Marine Pollution Bulletin 179 (2022) 113681

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Shipping in the north-east Atlantic: Identifying spatial and temporal patterns of change

James R. Robbins[a,*], Phil J. Bouchet[b], David L. Miller[b], Peter G.H. Evans[c,d], James Waggitt[c], Alex T. Ford[a], Sarah A. Marley[e]

[a] Institute of Marine Sciences, University of Portsmouth, Ferry Road, Eastney, PO4 9LY England, United Kingdom of Great Britain and Northern Ireland
[b] School of Mathematics & Statistics and Centre for Research into Ecological & Environmental Modelling, University of St Andrews, The Observatory, St Andrews, Fife, KY16 9LZ Scotland, United Kingdom of Great Britain and Northern Ireland
[c] School of Ocean Sciences, Bangor University, Menai Bridge, Anglesey, LL59 5AB, Wales, United Kingdom of Great Britain and Northern Ireland
[d] Sea Watch Foundation, Ewyn y Don, Bull Bay, Amlwch, Anglesey, LL68 9SD Wales, United Kingdom of Great Britain and Northern Ireland
[e] Scotland's Rural College (SRUC), Craibstone Estate, Aberdeen, AB21 9YA Scotland, United Kingdom of Great Britain and Northern Ireland

ARTICLE INFO

Keywords:
Marine conservation
Marine protected area
Maritime traffic
Automatic identification system
Vessel density
Generalized additive model

ABSTRACT

Maritime traffic is increasing globally, with a four-fold increase in commercial vessel movements between 1992 and 2012. Vessels contribute to noise and air pollution, provide pathways for non-native species, and collide with marine wildlife. While knowledge of shipping trends and potential environmental impacts exists at both local and global levels, key information on vessel density for regional-scale management is lacking. This study presents the first in-depth spatio-temporal analysis of shipping in the north-east Atlantic region, over three years in a five-year period. Densities increased by 34%, including in 73% of Marine Protected Areas. Western Scotland and the Bay of Biscay experienced the largest increases in vessel density, predominantly from small and slow vessels. Given well-documented impacts that shipping can have on the marine environment, it is crucial that this situation continues to be monitored – particularly in areas designated to protect vulnerable species and ecosystems which may already be under pressure.

1. Introduction

Human activities pose a number of threats to wildlife, with the level of pressure dependent on many factors including how activities and animals overlap in space, and how each changes in time. Effective conservation requires accurate information on how anthropogenic pressures are located in space and time, but this is often lacking at a regional scale. Maritime traffic is known to be changing globally (Jägerbrand et al., 2019) with a four-fold increase in commercial ship traffic between 1992 and 2012 (Tournadre, 2014), and a 3.5% growth in the world shipping fleet in 2016 alone (Fournier et al., 2018). The increase in shipping traffic is primarily driven by socio-economic factors such as population growth, along with the associated expansion in trade and transport of materials; by volume, 90% of global trade is carried by sea (Fournier et al., 2018). As human population growth drives further development and international trade, it is likely that shipping will continue to intensify, with a predicted global increase of between 240% and 1209% by 2050 (Sardain et al., 2019). Shipping can have a wide variety of impacts on the marine environment, with some of the strongest concerns relating to the spread of non-indigenous species, noise, chemical, and air pollution, collisions with wildlife, and marine litter (Jägerbrand et al., 2019).

Vessels are the most common vector for the unintentional introduction of non-indigenous species in marine habitats (Molnar et al., 2008). Shipping was found to be a likely vector for over half of non-indigenous species in European waters (Katsanevakis et al., 2013), both through biofouling and ballast release (de Castro et al., 2017). Once introduced, the species can become established and be further classed as invasive if they have negative impacts on the ecosystems they invade, recreation, and the economy (Molnar et al., 2008). Invasive species are

---

Abbreviations: AIS, Automatic Identification System; GAM, Generalized Additive Model; MPA, Marine Protected Area.

[*] Corresponding author at: Institute of Marine Sciences, University of Portsmouth, Ferry Road, PO4 9LY England, United Kingdom of Great Britain and Northern Ireland.

E-mail addresses: james.robbins@port.ac.uk (J.R. Robbins), pb282@st-andrews.ac.uk (P.J. Bouchet), dave@ninepointeightone.net (D.L. Miller), peter.evans@bangor.ac.uk (P.G.H. Evans), j.waggitt@bangor.ac.uk (J. Waggitt), alex.ford@port.ac.uk (A.T. Ford), sarah.marley@sruc.ac.uk (S.A. Marley).

https://doi.org/10.1016/j.marpolbul.2022.113681
Received 3 December 2021; Received in revised form 10 April 2022; Accepted 19 April 2022

recognised by the Convention on Biological Diversity as one of the biggest threats to global biodiversity.

Shipping activity is the main source of anthropogenic noise in the marine environment (de Mora et al., 2020), with relatively high levels of energy produced in the north-east Atlantic (Farcas et al., 2020; Duarte et al., 2021). Many marine animals rely on sound for navigation, communication, and foraging (Duarte et al., 2021). Human activities produce noise which can mask communication (Erbe et al., 2019), increase stress levels (Rolland et al., 2012), alter behaviour (Szesciorka et al., 2019), displace individuals from critical habitats (Erbe et al., 2019), or even cause physical damage and death (Weilgart, 2007).

Vessels do collide with animals, not only leading to severe injury and mortality, but also damage to vessels and injury to those aboard (Schoeman et al., 2020). Marine megafauna which spend a large proportion of their time in surface waters are most at-risk of collisions, with large whales (e.g., fin whales, *Balaenoptera physalus*; sperm whales, *Physeter macrocephalus;* or North Atlantic right whales, *Eubalaena glacialis*) widely accepted as most at-risk. Ship strike risk is greatest when susceptible species (e.g., those that spend time at the surface and do not avoid vessels) occur in high densities and overlap with high intensities of vessel traffic. Research on ship strikes is limited in the north-east Atlantic but preliminary evidence indicated a major concern for baleen whales with 15–20% recorded as dying from this cause (Evans et al., 2011); it was also found to be the leading cause of death for large whales stranded on French shores at increasing frequency (Peltier et al., 2019).

While global patterns in maritime traffic are well established (Wu et al., 2017), regional (e.g., in the north-east or north-west Atlantic) trends are not necessarily well understood. Automatic Identification Systems (AIS) data, which contain details of vessel transits, positions, and physical characteristics, are typically expensive to access and may be referred to as 'big data' as they are computationally challenging to process. As a result, studies have researched vessel traffic only at very broad scales (e.g., Wu et al., 2017) but coarse resolutions (e.g., Winther et al., 2014), or very localized levels (e.g., Mou and Ligteringen (2010) who investigated shipping at a single port). However, no study has focused on regional patterns in the north-east Atlantic at a high spatial resolution. Yet management and policy decisions are often made at the regional level (e.g., OSPAR: Matz-Lück and Fuchs, 2014; or EU: Soma et al., 2015), and animal distributions vary at fine spatio-temporal scales (Johnston et al., 2005; Fernandez et al., 2021). Therefore appropriate marine spatial planning and management for conservation at this intermediate spatial scale is required, particularly in regions experiencing increasing anthropogenic pressures.

The north-east Atlantic region includes some of the busiest seaways in the world, with a large human footprint on marine ecosystems (Halpern et al., 2008). However, it is not known how pressure from shipping activities is changing over time or space. As shipping patterns change, so will these environmental pressures — unless changes to policy or vessel design are mandated. Despite the introduction of various protective measures (e.g., Marine Protected Areas, MPAs), the effectiveness of these is debatable without on-going monitoring and mitigation (Pendleton et al., 2018). Environmental legislation in the north-east Atlantic largely comes under the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR), the EU Marine Strategy Framework Directive and the EU Habitats Directive, under which 237 Marine Protected Areas (MPAs) have been designated in the study area. Many of the species that rely on these MPAs have been documented to be susceptible to collisions with vessels and exposure to noise (e.g., marine mammals; Evans, 2020), or competition and smothering from invasive species for which vessels may act as a vector to introduction (Molnar et al., 2008; Seebens et al., 2016). Little information currently exists on the current situation of shipping in the north-east Atlantic, the impacts on this regional environment, or how shipping is changing over time.

