Application of the IMO taxonomy on casualty investigation: Analysis of 20 years of marine accidents along the North-East Passage

Laurent Fedi, Olivier Faury, Laurent Etienne, Ali Cheaitou, Patrick Rigot-Muller

▶ **To cite this version:**

Laurent Fedi, Olivier Faury, Laurent Etienne, Ali Cheaitou, Patrick Rigot-Muller. Application of the IMO taxonomy on casualty investigation: Analysis of 20 years of marine accidents along the North-East Passage. Marine Policy, 2024, 162, pp.106061. 10.1016/j.marpol.2024.106061 . hal-04483233

HAL Id: hal-04483233
https://hal.science/hal-04483233

Submitted on 29 Feb 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Distributed under a Creative Commons Attribution - NoDerivatives 4.0 International License

Abstract

In the context of global warming and ice melting in the Arctic Ocean, maritime activities have significantly increased over recent years. However, the Arctic remains a wild and risky region where marine accidents regularly occur. Despite the difficulty in compiling relevant data on Arctic shipping casualties, we have identified 156 accidents along the North-East Passage (NEP) over the last twenty years. Following a data-driven approach, we combine multiple sources and use the standardized International Maritime Organization (IMO) taxonomy on casualty investigation. We disclose and classify the concerned cases by severity level, cause, age, and type of vessels. We draw the profile of the vessels with the highest accidentology level, ascertain the high-risk areas and the seasons with the highest accident rate. Our results stress that serious casualties represent the largest part of the accidents occurring in this area. Fishing vessels show the highest accident rate, and machinery issues are one of the most common accident types. Furthermore, the NEP accidentology during the last two decades does not seem to decline unlike the downward trend elsewhere around the globe. Finally, we call for greater reporting of marine accidents and compliance with the IMO risk classification to better understand accidentology in this growing shipping zone. A plea in favor of stricter enforcement of the Polar Code and a holistic risk-based policy combining mandatory and non-mandatory measures are notably suggested to prevent casualties in the near future.

Keywords: Arctic navigation, maritime accidents, risk analysis, IMO Casualty Investigation Code, Polar Code.

Application of the IMO taxonomy on casualty investigation: Analysis of 20 years of marine accidents along the North-East Passage

Laurent Fedi[1*], Olivier Faury[2], Laurent Etienne[3], Ali Cheaitou[4], Patrick Rigot-Muller[5]

[1]KEDGE Business School, CESIT, Maritime Lab, Domaine de Luminy, 13288 Marseille, France, laurent.fedi@kedgebs.com
[2]École de Management de Normandie, Métis Lab, 20, rue de Richelieu 76087 Le Havre, France - ofaury@em-normandie.fr
[3]LabISEN, 20 Rue Cuirasse Bretagne, 29200 Brest, France, laurent.etienne@yncrea.fr
[4]Department of Industrial Engineering and Engineering Management, University of Sharjah, United Arab Emirates, acheaitou@sharjah.ac.ae
[5]Maynooth University School of Business, Maynooth, Ireland Patrick.RigotMuller@mu.ie

[*]Corresponding author

Abstract

In the context of global warming and ice melting in the Arctic Ocean, maritime activities have significantly increased over recent years. However, the Arctic remains a wild and risky region where marine accidents regularly occur. Despite the difficulty in compiling relevant data on Arctic shipping casualties, we have identified 156 accidents along the North-East Passage (NEP) over the last twenty years. Following a data-driven approach, we combine multiple sources and use the standardized International Maritime Organization (IMO) taxonomy on casualty investigation. We disclose and classify the concerned cases by severity level, cause, age, and type of vessels. We draw the profile of the vessels with the highest accidentology level, ascertain the high-risk areas and the seasons with the highest accident rate. Our results stress that serious casualties represent the largest part of the accidents occurring in this area. Fishing vessels show the highest accident rate, and machinery issues are one of the most common accident types. Furthermore, the NEP accidentology during the last two decades does not seem to decline unlike the downward trend elsewhere around the globe. Finally, we call for greater reporting of marine accidents and compliance with the IMO risk classification to better understand accidentology in this growing shipping zone. A plea in favor of stricter enforcement of the Polar Code and a holistic risk-based policy combining mandatory and non-mandatory measures are notably suggested to prevent casualties in the near future.

Keywords: Arctic navigation, maritime accidents, risk analysis, IMO Casualty Investigation Code, Polar Code.

1. Introduction

Over the last two decades, the North-East Passage (NEP) has become a matter of increased scientific interest, mainly due to the capabilities and economic potentials of the Northern Sea Route (NSR) compared to the Suez Canal Route (SCR) and Panama Canal (Faury et al., 2019; Kiiski, 2017; Pruyn, 2016). The impacts of global warming do not spare the Arctic Ocean (IPCC, 2022; Melia et al., 2016) and the presence of ice-free areas is more frequent, especially during summer.

The NEP is composed of the Norwegian Sea and of the following seas in the Russian waters: Barents Sea, Kara Sea, Laptev Sea, East Siberian Sea (Vostochno-Sibirskoye), Chukchi Sea, Bering Sea and Northern-Pacific. Open since 1991 (Pruyn, 2016; Zhang et al., 2016), the NSR extends for around 3,000 miles (4,800 km) and is managed by the 'Northern Sea Route Administration' (NSRA)[1] which monitors and controls navigation. Sailing along the NSR is generally feasible from July to November (ABS, 2014) while icebreaker assistance is often necessary. Throughout 2017 and 2022, the volume traffic on the NSR tripled reaching more than 34 million tons (CHNL, 2023). This increasing traffic is mainly due to the development of oil and gas projects in the Russian Arctic (Faury et al., 2020; Faury and Cariou, 2016; Humpert, 2014; Marchenko, 2014a) attracting investments in port infrastructures (Gritsenko and Efimova, 2017), such the Yamal LNG plant in the Ob Bay (Rigot-Muller et al., 2022) and the Prirazlomnoye platform in the Pechora Sea. Consequently, maritime traffic should progressively grow in the next decade (Iudin and Petrov, 2016) not only in terms of liquid or dry bulk but also for passengers (Palma et al., 2019). Bearing this in mind, the current conflict with Ukraine is likely to slow this continued growth as underlined by the reduction in foreign investments in Russia (OECD, 2022) and by the latest figures showing a slight downward trend (CHNL, 2023).

Nevertheless, the rise of maritime traffic in the NEP is not exempt from future challenges, especially regarding maritime safety and environmental protection. In response, the International Maritime Organization (IMO) adopted the 'International Code for Ships Operating in Polar Waters' called 'Polar Code' (PC hereafter) (IMO, 2014). Further, whereas some studies have already highlighted the accidentology patterns in this zone (Marchenko, 2012a; 2012b; FoU, 2016; Fedi et al., 2020a; 2020b), the picture provided is often fragmented and not standardized pursuant to the IMO Casualty Investigation Code (IMO, 2008). This absence of proper classification combined with a long trend of underreporting limits the understanding of marine accidents in the Arctic and prevents insurance companies from properly assessing the related risks (Fedi et al., 2018a).

Based on a 20-year observation from 2000 to 2020, this paper aims to categorize and map marine accidents that occurred along the NEP, including the Russian and Norwegian Arctic zones. It also draws the profile of accident-prone ships and ascertains the high-risk areas and the seasons with the highest accident rate. The main contributions of the paper are to:

- provide a deeper knowledge and understanding of marine accidentology in the NEP that still appears as a "black box" while this zone is deemed to welcome more maritime traffic,
- compare the ships' age subject to accidents to the age of ice-class vessels,
- put into perspective both the accidents map and existing/forthcoming infrastructures which may harbor Search and Rescue (SAR) operations,
- and define a holistic risk-based policy to prevent serious casualties in this zone.

[1] http://www.nsra.ru/en/glavnaya/celi_funktsii.html

Following the Introduction, Section 2 reviews the existing literature on marine accidentology in the Arctic and along the NEP. The methodology is explained in Section 3 while Section 4 focuses on the accident analysis and taxonomy. An in-depth discussion is proposed in Section 5 whereas conclusions are addressed in Section 6.

2. Marine accidentology in the Arctic and along the NEP: a literature review

2.1. NEP flows, risk models, and mitigation tools

There are currently three main areas for navigation within the Arctic, the North-West Passage (NWP), the Transpolar Route (TPR), and the North-East Passage (NEP) (Bennet et al., 2022). As the ice melts, the NWP and the NEP represent two future strategic routes allowing shipowners to significantly reduce distance and therefore time between the Atlantic and Pacific basins (Theocharis et al., 2018; Schøyen & Bråthen, 2011). These routes offer potential savings in terms of bunker costs (e.g. Cheaitou et al., 2020; Cariou et al., 2019; Cariou and Faury, 2015; Liu & Kronbak, 2010) while the assessment of the related air pollutant emissions remains questionable (Zhu et al., 2018; Yumashev et al., 2017; Lindstad et al., 2016). Between 2013 and 2019, a 75% increase has been observed in the distance sailed by ships in the Arctic Ocean (PAME, 2020). Moreover, maritime shipping in the NEP have substantially grown since 2010 (Faury et al., 2021), and notably thanks to Russia encouraging investments along its shores (Staalesen, 2018; 2019; Ministry of Energy of the Russian Federation, 2010; Russian Government, 2020, 2022). If the maritime activities are diversified (Faury et al., 2021; Marchenko et al., 2018; AMSA 2009), bulk trade is dominant (Gunnarsson, 2021) with more heavy parcels (Rigot-Muller et al., 2022). The western and eastern parts of the NEP welcome cruise and fishing vessels (Fu et al., 2021; Halliday et al., 2018) knowing that the latter constitutes more than half of the traffic in these areas (Silber and Adams, 2019).

However, sailing in the Arctic involves numerous inherent risks. A large combination of hazards, linked to harsh climate conditions, icebergs, ice presence and thickness during most of the year, very low temperatures, shallow waters, poor visibility, lack of up-to-date charts (Pastusiak, 2015), remoteness (Fedi et al., 2020a), the scarcity of navigational aids and SAR infrastructures (Christodoulou et al., 2022; Bentz et al., 2021; Parviainen et al., 2019; SARC, 2017) represent huge challenges for ships, crew (Montewka et al., 2015) and local communities (Afenyo et al., 2022). Significant investments have been recently made in port development and icebreaker fleet renewal to improve the safety response system (Gritensko & Efimova, 2017; Moe & Brigham, 2017). Risk appraisal is also paramount for underwriters who dread a second Titanic (Fedi et al., 2018a) and for shipowners (Tseng and Cullinane, 2018) who pay particular attention to technical factors notably communication tools, hydrographic data and icebreaker assistance (Gritsenko & Kiiski, 2016). Scholars and specialized bodies have evaluated these risks both for the Arctic Circle (Baksh et al., 2018; FoU, 2016; Marchenko et al., 2015; Kum and Sahin, 2015; AMSA, 2009) and for the Russian Arctic more specifically (Fedi et al., 2020a; Vihanninjoki, 2014; ABS, 2014; Marchenko, 2012a, 2012b, 2014a). This singular context has fostered growing research on risk management (for a synthesis: Fu et al., 2021) and risk analysis models applied to Arctic shipping, especially in ice-covered waters (for a review: Xu et al., 2021).

Polar risk management has been transposed in the PC (IMO, 2014) that entered into force in 2017 through a formal "proceduralization of risk mitigation" (Fedi, 2019) imposing new requirements such as the Polar Ship Certificate (PSC), the Polar Water Operational Manual (POWM) or the "Voyage Planning." Moreover, the mandatory and risk-and-goal-based PC (Henriksen, 2014; Bai, 2015) clearly identifies the risks that ships may face during navigation and sets out procedures to assess, control, and mitigate them. To prevent risk occurrence, the PC lays down different rules mainly focused on safety and secondarily on environmental

protection that frame the ship's "polarseaworthiness", i.e., her capacity to meet the very specific hazards of polar waters (Rigot-Muller et al., 2022). As shown in Fig. 1, the PC provisions are completed by the 'Polar Operational Limit Assessment Risk Indexing System' (POLARIS) that evaluates vessel operational capacities in different ice conditions as per the ship class (IMO, 2016). As the 'Arctic Ice Regime Shipping System' (AIRSS), POLARIS has a direct impact on the ship's operational evaluation and supports the decision-makers for a safer route (Fedi et al., 2018b) while it also shows some limitations (Bergström et al., 2022; Browne et al., 2022; Lee et al., 2021).

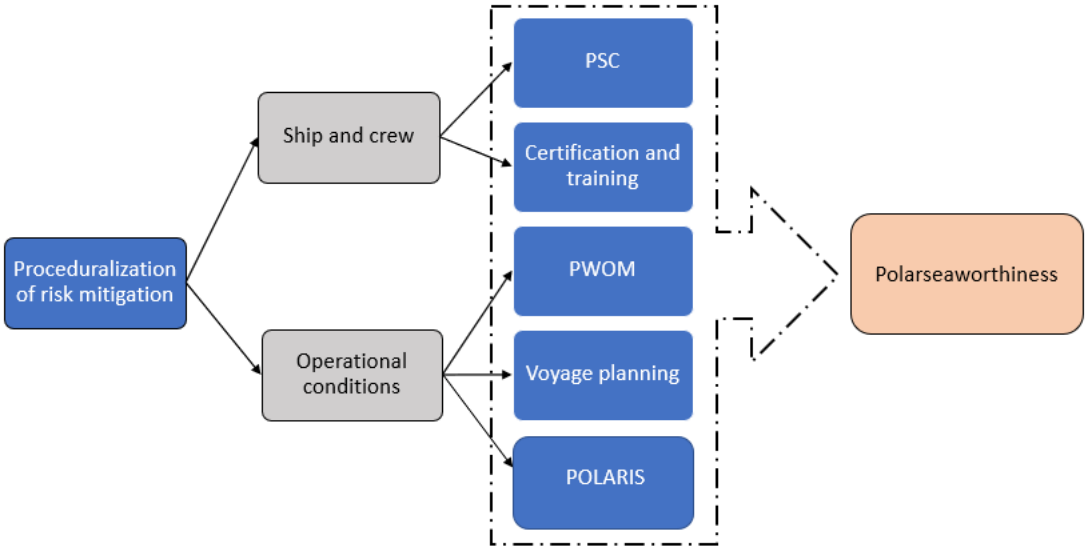

FIG. 1 The PC and proceduralization of risk mitigation

Source: based on Rigot-Muller et al. (2022) and Fedi (2019)

2.2. Knowledge of marine accidents at international level

Marine accidents are regularly reported through public and private institutions (Goerlandt & Liu, 2023). At international level, the IMO which unifies the rules on maritime safety, security, and environmental protection (Fedi, 2021; Monios, 2020), provides a database called "Global Integrated Shipping Information System" (GISIS) with a dedicated portal to "marine casualties and incidents"[2] maintained by IMO members further to the 2008 Casualty Investigation Code (IMO, 2008). Entered into force in 2010, this instrument sets out that "investigation and proper analysis of marine casualties and incidents can lead to greater awareness of casualty causation and result in remedial measures, including better training, for the purpose of enhancing the safety of life at sea and protecting the marine environment". That is why states must notify casualties when they occur and submit their *final marine safety investigation report* to the IMO (Chapter 14, Part II). At the European level, the same policy is implemented pursuant to Directive 2009/18/EC, and the member states associated with Iceland and Norway also notify casualties occurring in their waters or caused by their flag ships (EP, 2009) through the "European Marine Casualty Information Platform" (EMCIP).[3] Furthermore, private bodies such as the International Union of Marine Insurance (IUMI), and insurance companies such as Lloyds or ALLIANZ, regularly publish reports on shipping accidentology. Recent studies have underlined the lowest record of losses with 38 in 2022 compared to 207 in 2000 thanks to better ship designs, technological innovations, port operations, updated charts and risk management (ALLIANZ, 2023). While one could observe fewer accidents globally over the last decade,

[2] https://gisis.imo.org/Public/MCI/Default.aspx
[3] http://www.emsa.europa.eu/emcip.html

some reports have emphasized an increase of accidents in the Arctic Circle especially between 2012 and 2017 (CASA, 2021; ALLIANZ, 2021).

