The Risk of Synoptic-Scale Arctic Cyclones to Shipping

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Abstract.

The risk posed by Arctic cyclones to ships has seldom been quantified due to the lack of publicly available historical Arctic ship track data. This study investigates Automated Identification System (AIS) transponder derived Arctic ship tracks from September 2009 to December 2016. These are analysed with historical synoptic-scale cyclone tracks derived from ERA-5 and reports of past Arctic shipping incidents, to determine the number of ship tracks intersected by intense Arctic cyclones tracks, and how many of these intersections resulted in a reported shipping incident.

The number of ships operating in the Arctic has increased year-on-year from 2010 to 2016. The highest density of ships occurs year-round in the Barents Sea. Trans-Arctic shipping transits via the Northern Sea Route and the North-West Passage are limited to summer and autumn months when sea ice extent has sufficiently retreated from the coastlines. Ship track density along these trans-Arctic routes is far less than the thousands of ships travelling in the Barents Sea year-round. Between 2010 and 2016, 158 Arctic shipping incidents were reported, but only 6% of these reported incidents occurred following the passage of an intense Arctic cyclone. Arctic cyclones with significant wave heights greater than 6 metres are found to frequently intersect ships, but only 0.1% of these intersections resulted in a reported shipping incident. Results from this study indicate that ships are frequently impacted by Arctic cyclones, but cyclones have not been a dominant cause of reported Arctic shipping incidents between 2010 and 2016. This suggests that ships are resilient to the rough sea conditions that past Arctic cyclones have caused, therefore mitigating, and reducing risk.

1 Introduction

As a consequence of global warming, the Arctic Ocean is becoming increasingly accessible for ships as Arctic sea ice continues to decline (Stroeve et al., 2007, 2012, 2014). Annual mean Arctic sea ice extent has declined from 12.3 million km^2 in 1979 to 10.5 million km^2 in 2022, a decline of 15% (Fetterer and Windnagel., 2017). The fastest decline in Arctic sea ice extent occurred in September from 7.1 million km^2 in 1979 to 4.4 million km^2 in 2022, a decline of 38% (Fetterer and Windnagel., 2017). Arctic sea ice is projected to decline further into the future as global surface temperatures are projected to increase further (Stroeve et al., 2012; Wei et al., 2020).

This reduction in Arctic sea ice extent could have a detrimental consequences on the Arctic (Serreze and Barry, 2011), and mid-latitude climate systems (Coumou et al., 2018), which may include larger and more frequent Siberian wildfires, stress on local wildlife and ecosystems, and the enhanced release of greenhouse gases into the atmosphere through melting permafrost. However, reduced Arctic sea ice extent does also provide beneficial opportunities for industries such as shipping, oil exploration, and tourism, which could include shorter journeys between ports in North America, Europe, and Asia (Smith and Stephenson, 2013; Melia et al., 2016, Table 1), access to previously inaccessible natural resources (Harsem et al., 2015), and new destinations for tourism (Maher, 2017). These benefits may lead greater shipping traffic in the Arctic Ocean over the coming decades, consequently increasing the number of ships exposed to extreme weather and other Arctic hazards (Browse et al., 2013; Lasserre, 2014; Melia et al., 2016; Lasserre, 2019).

The shipping routes of the Northern Sea Route (NSR) and North-West Passage (NWP) are much shorter than traditional tropical shipping routes. Transits between major ports in Asia, Europe and North America could be shortened by as much as approximately 38% if these trans-Arctic routes are used rather than the more traditional Suez Canal and Panama Canal routes (Table 1). When Arctic sea ice has sufficiently retreated northward from the Eurasian and Canadian coastlines, the NSR that runs north of the Eurasian coastline can connect Europe and Asia, whilst the NWP that runs through the Canadian Archipelago can connect North America with Asia. These trans-Arctic shipping routes are becoming increasingly ice-free and feasible for shipping for longer periods in summer and autumn months (Melia et al., 2016), as Arctic sea ice extent has continued to decline (National Snow & Ice Data Centre, 2023).

But, the Arctic is a challenging and hazardous environment for such human activity. Cold temperatures can make working conditions difficult and can cause equipment failures (Larsen et al., 2016), and sea ice can force ships to travel over the shallow and perilous coastlines around the boundaries of the Arctic Ocean (Arctic Monitoring & Assessment Programme: Working Group of the Arctic Council, 2020). Conditions can be made even more dangerous by the passage of a cyclone or a Polar low, which can cause rough sea conditions due to high winds and high ocean waves (Thomson and Rogers, 2014; Liu et al., 2016; Waseda et al., 2018, 2021). Such conditions could endanger a ship's crew, potentially capsize the ship and its cargo, and cause delays in transit. Arctic cyclones can also enhance the break-up of sea ice (Simmonds and Keay, 2009; Asplin et al., 2012; Parkinson and Comiso, 2013; Peng et al., 2021), which can drive the ice into shipping lanes where it becomes an additional hazard for ships to navigate. Given the numerous hazards in the Arctic, it is important to assess their relative threat to human activity to inform decision-makers and the public and to ultimately increase the awareness of and resilience against the most threatening Arctic hazards.

Some recent Arctic shipping disasters highlight how perilous the Arctic can be for shipping. On 23 March 2019, the MV Viking Sky cruise ship, with 1,373 people on board, lost power whilst trying to contend with extremely high wind and ocean waves caused by the passage of an Arctic cyclone (Ibrion et al., 2021). Ocean waves were reported to be in excess of 15 metres in height, as the cruise ship started to drift toward the shallow coastlines of Norway. After a full evacuation, the cruise ship was salvaged, but some damage had to be repaired and imminent trips were consequently cancelled. Other Arctic cruise ship incidents unrelated to the passage of a cyclone have been documented, such as the MV Akademik Ioffe ship running aground On the 24^{th} August 2018 and spilling 80 litres of fuel (Transportation Safety Board of Canada, 2018;

Table 1. Approximate distances between major ports in Europe and North America to major ports in Asia when using Arctic routes (the Northern Sea Route between Europe and Asia or the North-West Passage between North America and Asia), or mid-latitude routes (the Suez Canal Route between Europe and Asia, and the Panama Canal Route between North America and Asia). The distances have been measured on Google Earth (2023) and are given to the nearest hundred nautical miles (nm).

Departure Port	Destination Port	Distance Using Mid-Latitude Route	Distance Using Arctic Route (1979-2020 mean Sept. Arctic Sea Ice extent)	Arctic Minus Mid-Latitude Route (1979- 2020 Sept. Arctic Sea Ice extent)
Rotterdam	Tokyo	11,300 nm	7,000 nm	**-4,300 nm** (-38%)
Rotterdam	Shanghai	10,500 nm	7,900 nm	**-2,600 nm** (-25%)
New York and New Jersey	Tokyo	9,700 nm	7,400 nm	**-2,300 nm** (-24%)
New York and New Jersey	Shanghai	10,700 nm	8,300 nm	**-2,400 nm** (-22%)

Johannsdottir et al., 2021), and the MV Clipper Adventurer being damaged whilst running aground in on 27^{th} August 2010 (Johannsdottir et al., 2021). Understanding these shipping incidents, and if they were driven by particular natural hazard that could be mitigated, is fundamental to direct research to understand and ultimately reduce the risks to shipping.

The spatial distribution and intensity of Arctic cyclones has been found to vary seasonally, with the highest density of winter (DJF) Arctic cyclones typically occurring over the Norwegian, Greenland and Barents seas, and the highest density of summer (JJA) cyclones typically occurring over the coastline of Eurasia and the Arctic Ocean (Reed and Kunkel, 1960; Serreze et al., 2001; Simmonds et al., 2008; Crawford and Serreze, 2016; Vessey et al., 2020). Vessey et al. (2022) showed that this seasonal spatial distribution is also shown in the maximum intensity locations of the most intense winter and summer Arctic cyclones. Arctic cyclones in winter are also generally more intense than summer Arctic cyclones (Zhang et al., 2004; Sorteberg and Walsh, 2008; Simmonds et al., 2008; Vessey et al., 2020, 2022). Although synoptic-scale Arctic cyclones have been the focus of many studies in the past, the exposure of ships to intense Arctic cyclones has seldom been reported on.

In December 2004, it became mandatory for all large ships with a gross tonnage greater than 300 tonnes and all passenger ships regardless of their size to have Automated Identification System (AIS) transponders, which transmit the ships' location to satellites in real time (International Maritime Organization, 2020). This regulation was established by the International Maritime Organization to increase the safety of ships in often busy shipping lanes. Due to their safety benefits, AIS transponders have been increasingly fitted to smaller vessels (U.K. Gov., 2014). This has allowed for the monitoring of ships and recording of past ship tracks. However, archived historical ship track data is often privately owned and difficult or costly to obtain publicly.