In this study, big data on vessel movements in the north-east Atlantic are analysed to determine spatio-temporal changes in shipping traffic over the period 2013–2017. This study aims to 1) describe maritime traffic characteristics and calculate vessel densities; 2) investigate whether patterns are changing across space and time; 3) determine whether shipping pressure is changing in marine protected areas. The information provided here should be used by conservation scientists and policy makers to determine the level of impact that shipping may have on the marine environment in the north-east Atlantic, which until now has remained largely unknown at a regional scale.

2. Methods

2.1. Study area

The spatial extent of this study covers 1.1 million km^2 in the contiguous north-east Atlantic, extending between 16°W - 10°E, and 41–65°N. The waters off Belgium, Denmark, France, Germany, Iceland, Ireland, The Netherlands, Norway, Portugal, Spain, and the UK are covered. The area includes the English Channel, which separates south-eastern England and northern France. It is widely accepted to be one of the busiest areas of shipping in the world (Halpern et al., 2008), with major shipping lanes serving countries bordering the North Sea, the Americas and further afield. The study area was projected into an Albers equal-area projection to minimize spatial error across Europe, and gridded into 10 km^2 cells. This resolution was chosen to account for variable timing in vessel updates while still providing an informative summary at an intermediate scale relevant to management decision-making.

2.2. Shipping data

Vessel positions were recorded by Automatic identification Systems (AIS), a transponder system installed on ships with shore- and satellite-based receivers. AIS records include location data (longitude, latitude), information which generally stays the same between voyages (e.g., identifiers including vessel name, call sign (a unique identifier), Maritime Mobile Service Identity number (MMSI), and vessel type), and dynamic information that changes between and within voyages (e.g., speed, course, time, destination, movement status, and draught). The pre-processed AIS data were made available by IHS Markit (www.ihsmarkit.com) and consisted of 538,260,959 records received within a total of 1095 days which fully covered the years 2013, 2015, and 2017. AIS is mandatory on large vessels over 300 gt on international voyages, cargo vessels over 500 gt not on international voyages, and all passenger vessels. Over the study period, the sizes of fishing vessels required to have AIS on-board changed, from over 24 m in 2012, to over 18 m in 2013, and over 15 m in 2014. To investigate how this may impact results, the number of fishing vessels overall, and newly present in the dataset for each year were compared, separated into vessels over 24 m, and those under 24 m that may have adopted AIS during the study period.

2.3. Data processing

Simplified stages of data processing are outlined in Supplementary Fig. 1. Records were processed in monthly blocks in R 4.0.3 (R Core Team, 2020), first removing aircraft and land-stations. As we were ultimately interested in moving vessels that create high noise levels or may injure marine megafauna, records where vessels were reported as moored, anchored, aground, or not under command were removed from the dataset. In addition, as this processing was in preparation for further work on collision risk to marine mammals, vessels travelling slower than 5 knots were also removed from the dataset. Unlikely vessel dimensions that were assumed to be erroneous were removed, including vessels wider than they were long, moving at speeds in excess of 70 knots, zero lengths or beams, and vessels in excess of 400 m in length. All vessels were assigned a country of registry based on the first three digits of the MMSI number (Ou and Zhu, 2008).

Call signs, which are provided to a vessel by a national radio authority (Falco et al., 2019), are generally accepted to be more reliable identifiers than MMSI numbers, which are unique to transmitters which may move between ships. As a result, data were grouped by call sign and sorted by date and time fields. Vessel tracks were created by joining sequential positions, and distance (geosphere package; Hijmans, 2019) and time spent traversing the line were calculated. If successive points were separated by more than 100 km or 6 h, it was assumed that the vessel had left the study area, stopped transmitting, or entered a state that was removed (e.g., moored, or travelling slower than 5 knots). Therefore, lines of travel that were over 100 km long, or over 6 h in elapsed time, were removed from the dataset.

A large proportion of vessel types reported in the dataset were uninformative, and either reported as a generic label (e.g., ‘Vessel’; 25.2% of records) or missing altogether (15.3% of records). Additionally, some vessel types (e.g., fishing) were not specified at all. To rectify this, vessel types were assigned from one of three sources: 1) the original dataset; 2) a list of fishing vessels from the Global Fishing Watch project (Kroodsma et al., 2018); or 3) an online repository of historic shipping data (https://www.vesseltracker.com/). A summary of vessel type assignment is available in Supplementary Fig. 2, with further detail in Supplementary Tables 1 and 2. If a vessel was present on the list of fishing vessels, it was assigned a vessel type of ‘fishing’, otherwise it was assigned a simplified form of the type from the original dataset (Supplementary Table 1). If a match was not found in the fishing dataset, or the type was ‘vessel’ in the original dataset, then a similarly simplified type was assigned from vesseltracker (Supplementary Table 2). Vessels were linked to the Global Fishing Watch dataset (73,009 available vessels) by MMSI (as call signs were not available in that dataset), and matched to vesseltracker data (43,995 available vessels) by call sign. If no vessel type could be matched, the vessel was recorded as ‘Other’ and used in overall summaries, but not vessel-specific analyses.

In addition to vessel types, a metric was calculated to capture the general size and speed of vessels (hereafter referred to as displacement rate), regardless of vessel type or function. Vessel size and speed are important in studies of collision risk with animals (Laist et al., 2001; Vanderlaan and Taggart, 2007) and noise production (Frisk, 2012; McKenna et al., 2012). The median speed for each vessel was calculated across the three years and assigned to each record of the vessel, by call sign where available, otherwise by MMSI. If no median speed was available, the speed (as reported in AIS) for that record was used. Displacement rates were calculated using the following equation:

$$Displacement\ rate\ \left(m^3\ per\ s\right) = Length\ (m) \times Beam\ (m) \times (median\ Speed\ (knots) \times 0.514) \tag{1}$$

Draught (the height of the vessel below the water line) was not included as it strongly correlates with Length × Beam (the vessel width; 0.8 Pearson correlation coefficient) and varies between transits. Knots were converted to m/s by multiplying by 0.514.

A four-level factor indicating the displacement rate of vessels was calculated, with factor cutpoints derived from quartiles from every record in 2017. The four-level factor ranged from small, slow vessels (Category A, less than 1158.6 m^3 per second; Category B, up to 3734.9 m^3 per second), to large, fast vessels (Category C, up to 6750.5 m^3 per second; Category D, above 6750.5 m^3 per second).

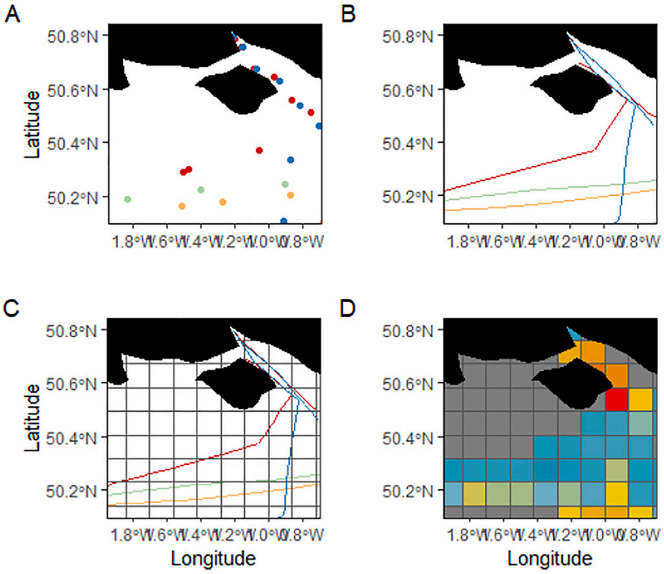

Fig. 1. Processing steps used to derive vessel density from AIS presence records, illustrated using vessel positions for four vessels. A) raw vessel positions, as given in the original in the dataset, B) successive points for each vessel are joined together into lines (j), of known length (l), and time taken to traverse (T) for each vessel, C) lines are intersected with a 10km^2 grid, resulting in segments of known length (s), D) vessel density (vessels per hour per 10km^2) is calculated according to Eq. (2) with grey cells depicting areas through which vessels did not travel (i.e., density of zero). Blue cells indicate low densities, with yellow to red indicating higher densities. In A-C, each vessel is visualized with a separate colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As AIS positions were not uniformly received through time, with variation in transmission rates both within and between vessels, the number of records within a grid cell could not be counted to calculate density. Instead, we adapted the approach used by Falco et al. (2019) to calculate the length of time that each ship spends in a given cell. Steps taken are visualized in Fig. 1. Vessel tracks were segmented by intersecting with the sampling grid, and the length of each segment was measured. Vessel density (ships per hour per 10km^2) was calculated using the equation:

$$D_{it} = \frac{\sum_{j} \frac{S_{itj}}{l_j} T_j}{24 d_t} \tag{2}$$

where S_{itj} is the length (in km) of the segment of line j that falls inside cell i in year-month t, l_j is the total length of line j (in km, potentially spanning multiple cells), T_j is the time spent traversing it (in hours), and d_t is the number of days in year-month t. This calculation was carried out for each vessel type, comprising the five outlined in Table 1, a combined category including all vessels, and four categories of displacement rate.