2.3. Knowledge of marine accidents in the Arctic and along the NEP: a 'black box'?

Statistics on marine accidents in Arctic waters are still limited nowadays. This limitation mainly lies in the fact that, compared to traditional maritime areas, shipping is not yet very developed in this zone due to risky sailing conditions (Lasserre et al., 2016; Fu et al., 2016; Haavik, 2017). The underlying risks exist even more substantially in the Russian Arctic and then along the NEP eastern part which is characterized by adverse variable weather conditions aggravated by persistent ice cover even in summer (ABS, 2014; AMSA, 2009). Ice features vary among ice massif or concentrated ice, drifting icepacks that make sailing difficult, hazardous, and unpredictable (Abbassi et al., 2017; Marchenko, 2012a, 2012b, 2014a).

Underreporting is the second key reason (Goerlandt et al., 2017; Fedi et al., 2020a) and consultation of the GISIS reveals the states' shortcomings (Fedi et al., 2020b). One assumes that states unequally comply with the IMO Casualty Investigation Code, and some events are not reported in the relevant databases. That is why we use the "black box" metaphor. It should also be noted that the Casualty Investigation Code only requires member states to notify "marine casualty" (art. 5.1) and to draft a "safety investigation" for "very serious marine casualty" (art. 6.1), meaning that investigation as regards simple "marine incident" and "serious casualties" is not mandatory.

Additionally, even though some reports have been published, they provide general data, a limited period of analysis, little or no details on the concerned vessel's characteristics and on the precise location of the accidents that hinder appropriate evaluation of Arctic accidentology (Grabowski et al., 2009; Fedi et al. 2020a). This is the case of AMSA (2009) between 1995-2004 but without the Russian Arctic, the yearly accident figures from ALLIANZ which never disclosed the concerned areas (ALLIANZ, 2014-2021) and the FoU (2016) report (2010-2015 period) which only focused on specific zones along the NEP. In the same vein, the 'Compendium of Arctic Shipping Accidents' (CASA) launched to collect statistics on Arctic marine accidents published a first study encompassing 12 years (2005-2017) which provided a general picture (CASA, 2021). Scholars carried out complementary analyses notably Marchenko (2012b) throughout the 1990-2010 period, Kum and Sahin (2015) for 1993-2011 and Fedi et al. (2020a; 2020b) as regards the 1991-2011 and 2007-2018 timeframes. As summarized in Table 1, the different published studies dealing with marine accidentology in the Arctic Circle including the NEP illustrate that data are currently discontinued, fragmented, and not fully standardized pursuant to IMO rules.

TABLE 1 Marine accidentology in Arctic Circle and NEP

Source	Timeframe	Zone	Number of reported cases	IMO taxonomy
AMSA report, 2009	1995-2004	Arctic Circle	293	No
Marchenko, 2012b	1990-2010	Russian Arctic	90	No
Kum and Sahin, 2015	1993-2011	Arctic	65	No
FoU Rapport, 2016	2010-2015	Arctic – High North: Russian Norwegian, Icelandic, Greenlandic waters	1702	No
ALLIANZ annual reports	2005-2021	Arctic Circle	688	No

CASA report, 2021	2005-2017	Arctic Circle: Canada, Denmark, Iceland, Norway, Russia, United States	2638	No
Fedi et al., 2020a	2007-2018	Russian Arctic	30	Yes
Fedi et al., 2020b	1991-2011	Russian Arctic	145	Yes

Moreover, the scarce data has been often coupled with approximate terminology. One notices that professional reports such as ALLIANZ (from 2014 to 2022), AMSA (2009), FoU (2016), CASA (2021) are generally vague on those events by concurrently referring to the notion of "incidents" or "accidents." Obviously, this current weakness found in other reports (Ladan & Hänninen, 2012) involves some confusion on the standardization of casualties, hiding their acuity level and thus their clear understanding (Xu et al., 2021; Fedi et al., 2020a; 2020b; Goerlandt et al., 2017).

Furthermore, as explained by Fu et al. (2021), most of the previous analyses are generally based on expert interviews due to the lack of information, they emphasized specific accident scenarios rather than accident reports and provided quantitative models to prevent their occurrence. While these authors recognized the usefulness of quantitative models "as a basis for identifying risk control options and developing management strategies", they finally questioned their "evidence base" and recommended "non-linear and data-driven approaches" for future research. Our paper attempts to fill this gap using a data-driven approach and to enrich the Arctic shipping accident statistics with a focus on the NEP considering its development that may relatedly induce more accidents.

3. Methodology

First, we have created our database for the period 2000 to 2020 via different sources such as IHS Markit database, marine investigation reports from CLARKSONS, the IMO GISIS, the existing literature on maritime accidents and specialized websites. We combined data coming from different sources to include the maximum number of incidents/accidents that occurred along the NEP. In line with other studies on maritime accidents (Luo & Shin, 2019), this cross-collection search is justified by the fragmented data from existing sources and by the difficulty in accessing appropriate statistics as stressed by Xu et al. (2021). These databases mainly provided temporal data (day, month, year), spatial data (latitude, longitude, accident area), data regarding the ship (age, type, class, dead weight (DWT)), and the main causes of the related events. We have identified 28 different primary reasons that we have classified into eight accidental factors (Table 2). We have selected the events that occurred along the NEP including the Russian and Norwegian Arctics, i.e., Northern Pacific, Laptev, East Siberian, Chukchi, Bering, and Okhotsk Seas. We justify the choice of the NEP since this represents a wider zone compared to the sole NSR, and it concentrates the busiest shipping area, especially in its western part. Second, we have defined the severity level of the different cases in accordance with the proper taxonomy of the IMO Casualty Investigation Code (IMO, 2008). Third, based on Faury et al. (2021), we have highlighted the level of remoteness of accident locations compared to the existing and forthcoming infrastructures. Fourth, we have underlined the most accident-prone ships. A special attention has been given to the age of the concerned vessels compared to the current fleet of ice-class vessels. We have identified the high-risk areas and the seasons with the highest accident rate, and we finally designed the related maps. The different steps that have been followed in the proposed methodology are detailed in Fig. 2.

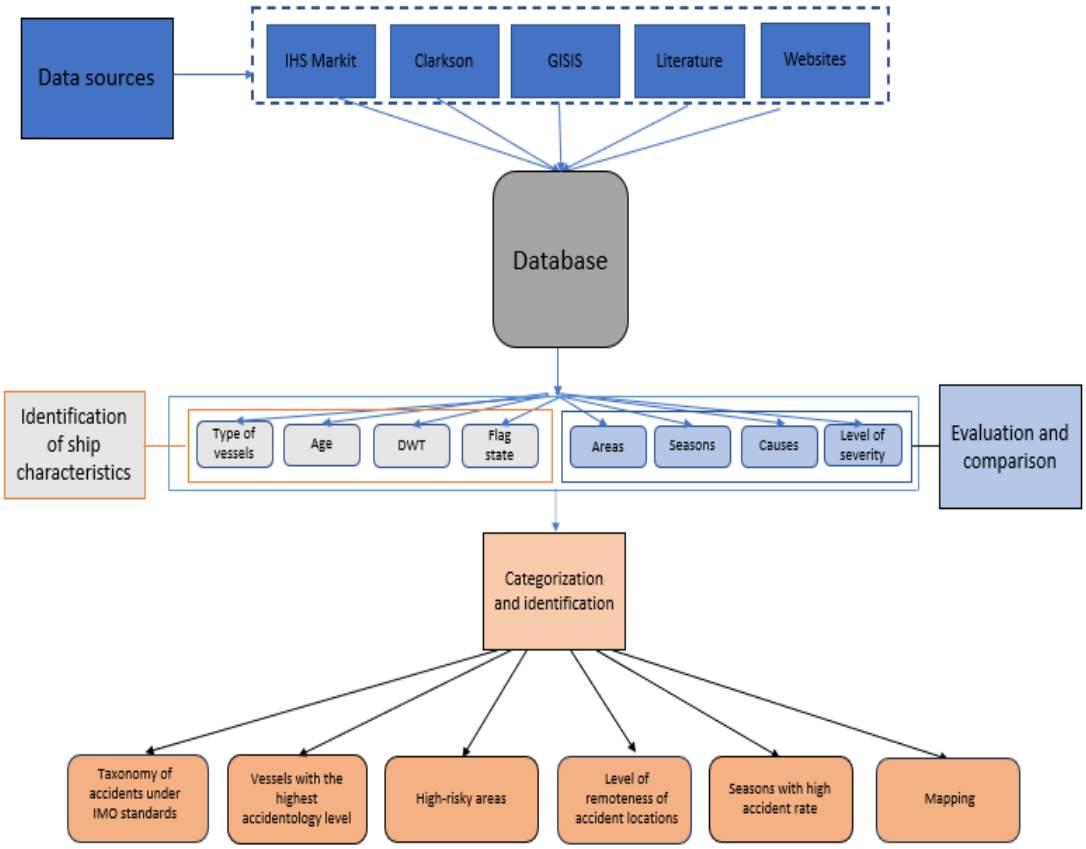

FIG. 2 Methodology model

TABLE 2 Accident factors and definition

Accident factors	Definition
Climate	Natural event that will endanger the ship safety and her crew leading to simple incident or casualty. E.g., stuck in ice/listing/ice contact/icing losing stability/collision with ice/propeller - ice conditions/storm
Hull damage	"Failures affecting the general structural strength of the ship." E.g., holed, cracks, structural failure/missing/overdue/went off mooring/ lost anchor
Machinery damage/failure	Damage or failure to ship machinery caused by external or internal events. E.g., Lost rudder, fouled propellor/temporary equipment breakdown/propeller entangled in own net, adrift/ propeller entangled in own net, adrift grounded/ engine failure/propeller fouled
Wreck/stranding	"Event during which a moving navigating ship, either under command (power), or not under command (drift), strikes the sea bottom, shore or underwater wrecks."
Fire/explosion	"Fire is the uncontrolled process of combustion characterized by heat or smoke or flame or any combination of these. Explosion is an uncontrolled release of energy which causes a pressure discontinuity or blast wave."
Collision	"A casualty caused by ships striking or being struck by another ship, regardless of whether the ships are underway, anchored or moored. This event might involve two or more ships."
Contact	"Contact is a casualty caused by a ship striking or being struck by an external object, floating, fixed, or flying (the sea bottom is excluded)." e.g., Contact with ice or harbor wall
Unknown	The accidental cause is not identified.

Source: Investigated cases by authors and definitions from EMSA report (2018)

To ease the analysis, we have gathered the vessels into 11 categories as shown in Table 3.

TABLE 3 Consolidation of fleet vessel types

Ship type	Vessels included
Bulk carrier	Bulk carrier/Bulk carrier with container capacity
Fishing vessel	Fish Carrier/Fish factory/Fishing/Fishing vessel/Trawler
FPSO	Floating Production Storage and Offloading (FPSO) vessel
General cargo	Cargo ship/Cargo vessel/General cargo/General cargo with container capacity/Palletized Cargo carrier
Icebreaker	Icebreakers
LNG	LNG (Liquified Natural Gas) carrier
Passenger	Cruise ship/Ferry/Passenger/Passenger ship/Ro-Ro
Reefer	Reefer
Tanker	Chemical tankers/Combined chemical & oil Tanker/Oil product tanker/Tanker/Water tanker

Tug	Tug
Supply vessel	Supply vessel

We have then categorized accidents pursuant to the proper terminology of the Casualty Investigation Code. Two categories are in force: "marine incident" (MI) or "marine casualty" (MC) depending on their severity level. As shown in Table 4, the lowest level of severity belongs to MI, the intermediate level is "serious casualty" (SC), and the highest is "very serious casualty" (VSC). This study did not evaluate the human factor and potentially unsafe practices already analyzed (Marchenko, 2009, 2014a; Kum & Sahin, 2015).

TABLE 4 Taxonomy of marine incidents and casualties

Taxonomy	**Marine incident**	**Marine casualty**	
		Serious casualty	**Very serious casualty**
Definition	- Endangers the safety of the ship, its occupants or any other person or the environment	- Fire - Explosion - Collision - Grounding - Contact - Heavy weather damage - Ice damage - Hull cracking - Suspected hull defect - Material damage to a ship - Stranding or disabling of a ship - Material damage to marine infrastructure - Severe damage to the environment	- Total loss of the ship - Death - Severe damage to the environment - Loss, presumed loss, or abandonment of a ship

Source: based on IMO Casualty Investigation Code

Finally, we have provided a detailed list (Appendix 1) with the identification of the respective vessels, their characteristics (name, IMO number, typology, DWT, year of construction, age), the appropriate taxonomy of the case, the location and the season (winter or summer). To the best of the authors' knowledge, little or no studies on Arctic marine accidentology have disclosed this amount of information so far.

4. Accident analysis and taxonomy

We have identified 156 cases that occurred along the NEP throughout the 2000-2020 period. 147 cases (94.2%) are MC which shows an obvious level of severity while 9 cases (5.7%) are MI. Among the MC cases, there are 127 SC (81.4%) and 20 VSC (12.8%) including 16 total losses.

