

## ARTICLE OPEN



# Arctic shipping trends during hazardous weather and sea-ice conditions and the Polar Code's effectiveness

Malte Müller<sup>1,2✉</sup>, Maaïke Knol-Kauffman<sup>3</sup>, Jelmer Jeuring<sup>1</sup> and Cyril Palerme<sup>1</sup>

The Arctic's extreme environmental conditions and remoteness make it a complex and dynamic environment for maritime operators. We find that Arctic shipping has grown by 7% per year over the past decade, despite the hazardous weather and sea-ice conditions that pose risks to vessels operating in the region. As a result of a strong increase in winter sailing, the time ships operate in these extreme conditions has even tripled. To mitigate maritime risks, the Polar Code has been introduced. Among other things, it regulates Arctic shipping by specifying hazardous conditions with a sea-ice classification scheme and design temperature threshold. However, we argue that the Polar Code needs refinement through the integration of maritime warning systems and a broader description of hazardous conditions. This is supported by an analysis of shipping activity patterns in severe sea-spray icing conditions and a discussion of a recent sea-ice induced incident along the Northern Sea Route.

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## INTRODUCTION

In the last decades the number of maritime operations in the Arctic has been steadily on the rise<sup>1–5</sup>. Those operations are related to various activities with complex mobility patterns in space and time<sup>5,6</sup>. Operating conditions in the Arctic are harsh, with sea-ice and potentially hazardous weather conditions, remote infrastructure, and limited information and communication services. This highly challenging Arctic operating environment leads to a substantial risk of human and environmental disasters. In order to reduce the risk of such events the 'International Code for Ships Operating in Polar Waters' (Polar Code) entered into force in 2017<sup>7–9</sup>. Each vessel under the Polar Code regulatory framework must be certified and assigned to a category, based on the sea ice conditions it anticipates to meet. Ship operators need to develop a Polar Waters Operational Manual (PWOM), which specifies how it will avoid hazardous sea-ice and hazardous temperature conditions<sup>8,10</sup>.

In the Polar Code framework, hazardous conditions are narrowly defined by the temperature and the sea-ice conditions in relation to the ships' respective classification (see Methods for details). Other metocean parameters, such as wind, waves, sea-spray icing, and visibility, which are relevant with respect to the safety of maritime operations in particular in the Arctic<sup>11</sup>, are, however, only vaguely considered. In addition, the Polar Code's recommendations for the operator's risk assessment are to a large extent restricted to the use of climatological approaches, i.e., the reflection on the weather and sea-ice conditions averaged over past years. Since the ability to avoid these hazardous conditions depends strongly on the availability of useful, usable, and exchangeable environmental information<sup>12</sup>, new insights are necessary on the meaningfulness of the Polar Code defined hazardous conditions and mitigation measures with respect to the actual spatio-temporal maritime activity patterns in the Arctic.

The possibilities to understand the development of Arctic shipping activity have grown tremendously in the past decade due to the introduction of satellite monitoring for vessel tracking through the Automatic Identification System (AIS)<sup>2–4,6</sup>. Every day,

hundreds of thousands of AIS messages from vessels operating in the Arctic are processed and stored, which include information on location, ship-category, flag state, and estimates of emission. The AIS applications and future opportunities are manifold and the integration of AIS data into a large amount of available environmental data, as well as into region-specific socio-economic information can give important insights into policy gaps, end-user needs, and pressing research questions<sup>13</sup>.

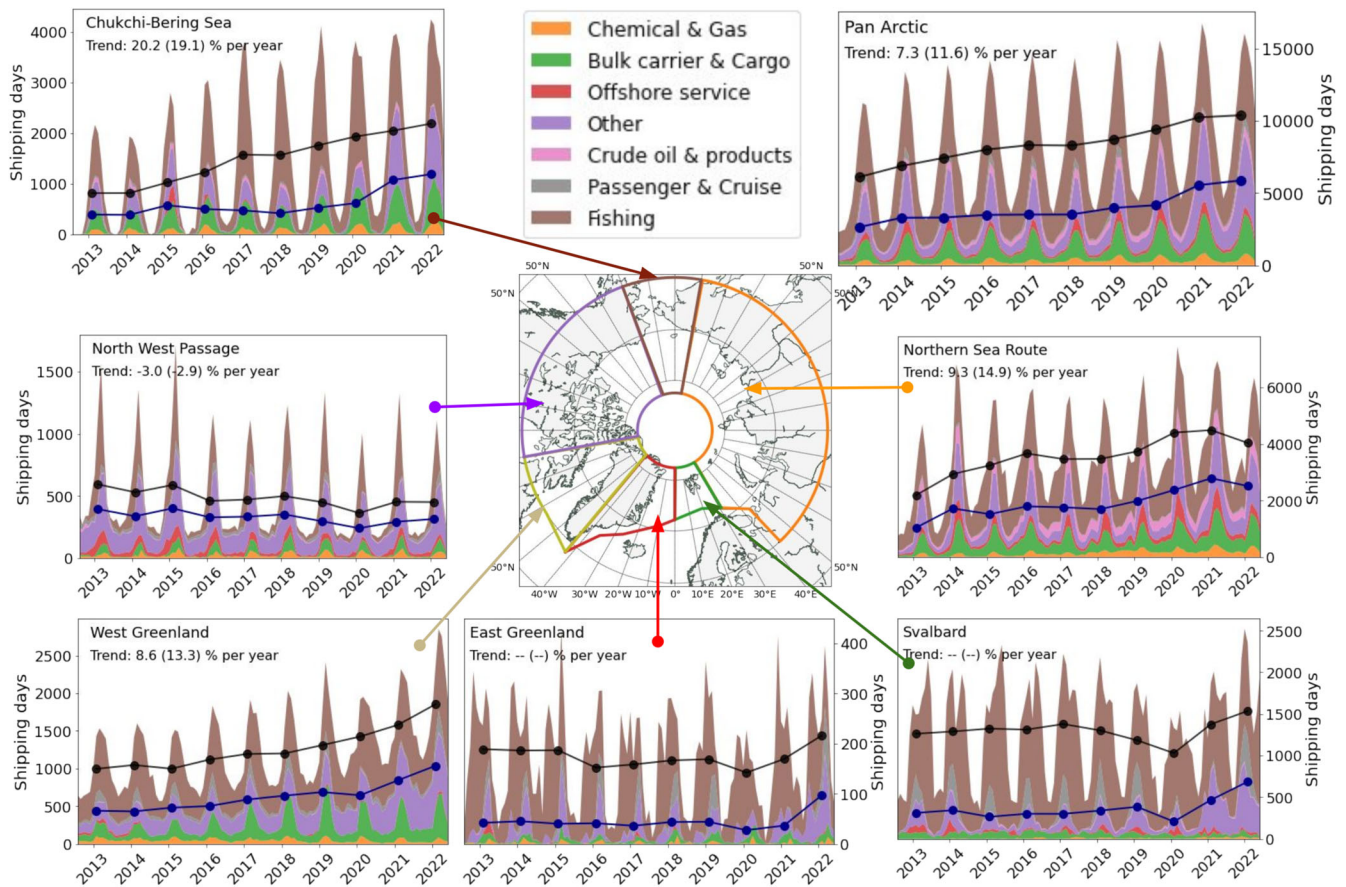
In the present study, we use a decade-long ship-tracking data set (AIS) in combination with environmental weather and sea-ice data. Our objectives are (1) to provide an overview of Arctic shipping activities and trends in the past ten years (2013–2022) on a pan-Arctic scale, (2) to understand where ships were exposed to hazardous environmental conditions as defined in the Polar Code framework and discuss related limitations of the Polar Code. In order to highlight important gaps in this definition of hazardous conditions we demonstrate the growing level of activities under metocean conditions that pose potential challenges for maritime operations. Thus, we discuss and open up the conceptualization of hazardous conditions as defined in the Polar Code framework. Furthermore, we provide a discussion of the climatological concept which is recommended in the Polar Code, and contrast it with the need to harmonize the Polar Code regulations with existing and emerging internationally governed maritime information services.