To determine whether any detected changes in vessel density between years were likely a reflection of the number of vessels being built, the level of adoption of AIS technology, or a true change in the density of vessels using the area, build dates of vessels were web-scraped using RSelenium (Harrison, 2020) from http://www.marinetraffic.com. Due to the large number of vessels in the dataset, and each query taking ~12 s, 10% of vessels present in 2017 (n = 3336) were randomly sampled and matched by call sign and plotted by year built.

Table 1

Summary of characteristics for each vessel type. Values are means, unless otherwise stated. Values provided here were calculated using all data in 2017 only, to minimize computational load. Vessels included in Categories A-D (A representing smallest and slowest vessels, to D representing largest and fastest) are also represented in other vessel types described by function, and vessels of type 'all' are represented in all other vessel types.

Vessel type	Speed (knots) [sd]	Length (m) [sd]	Beam (m) [sd]	Draught (m) [sd]	Displacement rate (m^3 per second) [sd]	Number of vessels	Distance (km) [sd]	Total distance (km)
All	10.2 [3.6]	109 [81.7]	17.1 [12.4]	4.99 [3.9]	17,894 [27,385]	33,366	1101 [1403]	267,948,311
Cargo	10.7 [3.1]	149 [74.8]	22.1 [12.5]	6.33 [4.1]	268,671 [30,715]	20,245	1500 [1445]	209,025,283
Fishing	8.7 [1.4]	33.8 [23.8]	7.9 [3.7]	4.04 [2.3]	1759 [3520]	2472	520 [543]	11,539,954
High-speed	16.9 [5.3]	28 [26.2]	8.1 [5.6]	1.78 [1.7]	3044 [7670]	460	748 [1225]	3,193,021
Operations	10.1 [4.1]	45.2 [34.1]	11.3 [8.6]	3.68 [2.2]	3763 [7824]	3114	445 [691]	10,458,242
Passenger	9.76 [4.4]	76.9 [71.5]	12.4 [10.5]	2.47 [2.5]	10,995 [23,671]	2447	881 [2618]	19,000,396
Other	8.83 [3.7]	53.4 [43.1]	8.85 [6.4]	2.19 [2.5]	3266 [8332]	7294	311 [568]	14,731,415
Category A	8.34 [3.5]	23.4 [10.9]	5.67 [1.7]	1.91 [1.9]	546 [291]	8209	215 [574]	15,563,667
Category B	9.11 [3.5]	60.2 [26.3]	9.13 [2.1]	2.47 [2.2]	2295 [743]	7317	493 [626]	33,191,372
Category C	9.05 [2.5]	95.3 [22.7]	12.2 [2.2]	3.15 [2.3]	5110 [809]	5115	1082 [1205]	53,420,011
Category D	12.1 [3.0]	183 [66.7]	28.6 [11]	8.31 [3.2]	38,220 [31316]	14,696	1810 [1655]	165,773,262

2.4. Analysis

To assess how different countries use the north-east Atlantic, we summarised processed AIS data by country of registry, with the understanding that flags of convenience will add additional noise to these data (Ford and Wilcox, 2019). For each country, month, and year, the following were calculated: number of unique vessels (based on MMSI as more records contained this identifier than call sign), mean speed, mean tonnage, mean displacement rate, total distance travelled (in km), and total time spent travelling (in hours).

Rasters of vessel densities were created and cropped to the contiguous Atlantic, removing the Mediterranean, Baltic, and Kattegat Seas, which were poorly represented in the dataset. Cells that overlapped with land were removed to discard river traffic. Density values were aggregated to a 100km^2 grain size for greater computational efficiency, and collated into a spatial dataset for analysis. Densities were summarised by: (1) maritime regions, defined according to International Hydrographic Organisation delineations (Flanders Marine Institute, 2018), and (2) in protected areas of various designations, as delineated by UNEP-WCMC and IUCN (2022). For each area, mean densities for each year and changes in density between 2013 and 2017 were calculated. For all designation types, a summary was produced which highlights the percentage of areas of each designation which experienced an increase in shipping density. A more detailed summary is also provided for Marine Protected Areas (MPAs). In addition, we tested for differences in vessel densities between seasons using a Kruskal Wallis test, with winter being categorised as December–February; spring as March– May; summer as June–August; and autumn as September–November.

As this study sought to assess spatio-temporal trends in vessel densities, simpler traditional tests were not appropriate. However, Generalized Additive Models (GAMs; e.g., Wood, 2017) are widely used to model complex processes and interactions, including in spatial contexts. GAMs are extensions of the classic linear modelling framework, where flexible functions of explanatory variables are used to model the relationships between response and predictors. These flexible functions include smooth functions of the variables as well as random effects. Here, GAMs were used to quantify the spatial and temporal patterns of change in vessel density, similar to applications with AIS data by Ford et al., 2018 and Queiroz et al., 2019. GAMs were fitted using the mgcv package (Wood, 2020) in the R statistical language (R Core Team, 2020). Exploratory models and visualization suggested that vessel densities were poorly explained (as judged by diagnostic plots of residuals, and deviance explained values) by one-dimensional smooths of latitude, longitude or temporal variables alone. This indicated there was a spatial-temporal change in vessel density. Therefore, interactions were modelled with hierarchical GAMs (Pedersen et al., 2019), following the structure of form 'GI' described in Pedersen et al., 2019. These allow global smoothers (here a global bivariate smooth of longitude and latitude), and group-level smoothers (here a common bivariate smooth of longitude and latitude for each unique year-month, with differing wigglyness) which captured variance between years and months combined.

Preliminary models were assessed for goodness of fit with diagnostic residual plots and models with suitable diagnostic results were compared by Akaike Information Criterion (AIC). As a result of the large size and spatial complexity of the dataset across a wide area, smoothers were allowed a relatively high degree of flexibility (basis sizes of 300 and 175 for global and group-level smoothers respectively, with more basis functions allowing more potential for greater wigglyness). To maximize computational efficiency, we used the 'bam' ("big additive model"; Wood et al., 2017) function with discretization enabled, and fast REML was used to estimate model parameters. A separate model was fitted to each vessel type, with structures which can be written as:

$$\mathbb{E}(D_{it}) = exp(\beta_0 + s(x_i, y_i) + s_t(x_i, y_i) + \beta_t) \tag{3}$$

where $\boldsymbol{D_{it}}$ is the vessel density in cell $\boldsymbol{i}$ at time $\boldsymbol{t}$ and $\boldsymbol{D_{it}} \sim$ Tweedie($\boldsymbol{\phi}$; $\boldsymbol{q}$), where $\boldsymbol{\phi}$ is the scale and $\boldsymbol{q}$ is the power parameter. $\boldsymbol{\beta_0}$ *is the* intercept. $\boldsymbol{\beta_t}$ is a random effect intercept for year-month combinations $\boldsymbol{t}$ where $\boldsymbol{\beta_t \sim N}$ $(\boldsymbol{0, \sigma_T^2})$. $\boldsymbol{x_i, y_i}$ are the spatial coordinates of cell $\boldsymbol{i}$ (longitude x, latitude y). $\boldsymbol{s}$ is a "global" spatial smooth, and $\boldsymbol{s_t}$ is a separate spatial smooth for each year-month.