4.1. MI/MC causes: a general overview

As illustrated in Table 5, it appears that *machinery damage* or *failure*, such as lost rudder or fouled propeller, constitute the most recurrent accidents with 57 cases (36.5%) mostly classified

as SC. *Wrecked* or *stranded ships* represent around 20% of the total. *Collision* accounts for around 10.9% and represents mainly SC. Moreover, *climate* is responsible for 16 MC including 3 VSC and equals 12.2% of the total. *Fire/explosion* is implied for more than 8% and involves SC/VSC. Finally, *contact* either with ice or port facilities forms the lowest part with 5.1%.

TABLE 5 Overview of the total distribution of marine accidents/incidents 2000-2020

Causes	Share of causes	MI	SC	VSC
Machinery damage/failure	36.5%	4	51	2
Wreck/stranding	19.9%	0	26	5
Climate	12.2%	3	13	3
Collision	10.9%	0	16	1
Fire/explosion	8.3%	0	10	3
Hull damage	6.4%	2	3	5
Contact	5.1%	0	8	0
Unknown	0.6%	0	0	1
TOTAL	**100%**	**9**	**128**	**19**

TABLE 6 Percentage share of the different levels of accident/incident depending on the cause

Causes	MI	SC	VSC	Total
Hull damage	20.0%	30.0%	50.0%	100.0%
Climate	15.8%	68.4%	15.8%	100.0%
Machinery damage/failure	7.0%	88,5%	3.5%	100.0%
Wreck/stranding	0.0%	83.9%	16.1%	100.0%
Fire/explosion	0.0%	76.9%	23.1%	100.0%
Collision	0.0%	94.1%	5.9%	100.0%
Contact	0.0%	100.0%	0.0%	100.0%
Unknown	0.0%	0.0%	100.0%	100.0%

Table 6 stresses that *machinery damage* occurrences generate mainly SC cases (88.5%) while they rarely lead to VSC (3.5%). *Climate* represents 68.4% of SC and 15.8% of VSC. Weather conditions are directly involved in 19 cases and constitute an aggravating factor for 16 others, especially very low temperatures with heavy weather or freezing conditions which may result in injuries, death of people, and total loss (e.g., Varnek in 2010 with eight killed crew members). Moreover, *hull damage* (holed, cracks, structural failure) clearly involves MC (30 % SC and 50% VSC) as well as *fire/explosion* (76.9% SC and 23.1% VSC). In the same vein, *wrecked/stranded ship* leads to 83.9% of SC and 16.1% of VSC whereas *collision* is mostly responsible for SC (94.1%). One notes that two collisions occurred during ice convoy (M/V SCF Amur and Mary Ugland in March 2010). Finally, *contact* implies 100% of SC.

4.2. Accident-prone ships, accident-prone areas, and seasons

As shown in Fig. 4, it appears that most MI/MC along the NEP concern fishing vessels (FVs), general cargoes, and tankers representing 61.5% of the total. Furthermore, it can be observed that passenger vessels represent 12.8% of MI/MC and constitute the fourth accident-prone ship type. It can also be seen that two MC involved nuclear-powered icebreakers: one

explosion/fire for M/S Arktika in 2007 and one collision M/S Taymyr in 2011. Around 60% of events occur in winter and 40% in summer.

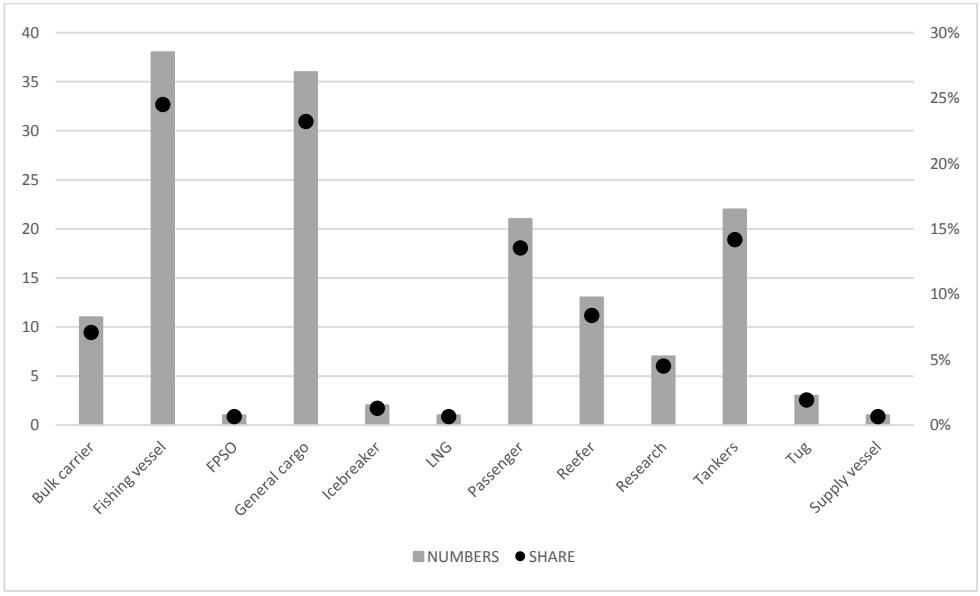

FIG. 4 Distribution of accidents by type of vessels

Fig. 5 reveals that 64.1% of occurrences took place in the Norwegian Sea and the Russian side of the western part of the NEP (Barents, Pechora and White Seas, Kola Bay, and Port of Murmansk) and for the majority during winter. The eastern part of the NEP (Okhotsk, Northern Pacific, and Bering Seas) represents 26.3% of events mainly in winter (75.6%). The NSR (Kara, Laptev, and East-Siberian Seas) accounts for 9.6% of cases which occurred mainly in summer (53%).

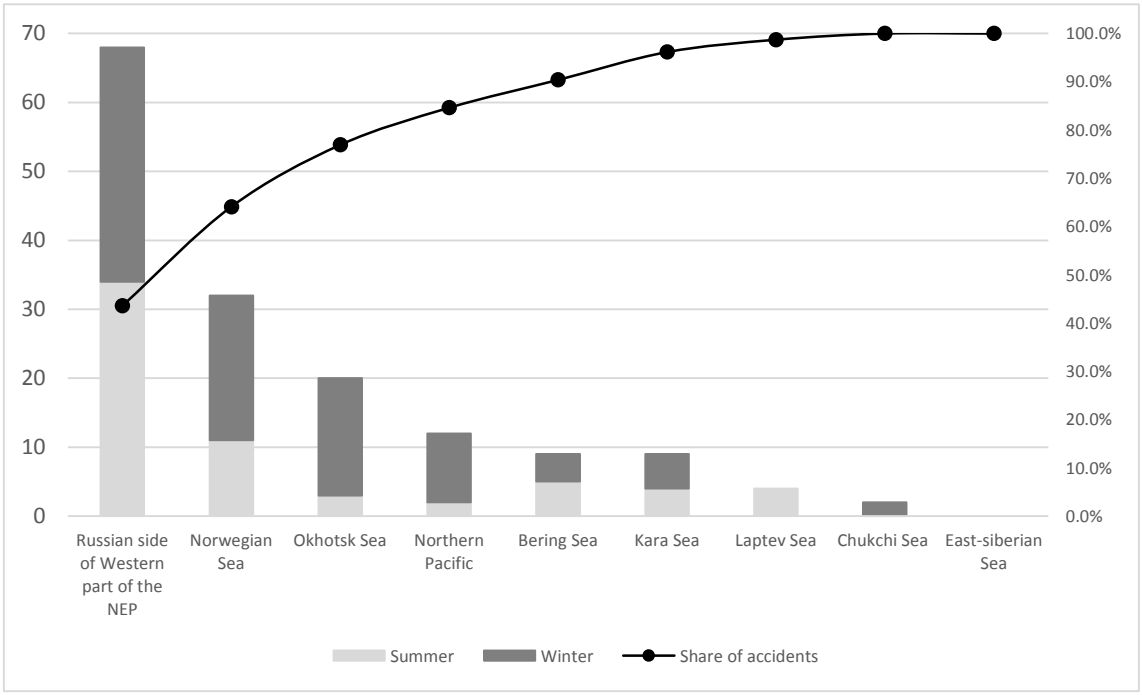

FIG. 5 Distribution of accidents by sea and season

FVs are the most frequent ship type for accident with 24.5% of cases and general cargoes are the second with 23% of the total (Fig. 6). In the Norwegian Sea, cruise ships account for 37.5%, FVs 28.1% and 55% in the Norwegian and Okhotsk Seas respectively. The Kara Sea shows the highest number of accidents along the NSR where tankers and general cargoes represent 44.4 % and 33.3 % of cases respectively.

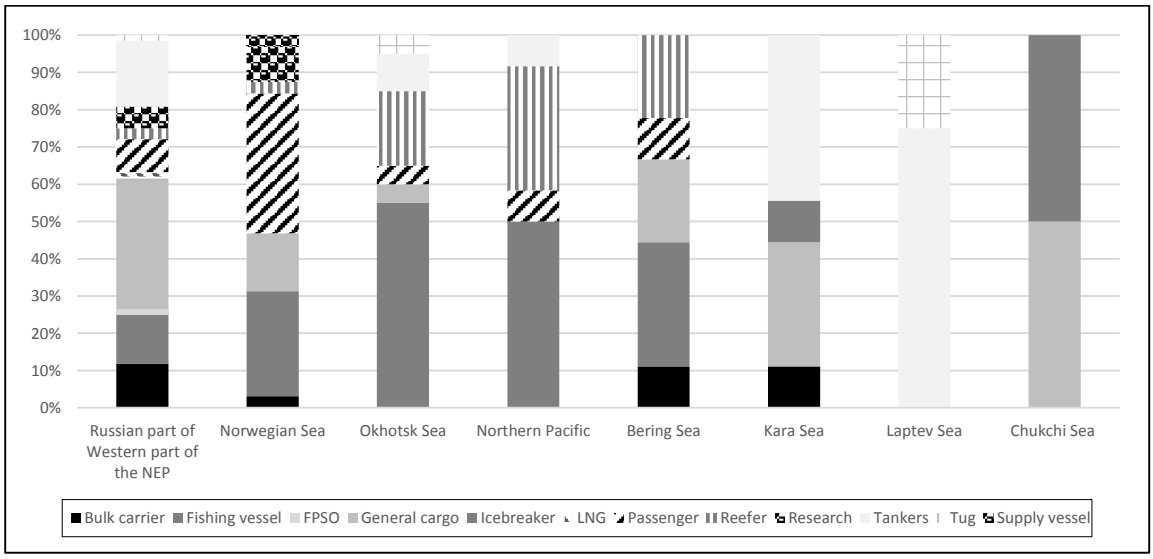

FIG. 6 Distribution of accidents/incidents by ship type and area

Fig. 7 sheds light on the reported cases by season (winter or summer), the existing infrastructures, and their connection with the rest of the national transportation network. One observes that the number of events is much higher in the western part compared to the eastern part. Second, if the number of occurrences regarding the season is greater in winter (60) than in summer (49) for the west (from Norwegian sea to Kara Sea, included), this is not the case for the east (from Laptev Sea to Northern-Pacific) where 14 MI/MC occurred in summer and 17 MI/MC in winter.

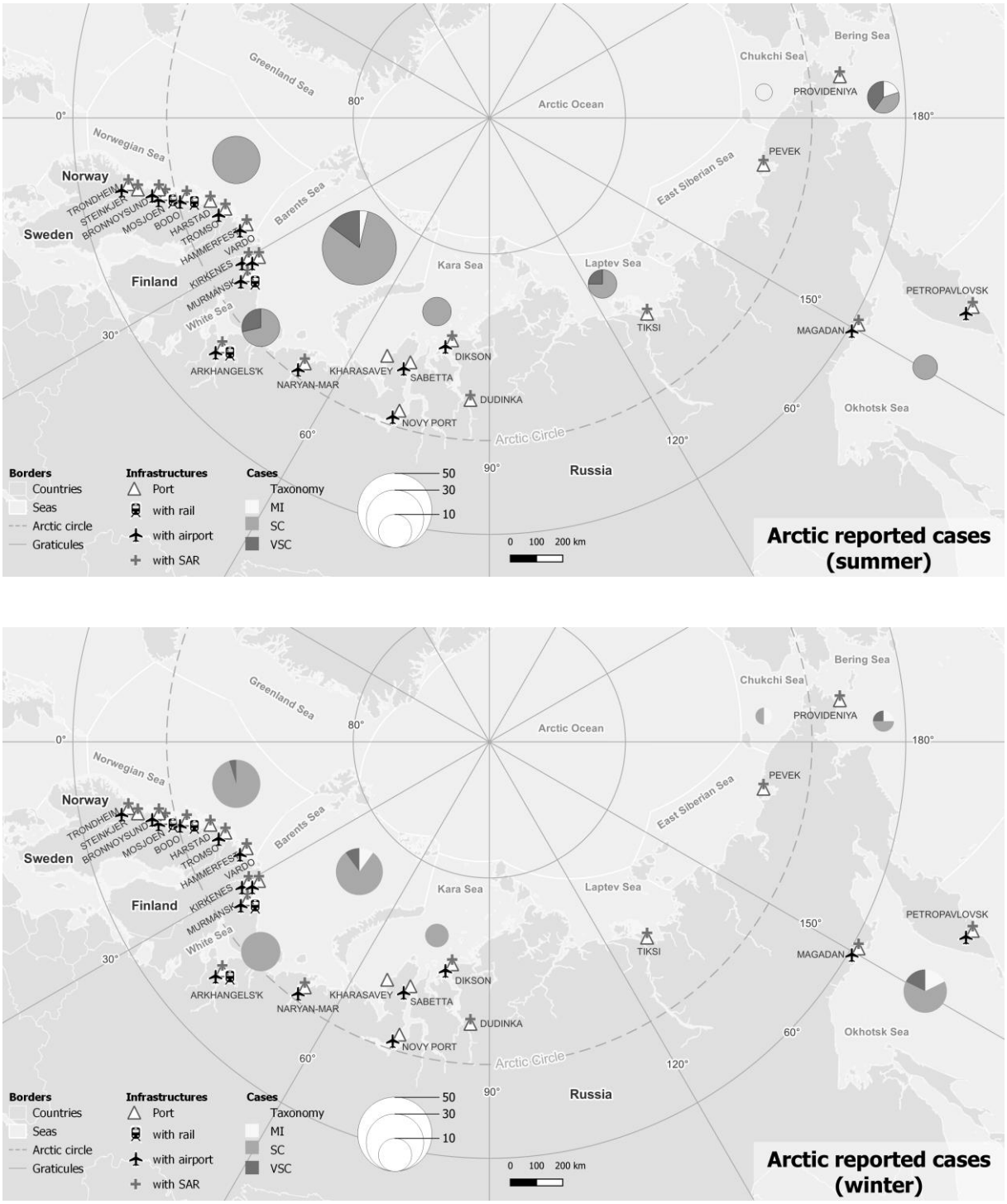

FIG. 7 Marine incidents/accidents per sea and season along the NEP

4.3. Age of the vessels

As illustrated in Fig. 8, except for LNG ships, one notices that most commercial vessels are older than 20 years, with a median age oscillating between 20 and 41.5 years. Tankers and FPSO show a median age of 24 and 28 years respectively. Passenger ships are around 26 years, research vessels around 35 years, FVs more than 21 years and icebreakers 41.5 years.

