensors include different types of radiometers (instruments that quantitatively measure the intensity of electromagnetic radiation in select bands) and spectrometers (devices that are designed to detect, measure, and analyse the spectral content of reflected electromagnetic radiation). Most passive systems used by remote sensing applications operate in the visible, infrared, thermal infrared, and microwave portions of the electromagnetic spectrum. These sensors measure land and sea surface temperature, vegetation properties, cloud and aerosol properties, and other physical attributes. Most passive sensors cannot penetrate dense cloud cover and thus have limitations observing areas like the tropics where dense cloud cover is frequent.

During polar night, when there is no illumination of the surface by the sun and frequent clouds cover, passive sensors operating in the visible range, such as the moderate-resolution imaging spectroradiometer (MODIS), Multi-Spectral Instrument (OLCI), Multi-Spectral Instrument (MSI), are limited in what they can observe, see Table 1 for applicability to shipping requirements. Sensors using microwave frequencies, such as Special Sensor Microwave/Imager (SSM/I), Advancing Microwave Scanning Radiometer (AMSR) and RadarSat are most often used for monitoring the Arctic Ocean, especially the sea ice.

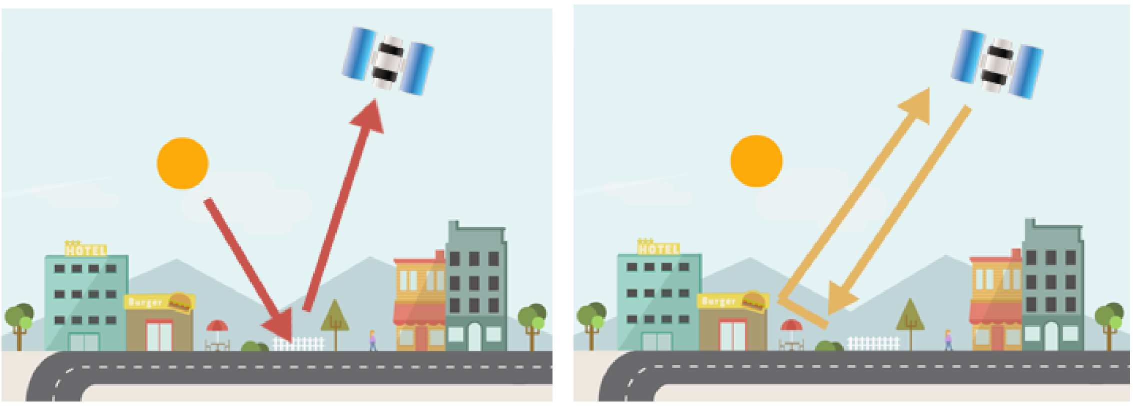

Figure 1 Schematic of passive (on the left side) and active (on the right side) remote sensing, source (GISgeography, 2023)

Active sensors have their own source of light or illumination. Those sensors actively send a pulse and measure the backscatter reflected to the sensor. Active remote sensing is capable to collect imageries at night and day and during cloud clover and poor weather conditions. Most active sensors operate in the microwave portion of the electromagnetic spectrum, which makes them able to penetrate the atmosphere under most conditions (penetration capability is strongly dependent on the wavelength of the emitted signal).

Active sensors include different types of radio detection and ranging (radar) sensors, altimeters, and scatterometers. These types of sensors are useful for measuring the vertical profiles of aerosols, precipitation and winds, sea surface topography, and ice, among others.

In Table 1, Table 2 and Table 3, we synthetise satellites and instruments relevant for the shipping sectors operating in the Artic and Baltic environment.

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Table 1 Summary of geoinformation requirements and some observational satellite platforms, sensors and variables supporting the requirements needs. The list of satellites and sensors aims to give an overview of available satellites and sensors operating, despite might be not exhaustive at global scale(Korres et al., 2023; Rampal et al., 2016; Sakov et al., 2012).

ID	Geo requirement	Description of fit to purpose EO information	Satellite	Instrument	Sensor (Passive/Active)	Models	Acronym
1	Ice concentration information	Ice fraction extend/concentration expressed as the extent to which a given area of water is covered by ice (area of sea ice relative to the total at a given point in the ocean)	Sentinel 1	SAR C	Active		SIC
			RadSat				
			TerraSAR-X	SAR X			
			COSMO-SKYMED				
			GCOM-W1	AMSR2	Passive		
2	Ice thickness information	Ice thickness referred as distance between the top surface of a body of ice and the underlying water or ground.	CryoSat-2,	Altimeter laser	Active		SIT
			ICESat-2				
3	Ice stage of development information	a classification of categorizes of sea ice based on thickness and age. age groups sea ice, as a function of ice thickness, include multiyear, first-year, young, and new ice.	Sentinel 1	SAR	Active		SIAGE SITYPE
			RadSat				
			Gaofen-3				
4	Long term ice condition statistic	Long-term statistics (time span) of ice information, such as sea ice extent, iceberg tracking, ice concentration, thickness	GCOM-W1	AMSR2	Passive MW		SIE, ICBG, SIC, SIT
5	Find leads in ice		Sentinel 1	SAR C	Active		NA
			RadSat				

		Ice leads referred as openings or channels in sea ice	TerraSAR-X Cosmo-SkyMed	SAR X			
6	Find polynyas in ice	Polynyas areas defined as the extent of open water area surrounded by sea ice	Sentinel 1 RadSat TerraSAR-X Cosmo-SkyMed	SAR C SAR X	Active		NA
7	Forecast ice drift	Movement and displacement of sea ice over a specific period				neXtSIM sea ice model (*)	SIUV
8	Ice edge information	Drifted ice consists of ice floes and individual pieces of sea ice 20 metres or more across	Sentinel 1 RadSat TerraSAR-X Cosmo-SkyMed	SAR C SAR X	Active		SIEDGE
9	Information on ice field compression and divergence	Compression and divergence in the ice field detected through u and v velocity components provided by modelling				neXtSIM sea ice model (*)	SIUV
10	Identify ice ridges and deformed ice	Wind and current velocity components (u, v) deforming and fracturing ice.				neXtSIM sea ice model (*)	SITYPE
11	Wind speed and direction	Wind and current velocity components (u, v) forming a line or wall of broken ice forced by pressure.	United States Air Force Defense Meteorological Satellite Program (DMSP) F-16, F-17, F-18	SSMI/I and SSMI/S	Passive microwave		SIUV

		Wind speed referred as how fast the air is moving past a certain point. Wind direction referred as a direction occurring during the indicated hour, using 36 points of a compass.	and F-19 satellites					
			The Tropical Rainfall Measuring Mission's (TRMM)	TRMM				
			NASA Aqua	AMSR-E				
			NASA/Japan Aerospace Exploration Agency Global Precipitation Measurement (GPM) Core Observatory	GMI				
			SMOS	SMAP				
			Sentinel 1	SAR C	Active microwave			
			RadSat					
			TerraSAR-X	SAR X				
			Cosmo-SkyMed					
			MetOp	ASCAT-A/B				
			ADEOS-1	QuickScat				
			International space station (ISS)	RapidSCAT				
			USA Department	WindSat				

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			of Defense Coriolis satellite				
			HaiYang-2A	HY2A-SM			
12	Wave height and direction monitoring	Wave heights described as the average height of the highest third of the waves (defined as the significant wave height). Wave direction referred as the direction from which the waves are coming.	Sentinel 1	SAR C	Active		SWH
			RadSat				
			TerraSAR-X	SAR X			
			COSMO-SkyMed				
						WAM model (***)	
13	Air temperature	Air temperature described as a measure of how cold or warm the air is at a certain altitude above the sea level.				GISS Surface Temperature Analysis (GISTEMP v4) AIRS ERA5	
14			Sentinel 1	SAR C	Active		ICBG
			RadSat				

	Iceberg and bergy bit information	Detection of the position and size of icebergs.	TerraSAR-X COSMO-SkyMed	SAR X			
15	Oil spill detection	Leakage of petroleum onto the surface of water	Sentinel 1 RadSat TerraSAR-X COSMO-SkyMed	SAR C SAR X	Active		NA
16	Icing conditions detection	A variety of variables, such as wave height, wind speed, air temperature (2 meters), sea temperature, etc provide info on conditions when water from either the atmosphere or the ocean freeze onto the ship.					
17	Sea current monitoring	Sea current components (x, y)				TOPAZ4 forecasting system (**)	UV
18	Ice drift monitoring	Sea ice drift components (x, y) to show the movement and displacement of sea ice over a specific period.			Active	neXtSIM sea ice model (*)	SIUV
19	Change in vegetation	Normalized differential vegetation index and radar vegetation index and their variation as a measure of the dynamics of vegetation.	Sentinel 1 Sentinel 3 Metop PROBA-V	SAR-C OLCI – SLSTR ASCAT	Passive OPT & Active		NDVI

			Sentinel 2	SMI OLCI			RVI
20	Algae blooming monitoring	Chlorophyll a is a measure of the amount of algae growing in a waterbody.	Sentinel 3	OLCI	Passive OPT		Chl
21	Ice season length	The number of days in which a geographical area is covered with sea ice in a time window.	Nibus-7 DMSP	SMMR SSM/I SSMIS	Passive MW		SIC
22	Fast ice information	Shapefiles of fast ice, anchored to the shore or ocean bottom. Fast ice is defined by the fact that it does not move with the winds or currents.	Sentinel 1 RadSat TerraSAR-X COSMO-SkyMed	SAR C SAR X	Active		NA
23	Snow on ice information	Snow thickness over sea ice regions (characterised by a sea ice thickness).			Active	neXtSIM sea ice model (*)	SNOW
24	Icing forecasting on the ship	A variety of variables, such as wave height, wind speed, air temperature (2 meters), sea temperature, etc provide info on conditions when water from either the atmosphere or the ocean freeze onto the ship				Forecast models	SST, T, wind speed
25	Sea surface temperature	Sea temperature between the depths of from approximately 10 µm to 1mm,	Sentinel 3 Metop-A VIIRS_NPP NOAA	SLSTR AVHRR	Passive		SST

		depending on sensors.					
26	Emissions to air	Sulfur dioxide, nitrogen oxide	Sentinel 5P	Tropomi	Passive		SO2
							NO2
			Sentinel 3	OLCI			
			AURA	OMI			
27	AIS, radar signal and other instruments suited for ship detection and monitoring	Automatic identification system of ships locations					AIS
28	Monitoring of shore changes, shore erosion and sediment deposit	Costal land cover and land use identifying alteration of land use	Sentinel 2	MSI	Passive		LULC
		Bathymetry to identify underwater topography, coastal erosion, and sedimentation					SDB
		Shoreline shift and subsidence	Sentinel 1	SAR	Active		NA

4.4 Resolution

Resolution is a critical factor in utilizing data from remote sensing sensors. It varies based on the satellite's orbit and sensor design. There are four types of resolution to consider for any dataset—radiometric, spatial, spectral, and temporal:

1. Radiometric Resolution: Radiometric resolution refers to the amount of information captured in each pixel. Specifically, it relates to the number of bits used to represent the recorded energy. For instance, an 8-bit resolution corresponds to 2^8, resulting in 256 potential digital values (ranging from 0 to 255) for storing information. Higher radiometric resolution allows better discrimination between subtle differences in energy. This is crucial, especially when assessing water quality or distinguishing ocean colors.

2. Spatial Resolution: Spatial resolution is determined by the size of each pixel within a digital image and the corresponding Earth surface area it represents. Different spatial resolutions can be tailored to address specific challenges and geospatial information requirements.

3. Spectral Resolution: Spectral resolution pertains to a sensor's ability to discern finer wavelengths. Many sensors are multispectral, meaning they capture data across multiple bands. Some advanced sensors are hyperspectral, offering hundreds or even thousands of narrow wavelength bands. The narrower the wavelength range for a given band, the finer the spectral resolution.

4. Temporal Resolution: Temporal resolution measures the time it takes for a satellite to complete an orbit and revisit the same observation area. This resolution depends on factors such as the satellite's orbit, sensor characteristics, and swath width.

4.5 Data processing

Remote sensing data acquired from instruments aboard satellites require processing before the data are usable by users. Most data are stored in Hierarchical Data Format (HDF) or Network Common Data Form (NetCDF) format. Numerous data tools are available to subset, transform, visualize, and export to various other file formats.

4.6 Satellites

A description of satellites and sensors are provided in this section to guide the stakeholders in navigating the several platforms that provide EO data information products fitting the shipping requirements defined in the EO4BAS project.

4.6.1 Sentinels

The sentinel constellation is aiming to monitor Earth with satellites operated by the European Space Agency (ESA). These satellites are part of the Copernicus program and are designed to monitor various aspects of the Earth's environment, such as land cover, atmospheric conditions, and climate change. The data from the Sentinels mission are freely available to the public, contributing to the accessibility and widespread use of Earth observation data for scientific research, commercial applications, and policymaking (European Space Agency, n.d.-o).

4.6.1.1 Sentinel-1

Sentinel-1 aims to provide a global environmental monitoring. It consisted of a constellation of two polar orbiting radar imaging satellites, Sentinel-1A and Sentinel-1B, launched in 2014 and 2016, respectively. Sentinel 1B malfunctioned Dec. 23, 2021, and it is currently not operative.

The primary objective of the Sentinel-1 mission is to provide all-weather, day-and-night radar images of the Earth's surface. The satellites are equipped with synthetic aperture radar (SAR) instruments that can penetrate clouds and darkness, allowing continuous monitoring of various areas, including land surfaces, oceans, and polar regions. Sentinel-1 SAR technology operates in the C band (5.6 cm) providing a good balance between resolution and penetration capability through clouds. Sentinel-1 SAR provide global high-resolution imageries, typically ranging from 10 meters to 20 meters, depending on the selected imaging mode and it can capture a large area in a single pass. The wide swath coverage enables efficient mapping of extensive regions and facilitates large-scale monitoring applications. Further, polarimetric SAR data provides additional information about the scattering properties of objects, allowing for advanced analysis and classification of land and ocean features. Sentinel-1 constellation data can support the generation of the almost all ice geo-products, including ID 1, ID 2, ID 3, ID 4, ID 5, ID 6 and several other, see also Table 1, (European Space Agency, n.d.-j).

4.6.1.2 Sentinel-2

The Sentinel-2 mission consists of a constellation of two optical satellites, called Sentinel-2A and Sentinel-2B (launched on 23.06.2015 and 07.04.2017). The development of the Sentinel-2 mission was required to provide continuity for services relying on multi-spectral high-resolution optical imager. Sentinel-2's Multi-Spectral Instrument (MSI) captures high-resolution optical imagery in 13 spectral bands, including visible, near-infrared, and shortwave infrared. This enables detailed observations of coastal areas, including the detection of features like water quality, coastal erosion, shore changes (e.g. in vegetation), sediment deposits and transport, detection of pollution, algal blooms. EO information products generated form these satellite can support the generation of ID 19, 20 and 28 products (European Space Agency, n.d.-k).

4.6.1.3 Sentinel-3

The Sentinel-3 mission is an ocean and land mission, which consists of two satellites in orbit, Sentinel-3A & Sentinel-3B (launched on 16.01.2016 and 25.4.2018). Every Sentinel-3 satellite is composed of multiple sensing instruments to achieve different goals:

- SLSTR (Sea and Land Surface Temperature Radiometer), measures sea surface temperature, helping to monitor ocean currents, identify oceanic front, and detect thermal pollution in coastal areas.
- OLCI (Ocean and Land Colour Instrument) provides high-resolution measurements of ocean colour, which helps in assessing water quality, detecting harmful algal blooms, and monitoring phytoplankton abundance, water turbidity, total suspended matter, aerosols over wate, and land products such as vegetation index and terrestrial chlorophyl index.
- SRAL (SAR Altimeter) provides information regarding sea ice thickness, while the backscatter coefficient and waveform shape gives information on surface roughness and snow pack characteristics such as stratification or ice grain size. Environmental parameters such as wind speed and components and water vapor content (European Space Agency, n.d.-i).
- DORIS (Doppler Orthography and Radio positioning Integrated by Satellite), is a satellite tracking system, with the primary purpose is to provide precise orbits for low Earth orbit satellites. The system relies on the Doppler effect induced by the relative motion of a satellite with respect to ground-based beacons. When a satellite moves relative to the beacons it can "see," the Doppler effect induces a frequency shift. This shift is directly related to the satellite's radial speed with respect to the beacon.
    - On Sentinel-3, DORIS plays a crucial role in precise orbit determination. It contributes to the satellite's overall mission, which includes measuring sea-surface topography, land- and sea-surface temperature, and land- and ocean-surface color with exceptional accuracy. By providing accurate orbits, DORIS enhances ocean forecasting systems, environmental monitoring, and climate studies.
- MWR (Microwave Radiometer) contributes to precise altimetry by accounting for atmospheric water vapor effects. Its design and calibration are critical for achieving expected performance in this important Earth observation mission.

Both Sentinel-2 and Sentinel-3 contribute to monitoring marine pollution incidents, including oil spills and other pollutants. Their frequent revisit times and high-resolution imagery enable timely response and assessment of the affected areas. The data they collect is freely available to users, contributing to the sustainable management of our oceans and coasts. This allows to generate ID 25 and 28 products (European Space Agency, n.d.-l).

4.6.1.4 Sentinel 5P

The Copernicus Sentinel-5 Precursor mission is the first Copernicus mission dedicated to monitoring our atmosphere (launched on 13.10.2017). The mission consists of one satellite carrying the TROPOspheric Monitoring Instrument (TROPOMI) instrument. The satellite's local time of ascending node crossing of 13.30 h has been chosen to facilitate the so-called loose formation operation with NASA's Suomi-NPP spacecraft. This concept will allow the utilization of collocated, high resolution cloud mask data provided by the VIIRS (Visible Infrared Imaging Radiometer Suite) instrument on-board Suomi-NPP during routine processing of the TROPOMI methane product. The Copernicus Sentinel-5 Precursor mission reduces gaps in the availability of global atmospheric data products between SCIAMACHY/Envisat (which ended in April 2012), the OMI/AURA mission and the future Copernicus Sentinel-4 and Sentinel-5 missions (European Space Agency, n.d). The main objective of the Copernicus Sentinel-5P mission is to perform atmospheric measurements with high spatio-temporal resolution, to be used for air quality, ozone and UV radiation, as well as for climate monitoring and forecasting; it has to be strongly envisaged that in the contest of the project, these data could support the detection of the ID 13 and ID 26 (see Table 1) (European Space Agency, n.d).

4.6.2 AIRS

AIRS in conjunction with the Advanced Microwave Sounding Unit (AMSU), senses emitted infrared and microwave radiation from Earth to provide a three-dimensional look at Earth's weather and climate. Working in tandem, the two instruments make simultaneous observations down to Earth's surface. With more than 2,000 channels sensing different regions of the atmosphere, the system creates a global, three-dimensional map of atmospheric temperature and humidity, cloud amounts and heights, greenhouse gas concentrations and many other atmospheric phenomena. Launched into Earth orbit in 2002, the AIRS and AMSU instruments fly onboard NASA's Aqua spacecraft and are managed by NASA's Jet Propulsion Laboratory in Pasadena, California. AIR S data will be exploited aiming to derive information about air temperature (ID 13) and emissions air (ID 26), see Table 1, (NASA JPL, n.d.-a).