Our model used interactions between space and time, so rather than being able to directly interpret a coefficient or smooth, we used summary statistics from posterior samples from the model to give appropriate summaries over space and time at the aggregated 100km^2 resolution.

3. Results

Following processing, 235,799,764 vessel positions were retained (43.8% of total records) for further analysis, including those moving at 5 knots or greater. In total there were 45,539 or 51,432 unique vessels, based on MMSI or call signs respectively, represented across the three years. Mean speed across the north-east Atlantic was 10.2 knots in 2017 (Table 1), with 34,785 vessels travelling a total of 267,948,311 km. The majority of these vessels were cargo vessels (20,245 vessels travelling 209,025,283 km). Full details of mean vessel characteristics are available in Table 1.

The majority of vessels were registered to the Netherlands (22%), followed by the United Kingdom (7%) and Germany (7%) (Supplementary Fig. 3). The number of vessels for each country appeared relatively stable between 2013 and 2017. The global fleet was well represented within the dataset, with vessels registered in every continent excluding Antarctica (Supplementary Fig. 4). The largest vessels (based on tonnage) appeared to be registered to northern African and south-east Asian nations (Supplementary Fig. 5). Vessels registered to countries within the north-east Atlantic travelled further in the study area than those registered elsewhere (Supplementary Fig. 6). The top 18 places of registry with vessels of the highest displacement rate were from outside of the north-east Atlantic, predominantly from Asia, the Middle East, and the north-west Atlantic (Supplementary Fig. 7).

Across the entire dataset, 83% (42,849 of 51,432 vessels based on call sign) of vessels had a maximum speed in excess of 10 knots, and 47% (24,363 out of 51,432) in excess of 15 knots. Vessels registered in China travelled at highest mean speeds in excess of 20 knots (Supplementary Fig. 8). Faster speeds are linked to greater sound output, and higher risk of mortality when collisions occur with megafauna (Conn and Silber, 2013).

3.1. *Spatial patterns*

Overall, high-density traffic occurred largely within constrained areas such as known shipping lanes, for example in the English Channel where traffic separation schemes are in place (Squire, 2003). Shipping lanes are similarly visible in cargo vessel traffic maps (Fig. 2A and B respectively). Trends in passenger vessels were less clear, but appeared to frequent coastal areas and shipping lanes (Fig. 2C). Fishing vessels were broadly distributed across the study area, with highest densities concentrated close to the northern Spanish coast, the south and south-west of the UK and Ireland, and the entrance to the Skagerrak Sea (Fig. 2D). Operations vessels were concentrated in the southern North Sea, and the northern North Sea between Scotland, Orkney, and Norway (Fig. 2E). High-speed vessels were largely restricted to the English Channel and the eastern North Sea (Fig. 2F).

When vessels were classified by the level of displacement rate created, rather than their characterised functions, the smallest and slowest vessels were restricted to coastal areas (Category A; Fig. 2G), with Category B similarly being concentrated in coastal areas, albeit with more offshore coverage (Fig. 2H). Category C also had large densities in coastal areas, although they had more presence in offshore shipping lanes, such as the area between the English Channel and northern Spain (Fig. 2I). The largest and fastest vessels occurred at highest densities in similar areas as overall shipping (Category D; Fig. 2J), with concentrations from the north of Spain up through the English Channel and southern North Sea, yet slightly lower densities in the Celtic Sea and northern North Sea.

When considered by sea region, there were considerable differences in the vessel density. The English Channel had the highest mean density of vessels (5.0 mean ships per hour per 10km^2), followed by the Bristol Channel (1.9), west of Scotland (1.7), Irish Sea (1.7), North Sea (1.6), Celtic Sea (0.7), Bay of Biscay (0.7), Norwegian Sea (0.4), and wider North Atlantic (0.2) (Supplementary Fig. 9).

Shipping activity was not restricted to Exclusive Economic Zones (EEZs); however, the Belgian EEZ contained the highest mean shipping density (2.59 ships per hour per 10km^2), followed by the Netherlands (1.55), and Germany (0.80), with lower than 0.50 in other EEZs.

3.2. *Temporal patterns*

When considered over time, overall shipping density increased across the north-east Atlantic by 33.6% between 2013 and 2017 (mean density of 0.78 vessels per hour per 10km^2 in 2013, compared to 0.80 and 1.05 in 2015 and 2017 respectively). Mean densities of each individual vessel type also increased over the study period, with a mean increase of 12% for cargo, 110% for fishing, 243% for high-speed, 75% for passenger, 13% for operations, 87% for Category A, 37% for Category B, 12% for Category C, and 2% for Category D vessels.

Vessel densities increased by 302% off the west coast of Scotland, 147% in the Bay of Biscay, 125% in the Irish Sea, 85% in the Norwegian Sea, 41% in the wider Atlantic, 37% in the North Sea, 20% in the English Channel,10% in the Celtic Sea, and decreased by 41% in the Bristol Channel. A breakdown of mean percentage change of each vessel type in each region is available in Supplementary Fig. 10. Notable changes in the Bay of Biscay include a decrease in operations and passenger vessel densities, as well as an increase in smaller and slower vessels (Categories A and B). The greatest increases in the Bay of Biscay, Celtic Sea, Bristol Channel, west Scotland, Irish Sea, and North Sea were represented by Category A and fishing vessels. The decrease in density in the Bristol Channel was driven by a reduction in the number of smallest and slowest vessels (Category A). The Norwegian Sea experienced a considerable

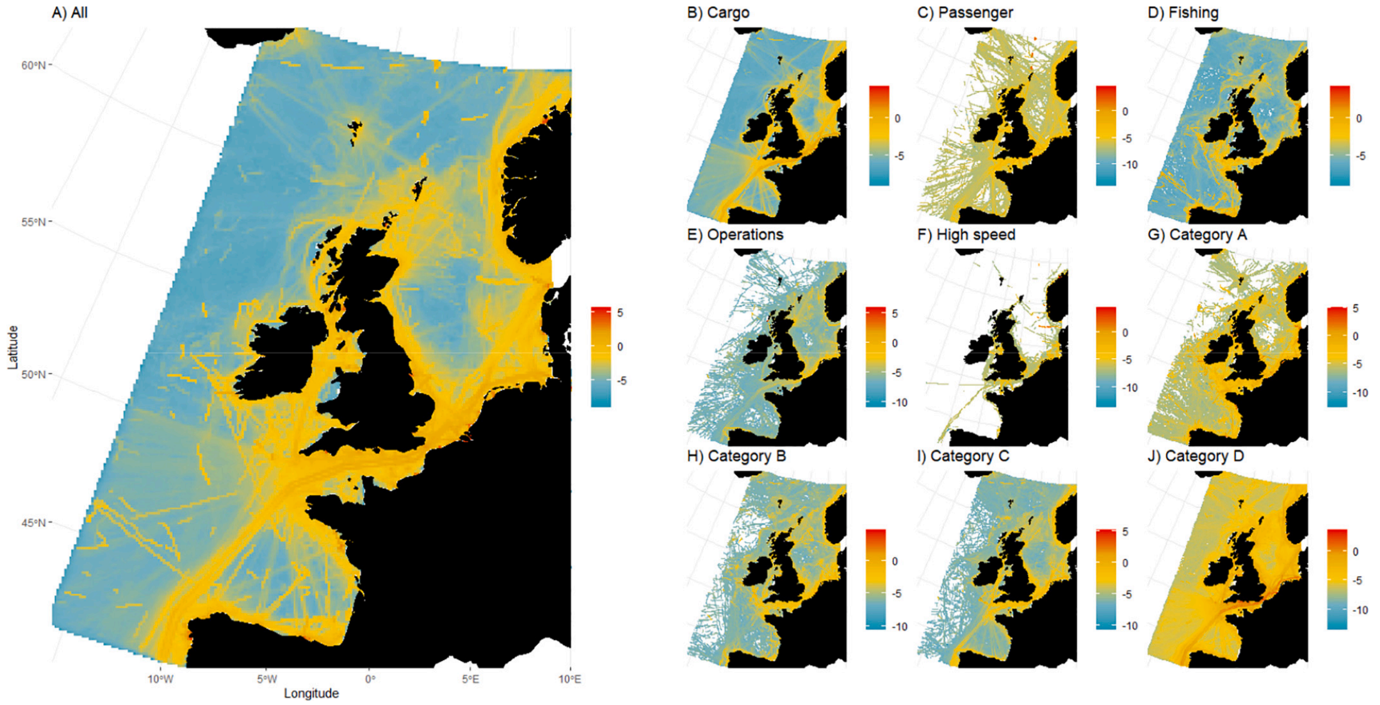

Fig. 2. Vessel density for all vessel types analysed. Values are log mean vessels per 10km^2 per hour. Value legends differ between plot panes to highlight areas of highest densities within each vessel type. Vessel types are A) all vessels, B) cargo, C) passenger, D) fishing, E) operations, F) high-speed, G) Category A, H) Category B, I) Category C, J) Category D. Categories A-D represent vessels categorised by size and speed, with A slowest and smallest and D largest and fastest.