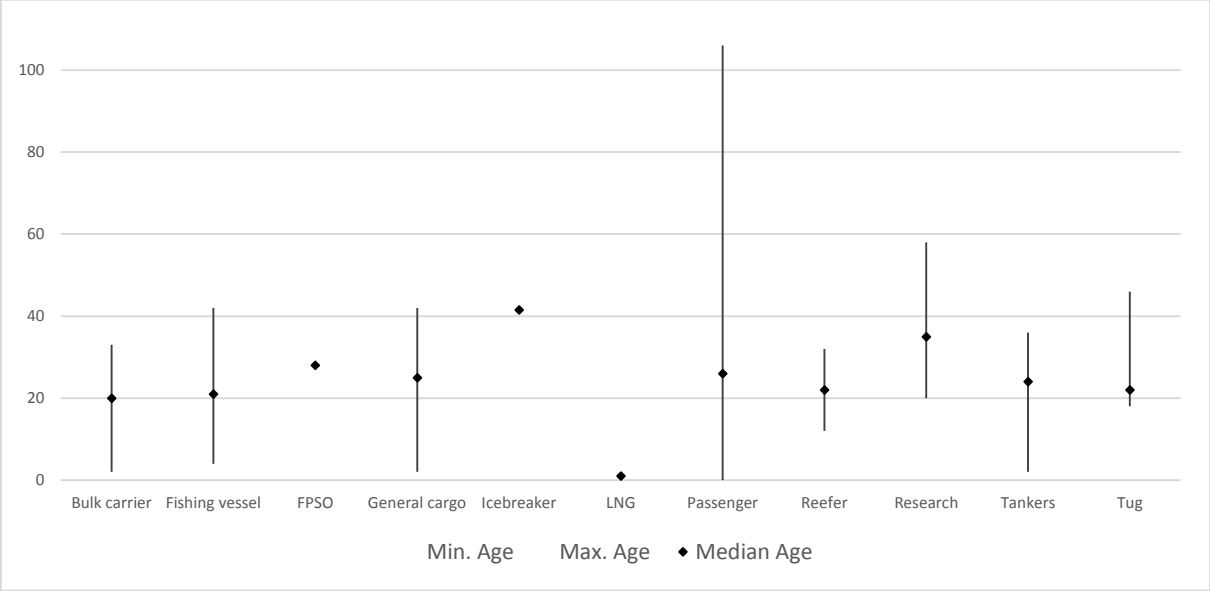

FIG. 8 Minimum, maximum and median age of vessels involved in MI/MC

Furthermore, we compared the median age of ships involved in accidents with the current median age of the world ice-class fleet considering the MI/MC involved by *machinery issue* (Fig. 9). It can be seen that the median age of the existing global ice-class fleet is younger than the median age of the ships from the database used in this study except for reefers (+14) and research vessels (+1). Consequently, it seems that old ships are more prone to *machinery failure* especially general cargo (15 cases) and FVs (11 cases).

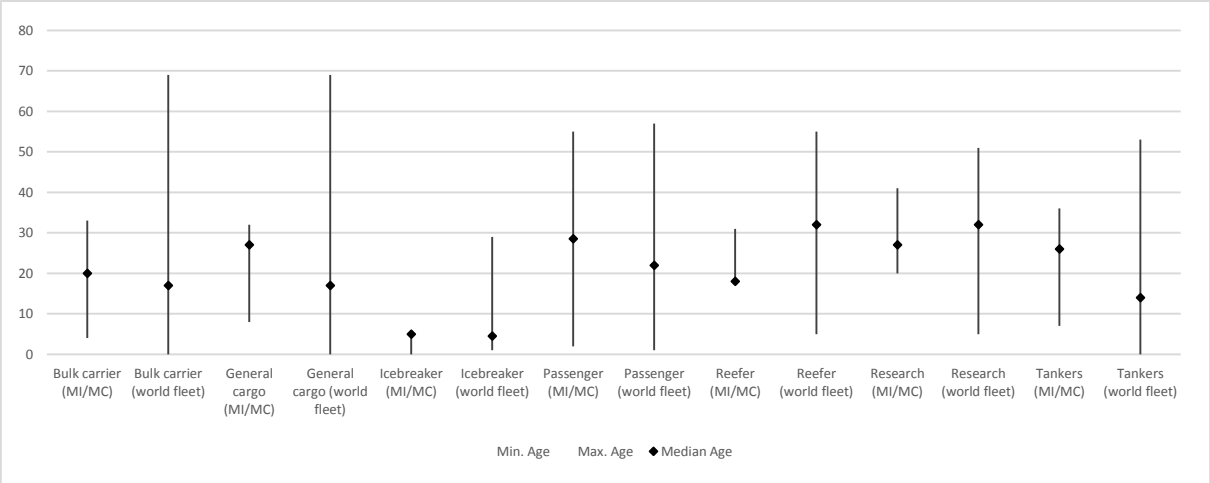

FIG. 9 Age of vessels with machinery issues compared to the existing fleet of ice-class vessels

4.4. Focus on vessels with the highest accidentology level

Table 7 underlines that fishing, general cargo, tanker, passenger, and reefer vessels represent the top five ship categories with the highest accidentology level. The first three types (fishing, general cargo, and tanker) account for 61.5% of the total.

With 38 cases at the two extremes of the NEP, FVs are most prone to accidents, representing 24.4% of the total number of events and 58.8% of total losses. *Machinery issue/damage* constitutes the dominant accident factor followed by *fire/explosion*, *wreck/stranding* and *Climate*. Most of the MI/MC dealing with FVs happened in winter (71.1%). General cargoes constitute the second category with the highest occurrences (23.1%) facing 80% of SC. If we consider that *machinery issues* are correlated with the average vessel's age, these ships were 23.1 years old when the accident occurred with a median age of around 10 years above the median age of the current world fleet of winterized general cargoes. *Machinery damage*, *wreck/stranding*, and *climate* are the main root causes and account for three total losses out of 36 events.

For their part, tankers remain the third accident-prone ships. Involved in 22 cases, mostly SC, they count for 5.88% of the total with a single total loss. *Collision* represents the key accident cause with *machinery damage*, *climate*, and *fire/explosion*. Aged 22.1 years on average, the median age of damaged vessels is 12 years older than the median age of the current winterized tanker fleet. Further, passenger vessels are the fourth type with numerous SC. With 12.9% of the total, they experienced *machinery failure* (30%) and *wreck/stranding* (30%) while *climate* represented for 10% of casualties. However, the average age of the concerned ships (31 years) and their median age are above the current age of ice-class passenger vessels (+6.5 years). Finally, reefer vessels represent the fifth type of vessels with high accident level (8.4%), with 23.5 years in average. These vessels face mostly SC that occur in winter and a wide range of accident factors is noticed from *machinery damage* (7 cases) to *wreck* (3 cases).

TABLE 7 Accidentology per type of vessels and per season

	Share	Mean DWT	Mean Age	Median Age	Summer	Winter	Actual total loss	Machinery damage/ failure	Wrecked/ stranded aground	Climate	Collision (involving vessels)	Fire/ explosion	Hull damage	Contact	Unknown
Fishing vessel	24.5%	851	22.4	21	11	27	9	11	7	5	3	8	3	1	0
General cargo	23.2%	5078	23.1	27	13	23	3	15	8	6	2	0	4	1	0
Tankers	14.2%	16746	22.1	26	13	9	1	5	2	4	7	3	1	0	0
Passenger	13.5%	1885	29.7	28.5	10	11	0	6	6	2	0	0	2	5	0
Reefer	8.4%	2032	23.5	18	3	10	1	7	3	2	0	0	1	0	0
Bulk carrier	7.1%	30462	19.0	20	6	5	1	7	2	0	2	0	0	0	0
Research	4.5%	2828	36.3	31	4	3	0	4	1	0	0	1	0	1	0
Tug	1.9%	90	32.0	23.5	3	0	1	1	1	0	0	0	0	0	1
Icebreaker	1.3%	7639	41.5	5	0	2	0	0	1	0	1	0	0	0	0
FPSO	0.6%	360700	28.0	28	0	1	0	0	0	0	1	0	0	0	0
LNG	0.6%	96958	1.0	1	0	1	0	1	0	0	0	0	0	0	0
Supply vessel	0.6%	4800	6.0	6	0	1	0	0	0	0	0	1	0	0	0
TOTAL	100.0%				63	93	16	57	31	19	16	13	11	8	1

5. Discussion

5.1. General patterns of the NEP accidentology: a prevalence of serious casualties

Our analysis showed an overwhelming predominance of SC (81.4%) and 12.8% of VSC. The existing reports have underestimated and not accurately described the exact nature of accidents that occurred along the NEP insofar as the appropriate IMO taxonomy has not been used notably by the reports of FoU (2016), CASA (2021), and ALLIANZ (2016-2021). This shortcoming is paradoxical since the Casualty Investigation Code aims to universally categorize marine casualties and has been mandatory since 2010. Regarding determining factors, *machinery damage* or *failure* and *shipwrecking* are the top two casualties caused by harsh operating conditions and particularly by ice which represents an aggravating factor for all ship types. In line with Marchenko (2009, 2012a, 2012b, 2014b), our analysis confirms that ice drifting, ice jet, or forced overwintering led to most SC related to machinery, hull damage, and shipwrecks. Further, if *climate* represents the third major cause, this is a second contributing factor, especially heavy weather and freezing conditions, leading to collision and hull or machinery damage. *Collision* and *fire/explosion* are the fourth and fifth most frequent factors respectively. Finally, *hull damage* is the sixth accident factor. These main identified causes are in line with those reported by previous analyses (ALLIANZ from 2016-2021; FoU, 2016).

In accordance with Xu et al. (2021), our dataset emphasizes the high median age of ships having faced casualties and especially those that foundered. While an old ship is not necessarily poorly maintained, the level of deficiencies increases (Rizzo and Lo Nigro, 2008) which reduces structural resistance against ice (Marchenko, 2014b). Further, the FVs accidentology is particularly questioning insofar as it involves the highest level of casualties. Even though numerous in the area, more than 2,500, they are "especially old and worn out" (FoU, 2016) and our analysis confirms the negative trends observed by AMSA over the 1995-2004 period (AMSA, 2009). Additionally, the accidents affecting old passenger vessels, occurring both in summer and winter, require investments for new units especially since this traffic is supposed to grow in the following years notably thanks to cruise shipping (Cajaiba-Santana et al., 2019). Even though we have identified a passenger ship that was 106 years old at the time of the accident in 2016 (S/V Noorderlicht), as the Viking Sky case showed in March 2019, a simple engine failure affecting a modern cruise ship in a remote area can turn into a severe accident.

Further, tankers and bulk carriers regularly have SC as they are dominant in this area (Faury et al., 2021; Li et al., 2020). Nevertheless, it can be noticed that the high average age of tankers (+22 years) combined with severe accidents such as hull damage, collision, fire and explosion represent possible sources of oil pollution (Konygin et al., 2015; Tikka et al., 2008) and therefore negative environmental impacts (Afenyo et al., 2022; Stevenson et al., 2019; Johannsdottir and Cook, 2019; AMSA, 2017).

5.2. PC compliance and enlargement of PC to fishing vessels

The current accidentology level along the NEP raises the question of compliance with the PC and the likely consequences of increased traffic. In 2017, the NSR rules faced some breaches (NSRA, 2017) whereas, paradoxically, the PC entered into force at the same period. Our preliminary results reveal that more accidents were reported in 2017 and 2018 compared to 2016. This observation is shared by some reports that showed an increased number of marine accidents in the aftermath of the PC implementation with a rise in 2017 (CASA, 2021; ALLIANZ, 2017). After two years of a slight decrease throughout 2018-2019, ALLIANZ observed higher accident rates in 2020 (ALLIANZ, 2021). Finally, our results confirm the

absence of tangible improvements in the Arctic area while, paradoxically, it is worth mentioning that the figures are the best ever recorded at a global scale (IUMI, 2022; ALLIANZ, 2022). Thus, considering the reported number of SC, stricter compliance with the PC provisions sounds necessary and IMO member states must set up closer monitoring notably on ship operational risk assessment and "polarseaworthiness" designed to reduce risk occurrence (Rigot-Muller et al., 2022; Fedi, 2019) and accidentology in Polar areas (Dalaklis et al., 2018; Fedi et al., 2018a). Even though some time is needed to evaluate the likely long-term positive effects of the PC, nevertheless, its compliance must be reinforced to better address and capture hazards in this zone.

The international safety standards applied to FVs have met with little or no success whereas several attempts since the 1977 Torremolinos International Convention for the Safety of Fishing Vessels (IMO, 1977). Further, in light of the 1995 International Convention on Standards of Training, Certification and Watchkeeping for Fishing Vessel Personnel (STCW-F) (IMO, 1995) or the 2007 Work in Fishing Convention and Recommendation (ILO, 2007), different relevant instruments aiming to universalize fundamental safety requirements either adopted by the IMO or by the International Labor Organization (ILO) have not received large ratifications (for a synthesis: Nuňez-Sanchez et al., 2020; Havold, 2010; Perez-Labajos, 2008). At the European level, the notable effort to transpose the IMO key rules on construction or equipment of FVs 24 meters and above (EC, 1997) have been undermined by a lack of regular updates (Nuňez-Sanchez et al., 2020) and lack of tangible improvements on FVs safety as revealed by a 2011-2017 survey showing that these ships had the most losses in EU waters (EMSA, 2018). Compliance with legislation and standards was clearly pointed out as one of the three main safety issues besides training/skills and safety assessment.

Regarding Arctic navigation, pursuant to the PC, if most categories of ships must satisfy the requirements of the Safety of Life at Sea (SOLAS) Convention (IMO, 1974), the Marine Pollution Prevention (MARPOL) Convention (IMO, 1978a), and STCW Convention (IMO, 1978b), this is not the case for FVs having a gross tonnage below 500 tons. FVs operating in Arctic do not apply the mandatory safety provisions on manning and training (DNV-GL, 2017) while they have to comply with the PC environmental requirements (i.e., MARPOL Certificate). Obviously, this category is at risk and their advanced age combined with their modest dimensions, do not mitigate risk exposure. In 2024, the PC will celebrate its 10 years of adoption and a revision must be encouraged to include FVs within its scope of application for specific safety provisions. Considering the investigated accidental causes of FVs mainly pertaining to *machinery damage/failure*, *fire/explosion*, *wreck/stranding* and *climate*, the crew certification for ice-covered waters and a simplified PWOM should be at least imposed for all existing FVs greater or equal to 15 meters. Other requirements on machinery installations (PC, chap. 6), fire safety and protection (PC, chap. 7), and safety of navigation (PC, chap. 9) would be imposed for new constructions to enhance their polarseaworthiness although one acknowledges the undoubted reluctance of IMO members to support such new requirements.

