Rita Alexandra André dos Santos

Assessing Close Encounters between whales and maritime traffic:

A study in the Eastern North Atlantic

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Declaração de autoria de trabalho

Assessing Close Encounters between whales and maritime traffic: A study in the Eastern North Atlantic

Declaro ser o(a) autor(a) deste trabalho, que é original e inédito. Autores e trabalhos consultados estão devidamente citados no texto e constam da listagem de referências incluída.

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Resumo

O grupo dos cetáceos é extremamente diverso e evoluiu no sentido das espécies apresentarem vidas longas e formarem populações estáveis. Estes predadores de topo são altamente sensíveis a alterações nos seus habitats e respondem rapidamente às mesmas, agindo assim como espécies sentinelas. As baleias (no sentido lato do nome comum, incluindo baleias de barbas e grandes baleias de dentes) são consideradas engenheiras do ecossistema, desempenhando um papel importante na manutenção de ambientes saudáveis e equilibrados. Além disso, desempenham funções socioeconómicas relevantes, nomeadamente na indústria de observação de cetáceos. Assim, estes mamíferos carismáticos são elementos essenciais para aumentar a consciência pública e política, visto que, quando se trata destas espécies, a maioria das pessoas demonstra maior predisposição para participar em esforços de conservação e de angariação de fundos. Adicionalmente, a proteção de cetáceos e dos seus habitats pode levar à preservação de animais que podem não atrair tanta atenção da sociedade. No entanto, os cetáceos estão expostos a numerosas ameaças antropogénicas, tais como: perturbações sonoras, colisões com embarcações, sobrepesca, enredamento acidental, e poluição química. Tais ameaças e consequentes impactos têm vindo a tornar-se cada vez mais alarmantes. Uma das maiores preocupações globais é a problemática das colisões entre baleias e embarcações, especialmente com navios de maior dimensão e/ou que navegam a maior velocidade. As colisões podem ocorrer com todos os tipos de embarcações e em todos os oceanos, sendo altamente prevalentes no Oceano Atlântico Norte, onde existe uma grande sobreposição de áreas de grande intensidade de rotas marítimas e, simultaneamente, com maior densidade de baleias. Medidas como a alteração de rotas, a redução da velocidade de navegação, e a presença de observadores a bordo (para facilitar a deteção antecipada dos cetáceos) são atualmente as mais utilizadas para mitigar as colisões. Contudo, a intensidade desta ameaça permanece difícil de quantificar, visto que a deteção destes eventos, principalmente em grandes embarcações, é desafiante e, portanto, os registos são raros. A maioria dos dados sobre colisões letais provém da examinação de carcaças, que representa apenas uma fração reduzida dos casos, sendo que parte dos corpos acaba por afundar. Adicionalmente, existem casos de colisões não letais que podem causar ferimentos ligeiros a lesões graves, condicionando a saúde, condição corporal, e eventualmente a viabilidade a longo-prazo das baleias atingidas. Estas colisões podem comprometer certas funcionalidades biológicas vitais, tais como a alimentação e reprodução. Assim, de modo a quantificar e estimar a ocorrência de colisões, reconhece-se que a melhor abordagem é a utilização de indicadores, tais como os Encontros-Surpresa e os Eventos de Quase-Colisão. Estes acontecimentos, coletivamente denominados de Encontros-Próximos, nos quais nenhuma colisão confirmada ocorre, são incidentes não planeados que não causam ferimentos externos comprovados, mas têm o potencial para o fazer. Mesmo sem colisão, a passagem tão próxima de certas embarcações, pode causar níveis elevados de stress ou problemas de saúde, incluindo danos auditivos. No entanto, existem desafios associados à definição destes eventos, já que diferentes estudos recorrem a critérios distintos. Com o presente estudo, pretendeu-se definir e quantificar Encontros-Surpresa e Eventos de Quase-Colisão, bem como investigar a influência de certos fatores (por exemplo, embarcação, espécie, condições ambientais) na ocorrência de Encontros-Próximos. Para tal, foram usados dados de ocorrência de cetáceos recolhidos entre 2012 e 2024, no Oceano Atlântico Nordeste, incluindo as águas ao longo da Península Ibérica e dos Arquipélagos da Macaronésia. Estes dados foram recolhidos por observadores de mamíferos marinhos, através de monitorização visual a bordo de cargueiros e navios oceanográficos, usados como plataformas de investigação. No âmbito deste estudo, os Encontros-Surpresa e os Eventos de Quase-Colisão foram definidos com base no tempo até uma potencial colisão, ao invés de uma distância fixa, permitindo uma abordagem mais dinâmica e com maior sensibilidade à velocidade da embarcação. Métodos de estatística descritiva e análise espacial foram aplicados para caracterizar as variáveis associadas aos Encontros-Próximos, tal como avaliar a sua distribuição geográfica ao longo da área de estudo. Modelos Aditivos Generalisados permitiram investigar os padrões espaço-temporais dos Encontros-Próximos e analisar a influência de variáveis relacionadas com a detetabilidade no tempo até uma potencial colisão. Para avaliar diferenças entre grupos de baleias, foram gerados modelos separados para i) todos os avistamentos de baleias, ii) apenas avistamentos de baleias de barbas, e iii) apenas avistamentos de baleias de bico. Ao longo de 13 anos de monitorização, um total de 1211 avistamentos de baleias foram registados, envolvendo 11 espécies. Destas, dez estiveram associadas a Encontros-Surpresa e apenas quatro a Encontros de Quase-Colisão. De todos os avistamentos, 433 (35.76%) foram classificados como Encontros-Surpresa e 24 (1.98%) como Eventos de Quase-Colisão. O cachalote (*Physeter macrocephalus*) foi a espécie mais envolvida nestes Encontros-Próximos, seguido do zífio (*Ziphius cavirostris)*, e da baleia anã *(Balaenoptera acutorostrata)*. A maioria dos Encontros-

Próximos foram associados a baleias que exibiram um comportamento indiferente em relação ao barco e a indivíduos solitários, em concordância com a literatura. Entre os Eventos de Quase-Colisão, sete ocorreram à proa do navio (Eventos de Provável Colisão), dos quais três apresentaram um comportamento indiferente em relação ao navio, aumentando potencialmente o risco de colisão. Relativamente aos modelos, foi possível verificar uma maior probabilidade de ocorrência de Encontros-Próximos junto ao arquipélago da Madeira, à costa de Portugal Continental e na rota entre as duas regiões. Também se observou uma tendência crescente de Encontros-Próximos desde 2021 (particularmente para as baleias de bico), e uma maior densidade destes eventos no final do verão (para as baleias de barbas). Foi ainda observado que o tempo até uma potencial colisão foi mais reduzido em navios de carga (comparativamente aos navios oceanográficos), em grupos com menor número de indivíduos, e em condições de pouca visibilidade e de chuva. Nestas condições, o tempo para a realização de manobras evasivas eficientes é, consequentemente, menor. Estes resultados contribuem para uma melhor compreensão das interações entre baleias e embarcações no Oceano Atlântico Nordeste e fornecem informações relevantes para o desenvolvimento de estratégias de gestão e conservação destinadas a reduzir o risco de colisão, promovendo simultaneamente práticas marítimas mais sustentáveis. É também reforçada a importância de ter Observadores de Mamíferos Marinhos a bordo de embarcações, para registar não só os avistamentos de cetáceos, como também as variáveis ambientais e comportamentais associadas, e identificar os Eventos-Próximos, idealmente prevenindo potenciais colisões. Por fim, destaca-se a importância da educação e comunicação entre biólogos, decisores políticos e utilizadores do espaço marítimo enquanto ferramentas essenciais, tanto para aumentar a consciencialização sobre esta ameaça, como para melhorar o registo/documentação de Eventos-Próximos e colisões.

Palavras-chave: Colisão de navios, Evento de Quase-Colisão, Encontros-Surpresa, Conservação de cetáceos, Monitorização de cetáceos, Risco de colisão

Abstract

Vessel-whale collisions are a growing global concern and remain extremely challenging to quantify. As such, the use of proxies, such as Surprise Encounters (SEs) and Near-Miss Events (NMEs), is considered the best approach to studying collisions. Collectively designated as Close Encounters (CEs), these interactions consist of unplanned events that do not cause any confirmed external injuries to the whale yet have the potential to do so. This study aimed to define and quantify CEs in the Eastern North Atlantic, using a dataset from 2012 to 2024. Cetacean occurrence data was collected through visual monitoring, onboard cargo and oceanographic vessels, used as Research Platforms. In this study, CEs were defined based on Time to Potential Collision (TPC), rather than distance, providing a more dynamic and speed-sensitive approach. In total, 1211 sightings of whales were recorded, of which 35.76% were classified as SEs and 1.98% as NMEs. *Physeter macrocephalu*s was the species most frequently involved in CEs, followed by *Ziphius cavirostris*. Seven NMEs were characterised as Likely Collision Events, and three of them exhibited indifferent behaviour, increasing collision risk. Generalised Additive Models were used to assess spatio-temporal patterns of CEs and the influence of detectability-related variables on TPC. In this study, CEs were more likely to occur near Madeira, mainland Portugal, and along the route connecting them. An increasing trend of CEs was observed since 2021, with a higher density of these events in late summer. A lower TPC, which implies less time to perform avoiding manoeuvres, was observed in cargo ships (compared to oceanographic vessels), in groups with fewer individuals, in conditions of low visibility, and in the presence of rain. These findings contribute to a better understanding of whale-vessel interactions in the Northeast Atlantic and provide valuable insights for developing management and conservation strategies designed to reduce collision risk.

Key-words: Ship collisions, Near-Miss Event, Surprise-Encounters, Cetacean conservation, Cetacean monitoring, Collision risk

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List of Abbreviations

ACCOBAMS – Agreement for the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area

AIC – Akaike Information Criterion

ANOVA – Analysis of Variance

AWD – Atlantic Whale Deal

CE – Close Encounter

CPA – Closest Point of Approach

DC – NRP Almirante D. Carlos I

DF – Degrees of Freedom

EDF – Estimated Degrees of Freedom

ENA – Eastern North Atlantic

FLT – Fixed Line Transect

GAM – Generalised Additive Model

GC – NRP Almirante Gago Coutinho

GCV – Generalised Cross Validation

GVIF – Generalised Variance Inflation Factor

I – Insular

IMO – International Maritime Organization

IMMA – Important Marine Mammal Area

IPMA – Portuguese Institute for Sea and Atmosphere

IUCN – International Union for the Conservation of Nature

IWC – International Whaling Commission

L – Lagoa

LCE – Likely Collision Event

MB – Monte Brasil

MG – Monte da Guia

MMO – Marine Mammals Observer

MPA – Marine Protected Area

NME – Near-Miss Event

NI – Non-identified

RP – Research Platforms

SE – Surprise Encounter

TPC – Time to Potential Collision

UBRE – Un-Biased Risk Estimator

VIF – Variance Inflation Factor

1. Introduction

1.1. Overview of Cetaceans

Cetaceans are an extremely diverse group, occupying a wide range of aquatic ecosystems (Katona & Whitehead, 1988; Ballance, 2018). From tropical rivers to deep oceans, these animals inhabit distinct ecological niches and are distributed across all oceans (Katona & Whitehead, 1988; Ballance, 2018). As long-lived marine mammals, cetaceans have evolved life-history strategies that support the maintenance of stable populations (Bannister, 2008).

Most cetaceans are considered apex predators, consuming large amounts of prey and massively impacting the food webs (Kareiva *et al*., 2006; Sergio *et al*., 2008; Ballance, 2018). Due to their ecological importance, these animals are regarded as umbrella and keystone species (Katona & Whitehead, 1988; Sergio *et al*., 2008; Ballance, 2018). Furthermore, cetaceans are highly sensitive to environmental changes and react rather quickly to disturbances in ocean health, making them valuable sentinels for marine ecosystems (Katona & Whitehead, 1988; Sergio *et al*., 2008). However, these mammals are highly mobile and spend most of their lives underwater, limiting their time at the surface, which complicates efforts to study them (Katona & Whitehead, 1988; Wartzok, 2009; Ballance, 2018; Fox, 2020). Thus, even though in the last decades there has been a notable increase in monitoring efforts, there are still a lot of knowledge gaps, and several cetacean species are still classified as “Data Deficient” in terms of conservation status (Mathias *et al*., 2024).

Taxonomically, cetaceans are divided into two distinct super families: Mysticeti (baleen whales) and Odontoceti (toothed whales, including dolphins and porpoises; Jefferson *et al*., 1993; WoRMS, 2025). Although it is not a formal classification, the larger cetaceans are often referred to as “whales”, including baleen whales and larger toothed species, such as the sperm whale (*Physeter macrocephalus*), beluga (*Delphinapterus leucas*), narwhal (*Monodon monoceros*), and beaked whales (Ziphiidae; Bannister, 2008). Accordingly, this definition of “whales” will be adopted throughout this study.

The Mysticeti are divided into four families: Balaenidae (right whales), Balaenopteridae (rorquals), Eschrichtiidae (grey whales) and Neobalenidae (pygmy right whales; Bannister, 2018; WoRMS, 2025). Known for their large size, baleen whales include the blue whale (*Balaenoptera musculus*), the largest known animal to have existed, reaching lengths up to 32 meters (Sears & Perrin, 2009; Bannister, 2018). These whales spend most of their lives far from the coast and feed primarily on zooplankton and small fish, staying within the first 100 meters of the water column (Bannister, 2018). Baleen whales undertake extensive migrations between feeding grounds, in colder regions, and breeding grounds, in warmer waters (Bannister, 2008; Hindell, 2009). Socially, they are relatively solitary, and when associations occur (e.g., during migration season), they tend to involve only few individuals (Bannister, 2008; Bannister, 2018).

In contrast, toothed whales are more socially active and can have structured groups and strong social bonds (Bannister, 2008). Across them, *P. macrocephalus* is the largest, growing up to 16 meters in length (Whitehead, 2018). It is also one of the most widely distributed animals with a preference for deep offshore waters, being recognised for its notable deep-diving skills (Ballance, 2018; Whitehead, 2018). Sperm whales primarily feed on large mesopelagic cephalopods, placing them in ecological competition with beaked whales (Whitehead, 2018).The Ziphiidae, or beaked whales, are medium-sized cetaceans known for performing some of the deepest and longest dives recorded across mammals (Mead, 2009). Their elusive behaviour and preference for oceanic waters makes them the least studied of all cetaceans (Mead, 2009; Ballance, 2018). In fact, some species are so rarely observed that they are known only through strandings (Podesta *et al*., 2005).

1.1.1. Ecological and Socio-Economic Importance

Whales are considered ecosystem engineers due to their profound influence on marine ecosystems, not only as consumers and predators but also as prey, source of detritus, and nutrient vectors (Roman *et al*., 2014; Willis, 2014; Polegatto, 2018). Their large body size and great longevity position them as top predators, capable of consuming large quantities of prey and potentially shaping population dynamics and food web structures (Roman *et al*., 2014).

Beyond their ecological roles, whales also contribute to oceanic carbon dynamics (Meynecke *et al*., 2023; Pearson *et al*., 2023). These large marine mammals store carbon in their biomass, which is an increasingly valuable process due to the accelerating climate change (Pershing *et al*., 2010; Barefoot & Pearson, 2023; Meynecke *et al*., 2023; Pearson *et al.*, 2023). Given their size, whales may play a larger role in carbon storage (Pershing *et al.*, 2010; Barefoot & Pearson, 2023; Pearson *et al.*, 2023). However, the extent to which this process can mitigate climacteric impacts from anthropogenic emissions remains debated and uncertain (Meynecke *et al.*, 2023; Pearson *et al.*, 2023).

Despite this uncertainty, whales surely have vital roles in marine ecosystems. When they die and sink to the bottom of the ocean, their carcasses provide food and habitat for deep-sea species, supporting a diverse benthic marine life – a phenomenon known as "whale fall" (Katona & Whitehead, 1988; Kareiva *et al.*, 2006; Ballance, 2018; Pearson *et al.*, 2023). In doing so, they transport organic matter, nutrients and carbon to the ocean floor, enhancing productivity in otherwise nutrient-poor environments (Polegatto, 2018). Wahles also influence nutrient cycling through their feeding and defecation patterns. Deep-diving cetaceans, such as the sperm and beaked whales, feed in nutrient-rich depths but return to the surface to defecate (Ballance, 2018; Barefoot & Pearson, 2023; Pearson *et al.*, 2023). Known as the "whale pump", this vertical nutrient transport can stimulate primary production in surface waters, particularly in nutrient-poor regions (Roman *et al.*, 2014; Ballance, 2018; Pearson *et al.*, 2023). Moreover, the process referred to as the "great whale conveyor belt", also contributes to marine productivity by delivering nutrients to low-nutrient areas (Roman *et al.*, 2014; Pearson *et al.*, 2023). While performing long migrations between distinct breeding and feeding areas, whales can aid in the transport of nutrients between high-latitude nutrient rich waters (feeding grounds) and low-latitude nutrient poor waters (breeding grounds; Katona & Whitehead, 1988; Pearson *et al.*, 2023). Furthermore, some marine species (e.g., marine birds and fishes) can form feeding associations with whales, benefiting from these interactions (Katona & Whitehead, 1988; Ballance, 2018). However, their overall ecological importance is difficult to quantify, given the complexity of ocean systems and the elusive nature of many cetaceans (Katona & Whitehead, 1988; Pearson *et al.*, 2023).

Besides the highly valuable ecological roles, whales also hold socio-economic and cultural importance. Recently, whales have been viewed as crucial and valuable animals that can bring multiple benefits both to the environment and human communities (Roman *et al.*, 2014; Meynecke *et al.*, 2023). For instance, the worldwide whale-watching industry provides undeniable economic benefits, which generate substantial economic revenue and support employment across many coastal regions (O'Connor *et al.*, 2009). Cetaceans also attract public interest due to their intelligence, charisma and complex behaviours

(Jefferson *et al.*, 2015; Notarbartolo di Sciara & Würsig, 2022). Furthermore, certain whale species hold cultural value to communities (Bannister, 2008). For instance, minke whales (*Balaenoptera acutorostrata*) have been observed cooperatively interacting with fishers by driving fish closer to shore (Bannister, 2008).

Given their overall importance (ecological, socio-economic and cultural), cetaceans hold significant value to conservation. As “flagship” species that act as sentinels, these charismatic animals raise public and political awareness for the growing anthropogenic threats they, and the oceans, face (Sergio *et al.*, 2008; Pace & Tizzi, 2015; Notarbartolo di Sciara & Würsig, 2022). Due to their public appeal, people are more willing to protect them and participate in conservation campaigns and fundraisings initiatives (Sergio *et al.*, 2008; Pace & Tizzi, 2015; Notarbartolo di Sciara & Würsig, 2022). Consequently, efforts regarding their conservation or the protection of key habitats for cetaceans, can generate umbrella effects, potentially leading to the preservation and maintenance of other species, which typically hold lower public visibility (Sergio *et al.*, 2008; Pace & Tizzi, 2015). Cetaceans also act as valuable educational tools, facilitating communication between biologists, policy makers and the general public, raising awareness on conservation actions (Pace & Tizzi, 2015).

1.1.2. Pressuring Threats and Conservation Efforts

Cetaceans are exposed to numerous anthropogenic threats. Over the recent decades, these threats have been a growing concern, significantly impacting populations’ distributions and behaviours, and putting several species at risk of extinction (Simmonds, 2018; Braulik *et al.*, 2023). Across the most worrying stressors are climate change, chemical and noise pollution, vessel strikes, overfishing (which can lead to cetaceans’ prey depletion), and accidental entanglement in fishing gear (Williams, 2014; Simmonds, 2018; Notarbartolo di Sciara & Würsig, 2022; Braulik *et al.*, 2023). These pressures can alter migration patterns, reduce prey availability, inflict physical injuries, and affect the population dynamics (Evans, 2018; Simmonds, 2018). When addressing these threats, a multi-stressor approach must be considered, as these stressors are not fixed over time and can act alone, in combination, or cumulatively (Simmonds, 2018). This makes efforts to conserve marine wildlife complex and very challenging (Simmonds, 2018). Furthermore, the importance and intensity of human stressors vary temporally and spatially, affecting species, populations, and individuals, in different ways (Braulik *et al.*, 2023). Although all cetaceans are exposed to anthropogenic threats, some species are more impacted than others. Species with wider geographic ranges, which generally occur in several areas and have larger populations, tend to have higher resilience to threats (Simmonds & Eliott, 2009; Braulik *et al.*, 2023). Nonetheless, comprehending the overall condition of cetacean populations and the pressures that they are exposed to is essential for their management and conservation (Williams, 2014).

Acknowledging these threats, the Habitats Directive (Council Directive 92/43/ECC of 21 May 1992) aims to protect thousands of species and several habitat types across European Union states, including the Azores, Madeira and Canary Islands (OceanCare, 2021). Under this directive, all cetaceans are listed in Annex IV, which ensures a strict protection of their populations. Moreover, two cetacean species (i.e., bottlenose dolphins (*Tursiops truncatus*) and harbour porpoises (*Phocoena phocoena*)) are listed in Annex II. This annex includes species of community interest whose conservation involves the implementation of Special Areas of Conservation.