## RESULTS AND DISCUSSION

### Increase in Arctic shipping

For the purposes of this paper, we delimit our geographical focus to the Arctic Polar Code area (Fig. 1). In this area, we find a steady increase in the number of shipping days. In 2021 and 2022 the increase is even more pronounced and in particular when the fishing sector is excluded from the analysis. Maritime activities have been increasing over the last ten years with a trend of 7% per year in shipping days (Fig. 1) and 6% in individual ships (not shown). Excluding the fishing sector in the trend analysis yields

<sup>1</sup>Development Centre for Weather Forecasting, Norwegian Meteorological Institute, Oslo, Norway. <sup>2</sup>Section for Meteorology and Oceanography, Department of Geosciences, University of Oslo, Oslo, Norway. <sup>3</sup>Norwegian College of Fishery Science, University of Tromsø - The Arctic University of Norway, Tromsø, Norway. ✉email: maltem@met.no



**Fig. 1** Pan-Arctic assessment of ship activities between 2013 and 2022. Number of shipping days per month calculated for different sectors (see legend), and areas (see the center figure with six indicated regions). The time series show the number of shipping days per sector (color-coded), and a black line indicates the annual mean for all sectors. The dark blue line below indicates the time series of the annual mean for all sectors excluding fisheries. The linear trend (2012 to 2022) of the annual total values is noted in the upper left corner of each of the sub-figures. In brackets, the linear trend is obtained when fisheries are excluded. Only trend values with a significance higher than 98% confidence are shown.

trend values of 12% and 8% for the increase in shipping days and individual ships, respectively. Further subdivision of the area of interest into six sections allows for a more contextual understanding of the complexity of Arctic shipping patterns (Fig. 1). The largest total number of shipping days are found along the Northern Sea Route (NSR) and, Chukchi-Bering Sea, West Greenland (including the Hudson Strait areas), and Svalbard. Along the NSR and the NWP shipping can be categorized into trans-Arctic voyages, where ships utilize the Arctic as an interoceanic passage, and destination shipping where specific goods are transported within, or in and out of the Arctic<sup>1</sup>. Along the NSR, transit navigation became active around 2010 and until 2022 there were in total 502 voyages with no significant increase in time (Fig. 2a). The largest amount of shipping takes place as destination shipping and in total, we observe around 300 to 500 individual ships per month in the waters of the NSR (Fig. 2b). A tremendous increase in shipping days (Fig. 1) along the NSR can be found in the first years of the record (most pronounced 2013–2015) and is largely economically driven by the exploitation of energy and mineral resources, which results in the high traffic density within the Kara Sea<sup>2,5,14,15</sup>. The increase in shipping seems to stagnate since 2021 with a significant decrease in shipping in 2022 presumably connected to the international conflicts with respect to the war in Ukraine.

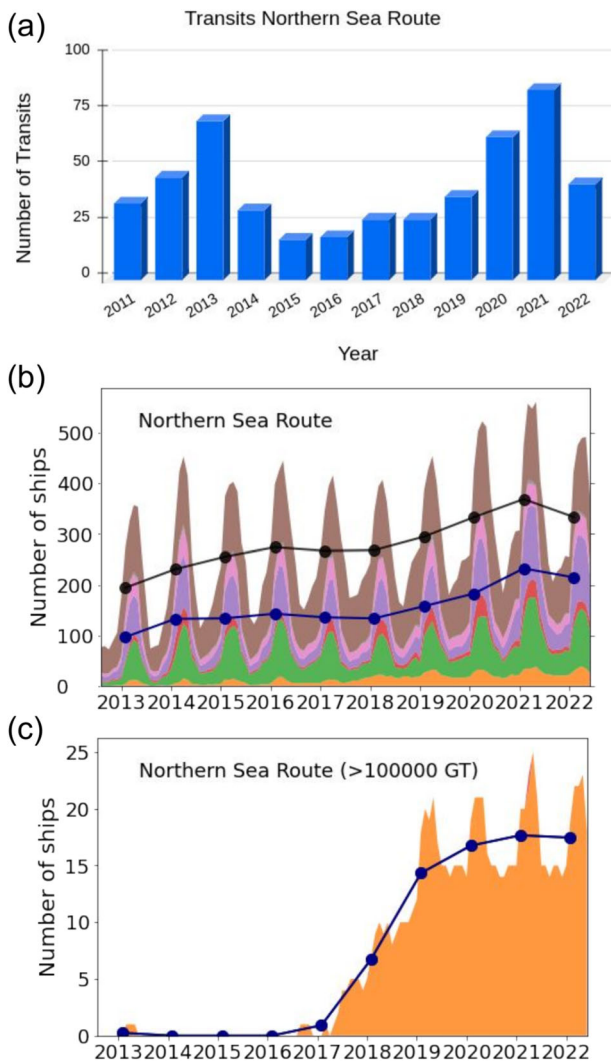
In the NWP area, shipping is related to community resupply during the summer. Here, shipping can also be divided into destination shipping and interoceanic passages<sup>16,17</sup>. Between

2008 and 2018 a total of 222 complete transits were observed<sup>17</sup>. Most of this traffic was performed by icebreakers and pleasure craft, while commercial traffic remains minimal along the NWP. In the present study, we divided our NWP analysis into the waters of West Greenland (including the Hudson Strait and the east Greenlandic coast) and an area named “North Western Passage”. In the latter, the activities are relatively low and slightly decreasing, which is in contrast to the strong increase in the “West Greenland” area over the last 10 years and in particular in the last two years 2021 and 2022.

For shipping around the Svalbard Archipelago, fisheries and cruise tourism make up the dominant activities. The Passenger and Cruise category has been increasing over the study period, with a clear decline in activities in the pandemic years of 2020, followed by a strong increase in 2021 and 2022. In the area of the Bering and Chukchi Seas a strong increase is visible, where shipping days more than doubled over the ten-year time period. The increase can be attributed to the fishing sector between 2013 to 2020, while in the last two years of the record the sudden increase in category ‘Other’ as well as ‘Bulk carrier & Cargo’ is dominating the upward trend in shipping days.

### From seasonal to year-round shipping

The maximum number of shipping days peak in the summer-autumn navigation period and increased in the period 2013 to 2022 from around 12 to 16 thousand (Fig. 1). Arctic shipping activities have a strong seasonal cycle determined by the seasonal



**Fig. 2** Number of individual ships and transits in the Northern Sea Route. **a** The number of interoceanic passages (transits) reported by the Center for High North Logistics Information Office from 2011 to 2022. **b** The number of individual ships for different sectors for the period from 2013 to 2022 and **c** the corresponding number of ships in the highest size class (larger than 100,000 GT) are shown.

sea-ice coverage, the strong contrast between the polar night and day, and the resulting seasonality of harsh weather conditions. However, our analysis shows that activity patterns have moved from seasonal to year-round shipping. For example, on a pan-Arctic scale, we find that during the winter-spring navigation period, where the minimum number of shipping days is observed, the numbers increase from 2 thousand shipping days in 2013 to about 5 thousand shipping days per month in 2022. This change is dominated by the strong increase of winter-spring season activities in the waters of the NSR (Fig. 3), where the number of shipping days roughly tripled from a few hundred shipping days in 2013 to more than 1500 in 2022 due to the establishment of the Liquefied Natural Gas (LNG) and oil projects. Along the NSR, the number of shipping days in the 'low-traffic' winter-spring season in 2022 is more than half of the shipping days in the 'high-traffic' summer-fall season in 2013. While the seasonal distribution in shipping activities in the waters of the NWP does not show any significant changes, around the Svalbard Archipelago a different seasonal development is visible, with a lengthening of the operational season for both fisheries (mostly autumn) and cruise

tourism (summer)<sup>6</sup>. For cruise tourism, the operational season lengthened from June–September in 2013 to about April–September in 2020 (Supplementary Figure 1).