Consequently, there are few publicly available studies that describe past Arctic shipping activity (e.g., Corbett et al., 2010; Eguiluz et al., 2016; Hreinsson, 2020; Berkman et al., 2020b, 2022; Müller et al., 2023), likely due to the lack of open-source Arctic shipping datasets. These studies show that there is typically a high density of ships in the Barents Sea year-round, and that trans-Arctic shipping along the NSR and the NWP is currently limited to months where sea ice is near its minimum extent, typically from August to October. But these previous studies have not combine these past ship tracks with past Arctic cyclone tracks to assess the risk that Arctic cyclones pose to shipping, nor do they combine these past ship tracks with past shipping incident reports to quantify the number of past shipping incidents and those incidents caused by the passage of Arctic cyclones. It is therefore unclear whether the number of ships and shipping incidents in the Arctic are increasing as the Arctic becomes increasingly more accessible due to declines sea ice extent, how many ships are presently impacted by hazardous weather conditions caused by Arctic cyclones, and how many Arctic shipping incidents have occurred following the passage of a cyclone.

The lack of publicly available historic ship track data has been somewhat addressed by Berkman et al. (2020a), who published an open-source Arctic ship track dataset. This contains the transmitted AIS-derived ship location data of ships that travelled north of the Arctic Circle (north of 66.5°N) but is only available for a limited period from September 2009 to December 2016. Berkman et al. (2020b, 2022) used this dataset and showed that the number of ships in the Arctic has increased between 2010 and 2016. Arctic shipping incidents from 2005 to 2017 have been collated and made publicly available from Protection of the Arctic Maritime Environment Agency (2023). This database includes incidents occurring due to various causes (e.g., collision, grounding etc.), and describes the ships impacted (e.g., name, tonnage), the incident itself (e.g., if the ship was lost or only partially damaged), and the incidents' consequences (e.g., marine casualty, cargo damage etc.). Combining past ship tracks and shipping incident reports with past cyclone tracks could provide new insights into quantifying the risk of cyclones to Arctic shipping.

This study aims to describe past Arctic shipping activity and incidents and quantify the number of Arctic ships that have been intersected by intense cyclones, using publicly available ship track, ship incident, and weather data. This will be achieved by answering the following research questions:

- Does the spatial distribution of Arctic shipping vary with the seasonal changes in Arctic sea ice extent?
- Given recent reductions in Arctic sea ice extent, is there evidence of any trend in the number of ships and shipping incidents in the Arctic?
- How many Arctic ships have been intersected by past intense cyclones, and how many of these led to a reported shipping incident?

The methods used in this study are described in Section 2, including a description of the data and storm tracking method used. In Sections 3 to 8, the results from this study are described, detailing the trends and seasonal spatial distribution of past Arctic ship tracks, past intense Arctic cyclones tracks and past Arctic shipping incidents. The number of ship tracks intersected by passed intense Arctic cyclone tracks, and the proportion of these intersections that resulted in a reported shipping incident is also quantified and described. Finally, a summary of the main conclusions is given in Section 9.

2 Methodology

2.1 Arctic Shipping Data

Berkman et al. (2020a) published Arctic ship location data from AIS transponders between September 2009 and December 2016, over a domain that includes areas north of the Arctic Circle (66.5°N). This dataset includes information such as the timestamp of the AIS transmission, the unique Maritime Mobility Service Identity (MMSI) number of each ship, the draught (vertical distance between the waterline and the bottom of the ships' hull, which can indicate the ships size and weight), and the latitude and longitude coordinates of the transmission.

The Berkman et al. (2020a) data needs to be transformed into ships tracks per ship (each unique MMSI). Ships are mandated to transmit their location at a high temporal resolution (i.e., minutes) to ensure safety within the busy network of mobile ships. This high temporal resolution is reduced from minutes to the point nearest every hour to match the temporal resolution of the atmospheric dataset used in this study, ERA-5. To account for ships having multiple tracks within each month, a new track from each ship is determined if there is a break in the AIS transmission of that ship of more than 48 hours. This break in transmission may be due to the ship being docked and the engine being switched off, causing no AIS transmission, signifying the end of the ships current journey and track.

Past Arctic shipping incidents and accidents data are documented by the Arctic Council (Protection of the Arctic Maritime Environment Agency, 2023). This database reports Arctic shipping incidents from 2005 to 2017 including details the incidents longitude and latitude coordinates, time, and type (e.g., marine casualty, cargo damage etc.). It is also indicated whether the vessel was completely lost or only partially damaged following the incident. Incidents south of the Arctic Circle are included, so this dataset can be filtered to retain shipping incidents that occurred north of 66.5°N between September 2009 to December 2016, to match period of the Berkman et al. (2020a) ship track dataset. Shipping incidents with no location data are omitted.

2.2 Historic Atmosphere and Ocean Data

This study uses atmospheric data from the most recent reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF), ERA-5 (Hersbach et al., 2018, 2020). Reanalysis datasets have been developed over recent decades to provide a consistent global perspective past atmospheric conditions, created by assimilating historical observations from a range of sources into state-of-the-art Numerical Weather Prediction (NWP) models. Although there are multiple reanalysis datasets available from various institutions, ERA-5 was chosen here as it is the most recent and highest spatial and temporal resolution of all reanalysis datasets available (Vessey et al., 2020).

ERA-5 contains atmospheric data from 1940-present at a 1-hourly temporal resolution and at an approximately 31 km (TL639) spatial resolution, with 137 vertical levels up to 0.01 hPa. Historical observations are assimilated into the ECMWF Integrated Forecast System (IFS) version CY41R2, using a 4-dimensional variation data assimilation scheme (4D-Var) (Hersbach et al., 2020). Prior to 1979, satellite observations were not available, so the reanalysis datasets may be less constrained. So, data from ERA-5 is used from 1979-2021 in this study to identify past Arctic cyclone tracks.

The ERA-5 atmospheric variables used in this study are the 850 hPa relative vorticity and 10-metre u- and v- component winds. The IFS model is also coupled to the ECMWF WAM (WAve Model) Model and gives information of past ocean states, but at a lower spatial resolution of 0.5°. The ECMWF WAM Model can determine past wave heights over the open ocean but cannot capture waves within sea ice. To assess how Arctic cyclones influence the ocean state and cause hazardous rough sea conditions, the ERA-5 significant wave height including tide and surge field is also used. These ERA-5 variables are used at 1-hourly intervals each day.

In this study, historic Arctic shipping activity is also related to past Arctic sea ice extent. For this purpose, the Met Office Hadley Centre Sea Ice and Sea Surface Temperature version 2.1 dataset (HadISST2.0) (Titchner and Rayner, 2014) is used to indicate past Arctic sea ice extent. This dataset was created by combining various Arctic sea ice records to produce a best-estimate of past sea ice extent globally at a 1° horizontal resolution and 6-hourly time resolution from 1850 to present (Titchner and Rayner, 2014). There are various Arctic sea ice data products available, from various institutions, and Berkman et al. (2020a, 2022) had previously only used Arctic sea ice data from the National Snow and Ice Data Center (NSIDC - Fetterer and Windnagel., 2017). However, Comiso et al. (2017) found that the historical Arctic sea ice extent and trends from HadiSST2.0 are very similar to that of other sea ice datasets, such as the NSIDC (Fetterer and Windnagel., 2017).

2.3 Storm Tracking

Arctic cyclones are identified in hourly ERA-5 data, which is at a different temporal resolution than the sub-hourly Arctic shipping data and the 6-hourly Arctic sea ice data, using the storm tracking algorithm developed by (Hodges, 1994, 1995, 1999, 2021). This storm tracking algorithm has been used in numerous studies to identify past Arctic cyclones in reanalyses (e.g., Day and Hodges, 2018; Day et al., 2018; Gray et al., 2021; Vessey et al., 2022). Vessey et al. (2020) showed that this storm tracking algorithm captures more Arctic cyclones when based on 850 hPa relative vorticity than mean sea level pressure (MSLP), so in this study 850 hPa relative vorticity is used as the storm tracking variable.

This field is first spectrally truncated to a spectral resolution of T42 and is filtered to remove the planetary scales for total wavenumbers less than or equal to five. This ensures that synoptic-scale systems that are independent of large-scale forcings are focused upon. Cyclone features are then identified at each time step as maxima in the T42 850 hPa relative vorticity field. Feature points between consecutive hourly time steps within a minimum displacement factor of 2° in all regions north of 30°N, are then linked into create cyclone tracks. This is achieved by optimising a cost function for track smoothness, which is subject to adaptive constraints on displacement and smoothness (Hodges, 1999).

Once all cyclone tracks have been identified between 1979-2021, they are then filtered to only retain those that last more than 2 days and travel more than 1000 km. This further ensures that only mobile and synoptic-scale cyclones are focused upon but means that smaller meso-scale cyclones such as Polar lows, are not retained. Arctic cyclone tracks are then filtered by those that travel north of Arctic Circle (66.5°N) at any point during their lifetime. To assess the hazardous weather conditions that may impact ships, the maximum full resolution ERA-5 10-metre wind speed and significant wave height (including tide and swell) within a 5° radius of the cyclone's centre are then identified and added to the cyclone tracks.