4.6.3 ALOS

The Advanced Land Observing Satellite (ALOS, renamed "Daichi") is a Japan Aerospace Exploration Agency (JAXA) satellite equipped by three remote-sensing instruments: the Panchromatic Remote-sensing Instrument for Stereo Mapping (PRISM) which provides panchromatic images at 2.5m used for digital elevation models (DEMs), the Advanced Visible and Near Infrared Radiometer type 2 (AVNIR-2) for land coverage observation (4 bands at 10m), and the Phased Array type L-band Synthetic Aperture Radar (PALSAR) with spatial resolution between 10 and 100m for day-and-night and all-weather land observations. The three sensors of ALOS-2 are split onto ALOS-3 (PRISM-AVNIR) launched in March 2023 and next ALOS 4 (L-SAR) scheduled in 2024, which will provide a wider SAR swath than ALOS-2 (700km in ScanSAR mode). Objectives of the mission are to provide maps for Japan and other countries including those in the Asian-Pacific region (cartography), to perform regional observation for "sustainable development", harmonization between Earth environment and development (regional observation), to conduct disaster monitoring around the world (disaster monitoring), to survey natural resources (resources surveying), to develop technology necessary for future Earth observing satellite (technology development). Quad pol data from ALOS could support the generation of several products, form ice classification map to the iceberg detection and other, see Table 1, (eoPortal, n.d.-a).

4.6.4 Capella Space

Capella Space is a US company which provides X-SAR imagery for defence and intelligence, supply chain, insurance, maritime and other purposes. The Capella constellation started in 2018 with the initial deployment of one satellite growing to 9 small satellites by the end of 2023. Each satellite features an X-band Synthetic Aperture Radar (SAR) instrument which provides single-polarized images in various modes including spotlight, stripmap, and sliding spotlight. Spotlight mode consists of high resolution imaging at 0.25 m for a swath of 5 x 5 km; sliding-spotlight mode produces an image at 0.5 m at a scene length up to 10 km, and stripmap mode produces imagery at 1.2 m up to 100 km x 10 km. Capella's satellites operate in a variety of orbits with a period of 90 minutes, which results in a revisit time of 2-5 hours with eight satellites. The frequent revisit time allows a variety of uses including monitoring military threats, observing glacial meltwater dynamics, coordinating disaster response, detecting vessels at sea and persistent global change monitoring. Due to sensitivity of the X-band data to the change in roughness of the surfaces, the exploitation of this data should be focused for the generation of the ID 10 and ID 15, see Table 1, (Capella Space, n.d.; eoPortal, n.d.-b).

4.6.5 Cosmo-SkyMed (CSK) and Cosmo-SkyMed Second Generation (CSG)

COSMO-SkyMed (CSK) is an Italian Earth-imaging constellation owned by the Italian Space Agency and consisting of four identical satellites operating in X-band SAR launched between 2007 and 2010. CSK-1, CSK-2 and CSK-4 remain operational. The nominal full constellation achieves a revisit time of a few hours on a global scale with a varying incidence angle. CSK satellites carry SAR-2000, a multi-mode X-SAR sensor providing different performance characteristics in terms of swath size, spatial resolution, and polarisation configurations. Available modes consist of Spotlight - 1 m; Stripmap HIMAGE - 3 m; Stripmap PING PONG - 15 m; ScanSAR Wide - 30 m; ScanSAR Huge - 100 m with a swath of 600 km. All modes use one polarization selectable among HH, VV, HV, or VH apart from Stripmap PING PONG, with two polarizations selectable among HH, VV, HV, or VH.

COSMO-SkyMed Second Generation (CSG) consists of two enhanced SAR satellites launched in December 2019 and January 2022. CSG guarantees continuity with CSK satellites, provides multiple polarizations improving quality and high precision features required for the interferometric activities. Available modes are Spotlight: less than 1m, 10x10 km swath, HH or VV or HH+HV or VV+VH; StripMap: 3 x 3 m, 40 x 40 km, HH or VV or HH+HV or VV+VH; Pingpong: 12 x 5 m, 40 x 40 km, HH+VV or HH/VH+HV/VV; Quad Pol: 3 x 3 m, 40 x 15 km, HH + VH + HV + VV; ScanSAR-1: 20 x 4 m, 100 x 100 km, HH or VV or HH+HV or VV+VH; ScanSAR-2: 40 x 6 m, 200 x 200 km, HH or VV or HH+HV or VV+VH. The availability of a constellation of a 5 VHR SAR satellites strongly suggests focusing the exploitation of the COSMO-SkyMed data for the generation of the ID 1, ID 6 and ID 8, see Table 1, (e-geos, n.d.; eoPortal, n.d.-c; European Space Agency, n.d.-a).

4.6.6 Cryosat

CryoSat is a ESA satellite mission dedicated to studying the Earth's cryosphere. CryoSat aims to determine variations in the thickness of Earth's continental ice sheets and marine ice cover. It's Europe's first ice mission, equipped with an advanced radar altimeter called the SAR/Interferometric Radar Altimeter (SIRAL). SIRAL employs synthetic aperture radar and interferometry techniques to enhance accuracy over rugged ice sheet margins and polar sea ice. The mission measures both freeboard (the difference in height between sea ice and adjacent water) and ice sheet altitude, tracking changes in ice thickness. CryoSat was launched on April 8, 2010.Originally designed for about 5 years, CryoSat has now spent over 13 years in orbit, continuing to provide valuable data, e.g. for ID 14, see Table 1, (European Space Agency, n.d.-b).

4.6.7 Formosat 5

FORMOSAT 5 was developed by NSPO (National Space Organization of China). Formosat-3 was responsible for observations on meteorology and climate. FormoSat-5, launched in 2017, is a follow-up to FormoSat-2, as the number 4 is considered to bring bad luck in the Taiwanese culture. FormoSat-5 has the objective to enhance the domestic capability for a high-resolution optical remote sensing instrument. Formosat-5 has an optical payload and a number of science payloads. The optical payload, Remote Sensing Instrument (RSI), provides images at spatial resolution of 2m (pan mode) and 4 m (multi-spectral) with a swath of 24 km. Additional scientific payloads are Magnetic Field Instrument (MFI) and Marine Data Relay Payload (MDRP). The objectives of the mission are to utilize remote sensing technology for the applications of disaster mitigation and environment monitoring, and to supply remote sensing images for the users of FORMOSAT-2. According to the Formosat 5 data features and characteristics, data form this satellite could be used for the generation of the ID 28 product, see Table 1, (eoPortal, n.d.-d; Wikipedia, 2023a).

4.6.8 GeoEye-1

GeoEye-1 is a high-resolution Earth observation satellite that was launched on September 6, 2008. It is operated by GeoEye Inc., a company specializing in commercial satellite imaging and geospatial information services. GeoEye-1 is capable of capturing very high-resolution imagery, with a ground sample distance (GSD) of 0.41 meters in the panchromatic band (resulting in a black and white image) and 1.65 meters in the multispectral bands. GeoEye-1 has a relatively wide swath width, which meant it could cover a larger area in a single pass. This feature was useful for capturing imagery over extensive regions. Data form this satellite can be used for the generation of the ID 18 and ID 19 products, see Table 1, (eoPortal, n.d.-e; European Space Agency, n.d.-c).

4.6.9 GPM

The Global Precipitation Measurement (GPM) mission is an international network of satellites that provide next-generation global observations of rain and snow. GPM is a joint mission between JAXA and NASA as well as other international space agencies to make frequent (every 2–3 hours) observations of Earth's precipitation. It is part of NASA's Earth Systematic Missions program and works with a satellite constellation to provide full global coverage. The project provides global precipitation maps to assist researchers in improving the forecasting of extreme events, studying global climate, and adding to current capabilities for using such satellite data to benefit society. GPM builds on the notable successes of the Tropical Rainfall Measuring Mission (TRMM), which was also a joint NASA-JAXA activity. The launch occurred on February 28, 2014, at 3:37am JST on the first attempt Agencies in the United States, Japan, India and France (together with Eumetsat) operate the remaining satellites in the constellation for agency-specific goals, but also cooperatively provide data for GPM (NASA, n.d.-a). GPM satellite has a microwave radiometer onboard called GMI (GPM Microwave Imager); GMI is a dual-polarization, multi-channel, conical-scanning, passive microwave radiometer with frequent revisit times. The GMI instrument was designed with a strict calibration accuracy requirement to a greater precision than any previous microwave satellite sensor, thereby enabling the instrument to serve as a microwave radiometric standard. Data from GPM should be used aiming to generate the ID 23 and the ID 28 geo products (NASA, n.d.-f, n.d.-a).

4.6.10 ICEYE

The ICEYE constellation is a constellation of X-band SAR Satellites; Each satellite of the ICEYE constellation carries an X-band Synthetic Aperture Radar (SAR), allowing the instruments to “see” through darkness, clouds and rain to observe Earth at all times. ICEYE-X1 is ICEYE's first proof-of-concept microsatellite mission with a SAR sensor as its payload. It was launched on January 12th, 2018. ICEYE-X1 is also the world's first SAR satellite in this size (under 100 kg). ICEYE uses the X-band frequency of 9.75 GHz at a wavelength of around 3 cm, has a pulse rate frequency of 2-10 kHz. Due to sensitivity of the X-band data to the change in roughness of the surfaces, the exploitation of this data should be focused for the generation of the ID 10 and ID 15, see Table 1.

These satellites are compact and can provide frequent and cost-effective radar imagery. ICEYE's radar technology is particularly useful for monitoring various aspects of the Earth, such as changes in ice, land, maritime surveillance, disaster monitoring, infrastructure monitoring and maritime environments (eoPortal, n.d.-g; ICEYE, n.d.).

4.6.11 ICESat-2

The Ice, Cloud, and Land Elevation Satellite-2, or ICESat-2 by NASA, measures the height of a changing Earth, one laser pulse at a time, 10,000 laser pulses a second. Launched September 15, 2018, ICESat-2 carries a photon-counting laser altimeter that allows scientists to measure the elevation of ice sheets, glaciers, sea ice.

The satellite mission has four science objectives:

- Measure melting ice sheets and investigate how this effects sea level rise,
- Measure and investigate changes in the mass of ice sheets and glaciers,
- Estimate and study sea ice thickness,
- Measure the height of vegetation in forests and other ecosystems worldwide.

ICESat-2 will also survey heights of the world’s forests, lakes, urban areas, cloud cover and more, adding a third dimension to flat images of Earth from space. Data ICESat-2 should be used for the generation of different geo-products, such as ID 2 and other (eoPortal, n.d.-f; McLennan, 2010; NASA, n.d.-b).

4.6.12 ISS-RapidScat (available 2014-2016)

The International Space Station Rapid Scatterometer (ISS-RapidScat) mission was launched on 20 September 2014 from the Cape Canaveral Air Force Station in Florida with the primary goal of measuring ocean surface wind vectors, calibrated to a 10-meter reference height, as a continuation of the QuikSCAT climate data record. As a bi-product of the low inclination orbit of ISS, RapidScat is in a unique position to provide measurements that are asynchronous with respect to the solar day cycle of the Earth; this translates to RapidScat having the unique capability (in contrast to all other past and present space-borne scatterometers) of observing diurnal and semi-diurnal variability over seasonal time scales. The ISS-RapidScat mission is particularly blessed to have contemporaneous measurements from QuikSCAT (albeit limited due to QuikSCAT's fixed antenna position) to ensure consistently calibrated measurements to ensure accurate observation. The PO.DAAC functions as the primary archive and distribution center for the RapidScat data produced directly by the ISS-RapidScat Science Data Systems (SDS) team at JPL.

On 19 August 2016, the ISS Columbus module experienced a power loss. Decommissioning of ISS-RapidScat began in December 2016 and continued through September 2018. Through this decommissioning phase, the ISS-RapidScat SDS team continued to provide higher quality, reprocessed versions of RapidScat science datasets (NASA JPL, n.d.-b; eoPortal, n.d.-h; NASA JPL, 2020).

4.6.13 KOMPSAT 7, 3, 3A

KOMPSAT 7 **(**Korean Multipurpose Satellite 7) is a lightweight Earth observation satellite developed by the Korea Aerospace Research Institute KARI. KOMPSAT-7 is the follow-up model of KOMPSAT-3A launched in 2012 and developed with the goal of providing high-resolution satellite images to satisfy the national needs. KOMPSAT-7 is equipped with the high-resolution space-borne camera named AEISS-HR (Advanced Earth Imaging Sensor System with High Resolution), which possesses 30 cm resolution in panchromatic mode, 1.2 m in colour mode, and 4 m in infra-red mode with a swath of 12 km. The AEISS-HR sensors provides data for landscape topography, vegetation and multi-purposes images on land. Objectives and applications of the KOMPSAT mission are cartography, land use and disaster monitoring. Since its own change detection capability, the usage of the KOMPSAT data is strongly suggested to generate the ID 19 product, see Table 1, (Arianespace, n.d.; Krebs, 2024).

4.6.14 Landsat 8

The Landsat 8 satellite payload consists of two science instruments—the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS). These two sensors provide seasonal coverage of the global landmass at a spatial resolution of 30 meters (visible, NIR, SWIR); 100 meters (thermal); and 15 meters (panchromatic). It was launched on February 11, 2013, and it is the eighth satellite in the series of Earth-observing satellites. The primary purpose of Landsat 8 is to gather high-quality imagery and data of the Earth's surface for various applications, including environmental monitoring. Landsat 8 continues the legacy of the Landsat program by NASA, which dates to the launch of Landsat 1 in 1972. The program has provided a valuable, long-term record of Earth's changing landscapes. One of the notable features of the Landsat program is the free and open access to its data. Data from Landsat-8 can be exploited to generate maps of sea surface temperature (ID 25), see Table 1, (NASA, 2021)

4.6.15 Metop - EUMETSAT Polar System

EUMETSAT Polar System (EPS) Metop mission consists of three polar orbiting Metop satellites, to be flown successively for more than 14 years. The first, Metop-A, was launched by a Russian Soyuz-2.1a rocket from Baikonur on October 19, 2006, at 22:28 Baikonur time (16:28 UTC). Metop-A was initially controlled by ESOC for the LEOP phase immediately following launch, with control handed over to EUMETSAT 72 hours after lift-off. EUMETSAT's first commands to the satellite were sent at 14:04 UTC on October 22, 2006. The second EPS satellite, Metop-B, was launched from Baikonur on 17 September 2012, and the third, Metop-C, was launched from Centre Spatial Guyanais in Kourou, French Guiana on 7 November 2018 by Arianespace using a Soyuz ST-B launch vehicle with a Fregat-M upper stage. Data from EUMETSAT will be used to generate ID 13 and other, see Table 1, (EUMETSAT, 2024).

4.6.16 Pléiades

The Pléiades constellation is composed of two very-high-resolution optical Earth-imaging satellites. Pléiades-1A and Pléiades-1B provide the coverage of Earth's surface with a repeat cycle of 26 days. Designed as a dual civil/military system, Pléiades meet the space imagery requirements of European defence as well as civil and commercial needs. The Pléiades system was designed under the French-Italian ORFEO Programme (Optical and Radar Federated Earth Observation) between 2001 and 2003. The Pléiades programme was launched in October 2003 with CNES (the French space agency) as the overall system prime contractor and EADS Astrium as the prime contractor for the space segment. Equipped with technologies like fibre-optic gyroscopes and control moment gyroscopes, Pléiades-HR 1A, and 1B offer roll, pitch, and yaw (slew) agility, enabling the system to maximize the number of acquisitions above a given area (eoPortal, n.d.-j; European Space Agency, n.d.-d; Wikipedia, 2023b).

4.6.17 Pléiades Neo

Pléiades Neo is a very high resolution optical constellation of two identical satellites phased at 180° from each other. The constellation provides continuity for the Pléiades mission, with enhanced performance in terms of accuracy, reactivity and frequency. Fast tasking, high agility and a huge volume of data are the main advantages of the mission. The constellation is manufactured, owned and operated by Airbus Defence and Space. Pléiades Neo 3, the first satellite in the constellation, was launched on 28 April 2021, followed by Pléiades Neo 4 on 16 August 2021. The constellation remains operational (eoPortal, n.d.-i; European Space Agency, n.d.-f, n.d.-e).

4.6.18 QuickSat

QuikSCAT is a NASA ESE Earth Science Enterprise (ESE) program satellite built by Ball Aerospace & Technologies Corporation (BATC), in Colorado. QuickSCAT is an artificial Earth satellite developed to analyse the direction and speed of the oceans. Observations from QuikSCAT had a wide array of applications, and contributed to climatological studies, weather forecasting, meteorology, oceanographic research, marine safety, commercial fishing, tracking large icebergs, and studies of land and sea ice, among others. QuikSCAT was launched on 19 June 1999 with an initial 3-year mission requirement. Data form this satellite should be used aiming to generate the ID 17 product, see Table 1, (eoPortal, n.d.-k; European Space Agency, 2020).

4.6.19 Radarsat-2

RADARSAT-2 is a Canadian Earth observation satellite equipped with Synthetic Aperture Radar (SAR) technology. RADARSAT-2 is part of the RADARSAT Constellation Mission (RCM) program, which aims to provide continuity and enhancements to the RADARSAT-1 mission. It was launched on December 14, 2007, and is operated by the Canadian Space Agency (CSA). RADARSAT-2 offers different imaging modes with varying spatial resolutions and coverage areas, including:

1. Ultra-Fine mode at 3-meter resolution with a coverage width of 20 km
2. Fine mode at 5-meter resolution with a coverage width of 50 km
3. Standard mode at 10-meter resolution with a coverage width of 100 km
4. Wide mode at 25-meter resolution with a coverage width of 500 km

RADARSAT-2 can acquire data in different polarization modes. Polarimetric SAR data allows for advanced analysis and classification of surface features. RADARSAT-2 data is utilized for a wide range of applications of relevance for EO4BAS, including:

1. Environmental monitoring of ice dynamics.

2. Monitoring sea ice, ocean currents, oil spills, and maritime surveillance.

RADARSAT-2 has a wide imaging swath that allows for global coverage. It captures data in different regions of the Earth, enabling comprehensive monitoring and analysis. RADARSAT-2 data is commercially available through various distributors and partners. Users can acquire imagery for their specific requirements and applications.
Since Radarsat-2 is SAR system, as largely known its data can support the detection of several ID products, such as ice concentration, ice drift, oil spill and other, see Table 1, (Canadian Space Agency, 2011; eoPortal, n.d.-l; European Space Agency, n.d.-g).

4.6.20 SAOCOM-1

The SAOCOM (SAtélite Argentino de Observación COn Microondas) is a constellation of two polarimetric L-band SAR satellites (SAOCOM-1A and -1B) launched in 2018 and 2020 and operated by the Argentina's Space Agency. The overall objective of SAOCOM is to provide an effective Earth observation and disaster monitoring capability. SAOCOM requirements call for a capability to provide timely information in support of natural and anthropogenic disaster management and to conduct monitoring services for agriculture, mining and ocean applications - including monitoring surveys of Antarctica (study of continental glacier evolution, global change indicators, etc.). SAOCOM data are available in Stripmap mode, swath 15- 60 km, resolution 5m; TopSAR narrow, swath around 100 km, resolution 30m; TopSAR wide, swath 200-350km, resolution 100m; all available at single, dual and quad polarizations. Quad pol data from SAOCOM-1 could support the generation of several products, form ice classification map to the iceberg detection and other, see Table 1, (eoPortal, n.d.-m; European Space Agency, n.d.-h) .