increase in high-speed vessels and passenger vessels. The wider Atlantic exhibited a 59% decrease in operations vessel densities, and the biggest increase from passenger vessels.

When investigating whether changes in density could be a result of increased adoption of AIS, newly built vessels, or a change in operations, it was apparent that the majority of vessels sampled in 2017 were built after 2000, with a peak between 2007 and 2012 (Supplementary material 11). A higher percentage of fishing vessels were newly present in the dataset in 2017 (11%) than in 2015 (3%). A higher percentage of newly present fishing vessels were larger vessels (over 24 m; 4% in 2015 and 12% in 2017), rather than smaller (under 24 m; 2% in 2015 and 9% in 2017) in both 2015 and 2017.

There was a significant difference ($H(3) = 158.08$, $P < 0.001$) in overall vessel density between seasons, with the highest density in summer (median 8.89 vessels per 100km^2), followed by autumn (7.37 vessels per 100km^2), winter (4.53 vessels per 100km^2) and spring (4.31 vessels per 100km^2).

3.3. Protected areas

Of all the protected areas investigated, regardless of designation type, 66% (219 out of 331 areas) experienced an increase in shipping density between 2013 and 2017. Density increased in over 75% of areas designated as Marine Conservation Zone, Natura 2000, UNESCO-MAB Biosphere Reserve, and National Scenic Areas (Table 2).

Vessel densities increased in 73% of Marine Protected Areas (169 of 232; Fig. 3), with the greatest increases in areas close to the Spanish coast, including Espacio marino de la Costa da Morte (413% increase) which is designated to protect seabirds; several areas surrounding the Hebrides off the west coast of Scotland, including the Inner Hebrides and the Minches (463% increase), which is designated to protect harbour porpoises; and Vadehavet med Ribe Å, Tved Å og Varde Å vest for Vard off the coast of Denmark (443% increase), designated to protect fish, harbour porpoises, and seals. Notable decreases in vessel densities include a 79% drop in the West Wales Marine area, a 23% decrease in the Dogger Bank, central North Sea, and 61% lower densities around Shetland, including Noss. Mean vessel densities for each area are shown in Supplementary Fig. 12.

3.4. Modelling

Changes in the densities of all vessel types were well explained (deviance explained ranging between 96.3 and 98.5%) by a spatial smooth of longitude and latitude varying by year-month combinations. Vessel densities predicted from the model posterior samples and accounting for spatial patterning show how densities of all shipping traffic across the study area changed over time, between years and months (Figs. 4 and 5). Overall, vessel densities increased between years (Fig. 4), with some vessel types exhibiting a large increase between 2013 and 2015, and others only between 2015 and 2017 (Fig. 4). Throughout the year, vessel densities peaked in June and November (Fig. 5). Densities were lowest in March across all vessel types. Densities of fishing vessels were highest in June and November, and operations vessel densities were highest in April. Confidence intervals for high-speed vessels were wide, with no clear patterns between months. When categorised by vessel displacement rate as opposed to function, patterns were less clear; although it appeared that larger and faster vessel densities (Category C and Category D) increased towards the end of the year (Fig. 5).

Table 2
Percentage of areas which experienced an increase in shipping density between 2013 and 2017, broken down by protected area designations. No type of designation had less than 25% of areas experiencing an increase.

Percentage of areas in which shipping increased	Area designation
75–100%	Marine Conservation Zone, Natura 2000, UNESCO-MAB Biosphere Reserve, National Scenic Area
50–75%	Marine Protected Area, Site of Special Scientific Interest, Heritage Coast, Site of Community Importance, Ramsar Site, Special Protection Area
25–50%	Area of Outstanding Natural Beauty, Emerald Network, Nature Conservation Act, Protected Landscape, Nature Reserve

4. Discussion

We present the first detailed analysis of shipping activity in the regional north-east Atlantic. The comprehensive account of spatio-temporal variation in vessel densities given here is expected to be of interest to marine managers working at national and regional scales. Vessel densities increased by 33.6% between 2013 and 2017, and across all individual vessel types, mirroring global trends detected over different periods (Kaplan and Solomon, 2016; Jägerbrand et al., 2019; Morse, 2021). This increase in traffic was evident in 73% of MPAs, which may have implications for the species that areas are designated to protect. An increase in shipping is likely to increase noise output, collision risk to animals, and potentially pollution.

If vessel types classed by displacement rate (Categories A – D) are considered in isolation, it appears that smaller, slower vessels (Category A) are responsible for the largest increase in density (87%), with increases becoming less pronounced in the faster and larger classes (2% increase in Category D). This may suggest that, even though high-speed vessels increased by 243%, they were represented by relatively few vessels and that Category D was largely driven by cargo vessels which only increased by 12%. This increase in smaller, slower vessels could suggest that larger vessels are more established and slower to change.

The English Channel experienced a modest increase in shipping densities over the five-year period, when compared with areas such as the Bay of Biscay which exhibited relatively low vessel densities overall but experienced the second largest increase over the period. This increase primarily comprised fishing and small, slow vessels (Category A), which may be partially accounted for by increased AIS uptake. Fishing vessels and either Category A or B vessels showed the greatest increases in seven of the nine regions. This may suggest that there is greater scope for the expansion of traffic in quieter areas, whereas already busy areas experienced slower growth. As smaller, slower vessels exhibited the greatest increases, it is also possible that vessels which are under the size category to require AIS installation could also be increasing at similar levels. Therefore, it would be prudent to investigate changes in the entire fleet, not only those required to transmit AIS records.

The majority of unique vessels were registered to countries within the study area, with a large number being registered in the Netherlands, which has a relatively small coastline and EEZ. Some of the fastest and largest vessels (likely to produce more underwater noise, and present greater risk of collision and mortality to animals they encounter; Laist et al., 2001; Vanderlaan and Taggart, 2007), originated from outside of the study area, namely south-east Asia and northern Africa. As such, it is important that any regulatory action taken to mitigate threats from shipping apply to all vessels, and not be mandated by country of origin.