Ships are typically built to withstand moderately intense weather conditions, and more intense Arctic cyclones are more likely to pose a significant threat to ships operating in the Arctic. The Beaufort Wind Scale and Douglas Sea State Scale can be used to gauge the severity cyclones, and whether their intensity can cause hazardous ocean conditions that could threaten a ship and its crew (Simpson, 1906; Schule, 1966; Met Office, 2010). These scales indicate when rough sea conditions are likely to occur depending on surface wind speed or wave height. The thresholds that result in rough sea conditions are marked as 17 ms^{-1} for surface wind speeds (Beaufort Wind Scale 8 and higher) and 2.5 m for significant wave heights (Douglas Sea State Scale 5 and higher). The identified ERA-5 derived Arctic cyclone tracks are then filtered to obtain the cyclone tracks that cause rough sea conditions in the Arctic and have a maximum 10 m wind speeds and significant wave heights within the Arctic exceeding these thresholds. Although the exceedance of these intensity thresholds does not guarantee that every ship will be damaged or affected, these thresholds do provide an objective measure to filter out cyclones that may be intense enough to be hazardous for ships.

2.4 Intersecting Past Arctic Ship Tracks with Past Cyclone Tracks

The number of past ship tracks intersected by an intense cyclone is quantified to determine the number of ship tracks impacted by past cyclones. The highest wind speeds do not occur at the centre of a cyclone, but often occur in the southern half of a cyclone due to near-surface air streams (Browning, 2004; Vessey et al., 2022). Vessey et al. (2022) showed that in the composite structure of the 100 most intense winter and summer Arctic cyclones, the maximum 10-metre wind speeds within these cyclones occur in an area approximately 5° south from the composite cyclone's centre, relative to the direction of propagation (see Vessey et al., 2022's Figure S3).

High surface wind speeds tend to cause tall ocean waves and high significant wave heights. Tall ocean waves are perhaps a more hazardous to ships than high surface wind speeds, as they have a greater ability to make the ship unstable. So, in this study, an intersection between a ship track and a cyclone track occurs if the Arctic ship track longitude and latitude coordinates at the same time step are within 3° (approximately 333 km) of the longitude and latitude coordinates of the cyclone's maximum significant wave height, and the significant wave height at the ship's location is greater than 2.5 m. This ensures that the ship is impacted by extreme wave heights and that the extreme wave height conditions are related to the passage of an Arctic cyclone. This intersection methodology is exemplified in Figure 8.

If there are multiple intersections between a ships coordinates and a particular cyclone, this ship and cyclone intersection is only counted once to avoid double counting ship and cyclone intersections. A similar procedure is followed to intersect the time and coordinates of a past reported shipping incident with the passage of a cyclone. But to account for a time lag between an intersection occurring and the incident being reported, incident reports within the next 48 hours after the passage of an Arctic cyclone are counted as being related to a cyclone. The sensitivity to this 3° (approximately 333 km) distance threshold is also tested, and intersections between ship track and cyclone and shipping incident is also determined within a 6° (approximately 666 km) of the longitude and latitude coordinates of the cyclone's maximum significant wave height, and the significant wave height at the ship's location is greater than 2.5 m. For some cases, cyclones may caused less extreme significant wave heights that are still greater than the 2.5 m threshold outside a 3° and 6° distance radius from the cyclone's maximum significant wave height, so the number of intersections between ship track and cyclone, and shipping incident and cyclone, may be underestimated. But this approach should identify the ship tracks and shipping incidents impacted by the most extreme significant wave heights conditions caused by the passage of a past Arctic cyclone.

3 Trends in Arctic Shipping and in Arctic Cyclones

Between September 2009 and December 2016, 176,961 ships with a unique identification number (MMSI) travelled north of the Arctic Circle (Figure 1a). The number of ships that travelled in the Arctic increased year-on-year from 2010 to 2016 (Figure 1a). This is similarly shown by Berkman et al. (2020b, 2022). In 2010, 15,666 ships with a unique MMSI transmitted an AIS location in the Arctic, whereas in 2016, the number ships operating in the Arctic was +122% higher (more than two times greater) and approximately 34,780 ships (Figure 1). This shows that the number of ships operating in the Arctic and transmitting their location has increased between 2010 and 2016.

There has been a greater increase in the number of small ships with a draught of less than 4.55 metres from 7,261 in 2010 to 12,193 in 2016 (+68% increase), than the increase in the number of large ships with a draught of more than 4.55 metres from approximately 8,611 in 2010 to 10,117 in 2016 (+17% increase) (Figure 1b and Figure 1c). The draught threshold of 4.55 metres represents the mean draught of all ships that travelled in the Arctic between September 2009 and December 2016. Since 2004, when large ships were mandated to fit AIS transponders, such devices have been increasingly fitted to smaller vessels, and it became mandatory in May 2012 for all fishing vessels with a size greater than 24 metres to have AIS transponders (U.K. Gov., 2014). Such a change in regulation may have artificially increased the number of ships reporting their position when in the Arctic. But, given the increase in the number of ships shown in Figure 1 are so great, and there is a strong increase in the number of large ships that were required to have a AIS transponder from 2004, it is highly likely that the number of ships operating in the Arctic has increased.

The number of Arctic ships per month varies seasonally, with changes in Arctic sea ice extent, which is also shown by Berkman et al. (2020b, 2022). The maximum number of ships in the Arctic per year generally occurs in the late summer and early autumn months when Arctic sea ice is typically at its annual minimum extent (Figure 1). The minimum number of Arctic ships generally occurs in winter months (Figure 1). For example, in 2012, Arctic sea ice extent was 15.2 million km^2 in March but had reduced to 3.6 million km^2 in September (National Snow & Ice Data Centre, 2023). So, the number of ships operating in the Arctic appears correlated with Arctic sea ice extent, where lower sea ice extent coincides with a higher number of ships operating in the Arctic. This is consistent with Berkman et al. (2020a, 2022).

The number of ships operating in the Arctic per year has increased by more than double between 2010 and 2016 (Figure 1). However, there is some evidence to suggest that the increasing number of ships in the Arctic has slowed between 2017 and 2019 (NOAA, 2022). Although using a different data source, NOAA (2022) showed that the maximum number of ships

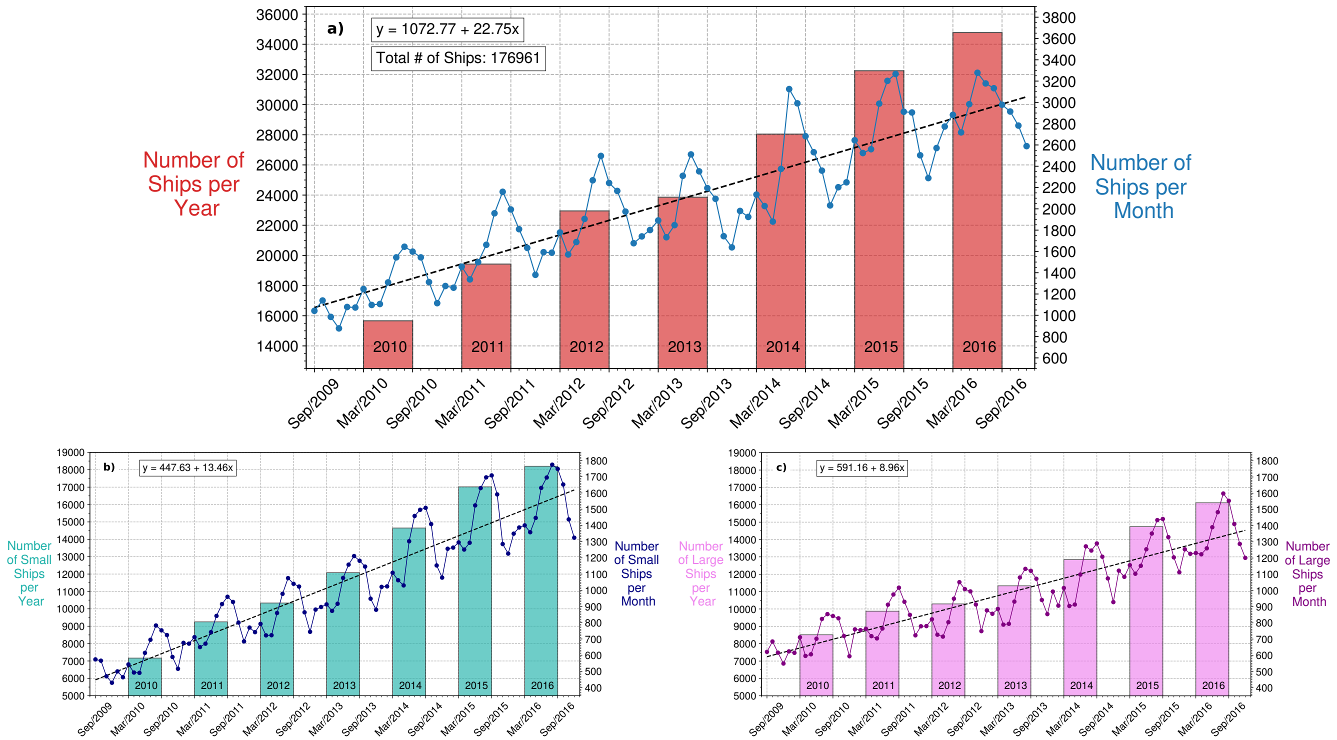

Figure 1. Trends in the frequency of **a)** all ships, **b)** all small ships with a draught less than the mean draught across all ships (4.55 m), and , **c)** all large ships with a draught more than the mean draught across all ships (4.55 m), with a unique identification number (MMSI) to travel north of the Arctic Circle (66.5°N) per year and month, from September 2009 to December 2016 from the Berkman et al. (2020a) Arctic shipping dataset.

per month travelling in the Arctic in 2018 was similar to 2016, with a maximum of approximately 4,000 ships travelling in the Arctic in late summer in both years. So the increase in the number of ships operating in the Arctic between 2010 and 2016 (Figure 1) may have slowed from 2016 to 2018. However, given the lack of up-to-date publicly available ship track data, there is insufficient evidence to describe shipping behaviour up to the present day.