5.3. Towards greater accident reporting

Availability of accurate and regular data on marine accidentology eases their analysis (Luo and Shin, 2019; Oltedal & Mc Arthur, 2011; Hassel et al., 2011; Psarros et al., 2010) and their readability is also an important determinant (Goerlandt & Liu, 2023). That is why the GISIS should provide proper accidentology information on all Arctic areas. Nevertheless, this is not the case since IMO members are not sanctioned in case of absence of reporting. The global database is therefore not adequately fed. The successful implementation of IMO conventions relies on states while negligence, or bad practices already observed in the last decade (Knudsen

& Hassler, 2011) are still valid today. Greater transparency is desirable to promote and to encourage states to maintain the GISIS database. Considering the current critics on transparency addressed to IMO (Fedi, 2021; Monios, 2020; InfluenceMap; 2017; Lister et al., 2015), an evolution would appear necessary in the short run. On the contrary, the European Union (EU) imposes stricter requirements since the occurrence of all types of events and all investigation reports must be notified by EU states under penalty, to be published and publicly available (EP, 2009). Accordingly, detailed reports are annually provided by the European Maritime Safety Agency[4] (EMSA).

However, the situation seems to be improving through the 'Compendium of Arctic Shipping Accidents' (CASA) which collects statistics on marine accidents occurring in the Arctic Circle (PAME, 2021). The first report published provided data from six Arctic States (i.e., Canada, the Kingdom of Denmark, Iceland, Norway, the Russian Federation, and the United States) while Sweden and Finland did not report cases (CASA, 2021). Further, the related data content and format showed numerous "inconsistencies" such as the absence or lack of precise geographical position for numerous accidents, unharmonized data, accidents without ship categorization or absence of reporting for certain years, and non-use of the appropriate IMO taxonomy. Additionally, comparing the 2016 FoU report and the 2021 CASA, one observes contractions in the number of accidents reported for the same years, especially for Russia, Iceland, and Norway. Consequently, while the launch of CASA has been successful, the quality of data collected is questionable and the war with Ukraine will possibly lead to an absence of reporting by Russia in the coming years. If the CASA were duly and regularly maintained in accordance with the IMO taxonomy, it would allow a stronger understanding of the marine accidents. This would enable public and private stakeholders to define appropriate policies on risk management for mitigating marine casualties in this singular area. Thus, it implies greater reporting both quantitively and qualitatively.

5.4. Enhancing response capacity along the NEP

One of the main persistent characteristics of the Arctic is the uneven development of infrastructures (Hermann et al., 2022), the lack of efficient communication systems (Larsen et al., 2016; Aase and Jabour, 2015), and the appropriate level of preparedness in case of emergencies (Andreassen & Borch, 2020; Marchenko et al., 2018; SARC, 2017). Out of the 135 existing ports, 92% are small or very small ones (Pahl and Kaiser, 2017), and deep-water ports are missing (Abe and Otsuka, 2019; Buixadé Farré et al., 2014) and this hinders the NEP development (Faury et al., 2021; Gritensko & Efimova, 2017). As highlighted by Fig. 7, transport and SAR infrastructures are well-established for the western part of the NEP, particularly in the Norwegian and Barents Seas. Looking at the Russian part, the highest infrastructure density is between the Yamal and Kola peninsula. Most ports here are connected to the rest of the country by air, facilitating the evacuation of injured people and via railroad, easing the supply of cargo for the maintenance of the infrastructures, but also for the vessels able to use these ports as a refuge (Faury et al., 2021).

Regarding the Russian side of the NEP and the NSR, most dynamic ports such as Sabetta, Novy or the upcoming Port of Kharasavey, may be used as SAR centers. Facing growing volumes, especially LNG (CHNL, 2023), Sabetta was supposed to establish a SAR in 2020 (Eilertsen, 2018) nonetheless it is not yet operational. Compared to the existing SAR facilities such as in Murmansk, Arkhangelsk, Naryan-Mar or Dikson, larger investments are still required to provide more efficient response capacity due to the vastness of the concerned area (Benz et

[4] http://www.emsa.europa.eu/accident-investigation-publications/annual-overview.html

al., 2021; FoU, 2016). Even though this zone is the home port of eight icebreakers, the safety of the nuclear-powered ones is in question considering their involvement in accidents (CASA, 2021). Although huge investments have been made for the construction of new Russian nuclear icebreakers (Skripnuk et al., 2020), the current fleet is aging and it raises the question of their operating conditions insofar as they remain the backbone of safe navigation in Arctic (Benz et al., 2021; Moe and Brigham, 2017). This situation is particularly worrisome at a time when around 47% of ships passing through the NSR are at least 30 years old (CHNL, 2023).

On the other hand, while we reported very few accidents in the eastern part of the NEP, this zone has experienced the lowest activity until recently (Faury et al., 2021) with a lack of appropriate infrastructure and capacity response. Ports are not accessible year-round; few railways connect them to the rest of the country and flying is the main valid means of transportation. New SAR are established in Pevek and another in Anadyr (Christodoulou et al., 2022). These SAR centers are closed during winter (Dalaklis, 2021) and only two icebreakers are based here limiting response capacity and response time in case of emergency. As an example, the 2017 Chukotka + tanker got trapped in the ice close to the Sannikov Strait on October 30, 2017 and only received assistance 12 days later. With a longer ice-free season in coming years, more vessels in winter (CHNL, 2023) notably due to a potential reorientation of traffic flows towards China and India (Brigham, 2022), the reinforcement of the response capacity has obviously become a sine qua non condition. Yet, above the geopolitical issues, the Russian-Ukrainian conflict poses serious challenges for maritime safety and marine environmental protection. In March 2022, seven Arctic states of the Arctic Council decided to suspend their participation in the Council' meetings (Kopra, 2023). This situation calls into question the future SAR development and state-to-state cooperation along the NEP as it has evolved so far.

5.5. Towards a holistic risk-based policy

The frequency and severity of accidents we reported question the current approach to risk management applied to harsh Arctic conditions. A "Guideline for Arctic Marine Risk Assessment" has been recently adopted with the aim to firstly "engage Arctic stakeholders to agree on best practice methods and data sources" and secondly to "better understand, communicate and incorporate specific Arctic risk influencing factors (ARIFs) into the risk assessment process" (EPPR, 2020). Safety and the environment constitute the two pillars of the Guideline proposing a marine and environmental risk assessment. The marine risk evaluation is focused on accident factors that our investigated cases underlined notably *fire/explosion*, *ship grounding*, *contact*, or *machinery damage*, their probability of occurrence, and likely consequences for people and the environment. In the same vein, the environmental risk assessment targets potential oil spills and measures their impacts on fragile ecosystems. An open electronic platform was launched in 2020[5] where public and private stakeholders can provide relevant navigational, meteorological, or oceanographic data for instance, and exchange best practices on risk management (EPPR, 2020). Promoting a shared framework on risk prevention and optimization, this initiative on Arctic "area wide-risk assessment" (ALLIANZ, 2020) is run on a completely voluntary basis.

Nonetheless, this Guideline ought not supersede the mandatory enforcement of the PC safety and environmental standards (Dalaklis et al., 2018) and its "proceduralization of risk mitigation" (Fedi et al., 2020a). Moreover, the enforcement of the PC combined with the use of POLARIS can reduce the potential frequency and severity of accidents (Fedi et al., 2020a; 2018b). Hence, a holistic risk-based policy combining a strict compliance with mandatory and

[5] https://eppr.dnvgl.com

non-mandatory requirements may prevent casualties within the Arctic. As shown in Fig. 10, this policy would rely on prophylactic measures involving the key players. Whereas shipowners have to perform their duties and implement best practices, insurers must apprehend the insured parties' risk profile, their experience in polar waters and since 2017, their documental compliance with the PC provisions (Fedi et al., 2018a). For their part, classification societies have to certify the ships pursuant to the PC and states/flag states, through Port State Controls especially, must monitor this conformity as a whole. States shall also pursue their standardization processes (Benz et al., 2021) and investments in SAR resources, infrastructures (Christodoulou et al. 2022; Dalaklis, 2021) in satellite-based Automated Identification System (AIS) (Aase & Jabour, 2015) or heavy equipment such as helicopters or aircrafts. More attention must be paid to FVs as regards the definition of fishing zones depending on the vessel's characteristics and crew competency. In addition, sustaining interstate cooperation for aeronautical and maritime SAR, oil pollution preparedness and response (Christodoulou et al., 2022) seems strategic to mitigate the aggravating consequences of marine accidents. While serious doubts exist on the Russia's collaboration in the coming years, the proposed due diligences are the prerequisites of this holistic risk-based policy.

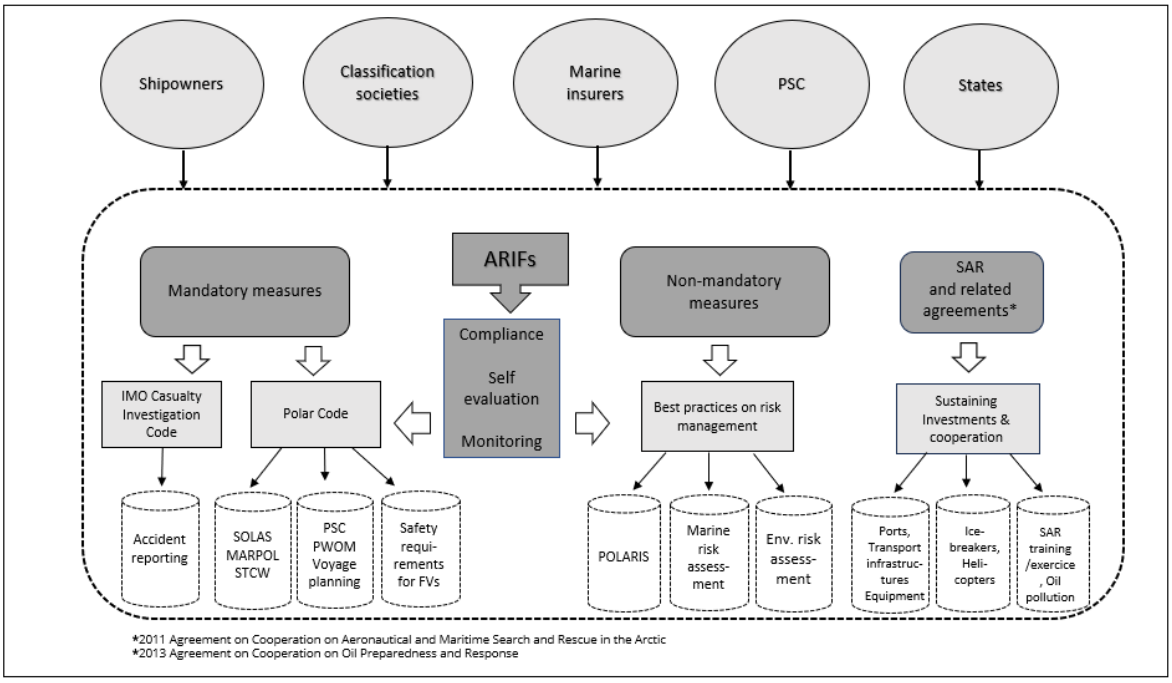

FIG. 10 Holistic risk-based policy framework

6. Conclusion

This empirical study aimed to shed light on maritime accidents that occurred along the NEP throughout the 2000-2020 period. We have reported and analyzed 156 cases. Our evaluation has highlighted the most dangerous ships, the accident-prone causes, areas, and seasons. The used and disclosed dataset has also stressed the impact of the climate and ice presence in the level of risk faced by vessels along the NEP. These records have contributed to the data-driven approach and to the attempt to fill the gap on Arctic marine accidentology. As limitations, this research did not encompass the whole Arctic Ocean, and thus, did not develop an exhaustive database.

The preliminary results clearly show the absence of tangible improvements in marine accidents in the Arctic NEP in the aftermath of the Polar Code enforcement while paradoxically, one can observe the best statistics ever recorded in most areas. This study also highlights the prevalence of serious marine casualties compared to incidents. In line with previous analyses, this research has obviously confirmed that this zone remains a very risky area which justifies additional prevention and mitigation measures at different levels. Even though there is general agreement on improving SAR infrastructures and creating new ones in the eastern part, stricter compliance with the PC would seem necessary to prevent risk occurrence along the NEP. Its stricter enforcement and enlargement to FVs must not exclude the respect of the Casualty Investigation Code which has been neglected so far. Greater reporting is obviously needed quantitatively and qualitatively for a better understanding of Arctic marine accidentology. We finally suggest a holistic risk-based policy combining constrained and voluntary measures to prevent serious casualties. Future research agenda would include the investigation of wider Arctic zones with more cases, deepening the human factor, and ultimately, evaluating whether the PC, as it is or amended, would become a "real game changer" for marine accidentology in this area.

Finally, our analysis has revealed the perceived gaps that need to be overcome and some uncertainties linked to the war in Ukraine. As the largest Arctic state, Russia's isolation is not a "good sign" for maritime safety and the marine environment along the NEP as it may lead to less transparency, cooperation, and accountability within a zone that requires the contrary.

References

Aase, J.G., J. Jabour. (2015). Can monitoring maritime activities in the European High Arctic by satellite-based Automatic Identification System enhance polar search and rescue? *Polar Journal* 5 (2) (2015) 386–402.

ABS. (2014). *Navigating the Northern Sea Route – Status and Guidance*. American Bureau of Shipping Advisory, 28 pages.

Abbassi, R., Khan, F., Khakzad, N., Veitch, B., S. Ehlers. (2017). Risk analysis of offshore transportation accident in arctic waters. *Transactions of the Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering*, *159*(A3), A213-A224.

Abe, M., N. Otsuka. (2019). Northern Sea Route (NSR) as a Major Transport Route: Opportunities and Challenges: Volume 5 Issue 4. Asian Transport Studies, 617–637.

Afenyo, M., K.Y. Ng, A., C. Jiang. (2022). A multiperiod model for assessing the socioeconomic impacts of oil spills during Arctic shipping. *Risk Analysis*, *42*(3), 614-633.