The International Union for the Conservation of Nature (IUCN) "Red List" is a crucial tool used to assess the conservation status and threats to a species and to inform decision-makers which actions to take (Braulik *et al.*, 2023; Mathias *et al.*, 2024). This list serves as a global indicator of the health of the world's biodiversity (Mathias *et al.*, 2024). Currently, 37% of cetacean species are considered threatened (i.e., Critically Endangered, Endangered, or Vulnerable) or Near Threatened, with conditions worsening over the last decades (Braulik *et al.*, 2023; IUCN, 2025). Despite the increasing monitoring efforts, there is still a significant percentage of cetacean species evaluated as "Data Deficient" (~11%), which can be attributed to the challenges in studying them (IUCN, 2025). Increasing the frequency and scope of population surveys may help address these knowledge gaps (Williams, 2014; IUCN, 2025). Moreover, consistent monitoring efforts of cetacean populations are crucial to impose conservation strategies and monitor their efficiency (Simmonds, 2018).

To minimise the impact of anthropogenic pressures, sanctuaries and Marine Protected Areas (MPAs) can be vital tools (Simmonds, 2018). These areas, which may include restrictions on fishing activities and/or vessel speeds, can offer protection to key habitat areas, particularly from combined and synergistic pressures (Weilgart, 2007; Simmonds & Eliott, 2009). However, to remain effective, MPAs need to be large and flexible enough to respond to species shifting distributions (Simmonds & Eliott, 2009). Despite remaining a challenge, close cooperation and communication between researchers and policymakers is essential to increase conservation efforts (Simmonds, 2018).

1.2. Vessel-Whale Collisions: A Growing Threat

Vessel-whale collisions are one of the main anthropogenic threats to cetaceans, particularly to large whales, as they often result in severe injuries or death (Figure 1.1; Laist *et al*., 2001; Van Waerebeek *et al*., 2007; Ritter, 2012; Ritter *et al*., 2016; Currie *et al*., 2017; Nisi *et al*., 2024). A vessel-whale collision or strike is defined as any impact, fatal or not, between any part of a vessel and a live whale (IWC, 2011; Peel *et al*., 2018). This is a global concern, as these events occur worldwide, especially in areas near continental shelves and in specific open-ocean regions, such as the Azores, where both vessel traffic and cetacean presence are high (Dolman *et al*., 2006; IWC, 2011; Ritter, 2012; Laist *et al*., 2014; Currie *et al*., 2017; Ritter & Panigada, 2019; Nisi *et al*., 2024). However, even the most threatening high-risk areas lack management efforts to mitigate this risk (Nisi *et al*., 2024).

Figure 1.1. Examples of outcomes of vessel-whale collisions: (A) injuries from a vessel strike observed on a live whale; (B) dead whale across a ship's bow.

Collisions may happen with several types of vessels (e.g., cargo and cruise ships, whale-watching vessels, and sailing vessels) and affect cetaceans and other marine fauna such as dugongs, manatees, seals, penguins, sharks, fishes, turtles, and sea otters (Ritter, 2012; Schoeman *et al*., 2020). These strikes can range from non-lethal, causing disorientation, stress, and/or injuries, to fatal impacts (Dolman *et al*., 2006; Ritter, 2010; Ritter & Panigada, 2019). Still, non-lethal injuries can compromise the animal's long-term survival success, due to pain, stress, or impaired mobility (Dolman *et al.*, 2006; Schoeman *et al.*, 2020).

In the case of small or endangered isolated populations, these events may be an even more significant concern, as the loss of some individuals can pose a significant population decline (Dolman *et al.*, 2006). For example, to the North Atlantic right whale (*Eubalaena glacialis*) vessel collisions are a major threat to its conservation, where the mortality rate is exceptionally high (Laist *et al.*, 2001; Van Waerebeek *et al.*, 2007; Conn & Silber, 2013; IWC, 2025). Assessing the risk of a collision is essential to identify high-risk areas and implement suitable mitigation measures (Schoeman *et al.*, 2020). There is still a lack of data regarding the location and magnitude of this issue, which poses a barrier to an accurate assessment of the problem (Dolman *et al.*, 2006; IWC, 2011; Ritter & Panigada, 2019). Despite the clear conservation concern, collisions additionally raise safety and economic implications, particularly in smaller vessels where a collision may cause a significant safety risk to crew and make substantial damages to the vessel (Ritter, 2012; Ritter & Panigada, 2019; Schoeman *et al.*, 2020; Sèbe *et al.*, 2020; IWC, 2025).

There is a higher risk of the incident occurring in areas with large spatial overlap between cetaceans habitats and vessel traffic, a situation that has intensified over time (Currie *et al.*, 2017; Schoeman *et al.*, 2020; David *et al.*, 2022; Nisi *et al.*, 2024). This problem started to increase from the 1950s to the 1970s, coinciding with the biggest increase in commercial shipping (Laist *et al.*, 2001). Today, most goods are transported by ships, contributing to an intense level of marine traffic worldwide (Ritter & Panigada, 2019; Robbins *et al.*, 2022; Nisi *et al.*, 2024). Due to the recent increase in size and speed, the risk of collision is particularly high (Dolman *et al.*, 2006; Ritter, 2012; Schoeman *et al.*, 2020). Moreover, the likelihood of encounters also fluctuates seasonally with whale abundance and migration patterns (Currie *et al.*, 2017).

Although several types of vessels are involved in this problem, the fatality and severity of injuries is closely linked to vessel size and speed (Vanderlaan & Taggart, 2007; Ritter & Panigada, 2019; David *et al.*, 2022). Larger vessels, typically with less manoeuvrability that travel at higher speeds, are more likely to cause fatal injuries (Laist *et al.*, 2001; Ritter & Panigada, 2019; David *et al.*, 2022). Accordingly, strikes involving vessels over 80 meters are generally the most lethal (Laist *et al.*, 2001). The lethality of a collision massively increases with vessel speed between 10 and 14 knots, making speed a strong predictor of collision-based mortality (Laist *et al.*, 2001; Vanderlaan & Taggart, 2007;

Ritter & Panigada, 2019; David *et al.*, 2022). Studies have proven that slower speeds can decrease the number of risky encounters and consequently reduce collision and mortality risk (e.g., Vanderlaan & Taggart, 2007; Conn & Silber, 2013; Martin *et al.*, 2016; Currie *et al.*, 2017). For example, Conn & Silber (2013) showed that speed restrictions, around 10 knots, can reduce ship strikes mortality for the endangered *E. glacialis* by 80-90%. Furthermore, vessels that suddenly change their course (e.g., jet-skis, wet bikes) can pose a greater risk to whales (Dolman *et al.*, 2006). Although highly manoeuvrable, these vessels are also very loud and travel at high speeds, which can cause cetaceans to panic (Dolman *et al.*, 2006; Ritter & Panigada, 2019). As such, most whale-watching companies include in their guidelines the importance of maintaining a stable heading, to cause the least amount of stress upon the animal (Chen & Lee, 2023).

1.2.1. Vessel-Whale Collisions: Mitigation Measures

Implementing vessel speed limits is a widely recognised and viable mitigation measure to ship strikes (IWC, 2011; Laist *et al.*, 2014; Ritter & Panigada, 2019; David *et al.*, 2022). Nonetheless, to be both efficient and safe, the suitable speed for each vessel type must be carefully considered, considering both economic, safety, and environmental factors (IWC, 2011). This can be instigated seasonally or in certain areas (e.g., MPAs or areas with large overlaps with whale occurrence), and even though it may be difficult to implement, it is more likely to be adopted by companies or mariners than to reduce marine traffic (Ritter, 2012; Martin *et al.*, 2016; Currie *et al.*, 2017; Ritter & Panigada, 2019). Reduced speed will also potentially allow vessels more time to manoeuvre and avoid collisions (Laist *et al.*, 2001; Vanderlaan & Taggart, 2007; Laist *et al.*, 2014; Currie *et al.*, 2017). Nonetheless, there are expressed concerns about its economic impacts and scepticism regarding the long-term effectiveness of this measure (IWC, 2011; Laist *et al.*, 2014; Ritter & Panigada, 2019). In fact, the best conservation and management strategies should be planned and result from a concerted effort from all sectors, facilitating their long-term implementation and ensuring that all parts benefit from it.

Despite speed limits having proved to be effective mitigation tools, the first approach should be minimising the overlap between whales presence and vessels, by re-routing shipping lanes or defining areas to avoid (Dolman *et al.*, 2006; IWC, 2011; Ritter & Panigada, 2019). Especially when thinking of vulnerable populations or regions with high cetacean concentration, managing vessels' movements outside of these crucial areas is vital for their conservation (Dolman *et al*., 2006; IWC, 2011). However, a multispecies approach should be considered, accounting for all the affected marine megafauna (Ritter & Panigada, 2019; Nisi *et al*., 2024).

Detecting the animals beforehand, allowing time for adjusting the route, is likely the most efficient way to mitigate collisions (Weinrich *et al*., 2010; IWC, 2011; Ritter & Panigada, 2019). As such, dedicated observers have proved to be effective in detecting a whale to then take avoiding actions (Dolman *et al*., 2006; Weinrich *et al*., 2010; Ritter, 2012; Ritter & Panigada, 2019). Trained observers also contribute to collecting data on these incidents, which is important for the assessment of ship strikes risk (IWC, 2011). Real or semi-real-time localisation of whales, such as the REPCET tool (i.e., software system that provides vessels the opportunity to share real-time whales' location, to limit collision risk), can also be useful for re-routing manoeuvres and avoiding cetaceans (Dolman *et al*., 2006; IWC, 2011; REPCET, 2018; David *et al*., 2022). Another important measure can be technical modifications, such as sonar systems, acoustic warning tools, propeller guards and deterrent devices (Ritter & Panigada, 2019; Schoeman *et al*., 2020). However, any type of mitigation measure can be challenging, as decisions to avoid a whale or re-route the vessel often must be made within seconds (Ritter & Panigada, 2019). So, even when animals are detected, it is necessary that the crew is willing to take timely action and undertake appropriate management and avoiding measures. Therefore, education and awareness about ship collisions are also especially relevant (Ritter & Panigada, 2019).

Although it is not a mitigation measure, *per se*, the establishment and development of the global ship strike database by the International Whaling Commission (IWC), provides a crucial and essential tool that can be used to report ship strike data, analyse the multiple variables related to collision risk (e.g., whales and vessels' characteristics, and geographic region), estimate collisions mortalities, detect trends over time, identify high-risk areas, and inform on mitigation measures (Van Waerebeek *et al*., 2007; IWC, 2011; Ritter & Panigada, 2019; Schoeman *et al*., 2020; IWC, 2025). The IWC has also established significant links between different parties (e.g., governments, marine industries, and leisure sectors) to increase cooperation and collaboration between stakeholders and international initiatives (e.g., International Maritime Organization (IMO), IUCN, Agreement for the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and Contiguous Atlantic Area (ACCOBAMS); Dolman *et al*., 2006; IWC, 2011; Ritter & Panigada, 2019; IWC, 2025). This is beneficial to provide important information on ship strike risk, define Important Marine Mammal Areas (IMMAs), and minimise this threat (Dolman *et al*., 2006; IWC, 2011; Ritter & Panigada, 2019, IWC, 2025).

1.2.2. Whales' Vulnerability to Ship Strikes

There are multiple factors that may increase the likelihood of a collision and influence its severity, either related to whales or to the vessel (Dolman *et al*., 2006). Every species can potentially be hit, but some are more vulnerable than others (Ritter & Panigada, 2019). For instance, large whales are across the ones most involved in collisions, possibly related to their slower swimming and/or spending longer periods near the surface, such as sperm or right whales (Laist *et al*., 2001; Dolman *et al*., 2006; Ritter & Panigada, 2019; IWC, 2025). Likewise, if whales are feeding, resting or socialising, they may be oblivious to boat presence, increasing collision risk (Dolman *et al*., 2006; Ritter & Panigada, 2019). Additionally, age and sex also have some importance when considering these events (Van Waerebeek *et al*., 2007). Calves and juveniles, occurring in nursery and breeding areas that are often located near coastal waters, are highly vulnerable to collisions and often involved in these incidents (Laist *et al*., 2001; Dolman *et al*., 2006; Van Waerebeek *et al*., 2007; Currie *et al*., 2017). Moreover, sick individuals or lone adults are also more likely to be involved in vessel-whale collisions, as they might be less aware of the moving vessel (Dolman *et al*., 2006; Currie *et al*., 2017). Lastly, whales who have become habituated to boat noise and individuals with hearing loss (possibly caused by acoustic overexposure) may not detect an approaching vessel, placing them at a higher risk of collision (Laist *et al*., 2001; Dolman *et al*., 2006; Ritter & Panigada, 2019). Cetaceans rely on hearing as their main sense, as they use sound to communicate, hunt and navigate (Barefoot & Pearson, 2023; Weilgart, 2007). As the noise levels rise, the adverse effects are also increasing, with some areas being significantly impacted (e.g., coastal areas; Cunha *et al*., 2023; Weilgart, 2007). This disturbance has additionally been linked to hearing damage, masked communication, increased stress levels and can reduce the efficiency of foraging and mating (Evans, 2018; Weilgart, 2007; Williams, 2014).

1.2. Estimating Collision Risk: Surprise Encounters and Near-Miss Events as Proxies

Despite the increase in monitoring efforts, there are still several challenges in accounting for the number of collisions. On large vessels, it is often unlikely for crew members to detect or sense a collision (IWC, 2011; Ritter & Panigada, 2019). Visibility towards the bow is frequently limited, as the bridge is usually positioned towards the stern, and, as a result, the crew is often unaware of the presence of cetaceans in the vessel's path (Dolman *et al.*, 2006). A lack of awareness of the problem and how to correctly report it also leads to a large and significant number of unreported collisions (Laist *et al.*, 2001; Dolman *et al.*, 2006; Van Waerebeek *et al.*, 2007; Van Waerebeek & Leaper, 2008; Ritter & Panigada, 2019). Furthermore, the reluctance to report collisions (or suspected collisions), often driven by fear of reprisals, fines or damage to reputation, is a major contributor to the underestimation of vessel strikes (Dolman *et al.*, 2006; Neilson *et al.*, 2012; Ransome *et al.*, 2021). To address this problem, Ransome *et al.* (2021) suggested the implementation of anonymous online platforms, to encourage collision reports. It is important to educate mariners on this threat, and involve them in the reporting of these incidents, encouraging them to be part of the solution and employment of mitigation measures (IWC, 2011; Ransome *et al.*, 2021).

As aforementioned, the placement of Marine Mammal Observers (MMOs) onboard can improve detection rates and potentially help prevent collisions (Dolman *et al.*, 2006; IWC, 2011; Ritter, 2012; Ritter & Panigada, 2019). Moreover, direct observations are valuable in collecting relevant data on these incidents, reinforcing the importance of dedicated observers (at least, in high-risk areas or vessels in those areas; IWC, 2011). However, currently, these *in-situ* records are scarce, and most available data on ship strikes comes from examinations of stranded or recovered carcasses (Dolman *et al.*, 2006; IWC, 2011). This represents only a small percentage of collisions, as many of the carcasses sink and it does not account for non-lethal strikes (Dolman *et al.*, 2006; IWC, 2011). Furthermore, it is also important to confirm that the whale was not dead at the time of the collision, which can be a challenge (Dolman *et al.*, 2006). Likewise, non-lethal collisions often go unnoticed and are consequently underreported. There have been several reports of cetaceans presenting injuries or scars consistent with vessel-whale interactions (Dolman *et al.*, 2006). Consequently, as direct observations of collisions are not common, these cases can only suggest the magnitude of this problem, still making it difficult to accurately estimate numbers. As a result, ship strike numbers are very likely underestimated, and the frequency of these events appears to be increasing, making it extremely challenging to accurately assess the full scale of this issue (Ritter, 2012; IWC, 2025).

Given that the number of collisions is uncertain, the use of proxies such as Surprise Encounters (SEs) and Near-Miss Events (NMEs) has been proposed (Ritter, 2010; Richardson *et al*., 2011; Ritter *et al*., 2016; David *et al*., 2022). However, there are different approaches and definitions when considering these events, highlighting the complexity of this issue. The definition of a SE was initially proposed by Richardson *et al*. (2011), corresponding to a close encounter between a vessel and a whale, although not as close as an NME. Richardson *et al*. (2011) defined a SE as any sighting at a distance below 300 meters from the vessel and an NME when a SE occurred near the vessel's bow and at a distance below 80 m. On the other hand, the Fixed Line Transect (FLT) Mediterranean Monitoring Network (Fixed Line Transect Using Ferries as Platform of Observation - Monitoring Protocol I, 2007) defined an NME (or Near Collision Event) as a situation in which an animal is sighted within 50 meters in front of the vessel and 25 meters on either side, without showing any clear approaching behaviour. In general, the term of an NME has been more widely used, and it can be defined as unplanned close encounters with whales, that do not involve any confirmed collision but could potentially have resulted in one, if whale or vessel had not taken action to avoid it (Figure 1.2; Martin *et al*., 2016; Ritter *et al*., 2016; Stack *et al*., 2016).

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Figure 1.2. Example of a potential Near-Miss Event (NME) between a whale and a cargo ship.

A clear definition is still required, and these incidents are still not recorded in a standard way (IWC, 2011; Ritter *et al*., 2016; Stack *et al*., 2016). Without a precise characterisation of these encounters, quantifying these events and comparing studies can become very challenging and subjective (Ritter *et al*., 2016; Stack *et al*., 2016). This lack of consistency underscores the urgent need for the development of consistent definitions and monitoring protocols to improve our understanding and mitigation of vessel-whale collisions.

1.3. Cetacean Monitoring and the Role of Research Platforms

Knowledge of cetaceans' abundance and distribution patterns and monitoring how and why it changes over time is crucial for their effective management and conservation (Brereton *et al*., 2004; Evans & Hammond, 2004; Correia *et al*., 2021). There is a need for long-term data to comprehend these population trends over time (Brereton *et al*., 2004). However, as cetaceans are wide-ranging mobile species and inhabit remote offshore areas, collecting this type of data is complex and challenging, both logistically and financially (Williams, 2003; Evans & Hammond, 2004; Correia *et al*., 2021). Cetaceans' visual monitoring can be conducted using a variety of methodologies, either from fixed observation points or mobile platforms (Evans & Hammond, 2004). It is important to decide the most suitable and cost-effective option by determining the information that can be gained and understanding its limitations (Evans & Hammond, 2004). Each methodology has its own advantages and limitations, underscoring the importance of a complementary approach, rather than relying on a single method (Evans & Hammond, 2004).

Cetacean occurrence data gathered through visual monitoring may be collected either from dedicated or other opportunistic research platforms. Despite the expensive constraints, in dedicated platforms used for studying cetaceans there is control over the route taken and enables the collection of specific data and samples that otherwise would not be possible (tagging and biopsy sampling, for instance; Evans & Hammond, 2004; Stack & Currie, 2022). Nonetheless, there are several logistical constraints, and with limited resources, there is a growing need for more cost-effective alternatives, such as the use of existing platforms (e.g., commercial, oceanographic) as Research Platforms (RPs; Williams, 2003; Evans & Hammond, 2004; Correia *et al*., 2021; Stack & Currie, 2022).

RPs have been widely used for cetacean monitoring (mostly, visual monitoring) and offer the possibility to provide large occurrence datasets in remote areas, over long periods of time and at a relatively low cost (Brereton *et al*., 2004; Evans & Hammond, 2004; Alves *et al*., 2018; Correia *et al*., 2019; Stack & Currie, 2022). Williams (2003) defined this type of platform as "any resource whose primary objective is not one's own project, but a resource that can carry one's project along with it". Several types of vessels can be used as RPs, including whale-watching boats, ferries, cargo ships, seismic survey vessels, cruises, and recreational and fishing vessels (Evans & Hammond, 2004; Alves *et al*., 2018; Stack & Currie, 2022). However, this methodology has limitations, including heterogeneous effort dependent on the vessels' routes and schedules, minimal control over the route taken or speed, and, particularly in the case of larger vessels, restricted manoeuvrability (Williams, 2003; Brereton *et al*., 2004; Evans & Hammond, 2004; Ritter & Panigada, 2019; Correia *et al*., 2020). Despite this, the use of RPs is vital to supplement existing data and provide continuous information on cetaceans' abundance and distribution (Stack & Currie, 2022).

The CETUS project consists of a long-term cetacean monitoring programme in the Eastern North Atlantic (ENA) that uses large vessels as RPs to conduct visual monitoring surveys along long-transect routes, covering extensive offshore areas, previously with little to no survey coverage (Correia *et al*., 2019). Active since 2012, CETUS has been implemented through established collaborations with Grupo ETE – Transinsular (a Portuguese shipping company), the Hydrographic Institute of the Portuguese Navy, and the Portuguese Institute for Sea and Atmosphere (IPMA; Correia *et al*., 2019). The main objective of CETUS is to gather comprehensive data on cetacean occurrence in this vast area of the Atlantic, to study cetaceans' distribution and habitat preferences (Correia *et al*., 2019; Correia *et al*., 2020; Oliveira-Rodrigues *et al*., 2022).