4.6.21 SMOS

SMOS is an European Space Agency (ESA) mission, aiming at providing new insights into Earth's water cycle and climate. Additionally, SMOS aims to enhance weather forecasting and monitor snow and ice accumulation. SMOS operates as a microwave imaging satellite and provides global observations of wind and sea surface salinity, e.g. ID 11 product, see Table 1. SMOS operates in the microwave L-band (eoPortal, n.d.-n).

4.6.22 Tandem-L

Tandem-L satellites are planned to carry a single instrument, an L-band Synthetic Aperture Radar (L-SAR). Based on user requirements, 26 preliminary geophysical products have been set out for Tandem-L acquisition. To satisfy these challenging mission requirements, the data acquisition concept consists of a 3-D structure mode and a deformation mode for its characteristic wavelength of 236 mm. 3-D structure mode employs fully-polarimetric SAR interferometry to derive tomographic images with fine vertical and horizontal resolutions. This is required for several accurate measurements including 3-D forest and ice structures, and the generation of digital terrain and surface models. Employing repeat-pass interferometry, the deformation mode will be able to measure displacements on the Earth's surface with high accuracy used for monitoring deformations for investigations of earthquakes and risk analysis.
A combination of L-SAR modes will be used to complete other important mission goals including global measurement of forest biomass and its temporal variation, glacier motion and melting, near-surface soil moisture and ocean surface dynamics (eoPortal, n.d.-o).

4.6.23 TerraSAR-X

TerraSAR-X, is an imaging radar Earth observation satellite, a joint venture being carried out under a public-private-partnership between the German Aerospace Center (DLR) and EADS Astrium. The exclusive commercial exploitation rights are held by the geo-information service provider Astrium. TerraSAR-X was launched on 15 June 2007 and has been in operational service since January 2008. With its twin satellite TanDEM-X, launched 21 June 2010, TerraSAR-X acquires the data basis for the WorldDEM, the worldwide and homogeneous DEM available from 2014. Using a phased array synthetic aperture radar (SAR) antenna (X-band wavelength 31mm, frequency 9.65 GHz), TerraSAR-X provides radar images of the entire planet from an Earth polar orbit of 514km altitude. This is selected so that the satellite follows a Sun-synchronous orbit. This specific orbit means that the satellite moves along the Day-Night boundary of the Earth and allows it to present the same face to the Sun: thus, providing the best solar incidence angles to its solar cells for power. TerraSAR-X is designed to carry out its task for five years, independent of weather conditions and illumination, and provides radar images with a resolution of up to 1m, (eoPortal, n.d.-p; European Space Agency, n.d.-n).

4.6.24 WindSAT

WindSat is the first satellite microwave polarimetric radiometer and was launched in 2003. A typical resolution for radiometer winds is about every 25 km over global oceans. A radiative transfer model and ocean emissivity model is needed to derive the wind speeds from ocean brightness temperatures. The consistent satellite MW radiometer wind speed data record began in 1987 with the launch of the DMSP F08 SSM/I. Data from WindSAT could be used to produce both ID 17 and ID 25 products, see Table 1, (Wentz et al., 2013).

Table 2 Specification of passive sensors

Platform	Bands	Instruments	Resolution (m)	Swath at Nadir (km)	Revisit (day)	Altitude (km)	Orbit	Operator	Country	# Satellite	Source
Formosat 5	PAN MS (B,G,R,NIR)	RSI Formosat-5 Optical Remote Sensing	2-4	24	2	720	Sun-synchronous	NSPO	Taiwan	1	https://www.eoportal.org/satellite-missions/formosat-5
GeoEye-1	PAN MS (B,G,R,NIR)		0.41 1.65	15.3	1.7	681	Sun-synchronous	GeoEye	USA	1	https://www.eoportal.org/satellite-missions/geoeye-1
KOMPSAT 3	PAN MS (B,G,R,NIR)	Korsch-type telescope	0.5 2	15	3.5	685	Sun-synchronous	KARI	Korea	1	https://www.eoportal.org/satellite-missions/kompsat-3
KOMPSAT 3A	PAN MS (B,G,R,NIR)	AEISS-A KOMPSAT-3A Advanced Earth Imaging	0.4 1.6	13		528	Sun-synchronous	KARI	South Korea	1	https://www.eoportal.org/satellite-missions/kompsat-3a
KOMPSAT 7	PAN MS IR	AEISS-HR (Advanced Earth Imaging Sensor System	0.3 1.2 4			500 – 600	Sun-synchronous	KARI/SIIS	Korea	1	Several Sources
Landsat 9	PAN MS (B,G,R,NIR) TIR	PAN OLI-2 TIRS-2	15 30 100	185		705	Sun-synchronous	NASA	USA	1	https://www.eoportal.org/satellite-missions/landsat-9
Landsat-8 LDCM	PAN MS (9 bands)		15 30	185	16	917	Sun-synchronous	NASA	USA	1	https://www.eoportal.org/satellite-missions/landsat-8-ldcm

Pleiades 1A/1B	PAN MS (B,G,R,NIR)	Korsch telescopes	0.7 2.8	20	daily	695	Sun-synchronous	Airbus/CNES	France	1	http://database.eohandbook.com/database/missionsummary.aspx?missionID=478
Pleiades Neo	PAN MS (deepB,B,R,Redge,NIR)		0.3 1.2	14	daily (30° off-nadir) Twice daily (46° off-	700	Sun-synchronous	ADS	Europe		https://www.eoportal.org/satellite-missions/pleiades-neo
Sentinel 2A	UV (B1) VIS, NIR (B2,B3,B4,B8) NIR (B5,B6,B6,B8A) SWIR	Multispectral Instrument	60 10 20 20 60	290	10 2-3 (with 2 satellite)	786	Sun-synchronous	ESA	Europe	1 (expected 4)	https://www.eoportal.org/satellite-missions/copernicus-sentinel-2
Sentinel 2B	UV (B1) VIS, NIR (B2,B3,B4,B8) NIR (B5,B6,B6,B8A) SWIR	Multispectral Instrument	60 10 20 20 60	290	10 2-3 (with 2 satellite)	700	Sun-synchronous	ESA	Europe	1 (expected 4)	https://www.eoportal.org/satellite-missions/copernicus-sentinel-2

Table 3 Specification for active sensors.

Platform	Band	Polarization	Resolution (m)	Swath Width (km)	Incident Angle	Operator	Country	Satellite	Roadmap	Governance	Mission status	Data Timeliness	Source
ALOS-2	L	SP SP, DP, QP, CP SP, DP	1 (Spotlight) 3/6/10 (StripMap) 100 (ScanSAR)	25 50-70 350	8° - 70°	JAXA	Japan	1	Complete	Civil	Operational (extended)		https://www.eoportal.org/satellite-missions?Inst
Capella X-SAR	X	SP	0.3 (Staring Spotlight), 0.5 (Sliding Spotloght)	5 x 20 (Staring Spotlight), 10x10 (Sliding Spotlight)	25º - 40º	Capella	USA	8	36 satellites foreseen	Civil	Operational (nominal)		https://www.eoportal.org/satellite-missions/cap
COSMO SkyMed	X	SP SP, DP SP	1 (SP) 3/15 (SM) 30/100 (WS)	10(x10) 40/30 (x2500) 100/200 (x2500)	25° - 50° (nominal) 20° - 59,5° (extended)	ASI	Italy	3	complete	Dual	Operational (extended)	up to 12 h	https://www.eoportal.org/satellite-missions?Inst
CSG (Cosmo-SkyMed	X	SP, DP DP, BDP, QP SP, DP	0.8/1 (SL) 3x3/5x20/3x3 (SM) 4x20/6x40 (WS)	10x10 40/30/15 x 2500 100/200 x 2500		ASI	Italia	2	4 satellites foreseen	Dual	Operational (nominal)	up to 12 h	https://www.eoportal.org/satellite-missions/cos
ICEYE Constellation	X	SP	Spotlight: 1x1 Stripmap: 3x3 ScanSAR: 15 x 15	Spotlight: 5x5 Stipmap: 30 x 50	10° - 35°	ICEYE	Finland	21	48 satellites foreseen	Civil	Operational (nominal)	≤ 8h from downlink	https://www.eoportal.org/satellite-missions/icey
RADARSAT-2	C	SP HH,VV,HV or VH SP or DP Quad-Pol Quad-Pol	2.8 (Wide Ultra Fine) 7.6 (Wide Multilook fine) 7.6 (Wide fine)	20 50 50 25 25	30 - 50° 29 - 50° 20 - 45° 18 - 42° 18 - 42°	CSA, MDA	Canada	1	Complete	Civil	Operational (nominal)	< 2days	http://www.asc-csa.gc.ca/eng/satellites/ra
SAOCOM-1	L	DP, QP	SM Dual Pol 10mx5m TopSAR 30mx10m TopSAR W 50mx10m	SM: 50 Km Top SAR:150Km Top SAR W:360 Km	20º - 50º	CONAE	Argentina	2	New geneartion	Civil	Operational (extended)		https://www.eoportal.org/satellite-missions/sao
Sentinel-1	C	DP	IW 20 x 22 (az x rg) SM 5m EW 25mx100m	80 - bigger than 400	20° - 46°	ESA	Europa	1	New satellite foreseen	Civil	Operational (nominal)	Within 3 h and 20 days,	https://www.eoportal.org/satellite-missions?Inst
TanDEM-L	L	SP, QP	1 - 7 (depending on acq. mode)	QP 175 - SP 350	26 - 47°	DLR	Germany	2	approved	Civil	Considered		https://www.eoportal.org/satellite-missions/tan
TerraSAR-X, Tandem-X	X	SP, DP Quad-pol (experimental only)	0,25 (Staring) 1 (HS / HS-300) 2 (Spotlight) 3 (StripMap) 18 (ScanSAR) 40 (Wide	5 5 10 30 100 200	15°-60°	ADS / DLR	Germany	1	New satellites are	Civil	Operational (extended)	From 7h to 7 days	https://www.intelligence-airbusds.com/en/8694-

GEOINFORMATION REQUIREMENTS

The increasing maritime operations in the Arctic and Baltic regions poses unique challenges due to harsh operating conditions, including sea ice and hazardous weather, as well as limited infrastructure and communication services. To mitigate the risks associated with these challenges, the International Code for Shipping Operations in Polar Waters, also known as the Polar Code, was implemented in 2017 to enhance safety and environmental standards for shipping in polar regions.

In this context, Earth observation (EO) satellites play a crucial role in providing geospatial information and data information products to support various aspects of the shipping sector (including ship design (SD), ship construction (SC), operation (SO), certification (SCE), insurance (SI), and end-of-life considerations (EOL). The geoinformation requirements are 28, see Table 1, and the **fit to purpose geoinformation** provided by EO will be described following a standard structure, as shown in Table 4:

Table 4 The table describes the EO information products fitting the geoinformation requirements and purposes.

Business Process	Geoinformation requirement fitting the specified business processes
Description (What is needed)	Information of the geoinformation requirement
EO information of interest	EO information products fitting the requirements
Main processes steps	Synthetic description of the retrieval assumptions and steps
Input data sources	Information about primary used data (e.g., Sentinel-1) and (secondary) additional data (e.g., meteorological data).
Spatial resolution and coverage	Information about the size of the pixel that represents and the availability
Accuracy and constrains	Information and accuracy of data information and constrains limiting availability and accuracy of data
Temporal resolution	Temporal frequency of the data over an area
Update frequency	Information about data latency
Delivery/output format	Info on standards used and formats
Accessibility	Information about the access to the EO information products

4.7 Sea ice and its properties

The sea ice, which is on average 2–3 m thick, can only be penetrated by ice-strengthened vessels or icebreakers with a sufficient ice class. Most ships and fishing vessels are not ice-strengthened and must therefore avoid all ice areas. In many cases, when the ice concentration is 100% and the ice pressure is high, even the most powerful icebreakers have problems moving forward through the icepack.

In the Polar Code framework, hazardous conditions are narrowly defined by the *temperature and the sea-ice conditions* in relation to the *ships' classifications*.

Polar orbiting satellite observations allow to monitor sea ice properties daily. Many different satellite sensors and techniques exist; some are available since more than 40 years, some are currently still under development (Spreen & Kern, 2017). Sea ice properties can be measured using a variety of measurement techniques and methods, properties include sea ice area, thickness, age, edges, motion, etc.

Various satellite sensors and instruments can detect and characterize sea ice, each with its specific capabilities and resolution, see Table 1. Measurements at microwave frequencies from radiometers, scatterometers, and synthetic aperture radars (SAR) have the advantage to be independent of clouds and the polar night. Observations in the visual spectrum can have higher spatial resolution and be used during months with daylight to derive additional quantities, like the coverage with melt ponds. The variety of technologies commonly used for sea ice detection and characterization (including sea ice concentration, ice lead, polynyas, ice edge, sea ice thickness, etc), include:

1. *Passive visible and near-infrared sensors*: These sensors capture images in the visible and infrared parts of the electromagnetic spectrum. They are commonly used for ice detection in polar regions (when occurring cloud free conditions), where changes in ice cover can be visually observed. These sensors can provide information about the optical properties of ice, such as its colour, texture, and temperature.

2. *Passive microwave sensors*: These sensors operate in the microwave frequency range and are highly effective for ice detection, because microwaves *can penetrate cloud cover* and measure the emitted or reflected radiation from the Earth's surface. Passive microwave sensors can detect the presence of ice by measuring the *differences in emissivity or reflectivity between ice and open water*.

3. *Active Synthetic Aperture Radar (SAR*) sensors: SAR sensors operate in the microwave region of the electromagnetic spectrum (at different frequencies X, C, L-band, etc). SAR sensors can penetrate clouds and are useful for ice detection because they can differentiate between different types of ice, such as sea ice and icebergs, based on the backscattered characteristics. Polarimetric SAR images are useful in the *sea ice detection and classification* because enhance the discrimination capability of the observed target, which is limited using single polarisation images. Indeed, the description of the backscattering behaviour of sea ice is particularly challenging and scientists moved toward systems able to increase the amount of information acquired. Different surfaces and materials respond differently to radar waves based on their polarization. The choice of polarization can influence the radar system's ability to detect and characterize different types of "targets" or ice features. Commonly used bands in the artic environment include (HH and HV). Polarimetric bands are define as:

    a. HH and VV (Horizontal-Horizontal and Vertical-Vertical): In HH polarization, both the transmit and receive antennas have their electric fields aligned horizontally or vertically. This means that the radar pulse is transmitted and received with its electric field in the horizontal plane.

    b. VH (Vertical-Horizontal) and HV (Horizontal-Vertical): In VH polarization, the radar pulse is transmitted with the electric field in the vertical plane, and it is received with the electric field in the horizontal plane and vice versa for the HV.

    Sea-ice in SAR polarimetry is currently investigated by scattering matrix, as the Pauli scattering vector k = [HH +VV, HH-VV, 2HV]. Classification methodologies that make advantage of polarimetric SAR data consist of the estimation of "polarimetric observables" (ratios and coherences between polarimetric channels) to build a feature vector able to separate the different ice types (and open water) on a multidimensional space, or on the statistical distance (in the covariance matrix space) of the pixel from the different classes. Polarimetry could help the data analysis solving eventual ambiguities; moreover next SAR sensors should be able to achieve large swaths (as ScanSAR images) in polarimetric mode, as QUAD mode images currently only cover limited portions of sea ice. With QUAD pol SAR data is intended full polarimetric images, containing the following electromagnetic channels:

    - HH (Horizontal – Horizontal) and VV (Vertical – Vertical)

▪ HV (Horizontal – Vertical) and VH (Vertical – Horizontal)

As largely known in the scientific literature, HH and VV channels are named as co-polar, the other ones as cross – polar channels. The use of QUAD pol images is strongly suggested for ice classification purposes. As final remark, it is worth to note that polarimetric SAR data are crucial for AI methods, which take advantage of extended input datasets.

4. Active laser altimetry sensors: Laser altimetry sensors emit laser pulses, and measure the time it takes for the pulses to return to the sensor. These sensors can accurately measure the height and thickness of ice sheets and glaciers, providing valuable data for monitoring changes in ice volume over time. Satellite altimeters measure the sea ice freeboard, which can be converted to ice thickness. Laser altimeters generally penetrate clouds.

5. Fusion of Multiple Sensors: Combining information from multiple sensors (e.g., SAR, optical, and microwave) through data fusion techniques improves the accuracy of ice information estimates. Each sensor provides unique insights, and integrating their data enhances the overall understanding of ice cover and characteristics.

Table 5 Summary of geoinformation requirements relating to ice information.

Sea ice information	Concentration
	Ice thickness
	Ice stage of development
	Long term statistics of ice condition
	Detection of leads in ice
	Detection of polynyas in ice
	Forecast ice drift
	Ice edge information
	Information on ice field compression and divergence
	Identify ice ridges and deformed ice
	Fast ice

4.7.1 Ice concentration

Ice concentration is typically measured using remote sensing techniques, including satellite imagery and aerial and ship surveys. Remote sensing methods involve capturing images of the water surface and using algorithms to distinguish between ice and open water based on the reflective properties of the surface.

The spatial resolution of ice concentration provided by satellite observations varies depending on the sensor and the specific dataset being used. Different satellites have different capabilities and sensors that capture data at varying levels of detail. It's important to note that while higher spatial resolution can provide more detailed information about ice concentration, it might also come with limitations in terms of coverage and frequency of observations. Additionally, different sensors and datasets might have varying degrees of accuracy and precision in estimating ice concentration, which can be affected by factors like the presence of clouds, snow cover, and surface roughness.

Data providers also often combine data from multiple sensors and sources to get a comprehensive understanding of ice concentration patterns. The choice of dataset depends on the specific objectives and the trade-offs between spatial resolution, coverage, and accuracy.

Satellite data is often used to create ice concentration charts, providing at the same time information about the percentage of open water in an area and ice as well. These charts help mariners identify ice leads; the information on ice concentration can be derived from multiple satellite sources -including SAR, optical imagery, and passive microwave data – however under certain constraint (i.e. severe cloud coverage) SAR data can be used as stand-alone to generate the ice concentration chart.

These satellite-based methods and technologies are essential for monitoring and navigating through ice-covered waters, enhancing safety for ships, research vessels, and other activities in polar regions. Various organizations, including national meteorological agencies and space agencies, provide satellite imagery and data to support ice lead detection and ice navigation.

Further, it must be take into account that data coming from commercial provider – MDA Space, e-GEOS, DNV and other – can be exploited as well to support the ice lead and navigation.

Table 6 EO driven intelligence providing information on sea ice concentration.