ALLIANZ. (2023). *Safety and shipping review: an annual review of trends and developments in shipping losses and safety*. https://www.agcs.allianz.com/news-and-insights/reports/shipping-safety.html

ALLIANZ. (2022). *Safety and shipping review: an annual review of trends and developments in shipping losses and safety*. https://www.agcs.allianz.com/news-and-insights/reports/shipping-safety.html

ALLIANZ. (2021). *Safety and shipping review: an annual review of trends and developments in shipping losses and safety*. https://www.agcs.allianz.com/news-and-insights/reports/shipping-safety.html

ALLIANZ. (2020). *Safety and shipping review: an annual review of trends and developments in shipping losses and safety*. https://www.agcs.allianz.com/news-and-insights/reports/shipping-safety.html

ALLIANZ. (2019). *Safety and shipping review: an annual review of trends and developments in shipping losses and safety*. https://www.agcs.allianz.com/news-and-insights/reports/shipping-safety.html

ALLIANZ. (2018). *Safety and shipping review: an annual review of trends and developments in shipping losses and safety*. https://www.agcs.allianz.com/news-and-insights/reports/shipping-safety.html

ALLIANZ. (2017). *Safety and shipping review: an annual review of trends and developments in shipping losses and safety*. https://www.agcs.allianz.com/news-and-insights/reports/shipping-safety.html

ALLIANZ. (2016). *Safety and shipping review: an annual review of trends and developments in shipping losses and safety*. https://www.agcs.allianz.com/news-and-insights/reports/shipping-safety.html

ALLIANZ. (2015). *Safety and shipping review: an annual review of trends and developments in shipping losses and safety*. https://www.agcs.allianz.com/news-and-insights/reports/shipping-safety.html

ALLIANZ. (2014). *Safety and shipping review: an annual review of trends and developments in shipping losses and safety*. https://www.agcs.allianz.com/news-and-insights/reports/shipping-safety.html

AMSA. (2009). *Arctic Marine Shipping Assessment 2009 Report*. Arctic Council, April 2009, second printing. http://www.arctic-council.org/index.php/en/documentarchive/category/20-main-documents-from-nuuk

AMSA. (2017). Status on Implementation of the AMSA 2009 Report Recommendations. May 2017.https://oaarchive.arctic-council.org/bitstream/handle/11374/1957/PAME_4th-AMSA_Implementation_Progress_Report_for_the_period_2015-2017.pdf

Andreassen, N., O.J. Borch. (2020). Crisis and Emergency Management in the Arctic: Navigating Complex Environments. Routledge. ISBN 9780367140557.

Bai, J. (2015). The IMO Polar Code: The Emerging Rules of Arctic Shipping Governance. *The International Journal of Marine and Coastal Law* 30: 674–699.

Baksh, A. A., Abbassi, R., Garaniya, V., F. Khan. (2018). Marine transportation risk assessment using Bayesian Network: Application to Arctic waters. *Ocean Engineering*, *159*, 422-436.

Bennett, M., Stephenson, S. R., Yang, K., Bravo, M. T., B. De Jonghe. (2020). The opening of the Transpolar Sea Route: Logistical, geopolitical, environmental, and socioeconomic impacts. *Marine Policy*, 121, 104178.

Benz, L., Münch C., E. Hartmann. (2021). Development of a search and rescue framework for maritime freight shipping in the Arctic, *Transportation Research Part A: Policy and Practice*, Volume 152, pp. 54-69.

Bergström, M., Browne, T., Ehlers, S., Helle, I., Herrnring, H., Khan, F., Kubiczek, J., Kujala, P., Kõrgesaar, M., Leira, B., Parviainen, T., Polojärvi, A., Suominen, M., Taylor, R., Tuhkuri, J., Vanhatalo J., B. Veitch. (2022). A comprehensive approach to scenario-based risk management for Arctic waters, *Ship Technology Research*, DOI: 10.1080/09377255.2022.2049967.

Brigham, L.W. (2022). Ten ways Russia's invasion of Ukraine impacts the Arctic and the world. The Hill, November, 15 2022. https://thehill.com/opinion/international/3736434-ten-ways-the-russia-ukraine-war-impacts-the-arctic-and-the-world/

Browne, T., Tran, T., Veitch, B., Smith, D., Khan, F., R. Taylor. (2022). A method for evaluating operational implications of regulatory constraints on Arctic shipping, *Marine Policy* 135, 104839.

Buixadé Farré, A., Stephenson, S. R., Chen, L., Czub, M., Dai, Y., Demchev, D., ... J. Wighting. (2014). Commercial Arctic shipping through the Northeast Passage: routes, resources, governance, technology, and infrastructure. *Polar Geography*, *37*(4), 298-324.

Cajaiba-Santana, G., Faury, O., M. Ramadan. (2019). The emerging cruise shipping industry in the Arctic: Institutional pressures and institutional voids. *Annals of Tourism Research*, 80, 102796.

Cariou, P., Cheaitou, A., Faury, O., S. Hamdan. (2019). The feasibility of Arctic container shipping: the economic and environmental impacts of ice thickness. *Maritime Economics & Logistics*, 1-17.

Cariou, P., O. Faury. (2015). Relevance of the Northern Sea Route (NSR) for bulk shipping, *Transportation Research Part A: Policy and Practice*, 78, 337-346.

CASA. (2021). *Compedium of Arctic accidents*. PAME, EPRP, Akureyri, Iceland, May 2021. https://www.arctic-council.org/projects/compendium-of-arctic-ship-accidents-casa/

Cheaitou, A., Faury, O., Cariou, P., Hamdan, S., G. Fabbri. (2020). Economic and environmental impacts of Arctic shipping: A probabilistic approach, *Transportation Research Part D*, 9, 102606.

Cheaitou, A., Faury, O., Etienne, L., Fedi, L., Rigot-Muller, P., S. Stephenson. (2022). Impact of CO2 emission taxation and fuel types on Arctic shipping attractiveness, *Transportation Research, Part D*, 112, 103491.

CHNL information office (2023). *Ship traffic at the NSR in 2022*. https://chnl.no/news/new-report-of-nrs-shipping-activities-2022-is-released/

Christodoulou, A., Dalaklis, D., Raneri, P., R. Sheehan. (2022). An overview of the legal search and rescue framework and related infrastructure along the Arctic Northeast Passage. *Marine Policy*, *138*, 104985.

Dalaklis, D., Baxevani, E., P. Siousiouras. (2018). The future of Arctic shipping business and the positive influence of the Polar Code. *The Journal of Ocean Technology*, vol. 13(4), 76-94.

Dalaklis, D. (2021). *Establishing infrastructure to ensure best practice incident and crisis control: Search and Rescue services*. Presentation at the World Maritime University, January 2021, 31 pages.

DNV-GL. (2017). Polar Code: Understand the code's requirements to take the right steps for smooth compliance, 31 pages.

Eilertsen, H. (2018). *Four new SAR Centers in the Russian Arctic. High North News*. https://www.highnorthnews.com/en/four-new-sar-centers-russian-arctic

EC, 1997. Council Directive 97/70/EC of 11 December 1997 setting up a harmonised safety regime for fishing vessels of 24 metres in length and over. OJ L 34, 9.2.1998, p. 1–29. Modified by Regulation (EC) no 219/2009 of 11 March 2009.

EMSA. (2018). Safety analysis on data reported in EMCIP. Analysis on marine casualties and incidents involving fishing vessels. April.

EPPR. (2020). Guideline for Arctic marine risk assessment- Fact sheet. 3 pages. https://www.arctic-council.org/projects/risk-assessment-methods-and-metadata/

EP (EU PARLIAMENT). (2009). Directive 2009/18/EC of the European Parliament and of the Council of 23 April 2009 establishing the fundamental principles governing the investigation of accidents in the maritime transport sector […], Official Journal L 131/114 28.05.2009.

Faury, O., Alix, Y., N. Montier. (2021). From the USSR to the polar silk road: the rise of the strategic Russian Arctic port range. *Post-Communist Economies*, 1-21

Faury, O., Cheaitou, A., P. Givry. (2020). Best maritime transportation option for the Arctic crude oil: A profit decision model. *Transportation Research Part E, 136*, 101865.

Faury, O., Fedi, L., Etienne, L., Rigot-Müller, P., Stephenson, S., A. Cheaitou. (2019). *La Route Maritime Nord : complément ou concurrent des routes conventionnelles ?*, *Baltic-Arctic: Strategic perspective*, Edition Océanides, 169-190.

Faury, O., P. Cariou. (2016). The Northern Sea Route competitiveness for oil tankers. *Transportation Research Part A, 94*, 461-469.

Fedi, L. (2019). Arctic shipping law from atomised legislations to integrated regulatory framework: The Polar Code (R)Evolution? In Lasserre, F. and Faury, O. Arctic Shipping, Climate Change, Commercial Traffic and Port Development, *Routledge*, 117-136.

Fedi, L. (2021). International Maritime Regulation: Closing the Gaps Between Successful Achievements and Persistent Insufficiencies, In: Vickerman, Roger (eds.) *International Encyclopedia of Transportation*. vol. 5, pp. 600-606. UK: Elsevier Ltd.

Fedi, L., Faury, O., D. Gritsenko. (2018a). The impact of the Polar Code on risk mitigation in Arctic waters: a "toolbox" for underwriters? *Maritime Policy & Management*, *45*(4), 478-494.

Fedi, L., Etienne, L., Faury, O., Rigot-Muller, P., Stephenson, S., A. Cheaitou. (2018b). Arctic navigation: stakes, benefits and limits of the POLARIS system. *The Journal of Ocean Technology*, *13*(4), 54-67.

Fedi, L., Faury, O., L. Etienne. (2020a). Mapping and analysis of maritime accidents in the Russian Arctic through the lens of the Polar Code and POLARIS system. *Marine Policy*, *118*, 103984.

Fedi, L., Faury, O., Cheaitou, A., Etienne, L., P. Rigot-Muller. (2020b). *Application and analysis of the IMO taxonomy on casualty investigation over 20 years of marine accidents in the Russian Arctic*. IAME Conference, 10-13 June, PolyU, Hong-Kong.

FoU-RAPPORT. (2016). Borch, O.J., Andreassen, N., Marchenko, N., Ingimundarson, V., Gunnarsdóttir, H., Jakobsen, U., Kern, B. ludin, U., Petrov, S., Markov, S., & Kuznetsova, S. *Maritime*

activity and risk patterns in the High North MARPART Project Report 2. Nord universitet, FoU-rapport nr. 4, 133 pp.

Fu, S., Zhang, D., Montewka, J., Yan, X., E. Zio. (2016). Towards a probabilistic model for predicting ship besetting in ice in Arctic waters. *Reliability Engineering & System Safety*, *155*, 124-136.

Fu, S., Goerlandt, F., Y. Xi. (2021). Arctic shipping risk management: A bibliometric analysis and a systematic review of risk influencing factors of navigational accidents. *Safety Science*, *139*, 105254.

Goerlandt, F., Goite, H., Banda, O. A. V., Höglund, A., Ahonen-Rainio, P., M. Lensu. (2017). An analysis of wintertime navigational accidents in the Northern Baltic Sea. *Safety science*, *92*, 66-84.

Goerlandt, F., H. Liu. (2023). Readability of maritime accident reports: a comparative analysis, *Maritime Policy & Management*, DOI: 10.1080/03088839.2023.2166685.

Grabowski, M., You, Z., Zhou, Z., Song, H., Steward, M., B. Stewards. (2009). Human and organizational error data challenges in complex, large-scale systems. *Safety Science*. 47, 1185–1194.

Gritsenko, D., E. Efimova. (2017). Policy environment analysis for Arctic seaport development: the case of Sabetta (Russia). *Polar Geography*, *40*(3), 186-207.

Gritsenko, D., T. Kiiski. (2016). A Review of Russian Ice-Breaking Tariff Policy on the Northern Sea Route 1991 – 2014. *Polar Record* 52(2):144-158.

Gunnarsson, B. (2021). Recent ship traffic and developing shipping trends on the Northern Sea Route—Policy implications for future arctic shipping. *Marine Policy*, *124*, 104369.

Haavik, T. K. (2017). Remoteness and sensework in harsh environments. *Safety science*, *95*, 150-158.

Halliday, W.D., Têtu, P.L., Dawson, J., Insley, S. J., R. Casey Hilliard (2018). Tourist vessel traffic in important whale areas in the western Canadian Arctic: Risks and possible management solutions. *Marine Policy*, 97, 72-81.

Hassel, M., Asbjørnslett, B. E., L. P. Hole. (2011). Underreporting of maritime accidents to vessel accident databases. *Accident Analysis & Prevention*, *43*(6), 2053-2063.

Havold, J. R. (2010). Safety culture aboard fishing vessels. *Safety Science* 48, 1054–1061.

Henriksen, T. (2014). The Polar Code: Ships in Cold Water – Arctic Issues Examined. *CMI Yearbook*: 332-344.

Hermann, R. R., N. Lin, J. Lebel, A. Kovalenko. (2022). Arctic Transshipment Hub Planning Along the Northern Sea Route: A Systematic Literature Review and Policy Implications of Arctic Port Infrastructure. *Marine Policy* 145: 105275. https://doi.org/10.1016/j.marpol.2022.105275.

Humpert, M. (2014). Arctic shipping: an analysis of the 2013 Northern Sea Route season. *Arctic Yearbook, 2014*, 195-205.

IHS MARKIT. (2020). https://ihsmarkit.com/index.html

ILO. (2007). C-188. Work in Fishing Convention (No. 188). https://www.ilo.org/dyn/normlex/en/f?p=NORMLEXPUB:12100:0::NO::P12100_ILO_CODE:C188

IMO. (1974). International Convention for the Safety of Life at Sea (SOLAS). London 1 November 1974. UN Treaty Series vol. 1184 p. 278.

IMO. (1977). Resolution MSC 92/26/Add.2 Annex 25 of 30 June 2013 International regulations for the safety of fishing vessels consolidated text of the regulations annexed to the Torremolinos Protocol of 1993 […] as modified by the Cape Town Agreement of 2012 […].

IMO. (1978a). International Convention for the Prevention of Pollution from Ships, as modified by the Protocol of 1978 relating thereto (MARPOL 1973/78). London 2 November 1973 and 17 February 1978. UN Treaty Series vol. 1340.

IMO. (1978b). International Convention Standards of Training, Certification and Watchkeeping for Seafarers. London 7 July 1978. UN Treaty Series vol. 1361.

IMO. (1995). International Convention on Standards of Training, Certification and Watchkeeping for Fishing Vessel Personnel. London 7 July 1995. UN Treaty Series vol. 3357.

IMO. (2008). Resolution MSC.255(84) adopted on 16 May 2008 adoption of the Code of the international standards and recommended practices for a safety investigation into a marine casualty or marine incident (Casualty Investigation Code).

IMO. (2014). Resolution MSC 385 (94) of November 21, 2014 and Resolution MEPC 264 (68) of May 15, 2015. International Code for Ships Operating in Polar Waters (Polar Code), 2014.