The present work explored the CETUS dataset and is part of the international project Atlantic Whale Deal (AWD) - "Mitigating Ship Strikes and Enhancing Carbon Sequestration in the Atlantic" (Interreg Atlantic). Initiated in 2023 by a multidisciplinary team, the project acknowledges the essential role of whales in maintaining healthy ecosystems. Its primary goal is to prevent biodiversity loss, and thereby enhance carbon sequestration, by reducing collision risk across the Atlantic. To achieve this, AWD employs innovative technologies, including acoustic, visual and thermal detection systems, alongside localisation methods, to identify high-risk areas and mitigate noise pollution and prevent vessel strikes. The project seeks to safeguard marine biodiversity, despite the increasing pressures on the Atlantic (https://www.atlanticarea.eu/discover-our-projects/approved-projects/atlantic-whale-deal).

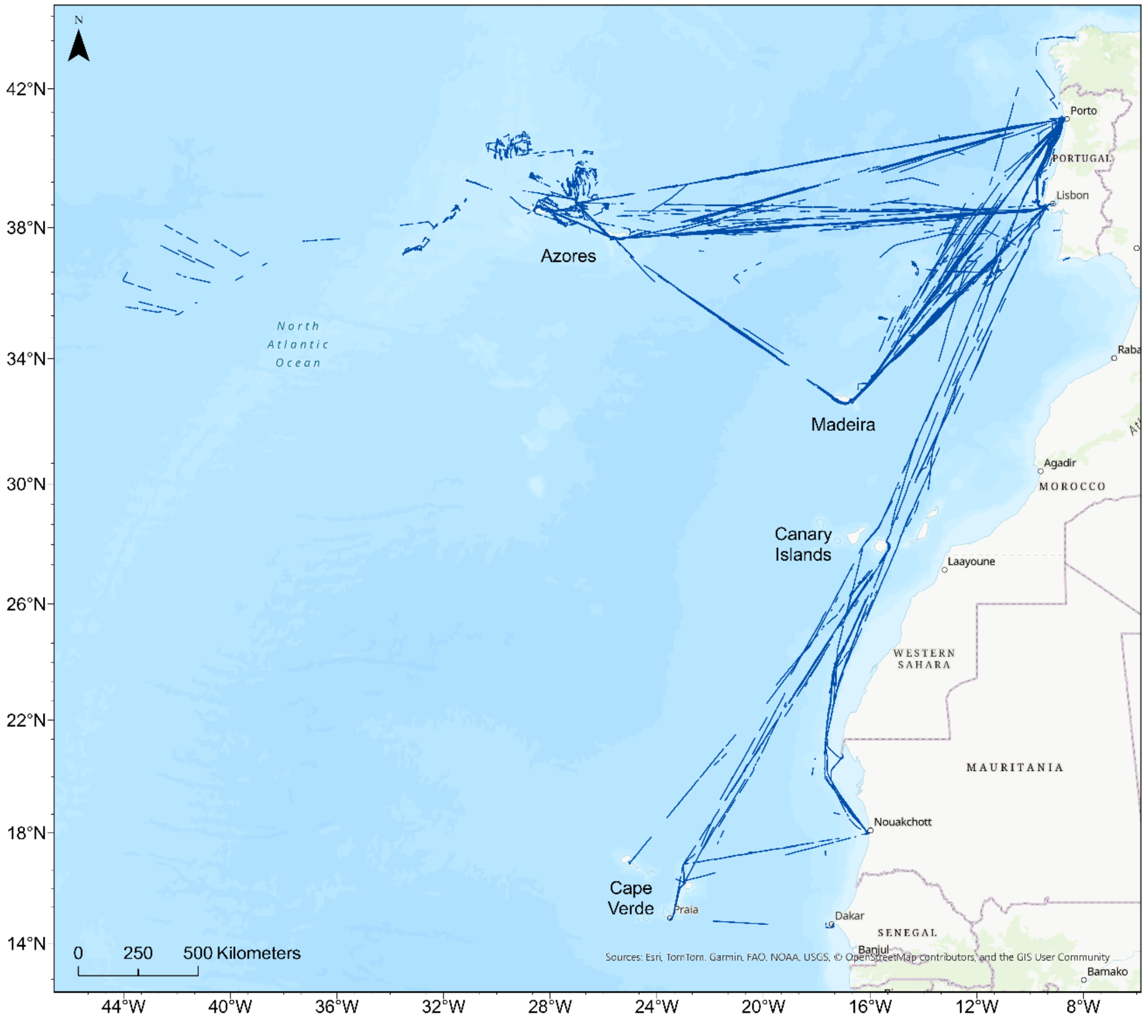
1.4. Objectives

The primary aim of this study is to define and quantify SEs and NMEs involving whales, using 13 years of occurrence data collected under the CETUS project onboard large vessels operating as RPs in the ENA. This study also aims to investigate how various factors, such as vessel, whale species, and environmental conditions, influence the likelihood of these events. Additionally, it seeks to map and model the spatial distribution of SEs and NMEs to identify potential high-risk areas. By enhancing our understanding of whale-vessel interactions in the ENA, this study will contribute with valuable insights to support the development of management and conservation strategies aimed at reducing collision risk.

2. Materials and Methods

2.1. Study Area

This study was carried out in the ENA, encompassing the waters off the Iberian Peninsula, the Macaronesia Archipelagos, and Northwest Africa. Four main routes were monitored for cetacean presence onboard cargo ships: mainland Portugal – Azores, mainland Portugal – Madeira, mainland Portugal – Azores – Madeira and mainland Portugal – Cape Verde, with stops in the Canary Islands, Senegal and Mauritania, and sporadic stopovers in Northwest Spain. Additionally, cetacean monitoring onboard oceanographic vessels was conducted offshore mainland Portugal and over the Azores and Madeira archipelagos (Figure 2.1).



Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

Figure 2.1. Study area and survey effort lines from cetacean monitoring surveys conducted between 2012 and 2024 in the Eastern North Atlantic, using cargo ships and oceanographic vessels as Research Platforms.

The ENA is characterised by a complex and dynamic oceanography, along with a diverse topography, contributing to high cetacean diversity and shaping their distribution in the region (Mason, 2009; Waring *et al.*, 2009; Correia *et al.*, 2019; Correia *et al.*, 2020; Cartagena-Matos *et al.*, 2021; Mártinez, 2021). This region includes four archipelagos collectively known as the Macaronesia: Azores, Madeira, Cape Verde and the Canary Islands (Mason, 2009; Carracedo & Troll, 2020). These islands have similar features, including its climate, which is strongly influenced by the Anticyclonic Eastern Subtropical Gyre, comprising the Azores, Canary and the North Equatorial Currents (Mason, 2009; Carracedo & Troll, 2020). Besides, the Canary Eddy Corridor, which consists in diverse long-lived eddies, contributes to the variability of this region (Mason, 2009). These are frequently associated with seamounts and canyons, and can enhance primary production (Mason, 2009). Moreover, the prevailing trade winds in the ENA contribute to the strong upwelling system found in the north-western Africa, making these waters extremely productive (Mason, 2009; Cartagena-Matos *et al.*, 2021).

The ENA's topography is dominated by the Mid Atlantic-Ridge, which divides the Atlantic Ocean in two parts, and rises 2000 meters above the abyssal seafloor (Mason, 2009; Mártinez, 2021). Seamounts are also commonly encountered in the ENA, which can also contribute to a higher abundance of marine mammals near this region (Morato *et al.*, 2008a; Morato *et al.*, 2008b; Mason, 2009). Another major feature of the ENA is the Madeira Abyssal Plain, which consists of one of the deepest parts of the Canary Basin, reaching a depth of 5500 meters (Mason, 2009; Carracedo & Troll, 2020). Overall, the diverse seafloor encountered in the ENA leads to a substantial mesoscale variability (Mason, 2009; Cartagena-Matos *et al.*, 2021).

Cetaceans are a vital component of the ENA and are widespread throughout the region (Waring *et al.*, 2009; Correia *et al.*, 2019; Correia *et al.*, 2020). A total of 36 species of cetaceans have been documented in the ENA, with at least 29 species being identified within the CETUS project (Correia *et al.*, 2020; Cartagena-Matos *et al.*, 2021; Correia *et al.*, 2024). This high diversity of cetaceans is strongly affected by the escalating levels of maritime traffic (Waring *et al.*, 2009; Robbins *et al.*, 2022; Cunha *et al.*, 2017). Specifically, the ENA is a very busy shipping region (Winkler *et al.*, 2020; Robbins *et al.*, 2022). Between 1820 and 2019, most of the reported ship strikes occurred in the North Atlantic Ocean, with the Canary Islands being one of the most affected regions worldwide (Winkler *et al.*, 2020; Carrillo & Ritter, 2010). Data from IWC Ship Strike database indicate that baleen whales were the most frequently involved cetaceans in vessel collisions, with fin whales (*Balaenoptera physalus*) accounting for the highest number of collisions, followed by humpback whales (*Megaptera novaeangliae*; Winkler *et al*., 2020). Odontocetes, such as sperm and beaked whales, were also significantly affected (Winkler *et al*., 2020).

2.2. Data Collection

Data was collected through visual monitoring conducted onboard cargo ships – Insular (I), Lagoa (L), Monte Brasil (MB) and Monte da Guia (MG) – and oceanographic vessels – NRP Almirante Gago Coutinho (GC) and NRP D. Carlos I (DC) – with vessel specifications presented in Table 2.1. Surveys were conducted between 2012 to 2024, with a temporary interruption in cargo ship's embarks from 2020 to 2022 due to the COVID-19 pandemic. Monitoring primarily took place during the summer months (July to October), when sea and weather conditions are most suitable for cetacean monitoring. In addition to cetacean occurrence data, observers also recorded information on other pelagic megafauna, maritime traffic, and meteorological conditions.

Table 2.1. Measurements of cargo ships and oceanographic vessels used as Research Platforms in cetacean monitoring surveys, conducted between 2012 and 2024 in the Eastern North Atlantic.

Vessel		Overall length (m)	Distance to the bow (from the bridge of navigation; m)	Beam (m)	Height of observation deck (m)
Cargo ships	Insular	119.8	109	20	13.5
	Lagoa	100.6	88	16.5	13.5
	Monte Brasil	126.3	110	19.4	16
	Monte da Guia	126.3	110	19.4	16
Oceanographic vessels	NRP Almirante Gago Coutinho	68.3	16.2	13.1	8.9
	NRP D. Carlos I	68.3	16.2	13.1	8.9

In this ongoing monitoring programme, data is collected by two dedicated MMOs positioned on the wings of the navigation bridge, working from sunrise to sunset and following a standardised protocol (Correia *et al*., 2015; Correia *et al*., 2019). Each MMO monitors a 90º field of view on their respective side of the vessel, starting from the bow. Every hour, observers switch sides to reduce fatigue and avoid data bias. At mealtimes or during breaks, a single observer remains on duty and covers a 180º field of view towards the front of the vessel. Each observer is equipped with binoculars featuring an integrated reticle scale and compass, which assists in the ocean's visual scans and supports data collection. While the standard protocol involves two observers, there were occasional instances when only one MMO was available.

Observations are recorded using a tablet. In earlier years, the applications "MyTracks" (https://my-tracks.pt.aptoide.com/) and "LocusMap" (https://www.locusmap.app/) were used to log observations. More recently, data have been collected using the "ILogWhale" app (EcoStrim, Interreg Maritime; CIMA Research Foundation). The data were always curated and standardised to the same format across years. These applications continuously record the date, time, vessel speed, and GPS coordinates. In cases of technical issues (e.g., app malfunctions or low tablet battery) data is recorded manually on paper sheets. At the beginning of each survey, observers enter key information into the app, including the name of the observers onboard, vessel, and the ports of departure and arrival. Likewise, the scale of the binoculars is also registered, after which the on-effort transect officially starts.

When a cetacean or group of cetaceans is sighted, the on-effort transect is interrupted. The observer handling the tablet marks the sighting point to save the GPS coordinates, after which both observers move to the side of the vessel where the sighting occurred. Key data is recorded, including the distance to the animal (i.e., measured in reticles below the horizon on the binocular's scale), the directions of both the animal and the vessel, the side of the sighting (port or starboard), and the name of the observer. At the end of the sighting, observers also document the number of individuals (minimum, maximum and best estimates), behaviour and heading of the group, the animal's response to the vessel (indifferent, approach or avoiding), and, whenever possible, identification to the species level. After, monitoring of the 180º field of view is resumed and a new on-effort transect starts.

Maritime traffic information is collected at the beginning and end of each survey, as well as following any cetacean sightings, and every hour. All vessels are counted within a 360º field of view and categorised into small (up to 20 meters in length) and large (over 20 meters). Weather conditions are assessed by evaluating wind direction, wind speed (according to the Beaufort scale), sea state (according to the Douglas scale), cloud cover, visibility, and occurrence of rain. This information is recorded at the beginning and end of each survey, and any time a significant change occurs. Observers pause on-effort transects whenever conditions become unfavourable for cetacean monitoring (e.g., Beaufort or Douglas values over 4, low visibility, or heavy rain). On-effort transects are also suspended when it is not possible to remain on the navigation bridge (e.g., instructions from the vessel's Commander, safety drills, or deck cleaning).

Lastly, observations of other pelagic marine megafauna, such as sharks, turtles and marine birds, are recorded opportunistically. When possible, the species and number of individuals are documented.

2.3. Data Processing

2.3.1. Data Curation

Every sampling season, the recorded data is downloaded from the app and stored automatically as CSV files, which are later imported into Microsoft Excel spreadsheets for processing. Initially, data from each survey is processed separately. The data is organised, structured and cleaned (e.g., conversion of variables, insertion of codes, correction of any detected errors) to ensure consistency and accuracy.

For the present study, all sighting records were compiled into a Microsoft Excel spreadsheet and filtered to only include whale sightings for further analysis.

2.3.2. Estimation of Distance to Sightings

To estimate the distance to the sightings, the Radial Distance (defined as the maximum distance from the observer to the animal, in meters) was estimated using the following formula:

$$\text{Radial Distance} = \text{Eye Height} \times \frac{1000}{\text{Reticles} \times \text{reticles mils}}$$

Eye Height refers to the sum of the height of the observation deck (in meters) and the average human eye level (1.59 meters), which corresponds to the mean value between average female and male eye levels (First in Architecture, 2019). Reticles refer to the number of binocular reticles measured from the horizon to the sighting. When the number of reticles was zero, indicating that the sighting took place near the horizon, the Radial Distance was not calculated.

Using the Radial Distance, the distance between the animal and the vessel, hereafter Vessel-to-Whale Distance (also in meters), was estimated. Sightings were categorised based on their relative position: either at the vessel's bow or abeam. The angular range corresponding to the bow area was calculated in order to determine the angle within which animals are in the risk of collision considering the full beam of the vessel. For the calculations the scheme illustrated in Figure 2.2 was followed.

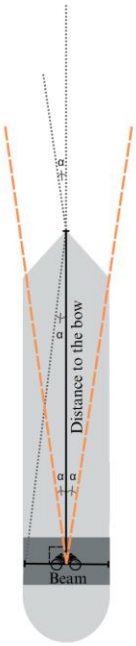


Figure 2.2. Schematic representation of the method used to determine the angular range corresponding to the vessel's bow area.

By using each vessel's dimensions, specifically the distance to the bow and the vessel's beam, the angle α for each vessel was calculated, using the following formula:

$$\tan^{-1}\alpha = \frac{\frac{1}{2}\,\text{Beam}}{\text{Distance to the bow}}$$

Based on this calculation, the bow area was defined as the angular range between -6º and 6º from the vessel's heading for cargo ships, and between -23º and 23º for oceanographic vessels. The measures were determined to be the highest angle for cargo and oceanographic vessels, rounded to the highest unit.

The Vessel-to-Whale Distance was then calculated using the Pythagorean theorem. For sightings observed at the bow (Figure 2.3), the formula below was applied:

$$\begin{aligned}&\text{Vessel} - \text{to} - \text{Whale Distance}\\ &\qquad = \sqrt{\text{Radial Distance}^2 - \text{Eye Height}^2} - \text{Distance to the bow}\end{aligned}$$

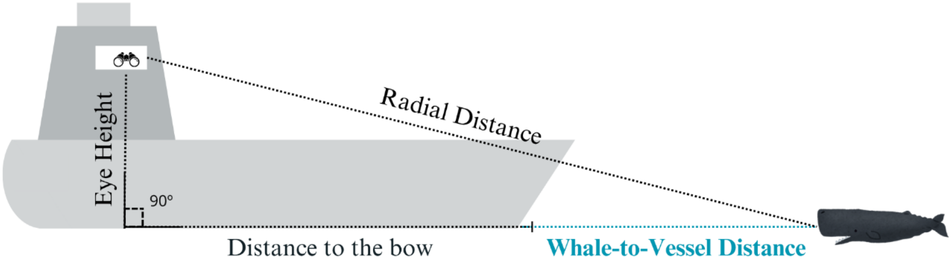


Figure 2.3. Schematic representation of the method used to calculate the Vessel-to-Whale Distance for sightings occurring at the vessel's bow (defined as between -6° and 6° for cargo ships and between -23° and 23° for oceanographic vessels).

For the sightings occurring abeam (Figure 2.4), the Vessel-to-Whale Distance was estimated using the following formula:

$$\text{Vessel} - \text{to} - \text{Whale Distance} = \sqrt{\text{Radial Distance}^2 - \text{Eye Height}^2}$$

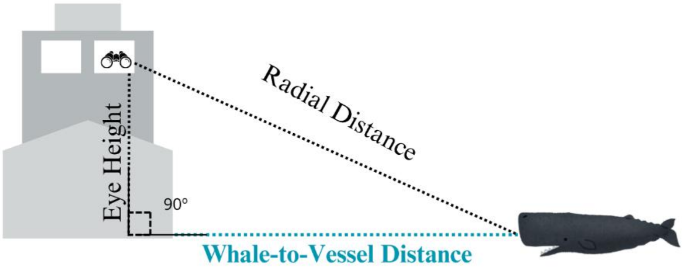


Figure 2.4. Schematic representation of the method used to calculate the Vessel-to-Whale Distance for sightings occurring outside the vessel's bow angular range (i.e., sightings abeam).

2.3.3. Defining SEs and NMEs

To define SEs and NMEs, collectively referred to as Close Encounters (CEs; Currie *et al.*, 2017), only sightings occurring between -90° and 90° relative to the vessel's heading were considered. Then, the approach described by Richardson *et al.* (2011), and later adopted by others (e.g., Stack *et al.*, 2013; Currie *et al.*, 2014; Stack *et al.*, 2016; Currie *et al.*, 2017), was used as a basis for definition. According to this framework, these events are defined based on the distance to the whale: an SE occurs when the distance is less than 300 meters, while an NME occurs when the whale is located at the vessel's bow and the distance is less than 80 meters (Richardson *et al.*, 2011).

As vessel speed in the present study varied considerably (ranging from 1 to 22 knots), thresholds were defined based on Time to Potential Collision (TPC) rather than distance alone. TPC (in seconds) was calculated by dividing the Vessel-to-Whale Distance (in meters) by the vessel's speed (in meters per second), at the time of the sighting. When speed data were unavailable (only occasionally missing for cargo ships), the average speed of cargo ships was used. Given that Stack *et al.* (2013) reported a similar range of vessel speeds, the TPC corresponding to their lowest vessel speed (5 knots) for 300 meters and 80 meters, was used to define the maximum TPC (threshold) for this study's definition of SEs and NMEs, respectively. This conservative approach ensured that all potential CEs were included. This methodology aligns with Stack *et al.* (2016), that suggested that time to manoeuvre the vessel and avoid a collision is a more suitable metric when assessing collision risk. The authors also consider that the time thresholds defined are "reasonable for quantification of near misses and surprise encounters" (Stack *et al.*, 2016).

Accounting for the conditions mentioned above, within the scope of this study, CEs were defined as whale sightings encountered near the vessel, between the -90º and 90º relative to the vessel's heading and categorised as: SEs, which were defined as sightings with a TPC between 31.10 and 116.63 seconds; and NMEs, defined as sightings with a TPC of 31.10 seconds or less. Additionally, a definition for the NMEs occurring at the vessels' bow area, as defined above based on the beam and distance of the observer to the bow – Likely Collision Events (LCEs) – was also proposed.

2.4. Descriptive and Spatial Analysis

Descriptive statistics were used to explore the general characteristics of the dataset. Minimum, maximum, and mean values were calculated for several variables, including vessel speed, TPC, and group size. Using Microsoft Excel, bar plots were produced to illustrate the frequency of recorded taxa involved in SEs and NMEs, while histograms were generated to show the distribution of CEs by the TPC.

For spatial analysis, ArcGIS Pro 3.4.3 was used to map whale sightings and visualise their distribution across the study area. Effort transects were mapped using the Data Management Tool “Points To Line”. Afterwards, the Data Management Tool “XY Table To Point” was applied to map all whale sightings, SEs, and NMEs. Different symbology was assigned to each event type to allow a clear visual distinction on the maps. The coordinate system used for all maps was World Mercator (projected from WGS84 coordinates).