Since 1979, surface temperatures in the Arctic have warmed approximately four times as much than the global average (Rantanen et al., 2022), due to the phenomenon of Arctic Amplification (Smith et al., 2019). Despite this, there are no evident trends in the frequency of intense Arctic cyclones with significant wave heights greater than 2.5 m (Figure 2). Despite some inter-annual variability leading the annual average of intense Arctic cyclones to vary by approximately 38% from a maximum of 219 cyclones to a minimum of 150, an average of 182 Arctic cyclones with significant wave heights higher than 2.5 m have occurred each year between 1979 and 2022 (Figure 2).

The frequency of intense Arctic cyclones does appear to vary seasonally, with the frequency of intense Arctic cyclones being highest in winter and lowest in summer (Figure 2). This seasonality in Arctic cyclone intensity was also shown in

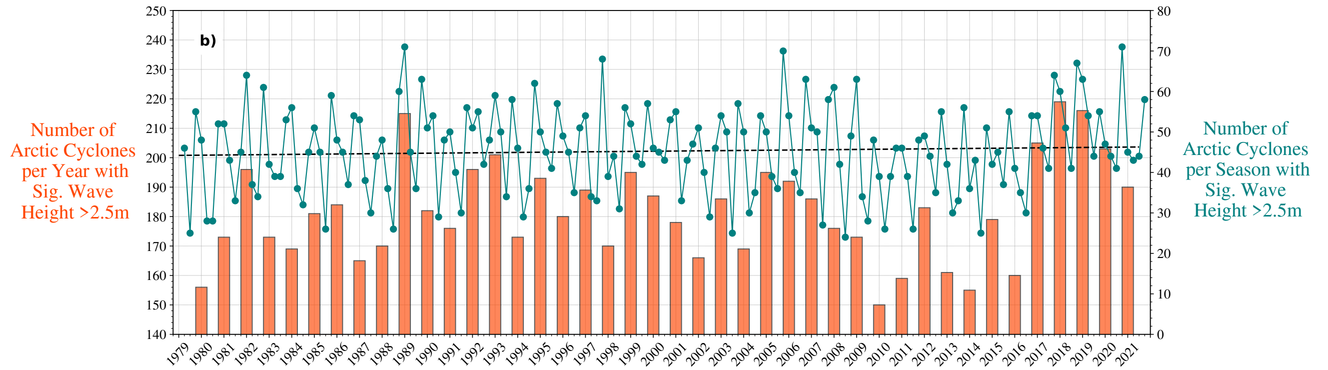

Figure 2. The total number of Arctic cyclones per year and per season (winter - DJF, spring - MAM, summer - JJA and autumn - SON) with significant wave heights greater than 2.5, from 1979 to 2022 based on ERA5.

Zhang et al., 2004; Sorteberg and Walsh, 2008; Simmonds et al., 2008; Vessey et al., 2020, 2022. Though, in this study, the seasonality in Arctic cyclone frequency and intensity is shown in terms of cyclones with extreme significant wave heights.

4 Seasonality in Arctic Ship Tracks and Arctic Cyclone Tracks

The number of ship tracks in the Arctic varies per month and is highest in summer months when Arctic sea ice is typically at its minimum extent. Between 2010 and 2016, there were a total of approximately 44,000 Arctic ship tracks in winter (DJF) months and 46,000 in spring (MAM) months (Figure 3a and 3b). But in all summer (JJA) and autumn (SON) months between 2010 and 2016, there were more than double the number of Arctic ship tracks than in winter and spring months, with approximately 95,000 and 122,000 Arctic ship tracks occurring in all summer and autumn months respectively (Figure 1c and 3d). This further shows that the number of ships operating in the Arctic is highest when Arctic sea ice extent is lowest.

The highest density of Arctic ship tracks in all seasons occurs in the Barents Sea, and just north of northern Norway in every season, with more than 200 ship tracks over this region in all seasons (Figure 3e - h). The highest density of ships over the Barents Sea is also shown when examining Arctic ship tracks over annual timescales (Figure S2 in the Supplementary Material). Other regions of high Arctic ship track density occur around Iceland and over Baffin Bay, where ship track density is approximately 50 to 200 tracks per season (Figure 3e - f). This is similar to Eguiluz et al. (2016), who also showed that these areas were the busiest shipping and fishing areas in the Arctic between 2010 and 2014.

There is also a seasonal variation in the spatial distribution of Arctic ship tracks, which shows that in winter and spring, shipping is confined to the Greenland, Norwegian and Barents Seas (Figure 3a - f). However, in summer and autumn, ship tracks are more widespread across the Arctic and there are many more ships travelling across the trans-Arctic shipping routes of the Northern Sea Route (NSR) (along the coastline of Eurasia), the North-West Passage (NWP) (through the Canadian Archipelago). Although, when considering the density of Arctic ship tracks, the number of ships in summer and

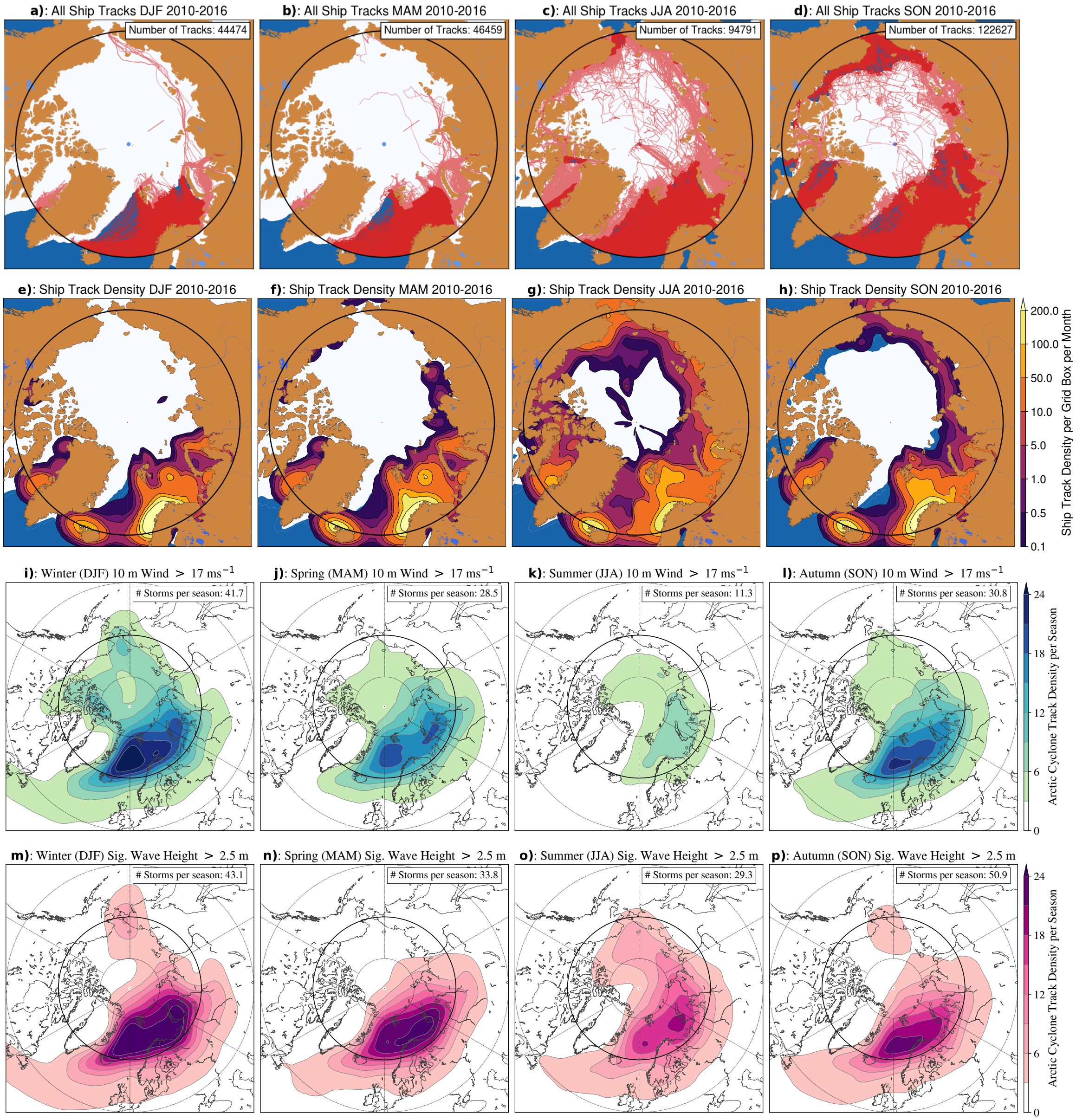

Figure 3. a) - d) All ship tracks from 2010 to 2016 per season (red lines), **e) - h)** ship track density from 2010 to 2016 per season per grid box (2.0°N x 5.0°E), **i) - l)** Arctic cyclone track density from 1979 to 2021 per season per unit area (5° spherical cap) of cyclones with 10 m wind speeds greater than 17 ms^{-1}, and **g) - h)** with significant wave heights greater than 2.5 m. **a), e), i) and m)** - winter (DJF), **b), f), j) and n)** - spring (MAM), **c), e), k) and o)** - summer (JJA), and **d), h), l) and p)** - autumn (SON)). Ship track densities are smoothed using a Gaussian filter equal to 1.0. Mean HadISST2.0 Arctic sea ice extent greater than 15% over each period is shown in white. The solid black line indicates the Arctic Circle (66.5°N).