IMO. (2016). MSC. 1/Circ 1519, 6 June 2016, Guidance on Methodologies for Assessing Operational Capabilities and Limitations in Ice. https://docs.imo.org/Final Documents/English/MSC.1-CIRC. 1519(E).docx

InfluenceMap. (2017). *Corporate capture of the International Maritime Organization How the shipping sector lobbies to stay out of the Paris Agreement.* Available at: https://influencemap.org/report/Corporate-capture-of-the-IMO-902bf81c05a0591c551f965020623fda

IPPC. (2022). *Climate Change 2022. Impacts, Adaptation and Vulnerability. Summary for Policymakers.* 40 pages.

Iudin, I., S. Petrov. (2016). *The Russian Sea Areas and Activity Level Up to 2025*. Maritime activity in the High North - current and estimated level up to 2025, Marpart Project Report 1. Nord Universitet, No 7. Bodø 2016.

IUMI. (2022). *Global marine insurance report 2022*. By A. Seltmann, Chicago, 18-21 September 2022. https://iumi.com/statistics/public-statistics

Johannsdottir, L., D. Cook. (2019). Systemic risk of maritime-related oil spills viewed from an Arctic and insurance perspective. *Ocean & Coastal Management*, *179*, 104853.

Kiiski, T. (2017). Feasibility of commercial cargo shipping along the Northern Sea Route. *Annales Universitatis Turkuensis*, University of Turku.

Knudsen, O., O. Hassler. (2011). IMO legislation and its implementation: Accident risk, vessel deficiencies and national administrative practices. *Marine Policy*, 35, 201-207.

Konygin, A., Nekhaev, S., Dmitruk, D., Sevastyanova, K., Kovalek, D., V. Cherenko. (2015). "Oil Tanker Transportation." In: The Russian Arctic. *International Journal of scientific & technology*. Research volume 4(03): 27-33.

Kopra, S. (2023). Arctic collaboration: The Arctic Institute's Spring Series 2023. February, 14. https://www.thearcticinstitute.org/arctic-collaboration-the-arctic-institute-spring-series-2023/

Kum, S., B. Sahin. (2015). A root cause analysis for Arctic Marine accidents from 1993 to 2011. *Safety science*, *74*, 206-220.

Ladan, M., M. Hänninen. (2012). Data Sources for Quantitative Marine Traffic Accident Modeling. *Science + Technology* n. 11/2012. Aalto University publication series Science + Technology. Aalto University, Department of Applied Mechanics, Helsinki, Finland.

Larsen, L.-H., Kvamstad-Lervold, B., Sagerup, K., Gribkovskaia, V., Bambulyak, A., Rautio, R., T.E. Berg, (2016). Technological and environmental challenges of Arctic shipping - a case study of a fictional voyage in the Arctic. *Polar Research*, 35, 27977.

Lasserre, F., Beveridge, L., Fournier, M., Têtu, P. L., L. Huang. (2016). Polar seaways? Maritime transport in the Arctic: An analysis of shipowners' intentions II. *Journal of Transport Geography*, 57.

Lee, H. W., Roh, M. I., K.S. Kim (2021). Ship route planning in Arctic Ocean based on POLARIS. *Ocean Engineering*, *234*, 109297.

Li, X., Otsuka, N., L.W. Brigham. (2020). Spatial and temporal variations of recent shipping along the Northern Sea Route. *Polar Science*, 100569.

Lindstad, E. Bright, R. M., A.H. Stromman. (2016). Economic savings linked to future Arctic shipping trade are at odds with climate change mitigation. *Transport Policy* 45(22):24-30.

Lister, J., Taudal Poulsen, R., S. Ponte. (2015). Orchestrating transnational environmental governance in maritime shipping. Glob. Environ. Chang. 34, 185–195.

Liu, M., J. Kronbak. (2010). The potential economic viability of using the Northern Sea Route (NSR) as an alternative route between Asia and Europe. *Journal of transport Geography*, *18*(3), 434-444.

Luo, M., S.H. Shin. (2019). Half-century research developments in maritime accidents: Future directions. *Accident Analysis & Prevention*, *123*, 448-460.

Marchenko, N. (2009). Ice Conditions and Human Factors in Marine Accidents at the Arctic. In *Marine Navigation and Safety of Sea Transportation* (pp. 461-466). CRC Press.

Marchenko, N. (2012a). Ice Conditions and Human Factors in Marine Accidents at the Arctic. The University Centre in Svalbard, Longyearbyen, Norway.

Marchenko, N. (2012b). *Russian Arctic Seas: navigational conditions and accidents*. Springer Science & Business Media.

Marchenko, N. (2014a). Northern Sea Route: Modern State and Challenges. In *International Conference on Offshore Mechanics and Arctic Engineering* (Vol. 45561, p. V010T07A022). American Society of Mechanical Engineers.

Marchenko, N., (2014b). Floating Ice Induced Ship Casualties. In *22nd IAHR International Symposium on Ice, Singapore*.

Marchenko, N., Borch, O. J., Markov, S. V., & Andreassen, N. (2015). *Maritime activity in the high north - The range of unwanted incidents and risk patterns*. POAC.

Marchenko, N., Andreassen, N., Borch, O. J., Kuznetsova, S., Ingimundarson, V., U. Jakobsen, (2018). Arctic shipping and risks: emergency categories and response capacities. *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, *12*.

Melia, N., Haines, K., E. Hawkins. (2016). Sea ice decline and 21st century trans- Arctic shipping routes. *Geophysical Research Letters*, *43*(18), 9720-9728.

Ministry of Energy of the Russian Federation. (2010). Energy Strategy of Russia for the period up to 2030. Decree N°1715-r of the Government of the Russian Federation dated 13 November 2009, 174 pages.

Moe, A., L. Brigham. (2017). Organization and management challenges of Russia's icebreaker fleet. *Geographical Review*, 107(1), 48-68.

Monios, J. (2020). Environmental governance in shipping and ports: Sustainability and scale challenges. In: A. K. Y. Ng, J. Monios, C. Jiang (Eds): *Maritime Transport and Regional Sustainability*. Elsevier: Cambridge, MA, 13-29.

Montewka, J., Goerlandt, F., Kujala, P., M. Lensu. (2015). Towards probabilistic models for the prediction of a ship performance in dynamic ice. *Cold Regions Science and Technology*, *112*, 14-28.

Nuñez-Sanchez, M.J., Perez-Rojas, L., Sciberras, L., J. Ramos Silva. (2020). Grounds for a safety level approach in the development of long-lasting regulations based on costs to reduce fatalities for sustaining industrial fishing vessel fleets. *Marine Policy* (113), 2020, 103806.

NSRA. (2017). Violation of the Navigation Rules on the NSR. http://www.arcticlio.com/node/277

OECD. (2022). International investment implications of Russia's war against Ukraine, OECD Publishing, Paris. https://doi.org/10.1787/a24af3d7-en

Oltedal, H. A., D. P., McArthur (2011). Reporting practices in merchant shipping, and the identification of influencing factors. *Safety Science*, *49*(2), 331-338.

Pahl, J., B. Kaiser. (2018). Arctic Port Development. In Arctic Marine Resource Governance and Development, by Verstergaard, N., Kaiser, B., Fernandez, L. Larsen, J. Springer Polar Science, Springer, 138-184.

Palma, D., Varnajot, A., Dalen, K., Basaran, I., K., Brunette, C., Bystrowska, M., Korablina, A.D., N., C., T. Robynne, Ronge. (2019). Cruising the marginal ice zone: climate change and Arctic tourism, *Polar Geography*, *42*, 215-235.

PAME. (2020). The increase in Arctic shipping 2013-2019. Arctic shipping status report. March, 31.

PAME. (2021). Compendium of Arctic Ship Accidents Final Report, Arctic Council SAO meeting 16-18 March, Reykjavik Iceland.

Parviainen, T., Lehikoinen, A., Kuikka, S., P. Haapasaari. (2019). Risk frames and multiple ways of knowing: Coping with ambiguity in oil spill risk governance in the Norwegian Barents Sea. *Environmental Science & Policy*, *98*, 95-111.

Pastusiak, T. (2015). The problem of the availability of nautical charts and publications on the Northern Sea Router. *Polish Cartographical Review*, *47*.

Perez-Labajos, C. (2008). Fishing safety policy and research. *Marine Policy*, 32(1): 40-45.

Pruyn, J. F. (2016). Will the Northern Sea Route ever be a viable alternative?. *Maritime Policy & Management*, *43*(6), 661-675.

Psarros, G., Skjong, R., M.S. Eide. (2010). Under-reporting of maritime accidents. *Accident Analysis & Prevention*, *42*(2), 619-625.

Rigot-Muller, P., Faury, O., Fedi, L., Cheaitou, A., L. Etienne (2022). The role of polarseaworthiness in shipping planning for infrastructure projects in the Arctic: the case of Yamal LNG plant, *Transportation Research, Part A*, 155, 330-353.

Rizzo, C.M., A. Lo Nigro (2008). A review of ship surveys practices and of marine casualties partly due to aging effects. Proceedings of the ASME 27th International Conference on Offshore Mechanics and Arctic Engineering OMAE2008 June 15-20, 2008, Estoril, Portugal.

Russian Government. (2020). Decree of the President of the Russian Federation of October 26, 2020 No 645 "Strategy for Developing the Russian Arctic Zone and Ensuring National Security until 2035." http://publication.pravo.gov.ru/Document/ View/0001202010260033.

Russian Government. (2022). Order dated August 1, 2022 No. 2115-r "A plan for the development of the Northern Sea Route (NSR) until 2035." http://static. government.ru/media/files/ldXCoUl6J2n5hZews6aJdEqABEDsJLAX.pdf

SARC. (2017). *Arctic Search and Rescue Capabilities Survey. Enhancing International Cooperation*. 56 pp.

Schøyen, H., S. Bråthen. (2011). The Northern Sea Route versus the Suez Canal: cases from bulk shipping, *Journal of Transport Geography*, 19, Issue 4, 977-983.

Silber, G. K., J.D. Adams. (2019). Vessel operations in the Arctic, 2015–2017. *Frontiers in Marine Science*, *6*, 573.

Skripnuk, D.F., Iliyushchenko, I.O., Kulik, S.V., M.M. Stepanov. (2020). Analysis of the current state of the Northern Sea Route and the potential development of the icebreaker fleet, in: IOP Conference Series: Earth and Environmental Science. 5th International Conference "Arctic: History and Modernity", Saint-Petersburg. 18- 19 March 2020.

Staalesen, A. (2018). *It's an order from the Kremlin: shipping on Northern Sea Route to reach 80 million tons by 2024*. The Barents Observer May 15, 2018. (https://thebarentsobserver.com/en/arctic/2018/05/its-order-kremlin-shipping-northern-sea-route-increase-80-million-tons-2024)

Staalesen, A. (2019). *Shipping on Northern Sea Route up 63 percent*. The Barents Observer. November 15, 2019.https://thebarentsobserver.com/en/industry-and-energy/2019/11/shipping-northern-sea-route-63-percent

Stevenson, T.C., Davies, J., Huntington, H.P., W. Sheard. (2019). An examination of trans-Arctic vessel routing in the Central Arctic Ocean. *Marine Policy*(100), 83-89.

Tikka, K., Riska, K., S. Liu. (2008). Tanker design considerations for safety and environmental protection of Arctic waters: Learning from past experience. *WMU Journal of Maritime Affairs*, *7*(1), 189-204.

Theocharis, D., Pettit, S., Sanchez Rodrigues, V., J. Haider. (2018). Arctic shipping: A systematic literature review of comparative studies, *Journal of Transport Geography*, 69, 112-128.

Tseng, P. H., K. Cullinane. (2018). Key criteria influencing the choice of Arctic shipping: a fuzzy analytic hierarchy process model. *Maritime Policy & Management*, *45*(4), 422-438.

Vihanninjoki, V. (2014). *Arctic Shipping Emission in the Changing Climate*. Finnish Environment Institute 41.

Yumashev, D., van Hussen, K., Gille, J., G. Whiteman. (2017). Towards a balanced view of Arctic shipping: estimating economic impacts of emissions from increased traffic on the Northern Sea Route. *Climatic Change*,143:143-155.

Xu, S., Kim, E., S. Haugen. (2021). Review and comparison of existing risk analysis models applied within shipping in ice-covered waters. *Safety Science*, *141*, 105335.

Zhang, Y., Meng, Q., L. Zhang. (2016). Is the Northern Sea Route attractive to shipping companies? Some insights from recent ship traffic data. *Marine Policy*, *73*, 53-60.

Zhu, S., Fu, X., Ng, A.K.Y., Luo, M., Y. E. Ge. (2018). The environmental costs and economic implications of container shipping on the Northern Sea Route. *Maritime Policy & Management*, 45:4, 456-477.

Appendix 1: List of 156 events analyzed.