2.5. Modelling

To assess the dynamics of CEs, Generalised Additive Models (GAMs) were fitted in RStudio (R Version 4.3.2). This analysis addressed two main objectives, through different models: (1) investigating the spatio-temporal patterns of CEs, and (2) evaluating the influence of detectability-related variables on TPC. Three models were fitted for each of the objectives: one for all whale sightings, one for baleen whale sightings, and one for beaked whale sightings. Sperm whale sightings were excluded due to insufficient sample size.

Prior to modelling, density plots were used to check variable’s distribution, and Pearson correlations identified highly correlated variables (threshold of 0.75), which were excluded from the first fitting process (Marubini *et al.*, 2009; Correia *et al.*, 2020; Correia *et al.*, 2021). To assess multicollinearity, the Variance Inflation Factor (VIF) was calculated, applying a threshold of 3 (Zuur *et al.*, 2010; Correia *et al.*, 2020; Correia *et al.*, 2021). In models with categorical variables, the Generalised Variance Inflation Factor (GVIF) was used instead, as this factor addresses multicollinearity for variables with more than one degree of freedom (i.e., categorical ones), using a threshold of 5 (Shikatani & Richman, 2024). Since GVIF values are equal to VIF values for continuous variables, the use of this factor poses no limitation (Hendrickx *et al.*, 2004).

For the first objective, the response variable was the occurrence of CEs, coded as 0 for absence of the incident and 1 for presence/occurrence of the incident. Given that this variable is binary, a GAM with a binomial distribution and a logit link function was applied (Correia *et al.*, 2021; Oliveira-Rodrigues *et al.*, 2022). Explanatory variables included latitude, longitude, year, month, and day of the year (1 to 366).

For the second objective, the response variable was the TPC. As this is a continuous positive variable with a non-normal distribution, a GAM with a gamma distribution and a log link function was used (Dunn & Smyth, 2018; Pedersen *et al.*, 2019). Detectability-related explanatory variables included vessel, group size, sea state, wind state, visibility, and rain. Figures A1 and A2 in the Appendix represent the distribution of sea and wind states across all whale sightings recorded during the sampling period. Categorical variables (vessel, visibility, and rain) were converted to factors.

Then, a backward selection was performed for each model, where variables were removed sequentially based on the highest p-value from the model (given by the "summary.gam" function; Correia *et al.*, 2015; Qian, 2016; Correia *et al.*, 2020). For categorical variables, an Analysis of Variance (ANOVA) chi-square test was performed instead. The process continued until the final model was reached. The best models were selected using the Akaike Information Criterion (AIC), with preference for the lowest AIC. When the AIC-difference between two models was less than two, an ANOVA chi-square test was performed to determine if the difference was significant (Zuur *et al.*, 2007; Correia *et al.*, 2020; Correia *et al.*, 2021; Oliveira-Rodrigues *et al.*, 2022). If non-significant, the simpler model was chosen. If models had an equal number of variables, the one with the lowest AIC was selected. In cases where some variables were previously excluded due to high correlation, these variables were reintroduced to the best-fitting model through a forward selection process. If any of these reintroduced variables improved the model and were retained, a subsequent backward selection was performed again to refine the model.

In all models, all smooth terms were fitted with four splines ($k = 4$; Qian, 2016; Correia *et al.*, 2021; Oliveira-Rodrigues *et al.*, 2022). Smooth terms with estimated degrees of freedom (EDF) close to 1 were replaced with linear terms (Correia *et al.*, 2021; Oliveira-Rodrigues *et al.*, 2022). Smooth terms were not used for categorical variables.

Lastly, the best-fitting models were summarised using the function "summary(gam)", and diagnostic plots performed with "gam.check" function (Oliveira-Rodrigues *et al.*, 2022). Influential data points and the correlation between the model residuals and explanatory variables were also checked. All GAM analyses were developed with the "mgcv" R package.

3. Results

3.1. Descriptive and Spatial Analysis

Between 2012 and 2024, a total of 1211 sightings involving 11 whale species were recorded across the entire study area and along all surveyed routes (Figure 3.1). The majority of sightings (57.06%) were non-identified (NI) baleen or beaked whales. *P. macrocephalus* was the most frequently sighted species (227 sightings – 18.74%), followed by *B. acutorostrata* (97 sightings – 8.01%), and *Ziphius cavirostris* (93 sightings – 7.68%; Table 3.1).

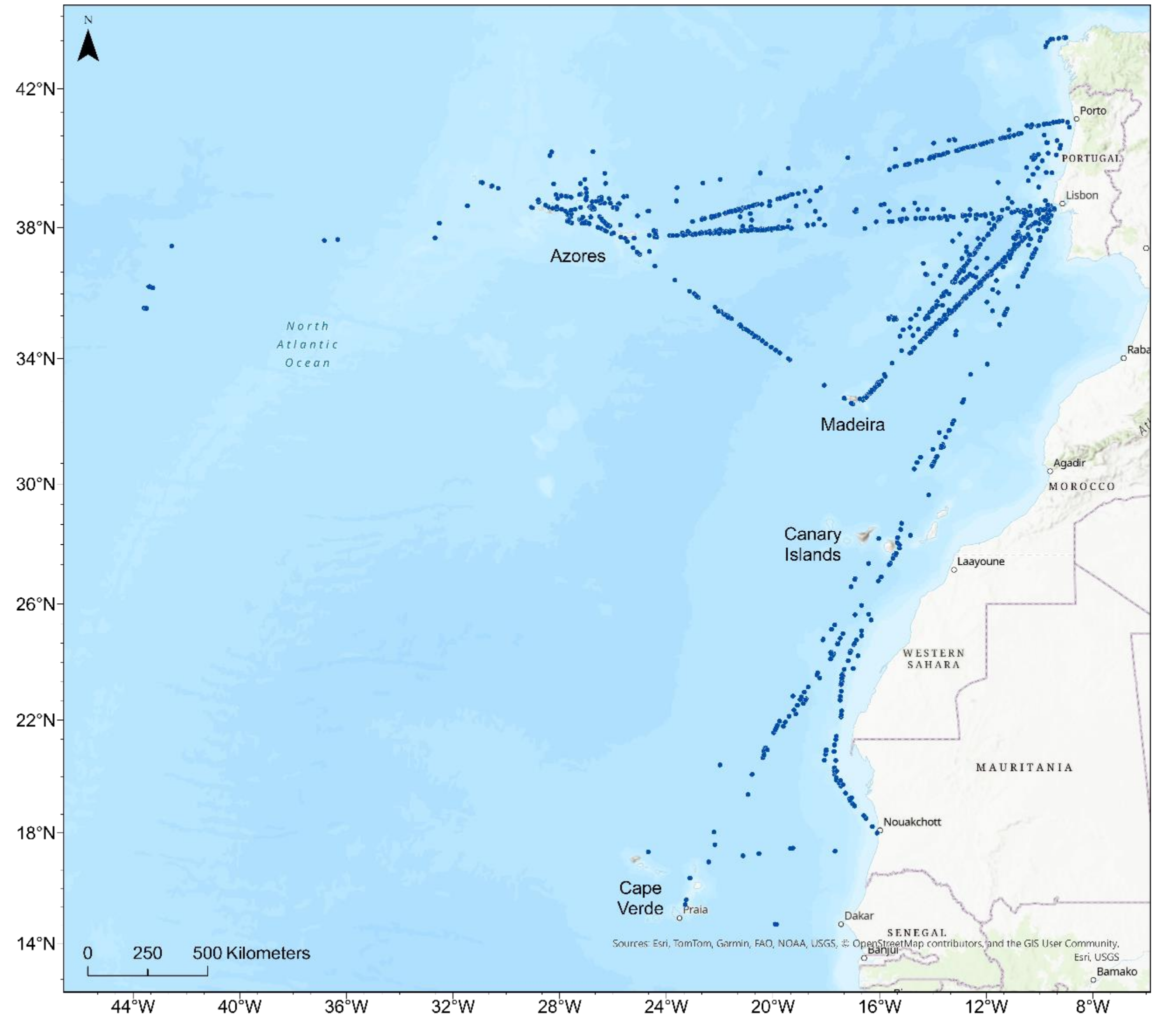


Figure 3.1. Spatial distribution of whale sightings recorded during cetacean monitoring surveys conducted between 2012 and 2024 in the Eastern North Atlantic, using cargo ships and oceanographic vessels as Research Platforms.

To our knowledge, no actual collisions were recorded during the course of this study. Over the 13 years of monitoring, 457 sightings (37.74% of all sightings) were classified as CEs, involving 10 out of the 11 whale species sighted. Although both Mysticeti and Ziphiidae accounted for 197 CEs each (each representing 43.11% of all CEs), beaked whales were proportionally more involved in these encounters – 59.70% of Ziphiidae sightings were associated with CEs. In relation to all CEs, the species most frequently involved in these encounters were *P. macrocephalus* (63 CEs, corresponding to 13.79% of all CEs), *Z. cavirostris* (55 CEs, corresponding to 12.04% of all CEs), and *B. acutorostrata* (42 CEs, corresponding to 9.19% of all CEs). Among these species, *Z. cavirostris* showed the highest proportion of CEs relative to its total number of sightings (59.14%). *B. musculus*, *Mesoplodon bidens*, *Balaenoptera edeni* and *Balaenoptera borealis* were the species least involved in CEs, collectively accounting for only seven of these events (1.53% of all CEs). Moreover, only one observed species (*M. novaeangliae*) was not involved in any CE (Table 3.1).

Table 3.1. Summary of whale sightings and Close Encounters (CEs) recorded during cetacean monitoring surveys conducted between 2012 and 2024 in the Eastern North Atlantic, using cargo ships and oceanographic vessels as Research Platforms. Percentages indicate the proportion of CEs relative to the total number of sightings for each taxon and in relation to all CEs. NI – non-identified.

Taxa	Number of sightings (% on total number of sightings)	Number of CEs (% within taxa; % on overall CEs)
Balaenoptera acutorostrata	97 (8.01%)	42 (43.30%; 9.19%)
Balaenoptera borealis	8 (0.66%)	3 (37.50%; 0.66%)
Balaenoptera edeni	6 (0.50%)	2 (33.33%; 0.44%)
Balaenoptera musculus	3 (0.25%)	1 (33.33%; 0.22%)
Balaenoptera physalus	57 (4.71%)	19 (33.33%; 4.16%)
Megaptera novaeangliae	9 (0.74%)	0
Mysticeti NI	474 (39.14%)	130 (27.43%; 28.45%)
Mysticeti	**654 (54.01%)**	**197 (30.12%; 43.11%)**
Mesoplodon bidens	3 (0.25%)	1 (33.33%; 0.22%)
Mesoplodon densirostris	8 (0.66%)	6 (75%; 1.31%)
Mesoplodon europaeus	9 (0.74%)	7 (77.78%; 1.53%)
Ziphius cavirostris	93 (7.68%)	55 (59.14%; 12.04%)
Ziphiidae NI	217 (17.92%)	128 (58.98%; 28.01%)
Ziphiidae	**330 (27.25%)**	**197 (59.70%; 43.11%)**
Physeter macrocephalus	227 (18.74%)	63 (27.75%; 13.79%)
Physeteridae	**227 (18.74%)**	**63 (27.75%; 13.79%)**
TOTAL	**1211**	**457**

Of all CEs, 433 (35.76% of all sightings and 94.75% of all CEs) were classified as SEs, and 24 (1.98% of all sightings and 5.25% of all CEs) as NMEs. These events occurred throughout the study area and were observed in all routes (Figure 3.2). Additionally, NMEs were most frequent on the route between mainland Portugal and Madeira Island, accounting for 13 of such events (54.17% of all NMEs).

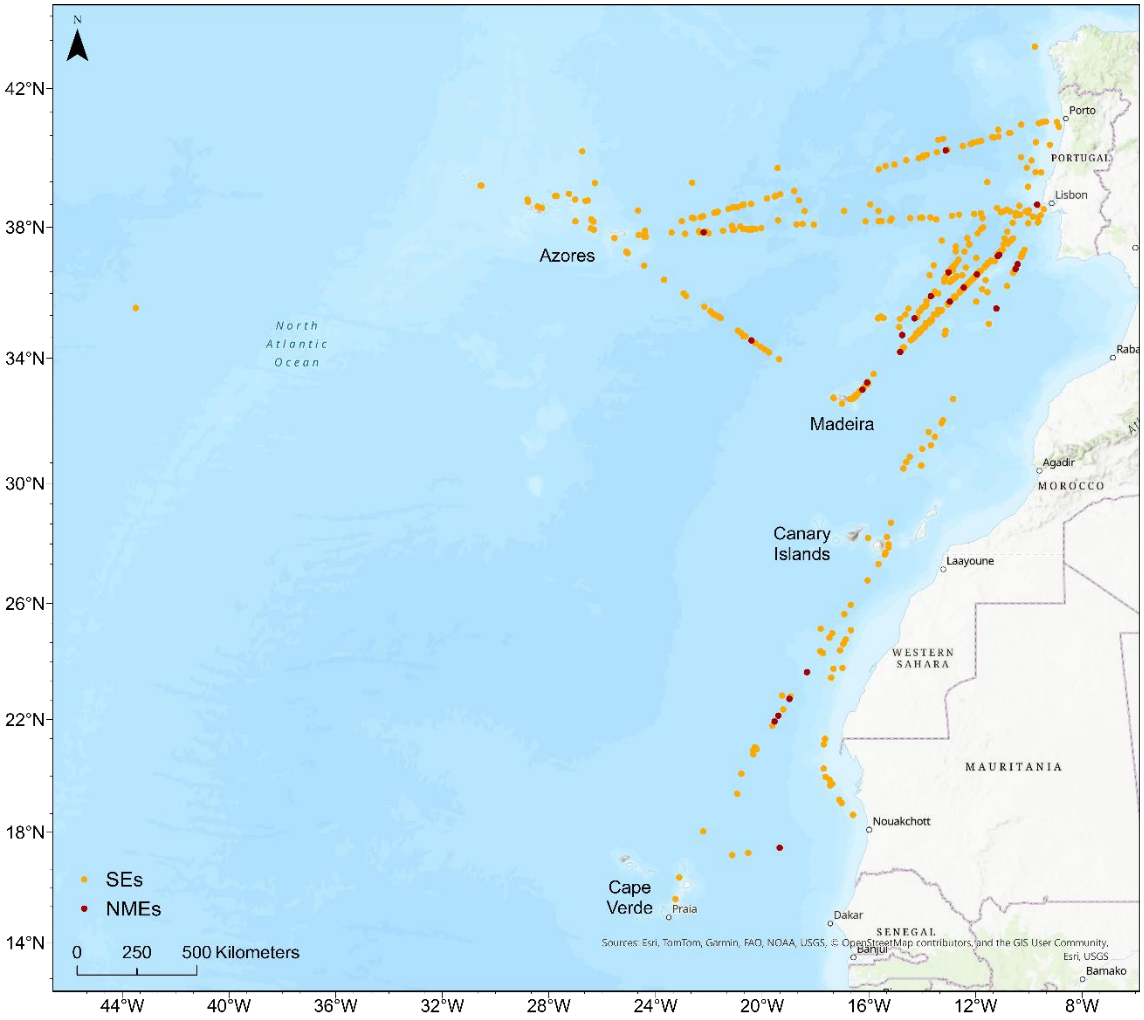


Figure 3.2. Spatial distribution of Surprise Encounters (SEs) and Near-Miss Events (NMEs) recorded during cetacean monitoring surveys, conducted between 2012 and 2024 in the Eastern North Atlantic, using cargo ships and oceanographic vessels as Research Platforms.

SEs involved 10 out of the 11 species sighted, whereas NMEs were associated with only four species: *B. acutorostrata*, *B. physalus*, *Mesoplodon densirostris* and *Z. cavirostris* (Figure 3.3). Of all SEs, Mysticeti was the group most frequently associated with these encounters, comprehending 187 sightings (43.19% of all SEs; Table A1 in Appendix). In relation to the total number of SEs, *P. macrocephalus* was the species most frequently associated with these encounters (14.55% of all SEs), although it was not involved in any

NME. When considering the total number of NMEs, Ziphiidae accounted for most of these events (14 NMEs, corresponding to 58.33% of all NMEs), with *Z. cavirostris* being the species most frequently involved (29.17% of all NMEs).

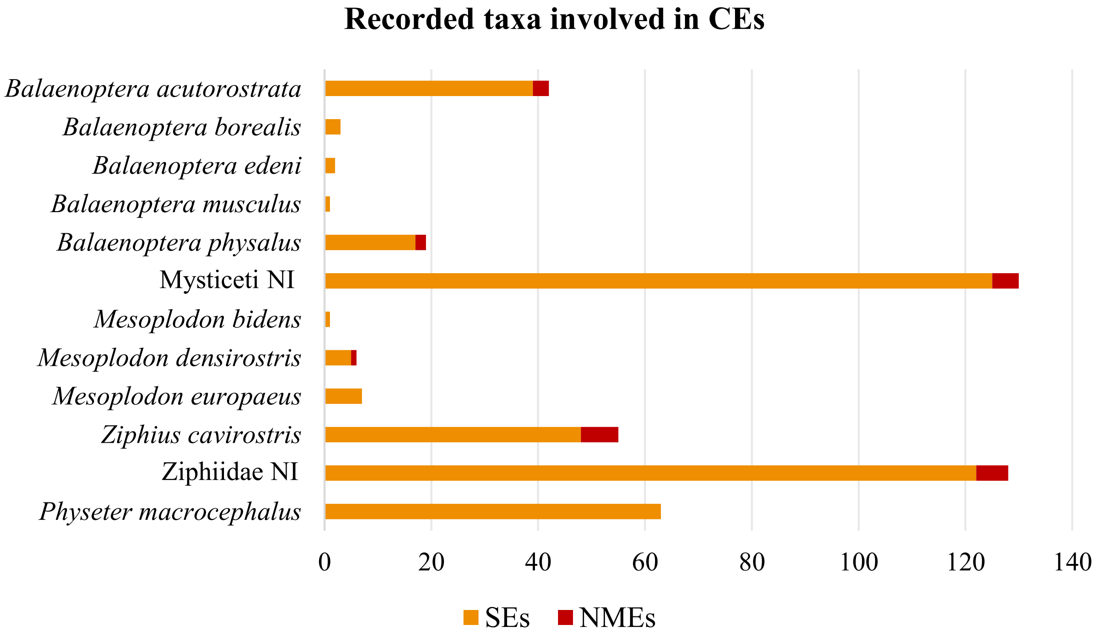


Figure 3.3. Histogram representing the taxa involved in Surprise Encounters (SEs) and Near-Miss Events (NMEs), collectively referred to as Close Encounters (CEs), recorded during cetacean monitoring surveys conducted between 2012 and 2024 in the Eastern North Atlantic, using cargo ships and oceanographic vessels as Research Platforms.

NMEs were only registered in the cargo ship routes (i.e., no NME was associated with oceanographic vessels). Among these events, seven were classified as LCEs: two sightings of *B. acutorostrata,* one sighting of *B. physalus,* one sighting of Mysticeti NI, one sighting of *M. densirostris* and two sightings of *Z. cavirostris* (Table A1 in Appendix). Out of the LCEs, three of them exhibited indifferent behaviour towards the vessel (sightings of *B. acutorostrata, B. physalus,* and *Z. cavirostris*).

Most whales involved in CEs were lone individuals (59.52% of all CEs), as were the majority involved in SEs (58.89% of all SEs) and NMEs (70.83% of all NMEs; Table 3.2). The largest group size recorded during a CE was 12 individuals, observed in a group of *P. macrocephalus*, which exhibited indifferent behaviour.

Table 3.2. Frequency of Close Encounters (CEs), including Surprise Encounters (SEs) and Near-Miss Events (NMEs), according to the best estimate of the group size, of data collected during cetacean monitoring surveys conducted between 2012 and 2024 in the Eastern North Atlantic, using cargo ships and oceanographic vessels as Research Platforms. Percentages indicate the proportion of SEs, NMEs and total CEs relative to the total number of events in each category, respectively.

Group size (best estimate)	Close Encounters		Total
	Surprise Encounters	Near-Miss Events	
1	255 (58.89%)	17 (70.83%)	272 (59.52%)
2	103 (23.79%)	4 (16.67%)	107 (23.41%)
3	39 (9.01%)	1 (4.17%)	40 (8.75%)
4	16 (3.70%)	1 (4.17%)	17 (3.72%)
5	11 (2.54%)	0	11 (2.41%)
6	3 (0.69%)	1 (4.17%)	4 (0.88%)
7	3 (0.69%)	0	3 (0.66%)
8	1 (0.23%)	0	1 (0.22%)
9	1 (0.23%)	0	1 (0.22%)
12	1 (0.23%)	0	1 (0.22%)

Most of the individuals associated with a CE exhibited indifferent behaviour (73.96% of all CEs), whilst 7.66% of CEs showed avoidance and 7.22% approaching behaviour. In 51 CEs (11.16% of all CEs) no behaviour response was recorded. As for the NMEs, there were nine sightings in which the animal(s) showed an avoiding behaviour (37.50% of all NMEs), eight who exhibited an indifference towards the vessel (33.33% of all NMEs), and only three that presented an approaching behaviour (12.50% of all NMEs; Table 3.3).