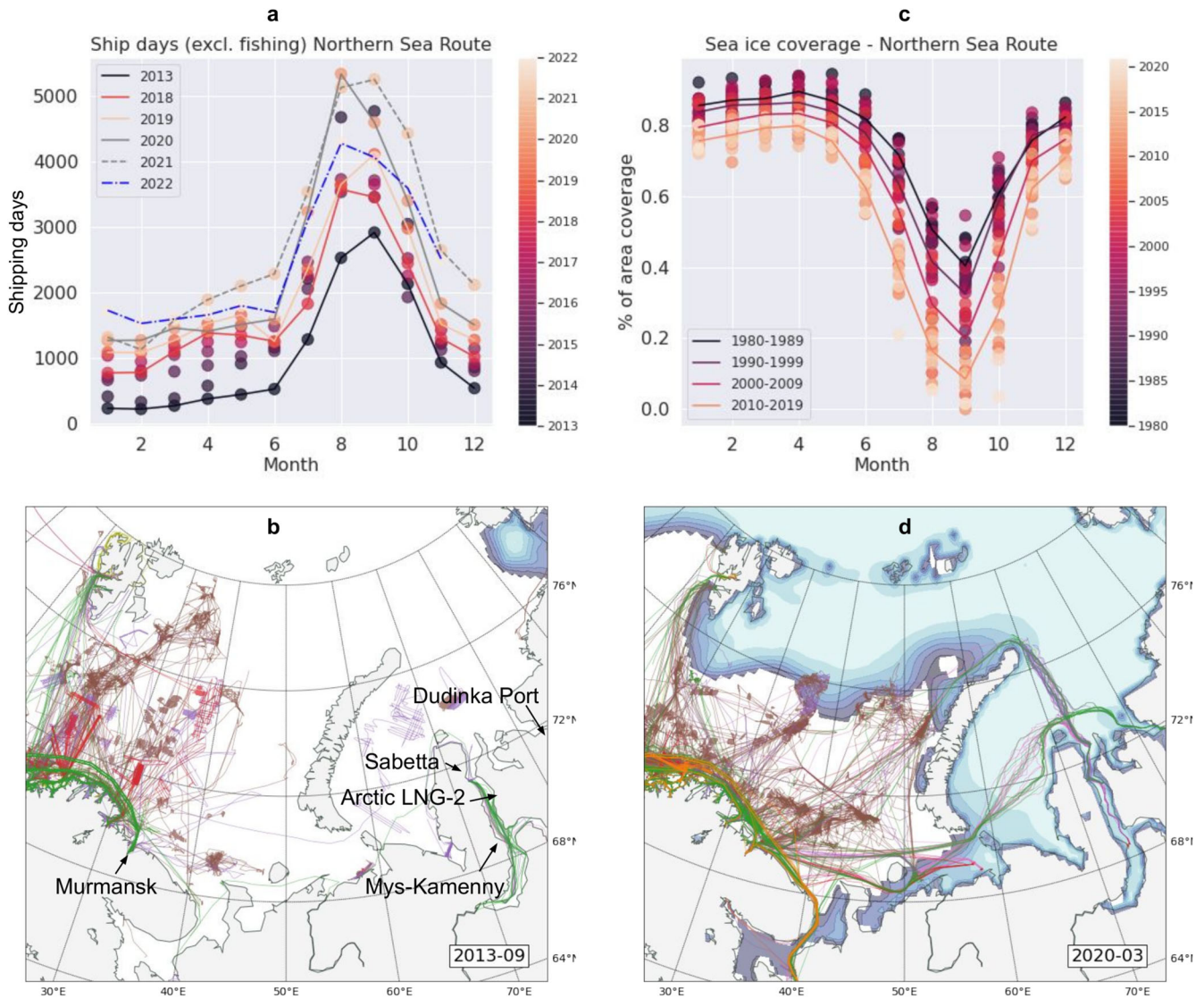
### Activities in Polar Code defined threshold conditions

In the Polar Code several threshold parameters are outlined to guide operators in their risk assessments and voyage planning ("Methods"). Building on the analyses of shipping activity in the previous section, we are able to combine these with metocean parameters to map out the spatio-temporal emergence of potentially hazardous conditions that operators may be confronted with. We co-locate the daily positions of all vessels with the sea-ice and temperature conditions obtained from remote sensing products and atmospheric reanalysis, respectively ("Methods").

A central characteristic of the Polar Code pertains to its description of vessel limitations which define the extent to which a given vessel can operate in sea-ice conditions. These limitations are set by the ship's category (Table 1). For the periods 2013 to 2022, we co-locate all ship positions with a daily sea-ice concentration remote sensing product and analyze those which occur in sea-ice concentrations higher than 80%, which is referred to as 'close ice' by the World Meteorological Organization's (WMOs) nomenclature (for more details see "Methods" section). In the period from 2013 to 2022, occurrences of vessel activity in close ice increased from 150 to 500 (days per month) for their annual mean values. The peak values, during the winter season, however, increased from around 250 to more than a thousand shipping days per month (Fig. 4c).

In 2021 in total 6318 shipping days are counted for shipping in close ice. The largest sectors herewith are ships from the 'Bulk carrier & Cargo', 'Other', and 'Crude oil & products' categories (Fig. 4b). In the central Arctic, shipping activities in sea-ice are dominated by the category 'Other' and to a large extent presumably connected to research vessels. Along the Northern Sea Route, vessels in the categories 'Chemical & Gas', 'Bulk carrier & Cargo', and 'Crude oil & products' are clearly visible. Some of these ships are part of the new Arc7 ice-class LNG tanker fleet which is the largest volume category (larger than 100,000 GT) that operates in the Arctic<sup>15</sup>. Their numbers increased rapidly over the last few years with no signs of seasonality in their activity patterns (Fig. 2c). The increase in shipping activities in the sea-ice-infested NSR can be attributed to the strong increase in winter-spring season activities (Fig. 3). In 2013 the destination shipping connecting European and Russian harbors in the Kara Sea was not yet established, which explains the increase in the following years. Economic incentives were a central driver for this increase through the establishment of the LNG and oil projects, which went into full production in 2018 and 2016, respectively<sup>15</sup>. A comparison of ship tracks and sea-ice maps of September 2013 versus March 2020 reveals that those activities developed rapidly and sea-ice had no negative impact (Fig. 3).

For ships that intend to operate in low air temperatures, the Polar Service Temperature (PST) needs to be defined in the Polar Ship Certificate. Low temperatures are referred to as the lowest mean daily minimum temperature (MDLT) below  $-10^{\circ}\text{C}$ , while the MDLT is defined as the mean value of the daily minimum temperature for each day of the year over a period of at least ten years. The PST for a certain area is then defined as the MDLT minus  $10^{\circ}\text{C}$  (Fig. 5). Since a low-temperature environment is classified by air temperatures below  $-10^{\circ}\text{C}$ , it means that the PST is limited to values below  $-20^{\circ}\text{C}$ . Based on these definitions we analyze the maritime activities in the AIS data which occurred during conditions of  $-20^{\circ}\text{C}$  and below, in order to get a spatio-temporal overview of the ships in such low-temperature conditions (Fig. 6). It shows that the occurrences where ships experience situations with air temperatures below  $-20^{\circ}\text{C}$  are largely



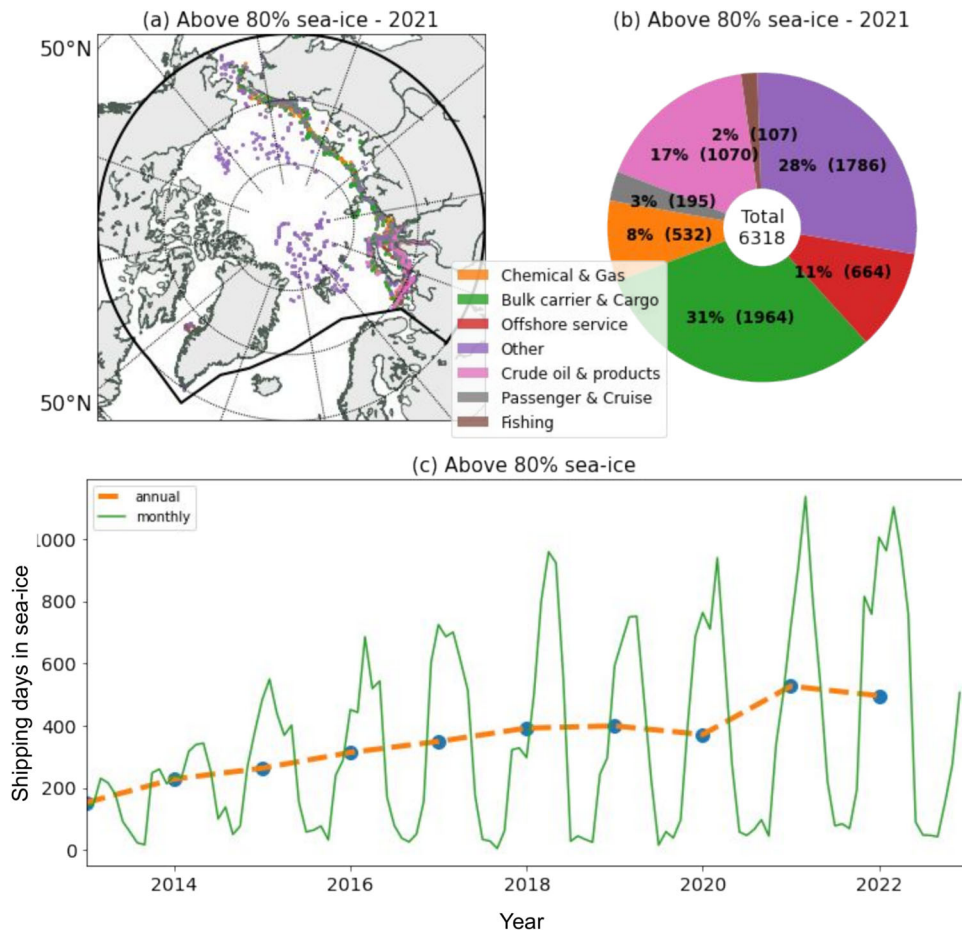
**Fig. 3 Seasonal distribution of shipping (excl. fishing sector) and sea-ice in the Northern Sea Route.** **a** The number of shipping days within each month from 2013 to 2022 is shown (the fishing sector is excluded). Solid lines represent the years 2013, 2018, 2019, and 2020. Dashed lines show 2021 and 2022. **c** The area covered (in %) is shown for each month from 1980 to 2020. Solid lines represent the decadal mean values from 1980 to 2020. **b, d** The ship tracks for September 2013 and March 2020 are shown, respectively. Colors are related to different ship types (see Fig. 1). Color-contoured is the month-averaged sea-ice concentration.