IMO	Vessel Name	New vessel type	DWT	Built	Month	Season	Location	Taxonomy	Age
7435383	Ryazan	General cargo	5657	1975	November	Summer	Bering Sea	VSC	25
7382495	Wilson Ross	Bulk carrier	6258	1975	March	Winter	Barents Sea	SC	29
7721275	Stepan Razin	Bulk carrier	19590	1980	October	Summer	Barents Sea	VSC	24
9245457	Diamant	Fishing vessel	350	2002	March	Winter	Okhotsk Sea	VSC	4
8721715	Rumyantsevo	Fishing vessel	414	1985	August	Summer	Northern Pacific	VSC	21
7831862	Navoysk	Fishing vessel	304	1980	February	Winter	Northern Pacific	VSC	27
8897409	Ekarma-2	Fishing vessel	423	1994	March	Winter	Okhotsk Sea	SC	13
9183829	Weichselstern	Tankers	21823	1999	August	Summer	White Sea	SC	8
6927717	Viktor Koryakin	General cargo	2208	1969	December	Winter	Barents Sea	VSC	38
8721595	Nemanskiy	Fishing vessel	414	1987	January	Winter	Barents Sea	SC	21
7708314	Belokamenka	FPSO	360700	1980	January	Winter	Kola Bay	SC	28
8139039	Sapfirovyy	Reefer	487	1983	January	Winter	Northern Pacific	SC	26
6919057	Agna	General cargo	2536	1967	October	Summer	White Sea	SC	42
8829177	Senite	Reefer	529	1990	February	Winter	Northern Pacific	SC	20
8834005	Tobago	Fishing vessel	414	1990	February	Winter	Barents Sea	VSC	20
8729391	Spitak	Fishing vessel	207	1989	March	Winter	Okhotsk Sea	SC	21
9311323	Zvezda Rybaka	Fishing vessel	50	2004	May	Winter	Barents Sea	SC	6
8930794	Snabzhenets-1	Reefer	144	1979	July	Summer	Bering Sea	SC	31
8943002	Varnek	Tankers	154	1974	July	Summer	White Sea	VSC	36
8857174	Dzhamrat	Tankers	3389	1986	August	Summer	Barents Sea	SC	24
9305104	Golden Seas	Bulk carrier	74475	2006	December	Winter	Bering Sea	SC	4
6924052	Soyana	General cargo	4570	1992	February	Winter	White Sea	SC	19
8904408	Mekhanik Brilin	General cargo	2636	1991	February	Winter	White Sea	SC	20
7902623	Asteropa	General cargo	3085	1980	March	Winter	White sea	SC	31
8826723	West	Fishing vessel	70	1990	June	Winter	Northern Pacific	SC	21
8721143	Seawind 1	Fishing vessel	1810	1987	June	Winter	Bering Sea	SC	24
8725711	Salnyy	Tankers	264	1986	September	Summer	Barents Sea	SC	25

IMO	Vessel Name	New vessel type	DWT	Built	Month	Season	Location	Taxonomy	Age
8620064	Ajaks-1	General cargo	1649	1986	September	Summer	Kara Sea	SC	25
8872708	Kapitan Kuznetsov	General cargo	1652	1984	November	Summer	Barents Sea	MI	27
7112577	Oriental Angel	Fishing vessel	4456	1971	November	Summer	Bering Sea	VSC	40
8505422	Plutonas	Fishing vessel	332	1986	September	Summer	Norwegian sea	SC	28
9228980	Arctica-1	General cargo	9141	2001	June	Winter	Kara Sea	SC	16
7927960	M/T Chukotka	Tankers	11548	1982	November	Summer	Laptev sea	SC	35
9079169	Nordic Barents	Tankers	43706	1995	March	Winter	Kara Sea	SC	22
9239458	Harriet	Bulk carrier	25565	2002	March	Winter	White Sea	SC	16
7435383	M/V Ryazan	General cargo	5657	1975	November	Summer	Bering Sea	MI	25
7808334	Belomorye	Reefer	3098	1979	August	Summer	White Sea	VSC	32
7383011	Huginn	General cargo	833	1975	December	Winter	Barents Sea	SC	32
8725694	M/V Rys	Reefer	77	1987	December	Winter	Bering Sea	MI	20
8519837	M/V Akademik Fyodorov	Research	7200	1987	July	Summer	Barents Sea	SC	20
9233258	M/V Trollfjord	Passenger	1186	2002	May	Winter	Norwegian sea	SC	5
7831862	F/V Navoysk	Fishing vessel	304	1980	March	Winter	Northern Pacific	VSC	27
7832775	F/V Pavel Korchagin	General cargo	6070	1980	March	Winter	White sea	SC	27
9133161	F/V Korsar	Reefer	534	1996	March	Winter	Northern Pacific	SC	12
8724406	Kurilsk	Reefer	495	1986	March	Winter	Northern Pacific	SC	22
9194012	Usinsk	Tankers	19995	2002	January	Winter	Kola Bay	SC	6
7828619	Kapitan Telov	Reefer	4402	1979	April	Winter	Norwegian sea	SC	31
8834005	Tobago	Fishing vessel	414	1990	February	Winter	Norwegian sea	SC	20
9333436	M/V SCF AMUR	Tankers	47095	2007	March	Winter	Barents Sea	SC	3
9326885	Mari Ugland	Tankers	74997	2008	March	Winter	Barents Sea	SC	2
9390276	M/V Svealand	General cargo	2100	2008	February	Winter	Norwegian sea	SC	2
7518202	M/V Mikhail Somov	Research	5305	1975	January	Winter	White sea	SC	35
8955677	Pinro 1	Fishing vessel	413	1999	November	Summer	Norwegian sea	SC	11
8714334	F/V Flogrunn	Fishing vessel	350	1970	November	Summer	Barents Sea	VSC	40
9326160	Yutai Ambitions	Bulk carrier	77283	2008	November	Summer	Barents Sea	SC	2
9650420	Viking Sky	Passenger vessel	4826	2017	March	Winter	Norwegian Sea	SC	2

IMO	Vessel Name	New vessel type	DWT	Built	Month	Season	Location	Taxonomy	Age
8936853	Alexei Kulakovsky	Tug	1190	1992	August	Summer	Laptev sea	VSC	18
8857174	Dzamrat	Tankers	3389	1986	August	Summer	Murmansk	SC	24
9030369	Sigrid	Passenger	460	1992	August	Winter	Norwegian sea	SC	18
6905754	Polar Star	Passenger	879	1962	June	Winter	Norwegian sea	SC	48
8322650	M/V Sunnmore	General cargo	2000	1985	November	Summer	Norwegian sea	SC	26
8218603	Bereg Nadezhdy	General cargo	13879	1982	November	Summer	Barents Sea	SC	29
8317942	Color Viking	Passenger	2390	1985	September	Summer	Norwegian sea	SC	26
8131922	Kapitan Chukhchin	Bulk carrier	19252	1981	April	Winter	Kara Sea	SC	30
6920094	Dudinka	Icebreaker	1219	1970	April	Winter	Kara Sea	SC	41
7232743	Bulk Viking	General cargo	945	1972	April	Winter	Norwegian sea	SC	39
9166118	F/V Atlantic	Fishing vessel	1001	1998	April	Winter	Norwegian sea	SC	13
9563172	Floyfjeli	Passenger	20	2011	December	Winter	Norwegian sea	SC	1
7052571	Umbrina	Fishing vessel	386	1970	September	Summer	Barents Sea	SC	42
8842026	Altay	Fishing vessel	203	1988	September	Summer	Barents Sea	SC	24
9379090	Skulbaren	Fishing vessel	77	2007	July	Summer	Norwegian sea	SC	5
5351894	Polargirl	Research	274	1962	February	Winter	Norwegian sea	SC	58
5351894	Polargirl	Research	274	1962	July	Summer	Norwegian sea	SC	48
9107772	Nordkapp	Passenger	1104	1996	November	Summer	Norwegian sea	SC	17
9641675	Le Soléal	Passenger	1440	2013	September	Summer	Bering Sea	SC	0
8845523	M/T Nordvik	Tankers	5872	1985	September	Summer	Kara Sea	SC	28
8960385	F/V Fugloytind	Fishing vessel	186	1986	May	Winter	Norwegian sea	SC	27
9370070	Siem Sailor	Supply Vessel	4800	2007	May	Winter	Norwegian sea	SC	6
9563172	Floyfjeli	Passenger	20	2011	May	Winter	Norwegian sea	SC	2
9034949	Kapitan Bolsunovskiy	Fishing vessel	1753	1993	May	Winter	Bering Sea	VSC	19
8714310	Kapitan Gromtsev	Fishing vessel	654	1987	March	Winter	Norwegian sea	SC	30
8845523	M/T Nordvik	Tankers	5872	1985	September	Summer	Kara Sea	SC	28
9768368	LNG/C Boris Vilkitsky	LNG	96958	2017	April	Winter	Barents Sea	SC	1
8927967	Belomorye	Passenger	158	1980	August	Summer	White Sea	SC	31
6417097	Marco Polo	Passenger	5180	1965	November	Summer	Norwegian sea	SC	49

IMO	Vessel Name	New vessel type	DWT	Built	Month	Season	Location	Taxonomy	Age
7945780	M/V Proliv Friza	Reefer	495	1981	December	Winter	Okhotsk Sea	MI	25
8228359	M/V Nikolay Przhevalskiy	Passenger	5500	1984	August	Summer	Okhotsk Sea	SC	22
8897485	Kapitan Kazantsev	Fishing vessel	386	1995	July	Summer	Okhotsk Sea	SC	12
8798574	F/V Mys Levenorma	Fishing vessel	90	1994	March	Winter	Okhotsk Sea	MI	13
7645299	F/V Pashkovskiy	Fishing vessel	77	1987	February	Winter	Okhotsk Sea	SC	20
8722422	F/V MRTK-0717	Fishing vessel	174	1987	February	Winter	Okhotsk Sea	VSC	20
8610265	Pyotr Zhitnikov	Fishing vessel	10070	1989	April	Winter	Okhotsk Sea	SC	21
8700125	Aeseneyev	Tankers	3086	1989	April	Winter	Okhotsk Sea	SC	22
8326113	Korsakov	Reefer	10055	1983	December	Winter	Okhotsk Sea	SC	25
8847131	Smolnenskiy	Reefer	1557	1990	January	Winter	Okhotsk Sea	SC	20
7043831	f/v Meridian	Fishing vessel	286	1971	November	Summer	Barents Sea	SC	38
8624515	Tug nord	Tug	90	1963	October	Summer	Barents Sea	SC	46
8038053	M-0406 Lotos	Fishing vessel	162	1982	October	Summer	Barents Sea	VSC	27
7923691	Ust-Khan	Tankers	4969	1981	April	Winter	Okhotsk Sea	SC	28
8723311	Baskunchalskiy	Reefer	2987	1987	November	Summer	Barents Sea	SC	21
9231391	Valeriy Maslakov	Fishing vessel	348	2003	June	Winter	Okhotsk Sea	MI	5
8714310	Kapitan Gromtsev	Fishing vessel	654	1987	May	Winter	Norwegian sea	SC	21
9100944	Runo	Fishing vessel	177	1993	May	Winter	Barents Sea	MI	15
7347603	Admiral Makarov	Icebreaker	14058	1975	January	Winter	Chukchi Sea	SC	42
8956554	Shikhan	General cargo	1378	1986	March	Winter	White Sea	SC	22
8878087	Professor Tronin	General cargo	1777	1984	August	Summer	Pechora Sea	SC	23
9131589	Inger	General cargo	4182	1996	March	Winter	White Sea	SC	13
8904434	Mekhanik Pyatlin	General cargo	2650	1992	February	Winter	White Sea	SC	25
8904393	Mekhanik Semakov	General cargo	2650	1991	September	Summer	Barents Sea (Murmansk)	SC	24
8118140	Murmansk	Bulk carrier	30650	1984	November	Summer	Barents Sea	SC	32
8650813	Noorderlicht	Passenger	250	1910	September	Summer	Barents Sea	SC	106
7911052	Norvag	Tankers	1063	1980	October	Summer	Barents Sea	SC	35
8870839	Letniy Bereg	General cargo	2781	1991	January	Winter	White sea	SC	22

IMO	Vessel Name	New vessel type	DWT	Built	Month	Season	Location	Taxonomy	Age
8520355	Markus	General cargo	1323	1986	December	Winter	Barents Sea	SC	32
9641730	Mein Schiff-3	Passenger	7900	2014	June	Winter	Norwegian Sea	SC	4
8904410	Mekhanik Kottsov	General cargo	2650	1991	August	Summer	White Sea	SC	27
8904458	Mekhanik Kraskovskiy	General cargo	2650	1992	November	Summer	White Sea	SC	26
8837942	Kern	Research	329	1991	July	Summer	Pechora Sea	SC	23
9132480	Kom	Bulk carrier	13971	1997	November	Summer	Barents Sea (Murmansk)	SC	20
9575436	Koznitza	Bulk carrier	32631	2010	March	Winter	Barents Sea	SC	7
9137038	Lady Irina	General cargo	4161	1997	March	Winter	Barents Sea	SC	20
763851	Lance	Research	975	1978	May	Winter	Norwegian sea	SC	41
7421942	Indiga	Tankers	15954	1976	March	Winter	White Sea	SC	33
9131589	Inger	General cargo	4182	1996	March	Winter	White Sea	SC	10
8704951	Jofjord	Passenger	434	1987	September	Summer	Norwegian Sea	SC	28
8934996	Kapitan Drabkin	Passenger	96	1971	January	Winter	Northern Pacific	SC	41
8025898	Kapitan Pershin	Tankers	5557	1982	January	Winter	White Sea	SC	31
7211074	Expedition	Passenger	965	1972	July	Summer	Barents Sea	SC	40
9563172	Floyfjell	Passenger	20	2011	March	Winter	Norwegian Sea	SC	7
9388912	Foresight	General cargo	12669	2008	February	Winter	White Sea	SC	8
8008618	Germes	Fishing vessel	2244	1983	April	Winter	Okhotsk Sea	SC	29
938879	Grumant	Bulk carrier	23278	2006	October	Summer	Pechora Sea	SC	12
7612228	Arctictrans	Bulk carrier	1258	1977	August	Summer	Norwegian sea	SC	33
8722109	Aurelia	Research	329	1988	October	Summer	Barents Sea	SC	29
7830777	Chastoozerskoye	Fishing vessel	87	1979	January	Winter	Northern Pacific	SC	40
9226126	Eidsvaag Junion	General cargo	1050	2001	November	Winter	Norwegian Sea	SC	2
8703919	Ray	Fishing vessel	430	1987	January	Winter	Northern Pacific	SC	23
8941808	Rembrabndt Van Rijn	Passenger	350	1924	June	Winter	Barents Sea	SC	95
9210359	S.Kuznetsov	General cargo	7625	2001	February	Winter	White Sea	SC	14
8035465	Saturn	Tankers	365	1981	September	Summer	Northern Pacific	SC	36
9333412	SCF Yenisei	Tankers	46187	2007	September	Summer	Kara Sea (OB Bay)	SC	7
7739777	Sjoveien	Passenger	331	1964	September	Summer	Barents Sea	SC	55

IMO	Vessel Name	New vessel type	DWT	Built	Month	Season	Location	Taxonomy	Age
9318565	Sten Aurora	Tankers	16596	2007	February	Winter	Barents Sea (Murmansk)	SC	7
9035826	Svyatoy Pavel	Tankers	10926	1992	November	Summer	Laptev Sea	SC	23
9035838	Svyatoy Petr	Tankers	9003	1992	November	Summer	Laptev Sea	SC	23
9014872	Tambey	General cargo	12239	1991	June	Winter	Kara Sea	SC	25
8821802	Tiksy	General cargo	12239	1990	September	Summer	Norwegian Sea	SC	27
7704980	Topaz A	Fishing vessel	700	1978	January	Winter	Norwegian Sea	VSC	31
8711289	Vysokogorsk	General cargo	7365	1991	June	Winter	Chukchi Sea	MI	11
9202041	Yamal Krechet	General cargo	20144	1999	June	Winter	Barents Sea	MI	18
780777	Chastoozerskoye	Fishing vessel	87	1979	January	Winter	Okhotsk Sea	SC	31
8714683	Diomid	General cargo	9575	1988	December	Winter	Okhotsk Sea	SC	25
8943002	Varnek	General cargo	154	1974	July	Summer	Barents Sea	VSC	36
8509181	Ortelius	Passenger	804	1989	June	Winter	Barents Sea	SC	27
8201416	M/V Grif	Tug	1199	1984	November	Summer	Okhotsk Sea	SC	22