Table 3.3. Frequency of Close Encounters (CEs), including Surprise Encounters (SEs) and Near-Miss Events (NMEs), according to the behaviour exhibited towards the vessel, of data collected during cetacean monitoring surveys conducted between 2012 and 2024 in the Eastern North Atlantic, using cargo ships and oceanographic vessels as Research Platforms. Percentages indicate the proportion of SEs, NMEs and total CEs relative to the total number of events in each category, respectively.

Behaviour towards the vessel	**Close Encounters**		**Total**
	Surprise Encounters	**Near-Miss Events**	
Approaching	30 (6.93%)	3 (12.50%)	33 (7.22%)
Avoiding	26 (6.00%)	9 (37.50%)	35 (7.66%)
Indifferent	330 (76.21%)	8 (33.33%)	338 (73.96%)
Non-recorded	47 (10.85%)	4 (16.67%)	51 (11.16%)

The TPC of CEs ranged from 15.50 to 116.51 seconds (Figure 3.4). The most frequent TPC interval was 26.72 - 37.95 seconds, accounting for 79 CEs (representing 17.29% of CEs). Only seven CEs (1.53% of all CEs) had a TPC below 26.72 seconds. The median TPC was 62.85 seconds, with 229 CEs (50.11% of all CEs) occurring below this threshold. Moreover, the shortest TPC was 15.50 seconds, recorded for a *B. acutorostrata* sighting, closely followed by a *M. densirostris* sighting with a TPC of 15.81 seconds.

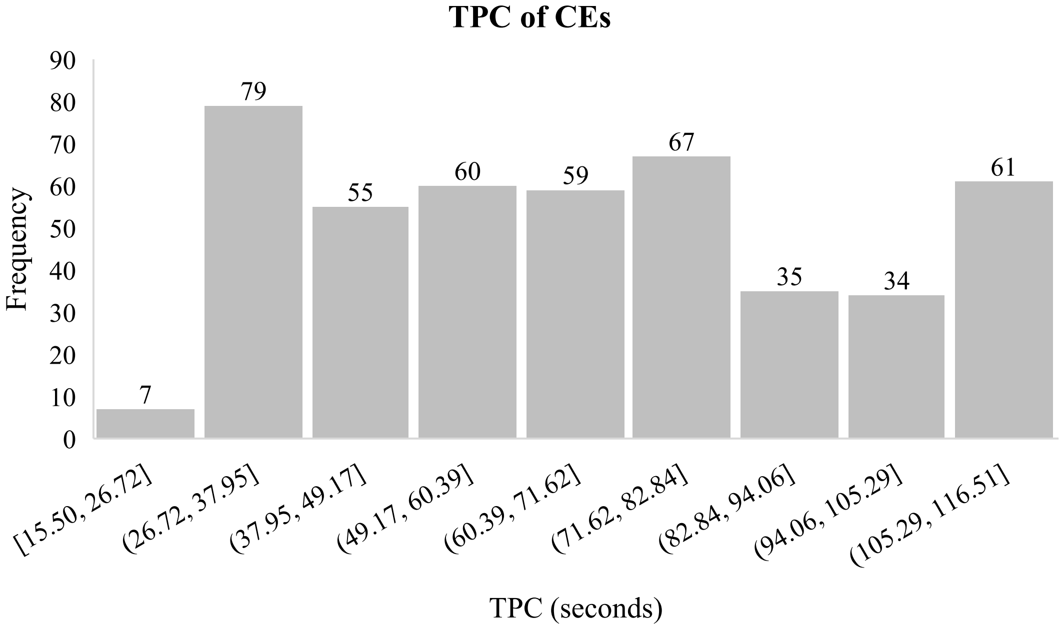


Figure 3.4. Histogram representing the distribution of Time to Potential Collision (TPC) of Close Encounters (CEs), recorded during cetacean monitoring surveys conducted between 2012 and 2024 in the Eastern North Atlantic, using cargo ships and oceanographic vessels as Research Platforms.

3.2. Modelling

No models' residuals displayed a normal distribution, as indicated by the histograms (Figures A3 to A8 in Appendix). Even though some models' variables presented significant p-values, the number of splines of each smoother was adequate, as the EDFs remained sufficiently below the maximum value (k'; Tables A2 to A5 in Appendix). No highly influential data points were identified in any of the models (Figures A9 to A14 in Appendix). Lastly, models' residuals showed no apparent correlation with any of the explanatory variables (Figures A15 to A20 in Appendix). For the spatio-temporal models, explained deviance ranged between 3.51% and 7.97%, while for the models considering TPC, it varied between 8.25% and 16.8%.

3.2.1. Modelling Spatio-temporal Patterns of CEs

CEs were modelled in relation to spatio-temporal variables, resulting in three separate models: one for all whale sightings (total CEs), one for baleen whale sightings, and one for beaked whale sightings. Based on the Pearson correlation analysis, the variables month and day of the year were excluded from the first fitting (backward selection) of all the three models due to high collinearity. Then, the re-introduction of each of these variables was tested, individually, through forward selection, retaining only the best resultant model (Figures A21, A22 and A23 in Appendix). VIF values of the remaining explanatory variables (i.e., year, longitude and latitude) were all below the threshold of 3, indicating no multicollinearity issues, so they were retained (Tables A6, A7 and A8 in Appendix).

For the model of all the whales' sightings, all 1211 whale sightings were considered, in which 457 are CEs, coded as 1, and the remaining 754 sightings were coded as 0. The best fitted GAM included the following explanatory variables: year, longitude, latitude, and day of the year – which explained 5.44 % of the deviance in CEs (Table 3.4).

Table 3.4. Results from the best fitted Generalised Additive Model (GAM) analysing the spatio-temporal patterns of Close Encounters (CEs) across all whale sightings. EDF – Estimated Degrees of Freedom. Lat – Latitude. Lon – Longitude. UBRE – Un-Biased Risk Estimator.

n = 1211; Deviance explained = 5.44%; R-square = 0.0613; UBRE = 0.26901				
Variable	**EDF**	**Reference EDF**	**Chi-Square**	**P-value**
s(year)	2.924	2.995	16.66	0.000848
s(lat)	2.888	2.990	25.23	9.13e-06
s(day)	1.610	1.974	13.65	0.001698
Variable	**Estimate**	**Standard Error**	**Z-value**	**Pr(>|z|)**
lon	0.04010	0.01265	3.170	0.00152

The number of total CEs increased slightly until 2016, then declined until 2021, and increased again towards 2024. Overall, the number of CEs increased with longitude (higher values towards east). As for latitude, the occurrence of CEs was mostly stable and then peaked around 32º to 37º (area encompassing Madeira and the routes between mainland Portugal and Madeira, and Madeira and Azores), starting to decrease thereafter. Regarding day of the year, the number of CEs increased towards the end of the summer sampling season and presented wide confidence intervals towards the first and last days of the year (Figure 3.5). As such, these results must be interpreted with caution, due to the reduced number of observations in other seasons.

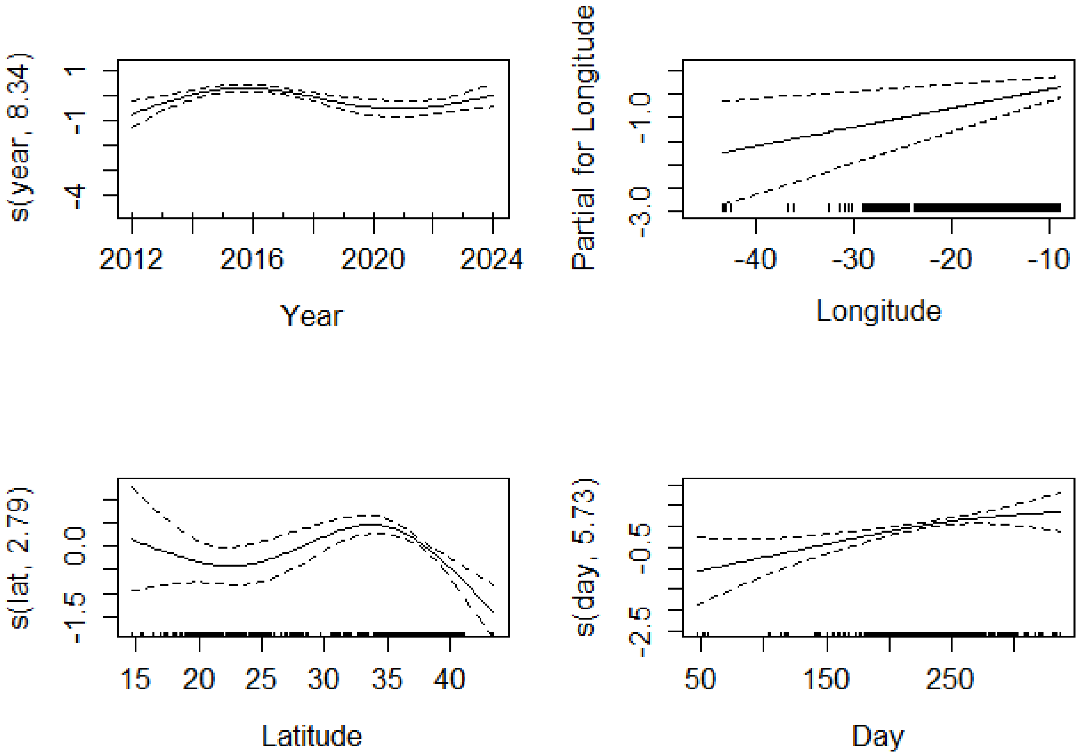


Figure 3.5. Plots of the final Generalised Additive Model (GAM) analysing the spatio-temporal patterns of Close Encounters (CEs) across all whale sightings. Lat – Latitude.

For the spatio-temporal model of baleen whale sightings, all 654 sightings of baleen whales were included, with 197 CEs (coded as 1) and the 457 non-CEs (coded as 0). The best fitted GAM included longitude and day of the year as explanatory variables, explaining 3.51% of CEs distribution (Table 3.5).

Table 3.5. Results from the best fitted Generalised Additive Model (GAM) analysing the spatio-temporal patterns of Close Encounters (CEs) across baleen whale sightings. EDF – Estimated Degrees of Freedom. Lon – Longitude. UBRE – Un-Biased Risk Estimator.

n = 654; Deviance explained = 3.51%; R-square = 0.034; UBRE = 0.19561				
Variable	**EDF**	**Reference EDF**	**Chi-Square**	**P-value**
s(lon)	1.802	2.194	9.615	0.01014
s(day)	2.037	2.434	14.073	0.00231

Similar to the model of all whale sightings, the number of CEs associated with baleen whale sightings tended to increase with longitude until -15º, where the values stabilise. Likewise, the frequency of CEs also peaked increased towards the end of September, presenting large confidence intervals in the extremities, which indicates some uncertainty in the estimates (Figure 3.6).

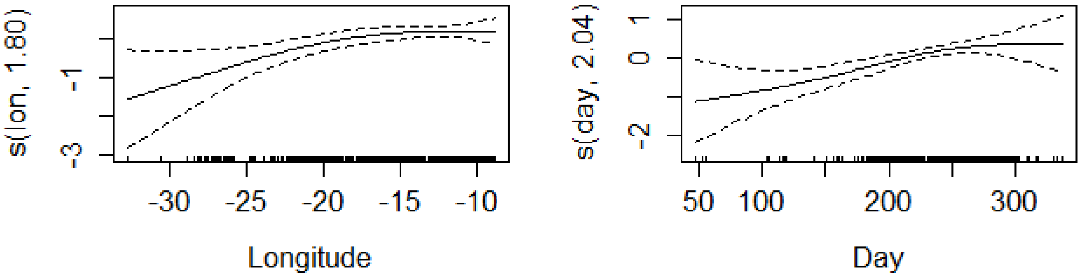


Figure 3.6. Plots of the final Generalised Additive Model (GAM) analysing the spatio-temporal patterns of Close Encounters (CEs) across baleen whale sightings. Lon – Longitude.

Lastly, for the occurrence of CEs among the 330 beaked whale sightings, a total of 197 CEs (coded as 1) and 133 non-CEs (coded as 0) were considered. The best fitted GAM included the year and latitude as explanatory variables, explaining 7.97% of the deviance in CE distribution (Table 3.6).

Table 3.6. Results from the best fitted Generalised Additive Model (GAM) analysing the spatio-temporal patterns of Close Encounters (CEs) across beaked whale sightings. EDF – Estimated Degrees of Freedom. Lat – Latitude. UBRE – Un-Biased Risk Estimator.

n = 330; Deviance explained = 7.97%; R-square = 0.0943; UBRE = 0.27995				
Variable	**EDF**	**Reference EDF**	**Chi-Square**	**P-value**
s(year)	2.934	2.996	16.11	0.001
s(lat)	2.494	2.826	12.50	0.012

The number of CEs involving beaked whales was mostly stable up until 2017, followed by a decline until 2021, and then rose again until 2024. These results must be interpreted with caution, as only oceanographic vessels were operating between 2020 and 2022, resulting in reduced data availability during this period and consequently less reliable model predictions. The frequency of CEs increased with latitude until 32º, after which it started to decrease until 40º. Data between 35º to 40º allow more robust conclusions, due to the narrower confidence intervals (Figure 3.7).

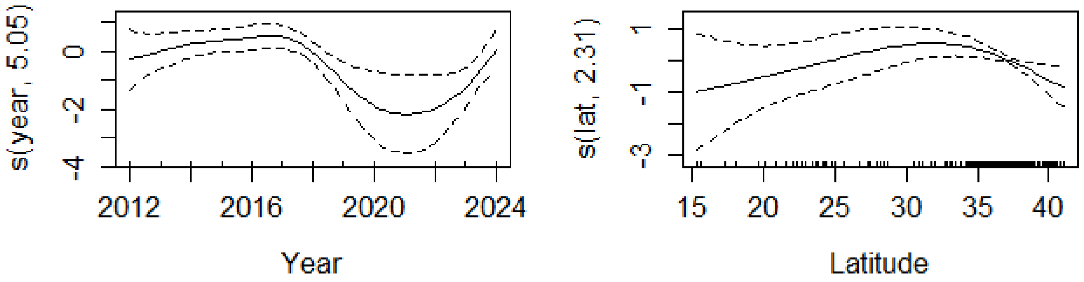


Figure 3.7. Plots of the final Generalised Additive Model (GAM) analysing the spatio-temporal patterns of Close Encounters (CEs) across beaked whale sightings. Lat – Latitude.

3.2.2. Modelling the Influence of Detectability-related Variables on TPC

When applying Pearson correlation to the models evaluating the influence of detectability-related variables on TPC, none of the explanatory variables were highly correlated, and therefore none were removed from any of the models (Figures A24, A25 and A26 in Appendix). In all three GAMs, the GVIF values of the explanatory variables were all below the established threshold of 5, so all the variables were kept (Tables A9, A10 and A11 in Appendix).

In the model considering the TPC for all whale sightings, the explanatory variables included were sea state, wind state, vessel, and rain, explaining 16.8% of the variation in TPC (Table 3.7).

Table 3.7. Results from the best fitted Generalised Additive Model (GAM) analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of all whale sightings. DF – Degrees of Freedom. EDF – Estimated Degrees of Freedom. GCV – Generalised Cross Validation.

n = 1090; Deviance explained = 16.8%; R-square = 0.169; GCV = 0.65687				
Variable	**EDF**	**Reference EDF**	**F**	**P-value**
s(sea_state)	2.285	2.684	1.882	0.2361
s(wind_state)	2.304	2.684	2.790	0.0307
Variable	**DF**	**F**	**P-value**	
vessel	5	26.617	<2e-16	
rain	1	2.073	0.15	

TPC was higher in oceanographic vessels, compared to the values associated with cargo ships, which remained relatively constant. When considering sea state influence, TPC remained rather stable with sea state, with lower and more stable values between 2 and 4 (although with very wide confidence intervals in the extremities). As for the wind state, TPC remained constant up to a wind state of 4, after which it started to decline (also with large confidence intervals in the extremities). Lastly, the presence of rain was associated with lower TPC values (Figure 3.8).

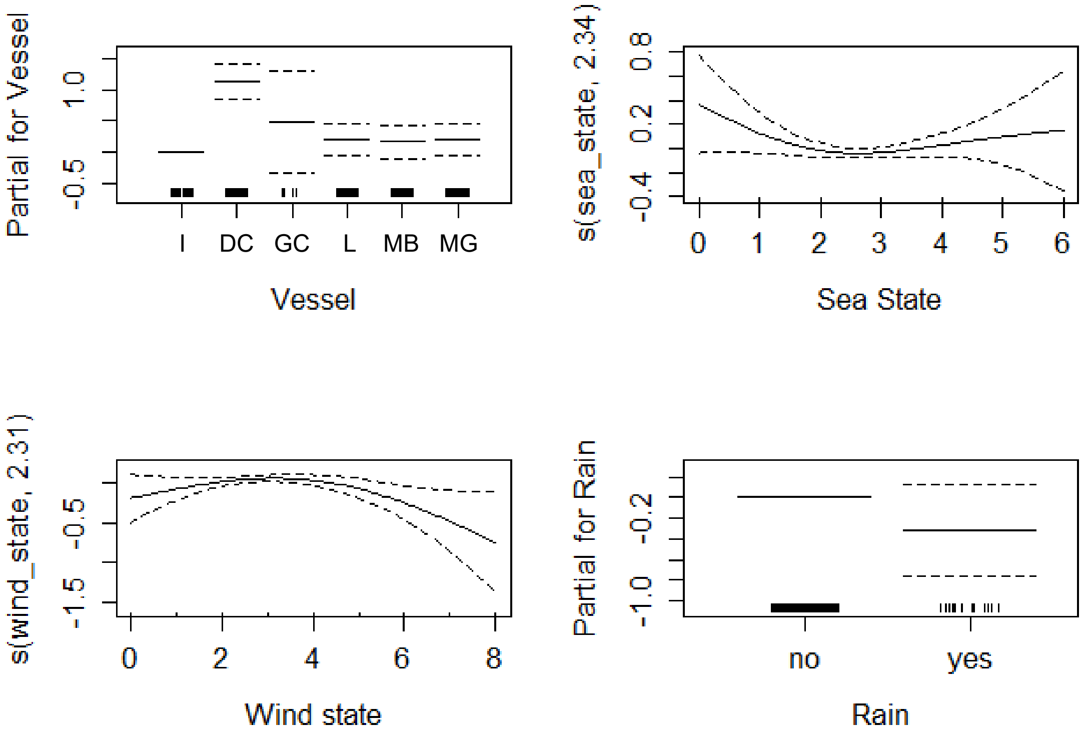


Figure 3.8. Plots of the final Generalised Additive Model (GAM) analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of all whale sightings. I – Insular. DC – NRP Almirante D. Carlos I. GC – NRP Almirante Gago Coutinho. L – Lagoa. MB – Monte Brasil. MG – Monte da Guia.

For the TPC model based on baleen whale sightings, the best fitted GAM included vessel, group size, visibility, and rain as explanatory variables, which explained 12.1% of the deviance in TPC (Table 3.8).

Table 3.8. Results from the best fitted Generalised Additive Model (GAM) analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of baleen whale sightings. DF – Degrees of Freedom. GCV – Generalised Cross Validation.

n = 593; Deviance explained = 12.1%; R-square = 0.171; GCV = 0.0047156			
Variable	**DF**	**F**	**P-value**
vessel	5	11.883	5.77e-11
group_size	1	2.466	0.117
visibility	3	2.787	0.040
rain	1	0.043	0.836

Overall, TPC still remained higher in oceanographic vessels, in comparison to cargo ships. Despite the slight increase of TPC with group size, there were very few observations of groups with more than four individuals. Consequently, the wide confidence intervals prevent robust assumptions. TPC increased with visibility, as visibility states range from low to optimum (low-medium-good-optimum). Similarly to the model including all whale sightings, the TPC under the presence of rain was lower, although with a minimal difference between categories (Figure 3.9).