There are many factors that influence the impact that vessels may have on the environment, including speed for lethal collision risk (Vanderlaan and Taggart, 2007; Conn and Silber, 2013) and noise production (Frisk, 2012; McKenna et al. 2012), country of origin (Heersink et al., 2016) and ballast procedures (Werschkun et al., 2014) for invasive species introduction, and design and fuel for emissions (Molland et al., 2014). Our results show that there are large amounts of activity in the English Channel, along the coasts of the southern North Sea, and shipping lanes that cross the outer Bay of Biscay. We expect that these areas could be currently at greatest risk from primary introduction of species, excessive noise pollution, and potentially contributing considerable emissions. Shipping noise maps already exist for a portion of the north-east Atlantic between France and Norway (Farcas et al., 2020), with the

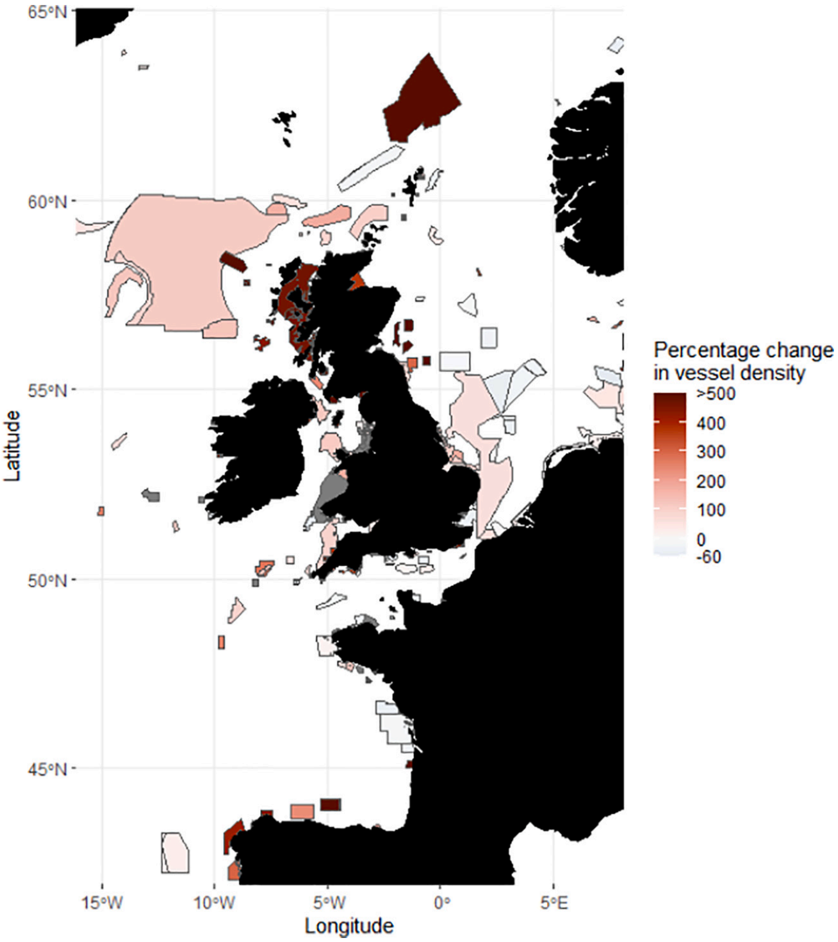

Fig. 3. Percentage change in vessel densities (vessels per 10km^2 per hour) between 2013 and 2017 in Marine Protected Areas. Note: Some areas with extreme growth showed very low densities in 2013, followed by a large increase until either 2015 or 2017; however, change is not always at a regular rate between years and therefore this change should not be assumed to be constant.

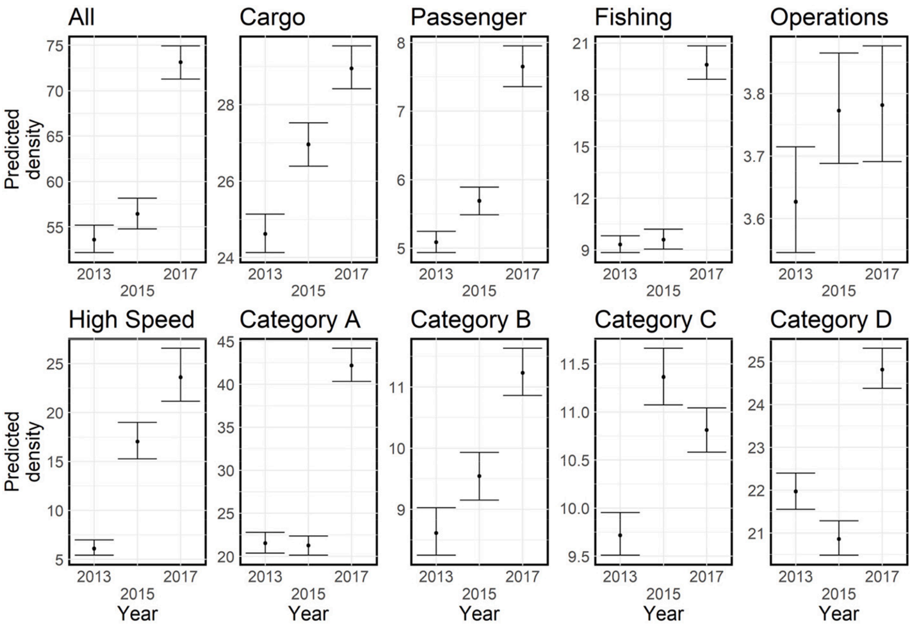

Fig. 4. Model predicted vessel densities (at 100km^2 resolution) in 2013, 2015 and 2017. Category A-D are categorised by vessel size and speed instead of function, with Category A including the slowest and smallest vessels, increasing to largest and fastest in Category D. Error bars represent 95% confidence intervals.

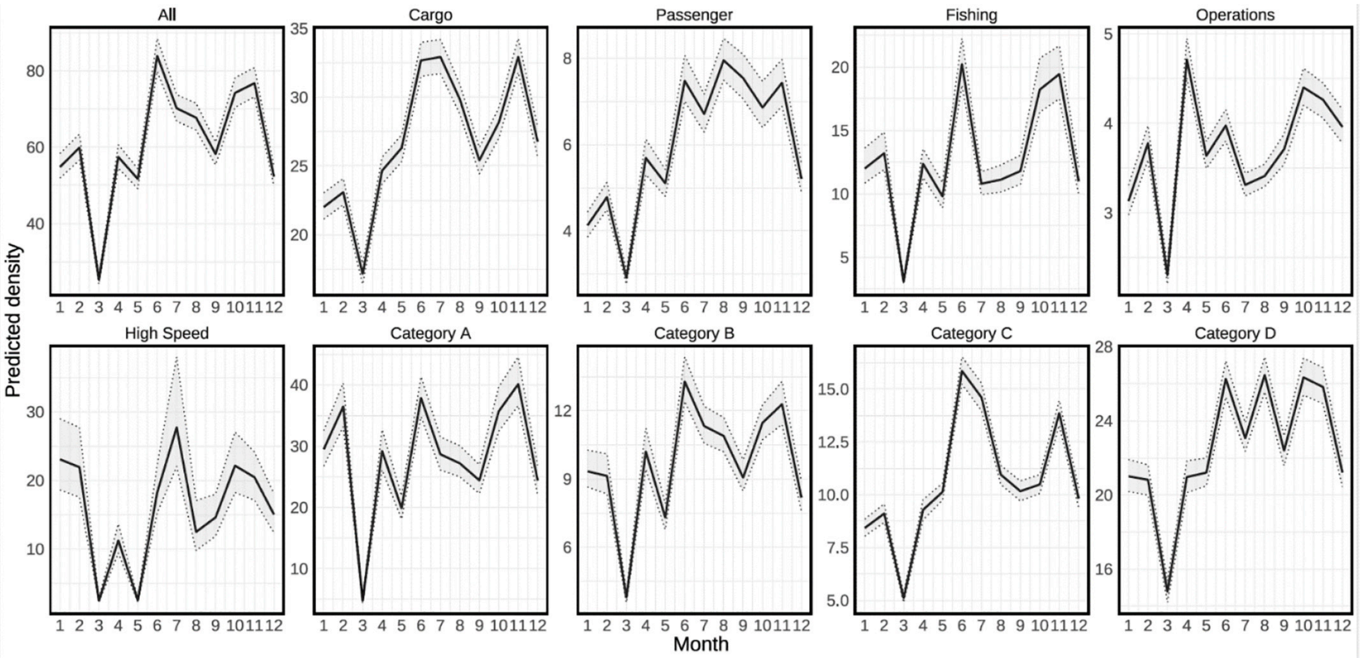

Fig. 5. Model predicted vessel densities (at 100km^2 resolution) across months. Category A-D are categorised by vessel size and speed instead of function, with Category A including the slowest and smallest vessels, increasing to largest and fastest in Category D. Dotted lines and areas shaded grey represent 95% confidence intervals.

loudest areas largely mirroring those areas identified with highest vessel densities in this study.