Polar Code <sup>8</sup>	Russian Maritime Register of Shipping <sup>47</sup>	Ice condition threshold
Category A	Arc6,Arc7	Medium first-year ice may include old ice inclusions
Category B	Arc4,Arc5	Thin first-year ice may include old ice inclusions
Category C	Ice1,Ice2,Ice3	open water or ice conditions less severe than Categories B and C

restricted to locations in sea-ice-covered areas, and in particular along the NSR. From 2013 to 2022 the mean annual exposure to these low temperatures increased from 50 to 140 days per month, while winter monthly-peak values changed from about 200 days

to around 500 to 800 days within the last ten years. The major driver of this increase is the development of winter sailings along the NSR, and the same sectors ('Chemical & Gas', 'Bulk carrier & Cargo', and 'Crude oil & products') as for the sea-ice threshold are dominating (Figs. 4b and 6b).

In order to better understand the PST in the context of Arctic temperatures, the pan-Arctic MDLT from a ten-year climatology and the minimum temperature in the time period 2013 to 2021 is shown (Fig. 5a, b). Over the sea-ice-covered areas and in particular, in the central Arctic, the MDLT is between  $-30$  and  $-20$  °C, and the minimum temperatures are between  $-40$  and  $-30$  °C. Over ocean areas, the MDLT is mostly above  $-10$  °C, while minimum temperatures are in the range of  $-20$  to  $-10$  °C within the range of a few hundred kilometers to the sea-ice edge. Within the sea-ice-covered areas, the sea-ice and snow layer insulates the relatively warm ocean from the atmosphere and thus allows for those cold winter temperatures<sup>18</sup>. While over the ocean relatively low temperatures can be observed only during cold air outbreaks, where the cold air from the sea-ice is advected over ice-free regions. This explains the finding in the previous paragraph and



**Fig. 4** Ships in the condition of sea-ice concentrations above 80%. Sea-ice concentration is obtained from a 6.25 km resolution satellite retrieval<sup>39</sup> and co-located with ship positions on a daily basis from 2013 to 2022. **a**, **b** It is shown for 2021 with a subdivision of all sectors. Numbers in brackets are shipping days and in the center of the pie-plot the total number is given. **c** The monthly and annual mean shipping days (per month) are shown for the entire time series.

shown in Fig. 6, that the ships exposed to the lowest PST threshold conditions (below  $-20^{\circ}\text{C}$ ) are operating mostly in the sea-ice.

For a location in the North-East Barents Sea which is mostly ice-free and where cold air outbreaks are observed frequently, we analyze the seasonal MDLT and minimum temperature to explain the climatological concept of MDLT and PST (Fig. 5). The lowest MDLT is observed in February with a value of around  $-11^{\circ}\text{C}$ . Hence, the PST requirement for this location would be  $-21^{\circ}\text{C}$ . For comparison, the lowest temperature that occurred in the record from 2013 to 2022 has been  $-22^{\circ}\text{C}$ , and hence the algorithm for the PST seems to be adequate for this example. However, it is questionable whether maritime operators have access to and are able to judge atmospheric climatologies. Therefore, using weather forecasts which assess the probability of a low-temperature event would be more useful.

#### Threshold conditions not included in the Polar Code

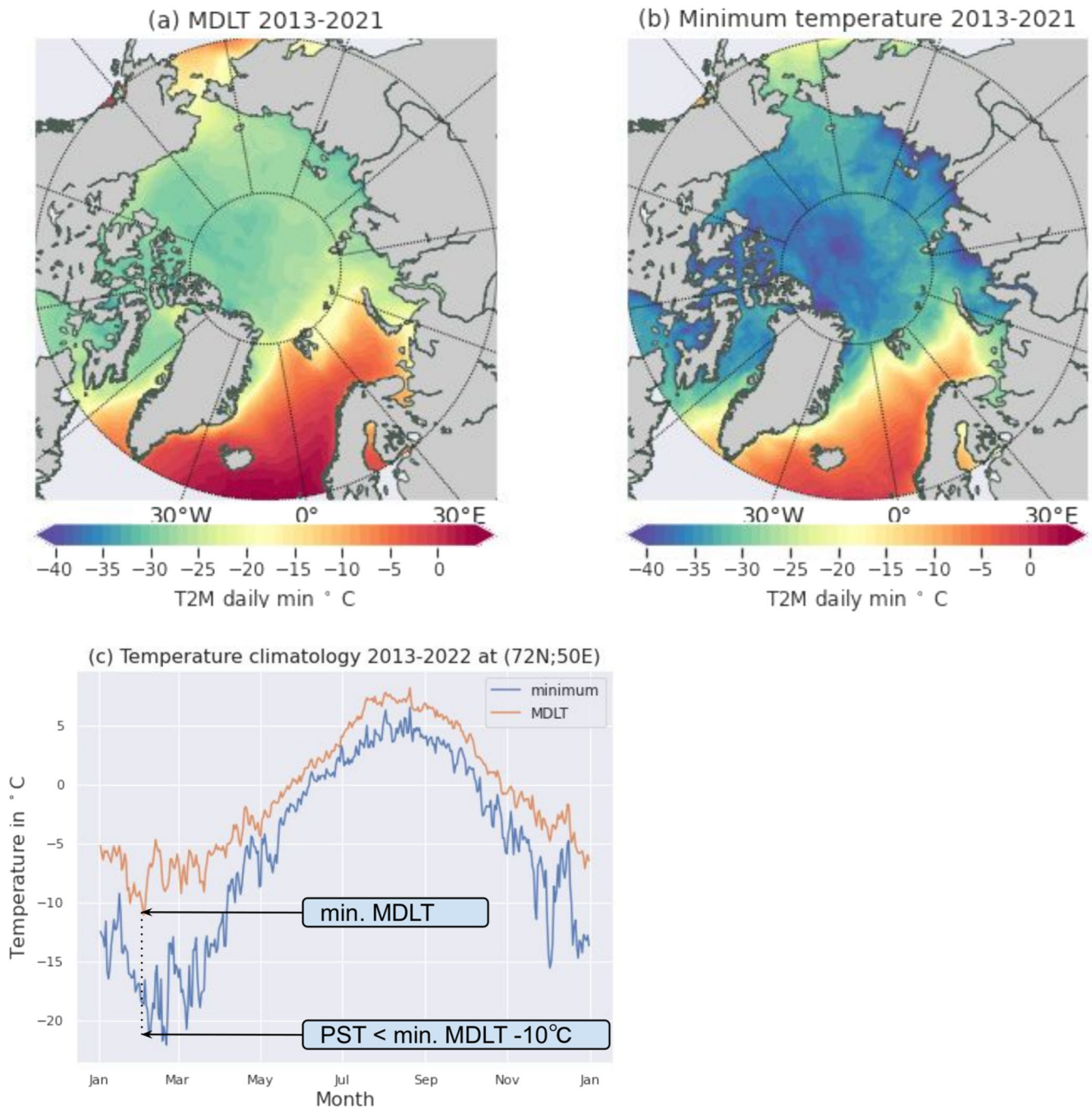
The Polar Code framework only includes two threshold metocean conditions in their recommendations on risk assessments in order to avoid hazardous conditions. However, maritime operations in the Arctic are also challenged by the impact of wind, waves, and visibility and the combinations of different atmospheric and oceanic parameters (icing, wind chill, sea-ice pressure, drift, and ridging).