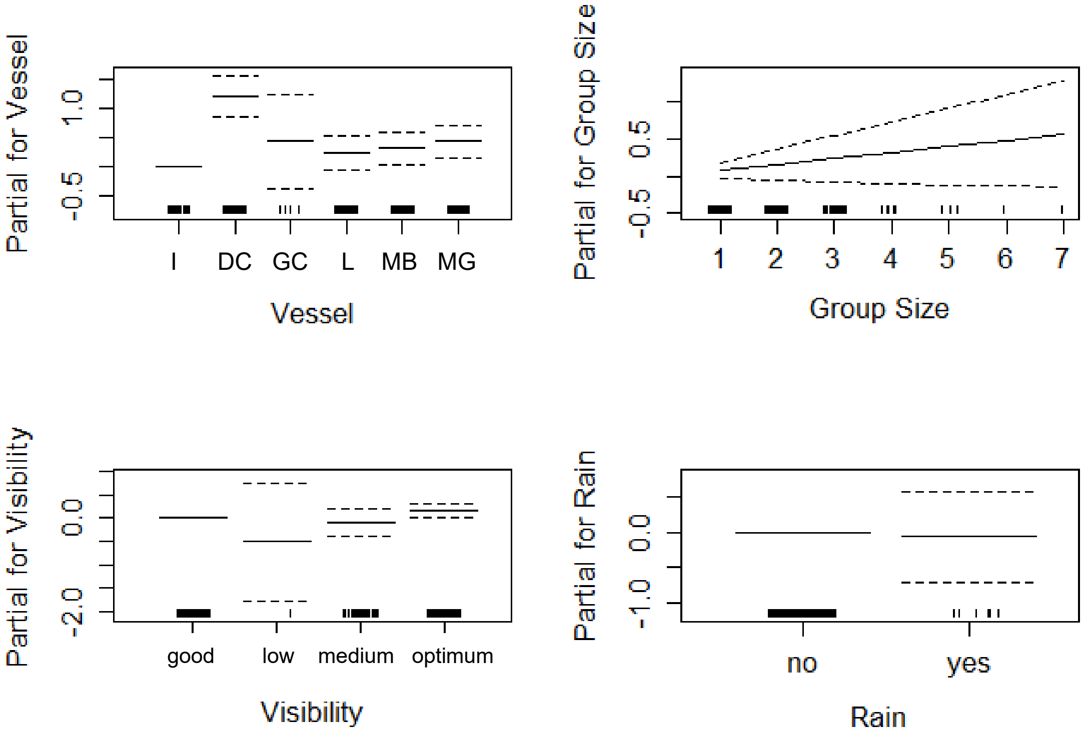


Figure 3.9. Plots of the final Generalised Additive Model (GAM) analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of baleen whale sightings. I – Insular. DC – NRP Almirante D. Carlos I. GC – NRP Almirante Gago Coutinho. L – Lagoa. MB – Monte Brasil. MG – Monte da Guia.

Lastly, for the final fitted GAM considering the TPC of beaked whale sightings, the explanatory variables included were group size, rain, and vessel, which explained 8.25% of the deviance (Table 3.9).

Table 3.9. Results from the best fitted Generalised Additive Model (GAM) analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of beaked whale sightings. DF – Degrees of Freedom. EDF – Estimated Degrees of Freedom. GCV – Generalised Cross Validation.

n = 293; Deviance explained = 8.25%; R-square = 0.0395; GCV = 0.0052788			
Variable	**DF**	**F**	**P-value**
vessel	4	3.512	0.0081
group_size	1	1.875	0.1719
rain	1	0.253	0.6155

Regarding TPC variation with group size, as in the baleen whale sightings model, the TPC slightly increases with group size, despite the increasingly wide confidence interval towards bigger groups (less data). In the presence of rain, TPC was also lower, consistent with previous TPC models. Also similar to both other models, the TPC was higher on oceanographic vessels (Figure 3.10).

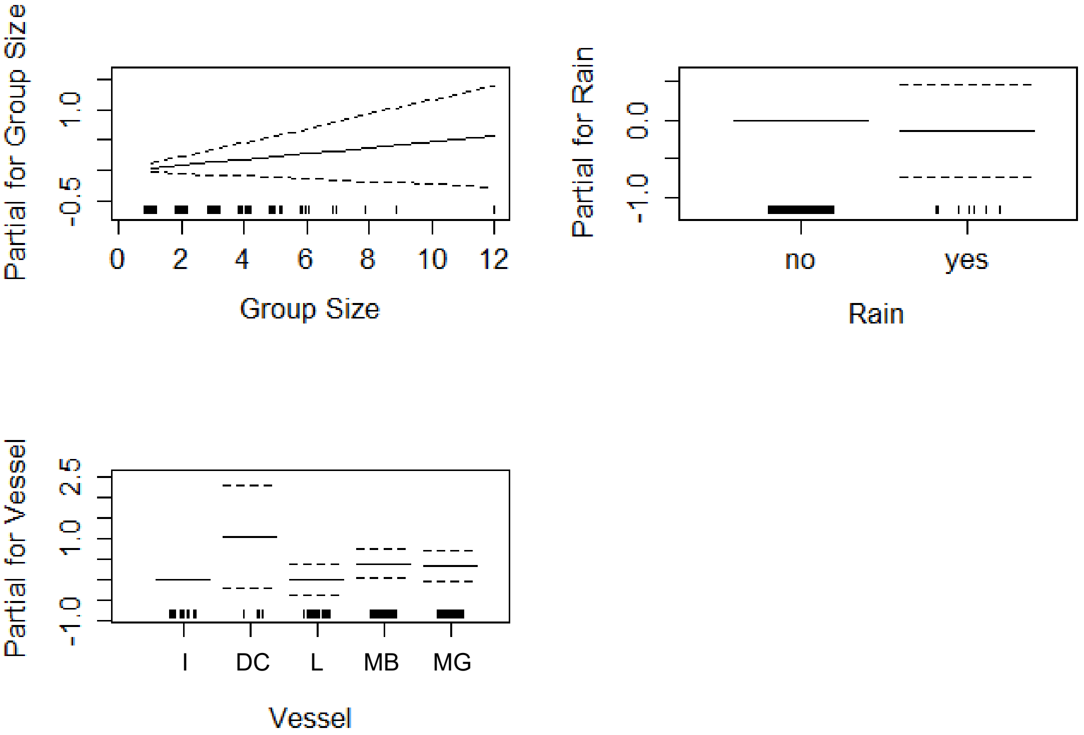


Figure 3.10. Plots of the final Generalised Additive Model (GAM) analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of beaked whale sightings. I – Insular. DC – NRP Almirante D. Carlos I. L – Lagoa. MB – Monte Brasil. MG – Monte da Guia.

4. Discussion

The results of this study highlight the strong presence of cetaceans in the ENA. With maritime traffic continuing to increase, there is a growing risk of vessel-whale collisions and, as previously mentioned, studying the occurrence and characteristics of CEs is fundamental to assess it.

4.1. Defining SEs and NMEs

Richardson *et al*. (2011) considered a distance of less than 300 meters for SEs and less than 80 meters for NMEs, for a maximum speed of 15 knots; while using the same definitions, Stack *et al*. (2013), Currie *et al*. (2014, 2017) used speeds varying between 5 and 20 knots. In another approach, David *et al*. (2022) used a maximum distance of 50 meters to consider an NME, with speeds ranging between 18 and 25 knots. In this study, the use of TPC (instead of a fixed distance) is proposed to assess collision risk, providing a more speed-sensitive approach while considering the diverse array of possible speeds. SEs were then defined as sightings with a TPC between 31.10 and 116.63 seconds, and NMEs as sightings associated with a TPC of 31.10 seconds or less (considering only sightings occurring within -90º and 90º of the vessel's heading). Furthermore, the designation of sightings occurring at the vessel's bow as LCE is also proposed here. When relying solely on distance to classify SEs or NMEs, the actual risk of the whale being struck by the vessel is not being entirely considered as it varies significantly with speed, as does the time available for either the vessel or the whale to move away from the other. Using TPC as a metric allows a more dynamic and risk-based classification of CEs, especially when vessel speed is highly variable, as is the case of this study. Furthermore, these speed-dependent thresholds represent critical measurements of the available time to take avoiding actions, as stated by Stack *et al*. (2016).

This methodology can further improve consistency when comparing CEs across different studies and vessels. Including the influence of vessel speed on the definition of these encounters is essential, as it is known that vessel speed increases the risk of vessel-whale interactions (Vanderlaan & Taggart, 2007; Conn & Silber, 2013; Ritter & Panigada, 2019). At faster speeds, the time to react and implement avoiding actions decreases significantly and the interaction's impact can be more harmful, or even lethal (Stack *et* *al.*, 2013). However, the biggest limitation associated with this methodology is the difficulty in identifying a CE at the time of its occurrence. It is therefore advisable that the necessary measures to calculate the TPC are recorded: distance to sighting and vessel speed in that instance. Then, for a timely action at-sea, a good strategy is to consider those measures and the TPC thresholds here defined (up to 116.63 seconds, or a conservative rounding such as 120 seconds) and take precautionary measures if a whale is detected within this range. Additionally, one should always account for the manoeuvrability of the vessel and realise if 2 minutes is sufficient to re-route and avoid collision. Although TPC is useful, predicting a whale's trajectory and behaviour towards an approaching vessel is challenging, which limits the ability to avoid a potential strike (Ritter & Panigada, 2019). Actually, there are documented cases of vessel-whale interactions where the animal was seen in advance (Ritter, 2010; Ritter & Panigada, 2019). This means that even if there is enough time to manoeuvre the vessel away from the whale, there are still challenges in doing so. In fact, a linear vessel's course and a fixed whale position are usually assumed, but real conditions (e.g., sea state fluctuations, movement/animal behaviour) may introduce some variability in the Vessel-to-Whale distance and consequently lead to a certain level of uncertainty in the TPC. As such, the definition of a conservative and higher TPC threshold to define CEs (based on a low vessel speed – 5 knots), as adopted in this study, is an important approach. If used as a basis to take avoiding actions, it can help alert the crew to take precautionary measures and effectively avoid incidents. In summary, mitigation measures (e.g., re-route and/or reducing speed) should be adapted to the situation and scaled to the level of risk, accounting for: type of CE (SE or NME), vessel manoeuvrability, location of the sighting (bow or abeam), and behaviour of the animals (indifferent or aware).

4.2. Descriptive and Spatial Analysis

A high percentage of sightings were classified as CEs, as the taken definition was quite broad – up to 116.63 seconds to a potential collision, ensuring that all possible CEs were included (as previously defined in the literature as less than 300 meters from the vessel, considering a very low vessel speed of 5 knots). In the bibliography, *B. physalus*, *M. novaeangliae*, *B. acutorostrata*, *P. macrocephalus*, *B. musculus,* and *B. borealis* are among the species most frequently involved in vessel-whale collisions (Dolman *et al.*, 2006; Vanderlaan & Taggart, 2007; Winkler *et al*., 2020). As such, it was to be expected that *P. macrocephalus* and *B. acutorostrata* were among the species most associated with CEs in this study. Specifically, *B. acutorostrata* is known to show much curiosity towards vessels and can sometimes appear suddenly at the bow (Perrin *et al*., 2018). This approaching behaviour can, at times, lead to alarmed reactions by either the whale or crew members, imposing a greater risk of collision.

Although most studies on vessel-whale strikes focus on great whales, beaked whales are also heavily affected, as it was possible to observe in this study (Dolman *et al*., 2006; Schoeman *et al*., 2020; Winkler *et al*., 2020; Feyrer *et al*., 2024). As these animals inhabit extremely deep oceanic waters, there may be a larger overlap with the routes in this study, where most effort was in offshore areas (Mead, 2009). Additionally, the seamounts and canyons associated with the ENA may contribute to this overlap, as beaked whales are often abundant near these features (Barlow & Gisiner, 2006; MacLeod & D'Amico, 2006). For instance, due to the significant depth of the Azores archipelago's waters, this region can be an important area for these whales (Silva *et al*., 2014). Moreover, as explained by Van Waerebeek *et al*. (2007), despite not spending much time at the surface, it is possible that their need for several breaths after long and deep dives puts these animals at greater risk of collision at that times, by inducing anaerobic physiological stress, which can diminish their avoidance skills. According to Winkler *et al*. (2020), *Z. cavirostris* is the beaked whale most frequently associated with these incidents within the Ziphiidae family, consistent with the high percentage of *Z. cavirostris* involved in CEs in this study.

In the present study, 1.98% of all sightings were classified as an NME, representing only four species. This low percentage is comparable to findings reported by Richardson *et al.* (2011), Stack *et al.* (2013) and David *et al.* (2022), despite the different employed methodologies. Even though NMEs are considered somewhat rare, they present high-risk scenarios (David *et al*., 2022). Moreover, Richardson *et al.* (2011) suggested that at least 5% of SEs may result in vessel-whale interactions. It is particularly challenging to confirm that no actual collision occurred or that these encounters did not have any harmful impact on the animal. NMEs are known to involve a greater risk of collision and can cause substantial disturbance to the whale, possibly leaving them heavily startled (Laist *et al*., 2001; David *et al*., 2022).

A large proportion of NI whales (~56.46%) were involved in CEs, suggesting that available data likely underestimates how often certain species are actually affected. This may underscore the challenges associated with monitoring and detecting cetaceans at sea, as they only spend brief moments at the surface (Ballance, 2018). Particularly, accurately identifying species becomes even more challenging in the presence of poor weather conditions, or when MMOs are less experienced (Oliveira-Rodrigues *et al.*, 2022). Additionally, baleen and beaked whales have several morphological similarities within their respective families, increasing the level of uncertainty in the moment of identification and contributing to the high frequency of NI species (Dolman *et al.*, 2006; Mead, 2009; Bannister, 2018; Oliveira-Rodrigues *et al.*, 2022). Moreover, as this study is limited to daylight hours, it is not possible to account for the sightings and CEs that occur at nighttime, highlighting the probable underestimation of these encounters, as discussed by David *et al.* 2022. The use of optical night vision and thermal infra-red imaging can mitigate this issue, as there are certain whales (e.g., right whales) that can spend more time at the surface during the night, increasing collision risk (Dolman *et al.*, 2006; Ritter & Panigada, 2019). However, both methodologies still present some restraints, such as being limited by detectability factors, such as the presence of fog and heavy rain (Verfuss *et al.*, 2016; Ritter & Panigada, 2019).

Speed is a determining factor regarding collision risk, with higher speeds associated with greater risk of impact. In this study, NMEs were observed exclusively with cargo ships, which is consistent with their larger size and typically higher operating speeds compared to oceanographic vessels. Within the NMEs, the proposed definition of a LCE represents the highest-risk scenario, as the whales emerge right at the vessel's bow. Although not confirmed, it is possible that some of these individuals may have been struck. Even in the absence of confirmed collisions, LCEs are expected to induce at least high levels of stress in whales, particularly in individuals that displayed indifferent behaviour towards the vessel (were likely not aware, at least timely, to avoid negative impacts).

Since this study occurred onboard RPs, the survey effort is heterogeneous throughout the study area and across the different routes. As a result, the highest number of NMEs records were registered along the route with greater survey effort (mainland Portugal – Madeira), in accordance with David *et al.* (2022).

In the literature, a high percentage of these events is often associated with lone individuals, rather than groups of two or more whales (Stack *et al.*, 2013; Currie *et al.*, 2017). For example, Ritter (2010) described an NME involving two whales, in which it appeared that the second whale only seemed to notice the approaching vessel when the first whale got startled. This alarmed reaction can suggest that lone whales may not always be aware of passing vessels and can benefit from social awareness in detecting potential threats (Ritter, 2010). Whales who display an apparent indifferent behaviour are also more likely to be hit, and, therefore, are more likely to be involved in CEs (Dolman *et al*., 2006; Ritter & Panigada, 2019). Behaviours such as feeding, socializing or resting, are often associated with some indifference to the whales' surroundings, which can pose a higher risk for the animals (Dolman *et al*., 2006; Ritter & Panigada, 2019). The high percentage of individuals associated with CEs, and specifically NMEs, who seemed indifferent to the vessel's passage, represent a higher risk of strike. Moreover, the nine sightings associated with an NME in which whales exhibited an avoiding behaviour towards the vessel suggest that, in those cases, the ship might have been close enough for the whales to be aware of its approach and provoked an alarming and avoiding reaction from the individuals.

Lastly, as aforementioned, the mean TPC of CEs was 62.85 seconds and approximately half of CEs had a TPC below that threshold, indicating a relatively high collision risk, with an extremely short reaction time to take avoiding actions.

4.3. Modelling

Some models must be interpreted with caution, as certain surveyed areas and years had limited monitoring effort and recorded data, resulting in wide confidence intervals. Moreover, the occurrence of CEs may be underestimated, as discussed above.

4.3.1. Modelling spatio-temporal distribution of CEs

The deviance explained of the fitted models was relatively low, suggesting that the variables included only explain a small percentage of the variability in the occurrence of CEs. It is possible that the variability in the occurrence of these encounters is mostly influenced by factors reflecting ecological variation, species/vessel characteristics, maritime traffic intensity, and is likely poorly represented by spatio-temporal variables alone. Also, correlation could have been more evident if interactions between the spatial or within the temporal variables were considered.

Overall, the models predicted a higher likelihood of CEs occurring in areas near Madeira, the coast of Mainland Portugal, and along the route connecting them, mainly towards the end of the summer (particularly for baleen whales). There was also an increasing trend in the number of CEs since 2021, in the models for all whale and beaked whale sightings.

The way whales use these areas, specifically in late summer, may influence the number of these incidents. The ENA is known for its rich cetacean diversity and for holding important areas for whales to feed, rest, and socialize (Santos, 2008; Waring *et al.*, 2009; Cunha *et al.*, 2017; Correia *et al.*, 2019; Valente *et al.*, 2019; Correia *et al.*, 2020). As such, whales involved in these key behaviours are often less responsive towards the approaching vessels, which potentially increases the risk of a CE (Dolman *et al.*, 2006). Furthermore, there are several factors that also influence the likelihood of a CE, such as species and whales' behaviour and age.

Moreover, poorer weather and visibility conditions towards the end of the summer may reduce detectability and, consequently, increase the occurrence of CEs, as the animals are first spotted closer to the vessel.

In this region, there is also a significant overlap between whales and intense marine traffic. Madeira and its surrounding waters are positioned close to several marine traffic corridors (used by cruise and cargo ships, and leisure boats), with many different destinations (North Sea, Mediterranean, Americas, North Africa and Middle East; Cunha *et al.*, 2017). Additionally, high speed vessels are particularly common in this area, contributing to a higher risk of collision (Vanderlaan & Taggart, 2007; Cunha *et al.*, 2017). Similarly, the coast of mainland Portugal is crossed by numerous fishing vessels, commercial and cruise ships, and leisure crafts, from many different ports (e.g., Mediterranean, North America, Africa and Europe), creating a high concentration of maritime traffic (Silveira *et al.*, 2012; Silveira *et al.*, 2013). The spatial overlap near these areas makes whales even more susceptible to being in the ship's path, increasing the number of CEs (Currie *et al.*, 2017; David *et al.*, 2022). Additionally, especially in areas where noise pollution levels are high (e.g., coastal areas), animals may be habituated to vessel noise or have hearing loss (temporary or permanent), contributing to decreased awareness of the approaching vessels and causing them to get too close to the ship (Laist *et al.*, 2001; Dolman *et al.*, 2006; Weilgart, 2007; Evans, 2018; Ritter & Panigada, 2019).

Also, the overall recent increase in marine traffic further enhances this overlap and poses a challenge for whales to avoid vessels routes, potentially contributing to the growing numbers of CEs (Dolman *et al.*, 2006; Ritter, 2012; Ritter & Panigada, 2019; Schoeman *et al.*, 2020; Robbins *et al.* 2022, Nisi *et al.*, 2024). Considering this extensive overlap and given the high CE probability predicted by the models, there is a very high risk of a CEs occurring in this region, which could possibly result in vessel-whale collisions.

Based on the spatial trends of CEs, the route between mainland Portugal and Madeira can be designated as a "high-risk" area, where mitigation measures should be looked into more thoroughly. Additionally, attention should also be given to coastal areas, where there is a significant overlap between cetaceans and marine traffic. These regions often face a high number of anthropogenic threats, which can cause additional stress in marine megafauna and increase their vulnerability to vessel-whale collisions (Piwetz *et al.*, 2012; Cunha *et al.*, 2017; Evans, 2018).

In conclusion, spatial-temporal variations in CEs across the sampled routes were observed. It is known that the frequency of collisions varies with seasonality and whale abundance, and a similar trend might be observed with the occurrence of CEs (Currie *et al.*, 2017). Spatial-temporal variables do not explain the occurrence of CEs, *per se*, but can highlight trends or areas with higher incidence.

4.3.2. Modelling TPC in relation to detectability factors

The deviance explained by these models was slightly higher compared to the previous models, which indicates a better explanatory power and predictability. Nevertheless, there was still a certain level of uncertainty as the deviance values were still relatively low (between 8.25% and 16.8%).

In all three models, there was a consistent pattern in the TPC across the vessels. Overall, TPC was higher in oceanographic vessels compared to cargo ships. Within the context of this study, these variations are likely associated with travelling speeds, with the oceanographic vessels operating at slower speeds, compared to the cargo ships. At slower speeds, the whale can be detected earlier, meaning a higher TPC and allowing more time to implement avoiding manoeuvres. Despite this apparent trend between vessel speed and TPC, other differences between vessels may have an influence (e.g., platform height, length, tonnage). All these characteristics can influence detectability and sightings' rates, and inherently collision risk (Laist *et al.*, 2001; Evans & Hammond, 2004; Vanderlaan & Taggart, 2007; Stack *et al.*, 2013).