SPECIFICATIONS	
BUSINESS PROCESS	SD, SC, SCE, IN, SO
DESCRIPTION	Ice concentration refers to the extent to which a given area of water is covered by ice. It is typically expressed as a percentage, representing the proportion of the water surface that is covered by ice at a specific point in time.
EO INFORMATION OF INTEREST	Sea ice concentration (SIC).
MAIN PROCESS STEPS	Various EO sensors and techniques are employed to monitor ice concentration. The calibration of sea ice fraction retrieval from SAR involves the use of observations from an open ocean area, and another presumed to be completely ice-covered. Various empirical schemes are employed to derive sea ice concentration, incorporating diverse assumptions and corrections to accommodate distinct surface conditions and the influence of snow and rain. To mitigate the impact of weather interference on ice concentration retrievals, a predetermined threshold in ice concentration is frequently applied. It is important to underline that the processing steps to generate the ice concentration maps might change depending on the sensors/input data; as an example, using AMSR-E data, the sea ice concentration maps can be retrieved compensating for atmospheric correction. Further, along the coast a land spillover correction is generally applied to refine the product. In the case of other sensors, calibration, as well as atmospheric compensation, stands out as the pivotal and pertinent processing steps essential for generating the ice concentration product.

INPUT DATA SOURCE	SAR data and microwave radiometer. Harmonized data products also exist blending multiple sensors. e.g., SENTINEL-1 SAR EW mode dual-polarized HH/HV data combined with AMSR2 radiometer data.
SPATIAL RESOLUTION AND COVERAGE	1 to 6 km Baltic and Arctic
ACCURACY / CONSTRAINS	The uncertainties in the retrievals are largest in summer, because melt ponds are difficult to distinguish from open water and generally the techniques cannot see thin ice (which does not mask the microwave emission of the underlying ocean) or ice concentrations greater than 90% (owing to spatial and temporal variability in the overlying snow characteristics). Overall, an uncertainty of one million square kilometres (20% error in summer and 7% error in winter) might be expected for a measurement of total Arctic ice area (Metoffice, 2023). All SIC products have some limitations and uncertainties (Spreen & Kern, 2017), but overall, the trends agree well (Comiso et al., 2017).
LIMITATIONS	The observations have a spatial coverage limitation/'hole' north of 87 degrees, where satellites are unable to take measurements, because of the nature of their orbits. However, this limitation can be overcome using - in case of SAR -extended range incidence angle, allowing to increase the coverage capability. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.
TEMPORAL RESOLUTION/	Data is available from 1979 to ongoing at a variety of spatial and temporal resolution. Various products with various frequency, including hourly, daily mean.
UPDATE FREQUENCY	Various products with various frequency, including daily, monthly, yearly, twice yearly
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4
ACCESSIBILITY	Information products are available from Met office, DMI, MetNO, Copernicus Marine Service and Artic hub. and commercial providers.

4.7.2 Ice thickness

Sea ice thickness combined with sea ice concentration (see Section Ice concentration 4.7.1) provides an estimate of ice volume (described as the amount of space occupied by ice in a three-dimensional unit). Although sea ice floats over the ocean, part of the sea ice can be found under the water. The depth of sea ice below the surface of the ocean is known as the 'draft', while the depth of ice above the waterline is known as the 'freeboard'. On average approximately 1/9th of the sea ice is above the waterline and 8/9ths below although the exact amount depends on the buoyancy of the ocean below (Metoffice, 2023). The sea ice thickness is the sum of the freeboard and the draft. Only the freeboard ice may be measured by several platforms (e.g., airborne, satellite) and the draft from submersible and sonar, therefore the sea ice thickness derived by satellite altimeters refers to measurements of the sea ice freeboard, which is the difference between the height of the surface of sea ice and the surface of water in open leads (areas of open water within the sea ice). The snow on top of sea ice changes this ratio and complicates the estimation of the ice thickness, requiring the use of auxiliary information about snow depth and density. The retrieval of ice thickness uses the narrow radar swath at the nadir of the satellite at full resolution of approximately 1-10 km and a point spacing of 300 meters. The requirement to correct measurements for the snow depth introduces uncertainty into the measurement of sea ice freeboard. As freeboard is approximately 1/9th of the total sea ice thickness (freeboard plus draft), the described uncertainty can lead to larger impacts to navigation, as. sea ice with a thickness of 2-3 m can only be penetrated by ice-strengthened vessels or icebreakers with a sufficient ice class. Most ships and fishing vessels are not ice-strengthened and must therefore avoid all ice areas.

Table 7 EO driven intelligence providing information on ice thickness.

SPECIFICATIONS	
BUSINESS PROCESS	SD, SC, SCE, IN, SO
DESCRIPTION	Ice thickness refers to the distance between the top surface of a body of ice and the underlying water
EO INFORMATION OF INTEREST	Sea Ice Thickness (SIT)
MAIN PROCESS STEPS	Satellites equipped with altimeters use laser beams to measure the height of the ice surface above the underlying surface. By subtracting the known elevation of the land or water beneath the ice, ice thickness is retrieved. Assumptions are made to remove influence of snow cover.
INPUT DATA SOURCE	Altimeter data, snow cover thickness and density information
SPATIAL RESOLUTION AND COVERAGE	25-111km
ACCURACY / CONSTRAINS	The requirement to correct measurements for the snow depth introduces uncertainty into the measurement of sea ice freeboard.
LIMITATIONS	The snow on top of sea ice complicates the estimation of the ice thickness, requiring the use of auxiliary information about snow depth and density. Once retrieved the emerged portion of ice and assuming that is 1/9th of the submerged part, it can be estimated the total volume of the ice. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.

TEMPORAL RESOLUTION	Available from 1981 to ongoing at a variety of spatial and temporal resolution (weekly mean, monthly mean).
FREQUENCY UPDATE	Daily, yearly
DELIVERY / OUTPUT FORMAT	NetCDF, PNG, ASCII, XML
ACCESSIBILITY	Copernicus Marine Service, Artic hub, NSIDC DAAC

4.7.3 Ice stage development information

Sea ice moves through several stages developing in different types of ice depending on time and environmental conditions. The variety of ice types/developments can vary in how being classified. For example, the Australian Government (2017) defines as developments the following ice types: 1. new ice, 2. nilas, 3. pankcake ice, 4. young ice, 5. old ice. While the National Snow and Ice data Center defines each stage of sea ice developments as new ice, nilas, young ice, and multiyear ice (National Snow and Ice Data Center, n.d.). A classification of sea ice stage development is used for operational purposes using the age of the ice as a proxy for its thickness, see sea ice nomenclature (Norwegian Metrological Institute, n.d.).

The ice charts showing ice type are high-resolution routine products based on variety of satellite data sources, primarily SAR and optical sensors and provide sea ice concentration as well as delineating areas of fast ice.

Identifying sea ice concentration and type from SAR data remains challenging due to many-to-one scenarios, where different sea ice geophysical properties have the potential to appear with the same SAR backscatter, or to the same combination of polarimetric backscatter in the different SAR bands (C-, X- and S-band). Automated processes that apply machine learning techniques to large datasets including multiple sensors and frequencies could improve the retrieval of ice type by solving the response signatures ambiguities (Kruk et al., 2020; Wakabayashi et al., 2004). For instance, a recent method based on quad-pol Gaofen-3 (C-band) discriminates the characterization of a variety of ice types/developments, such as open water (OW), New ice (NI), Young Ice (YI), and First Year Ice (FYI), with an overall accuracy of over 90% (Yang et al., 2023).

Table 8 EO driven intelligence providing information on ice stage development.

SPECIFICATIONS	
BUSINESS PROCESS	SD, SC, SCE, IN, SO
DESCRIPTION	Sea ice moves through several stages developing in different types of ice depending on time and environmental conditions. A classification of sea ice stage development is used for operational purposes using the age of the ice as a proxy for its thickness. Specific

	terms such as new ice, nilas, young ice, and multiyear ice are used in the shipping sector for each stage of sea ice development.
EO INFORMATION OF INTEREST	Detection of categories of sea ice developments/types, including open water, first year ice, multiple year ice, ambiguously, unclassified ice.
MAIN PROCESS STEPS	Raw satellite data undergo preprocessing to correct for atmospheric effects, sensor noise, and geometric distortions. Calibration ensures that measurements are accurate and consistent. Satellite SAR data play a crucial role in sea ice classification, algorithms classify ice types (e.g., multiyear ice, first-year ice, open water) based on backscatter properties of polarimetric SAR signature (also using neural networks). Sea ice classification can be also retrieved based on analysis of emissivity spectra from microwave sensors.
INPUT DATA SOURCE	RADARSAT-2 and RADARSAT (Canada), Sentinel-1A and -1B (EU), Gaofen-3 (China), AMSR2 and ERA 5
SPATIAL RESOLUTION AND COVERAGE	RADARSAT and Sentinel-1 spatial resolution below 100 m ground resolution and regional coverage (e.g., up to 500 km by 500 km); Gaofen 3 Stripmap I (QPSI) with 30 km ground swath and 8 m nominal resolution. To summarize, the final resolution ranges between 8 and 100 meters, while the swath extent ranges between 30 km up to 500 km.
ACCURACY / CONSTRAINS	Accuracy varies based on sensor type, resolution, algorithms, and validation efforts. Researchers continually refine methods to enhance accuracy. Tests of Gaofen-3 (C-band) SAR report accuracy > 0.90 for open water (OW), new ice (NI), young ice (YI), and first-year ice (FYI).
LIMITATIONS	Currently limited to few categories (open water, new ice, and first-year ice, multiple years ice). The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.
TEMPORAL RESOLUTION	Daily for opensource data, more images per day using commercial satellite e.g. SAR image 1 per day (Sentinel-1), more images per day under request (RADARSAT, Gaofen-3)
FREQUENCY UPDATE	Sea ice classes updated on weekly (or longer) intervals
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4
ACCESSIBILITY	Copernicus Maritime Service and Artic hub and other commercial satellite data providers

4.7.4 Long term statistics of ice condition

Long term statistics of ice conditions for shipping are useful for assessing the feasibility, safety, and efficiency of different shipping routes in the Arctic and other ice-covered regions. From 1979 to 2023, Arctic Sea ice shrank by 32,000km^2 every year in winter (March) and by 74,000 km^2 every year in summer (September). Summer sea ice lost about 12.8% of its area per decade. Since 2007, every summer had less sea ice than any year before 1979, when satellites started measuring. Arctic sea ice also became much thinner and younger, as more ice melted in summer and less ice grew into thicker, multi-year floes. In the mid-1980s, old ice that was four years or older covered one third of the total ice area in March, but since 2011, old ice only covered 5% (European Enviroment Agency, 2023; Min et al., 2022; National Snow and Ice Data Center, 2024).

Table 9 EO driven intelligence providing long term statistics of ice condition.

SPECIFICATIONS	
BUSINESS PROCESS	SD, SC, SCE, IN, SO
DESCRIPTION	Long-term statistics refer to the analysis of data over an extended period (longer than 5 years). Data for long-term statistics are collected at regular intervals or continuously over the specified time range.
EO INFORMATION OF INTEREST	Iceberg tracking (ICBG), sea ice concentration (SIC), and thickness (SIT)
MAIN PROCESS STEPS	Observations of Arctic Sea ice are available from the EUMETSAT OSI SAF reanalysis, in which a consistent time series of daily, gridded data for sea ice concentration is made from the passive microwave sensors SMMR and SSM/I data. Ice extent for the winters of 1720-1940 is based on a construction from various sources, including observations at lighthouses, old newspapers, records of travel on ice, scientific articles, and air temperature data from Stockholm and Helsinki. Data for 1945-1995 stems from the Finnish operational ice service. Data since 1995 are based on satellite observations.
INPUT DATA SOURCE	AMSR-2 or other radiometers satellite data due to the requirement of long time series.
SPATIAL RESOLUTION AND COVERAGE	SIC Global: 1979-ongoing, 25x25km - 6km (Finer resolution is available for the Artic from 2019 to the present at 1km and for the Baltic area from 1982 to the present at 2km)
	ICBG Artic: 2003 – 2023, 10km

	SIT Baltic:1981 – 2022,1km Artic: 2002 – 2015, 111km
	SIE Artic: NA Baltic:1981 – 2022, 1km
ACCURACY / CONSTRAINS	See description of variables in the relevant information sheet
LIMITATIONS	See variables information sheet. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.
TEMPORAL RESOLUTION	Daily
FREQUENCY UPDATE	Daily, Yearly, Twice Yearly
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4
ACCESSIBILITY	MetNO, Copernicus Maritime service and Artic hub, Monthly aggregated sea ice products are provided by the EUMETSAT OSI SAF.

4.7.5 Detection of ice leads

Sea ice consists of blocks of frozen seawater known as "floes", which are always in motion pushed along by winds and ocean currents. Sea ice floes range in size between 10 m and 5 km wide and are of the order of 0.5 to 5 m thick. Areas of open water between ice floes are called "leads". Snowfall remains on the floes all year round and over winter can get to 10-20 cm deep. Sea ice floes can freeze together and can be broken by collisions or ocean waves. Depending on the time of year and the location, ice floes may float independently from each other or be squashed together to form an almost continuous pack ice cover permeated by cracks and ridges of thicker ice (Australian Government, 2017). The detection of ice leads by satellite is an important capability for monitoring and navigating through ice-covered waters, particularly in polar regions. Various satellite sensors and technologies are used to detect and track ice leads.

Table 10 EO driven intelligence providing information on detection of ice leads.

SPECIFICATIONS	
BUSINESS PROCESS	SO
DESCRIPTION	Detection of leads, defined as openings or channels in sea ice
EO INFORMATION OF INTEREST	Polygons defining openings or channels in sea ice.

MAIN PROCESS STEPS	Leads are detected as areas of open water between ice floes using a variety of sensors: 1. dark linear features in SAR imagery often correspond to ice leads. SAR backscattering values of open water and sea ice are used for classification, and leads are detected as open water areas within the sea ice. Empirical schemes can be used to retrieve leads employing different assumptions and corrections to account for differing surface conditions. 2. Variation in thermal data highlights the presence of leads. 3. Variation in altimeter data showing leads, where the sea surface is lower due to the absence of ice. 4. Ice concentration maps providing information about the spatial distribution of sea ice. Ice leads, being areas with lower ice concentration, can be identified on these maps as regions with reduced ice cover. Leads detection, as for the sea ice fraction, requires calibration using observations of an open ocean location and one which is thought to be 100% ice covered for all the sensors.
INPUT DATA SOURCE	Mostly used X-, C- and S-band SAR data; in case of strong wind, cross-polarized bands (as HV in Sentinel-1 SAR EW mode) support HH or VV bands (see limitations). IST (Ice Surface Temperature) from MODIS and other satellites providing thermal bands.
SPATIAL RESOLUTION AND COVERAGE	Spatial resolution 1-6km (2 to 5 times lower than the original SAR, as the processing requires some sort of data aggregation); same coverage of the original SAR.
ACCURACY / CONSTRAINS	The calibration of open water and sea ice backscatter thresholds is difficult in case of strong wind.
LIMITATIONS	In case of weak wind, leads detection is easy using HH or VV bands. With strong wind, cross-polarized SAR bands, more noisy but less sensitive to rough sea, support the detection. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.
TEMPORAL RESOLUTION	Daily, Monthly, Yearly, twice yearly
FREQUENCY UPDATE	Daily (Sentinel-1A)
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4, geo-located raster and shape formats
ACCESSIBILITY	Copernicus Maritime and Artic hub, other commercial data satellite providers.

4.7.6 Detection of polynyas in ice

Coastal polynyas, which can be found year-round near the Arctic coasts, are formed through the action of katabatic winds, which act to drive ice away from a fixed boundary such as a coastline, fast ice, or an ice bridge. It's important to note that while polynyas offer advantages for shipping, their presence and characteristics can change due to various factors, including climate change, weather conditions, and seasonal variations. Therefore, the shipping industry must continuously monitor and adapt to these dynamic conditions to ensure safe and efficient operations in polar regions.

Table 11 EO driven intelligence providing information on detection of polynyas in ice

SPECIFICATIONS	
BUSINESS PROCESS	SO
DESCRIPTION	Polynyas are areas of open water or thin ice surrounded by sea ice. Polynyas can provide open water routes through sea ice, making navigation more efficient and less risky for ships. This is especially crucial in polar regions where sea ice can be extensive.
EO INFORMATION OF INTEREST	Polygons defining areas of open water or thin ice surrounded by sea ice.
MAIN PROCESS STEPS	Polynya detection (as sea ice fraction and leads detection) is based on the identification of open water areas forming near the coast. Polynyas presence can be captured: 1- from maps that depict the concentration of sea ice (SIC). Polynyas are areas of open water within the ice, will appear as regions with lower ice concentration. 2- from thermal data/imagery showing different characteristics than surrounding ice-covered regions 3- from SAR imageries appearing as dark areas due to lower ice concentration 4- from altimeter providing information of ice thickness. Polynya detection requires calibration using observations of an open ocean location and one which is thought to be 100% ice covered. Considering the extension of the polynya area (larger than leads) thermal data (even though affected by clouds) can be also used, as the polynya signature of open water is considerably warmer than the surrounding sea ice.
INPUT DATA SOURCE	X-, C- and S-band SAR data; with strong wind cross-polarized bands (as HV in Sentinel-1 SAR EW mode) support HH or VV bands (see limitations); IST (Ice Surface Temperature) from MODIS and other satellites providing thermal bands.
SPATIAL RESOLUTION AND COVERAGE	Spatial resolution 1-6 km (2 to 5 times lower than the original SAR, as processing requires some sort of data aggregation) and same coverage of the original SAR; around 1 km per pixel for IST products (geometric resolution is depending on the available data, ranging between 20 to 100 meters).

ACCURACY / CONSTRAINS	No specific constraints: under strong wind the polynya area can be characterized by Langmuir stripes, i.e. along-wind stripes where frazil ice accumulates.
LIMITATIONS	No specific limitation for SAR based detection; cloud coverage for IST products. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.
TEMPORAL RESOLUTION	From daily to weekly temporal monitoring.
FREQUENCY UPDATE	Any time a SAR image is available; daily for IST products
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4, geo-located raster and shape formats
ACCESSIBILITY	Copernicus Marine Service and Artic hub, IST products from National Snow & Ice Data Center, Colorado, U.S.

4.7.7 Ice drift monitoring and forecast.

Forecasting ice drift involves predicting the movement and displacement of sea ice over a specific period. Ice drift forecasts are typically based on a combination of observational data, numerical models, and meteorological information. Key components involved in forecasting ice drift include:

1. Satellite observations, including Synthetic Aperture Radar (SAR), microwave and optical imagery, provide real-time and historical information about ice conditions, data needed to initialize and validate ice drift models.
2. Meteorological data, such as wind and atmospheric pressure, are critical inputs for ice drift forecasting. Wind forces exert a significant influence on the movement of sea ice, and accurate meteorological information is essential for modelling ice drift.
3. Numerical models, simulate the dynamics of sea ice based on physical principles, considering factors such as wind forcing, ice thickness, ocean currents, and the geometry of the ice pack. Models more commonly used include TOPAZ5 and neXtSIM.
    a. TOPAZ5 is operated by MET Norway and distributed to the Copernicus Marine Services. Recently TOPAZ4 has been updated to TOPAZ5, the upgrade of the sea ice model includes five categories of sea ice thickness among other changes of the model system. The forecast system uses however the same ensemble Kalman Filter for data assimilation as before.
    b. The Copernicus Marine Services also offer a stand-alone sea ice model with the recent sea ice model neXtSIM, which shows a more realistic picture of the deformation features of the sea ice than the standard sea ice models (Sievers et al., 2022). The neXtSIM forecasts have also been upgraded in 2023 to include the assimilation of sea ice thickness in the winter and the concentration of young ice, which is navigable for ships of high ice class. neXtSIM forecasts are operated by NERSC.
4. Data assimilation involves integrating observational data into numerical models to improve their accuracy. Assimilating satellite-derived ice concentration, thickness, and drift observations helps correct model errors and enhance the reliability of forecasts.