autumn is much greater in the Barents Sea than in these trans-Arctic shipping routes (Figure 3a - f). This spatial distribution in Arctic ship tracks is consistent with Arctic ship tracks described by Corbett et al. (2010), Eguiluz et al. (2016) and Hreinsson (2020). So, despite large reductions in Arctic sea ice extent since 1979, trans-Arctic shipping along the NSR and the NWP was limited to summer and autumn, when Arctic sea ice was at its minimum extent. Moreover, the density of trans-Arctic shipping appears much lower than the density of ships in the Barents Sea (Figure 3a - f).

The highest track density of intense Arctic cyclones with 10 m wind speeds greater than 17 ms^{-1} and significant wave heights greater than 2.5 m is also in the Barents Sea and around Iceland, the same regions where ship track density is highest (Figure 3). In summer, the track density per season of intense Arctic cyclones appears more extended from the Barents Sea to over the Kara Sea (Figure 3i - p), perhaps due to the difference in the spatial distribution of summer Arctic cyclones which is highest over the Eurasian coastline (Reed and Kunkel, 1960; Serreze et al., 2001; Simmonds et al., 2008; Crawford and Serreze, 2016; Vessey et al., 2020).

Overall, there is higher track density in winter intense Arctic cyclones than summer intense Arctic cyclones (Figure 3i - p), with winter Arctic cyclones having significant wave heights as high as 13 m (Figure S3 in Supplementary Material). When applying more extreme intensity thresholds of 10 m wind speeds greater than 25 ms^{-1} and significant wave heights of 4 m, the Barents Sea is still identify as the region with the highest track density of intense Arctic cyclones (Figure S4 and S5 in the supplementary material). So, the highest density of ship tracks is also where there is the highest density of intense Arctic cyclone tracks (Figure 3).

5 Trans-Arctic Shipping Trends through the Northern Sea Route and North-West Passage

One benefit of reduced Arctic sea ice extent is that it offers shorter routes between ports in North America, Europe and Asia than traditional mid-latitude routes through the Suez Canal and Panama Canal (see Table 1). The number of ships travelling through the NSR has increased significantly from 2010 to 2016 (Figure 4). In 2010, approximately 150 ships travelled along the NSR between the Kara and Laptev Seas and along the coastline of Eurasia (see red box in Figure 4a), whereas in 2016, approximately 460 (+200% increase) travelled through these Seas (Figure 4b). This increase in ship traffic through the NSR was similarly shown by Müller et al. (2023).

Fewer ships travelled through the NWP (through the Canadian Archipelago) from 2010-2016 than in the NSR (see blue box in Figure 4a). Less than 40 ships travelled in the NWP between 2010 and 2013, but this number was higher in 2014, 2015, and 2016 (Figure 4b). In 2016, approximately 240 ships travelled through the Canadian Archipelago (+500% increase) (Figure 4b). However, considering that there are tens of thousands of ship tracks north of the Arctic Circle each year between 2010 and 2016 (Figure 3), the hundreds of ships travelling through the trans-Arctic shipping routes of the NSR and NWP each year (Figure 4) is significantly less than the thousands, even tens of thousands, of ships travelling in the Barents Sea each year.

Arctic sea ice is much thicker in the Canadian Archipelago and the NWP than sea ice located north of the Eurasian continent and the NSR (Sallila et al., 2019). Therefore, sea ice over the NSR is more susceptible to melting in summer and

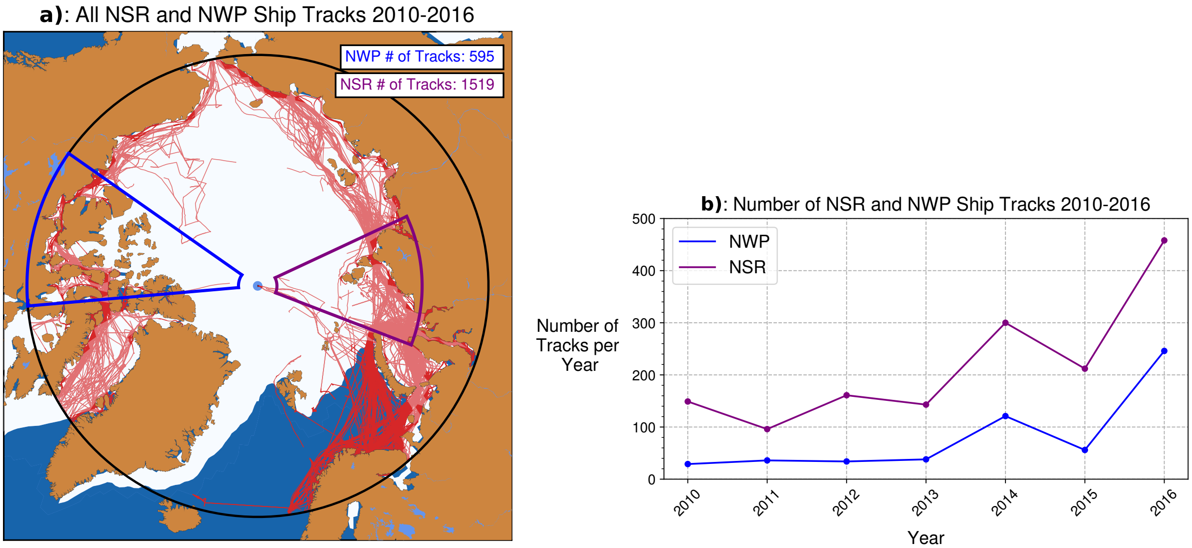

Figure 4. (a) All trans-Arctic ship tracks (red lines) that travel through the Northern Sea Route (NSR) (along the coastline of Eurasia and through the purple box) and the number of ship tracks through the North-West Passage (NWP) (through the Canadian Archipelago and through the blue box), from January 2010 to December 2016 from the Berkman et al. (2020a) Arctic shipping dataset. The total number of ship tracks across the NSR and NWP are also indicated. Mean HadISST2.0 Arctic sea ice concentration greater than 15% is shown in white. The solid black line indicates the Arctic Circle (66.5°N). **(b)** The annual number of trans-Arctic ship tracks that travel through the NSR (purple line) and NWP (blue line), from January 2010 to December 2016.

autumn months and the NSR would have a greater likelihood of being navigable for ships than the NWP. This is a likely reason for the higher number of ships in the NSR than the NWP between 2010 and 2016 (Figure 4). However, the number of ships travelling through the NSR per year does not show a consistent increase year-on-year, with approximately 300 and 210 ship tracks occurring in 2014 and 2015 respectively (Figure 4b). So, the annual variation in the minimum Arctic sea ice extent may still influence the number of ships travelling across these trans-Arctic shipping routes.

6 Trends in Past Arctic Shipping Incidents

Between 2005 and 2017, there were a total of 250 reported shipping incidents north of the Arctic Circle (Figure 5a), with 158 occurring between 2010 and 2016 (Figure 5b). This is only 0.09% of all ships (176,961) that travelled through north of the Arctic Circle between 2010 and 2016 (Figure 1). These incidents resulted in damage and disruption to the ship and its crew, and include 83 various types of incidents, including capsizing, allision, equipment failure, fire, flooding, grounding, loss of control/propulsion and person overboard (Protection of the Arctic Maritime Environment Agency, 2023).