The lower TPC observed in the presence of rain across all three models, can be explained by the possible reduced visibility in these conditions, which can affect cetacean detectability (Evans & Hammond, 2004; Oliveira-Rodrigues *et al.*, 2022)

In the model for all whale sightings, the sea and wind states with stable TPC values (between 2 and 4) coincide with the most commonly observed sea and wind states. On the contrary, below 2 and above 4, where the number of records was lower, the confidence intervals were very wide, compromising the ability to draw robust conclusions. Moreover, it is also to point out that above 4, in both Douglas and Beaufort scales, the effort is off and so there are less sightings associated with higher values of sea and wind states. Accordingly, other authors have pointed out that higher sea and wind states are associated with lower cetaceans' detectability (which leads to reduced capacity to monitor and track whales), and consequently with CEs of higher risk (Evans & Hammond, 2004; Richardson *et al.*, 2011; Stack *et al.*, 2016; Oliveira-Rodrigues *et al.*, 2022). Consequently, lower detectability can possibly decrease TPC and, consequently, the time to manoeuvre (Richardson *et al.*, 2011; Stack *et al.*, 2016). A possible solution to complement visual monitoring surveys when the weather conditions are poor, can be the use of acoustic techniques, which are less dependent on weather conditions and can operate through day and nighttime. On the other hand, these detection methodologies are dependent on vocalising whales (Gordon & Tyack, 2002; Evans & Hammond, 2004).

In the baleen and beaked whale sightings models, although the wide confidence intervals present in the variation of TPC with group size prevent robust conclusions, it is known that with fewer individuals it is harder to detect the cetacean group, especially when considering elusive species (such as beaked whales; Evans & Hammond, 2004; Oliveira-Rodrigues *et al.*, 2022). In these situations, the MMOs may only sight the whales when they are already close to the vessel, leaving less time to move away from them.

Finally, the increase of TPC with visibility, in the model considering baleen whale sightings, is consistent with previous observations. With optimum visibility, the animal can be detected earlier and at greater distances, contributing to a higher TPC.

Overall, the models behaved similarly across the different groups, with no notable differences.

In the future, variables related to the whales themselves (such as species and behaviour towards the vessel), other vessels' characteristics instead of the vessel itself (including size, average speed, height, width, tonnage, and distance to the bow), and sightings' angle should be considered, as these can also influence whether cetaceans are detected earlier or later.

Lastly, the inclusion of MMOs experience should also be considered, as it is known that experience of the dedicated observers onboard can influence their ability to spot and detect cetaceans early, and consequently influence TPC (Evans & Hammond, 2004; Oliveira-Rodrigues *et al*., 2022). As previously mentioned, MMOs consist of a real-time mitigation measure, as they can improve detection rates and possibly help to reduce collision risk (Dolman *et al*., 2006; Todd, *et al*., 2015; Weinrich *et al*., 2010). As such, the employment of trained MMOs should be established in mandatory guidelines, particularly onboard large vessels that travel at high speeds, where collision-risk is very high. However, MMOs efficiency depends on daylight and decreases with fatigue, and in the presence of poor weather conditions, detecting cetaceans becomes even more challenging (Oliveira-Rodrigues *et al*., 2022). Automatic detection systems, such as thermal infrared imaging devices, serve as complementary techniques to MMOs and can increase detectability (IWC, 2011; Verfuss *et al*., 2016; Horton *et al*., 2017; Zitterbart *et al*., 2020; Baille & Zitterbart, 2022). These devices have proved to be effective in detecting whales' blows in Atlantic waters, contributing to an earlier detection rate (IWC, 2011). Consequently, this can contribute to an overall higher TPC and provide more time to take on avoiding manoeuvres. Within the scope of the AWD, to which this work contributes, there has been progress in the employment of thermal cameras onboard ferries and cargo ships, along with the MMOs, to assess and prevent collision risk in real-time. Nonetheless, as previously mentioned, these methodologies are costly and still present some limitations, such as the generation of large datasets, malfunctions, occasional inaccuracies, and challenges associated with automatic detections and alert systems (Horton *et al*., 2017; Baille & Zitterbart, 2022). Whether these methodologies can function as an effective mitigation measure depends on certain parameters, such as vessel speed and manoeuvrability and the accuracy of the detection system (Baille & Zitterbart, 2022). The optimisation and validation of these methods, as well as the correction of errors and malfunctions associated with them, continues to require the presence of MMOs onboard, hence their significance (Baille & Zitterbart, 2022).

5. Conclusion

This study aimed to define and characterise SEs and NMEs between whales and maritime traffic, using visual occurrence data collected onboard RPs in the ENA.

The results confirmed the occurrence of SEs and NMEs within the ENA, highlighting a serious risk of vessel strike to the whales. However, as this study had heterogeneous monitoring effort throughout the study area and seasons (mostly concentrated in summer months), and observations were limited to daylight hours, the number of SEs and NMEs reported here is likely very underestimated, meaning that the threat may be even more significant.

This work highlights the importance of RPs to perform continuous cetacean monitoring over a long period of time. Despite its limitations (e.g., no control over the route), the use of RPs proves to be vital to enable extensive and representative coverage of offshore areas. This way, it is possible to detect trends and strengthen the collection of data regarding CEs over time. This study also emphasises the relevance of qualified MMOs onboard, as they provide essential information on species identification, behaviour and group size. Furthermore, dedicated observers can alert crew members about collision risk (ideally avoiding these incidents when onboard), report data on CEs and collisions, and outreach to sea-users about this issue. Without MMOs, many more CEs and collisions would likely go unnoticed.

A definition of CEs based on the TPC, rather than distance, is proposed, providing a more speed-sensitive approach to assess collision risk. Standardizing SE and NME quantification remains a challenge, but continuous and prevalent efforts represent considerable progress.

The descriptive results in this thesis confirm the influence of whale's behaviour and group size on the occurrence of CEs. Whales that are feeding or socializing can show a higher level of unawareness towards the vessel (apparent indifferent behaviour), putting them at a greater risk. As both baleen and beaked whales were equally involved in CEs, equal attention should be given to these groups.

Despite the low deviance explained by the models, they were still useful for inferring spatio-temporal trends of CEs and the influence of detectability-related variables on TPC (e.g., vessel type, group size, and weather conditions). In this study, CEs were more likely to occur in the areas near Madeira and mainland Portugal. There was also an increasing trend in the number of CEs since 2021 (particularly for beaked whales), and a higher incidence of CEs in late summer (involving baleen whales). Moreover, conditions that decrease detectability negatively impacted TPC, with poorer conditions leading to lower values of TPC. As CEs act as proxies for vessel-whale strikes, predictions based on them can also provide valuable insights regarding collision risk.

This thesis acknowledges the importance of the already imposed mitigation measures to reduce vessel-whale collision risk. Re-routing vessel courses away from high-density whales areas should be the first approach, in order to reduce the occurrence of these interactions. However, when that is not possible (e.g., when whales are spread over a large area), speed restrictions and the use of MMOs onboard can be useful and effective. Despite some limitations, MMOs are a very powerful tool, possibly the most effective so far, to mitigate vessel-whale collisions worldwide. Furthermore, education campaigns should be the first step to raise awareness of this anthropogenic pressure. Specifically, the training of mariners can be particularly relevant, which may foster collaboration and willingness to adjust course in the presence of whales. When MMOs are unavailable (e.g., in winter months), trained mariners could also aid in data collection. To achieve this, close cooperation and communication between biologists, policymakers and the maritime community needs to be implemented.

In conclusion, continuous monitoring of whales' patterns and ecology as well as vessel's distribution is vital to accurately quantify SEs and NMEs, and consequently collision risk. This study contributes to ongoing conservation efforts by providing valuable insights to management and mitigation strategies, ultimately contributing to a safer coexistence between marine fauna and maritime traffic.

6. References

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7. Appendix

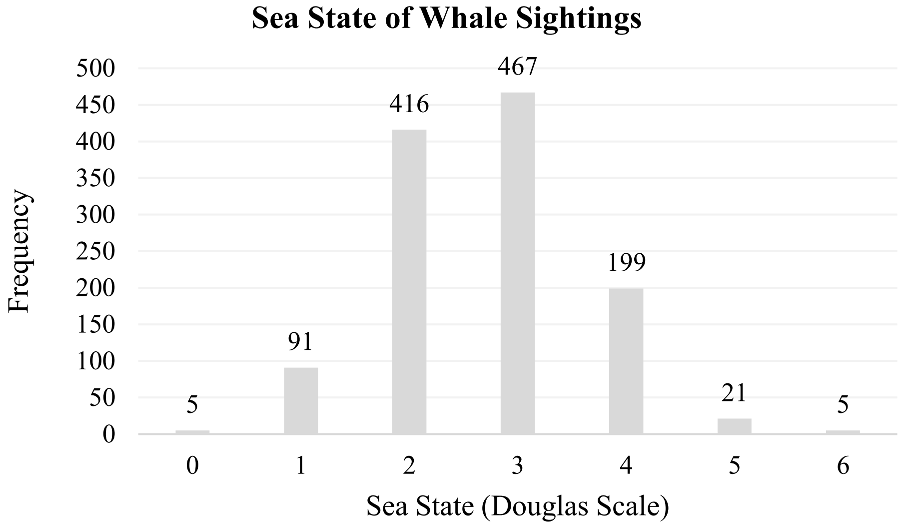


Figure A1. Histogram representing the distribution of Sea State across all whale sightings, recorded during cetacean monitoring surveys conducted between 2012 and 2024 in the Eastern North Atlantic, using cargo ships and oceanographic vessels as Research Platforms.

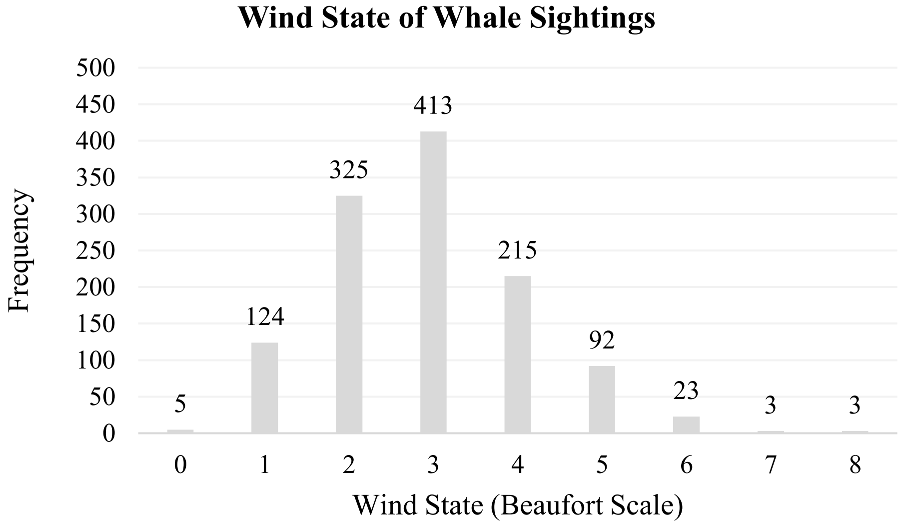


Figure A2. Histogram representing the distribution of Wind State across all whale sightings, recorded during cetacean monitoring surveys conducted between 2012 and 2024 in the Eastern North Atlantic, using cargo ships and oceanographic vessels as Research Platforms.

Table A1. Summary of whale sightings, Close Encounters (CEs), Surprise Encounters (SEs), Near-Miss Events (NMEs) and Likely Collision Events (LCEs) recorded during cetacean monitoring surveys conducted between 2012 and 2024 in the Eastern North Atlantic, using cargo ships and oceanographic vessels as Research Platforms. NI – non-identified.

Taxa	**Whale sightings**		**CEs**		**SEs**		**NMEs**		
	Frequency	**% (in relation to all sightings)**	**Frequency**	**% (in relation to the total of CEs)**	**Frequency**	**% (in relation to the total of SEs)**	**Frequency**	**% (in relation to the total of NMEs)**	**LCEs**
Balaenoptera acutorostrata	97	8.01	42	9.19	39	9.01	3	12.50	2
Balaenoptera borealis	8	0.66	3	0.66	3	0.69	0	0	0
Balaenoptera edeni	6	0.50	2	0.44	2	0.46	0	0	0
Balaenoptera musculus	3	0.25	1	0.22	1	0.23	0	0	0
Balaenoptera physalus	57	4.71	19	4.16	17	3.93	2	8.33	1
Megaptera novaeangliae	9	0.74	0	0	0	0	0	0	0
Mysticeti NI	474	39.14	130	28.45	125	28.87	5	20.83	1
Mysticeti	**654**	**54.01**	**197**	**43.11**	**187**	**43.19**	**10**	**41.67**	**4**
Mesoplodon bidens	3	0.25	1	0.22	1	0.23	0	0	0
Mesoplodon densirostris	8	0.66	6	1.31	5	1.15	1	4.17	1

Mesoplodon europaeus	9	0.74	7	1.53	7	1.62	0	0	0
Ziphius cavirostris	93	7.68	55	12.04	48	11.09	7	29.17	2
Ziphiidae NI	217	17.92	128	28.01	122	28.18	6	25.00	0
Ziphiidae	**330**	**27.25**	**197**	**43.11**	**183**	**42.26**	**14**	**58.33**	**3**
Physeter macrocephalus	227	18.74	63	13.79	63	14.55	0	0	0
Physeteridae	**227**	**18.74**	**63**	**13.79**	**63**	**14.55**	**0**	**0**	**0**
TOTAL	**1211**		**457**		**433**		**24**		**7**

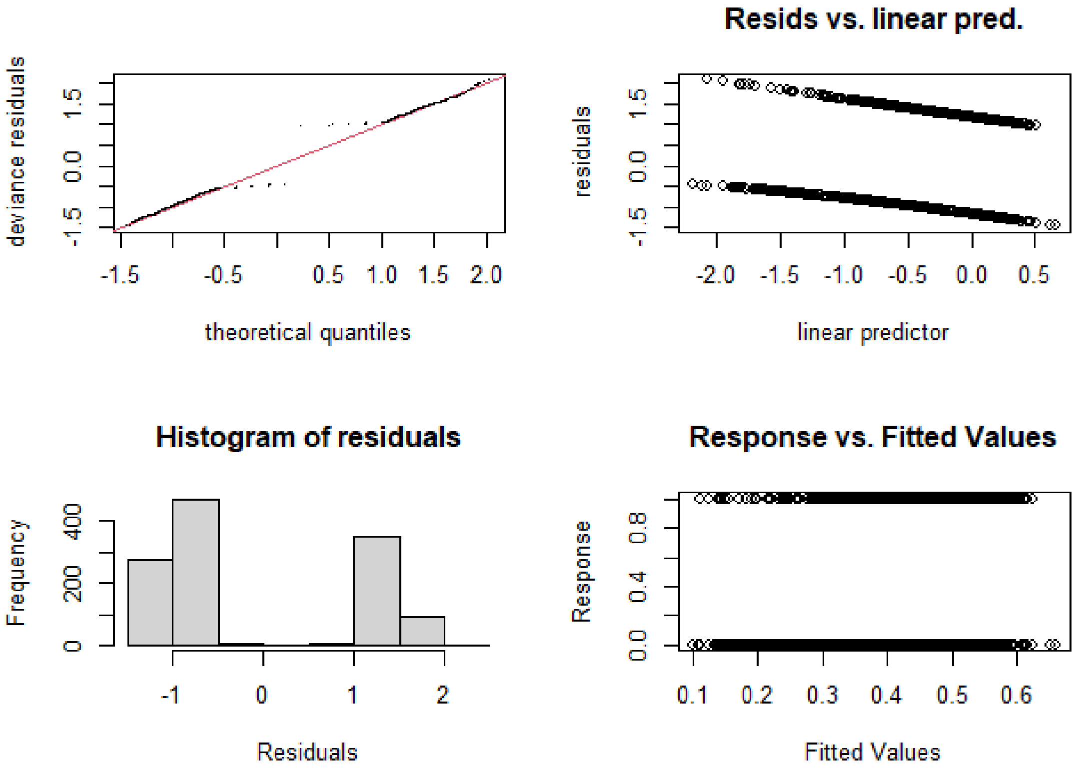


Figure A3. Generalised Additive Model (GAM) Check Plots of the model analysing the spatio-temporal patterns of Close Encounters (CEs) across all whale sightings.

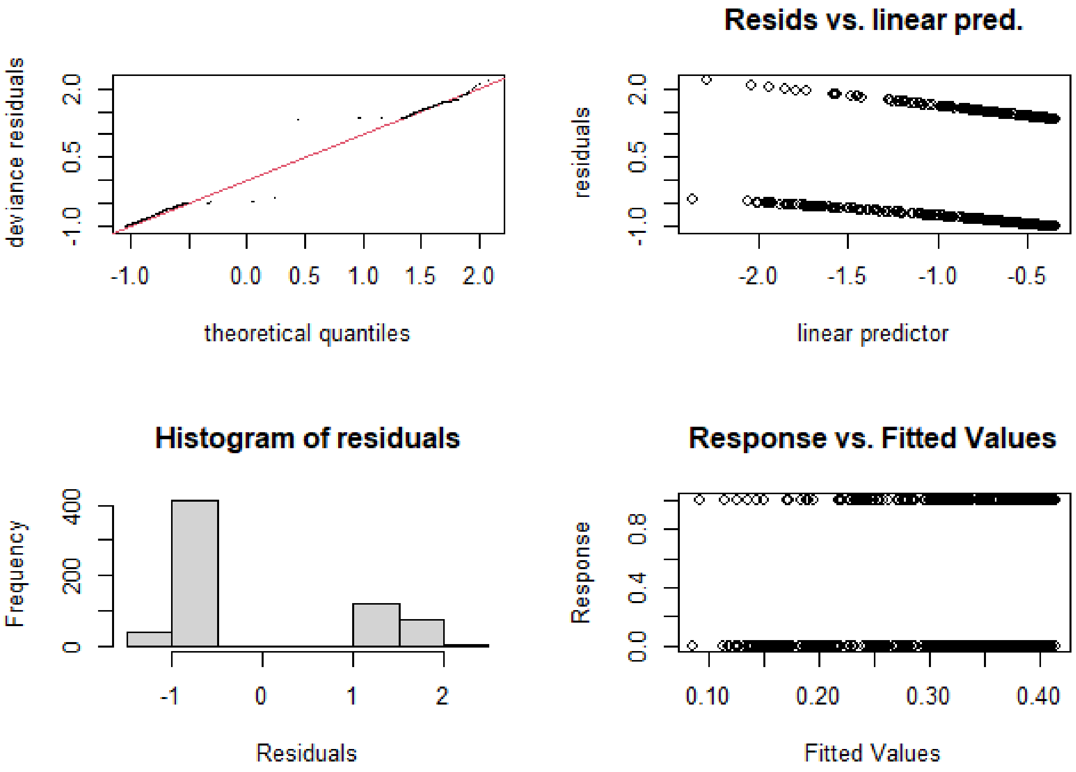


Figure A4. Generalised Additive Model (GAM) Check Plots of the model analysing the spatio-temporal patterns of Close Encounters (CEs) across baleen whale sightings.

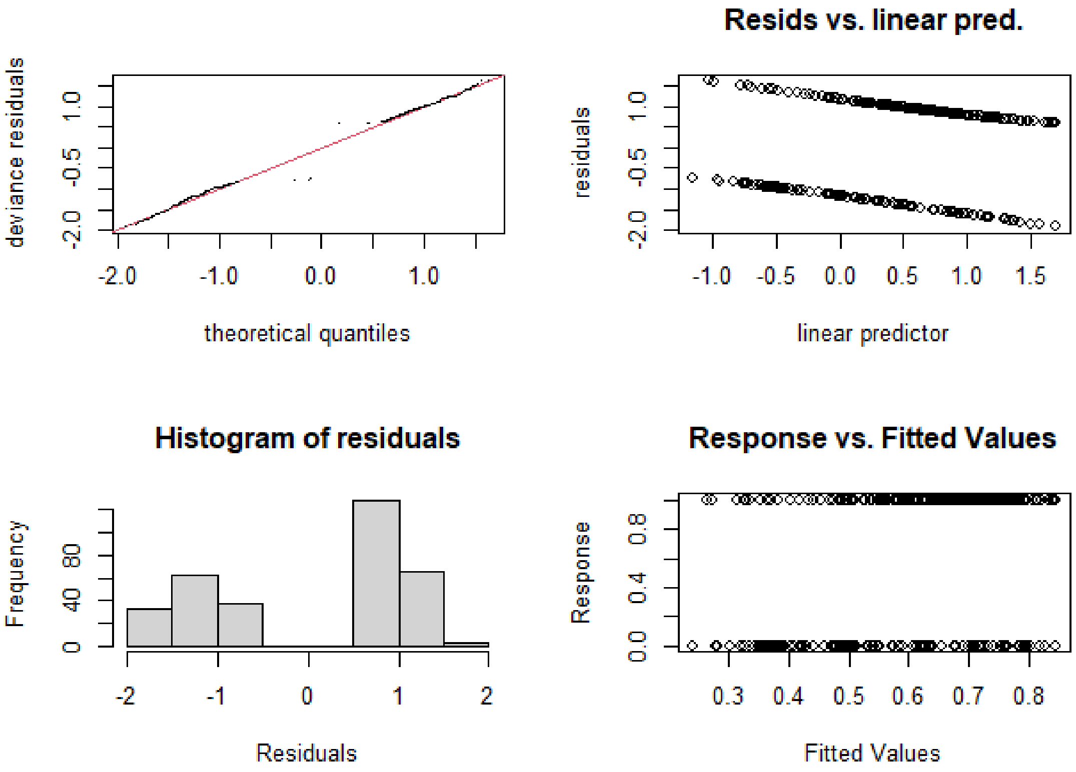


Figure A5. Generalised Additive Model (GAM) Check Plots of the model analysing the spatio-temporal patterns of Close Encounters (CEs) across beaked whale sightings.