5. Ensemble forecasting involves running multiple simulations with slightly different initial conditions to account for uncertainties in the model and input data. This approach provides a range of possible outcomes, allowing for a more comprehensive assessment of forecast uncertainty.

Table 12 EO driven intelligence providing information on ice drift monitoring and forecast.

SPECIFICATIONS

BUSINESS PROCESS	SC, SO
DESCRIPTION	Monitoring and forecasting ice drift involves predicting the movement and displacement of sea ice over a specific period
EO INFORMATION OF INTEREST	SIC, SIT, SITYPE, SIUV
MAIN PROCESS STEPS	Models: Ocean forecast, and analysis data produced by a coupled numerical ocean-ice model with data assimilation: Observations: The products are based on SAR images and are produced on pass-by-pass basis during the Baltic Sea ice season and show the ice thickness and drift in a 500 m and 800m grid, respectively. The Baltic Sea ice concentration product is based on data from SAR and microwave radiometer. The algorithm uses Sentinel-1 SAR EW mode dual-polarized HH/HV data combined with AMSR2 radiometer data.
INPUT DATA SOURCE	SAR, Microwave, Optical satellite data, weather data
SPATIAL RESOLUTION AND COVERAGE	Artic observations: 62.5km from 1991-2023, 31 x 31.km (1999-ongoing) Artic/Baltic model: 3x3 km. – 12 km Lat 52.6° to 90°Lon -180° to 179.96 (1991 – ongoing) Baltic Observations: 0.5x0.5 km Baltic Sea Lat 53° to 66°Lon 9° to 31°(2019-ongoing)
ACCURACY / CONSTRAINS	Not specified
LIMITATIONS	Limited availability of ground truth. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.
TEMPORAL RESOLUTION	Satellite: hourly (strongly depending on the native input data) Models: to be set

FREQUENCY UPDATE	Models: Daily – Following day at 9:30 UTC; Second day of the following month at 12:00Monthly Observations: Daily – within 04:00 hours Between Jan and Apr, dependent on the availability of X-band SAR data
DELIVERY / OUTPUT FORMAT	NetCDF-4
ACCESSIBILITY	Copernicus Marine Services and Artic hub, MetNo, NERSC

4.7.8 Ice edge information

The ice edge is the boundary at any given time between open water and sea, whether drifting or fast; may be termed compacted when it is clear-cut, or open when it forms the indefinite edge of an area of dispersed ice (NSIDC definition).

Table 13 EO driven intelligence providing information on ice edge.

SPECIFICATIONS	
BUSINESS PROCESS	SD, SC, IN, SO
DESCRIPTION	The ice edge is the boundary at any given time between open water and sea ice.
EO INFORMATION OF INTEREST	Detection of the boundaries between water and sea ice.
MAIN PROCESS STEPS	Ice edge detection requires calibration using observations of an open ocean location and one which is thought to be 100% ice covered. SAR backscattering values of open water and sea ice are then used for classification. Empirical schemes employing different assumptions and corrections can be used to account for differing surface conditions.
INPUT DATA SOURCE	X-, C- and S-band SAR data; with strong wind, cross-polarized bands (as HV in Sentinel-1 SAR EW mode) support HH or VV bands (see limitations).
SPATIAL RESOLUTION AND COVERAGE	Spatial resolution 1-6km (2 to 5 times lower than the original SAR, as processing requires some sort of data aggregation) and same coverage of the original SAR.
ACCURACY / CONSTRAINS	The calibration of open water and sea ice backscatter thresholds is difficult in case of strong wind
LIMITATIONS	With weak wind, ice edge detection is easy using HH or VV bands. With strong wind, cross-polarized SAR bands, more noisy but less sensitive to rough sea, support the detection. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.

TEMPORAL RESOLUTION	Similar to SIC. Various products with various frequency, including hourly, daily mean
FREQUENCY UPDATE	Any time a new SAR image is available
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4, geo-located raster and shape formats
ACCESSIBILITY	Same as for SIC products

4.7.9 Information on ice field compression and divergence

Sea ice is susceptible to tension forces and compression occurs when ice is pushed together by converging winds or currents. Sea ice pressure can lead to ship besetting and damages (Lemieux et al., 2020) and poses great risk for navigation. Some of the areas where ice compression occurs can be estimated based on ice deformation indicators based on SAR ice motion, and these indicators are very useful in the validation of ice models trying to forecast ice compression for ice navigation (Karvonen, 2012).

The estimate (and forecast) of compression and divergence of the ice field is currently based on outputs of sea ice forecasting systems. The 'true' ice drift, obtained tracking the ice features from a SAR image to another, would be very useful to drive the model outputs, but overlapping SAR images are currently acquired at too long time intervals – several hours in the best case – which does not allow to estimate the drift at high spatial resolution, a necessary condition to estimate convergence and divergence of the drift field.

SPECIFICATIONS	
BUSINESS PROCESS	SD, IN, SO
DESCRIPTION	Sea ice compression / divergence estimated by modelled sea ice drift.
EO INFORMATION OF INTEREST	Sea ice x velocity (SIUV), Sea ice y velocity (SIUV)
MAIN PROCESS STEPS	Calculation of convergence/divergence of the sea ice drift, geo-spatial data filtering
INPUT DATA SOURCE	Outputs from the neXtSIM sea ice model
SPATIAL RESOLUTION AND COVERAGE	Ice drift available on the 3 x 3km grid over the Arctic Ocean, grid of convergence/divergence to be defined
ACCURACY / CONSTRAINS	Not available
LIMITATIONS	Limited availability of ground truth. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.

TEMPORAL RESOLUTION	Hourly
FREQUENCY UPDATE	Daily (output of the neXtSIM sea ice model)
DELIVERY / OUTPUT FORMAT	To be defined (raster, shapefiles, NETCDF)
ACCESSIBILITY	Copernicus marine Service and Artic hub (Ice drift datasets)

4.7.10 Identify ice ridges and deformed ice

Ridges form when sea ice is deforming and fracturing due to forces from winds and currents. Ridges are elongated accumulations of broken ice resulting from deformation of sea ice. Rafting is another form of deformed ice occurring when one ice sheet overrides another ice sheet. Ridging and corresponding ice keels represent the thickest part of the sea ice cover. Detection and monitoring of ridges is therefore an important part of met-ice-ocean services to support operations in ice-covered seas. On large scale ridges can be observed by laser and radar altimeter data through a surface roughness parameter that is defined by standard deviation of the surface elevation measurements along the satellite orbit (as ICESAT laser altimeter). On regional and local scale, SAR images have been used for ridge detection and sea ice processes in the Baltic Sea, the Barents Sea and Svalbard area, in the Russian Arctic and in Canadian waters. SAR image cannot provide any quantitative estimate of the height of ridges. Use of SAR images with alternating polarization and high spatial resolution (better than 10 m) is expected to improve the classification of rough ice and detection of ridges.

SPECIFICATIONS

BUSINESS PROCESS	SD, SC, IN
DESCRIPTION	Ice ridges refer to elongated and elevated formations of ice that develop in ice-covered seas. These ridges are typically created through the interaction of drifting sea ice and external forces such as wind, currents, and collisions between ice floes.
EO INFORMATION OF INTEREST	Wind and current velocity components (u, v) deforming and fracturing ice drift fields, SIT
MAIN PROCESS STEPS	Sea ice deformation derived from models
INPUT DATA SOURCE	SAR and in situ measurements used for assimilation/validation
SPATIAL RESOLUTION AND COVERAGE	Coverage of the model domain (an enclosed sea, a bay), spatial resolution based on the model grid
ACCURACY / CONSTRAINS	Not specified

LIMITATIONS	Limited availability of ground truth. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.
TEMPORAL RESOLUTION	Same as SIUV
FREQUENCY UPDATE	Very high (model time-steps) from hourly to days
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4, Raster (geo-located) and shape formats
ACCESSIBILITY	Copernicus marine service and Artic hub

4.7.11 Iceberg and bergy bit information

An iceberg is a large piece of freshwater ice that has broken off from a glacier or an ice shelf and is floating freely in open water. The visible portion of an iceberg is typically only a small fraction of its total size, with about 90% of its mass submerged underwater. Icebergs can vary in size. A bergy bit is a medium to large fragment of ice, growlers are smaller fragments of ice.

Icebergs can be detected using a variety of technology, including optical, SAR, thermal infrared imaging. A combination of information from different sensors and iceberg drift models can enhance the accuracy of iceberg detection. In the specific, DMI has implemented improvements to the near-real-time iceberg detection system to make it more accurate and reliable, addressing:

- ships being mistaken for icebergs:

DMI now combines real-time AIS ship tracking data with satellite radar imagery. By matching the ship positions with the satellite data, false iceberg targets, that are actually ships, are removed.

Sea-ice floes near the sea-ice edge being incorrectly identified as icebergs: a new filtering process has been introduced using Automated Sea Ice Products (ASIP). These products are derived from the same satellite radar scenes as the iceberg detection, ensuring accurate alignment in both time and space.

These improvements significantly enhance the accuracy of a iceberg detection system, reducing false detections and providing users with more reliable information about real icebergs, see ACCIBERG(n.d.).

Further, it has to be highlighted that the multi polarization approach – i.e. the usage of a time series of QUAD Pol SAR data – should support the detection and distinction of icebergs and ships.

SPECIFICATIONS

BUSINESS PROCESS	IN, SO
DESCRIPTION	Icebergs are large masses of freshwater ice that have broken off from glaciers or ice shelves and are floating freely in open water. Icebergs can vary widely in size, shape, and height.

EO INFORMATION OF INTEREST	Detection of icebergs
MAIN PROCESS STEPS	The iceberg concentration is derived by applying a Constant False Alarm Rate (CFAR) algorithm on data from Synthetic Aperture Radar (SAR) satellite sensors.
INPUT DATA SOURCE	SAR imagery (e.g. Sentinel-1, EW and IW mode and mosaic for the two modes)
SPATIAL RESOLUTION AND COVERAGE	10x10km Coverage of the model domain (an enclosed sea, a bay)
ACCURACY / CONSTRAINS	Generic and automated product. Expertise is needed to be correctly used.
LIMITATIONS	Limited availability of ground truth. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.
TEMPORAL RESOLUTION	Irregular, weekly
FREQUENCY UPDATE	Irregular, daily at any new SAR overpass
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4, and esri shapefiles.
ACCESSIBILITY	Copernicus Maritime service and Artic hub

4.7.12 Ice season length

Sea ice opening, retreat, advance, and closing are identified from the time series of daily sea ice concentration maps (SIC). Due to the large area to be monitored, the data used for these estimates comes from SICs estimates by satellite passive-microwave data (as from SMMR, SSM/I and SSMIS) available at the NOAA/NSIDC SIC climate data record (CDR) and SICs estimates by models, as the ARCTIC_ANALYSIS FORECAST PHY_ICE_002_011 product available at the Copernicus Marine Service (see the SIC section of this document). Previous studies used SICs at 25 km resolution from MW radiometers produced by the NASA Team and Bootstrap algorithms (Bliss et al., 2019; Parkinson, 2014). The extraction of the Ice Season Length requires some geo-spatial processing in agreement with the standard adopted in previous literature.

SPECIFICATIONS

BUSINESS PROCESS	SD, SC, IN
DESCRIPTION	Ice sea season length is the duration/ period in which icy or freezing conditions lead to the formation and persistent sea ice cover.
EO INFORMATION OF INTEREST	Sea Ice Concentration from satellite microwave passive radiometers data
MAIN PROCESS STEPS	Sea ice concentration is computed from atmospherically corrected brightness temperatures, using a combination of state-of-the-art algorithms and dynamic tie points. It includes error bars for each grid cell (uncertainties).
INPUT DATA SOURCE	SMMR, SSM/I and SSMIS passive microwave sensors
SPATIAL RESOLUTION AND COVERAGE	25 km x 25 km grid over north and south Polar Regions (above 31°N and below 39°S)
ACCURACY / CONSTRAINS	Not specified
LIMITATIONS	Not specified. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.
TEMPORAL RESOLUTION	from 1978 – present, daily and monthly products
FREQUENCY UPDATE	Preliminary data updated daily, final data updated annually
DELIVERY / OUTPUT FORMAT	NetCDF
ACCESSIBILITY	NOAA, Copernicus marine service and Artic hub

4.7.13 Fast ice

Fast ice, also known as land-fast ice, is a type of sea ice that is anchored to the coastline, the sea floor along shoals, or grounded icebergs, Australian Government(2017) and National Snow and Ice Data Center(n.d)

The edge and extension of fast ice is relevant for arctic navigation and regional environmental studies. Methods for fast ice delineation from SAR imagery are based on the results of drifting analysis, i.e. fast ice is the part of the sea ice which does not drift away under the wind and sea current action. The longer the time interval between the SAR scenes, more accurate is the detection of fast ice (the ice drift error is inversely proportional to the time interval).

SPECIFICATIONS

BUSINESS PROCESS	SD, IN, SO

DESCRIPTION	Fast ice is defined by the fact that it does not move with the winds or currents.
EO INFORMATION OF INTEREST	Sea ice detection and drifting analysis
MAIN PROCESS STEPS	Fast ice can be detected by two SAR images over the same area, better if acquired at long time intervals, or accessing CMEMS products listed below
INPUT DATA SOURCE	X-, C- and S-band SAR data; better using VV or HH polarization, where ice features are more evident.
SPATIAL RESOLUTION AND COVERAGE	Coverage limited to the overlapping area of the two SAR images, spatial resolution up to 10 times the original SAR resolution (some data aggregations are used). Spatial resolution of the final product is depending on the input data, ranging between tens of meters and hundreds of meters.
CCURACY / CONSTRAINS	Fast ice mapping requires an accurate land mask
LIMITATIONS	The main limitation is in the generation of an accurate coast land mask. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.
TEMPORAL RESOLUTION	Monthly at least, it has to highlight that long time interval acquisitions are better support the detection.
FREQUENCY UPDATE	Maps can be updated any time a new SAR image is acquired
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4
ACCESSIBILITY	Copernicus marine service and Artic hub

4.8 Snow on ice

Current estimates of sea ice thickness and volume trends are affected by the variability of sea ice and snow densities (Kurtz & Markus, 2012). Snow detection over ice can be made by passive microwave sensors, as AMSR-E (Tonboe et al., 2011), CryoSat-2, and the Sentinel-3 altimeters (Nab et al., 2023). The scarcity of 'in situ' data for retrieval validation represents a limitation.

Snow on sea ice can be estimated by models. First estimates of the depth and density of snow on sea ice across the Arctic Ocean were made by daily runs of the low spatial resolution (100 km) NASA Eulerian Snow On Sea Ice Model (NESOSIM), that includes two (vertical) snow layers and several simple parameterizations (accumulation, wind packing, advection–divergence, blowing snow lost to leads) to represent key sources and sinks of snow on sea ice (Petty et al., 2018). Today, Copernicus Marine Service provides Sea ice thickness (SIT) and Surface snow thickness (SNOW) as outputs of two models, such a TOPAZ5 and neXtSIM:

The operational TOPAZ5 Arctic Ocean system uses the HYCOM model and a 100-member EnKF assimilation scheme. It is run daily to provide 10 days of forecast (average of 10 members) of the 3D physical ocean, including sea ice; data assimilation is performed weekly to provide 7 days of analysis (ensemble average). Output products are interpolated on a grid of 12.5 km resolution at the North Pole (equivalent to 1/8 deg at mid-latitudes) on a polar stereographic projection.

The Arctic Sea Ice Analysis and Forecast system uses the neXtSIM stand-alone sea ice model running the Brittle-Bingham-Maxwell sea ice rheology on an adaptive triangular mesh of 10 km average cell length. The model domain covers the whole Arctic domain, including the Canadian Archipelago, the Baffin and Hudson Bays. neXtSIM is forced with surface atmosphere forcing from the European Centre for Medium-Range Weather Forecasts (ECMWF) and ocean forcing from TOPAZ5, the ARC MFC PHY NRT system (002_001a). neXtSIM runs daily, assimilating OSI-SAF sea ice concentrations (both SSMI and AMSR2) from the SI TAC combined with manual ice charts and providing 7-day forecasts. The output variables are the ice concentrations, ice thickness, ice drift velocity, snow depths, sea ice type, ridge area fraction and albedo, provided at hourly frequency. The adaptive Lagrangian mesh is interpolated for convenience on a 3 km resolution regular grid in a Polar Stereographic projection.

SPECIFICATIONS

BUSINESS PROCESS	IN, SO
DESCRIPTION	Snow thickness refers to the depth or height of a layer of snow covering an ice sheet
EO INFORMATION OF INTEREST	Sea ice thickness (SIT) and Surface snow thickness (SNOW)
MAIN PROCESS STEPS	Assimilation of OSI-SAF sea ice concentrations (both SSMI and AMSR2) combined with manual ice charts
INPUT DATA SOURCE	Assimilation of Sea Ice Concentration and/or Thickness
SPATIAL RESOLUTION AND COVERAGE	3 × 3 km/12x12km, Arctic Ocean from Lat 52.6° to 90°; Lon -180° to 179.96°
ACCURACY / CONSTRAINS	Not specified
LIMITATIONS	Not specified. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.
TEMPORAL RESOLUTION	Daily, 1-week forecasts. Products available from 1 Aug 2019 to 1 Sep 2023
FREQUENCY UPDATE	Daily
DELIVERY / OUTPUT FORMAT	NetCDF-4

ACCESSIBILITY	Copernicus marine service

4.9 Sea Surface Temperature

Several satellite instruments are used to measure sea surface temperature (SST) with high accuracy based on the principles of infrared radiation, which is emitted by the Earth's surface, including the ocean. Table 1 shows some satellite instruments for measuring SST.

SPECIFICATIONS

BUSINESS PROCESS	SCE
DESCRIPTION	Sea surface temperature (SST) is a measurement of the ocean's temperature close to the surface
EO INFORMATION OF INTEREST	Sea surface temperature (SST) details the sea temperature between the depths of from approximately 10 µm below the surface (infrared bands) to 1mm (microwave bands) depths using radiometers.
MAIN PROCESS STEPS	Data is gathered from different satellites, Metop-A, VIIRS_NPP, NOAA 20 and Sentinel A and B. SST data is corrected for bias and then processed through optimal interpolation creating temperature maps. Temperatures data is validated using both drifting and moored in situ buoys. Data which contains clouds or more than 70% ice is discarded.
INPUT DATA SOURCE	Infrared data from AVHRR on Metop-A, VIIRS_NPP, and NOAA 20. SLSTR data from Sentinel 3 A and B
SPATIAL RESOLUTION AND COVERAGE	Arctic: 6km from 1982-ongoing Baltic: 2km from 1982-ongoing] 4-9km day and night capability VIIRS and MODIS from 2002 - ongoing
ACCURACY / CONSTRAINS	The cloud cover makes measurement and consequently the generation of the product impossible
LIMITATIONS	Cloud cover. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.