As a follow-up to our results of the PST in the previous section, we provide a more detailed analysis of sea-spray icing. It is

strongly connected to low temperatures but takes into account other parameters such as wind conditions (“Methods”). Sea spray icing negatively impacts the stability of vessels, due to the ice aggregation on the ship structure and, in the worst case, can lead to the capsizing of ships. Smaller vessels are due to their construction more vulnerable to sea spray icing but, generally, icing also affects the usability and functionality of certain types of equipment.

Icing can form either due to the freezing of atmospheric moisture or of sea-spray. In the following, we focus on sea-spray icing, which is the more dominant mechanism to occur in the maritime Arctic<sup>19</sup>. For sea-spray icing the combination of low temperatures, strong winds, and large waves is important and calculation of seaspray icing can have various levels of complexity and even include the vessels’ shape, as well as their speed and direction<sup>20</sup>. Here, we follow a simplified approach to calculate sea-spray icing for 20–75 meter vessels that are steaming into the wind. This gives us an estimate of light, moderate, heavy, and extreme icing conditions<sup>18</sup> (“Methods”). Almost all hazardous conditions in the Polar Code region related to sea-spray icing occur in the Barents and Bering Seas (Fig. 7).

A vessel icing incident in the Barents Sea is considered in the following to illustrate the potential risks for ships operating in those areas. The fishing vessel *Onega* capsized in December 2020 after a period of extreme sea-spray icing conditions<sup>21</sup> (Fig. 8). Following the simplified icing algorithm in the present study, the sea-spray icing condition was categorized as ‘heavy’ for more than



**Fig. 5** The concept of the Polar Service Temperature. **a** The mean daily minimum 2-meter temperature (MDLT) and **b** the lowest value of the daily minimum 2-meter temperature between 2013 and 2021 is shown for the pan Arctic region. **c** For the location (72°N and 50°E), the annual MDLT and the minimum value (2013–2021) is shown in addition to the illustration of the Polar Service Temperature (PST).

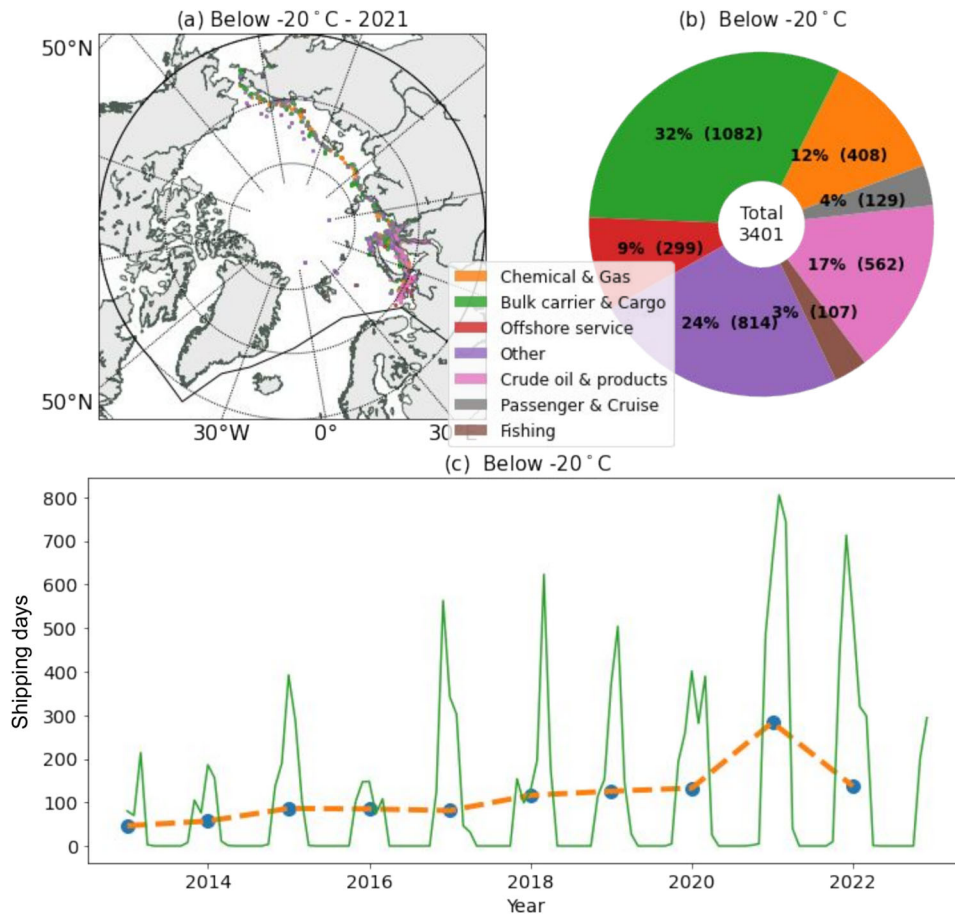
24 h. Also, the forecast issued 2 days in advance by the operational forecasting system AROME Arctic<sup>22</sup>, which is used for maritime weather warnings in the European Arctic, shows a well-predicted heavy icing event.

There is no significant trend in the exposure of vessels to sea-spray icing over the last decade (not shown) and in total, about 400 shipping days with heavy or extreme sea-spray icing conditions are observed in 2021. The fishing sector makes up for 63% of the occurrences which experience these icing conditions. Fishing vessels operate year-round, including in winter, close to the sea ice. They are particularly vulnerable to icing conditions due to their often relatively small vessels and their additional superstructures which can add to the instability. The

spatial and sector-specific characteristics of the occurrences of sea-spray icing compared to those of threshold PST conditions are obvious and showcase the need for a more elaborated and sector-specific list of hazardous conditions in the Polar Code framework. This also supports recent arguments to include all vessel categories which operate in the Arctic in a revised version of the Polar Code<sup>23</sup>.

#### Use of existing information services

The operators' risk assessment, which is required in the context of the implementation of the PWOM, is to a large extent based on a climatological approach. A mandatory requirement for the use of



**Fig. 6** Ships in conditions of 2-meter temperature below  $-20^{\circ}\text{C}$ . a–c The same as Fig. 4, but for the 2-meter temperature threshold.

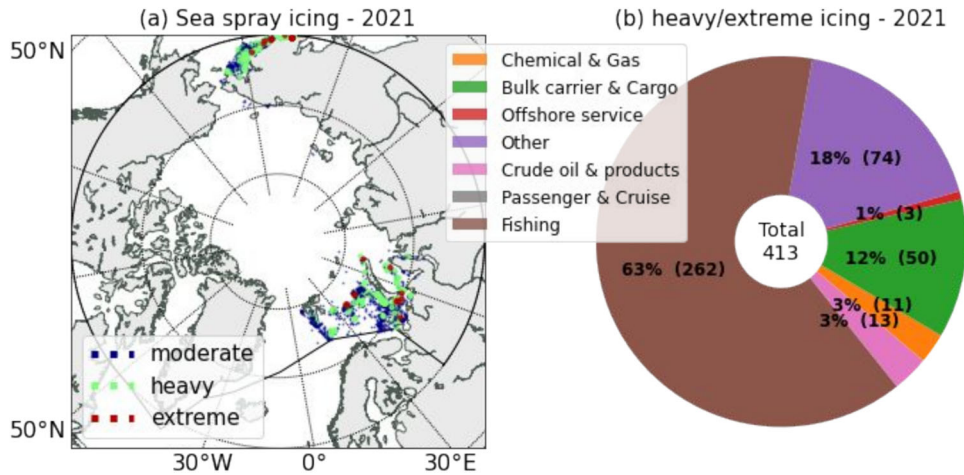
real-time monitoring or forecasting information is not included. Also, there is no standardized procedure to obtain climatological information, for example through the provision of guidelines in which state-of-the-art and quality-controlled climatologies are outlined or a specification of the use of information systems.