The ship with the highest tonnage to report an incident north of the Arctic Circle between 2005 and 2017 was the Stride Tanker Ship on 9^{th} of September 2013, which occurred in Murmansk in Russia. This ship is a large tanker with a tonnage of

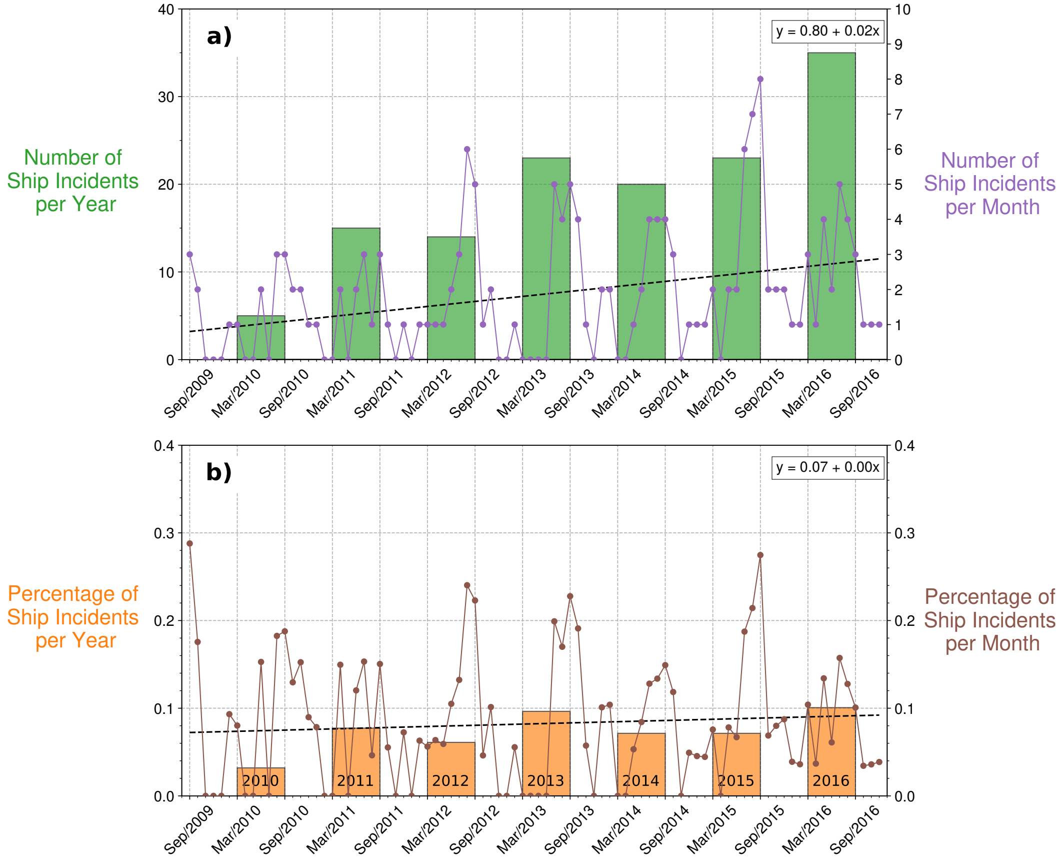

Figure 5. a) The total number of ships that reported an incident north of the Arctic Circle (66.5°N) per month and per year between September 2009 and December 2016 from the Protection of the Arctic Maritime Environment Agency (2023) dataset. **b)** The percentage of ships that travelled north of the Arctic Circle (66.5°N) per month and per year between September 2009 and December 2016 that reported a shipping incident.

60,325 tn and a horizontal size of approximately 240 m. The incident report shows that this ship experienced contact with a fixed object in the Barents Sea (Protection of the Arctic Maritime Environment Agency, 2023). The report of this incident aligns with other media reports (e.g., Shipwreck Log, 2014). Another large oil tanker with a tonnage of 29,844 tn, the SKF Enisey / SCF Yenisei reported an incident on 26^{th} of September 2014. The incident report shows that this ship experienced contact with a fixed object in the Kara Sea, consequently leading to "marine casualties" (Protection of the Arctic Maritime Environment Agency, 2023). The report of this incident aligns with other media reports (e.g., Shipwreck Log, 2014). Most Arctic reported shipping incidents between 2005 and 2017 were from fishing vessels, and those ships a tonnage less than

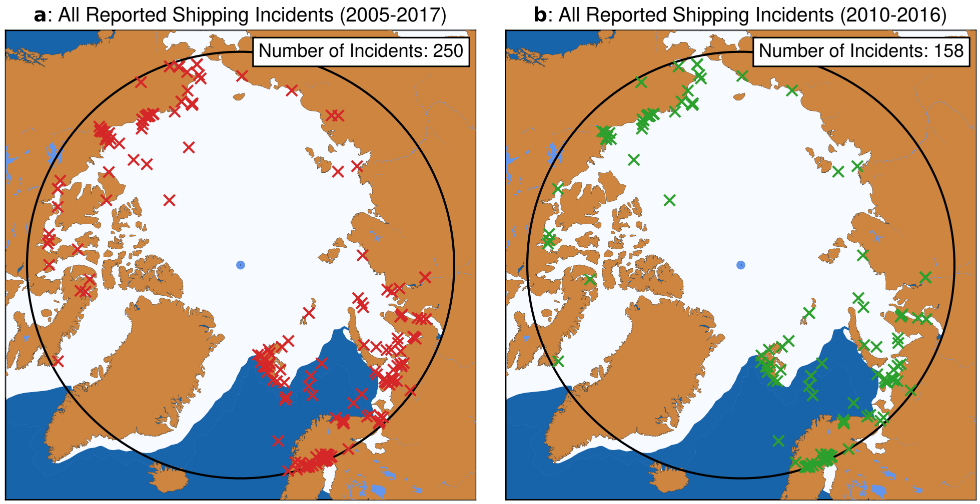

Figure 6. The total number of reported shipping incidents in the Arctic (north of 66.5°N) between **a)** 2005 and 2017, and **b)** 2010 and 2016, from the Protection of the Arctic Maritime Environment Agency (2023) database.

1,000 tn (Figure S6 in the Supplementary Material). However, the cause of these incidents is not reported, and it is not indicated if these events occurred due to bad weather such as Arctic cyclones. This requires matching the position and time information with past Arctic cyclone tracks.

The number of Arctic shipping incidents is generally highest in summer months (Figure 5a), which is when the number of ships operating in the Arctic is generally highest (Figure 1). Up to 36 Arctic shipping incidents were reported per year, with this maximum occurring in 2016 (Figure 1). The spatial distribution of reported Arctic shipping incidents also shows that the majority of incidents occur very close to coastlines (Figure 6). In fact, very few incidents occur over the open Arctic Ocean (Figure 6).

Although there is an increasing trend in the number of reported shipping incidents in the Arctic, these numbers are far less than the total number of ships travelling in the Arctic per year, which in 2016 was approximately 34,780 ships (Figure 1). In 2016, of the 34,780 ships that travelled across the Arctic Ocean, only 36 (approximately 0.1%) shipping incidents were reported. Similarly in other years, less than approximately 0.1% of all ships travelling in the Arctic Ocean reported a shipping incident (Figure 5b). This shows that it is very uncommon for shipping incidents to occur given the very high number of ships travelling in the Arctic Ocean.

7 Number of Arctic Ships Intersected and Impacted by Past Intense Arctic Cyclones

Between 2010 and 2016, a total of 32,103, 15,246 and 4,633 ship tracks were intersected by an Arctic cyclone, where each ships longitude and latitude coordinates were within 3° (approximately 333 km) of the longitude and latitude coordinates of a cyclone's maximum significant wave height at the same time step, and the significant wave height at the ship tracks