TEMPORAL RESOLUTION/	Various products with various frequency, including hourly, daily mean and monthly
UPDATE FREQUENCY	Various products with various frequency, including daily-monthly-yearly- twice yearly
DELIVERY / OUTPUT FORMAT	NetCDF-3
ACCESSIBILITY	Copernicus marine service, NASA LAADS DAAC

4.10 Wind speed and direction monitoring

Two types of microwave instruments measure ocean surface winds, the passive microwave radiometer and the active microwave scatterometer (Remote Sensing Systems, n.d.) :

- **Radiometer** measures ocean surface roughness, which correlates to wind speeds at 10 meters above the water's surface. Radiometers can only retrieve wind speeds, except for the polarimetric radiometer WindSat, that can measure both wind speed and wind direction**.**
- **Scatterometer** sends a signal to the Earth's surface, which reflects off the ocean Bragg waves (these are wind generated surface ripples—capillary waves) on the surface of the larger scale ocean waves. The reflected energy measured by the scatterometer is translated using a geophysical model function into a 10 meter neutral wind speed and direction. Scatterometers typically operate at either C-band (~5GHz frequency) or Ku-band (~14 GHz frequency). With special processing techniques, it can only be obtained wind speeds and directions every 12 km over the oceans. Scatterometers can also be used to measure sea ice and land ice characteristics. The scatterometers that have been in operation longer than a brief period are ERS-2 (C-band), QuikScat (Ku-band), and ASCAT (C-band) and scientists are working on merging these long-term wind vectors into a product for climate study. e.g., the ccmp product (Remote Sensing Systems, n.d.). In 2003, both a radiometer (AMSR) and scatterometer (SeaWinds) were flown on the Midori-2 satellite.

Wind speeds from these two instruments showed excellent agreement in rain-free conditions. Sensors, that operate at microwave frequencies, can make measurements day and night and under nearly all-weather conditions. Examples of datasets include:

- 1-DEGREE, MONTHLY Wind Speed

The dataset consists of merged wind speed measurements from the many radiometers in operation since 1987, including SSM/I, SSMIS, and WindSat. These data were all processed in a consistent manner using radiative transfer model and careful instrument intercalibration. The wind speeds from these instruments are used to create a Mean Wind Speed product that is best for use in climatological study (long term time series analysis) (Kent et al., 2013).

- CCMP 4x-Daily VAM Analysis Wind Fields

The Cross-Calibrated Multi-Platform (CCMP) gridded surface vector winds are produced using RSS V7 radiometer winds, QuikSCAT and ASCAT scattereometer winds, quality-checked moored buoy winds, and the ECWMF ERA-Interim Reanalysis model wind field as a background wind (Remote Sensing Systems, n.d.). A 4-dimensional variational analysis (VAM) is used to produce the fully populated nearly-global wind fields from the input data. As such, the CCMP is considered to be a Level-3 ocean vector wind analysis product consisting of four maps daily of a 0.25 degree gridded vector wind field. This product is an update and extension of the original V1.1 CCMP product. RSS has transitioned the CCMP processing code to run using our most up-to-date satellite data observations. All methodology remains the same as that used in the original CCMP product and most of the CCMP processing code is unchanged, with only minor alterations to compensate for the different operating systems and compilers.

- Individual Radiometer and Scatterometer Gridded Binary Data Files

In addition, wind speed is one of the measurements in the radiometer binary gridded data files and is also available along with wind direction in the scatterometer data files. For detailed product information and data access, see the section Satellites.

SPECIFICATIONS

BUSINESS PROCESS	SC, SCE, IN, SO, ELD
DESCRIPTION	Wind and current velocity components (u, v) forming a line or wall of broken ice forced by pressure. Wind speed referred as how fast the air is moving past a certain point. Wind direction referred as a direction occurring during the indicated hour, using 36 points of a compass.
EO INFORMATION OF INTEREST	Wind speed derived using a variety of channels and separate algorithms to obtain winds in all weather conditions. Wind direction is the oceanographic-convention wind direction, relative to north. The most common reference height for near-surface ocean wind measurements is 10 meters above sea level. Active and passive satellite remote sensing provide high-resolution, near-surface ocean wind measurements over the ice-free ocean multiple times per day.
MAIN PROCESS STEPS	The radiometers measure ocean surface roughness, which can be correlated to wind speeds at 10 meters above the water's surface. Scatterometers measure the radar cross section of the ocean surface and a Geophysical Model Function (GMF) provides the radar cross section, as a function of the equivalent neutral wind vector at 10 m, incidence angle, relative azimuth angle, radar frequency, and polarization. Scatterometer allows to measure both speed and wind direction.
INPUT DATA SOURCE	Microwave radiometers for wind speed: SSMI/I and SSMIS (1987-present), TMI (1997-2015), AMSR-2 (2012-present), AMSR-E (2002-2011), GMI (2014-present), SMAP (2015-present). Polarimetric scatterometers for wind speed and direction: windSat (2003 – present), QuikScat (1999-2009), SeaWinds (2003 (apr-Oct), ASCAT (Metop A and B) (2007-present) Assimilation of Sea Ice Concentration and/or Thickness

SPATIAL RESOLUTION AND COVERAGE	Global Ocean, Spatial resolution 1km, 12 km to 111 km
ACCURACY / CONSTRAINS	Wind direction: 0. to 360.0 deg Wind speed: Valid range from 0 to 50 m/s
LIMITATIONS	Wind speed; less detection in the higher wind range (> 60 kt), near the coast, sensitive to rain,sun glint, rain, RFI, near sea ice or land (~50 km no rain, ~75 km in rain). A daily gridded map is not strictly comparable to the daily average output from a numerical model. The interpretation of data can indeed be challenging, especially when handled by personnel without extensive experience in the field.
TEMPORAL RESOLUTION	6 hours, daily, monthly Products available from 1 Jan 2016 to 8 Oct 2023 1987 - present
FREQUENCY UPDATE	Daily – 12:00 UTC at day + 1; daily at 0:00 UTC at day + 2
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4
ACCESSIBILITY	Copernicus Marine Service

4.11 Wave height and direction monitoring

Satellite altimetry is one of the most common techniques used to measure ocean wave height. It involves using radar to measure the height of the ocean surface from space. The Significant Wave Height (SWH) is the average height of the highest one-third of waves in a given sample period (European Space Agency, n.d.-m; NASA, n.d.-e). Satellite altimeter data of significant wave height (SWH) from Jason-3 and Sentinel-3A were available in real-time since July 2017, covering the global ocean.

Satellite altimeter data of SWH from multiple missions were available since 1986, covering 30 years of continuous records.

In the specific, two wave products are available at Copernicus Marine Service from altimeter satellite along-track sea surface heights anomalies (SLA) as: SEALEVEL_GLO_PHY_L3_NRT_OBSERVATIONS_008_044 for single altimeter, and WAVE_GLO_PHY_SWH_L4_NRT_014_003 which is the merged product of multi-mission altimeters.

As the spatial coverage of altimeters data is not homogeneous and the data refer to short time intervals, waves spectra available from altimeters could be not reliable if extracted far from the altimeter's tracks. More homogenous wave data over the Arctic are provided by wave models, as for the ARCTIC ANALYSIS FORECAST WAV_002_014 dataset. This product is originated by the WAM model at 3 km resolution forced with surface winds and boundary wave spectra from the ECMWF (European Centre for Medium-Range Weather Forecasts), together with currents and ice from the ARC MFC analysis (Sea Ice concentration and thickness). WAM runs twice daily providing one hourly 10 days forecast and one hourly 5 days forecast. From the output variables the most used are peak period and mean direction of the significant wave height. Significant wave height is an average measurement of the largest 33% of waves.

SPECIFICATIONS

BUSINESS PROCESS	SC, SCE, IN, SO, ELD
DESCRIPTION	Wave heights describe the average height of the highest third of the waves (defined as the significant wave height – see diagram below). It is measured by the height difference between the wave crest and the preceding wave trough (Bureau of Meteorology, n.d.).
EO INFORMATION OF INTEREST	Sea wave height (SWH)
MAIN PROCESS STEPS	Observation: Altimeters emit microwave radar signals towards the ocean surface. The signal bounced back contains information about the sea state, as the variance of the surface elevation within the footprint (σ) inversely relates to SWH. Model: WAM is forced by DMI's numerical weather prediction model Harmonie and ECMWF's global weather prediction model, which provides wind forcing. Wave energy is primarily driven by surface wind. The variance of the surface elevation within the footprint (σ) inversely relates to SWH. Sea ice is included in the model, but sea current interaction is not considered. The water depth is assumed to be constant, and effects due to varying sea levels (tides or storms) are not incorporate.
INPUT DATA SOURCE	Observation: Gridded significant wave height level-4 product based on all available significant wave height level-3 products: • SAR spectral integral parameter level-3 product based on Sentinel-1A, Sentinel-1B and CFOSAT off-nadir measurements. • Altimetry along-track significant wave height level-3 product based on Sentinel-6A, Jason-3, Sentinel-3A, Sentinel-3B, Saral/AltiKa, Cryosat2, CFOSAT nadir, SWOT nadir, Hai Yang-2B and Hai Yang-2C measurements. Model: WAM input includes the following components 1. 10 m wind fields provided by numerical weather prediction, 2. A parametrization of the source term represented by the energy transfer between wind and wave, 3. Data assimilation scheme (satellites, buoys), 4. Validation.
SPATIAL RESOLUTION AND COVERAGE	Observation: 7x7km Model: 3 × 3 km,

	Arctic Ocean, from Lat 63° to 90°; Lon -180° to 180°
ACCURACY / CONSTRAINS	Observation: The accuracy of satellite derived data on wave (typically of few centimetres) depends on several factors, such as the type of satellite sensor, the wave parameter, atmospheric conditions, the sea state condition, and the validation method (e.g. 0.3 – 1 m altimeter vs SAR).The Copernicus Marine Service aims to provide accurate and reliable sea level data by combining observations from multiple altimeter missions. Model: WAM can be run at different resolutions (e.g., 50 km, 10 km, and 4 km). Higher resolution models tend to perform better. WAM relies on surface wind data (usually from numerical weather prediction models) to drive wave simulations. Accurate wind input improves model accuracy. Comparing WAM results with observations (e.g., EnviSat Radar Altimeter and in-situ data) helps assess accuracy. Changes in model resolution and forcing data impact accuracy. WAM's spatial resolution determines its ability to capture small-scale features. Coarser resolutions may miss localized effects
LIMITATIONS	Some of the challenges of wave monitoring from satellite are: 1. The limited spatial and temporal resolution of satellite data, which may not capture the fine-scale features and variability of ocean waves 2. The interference of sea ice, rain, clouds, and other atmospheric conditions on the satellite signals, which may affect the accuracy and reliability of wave measurements . 3. The complexity of retrieving wave parameters from different types of satellite sensors, such as radar altimeters, scatterometers, synthetic aperture radars, and radiometers, which may require different algorithms and assumptions (Dohan & Maximenko, 2010; Dubovik et al., 2021; Hauser et al., 2023) Model: limitations in the assumptions in the Spectral Shape in Representation of Physical Phenomena, etc (Dubovik et al., 2021)
TEMPORAL RESOLUTION	Hourly, products available since 3 Dec 2017
FREQUENCY UPDATE	Daily – Following day at 4:00 UTC and 16:00 UTC
DELIVERY / OUTPUT FORMAT	NetCDF-4

ACCESSIBILITY	Copernicus Marine Service, AVISO - CNES data center.

4.12 Air temperature

Satellites can detect the temperature of the atmosphere at various altitudes as well as sea and land surface temperatures using radiometric measurements.

Satellite retrieval of air temperature over ocean is a challenging task that requires sophisticated algorithms and models to account for the effects of clouds, water vapor, sea surface temperature and other factors. Some examples of methods and products that have been developed for this purpose:

- Near-Surface Air Temperature Retrieval Derived from AMSU-A is a method that uses microwave radiometer data from the Advanced Microwave Sounding Unit-A (AMSU-A) to estimate the near-surface air temperature over ocean, with corrections for atmospheric and surface emissivity effects. It has been shown to have less bias and smaller errors than previous methods. The Advanced Microwave Sounding Unit-A (AMSU-A) is a microwave instrument on board several satellites, such as NOAA-15, NOAA-16, NOAA-17, NOAA-18, NOAA-19, Aqua, and MetOp-A. AMSU-A has 15 channels that measure atmospheric temperature profiles from the surface to the stratosphere. AMSU-A data are available at **hourly** resolution.
- AIRS V7 Level 2 & 3 are products that use infrared and microwave data from the Atmospheric Infrared Sounder (AIRS) on board of Aqua satellite to retrieve various atmospheric variables, including mid-tropospheric carbon dioxide, water vapor and temperature profiles over ocean and land, under cloudy conditions (Wikipedia, 2023c)

For Arctic/Baltic marine and coastal structures, such as ships and platforms, besides the need to withstand anticipated ice conditions, the ability to withstand the risk of low temperature is equally important. The designs of ships and infrastructures in the Arctic and Baltic low temperature regions need to meet requirements of engineering design criteria and standards.

The long-term time series of historical temperature is needed to satisfy requirements of these criteria and standards. In the past, estimating the minimum design temperature distributions in large-scale areas by only using the historical temperature data of very few ground meteorological stations in the corresponding areas was difficult to meet the accuracy requirements of ocean engineering applications. Satellite observations are good means to obtain large-scale temporal and spatial meteorological data in the Arctic and Baltic Ocean (Xiu et al., 2019).

Reanalysis datasets, such as MERRA and ERA, provide global atmospheric data. MERRA stands for Modern-Era Retrospective analysis for Research and Applications and was introduced in 2008 by NASA [1]. MERRA-2 is the latest version of MERRA and provides data beginning in 1980. ERA stands for ECMWF Re-Analysis and was introduced in 1991 by the European Centre for Medium-Range Weather Forecasts (ECMWF).

MERRA-2 incorporates observation types not available to its predecessor, MERRA, and includes updates to the Goddard Earth Observing System (GEOS) model and analysis scheme to provide an advanced product suite suitable for weather and climate applications.

ERA5 is the latest version of ERA and provides data beginning in 1950. ERA5 is a global atmospheric reanalysis dataset produced by ECMWF that uses a 4D-Var data assimilation system.

While both datasets provide similar atmospheric data, they differ in terms of the data assimilation system used, the observation types incorporated, and the time period covered (Jourdier, 2020; NASA, n.d.-c, n.d.-d; National Center for Atmospheric Research Staff, 2022).

GISS Surface Temperature Analysis (GISTEMP v4) is an estimate of global surface temperature change based on current data files from NOAA GHCN v4 (meteorological stations) and ERSST v5 (ocean areas), combined as described in NASA publications (Lenssen et al., 2019; NASA Goddard Institute for Space Studies, 2024).

These sources may have different accuracies, biases, uncertainties and trends depending on the region, period and variable of interest (Luo et al., 2020).

SPECIFICATIONS

BUSINESS PROCESS	SD, SC, SCE, IN, SO
DESCRIPTION	Air temperature is referred to the temperature at some distance above the surface.
EO INFORMATION OF INTEREST	Air temperature long term statistics (min 10 years) and forecast at 2 m of altitude.
MAIN PROCESS STEPS	1. Near-Surface Air Temperature Retrieval Derived from AMSU-A is a method that uses microwave radiometer data from the Advanced Microwave Sounding Unit-A (AMSU-A) to estimate the near-surface air temperature over ocean, with corrections for atmospheric and surface emissivity effects. It has been shown to have less bias and smaller errors than previous methods. 2. AIRS V7 Level 2 & 3 are products that use infrared and microwave data from the Atmospheric Infrared Sounder (AIRS) to retrieve various atmospheric variables, including mid-tropospheric carbon dioxide, water vapor and temperature profiles over ocean and land, under cloudy conditions. 3. GISS surface temp analysis (GISTEMPT V4) consists of several datasets. It has mean temperatures on the northern hemisphere from1880 to today on and another dataset detailing temperature anomalies from 2002 to today which are based on AIRS data vs. 2007-2016. 4. In ERA5 dataset from the C3S in the Copernicus Climate Data Store (CDS) Air Temperature is defined as the “Average air temperature valid for a grid column 2m above the surface.” The air temperature is an average of the temperatures computed for 4 surface types such as sea, inland water, natural land and urban. Temperatures are computed from the temperature at the surface, at the lowest model level, the surface roughness variable and atmospheric stability. ERA5 is a

	continuous climate reanalysis dataset, while the C3S Arctic Regional Reanalysis (CARRA) provides 3-hourly analyses and hourly short-term forecasts of the average air temperature 2m above the surface. 5. MERRA-2 is a global reanalysis product that provides data on the atmosphere, land, and oceans, based on observations and a model. MERRA-2 data are gridded datasets that cover various variables, such as temperature, wind, and aerosols. MERRA-2 data are available at different resolutions and span from 1980 to present. MERRA-2 processing steps involve assimilating observations from different sources, using the GEOS-5 model to produce forecasts, and merging the observations and forecasts in a statistical way.
INPUT DATA SOURCE	Models assimilate a variety of observations from different sources, such as satellites, radiosondes, aircrafts, ships, buoys, and ground stations, such as radiances, winds, temperatures, humidities, pressures, ozone, aerosols, and sea ice Satellite: Aqua – AIRS, AMSU and HSB data
SPATIAL RESOLUTION AND COVERAGE	1. AMSU-A 48 km from 1998-2015 2. AIRS resampled into a 32 km/pixel visualization.) 3. GISSTEMP V4 – 250 km and 1200km from 1880 - ongoing 4. ERA5 - 2.5km x 2.5km from 1991-ongoing 5. MERRA 50 km x 50km from 1980- ongoing
ACCURACY / CONSTRAINS	The accuracy of temperature data from satellite depends on several factors, such as the type of sensor, the method of retrieval, the calibration and validation process, and the comparison with other sources of data
TEMPORAL RESOLUTION/	1. AMSU-A - Daily resolution 2. AIRS – Daily, 8-day or monthly, depending on the product level 3. GISSTEMP Monthly, seasonal and annual 4. ERA5 Hourly 5. MERRA 3-hourly
UPDATE FREQUENCY	ERA5, GISTEMP V4 GISTEMP v4 and MERRA2 – Monthly AIRS – daily

DELIVERY / OUTPUT FORMAT	AMSU-A and AIRS HDF-EOS ERA5 – GRIB2 GISSTEMP v4NetCDF MERRA netCDF AND HDF-EOS
LIMITATIONS	AMSU-A data have limited vertical resolution, especially in the lower troposphere, where the temperature sounding channels have broad weighting functions. AMSU-A data also have limited horizontal resolution, as the instrument has a swath width of about 2200 km and a nadir footprint of about 48 km (Hearty et al., 2014). AIRS data have limited sensitivity to air temperature and specific humidity near and below clouds, as the instrument is an infrared spectrometer. AIRS data also have limited coverage by the presence of optically thick clouds, which block the infrared radiation . GISTEMP v4 data have limited spatial coverage, especially in the polar regions and over the oceans, where there are fewer meteorological stations and ocean area data. GISTEMP v4 data also have uncertainties due to measurement errors, homogenization adjustments, and interpolation methods . ERA5 data have limitations due to the model assumptions, parameterizations, and errors that are inherent in any reanalysis. ERA5 data also have uncertainties due to the quality and availability of the observations that are assimilated into the reanalysis. MERRA data have similar limitations as ERA5, as they are also based on a reanalysis. MERRA data also have discontinuities due to changes in the observing system over time, such as the introduction or removal of satellite instruments (European Space Agency, 2022; Hearty et al., 2014; National Center for Atmospheric Research, n.d.-a, n.d.-b).
ACCESSIBILITY	AIRS -nasa GES DISC GISSTEMP v4 -NASA GISS ERA5 – Copernicus Service MERRA2 NASA GES DISC Artic hub

4.13 Oil spill detection

Among all satellite sensors, SAR is the most utilized for operational oil spill detection and SAR imagery are routinely used for monitoring especially where the use of optical images is limited by clouds, as in the Arctic and Baltic regions. Oil spills are detected as low backscattering areas in C- and X- band SAR images but the discrimination of oil spills and look-alike phenomena e.g., low wind area, wind front area and natural slicks is a crucial task in the SAR image analysis process. Two relevant considerations apply: the first is that the oil is detected as dark spot with respect to the surrounding sea backscattering, but the crucial point is that the sea backscatter can be more or less bright depending on the sea roughness (or wind). As example, in presence of grease ice in the Arctic region, if the sea is rough the sea will look bright and both greasy ice and oil will appear as dark spots, generating confusion. Instead, in a calm sea which is dark, the brighter grease ice will be not confused with the dark oil spots. The second consideration is that oil spill detection by SAR has very clear limitations in the wind speed range: oil detection by SAR is effective excluding very low wind speed (< 3m/s) and high wind speed (> 9 m/s). The first case is relevant because at low wind speed a lot of surfactants (bio-genic oil) appear as dark spots, and surfactants vanish for wind speed > 3m/s. With high wind speed (> 9 m/s), the sea surface appears as a homogeneous bright surface independently if the sea surface is contaminated by the oil.