There is, however, existing infrastructure jointly organized by the WMO, International Maritime Organization (IMO), and International Hydrographic Organization (IHO), that distributes maritime safety information globally. Forecasts and warning products (weather, waves, and sea ice) are provided to mariners via tailored communication systems (SafetyNet and NAVTEX). This Worldwide Met-Ocean Information and Warning Service (WMMIWS) must follow WMO guidelines for maritime services and is subdivided into 21 areas (METAREAS/NAVAREAS). For each area, individual National Meteorological and Hydrographic Services (NMHSs) have the responsibility to feed in weather, sea ice, and wave-related forecast and monitoring information. In particular, the Arctic region is divided into 5 regions, with delegated responsibilities to Russia, Canada, and Norway. This international system could be used for a more specified and stricter requirement in the Polar Code, on the use of forecast and warning information. In fact, the International Convention for the Safety of Life at Sea (SOLAS) mandates that all ships over 300 GT and passenger ships must carry NAVTEX. In that sense, there is a potential in expanding the requirement to a wider range of ships operating in the Polar Code area, as well as tailoring information within the WMMIWS to Arctic hazardous conditions as described in the regulation.

Adapting the WMMIWS towards Arctic hazardous environmental conditions and connecting it to the Polar Code framework would also allow for more efficient use of the existing information services provided by NMHSs. The use of a climatological approach

for sea-ice and the PST in order to assess the potential of hazardous conditions seems to be outdated given the monitoring and forecast model developments of recent decades. While Arctic weather prediction is still challenging in comparison to lower latitude predictions<sup>24</sup>, operational forecast systems are significantly more accurate than climatological approaches in particular when it comes to extreme weather conditions<sup>22,25</sup>. In contrast, the skill and resolution of current sea-ice forecast systems are still not fulfilling the requirements of users for tactical decision-making<sup>26,27</sup>. However, the combination of manual ice charts provided by the national ice services, the latest high-resolution satellite images, as well as machine learning-based calibration of sea-ice forecast information is under development and can be expected to be in operation in the coming years<sup>28,29</sup>.

Without guidance toward more efficient use of weather and sea-ice information systems, incidents are likely to increase together with growing maritime activity. In October 2021, more than a dozen ships got stuck for several weeks in the sea-ice along the eastern section of the NSR. Two of those ships had low-strengthened hulls and were of the Ice2 sea-ice class (Table 1), which has only permitted access to the NSR between July 1 and November 15 and in low sea ice conditions. In addition, this crisis happened only one year after new ice-class requirements had been introduced which allow medium-strengthened vessels to operate longer into the winter season and earlier in the summer season<sup>30,31</sup>. The situation was complex since the ships got stuck in different places, and only one icebreaker was close by. The two bulk carriers, Nordic Nuulujaak (Arc4 ice class) and Golden Suek (Ice2 ice class) were stuck and drifting with the sea-ice for about 10 days in the East Siberian Sea (Fig. 9b) before they could join with several other ships the escort led by the nuclear-powered



**Fig. 7 Ship's exposure to sea-spray icing condition.** Following a simple parameterization of sea-spray icing<sup>18</sup>, the risk for icing is calculated for all ships on a daily basis for 2021 in (a). A subdivision of icing conditions (heavy/extreme) for all sectors is given in (b). Numbers in brackets are shipping days and in the center of the pie-plot the total number is given.

icebreaker Vaygach to the harbor of Pevek. The sea-ice conditions in the East Siberian Sea were anomalous for October compared to the last 10-year climatology and thus could not be anticipated by only using a climatological approach (Fig. 9c). By reviewing the timeline of the freeze-up of the East Siberian Sea and a comparison of the ship locations, it shows that the early freeze-up has been already indicated in the actual sea-ice conditions on 22 Oct. 2021 before the vessels entered the area of the East Siberian Sea (Fig. 9a). In addition, the early freeze-up situation was correctly indicated by a 10-day forecast of a state-of-the-art sea-ice prediction system<sup>32</sup> (Fig. 9d). In the case of the Golden Suek, which departed on 18 Oct. 2021 in Murmansk, the sea-ice forecast information arguably would have been critical information at the stage of route-planning for an Ice2 categorized ship, which is only allowed to enter the West East Siberian Sea in low sea-ice conditions<sup>33</sup>.

### Towards a more efficient use of information systems

Ships operating in the Arctic need to follow the requirements described in the Polar Code, which includes the development of a ship protocol to avoid hazardous sea-ice and weather conditions. However, we observe an important tension between regulation and implementation, as on the one hand, the defined parameters do not cover the most relevant ones, while on the other hand, the existing service infrastructure does not reflect these Polar Code requirements. This means that the so-called goal-based approach of the Polar Code allows, from an optimistic perspective, for flexibility in compliance and implementation, while from a pessimistic perspective, it may create unclarity and confusion in operational decision-making. Importantly, this discrepancy may lead to a higher risk of incidents, which is compounded by the increase in shipping activities across the Arctic.

The main objectives of the present study are to provide a pan-Arctic overview of shipping activities and trends for the past decade. A particular focus is on the ships which are exposed to hazardous environmental conditions as defined in the Polar Code framework and to discuss related limitations. On a pan-Arctic scale from 2013 to 2022, shipping activities have increased by 7% and the exposure to potentially hazardous conditions of ships has roughly tripled. Thus, an increasing number of ship operators need to take sea-ice and weather conditions into account in their risk assessments and voyage planning to follow the Polar Code regulations. The required practice in the Polar Code is to focus on hazardous conditions related to sea-ice and temperature only, as

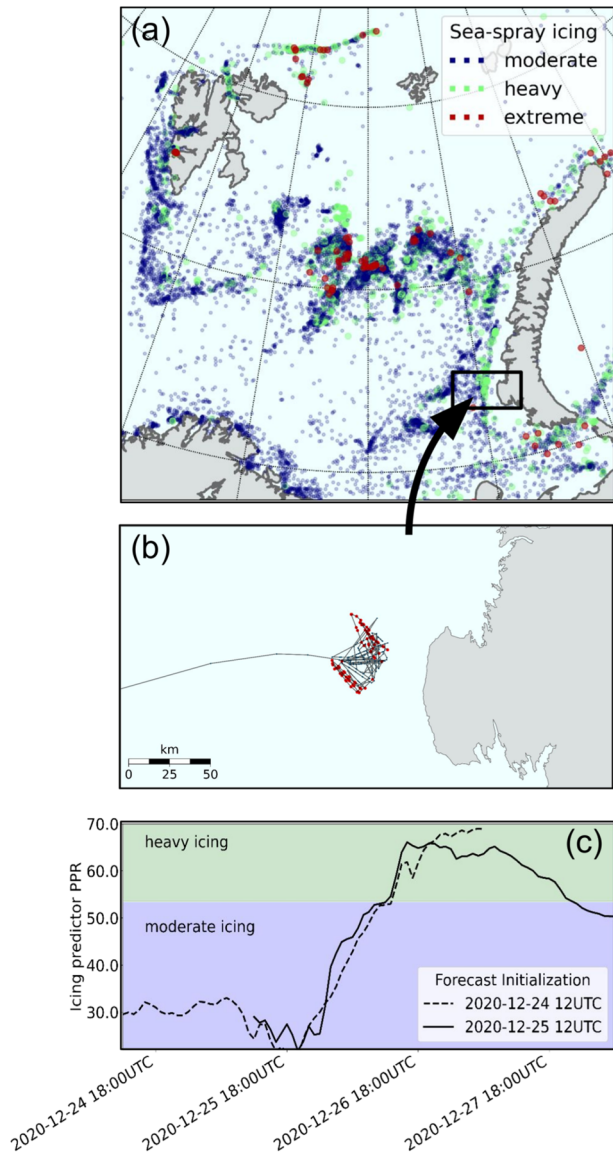
well as the use of a climatological concept to assess those conditions.

In this paper, we capitalized on the potential of combining AIS ship data with pan-Arctic environmental data sets and explored ways for meeting the urgent need for compliance-oriented information about potentially hazardous conditions in Arctic navigation contexts. While there is no clear instruction in the Polar Code on how ship operators shall utilize sea-ice and weather information, for many Arctic regions, the type of information outlined above is not yet readily accessible to users<sup>27,34</sup>. The vessel operators' ability to avoid hazardous weather and sea-ice conditions critically depends on the accessibility, understandability, usefulness, and reliability of environmental information in all voyage planning and execution stages. There is a clear disconnect 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. This constrains the practical value of the Polar Code and arguably compounds operational risks. The continued high demands on weather and sea-ice information services<sup>27,34</sup> are thus warranted and such services should form an essential element of the regulatory system.