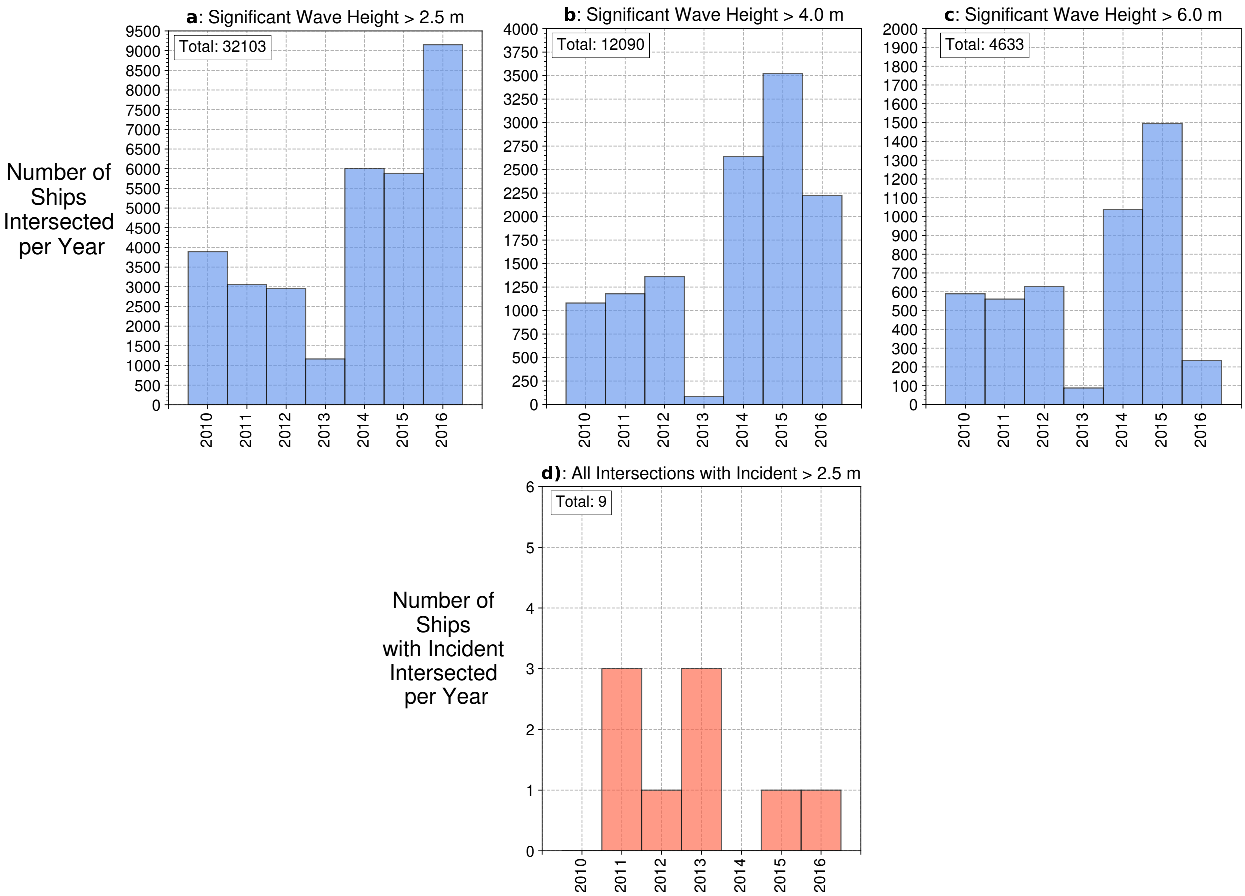

Figure 7. The annual number of Arctic ship and cyclone intersections from 2010 to 2016, where a ship's longitude and latitude coordinate are within 3° (approximately 333 km) of the longitude and latitude coordinate of the cyclone's maximum significant wave height at the same time step, and the significant wave height at the ship tracks coordinates is greater than **a)** 2.5m, **b)** 4.0m and **c)** 6.0m. **d)** Shows how many intersections led to a reported shipping incident within 48 hours of an Arctic ship and cyclone intersection. Note: multiple intersections between a cyclone and the same ship track are not double counted.

coordinates is greater than 2.5 m (Figure 7a), 4.0 m (Figure 7b) and 6.5 m (Figure 7c) respectively. These intensity thresholds are typically considered to lead to rough to very rough sea conditions using the Douglas Sea State Scale. But, between 2010 and 2016, only 9 shipping incidents (0.2% of all intersections with significant wave height greater than 6.0 m, and 6% of all reported Arctic shipping incidents) were reported within two days following the intersection between a ship and an intense Arctic cyclone (Figure 7d). So ships are frequently intersected and impacted by intense Arctic cyclones with significant wave heights exceeding 6 m, but only a handful of these intersections resulted in a report shipping incident.

All of these shipping incidents following the intersection between a ship and cyclone are only described as causing partial damage to the ship, and none of these intersections resulted in the ship being lost (Table 2). These shipping incidents

Table 2. Summary of all reported incidents following an intersection between a ship track and an Arctic cyclone track, where a ship's longitude and latitude coordinate are within 3° (approximately 333 km) of the longitude and latitude coordinate of the cyclone's maximum significant wave height at the same time step, and the significant wave height at the ship tracks coordinates is greater than 2.5m, between 2010 and 2016. Shipping incident data from Protection of the Arctic Maritime Environment Agency (2023).

Time of Incident (YYYY/MM/DD)	Vessel Name	Type of Incident	Vessel Lost or Damaged	Vessel Tonnage (Tonnes)	Consequences
2011/07/04	Arctic Hawk	Fire	Damaged	17	Marine Casualty
2011/07/22	Barge 210	Allision	Damaged	1255	Marine Casualty
2011/09/11	Barge 211	Equipment failure	Damaged	1016	Marine Casualty
2012/08/31	Aiviq	Flooding	Damaged	12892	Marine Casualty
2013072818	Tony Saganna	Set Adrift	Damaged	40	Marine Casualty
2013/10/12	Beauty Bay	Fire	Damaged	196	Marine Casualty
2013/11/15	AP 1-88-8701	Equipment failure	Damaged	18	Marine Casualty
2015/08/23	Capt Frank Moody	Collision	Damaged	166	Marine Casualty
2016/01/02	Arctic Hawk	Loss of electrical power	Damaged	17	Marine Casualty

include fire, allision/collision, equipment failure, loss of electrical power and loss of control (Table2). The consequences of these incidents included marine casualties (Table2). All but one of the ships to report an incident had a tonnage of approximately 1,000 tonnes or lower. As larger ships (e.g., cargo ships), often have a tonnage greater than 10,000 tonnes (UNCTAD, 2022), these ships that reported a shipping incident following the passage of an Arctic cyclone are likely smaller ships e.g., fishing vessels.

There are reports of other fishing vessels being impacted by the passage of Arctic cyclones, which are not included in the Protection of the Arctic Maritime Environment Agency (2023) shipping incidents database, which is limited to incidents that occurred between 2005 and 2017. For example, the Arctic Rose fishing vessel sank in the Bering Sea in April 2001, after being impacted by high wind and waves that could have resulted from the passage of an Arctic cyclone (Borlase, 2003). Another example includes the sinking of the Gaul fishing vessel, which sank in 1974 after being impacted by the passage of an intense cyclone (BBC News, 2014).

When searching for shipping incidents within a greater distance from Arctic cyclone's maximum significant wave heights of 6.0° (approximately 666 km), only 10 Arctic shipping incidents were reported within 48 hours of the passage of an Arctic cyclone (Figure S7 in the Supplementary Material). This is still only a very small percentage (less than approximately 0.02% of all the intersections with significant wave height greater than 6.0 m) of the total number of intersections between ship tracks and Arctic cyclone tracks, as a total of 47,327, 26,530 and 6,661 ship tracks were found to intersect within a 6.0° radius of a past Arctic cyclone track, which caused significant wave heights at the ships location to be greater than 2.5 m, 4.0 m and 6.0 m respectively (Figure S7 in the Supplementary Material). So, even when altering the ship and cyclone intersection method, intersections between ships and intense Arctic cyclones are found to be very common from 2010 to 2016, with a very low percentage of these intersections resulting in a reported shipping incident.

8 How do Arctic Ships Respond to the Passage of an Intense Arctic Cyclone?

To gauge how ships respond to the passage of intense Arctic cyclones, the most intense cyclones between 2010 and 2016 that travel through the busiest cluster of Arctic ships (in the Barents Sea - Figure 3), have been identified within ERA-5. According to ERA-5, the five most intense Arctic cyclones that caused the highest and most intense significant wave heights in the Barents Sea between 2009 and 2016 occurred in Dec. 2012, Dec. 2014, Feb. 2015, Mar. 2015 and Mar. 2016, where significant wave heights in the Barents Sea exceeded 10 m (Figure 8).

It would be expected that ships may avoid the paths of these most intense Arctic cyclones, given that ships have been provided with weather forecasts. This however does not seem to be the case, as ships were located within the regions of the tallest waves, even in regions where waves exceeded 10 m (Figure8). As many as 103 intersections between these cyclones and ships occurred, but no shipping incident was reported up to 48 hours after these intersections (Figure8). Ships appear able to withstand and even travel through the passage of the most intense historical Arctic cyclones. Furthermore, after consulting the shipping incidents reports, none of these most intense Arctic cyclones resulted in a reported shipping incident (Table 2).

So perhaps the risk of total loss of the ship and its cargo is low and mitigated by the ships ability to withstand the roughest sea conditions caused by an intense Arctic cyclone. However, other than direct damage to the ships and its cargo, the ship could experience business interruption due to the passage of intense Arctic cyclones. This could lead to a delay in the ships transit if the ship has to slow down and prepare for the cyclones approach. Other damage could occur to port facilities, which is not considered here. So indirect damage could occur following the passage of an intense Arctic cyclone, leading to financial losses.

9 Conclusions

The risk posed by Arctic cyclones to ships has seldom been quantified due to the lack of publicly available past Arctic ship track data. Such data is often privately owned and difficult and costly to obtain. However, the lack of publicly available historic ship track data has been somewhat reduced by Berkman et al. (2020a), who published Arctic ship track data derived from Automated Identification System (AIS) transponders over a limited time period between September 2009 and December 2016. This publicly available dataset is used in this study with past shipping incident reports and past cyclone tracks to quantify how many ships were impacted by hazardous weather conditions caused by Arctic cyclones, and how many Arctic shipping incidents have occurred following the passage of a cyclone.