SPECIFICATIONS

BUSINESS PROCESS	SCE, IN, SO, ELD
DESCRIPTION	Oil spill detection and drift
EO INFORMATION OF INTEREST	Detection of hydrocarbon contamination, drift, and source accounting.
MAIN PROCESS STEPS	Geocoding, radiometric conversion multi-looking, speckle filtering, edge enhancement, texture analysis, and shape analysis techniques.
INPUT DATA SOURCE	C- and X-band SAR imagery.
SPATIAL RESOLUTION AND COVERAGE	Spatial resolution from 20 (IW) to 40m (Sentinel-1 EW), coverage from 20 to 400 km (Sentinel-1). SAR VHR lower than 30 meters
ACCURACY / CONSTRAINS	Limited by noise, speckle, and resolution. SAR sensors can achieve detection accuracies of up to 93% for dark spots in SAR images, using deep learning frameworks such as SegNet (Shaban et al., 2021). PolSAR sensors can achieve detection accuracies of over 95% for oil spills in PolSAR images, using polarimetric features and machine learning algorithms such as support vector machines (McGrath et al., 2021)
LIMITATIONS	Radar detection of oil is difficult in low or high wind areas, due to backscattering of water. Wind speed between 3 and 9 m/s are optimal. Thin oil films may not produce strong enough signals to be easily distinguishable from the surrounding water.
TEMPORAL RESOLUTION	Daily (Sentinel-1), sub-daily using other satellites
FREQUENCY UPDATE	Daily
DELIVERY / OUTPUT FORMAT	Raster images, oil shapes, NetCDF
ACCESSIBILITY	Copernicus Marine service commercial SAR satellite data providers

4.14 Icing conditions detection

Icing condition calculation using satellite data is relevant for the shipping industry because it can help to avoid or mitigate the risks of ice accretion on ships, which can affect their stability, performance, and safety. Marine icing can be divided into two main categories based on the origin of the ice:

1. sea spray icing, and
2. atmospheric icing.

As the ice forms on the hull, superstructure, and equipment of a vessel it can add significant weight and may reduce the vessels stability, safety, and navigational properties. Early detection of icing conditions by earth observational data can assist vessels, especially those poorly suited to deal with icing, to take appropriate risk reducing measures.

Various models have been developed for the estimation of ice accretion rate using meteorological and oceanographic parameters. Various data sets are also available containing observations of spray icing events for different Arctic offshore regions. However, there is limited climatological information that can be used for providing decision-makers with the necessary information on optimal options and solutions in advance for assessing, managing, and mitigating the risks imposed by spray icing (Naseri & Samuelsen, 2019).

SPECIFICATIONS

BUSINESS PROCESS	SC, IN, SO
DESCRIPTION	Detection of marine ship-icing, due to sea spray icing and atmospheric icing
EO INFORMATION OF INTEREST	Sea icing is affected by the following environmental factors: 1. Wind Speed 2. Air Temperature 3. Water Temperature 4. Freezing Temperature of Water 5. Wind Direction, Relative to the Ship 6. Swell and Wave Characteristics ○ Wave Size ○ Wave Length ○ Wave Propagation Direction
MAIN PROCESS STEPS	Sea spray can be visualized at a high spatial resolution in a RGB. Environmental factors detection involves multiple technologies e.g. scatterometers, radiometers and SAR, see the main processing steps for each variable in the relevant information sheets (main processes include e.g. geocoding, radiometric calibration, atmospheric correction).
INPUT DATA SOURCE	Scatterometers, radiometers and SAR
SPATIAL RESOLUTION AND COVERAGE	Depending on native input satellite data
ACCURACY / CONSTRAINS	Strongly dependent on a time sampling and availability of the input satellite data

LIMITATIONS	The RGB relies on solar reflectance from visible and near-IR bands, so it's available only during daylight hours. The detection of icing conditions is strongly dependent on the availability of the environmental factors.
TEMPORAL RESOLUTION	To be set during modelling runs and depending on input data availability
FREQUENCY UPDATE	Daily, generally depending on input data and its availability and light conditions
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4
ACCESSIBILITY	Copernicus Marine service commercial providers, commercial Electro Optical data providers.

4.15 Icing forecasting

Forecast of marine icing condition could assist vessels in route planning, avoidance or give the crew time to plan appropriate risk reducing measures and prepare for the icing conditions.

There are different types of predictive models of sea spray icing on marine vessels, such as empirical, semi-empirical, analytical, and numerical models. Empirical models are based on experimental data and correlations, while semi-empirical models combine empirical data with physical principles. Analytical models are based on mathematical equations that describe the physical processes of sea spray icing, such as droplet trajectories, heat transfer, and ice accretion. Numerical models are based on computational fluid dynamics (CFD) simulations that can capture the complex fluid-structure interactions and the effects of wind, waves, and vessel motion.

Many of those studies have focused on icing prediction systems, but a knowledge gap exists in the detection of sea spray using remote sensing data. The recent availability of data from new and advanced imagers, such as JPSS Visible Infrared Imaging Radiometer Suite (VIIRS), offers new tools for the detection and tracking of sea spray for forecasters. VIIRS contributes to higher spatial detail, allowing for improved analysis of sea spray extent, particularly within smaller bodies of water. Forecasters can implement these detection techniques to help verify sea spray–related forecast products, and to pass along potentially life-saving information to their mariner core partners.

The prediction of icing rate and forecasting icing events are challenging to uncertainties related to e.g., accurately estimating the spray amount, modelling turbulent heat transfer between the atmosphere and wetted surfaces on the ship, estimating brine salinity and, therefore, the freezing temperature. In addition, documented icing events required for model verification, forecasting oceanographic and meteorological parameters, that affect the spray-icing process, are limited (Naseri & Samuelsen, 2019). The incorporation in the model of vessel characteristics, including geometry of vessel/platform-wave interactions, location of equipment and facilities on-board are other parameters makes spray ice modelling even more complex. An example of a ship-icing model is the MINCOG model, which uses gridded meteorological and oceanographic data as input to estimate the ice accretion rate on vessels operating in the Arctic waters.

SPECIFICATIONS

BUSINESS PROCESS	SC, IN, SO
DESCRIPTION	Forecast marine ship-icing due to sea spray icing and atmospheric icing

EO INFORMATION OF INTEREST	Time series of: • wind speed, • air temperature, • sea temperature, • salinity, • wind speed, • air temperature, • relative humidity, • mean-sea level pressure, • significant wave height, • significant wave period
MAIN PROCESS STEPS	Modelling of wave-ship interaction, use of a ship class e.g. KV Nordkapp as a reference ship type for ship-icing calculations, assimilation of atmospheric, and ocean data for which is necessary geocoding, radiometric calibration, data modelling assimilation.
INPUT DATA SOURCE	Electro Optical satellite data, radiometer, altimeters
SPATIAL RESOLUTION AND COVERAGE	50x100km, finer grids are possible if higher-resolution input data are available.
ACCURACY / CONSTRAINS	Strongly dependent on the: • accuracy of input of gridded meteorological and oceanographic data. • representation of modelling complexity of the physical processes related to ice accretion, such as air temperature, wind speed, sea surface temperature, and ocean currents. • validation against observational data (e.g., ship icing measurements). • limited spatial resolution

LIMITATIONS	• Simplified Physics: e.g., steady-state conditions (not account for transient effects). • Inaccuracy of capturing local variability (e.g., coastal effects, fjords, narrow straits). • Propagation of uncertainties in input data, parameterizations, and model assumptions. • Assumption of homogeneity within each grid cell. In reality, local variations (e.g., icebergs, leads, polynyas) can impact ice accretion. • Limited Observations: Ship icing measurements are sparse, limiting the availability of validation data. • Model's accuracy may be affected by changing climate conditions, especially in the Arctic region.
TEMPORAL RESOLUTION	The model calculates the icing rate for each 3-hour time interval and then aggregates the results to daily, monthly, or annual values.
FREQUENCY UPDATE	The frequency of data updates depends on the source: e.g. The MINCOG model uses 3-hourly data from the NORA10 data reanalysis. Other data sources may have different update frequencies.
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4
ACCESSIBILITY	Copernicus Marine service commercial providers, commercial Electro Optical data providers

4.16 Sea current monitoring

Sea currents or estimates of the horizontal flow of water near the sea surface can be derived from satellite data and models. Satellites equipped with microwave monitoring instruments, optical imagers, and infrared radiometers can map ocean variables related to ocean currents, sea ice, and sea surface. Sea currents from satellite products include, e.g.:

1. **OSCAR** from NASA JPL, a product that contains near-surface ocean current estimates, derived using quasi-linear and steady flow momentum equations. The horizontal velocity is directly estimated from sea surface height, surface vector wind and sea surface temperature. These data were collected from various satellites and in situ instruments.
2. Reanalysis and forecast products from the Copernicus Marine Service:
    1. a forecasting product, ARCTIC_ANALYSIS_FORECAST_PHYS_002_001_available since 1 Jan 2018,
    2. a re-analysis product ARCTIC_MULTIYEAR_PHY_002_003 available from 1 Jan 1991 to 31 Dec 2022.

Both are based on the operational TOPAZ4 Arctic Ocean system which uses the Hybrid Coordinate Ocean Model (HYCOM) developed at University of Miami (Bleck, 2002) coupled to a sea ice model, and the deterministic version of the Ensemble Kalman filter (DEnKF) to assimilate remotely sensed as well as temperature and salinity profiles. The output is interpolated onto standard grids and depths. The model's native grid covers the Arctic and North Atlantic Oceans with fairly homogeneous horizontal spacing (between 11 and 16 km). Small differences between the two products are the number of vertical layers and the assimilation scheme used. Priority can be given to the re-analysis product, if covering the period when the sea current must be extracted; otherwise, the forecasting product is the alternative source of data.

SPECIFICATIONS

BUSINESS PROCESS	SC, IN, SO
DESCRIPTION	Sea currents from satellite are measurements or estimates of the horizontal flow of water near the sea surface, derived from satellite data and models.
EO INFORMATION OF INTEREST	Ocean Surface Current Analyses-Real time
MAIN PROCESS STEPS	• OSCAR ocean mixed layer velocities are calculated from satellite-sensed sea surface height gradients, ocean vector winds, and sea surface temperature gradients using a simplified physical model for geostrophy, Ekman, and thermal wind dynamics (Earth and Space Research, n.d.). • TOPAZ4 Arctic Ocean system which uses the Hybrid Coordinate Ocean Model (HYCOM) coupled to a sea ice model, and the deterministic version of the Ensemble Kalman filter (DEnKF) to assimilate remotely sensed as well as temperature and salinity profiles. The output is interpolated onto standard grids and depths.
INPUT DATA SOURCE	OSCAR multiple sensors TOPAZ 4 satellite and in situ observations, atmospheric forcing, river run off data
SPATIAL RESOLUTION AND COVERAGE	12.5 - 25 kmLat 50° to 90°; Lon -180° to 179.88°

ACCURACY / CONSTRAINS	OSCAR 0.1 m/s Not specified accuracy for sea surface currents. The accuracy of TOPAZ4 reanalysis for ocean surface current is about 0.05 m/s (root mean square error) and 0.8 (correlation coefficient) in the Nordic Seas, and about 0.1 m/s and 0.7 in the Barents Sea, respectively (Johnson et al., 2007). The accuracy of OSCAR and TOPAZ ocean surface current depends on the region and the season of interest. Both OSCAR and TOPAZ are derived from satellite datasets using different methods and assumptions, so they may have different uncertainties and biases depending on the region and time period.
LIMITATIONS	OSCAR and TOPAZ5 are two different models for ocean currents, with different strengths and limitations. OSCAR is a simplified physical model that calculates surface currents from satellite datasets, while TOPAZ5 is a data assimilation system that provides reanalysis and forecast products for the Arctic Ocean. Some of the limitations of OSCAR are, see Johnson et al.(2007): • It does not resolve the vertical structure of the ocean, only the surface layer . • It has a coarse spatial resolution (25 km), which may not resolve the mesoscale features . Some of the limitations of TOPAZ5 (Bertino et al., 2015) are: • It has a limited temporal resolution of daily output for reanalysis and hourly output for real-time forecast • It has a limited spatial resolution of about 12 km, which may not resolve the sub-mesoscale feature • It has some biases in the interior of the ocean and for ice thickness, where observations are sparse
TEMPORAL RESOLUTION	OSCAR 5 days since 1992 to present. TOPAZ5 Hourly, Daily, Monthly, products available since 1 Jan 2018
FREQUENCY UPDATE	OSCAR 5 days Daily – Forecast: following day at 00:30 UTC; Analysis: Mondays at 14:00 UTC Seventh day of following month at 12:00; Monthly
DELIVERY / OUTPUT FORMAT	NetCDF-3 and 4

ACCESSIBILITY	Copernicus Maritime Serivce, podaac JPL NASA

4.17 Algae blooming

An algal bloom, also known as an algae bloom, occurs when there is a rapid increase or accumulation in the population of algae within marine water systems. These blooms are often recognizable by the distinct discoloration of the water caused by the pigments produced by the algae. An example of a macroscopic algal bloom is the majestic kelp forest. Algal blooming is relevant for

- **Water Quality and Navigation**: Algal blooms can reduce water clarity due to the increased presence of algae and other suspended particles. This reduced visibility affects navigation for ships, especially in coastal areas and harbours. Shipping vessels rely on clear water to safely navigate, avoiding collisions with other ships, underwater obstacles, or shallow areas.
- **Biofouling**: Algal blooms contribute to biofouling, where algae and other organisms attach to the hulls of ships. Biofouling can increase drag, reduce fuel efficiency, and impact vessel performance. It also facilitates the transport of invasive species across different regions.
- **Harmful Algal Blooms (HABs)**: Some algal blooms produce toxins harmful to marine life and humans. These are known as HABs. HABs can lead to fish kills, affecting local fisheries and disrupting the food chain. Shipping vessels may inadvertently transport toxic algae or their spores to new areas, exacerbating HABs.
- **Ballast Water Exchange**: Ships use ballast water to maintain stability during voyages. However, this water often contains algae and other organisms. To prevent the spread of invasive species, international regulations require ships to exchange ballast water in open seas. Proper ballast water management is crucial to prevent the unintentional transfer of algal species.

SPECIFICATIONS

BUSINESS PROCESS	SCE, ELD
DESCRIPTION	Algae blooming is a rapid increase or accumulation in the population of algae within marine water systems.
EO INFORMATION OF INTEREST	Chlorophyll-a concentration, a pigment found in algae and phytoplankton. Changes in chlorophyll concentration can indicate the presence of harmful algal blooms.
MAIN PROCESS STEPS	Correct for sensor-specific biases, atmospheric effects, and sensor gain/offset. Rectify geometric distortions due to Earth's curvature and sensor viewing angles. Remove cloudy or obstructed pixels. Identify the spectral bands sensitive to chlorophyll fluorescence (e.g., red and far-red wavelengths)
INPUT DATA SOURCE	Passive sensors, such as Modis-Aqua, NPP-VIIRS and NOAA20 -VIIRS and Senitnel-3 OLCI A and B. Sentinel-2 A & B MSI are used for high resolution products. In situ measurements used for assimilation/validation

SPATIAL RESOLUTION AND COVERAGE	Artic and Baltic at 300m – 1 km
ACCURACY / CONSTRAINS	Varying depending on sensors and locations
TEMPORAL RESOLUTION/	Daily, Monthly
UPDATE FREQUENCY	Arctic and Baltic: 1- 3 days
DELIVERY / OUTPUT FORMAT	NetCDF-3
ACCESSIBILITY	Copernicus Ocean Service
LIMITATIONS	Cloud cover

4.18 Change in vegetation

Coastal vegetation, e.g. mangroves and salt marshes, plays a vital role in shaping the maritime environment. These ecosystems act as a natural buffer against erosion, safeguarding coastlines and shorelines from the relentless forces of waves and tides. Their root systems stabilize sediments, preventing soil loss and maintaining the integrity of coastal landforms.

Beyond erosion control, these vegetated coastal zones provide critical habitat for marine life. Mangroves serve as nurseries for juvenile fish, crustaceans, and other aquatic organisms. Salt marshes offer shelter and feeding grounds for migratory birds, crabs, and small fish.