By contrast, areas with the largest growth in shipping activity, such as western Scotland and the Bay of Biscay may be exposed to increasing pressures. For example, fin whales occur in the Bay of Biscay and nearby areas year-round with densities greatest in summer months and are susceptible to collisions with vessels (Peltier et al., 2019). Any increase in vessel densities could lead to collision risk becoming a larger problem. With shipping increasing in 73% of MPAs, it is very important that management remains appropriate for the growing pressures on protected species and habitats. The rate of change presented here is relative to an area to identify areas undergoing change; however, it is also worth noting the density of vessels in areas, which are presented in Supplementary Fig. 12. Further work is needed on a local level to ensure that areas are adequately protecting species they are designated for under changing environmental and anthropogenic conditions. Areas such as western Scotland and the Bay of Biscay which are experiencing increased traffic, but at lower overall levels than neighbouring areas, may benefit most from such management. It is arguably easier to maintain low levels, than it is to reduce activity in already busy areas, as discussed in Williams et al., 2015. It is hoped that the data presented here and made available online will allow other researchers to further investigate the prevalence of these threats through their relationship with shipping activity.

While our findings present the first in-depth look at regional shipping activity in the north-east Atlantic, the data presented in this study are restricted to vessels that carry AIS transponders and are transmitting. Smaller vessels that are not mandated to carry AIS will also contribute pressure; however, they are much more difficult to quantify. As a result, shipping densities will be higher than reported here, particularly in coastal areas where smaller vessels are concentrated. Further work that considers recreational vessels that do not carry AIS would be valuable, as these vessels will also contribute to potentially more localized input of anthropogenic noise, ship strike risk, and secondary spread of non-indigenous species (Clarke Murray et al., 2011). Similarly, these findings are restricted to vessels travelling faster than 5 knots, so outputs should not be interpreted as overall shipping density, but instead as relative density for vessels travelling faster than 5 knots. It is also important to note that fishing vessel presence does not necessarily relate to fishing activity.

The increase in shipping densities across the study period is coherent with similar increases in shipping activity globally. However, we advise caution when interpreting trends from three years of data. It is also possible that some of the increase in observed traffic may represent wider adoption of AIS rather than changes in vessel numbers, which could be supported by the majority of vessels present in 2017 being built around 2010, rather than during the study period. Conversely, when new fishing vessels in the dataset were investigated they consisted of more large vessels rather than expected small vessels – this suggests that AIS adoption mandated for vessels under 24 m during the study period did not drive observed increase in densities. Therefore, the increased vessel density reported here is likely a result of some new adoption, some newly built vessels, and both vessels operating in the area which were not previously, and a change of behaviour of existing vessels. Given the scarcity of information on broad-scale changes in the north-east Atlantic shipping industry, it is believed that the information presented here provides a first step to gaining a better understanding of the current situation and how that is changing. Future studies are recommended to build on this work by accessing longer-term datasets to better account for inter-annual variation, and to better understand overall trends.

4.1. Future research

The exposure that ecological communities experience from these pressures are likely to be influenced by seasonal changes in animal distribution, and the overlap with vessel densities that similarly vary throughout the year. For example, highly migratory species such as fin whales feed in the north-east Atlantic, with peak densities during summer months, particularly between the Bay of Biscay and southern Ireland (Waggitt et al., 2019). Vessel densities were highest in summer and autumn months during the study period, with relatively high densities on the northern Spanish coast, shipping lanes to the west of the Bay of Biscay, and the south-west of the UK, when compared to other areas in the north-east Atlantic. It is possible that this species may be at risk of exposure to noise, and collisions with vessels in these areas and times. Additional focused work is underway to investigate the overlap between this species which is thought to be the most commonly ship-struck species globally, and other cetacean species and vessels in the north-east Atlantic.

5. Conclusions

Vessel densities are increasing across the north-east Atlantic, including in 73% of marine protected areas. This change is likely to put more pressure on the marine environment, and consequently may have implications for the conservation of exposed and at-risk species. Renewed monitoring effort is needed to ensure that protective measures are adequate to conserve species at-risk in a changing environment where the footprint of human activities is expanding.

Funding

This work was supported by a faculty PhD bursary from the University of Portsmouth. Work was supported by the Marine Ecosystems Research Programme.

CRediT authorship contribution statement

James R. Robbins: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Phil J. Bouchet:** Methodology, Writing – review & editing, Supervision, Resources. **David L. Miller:** Methodology, Writing – review & editing. **Peter G.H. Evans:** Writing – review & editing, Resources. **James Waggitt:** Writing – review & editing, Resources. **Alex T. Ford:** Writing – review & editing, Funding acquisition. **Sarah A. Marley:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are thankful to IHS Markit for providing the AIS data. Thank you to Jan Geert Hiddink for feedback on preliminary iterations of this work. Two anonymous reviewers provided constructive feedback that helped to improve this work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2022.113681.

References

Clarke Murray, C., Pakhomov, E.A., Therriault, T.W., 2011. Recreational boating: a large unregulated vector transporting marine invasive species. Divers. Distrib. 17 (6), 1161–1172.

Conn, P.B., Silber, G.K., 2013. Vessel speed restrictions reduce risk of collision-related mortality for North Atlantic right whales. Ecosphere 4, art43.

de Castro, M.C.T., Fileman, T.W., Hall-Spencer, J.M., 2017. Invasive species in the northeastern and southwestern Atlantic Ocean: a review. Mar. Pollut. Bull. 116, 41–47.

de Mora, S., Fileman, T., Vance, T., 2020. Environmental Impact of Ships. Cambridge University Press.

Duarte, C.M., Chapuis, L., Collin, S.P., Costa, D.P., Devassy, R.P., Eguiluz, V.M., et al., 2021. The soundscape of the Anthropocene ocean. Science 371.

Erbe, C., Marley, S.A., Schoeman, R.P., Smith, J.N., Trigg, L.E., Embling, C.B., 2019. The effects of ship noise on marine mammals—a review. Front. Mar. Sci. 6, 606.

Evans, P.G.H., 2020. European Whales, Dolphins and Porpoises. Marine Mammal Conservation in Practice. Academic Press, London & New York, p. 306.

Evans, P.G.H., Baines, M.E., Anderwald, P., 2011. Risk Assessment of Potential Conflicts between Shipping and Cetaceans in the ASCOBANS Region. ASCOBANS AC18/Doc. 6-04 (S), p. 32.

Falco, L., Pititto, A., Adnams, W., Earwaker, N., Greidanus, H., 2019. EU vessel density map: detailed method. EMODnet. Available at: https://www.emodnet-humanactivities.eu/documents/Vessel%20density%20maps_method_v1.5.pdf. Last accessed 5 February 2021.

Farcas, A., Powell, C.F., Brookes, K.L., Merchant, N.D., 2020. Validated shipping noise maps of the Northeast Atlantic. Sci. Total Environ. 735, 139509.

Fernandez, M., Alves, F., Ferreira, R., Fischer, J.-C., Thake, P., Nunes, N., et al., 2021. Modeling fine-scale cetaceans' distributions in oceanic islands: Madeira archipelago as a case study. Front. Mar. Sci. 8.

Flanders Marine Institute. IHO Sea Areas, Version 3. Available online at. https://www.marineregions.org/.

Ford, J.H., Wilcox, C., 2019. Shedding light on the dark side of maritime trade – a new approach for identifying countries as flags of convenience. Mar. Policy 99, 298–303.

Ford, J.H., Peel, D., Kroodsma, D., Hardesty, B.D., Rosebrock, U., Wilcox, C., 2018. Detecting suspicious activities at sea based on anomalies in Automatic Identification Systems transmissions. PLoS One 13, e0201640.

Fournier, M., Casey Hilliard, R., Rezaee, S., Pelot, R., 2018. Past, present, and future of the satellite-based automatic identification system: areas of applications (2004–2016). WMU J. Marit. Aff. 17, 311–345.

Frisk, G., 2012. Noiseonomics: the relationship between ambient noise levels in the sea and global economic trends. Sci. Rep. 2, 437. https://doi.org/10.1038/srep00437.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., et al., 2008. A global map of human impact on marine ecosystems. Science 319, 948–952.