In other words, our analyses can provide an important guideline for prioritizing and tailoring environmental service provision towards user-oriented support about prevailing weather and sea-ice conditions. Given the context-sensitive nature of maritime navigation weather hazards, there is a clear need as well for continued iteration and co-production between providers and users throughout the process of service development. Our pan-Arctic perspective showcases examples of relevant parameters but is by no means comprehensive. Based on our work presented here, future research may flesh out various (combinations of) parameters, and their predictive capabilities, and zoom in on particular areas and seasons. Hence, it can serve as a basis for the development of tailored services for user groups.

Industry-initiated guidelines for compliance on the level of ship categories and local climatology are already developing. For example, the International Chamber of Shipping and the Oil Companies International Marine Forum have developed joint guidelines to support operators in their development of a PWOM, in which it is recommended to provide detailed information about daily mean low temperatures, minimum recorded temperatures for each of the days during the intended operating period, and worst recorded ice conditions (among others) in the areas in which vessels intend to operate. Such guidelines will contribute to





**Fig. 8** Sea spray icing incident Barents Sea, December 2020. **a** Moderate, heavy, and extreme sea-spray icing for all sectors and from 2013 to 2021 is shown. **b** The AIS track of fishing vessel Omega is shown from Dec. 12 to Dec. 27. The red dots mark the time periods from Dec. 24 1800UTC to Dec. 27 2241UTC. **c** Sea spray icing conditions forecasts from the weather forecast model AROME Arctic<sup>22</sup> are shown for the time period of the accident (as marked by red dots in **(b)**). The location of the weather forecast is where the last AIS message was received from the vessel Omega (72.13°N,50.55°E).

the translation of hazardous conditions for specific vessel types or categories.

To improve the relevance of Arctic maritime regulatory frameworks, as well as weather and sea-ice services, Research & Development, information services, and policy-making, have to be aligned along the entire value chain and science-for-service thinking is imperative<sup>35,36</sup>. This requires that the most urgent end-user needs are understood in an interdisciplinary framework<sup>37</sup> and that research questions and regulatory frameworks are formulated in the context of service infrastructure. While a number of studies have started to explore these challenges in Arctic contexts<sup>27</sup> these studies have not yet entered the discussion for a revised Polar Code framework.

## METHODS

### Polar Code

The International Code for Ships Operating in Polar Waters (Polar Code) entered into force in 2017. The Polar Code applies to ships operating in polar regions and depends on their international certification requirements. The regulatory framework is goal-based, meaning that it sets various requirements for safe operations which operators need to meet, but does not prescribe how these results should be achieved. This approach applies to various measures that pertain to a combination of processes, procedures, equipment and systems. Since there is no standardized approach for these procedures, a major part of the responsibility is attributed to the operators themselves<sup>10</sup>.

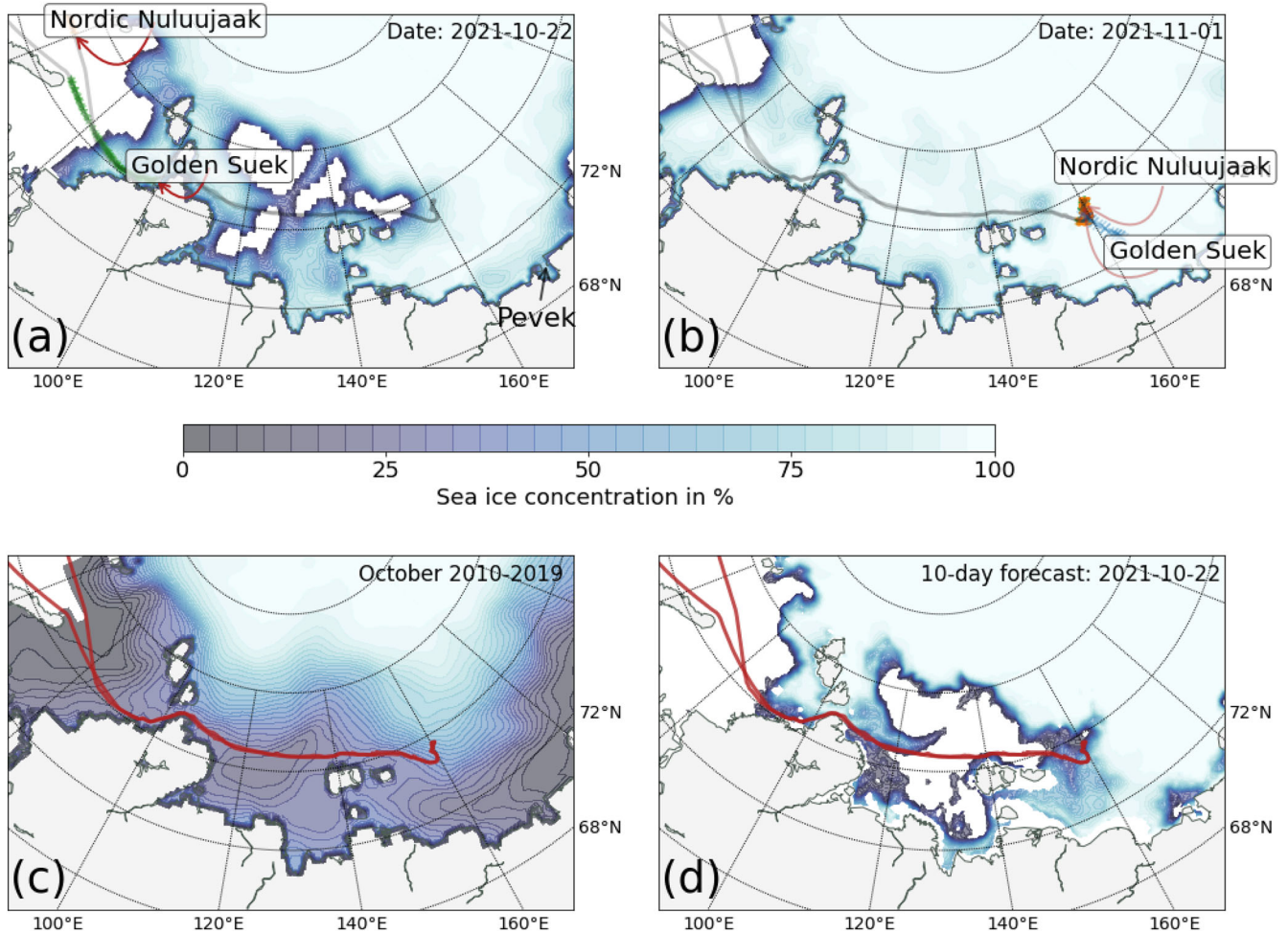
The Polar Code consists of two parts. Part I comprises safety requirements and manning and training requirements. It applies to ships certified in accordance with SOLAS. Part II is on environmental protection requirements and applies to ships that must comply with MARPOL. Note, that non-SOLAS ships that are required to hold a MARPOL certificate (e.g., fishing vessels) only need to comply with the Part II of the Polar Code. However, in November 2022 the IMO approved a set of draft amendments to the Polar Code, with new requirements for certain non-SOLAS ships concerning the safety of navigation and voyage planning. Among other ship types, this will apply to fishing vessels that are longer than 24 m.

In the context of this paper, Part I of the Polar Code, and in particular the part about safety requirements, is the most relevant. First, it outlines requirements for operational limitations in a Polar Ship Certificate for a given vessel. It discerns between three ship categories which are central for defining the requirements and are based on anticipated hazards within the operating environment based on temperature, sea-ice conditions, and latitude of operations. The categorization for sea-ice is listed in Table 1. Part I also includes the Polar Water Operational Manual (PWOM), which is specific to each ship and provides information about the vessel's possibilities and limitations<sup>38</sup>. It includes risk assessment procedures, related to the information required to avoid hazards en route within the boundaries of the operational limitations. In particular, in Division 2 'Ship Operations', Chapter 1 'Strategic Planning', the ship operators need to plan for hazardous environmental conditions, namely sea ice and extremely low temperatures. This strategic planning needs to be in compliance with the ship's sea-ice and Polar Service Temperature classification. In addition, as sources of hazards, 'topside icing' and 'visibility' are mentioned in the Polar Code, however, no additional guidance or categorization is made for those. Hence, the PWOM's is very specific in the description of its measures for avoiding temperatures or sea-ice conditions that may pose a hazard, however, there are no set procedures in the code for other hazardous environmental conditions, nor on how and which information shall be utilized in the decision process.