Satellite multispectral data allows to detect, quantify, map, and monitor changes in vegetation at different spatial-temporal scales. These changes can occur in terms of vegetation type (different species associations) and vegetation condition (health, deforestation, growth stages) and can be monitored by several variables, including:

- Fraction of Green Vegetation Cover (FCOVER) denotes the fraction of ground covered by green vegetation. The variable is sensitive to the vegetation amount, making it valuable in monitoring vegetation ecosystems
- Fraction of Absorbed Photosynthetically- (FAPAR) denotes the fraction of the solar radiation absorbed by alive leaves (FAPAR only refers to green and alive elements of the canopy).
- Leaf Area Index (LAI) is defined as half of the total area of green elements of the canopy per unit horizontal ground area. This includes all the layers of a canopy which makes LAI a good variable for quantifying the thickness of the vegetation cover.
- Normalized Difference Vegetation Index (NDVI) is an indicator quantifying the health and density of vegetation using sensor data.
- Vegetation Condition Index - (VCI) – Vegetation Condition Index compares NDVI to the range of values collected the in the same period in previous years. VCI is given as a % and gives an indication on the observed value on where it is situated between the minimum and maximum from the previous years.
- Land Cover (LC) shows different classes of earth’s surface e.g. forest, grassland, lakes etc.

SPECIFICATIONS

BUSINESS PROCESS	ELD
DESCRIPTION	Change in the vegetation can highlighting environmental impacts of operations to local nature
EO INFORMATION OF INTEREST	FCOVER, FAPAR, LAI, NDVI, VCI, LC
MAIN PROCESS STEPS	All the variables are retrieved using multiple spectral bands and knowledge of absorption lines of relevant features of interests
INPUT DATA SOURCE	Any passive satellite with multispectral capability
ACCURACY/ CONSTRAINTS	300-1000m
LIMITATIONS	Atmospheric effects. Saturation occurs in areas with very low or dense vegetation. Sensor factors affect accuracy
TEMPORAL RESOLUTION	300 m – 1 km from 1999 to present
FREQUENCY UPDATE	Almost daily
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4
ACCESSIBILITY	Copernicus Global Land Service

4.19 Emissions to air

Even though various methods are used to assess ships' pollution in ports and off the coastal areas, monitoring over the open sea has been infeasible until now Ship tracks can be observed by satellites. Ship tracks are cloud trails formed by particles and gases emissions from ships. Both NOx and SOx are combustion products that are emitted into the environment in the form of smoke, their emission change as a function of load operation, fuel type, etc... MARPOL Annex VI is strictly followed to have the air pollution under control limits.

4.19.1.1 Nitrogen Dioxide (NO_2)

Combustion engines from ships are a major source of NO_2 pollution. NO_2 is a member of the NOx family (NO_x = NO + NO_2), where Nitrogen Oxides (NOx) is the collective name for nitrogen oxide (NO) and nitrogen dioxide (NO2), (EEA, 2023). About 15%-30% of total NOx emissions originate from shipping. Starting from 2021, the International Maritime Organization (IMO) has further tightened the NOx emission constraints for diesel engines of newly built ships operating in the North and Baltic Sea (Kurchaba et al., 2021)

Satellite technology has been used to map NO_2 traces from shipping activities. Attribution of plumes are possible when the concentrations are sufficiently stronger than the NO_2 background concentration. Therefore, possible mainly during conditions of low dispersions or when plumes are coming from larger ships were assessable.

4.19.1.2 Sulphur Dioxide (SO_2)

Most ships use heavy fuel oil as fuel. Fuel oil has a relatively high sulphur content compared to other types of fuel, and the sulphur is emitted with the ship's exhaust gas in the form of sulphur dioxide (SO_2). In 2008, United Nations' International Maritime Organization (IMO) adopted MARPOL Annex VI, which regulates the sulphur content of ships' fuels. The global upper limit for the permitted sulphur content in fuel is 3.5 per cent, but in October 2016 the IMO adopted a sulphur content limit of 0.5 per cent from 2020. Especially low limits of 0.1 per cent have been introduced in so-called SECAs (Sulphur Emission Control Areas), including area along the North American coasts, parts of the Caribbean Sea, the North Sea and the Baltic Sea.

To comply with these regulations, it is necessary to use fuel with a low sulphur content or alternative fuels such as liquefied natural gas (LNG), batteries and others. Another option is to clean the smoke containing sulphur by means of a so-called scrubber (smoke gas cleaning system)

BUSINESS PROCESS	SCE, IN, ELD
DESCRIPTION	Exhaust gases from ships are a significant source of air pollution, including sulfur dioxide, nitrogen oxide, particulate.
EO INFORMATION OF INTEREST	NO_2, SO_2
MAIN PROCESS STEPS	Step 1: Fitting the differential absorption cross-sections to the measured sun-normalized Earth radiance spectrum. This step provides the slant column density of the trace gas. Step 2: Using the slant column density, the Air Mass Factor (AMF) is calculated to translate it into a vertical column density.
INPUT DATA SOURCE	OMI, TROPOMI
SPATIAL RESOLUTION AND COVERAGE	OMI: 13x24 km2 minimum pixel size Tropomi: 5.5x3.5km^2

ACCURACY / CONSTRAINS	Wind can disperse plumes and make difficult identification of ship source
LIMITATIONS	Cloud cover in summertime and solar illumination in wintertime. For source allocation dispersion and signal to noise ratio are strong determinants. AIS, wind data (10m at 0.25 degrees) can be added as layers together with algorithms providing a better isolation of the background to increase the enhancement of the ship signature. Sensors ERS-2, MetOp_a to be added for improved source accounting. Risks of misuse without remote sensing education
TEMPORAL RESOLUTION	Approx. daily
FREQUENCY UPDATE	daily
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4
ACCESSIBILITY	Copernicus

AIS, radar signal and other instruments suited for ship detection and monitoring

The Automatic Identification System (AIS) is an automatic tracking system used primarily for maritime purposes. In fact, it was developed in 1990s, as a collision avoidance tool. It operates via transceivers installed on ships and is also utilized by vessel traffic services (VTS). Ships equipped with AIS transceivers continuously broadcast information such as position, speed, course, and vessel details. Shore stations and satellites receive AIS signals, allowing real-time tracking of vessels. However, AIS data is limited to VHF range (about 10–20 nautical miles). When satellites receive AIS signals, it's referred to as Satellite-AIS (S-AIS). AIS systems have limited in range. Due to Earth curvature AIS signals cannot travel further than 50 nautical miles. Therefore, at open sea or in areas where costal base stations are limited AIS data can be relayed using satellites. This is invaluable in tracking and monitoring ships in remote areas and open oceans. While S-AIS gives a detailed overview over ships with AIS equipment installed, it can be combined with satellite imagery to detect and identify ships that turns off their AIS or are not equipped with it.   Other instruments can be used for monitoring vessel traffic in the Arctic and Baltic Sea, including:

Radar (Radio Detection and Ranging): Radar predates AIS and provides information on ship positions, distances, and relative speeds. The sensor can operate in various radar modes (e.g., X-band, S-band) and offer varying ranges and resolutions. All ships over 300 GRT are required to be equipped with 9ghz radar, in addition, vessels over 500 GRT requires an automatic tracking aid. Radars are then used to identify, tracking and position vessels to sail safely. The radars are classified under two different bands: X-band (10 GHz) uses high frequencies to create sharp images while S-band (3GHz) tends to work better in foggy and rainy conditions.

Sonar: Sonar is used for underwater surveillance, including detecting ice and underwater objects. Passive sonars register the soundwaves of underwater entities while active sonars emit a pulse and registers the echo or reflection of the pulse.

Vessel Traffic Management Systems (VTMS): VTMS combines radar, AIS data, and other sensor inputs to manage vessel traffic in busy ports and waterways. It can provide real-time information to support safe navigation and traffic flow.

Costal Surveillance Systems: These integrated systems combine various sensors, including radar, AIS, and cameras, to monitor and secure coastal areas, ports, and critical maritime infrastructure.

UAVs: Drones equipped with cameras or other sensors can be used for aerial surveillance of ships and maritime areas. They are especially useful for monitoring illegal fishing and environmental compliance.

Satellites with sensor operating in the optical range:

- High-resolution optical satellite images typically have a sub-meter level resolution. This means that they can resolve details down to less than a meter in size. For ship detection, optical imagery provides clear visual information about ships, their shapes, and other features. Optical technology is widely used for ship detection due to its ability to capture detailed surface features, including ship structures, colors, and patterns.

Satellites with sensor operating in the thermal infrared technology:

- Thermal infrared sensors on satellites have a coarser resolution compared to optical sensors. They typically operate at resolutions ranging from tens of meters to several hundred meters. These sensors detect thermal emissions from objects, including ships, based on their temperature differences. Thermal infrared technology is valuable for detecting ships at night or in adverse weather conditions when visible light is limited. However, it may not provide fine details about ship shapes or individual vessels.

Satellites with sensor operating with radar technology (Synthetic Aperture Radar, SAR):

- SAR operates at various resolutions, depending on the specific satellite system. It can achieve resolutions ranging from a few meters to tens of meters. The higher the frequency of the radar, the finer the resolution. For example, X-band SAR provides better resolution than L-band SAR. SAR is particularly useful for ship detection because it is not affected by cloud cover, darkness, or atmospheric conditions. It can penetrate through clouds and capture ship signatures based on their radar backscatter properties. SAR can detect ships even in rough seas and challenging environments.

SPECIFICATIONS

BUSINESS PROCESS	SCE, IN, SO, ELD
DESCRIPTION	Vessel detection, identification, and tracking (VDIT) are fundamental tasks in maritime surveillance and intelligence for incident investigation and situational awareness. Vessel detection involves identifying the presence of ships or vessels in a given area. Vessel identification includes gathering information about the vessel, such as its name, type (e.g., cargo ship, fishing boat, tanker), flag, and other relevant details. AIS data, ship registries, and databases play a crucial role in vessel identification. Vessel tracking involves keeping tabs on a vessel's position, course, speed, and other dynamic information. AIS networks, satellite-based systems, and shore-based stations contribute to real-time vessel tracking.
EO INFORMATION OF INTEREST	Vessel detection, class identification and tracking using a variety of sensor technology.

INPUT DATA SOURCE	AIS, S-AIS, optical, thermal and SAR sensors on board of satellites to track vessels without AIS
MAIN PROCESS STEPS	Pre-processing varying depending on technology. Post-processing might include a combination of deep learning techniques to resolve ship detection and classification
SPATIAL RESOLUTION AND COVERAGE	35 cm to 10 m depending on sensor technology: • Optical technology offers high-resolution imagery for detailed ship detection. • Thermal infrared technology detects thermal emissions at coarser resolution. • Radar technology (SAR) provides all-weather capabilities and varying resolutions for ship detection.
ACCURACY / CONSTRAINS	Cloud cover and solar illumination for variables retrieved using passive sensors
LIMITATIONS	For optical sensors cloud cover and illumination. Vessel identification relies on AIS data. EO data can provide information on the type of vessels, without to provide an ID. Skills and knowledge in remote sensing and data science are essential. Risks of misuse without remote sensing education.
TEMPORAL RESOLUTION	Daily for EO data
FREQUENCY UPDATE	The frequency of updates varies based on the specific satellite sensor, the variable being monitored, and the desired level of temporal resolution.
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4
ACCESSIBILITY	DNV, commercial vendors, copernicus

4.20 Monitoring of onshore changes, shore erosion and sediment deposits

The shipping industry faces significant challenges related to monitoring onshore changes, shore erosion, and sediments in coastal zones. These areas are critical for maritime activities, tourism, fisheries, and ecological balance. Sediment dynamics affect shipping channels, harbour entrances, and nearshore areas. Coastal processes, wind waves, and subsiding coastlines impact sediment movement. An holistic approach combining satellite observations, long-term data, advanced processing techniques, and numerical models is crucial for effective monitoring and sustainable coastal zone management in the shipping industry.

SPECIFICATIONS

<table>
<tr><td>BUSINESS PROCESS</td><td>SO</td></tr>
<tr><td>DESCRIPTION</td><td>Costal land cover and land use identifying alteration of land use.

Bathymetry to identify underwater topography, coastal erosion, and sedimentation.

Shoreline shift and subsidence.</td></tr>
<tr><td>EO INFORMATION OF INTEREST</td><td>Land cover and usage change, bathymetry, subsidence.</td></tr>
<tr><td>MAIN PROCESS STEPS</td><td>Land usage changes: Supervised classification using algorithms (e.g., maximum likelihood) identifies land cover classes

Bathimetry can be retrieved using several approaches and satellite data (see (Coastal National Elevation Database Application Project, 2019; Pe'rei et al., 2013; Shaban et al., 2021; Xie et al., 2023), e.g.

Combining Sentinel-2 and ICESat-2 Datasets with Machine Learning, involving

Adaptive Ellipse DBSCAN (AE-DBSCAN) algorithm, which extracts a priori bathymetric data from ICESat-2 observations, adapting to terrain complexity.
These a priori bathymetric data are then used in Sentinel-2 images to build a model between remote sensing reflectance (Rrs) and water depth.
Three machine learning (ML) methods are employed to estimate bathymetry, with root mean square error (RMSE) of less than 1.5 meters

Passive Optical Satellite Remote Sensing, utilizing satellite imagery acquired from platforms such as Landsat 8, DigitalGlobe WorldView, Sentinel 2, 3. By analysing the relationship between reflected radiation and water depth in shallow water, bathymetry elevation values can be estimated.
Blue-Green Band Ratio Algorithm, where dry land and most clouds, speckle noise are removed using the Near-Infrared and blue-green band. And a blue-green band ratio algorithm is applied to derive bathymetry.

Subsidence can be estimated using a differential SAR interferometry (DInSAR). The technique detects ground deformation by comparing SAR images acquired at different times. Differential interferograms are created by comparing pairs of SAR images. These interferograms reveal ground motion with centimeter-level accuracy. By analyzing the phase differences in the interferograms, land subsidence rates are calculated.</td></tr>
<tr><td>INPUT DATA SOURCE</td><td>Landsat, Sentinel-2, MODIS, Sentinel 1, etc..</td></tr>
<tr><td>SPATIAL RESOLUTION AND COVERAGE</td><td>From 15/30 to 500 m</td></tr>
</table>

ACCURACY / CONSTRAINS	The accuracy and constrains varies based on the specific satellite sensor, the variable being monitored and the areas of interest
LIMITATIONS	Cloud cover and solar illumination for variables retrieved using passive sensors. Risks of misuse without remote sensing education
TEMPORAL RESOLUTION	Almost daily
FREQUENCY UPDATE	The frequency of updates varies based on the specific satellite sensor, the variable being monitored, and the desired level of temporal resolution.
DELIVERY / OUTPUT FORMAT	NetCDF-3, NetCDF-4
ACCESSIBILITY	Copernicus Marine Service and Artic Hub

5 ANNEX

Table 14 New ice is a general term for ice that is recently formed, including frazil ice, grease ice, slush and shuga. These types of ice are composed of ice crystals, which are only weakly frozen together (if at all). They only have a definite form while they are afloat (National Snow and Ice Data Center, n.d.).

New Ice (NI)	**Frazil ice**	Frazil ice forms fine spicules or plates of ice, which are suspended in the water. This is the first stage of sea ice growth. The frazil crystals are usually suspended in the top few centimetres of the surface layer of the ocean and give the water an oily appearance.
	Grease ice	Grease ice is later stage of freezing than frazil ice. The crystals have coagulated to form a soupy layer on the surface. Grease ice reflects little light, giving the sea a matt appearance. Grease ice behaves in a viscous fluid-like manner, and does not form distinct ice floes.
	Slush	Slush is snow that is saturated and mixed with water. It can be found on land or ice surfaces, or as a viscous floating mass in water after a heavy snowfall.
	Shuga	Shuga is an accumulation of spongy white ice lumps, a few centimetres across. Shuga ice is formed from grease ice or slush and sometimes from anchor ice rising to the surface.

Table 15 Nilas is thin, elastic crust of ice, easily bending on waves and swell and under pressure, thrusting in a pattern of interlocking 'fingers. It has a matt surface and is up to 10 cm in thickness. Nilas include dark nilas, light nilas, ice rind (National Snow and Ice Data Center, n.d.).

Nilas	**Dark nilas**	Dark nilas is under 5 cm in thickness and is very dark in colour.
	Light nilas	Light nilas is more than 5 cm in thickness and is lighter in colour.
	Ice rind	Ice rind is a brittle shiny crust of ice formed on a quiet surface by direct freezing or developing from grease ice. It usually forms in water of low salinity and reaches up to about 5 cm in thickness. Ice rind is easily broken by wind or swell, and commonly breaks into rectangular pieces.

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Table 16 Pancake ice is made of predominantly circular pieces of ice, 30 cm to 3 m in diameter, and up to about 10 cm in thickness (National Snow and Ice Data Center, n.d.).

Pancake ice	Pancake ice is made of predominantly circular pieces of ice, 30 cm to 3 m in diameter, and up to about 10 cm in thickness. The discs of ice have raised rims, created when the pieces strike against each other. Pancake ice may form on a slight swell from grease ice, shuga or slush, or as a result of the breaking of ice rind, nilas or — under severe conditions of swell or waves — of grey ice. It also sometimes forms at some depth at an interface between water bodies of different physical characteristics, from where it floats to the surface. Its appearance may rapidly cover wide areas of water.

Table 17 Young ice is the transition stage between nilas and first-year ice. Young ice ranges from 10 cm to 30 cm in thickness. It can be subdivided into grey ice and grey-white ice (National Snow and Ice Data Center, n.d.).

Young ice	**Grey ice**	Grey ice is 10 cm to 15 cm thick. It is less elastic than nilas and breaks on swell. It usually rafts under pressure.
	Grey-white ice	Grey-white ice is 15 cm to 30 cm thick. Under pressure it is more likely to ridge than to raft.

Old ice	**Residual ice**	Residual ice is first-year ice that has survived the summer's melt and is now in the new cycle of growth. Its thickness ranges from 30 cm to 180 cm. After 1 July, this ice is called second-year ice
	Second year ice	Survived only one summer's melt.. Typically up to 2.5 m thick,. Because it is thicker than first-year ice, it stands higher out of the water. Summer melting produces a regular pattern of numerous small puddles. Bare patches and puddles are usually greenish-blue.
	Multi year ice	Survived at least two summers' melt. It is up to 3 m or more in thickness. Hummocks (hillocks of broken ice that have been forced up by pressure) on multi-year ice are even smoother than in second-year ice. The ice is almost salt-free. Colour, where bare, is usually blue. Melt pattern consists of large interconnecting irregular puddles and a well-developed drainage system.

Table 18 First-year ice is sea ice of not more than one winter's growth. It develops from young ice and has a thickness of 30 cm to 2 m. First-year ice can be subdivided into thin first-year ice/white ice, medium first-year ice and thick first-year ice (National Snow and Ice Data Center, n.d.).

Young ice	**First-year ice**	First-year ice is sea ice of not more than one winter's growth. It develops from young ice and has a thickness of 30 cm to 2 m. First-year ice can be subdivided into thin first-year ice/white ice, medium first-year ice and thick first-year ice.
	Thin first-year ice/white ice	Thin first-year ice/white ice is 30 cm to 70 cm thick. It is 30 cm to 50 cm thick in its first stage, and 50 cm to 70 cm thick in its second stage.
	Medium first-year ice	Medium first-year ice is 70 cm to 120 cm thick.
	Thick first-year ice	Thick first-year ice is over 120 cm thick.

Table 19 Old ice is sea ice that has survived at least one summer's melt. It is typically up to 3 m or more in thickness. Most topographic features are smoother than on first-year ice (National Snow and Ice Data Center, n.d.).

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