Harrison, J., 2020. RSelenium: R Bindings for 'Selenium WebDriver'. R package version 1.7.7. http://docs.ropensci.org/RSelenium.

Heersink, D.K., Caley, P., Paini, D.R., Barry, S.C., 2016. Quantifying the establishment likelihood of invasive alien species introductions through ports with application to honeybees in Australia. Risk Anal. 36, 892–903.

Hijmans, R.J., 2019. Geosphere: Spherical Trigonometry.

Jägerbrand, A.K., Brutemark, A., Barthel Svedén, J., Gren, I.-M., 2019. A review on the environmental impacts of shipping on aquatic and nearshore ecosystems. Sci. Total Environ. 695, 133637.

Johnston, D.W., Westgate, A.J., Read, A.J., 2005. Effects of fine-scale oceanographic features on the distribution and movements of harbour porpoises Phocoena phocoena in the Bay of Fundy. Mar. Ecol. Prog. Ser. 295, 279–293.

Kaplan, M.B., Solomon, S., 2016. A coming boom in commercial shipping? The potential for rapid growth of noise from commercial ships by 2030. Mar. Policy 73, 119–121.

Katsanevakis, S., Zenetos, A., Belchior, C., Cardoso, A.C., 2013. Invading European seas: assessing pathways of introduction of marine aliens. Ocean Coast. Manag. 76, 64–74.

Kroodsma, D.A., Mayorga, J., Hochberg, T., Miller, N.A., Boerder, K., Ferretti, F., et al., 2018. Tracking the global footprint of fisheries. Science 359, 904–908.

Laist, D.W., Knowlton, A.R., Mead, J.G., Collet, A.S., Podesta, M., 2001. Collisions between ships and whales. Mar. Mamm. Sci. 17 (1), 35–75.

Matz-Lück, N., Fuchs, J., 2014. The impact of OSPAR on protected area management beyond national jurisdiction: effective regional cooperation or a network of paper parks? *Mar.* Policy 49, 155–166.

McKenna, M.F., Ross, D., Wiggins, S.M., Hildebrand, J.A., 2012. Underwater radiated noise from modern commercial ships. J. Acoust. Soc. Am. 131 (1), 92–103.

Molland, A.F., Turnock, S.R., Hudson, D.A., Utama, I.K.A.P., 2014. Reducing ship emissions: a review of potential practical improvements in the propulsive efficiency of future ships. Transactions of The Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering 156, 175–188.

Molnar, J.L., Gamboa, R.L., Revenga, C., Spalding, M.D., 2008. Assessing the global threat of invasive species to marine biodiversity. Front. Ecol. Environ. 6, 485–492.

Morse, L., 2021. Increasing shipping traffic through the Bering strait: challenges of international policy in a rapidly changing climate and managing impacts to regional cetacean populations. Available at: https://nsuworks.nova.edu/cgi/viewcontent.cgi?referer=https://scholar.google.co.uk/&httpsredir=1&article=1324&context=cnso_stucap/. Last accessed 29 October 2021.

Mou, J.M., Tak, C. van der & Ligteringen, H. (2010). Study on collision avoidance in busy waterways by using AIS data. Ocean Eng., 37, 483–490.

Ou, Z., Zhu, J., 2008. AIS database powered by GIS Technology for Maritime Safety and Security. J. Navig. 61, 655–665.

Pedersen, E.J., Miller, D.L., Simpson, G.L., Ross, N., 2019. Hierarchical generalized additive models in ecology: an introduction with mgcv. PeerJ 7, e6876.

Peltier, H., Beaufils, A., Cesarini, C., Dabin, W., Dars, C., Demaret, F., et al., 2019. Monitoring of marine mammal strandings along French coasts reveals the importance of ship strikes on large cetaceans: a challenge for the European Marine Strategy Framework Directive. Front. Mar. Sci. 6, 486.

Pendleton, L.H., Ahmadia, G.N., Browman, H.I., Thurstan, R.H., Kaplan, D.M., Bartolino, V., 2018. Debating the effectiveness of marine protected areas. ICES J. Mar. Sci. 75, 1156–1159.

Queiroz, N., Humphries, N.E., Couto, A., Vedor, M., da Costa, I., Sequeira, A.M.M., et al., 2019. Global spatial risk assessment of sharks under the footprint of fisheries. Nature 572, 461–466.

R Core Team, 2020. R: A Language and Environment for Statistical Computing.

Rolland, R.M., Parks, S.E., Hunt, K.E., Castellote, M., Corkeron, P.J., Nowacek, D.P., et al., 2012. Evidence that ship noise increases stress in right whales. Proc. Biol. Sci. 279, 2363–2368.

Sardain, A., Sardain, E., Leung, B., 2019. Global forecasts of shipping traffic and biological invasions to 2050. Nature Sustainability 2, 274–282.

Schoeman, R.P., Patterson-Abrolat, C., Plön, S., 2020. A global review of vessel collisions with marine animals. Front. Mar. Sci. 7, 292.

Seebens, H., Schwartz, N., Schupp, P.J., Blasius, B., 2016. Predicting the spread of marine species introduced by global shipping. Proc. Natl. Acad. Sci. U. S. A. 113 (20), 5646–5651.

Soma, K., van Tatenhove, J., van Leeuwen, J., 2015. Marine governance in a European context: regionalization, integration and cooperation for ecosystem-based management. Ocean Coast. Manag. 117, 4–13.

Squire, D., 2003. The hazards of navigating the Dover Strait (Pas-de-Calais) traffic separation scheme. J. Navig. 56, 195–210.

Szesciorka, A.R., Allen, A.N., Calambokidis, J., Fahlbusch, J., McKenna, M.F., Southall, B., 2019. A case study of a near vessel strike of a blue whale: perceptual cues and fine-scale aspects of behavioral avoidance. Front. Mar. Sci. 6, 761.

Tournadre, J., 2014. Anthropogenic pressure on the open ocean: the growth of ship traffic revealed by altimeter data analysis. Geophys. Res. Lett. 41, 7924–7932.

UNEP-WCMC and IUCN, 2022. Protected Planet: The World Database on Protected Areas (WDPA) and World Database on Other Effective Area-based Conservation Measures (WD-OECM) [Online], February 2022. UNEP-WCMC and IUCN, Cambridge, UK. Available at: www.protectedplanet.net.

Vanderlaan, A.S.M., Taggart, C.T., 2007. Vessel collisions with whales: the probability of lethal injury based on vessel speed. Mar. Mamm. Sci. 23, 144–156.

Waggitt, J.J., Evans, P.G.H., Andrade, J., Banks, A.N., Boisseau, O., Bolton, M., et al., 2019. Distribution maps of cetacean and seabird populations in the North-East Atlantic. J. Appl. Ecol. 8, 1.

Weilgart, L.S., 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool. 85, 1091–1116.

Werschkun, B., Banerji, S., Basurko, O.C., David, M., Fuhr, F., Gollasch, S., et al., 2014. Emerging risks from ballast water treatment: the run-up to the International Ballast Water Management Convention. Chemosphere 112, 256–266.

Williams, R., Erbe, C., Ashe, E., Clark, C.W., 2015. Quiet(er) marine protected areas. Mar. Pollut. Bull. 100, 154–161.

Winther, M., Christensen, J.H., Plejdrup, M.S., Ravn, E.S., Eriksson, Ó.F., Kristensen, H. O., 2014. Emission inventories for ships in the arctic based on satellite sampled AIS data. Atmos. Environ. 91, 1–14.

Wood, S.N., 2017. Generalized Additive Models: An Introduction With R.

Wood, S., 2020. Package ‘Mgcv.’. cran.uib.no. http://cran.uib.no/web/packages/mgcv/mgcv.pdf.

Wood, S.N., Li, Z., Shaddick, G., Augustin, N.H., 2017. Generalized additive models for gigadata: modeling the U.K. black smoke network daily data. J. Am. Stat. Assoc. 112, 1199–1210.

Wu, L., Xu, Y., Wang, Q., Wang, F., Xu, Z., 2017. Mapping global shipping density from AIS data. J. Navig. 70, 67–81.