### AIS data processing

The analyzed AIS data is from the Arctic Ship Traffic Data (ASTD) provided by the Arctic Council working group Protection of the Arctic Marine Environment (PAME). In the present study, the ASTD level 2 data is used and it consists of monthly data sets starting from January 2013, with each containing about 10 to 20 million individual messages, which include information on time, location, ship type, flag, etc. from about 5 to 10 thousand individual ships. ASTD utilizes the IHS Markit StatCode 5 Shiptype Coding System for the categorization of ship types. The ASTD level 2 data utilizes the IHS Fairplay - Level 3 aggregation and groups the data into 15 ship types.

There is no information available from the data provider (PAME) on which satellites are used for the collection of the tracking data. However, in the ASTD Data Document, it is indicated that AIS Class



**Fig. 9 Incident in the Northern Sea Route, October and November 2021.** The shipping tracks of the bulk carriers Nordic Nuluujaak (NN) and Golden Suek (GS) are shown from Oct. 12 to Nov. 13 in gray and red. **a** Shipping tracks of NN and GS are highlighted from Oct. 22 to Oct. 23 and sea-ice cover for Oct. 22 is shown. **b** Shipping tracks, where NN and GS are stuck in the sea-ice, are highlighted from Nov. 3 to Nov. 13 and sea-ice coverage is shown for Nov. 1. **c** The October climatology for 2010 to 2019, and **d** a 10-day sea-ice forecast valid for Oct. 22.

A transponder data from the USA supplements Norway's AIS Class A transponder data. This means that ship traffic is potentially more detailed and more accurate than only relying on one of the transponders as it is the case for nationally provided data. PAME states: 'AIS data in the ASTD system does not cover 100% of all ship traffic, but data quality is very high. This has been confirmed by comparing data from other sources, including nationally collected information. Identifying smaller pleasure craft and fishing vessels can be challenging because of limitations in registries and AIS information.' Other AIS limitations are factors that affect the transmission and receipt of AIS signals, including technical failure due to faulty infrastructure, erroneous onboard installation, problems with data networks, manipulated AIS signals, and challenges regarding satellite coverage.

For our study, we grouped types of ships into 7 distinct categories (Table 2). The messages are then quality-controlled to allow for consistent ship-tracks and the information on the daily mean position, ship type, and ship-size is extracted. For the quality control for each individual ship a ship track is computed and outliers in terms of space and time are removed.

#### Sea-ice satellite product and atmospheric reanalysis

Sea-ice concentration is a daily product provided by the University of Bremen. It is obtained from a remote sensing instrument for measuring weak microwave emissions from the surface and the

**Table 2.** Categorization of ship types.

Ship types used in the present study	ASTD - Ship types
Chemical & Gas	Chemical tankers Gas tankers
Bulk carrier & Cargo	Bulk carriers General cargo ships Container ships Ro-Ro cargo ships Refrigerated cargo ships
Offshore services	Offshore supply ships Other service offshore vessels
Other	Other activities
Fishing	Fishing vessels
Crude oil & products	Crude oil tankers Oil product tankers
Passenger & Cruise	Passenger ships Cruise ships

The ASTD level 2 data utilizes the IHS Fairplay - Level 3 aggregation and groups the data into 15 ship-types (ASTD - Ship types right column, [https://www.pame.is/images/03\\_Projects/ASTD/Ship\\_type/ASTD\\_Ship\\_types.xlsx](https://www.pame.is/images/03_Projects/ASTD/Ship_type/ASTD_Ship_types.xlsx)). For our study, we further grouped types of ships to 7 distinct categories (left column).

atmosphere of the Earth. The AMSR-2 sea ice concentration used here is derived from passive microwave sensors from the 89 GHz channel data and has a spatial resolution of 6.25 km<sup>39</sup>. Sea-ice concentration products which are available from passive microwave sensors have an effective resolution of around O(20 km)<sup>40</sup>.

The atmospheric variables (10-meter wind speed and 2-meter temperature) are from the ERA5 atmospheric reanalysis which utilizes cycle 41r2 of ECMWF's Integrated Forecast System (IFS), with a horizontal T639 resolution (~36 km resolution) and 137 vertical levels<sup>41</sup>. In ERA5 sea-ice is prescribed from 1979 to 2007 by the HadISST2<sup>42</sup> and from 2007 to 2021 by the OSTIA<sup>43</sup> satellite products<sup>44</sup>. The daily mean sea surface temperature, daily minimum 2-meter temperature, and maximum daily 10-meter wind speed are used in the present study. Due to the sparse observation network in the Arctic, the uncertainties are higher than in lower latitudes<sup>24</sup>. An important systematic error is a warm bias over sea-ice with values of around 2 to 5 K in the Arctic winter<sup>45,46</sup>. We assume that wind speed has errors (RMSE) of about 2–3 m/s in Arctic areas based on a study with the predecessor atmospheric reanalysis ERA-Interim<sup>22</sup>.

### Sea-spray icing

Sea-spray icing is calculated following the algorithms developed by Overland (1990)<sup>18</sup> for the icing predictor *PPR*:

$$PPR = \frac{v(T_f - T_a)}{1 + 0.3(T_w - T_f)} \quad (1)$$

where  $v$  is the wind speed,  $T_f$  freezing point of seawater (−1.7 °C),  $T_a$  the 2-meter air temperature, and  $T_w$  the sea surface temperature. The icing class of light, moderate, heavy, and extreme follows the guide given in Overland (1990) and are corresponding to below 0.7, 0.7–2.0, 2.0–4.0, and above 4.0 cm h<sup>−1</sup> icing rates. Note, these are only estimates since the algorithm is simplified and does not include wave conditions or ship characteristics.

### Data analysis, uncertainties, and linear trend

The daily AIS ship positions are co-located in space and time with the sea-ice concentration fields and atmospheric reanalyses. The AIS data is analyzed for seven regions, i.e., pan-Arctic, the Northern Sea Route, Svalbard, East Greenland, West Greenland, North West Passage, and Chukchi-Bering Sea (Fig. 1). On the one hand, the number of individual ships and days of shipping in these specific areas is extracted from the AIS data set, on the other hand, the number of shipping days with sea-ice concentration larger than 80%, temperatures below −20 °C, and a sea-spray icing classification are calculated. The main measure in the present study is shipping days per month, as a measure of the time period ships are exposed to certain environmental conditions in the Polar Code region. For the calculation of linear trends, the time series are presented as annual means and a linear regression is performed. All trends given in the analysis are having a confidence larger than 98% ( $p$ -values smaller than 0.02).

Based on the uncertainties in the input data of our analysis, we estimate potential implications for our results and conclusions. (1) There is a potential underestimation of ship tracks due to the limitations of the AIS data. (2) A potential underestimation of ships in low-temperature conditions due to the warm bias in ERA5 over sea-ice. (3) The effective spatial resolution of the sea-ice product of around 20 km is problematic and can lead to a misdetection of ships close to the sea ice edge. Usually, the sea-ice edge is considered with sea-ice concentration levels of 10–20%. However, for our results we use an 80% sea-ice concentration threshold, to make the analysis more robust. (4) The sea spray icing estimate is based on the wind and temperature of ERA5. Uncertainties in those estimates can be expected, however, the indication of

where and when ships are exposed to heavy/extreme icing can be assumed to be reliable, which is further supported by a case study.

### DATA AVAILABILITY

The ERA5 data are available from the Copernicus Climate Change Service (C3S) Climate DataStore (<https://cds.climate.copernicus.eu/>). The AMSR2 sea-ice product is retrieved from the University of Bremen (<https://seaice.uni-bremen.de/data/amr2/>). The extracted values from both data sets will be made available as part of a GitHub repository. AIS level 2 data is available through the ASTD.

### CODE AVAILABILITY

The extracted data from ERA5 and the code (python) in order to reproduce the analysis in this paper will be made available as a GitHub repository.

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## AUTHOR CONTRIBUTIONS

M.M.: Writing—original draft, conceptualization, methodology, software, formal analysis, visualization, funding acquisition. M.K.-K.: Writing—original draft, conceptualization, project administration, funding acquisition. J.J.: Writing—original draft, conceptualization. C.P.: Writing—review & editing.

## COMPETING INTERESTS

The authors declare no competing interests.

## ADDITIONAL INFORMATION

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**Correspondence** and requests for materials should be addressed to Malte Müller.

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