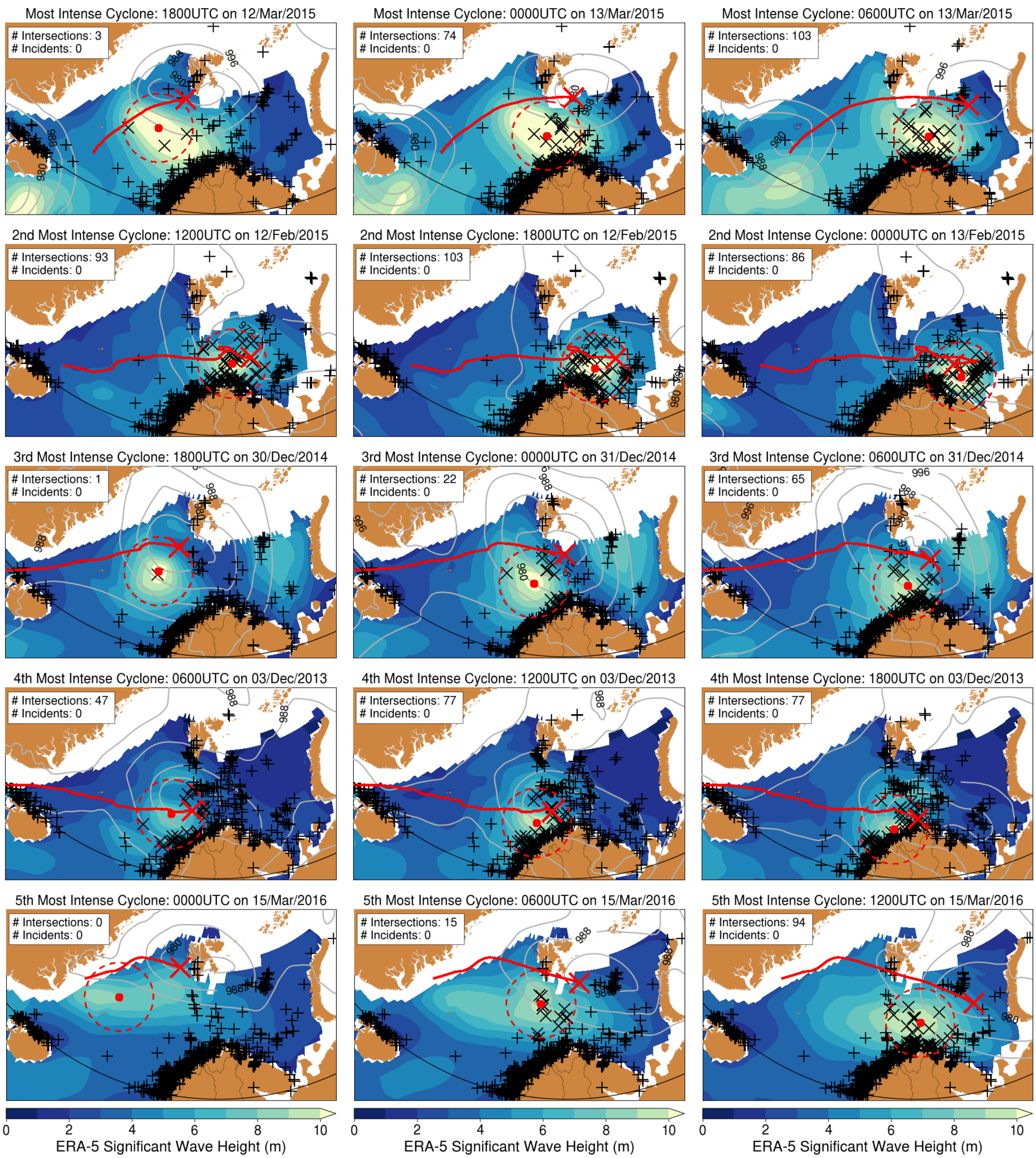

Figure 8. Tracks of the five most intense Arctic cyclones with the highest maximum significant wave height over the Barents Sea (between 20-30°E and 71-77°N) from 2009 to 2016 based on ERA-5. The cyclone 850 hPa relative vorticity centre is denoted by the red cross, and its track by the solid red line. The location of the cyclone's maximum significant wave height is denoted by the red dot marker, with the 3° radius around this point being denoted by the red dashed line. Significant wave height is given by the colour contours, and the sea level pressure is given by the grey contours. Arctic sea ice extent (sea ice concentration >15%) is indicated in white. The black "+" markers denote AIS-derived ship coordinates at each timestep, with ships intersected by the cyclone track denoted by the black "x" markers.

Overall, the number of ships operating in the Arctic (north of 66.5°N) and exposed to intense Arctic cyclones has greatly increased between 2010 and 2016. Intense Arctic cyclones are found to very frequently intersect Arctic ship tracks, with tens of thousands of intersections occurring each year. But only a very small percentage of these intersections caused a reported shipping incident, suggesting that past Arctic cyclones are not hazardous to ships, and ships are instead able withstand weather conditions caused by the most hazardous Arctic cyclones.

- The number of ships operating in the Arctic and transmitting their location using AIS transponders has more than doubled from 2010 to 2016, and the highest track density of ships and intense cyclones in the Arctic occurs over the Barents and Norwegian Seas and around Iceland

Arctic sea ice extent has decline greatly over the last few decades due to global warming. It is shown in this study that the annual number of ships operating in the Arctic has increased year-on-year from 2010 to 2016, from 15,666 ships in 2010 to 34,780 ships in 2016. Arctic ship track and intense cyclone track density is greatest year-round in the Barents and Norwegian Seas and around Iceland. This is especially the case in winter and spring, where ships are rarely found in trans-Arctic shipping routes, and there is a higher density of intense Arctic cyclones in these regions. In summer and autumn, Arctic ship tracks are found more widely across the southern Arctic and in the trans-Arctic shipping routes of the Northern Sea Route (NSR) - along the coastline of Eurasia, and the North-West Passage (NWP) - through the Canadian Archipelago.

The number of ships operating in the Arctic correlates with Arctic sea ice extent, with a higher monthly and seasonal number of ships operating in the Arctic coinciding with lower Arctic sea ice extent in late summer and early autumn months. The number of ships travelling through the NSR and NWP has increased from 2010 to 2016, with the NSR typically having more ship transits than the NWP per year. This is likely due to the NSR being typically more ice-free in summer and autumn months than the NWP, where sea ice tends to be thicker and less susceptible to melting.

- The number of reported shipping incidents has increased from 2010 to 2016, but the total number of reported shipping incidents is only approximately 0.1% of the total number of ships operating in the Arctic

Between 2010 and 2016, a total of 176,961 ships travelled in the Arctic between 2010 and 2016, but there were only a total of 158 reported Arctic shipping incidents, which is approximately only 0.1% of the total number of ships. Most ships that reported an incident had a gross tonnage of less than 1,000 tn, suggesting that smaller vessels, such as fishing vessels, are more prone to incidents than larger ships, such as cargo vessels. Most reported shipping incidents occurred near the coastlines of the Arctic, and fewer incidents were located in the open Arctic Ocean. The increasing number of reported shipping incidents from 2010 to 2016 is likely a consequence of the number of ships travelling in the Arctic increasing year-on-year, but the number of reported incidents remains a very small percentage of all ships operating and travelling in the Arctic.

- Despite Arctic ships being very frequently intersected by the track of an intense Arctic cyclone, only a handful of these intersections resulted in a report shipping incident

Between 2010 and 2016, a total of 32,103, 15,246 and 4,633 ship tracks were intersected and located within 3° (approximately 333 km) of an Arctic cyclone, with the significant wave height at the ship's location being greater than 2.5 m, 4.0 m and 6.5 m respectively. But only 9 reported shipping incidents (0.2% of the all intersections with significant wave height greater than 6.0 m) were found to have occurred within two days of the intersection between Arctic ship and intense cyclone. So, the vast majority of past reported shipping incidents appear unrelated to the passage of intense Arctic cyclones.

It is surprising how frequently Arctic ship tracks are intersected by an intense Arctic cyclone. The track of an intense Arctic cyclone would likely be communicated through weather forecasts, allowing ships to avoid the forecasted paths of the intense Arctic cyclones. In this study, numerous ships are found to be positioned and impacted by the tracks of the most intense Arctic cyclones, but were able to withstand the severe weather conditions and no shipping incidents were reported.

This study suggests that cyclones are not a dominant cause of reported Arctic shipping incidents in the present climate, even though ships are frequently impacted by intense Arctic cyclones. However, ships could also experience other consequences than damage to the ship and crew, such as business interruption and delays in transit, and damage could also occur to port facilities. Although we conclude that synoptic scale cyclones pose a low risk to Arctic shipping, other severe weather phenomena not considered in this study, such as Polar lows, which have been found to impact normal shipping operations (Rasmussen, 2003) and to have caused the loss of numerous small vessels (Rasmussen, 2003), could threaten shipping in the Arctic.

This study exemplifies the capabilities of open access risk analysis and quantifies the risk of past Arctic cyclones impacting Arctic shipping, and the number of past shipping incidents caused by Arctic cyclones, which could be useful for decision-making institutions, the insurance industry, and the public. This study relies on open access atmospheric, ship track and shipping incidents data repositories. Whilst there are considerable amounts of freely available atmospheric data available from various institutions, open access social data such as ship tracks and shipping incidents is much less attainable and is often privatised. Consequently, this study was limited to investigating the risk of Arctic cyclones to shipping in such a short time-period and between 2010 to 2016. As global warming continues to rapidly change the Arctic, extensive and up-to-date ship track and incident data needs to be more publicly available, so that the risks to shipping can be monitored and ultimately mitigated.

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