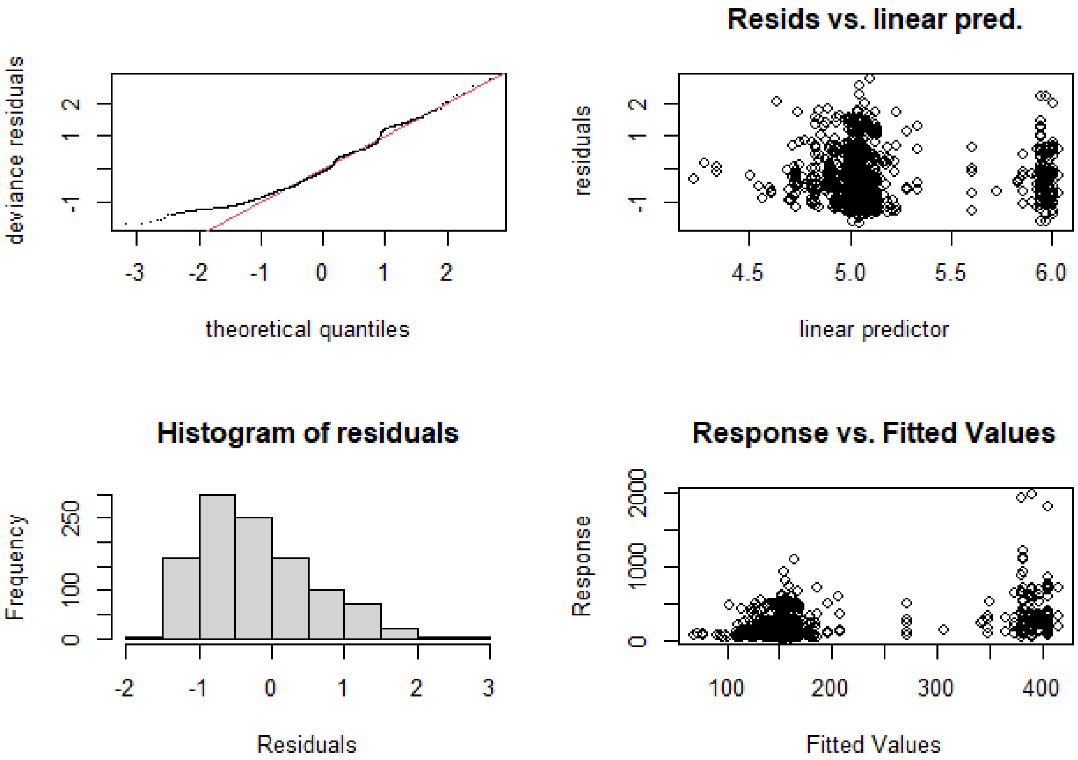


Figure A6. Generalised Additive Model (GAM) Check Plots of the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of all whale sightings.

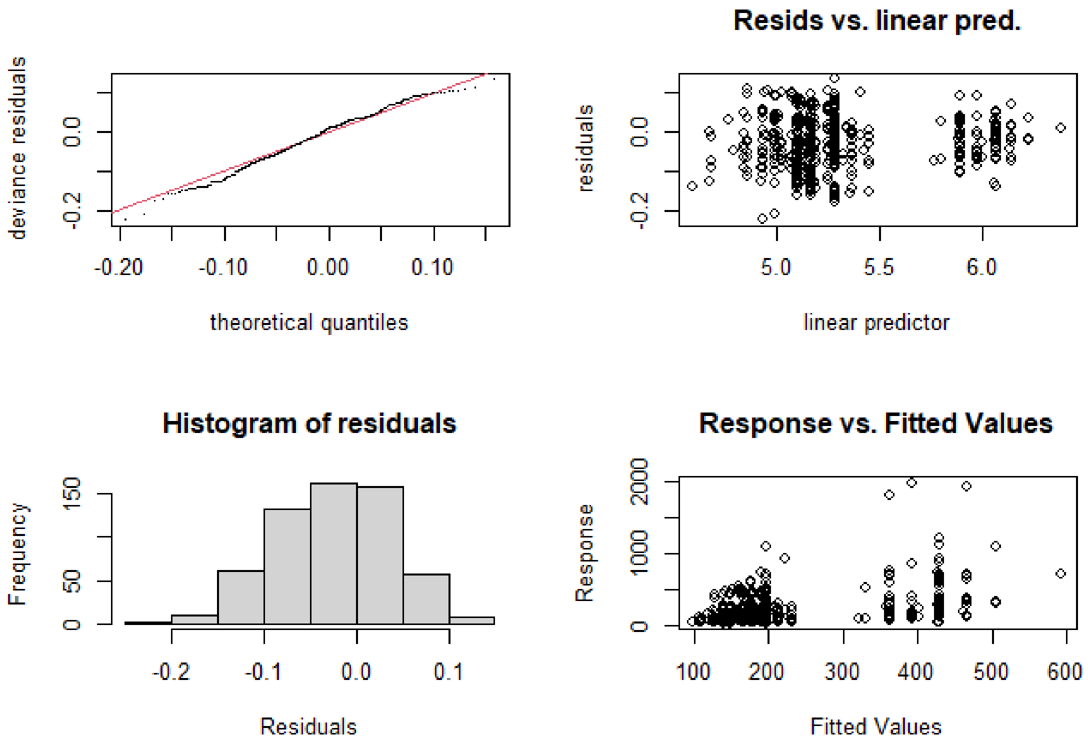
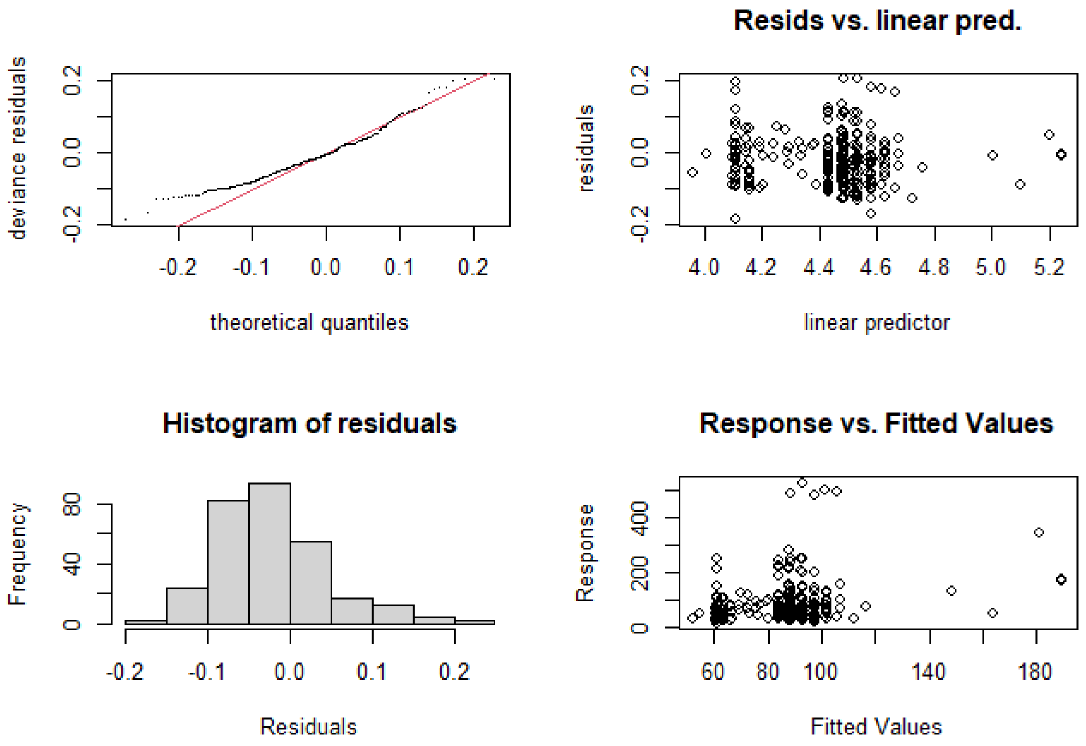


Figure A7. Generalised Additive Model (GAM) Check Plots of the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of baleen whale sightings.


Resids vs. linear pred.

Histogram of residuals

Response vs. Fitted Values

Figure A8. Generalised Additive Model (GAM) Check Plots of the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of beaked whale sightings.

Table A2. Results of basis dimension (k) checking (with gam.check) of the model analysing the spatio-temporal patterns of Close Encounters (CEs) across all whale sightings. EDF – Estimated Degrees of Freedom. Lat – Latitude.

Variable	K’	EDF	K-index	P-value
s(year)	3.00	2.92	0.76	<2e-16
s(lat)	3.00	2.89	0.99	0.42
s(day)	3.00	1.61	0.88	<2e-16

Table A3. Results of basis dimension (k) checking (with gam.check) of the model analysing the spatio-temporal patterns of Close Encounters (CEs) across baleen whale sightings. EDF – Estimated Degrees of Freedom. Lon – Longitude.

Variable	K’	EDF	K-index	P-value
s(lon)	3.00	1.80	0.93	0.08
s(day)	3.00	2.04	0.94	0.10

Table A4. Results of basis dimension (k) checking (with gam.check) of the model analysing the spatio-temporal patterns of Close Encounters (CEs) across beaked whale sightings. EDF – Estimated Degrees of Freedom. Lat – Latitude.

Variable	K'	EDF	K-index	P-value
s(year)	3.00	2.93	0.59	<2e-16
s(lat)	3.00	2.49	1.01	0.6

Table A5. Results of basis dimension (k) checking (with gam.check) of the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of all whale sightings. EDF – Estimated Degrees of Freedom.

Variable	K'	EDF	K-index	P-value
s(sea_state)	3.00	2.28	0.86	0.01
s(wind_state)	3.00	2.30	0.88	0.03

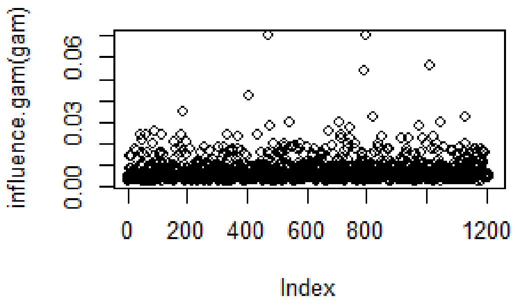


Figure A9. Generalised Additive Model (GAM) influence plot of the model analysing the spatio-temporal patterns of Close Encounters (CEs) across all whale sightings.

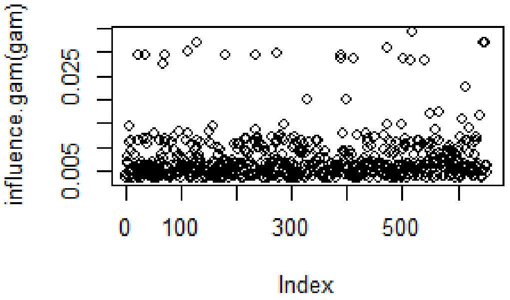


Figure A10. Generalised Additive Model (GAM) influence plot of the model analysing the spatio-temporal patterns of Close Encounters (CEs) across baleen whale sightings.

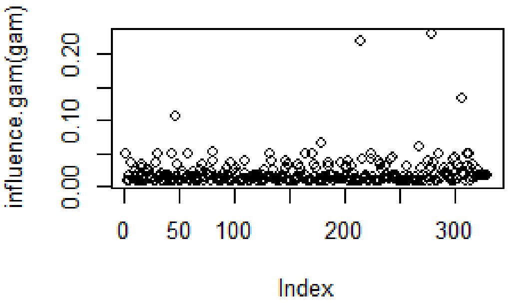


Figure A11. Generalised Additive Model (GAM) influence plot of the model analysing the spatio-temporal patterns of Close Encounters (CEs) across beaked whale sightings.

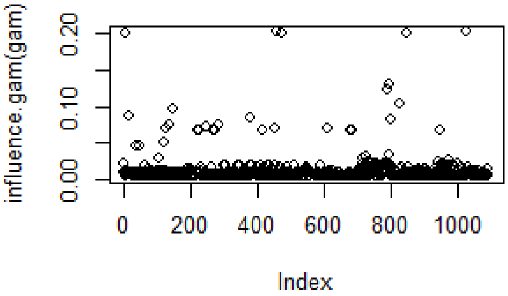


Figure A12. Generalised Additive Model (GAM) influence plot of the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of all whale sightings.

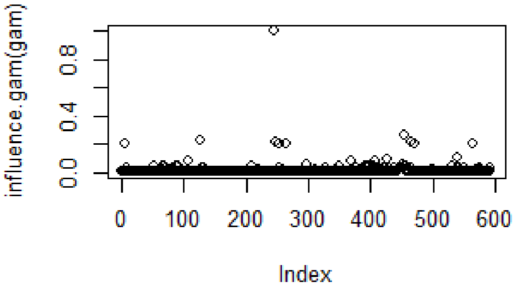


Figure A13. Generalised Additive Model (GAM) influence plot of the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of baleen whale sightings.

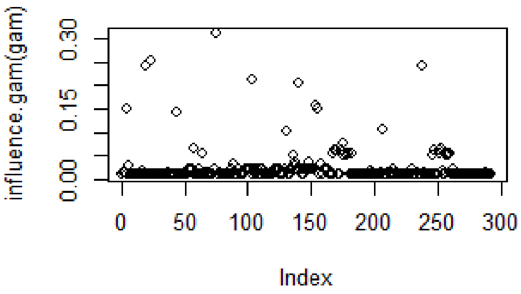


Figure A14. Generalised Additive Model (GAM) influence plot of the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of beaked whale sightings.

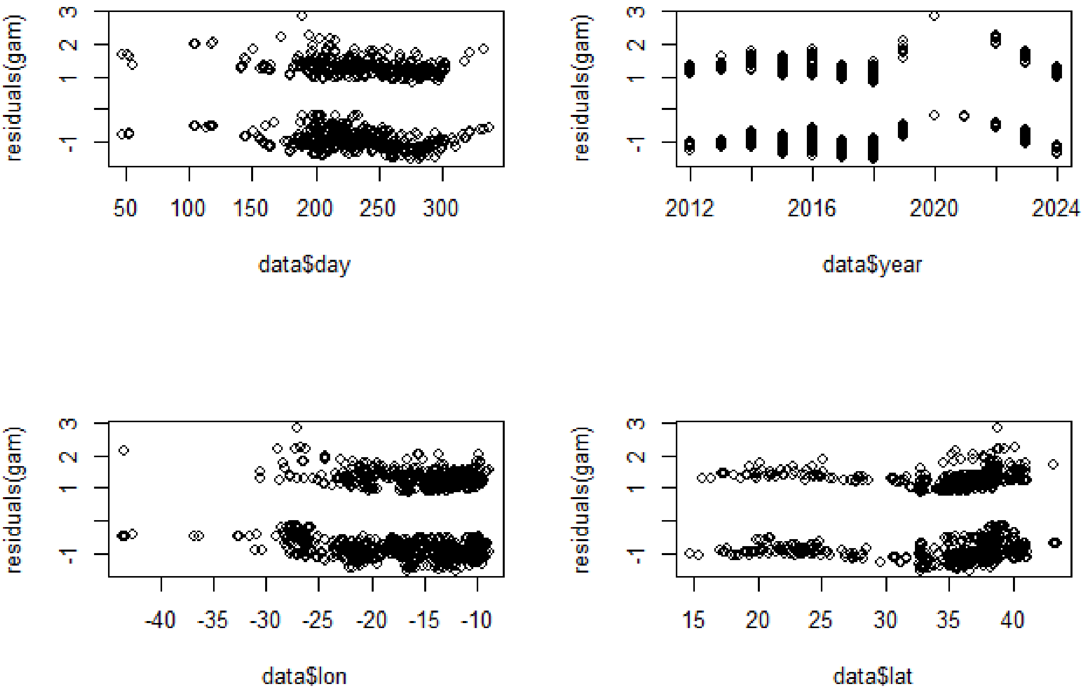


Figure A15. Residuals plots of the explanatory variables included in the Generalised Additive Model (GAM) analysing the spatio-temporal patterns of Close Encounters (CEs) across all whale sightings. Lat – Latitude. Lon – Longitude.

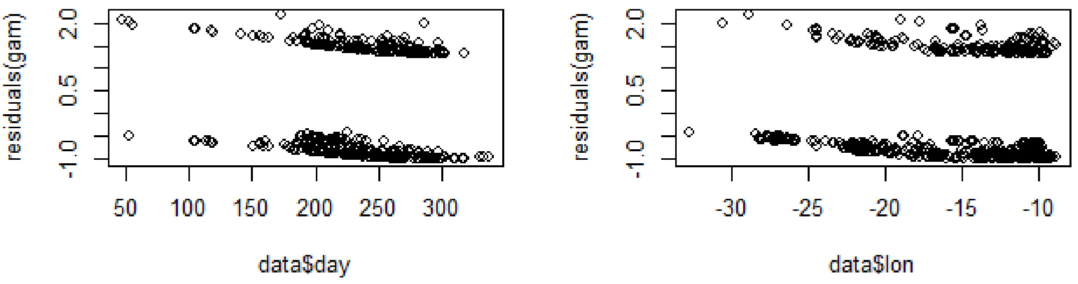


Figure A16. Residuals plots of the explanatory variables included in the Generalised Additive Model (GAM) analysing the spatio-temporal patterns of Close Encounters (CEs) across baleen whale sightings. Lon – Longitude.

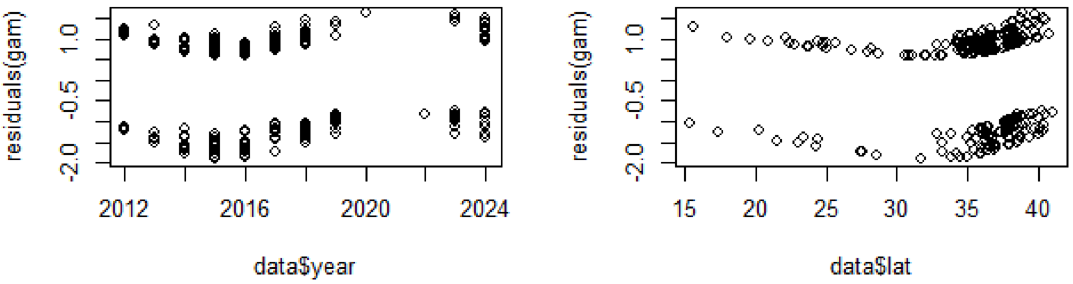


Figure A17. Residuals plots of the explanatory variables included in the Generalised Additive Model (GAM) analysing the spatio-temporal patterns of Close Encounters (CEs) across beaked whale sightings. Lat – Latitude.

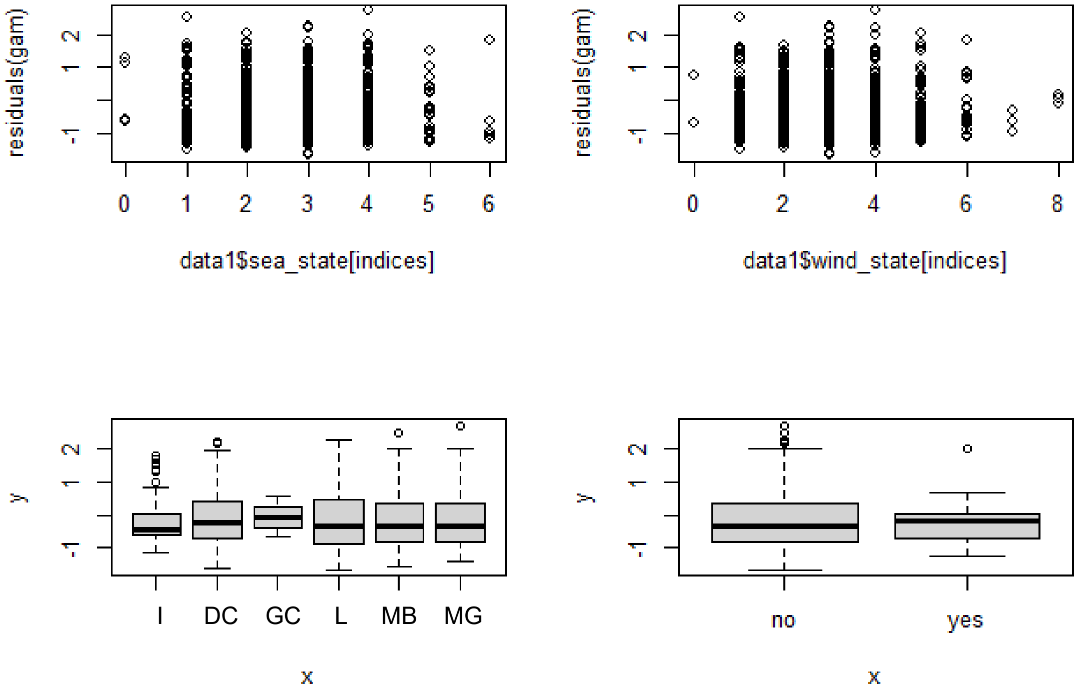


Figure A18. Residuals plots of the explanatory variables included in the Generalised Additive Model (GAM) developed evaluate the influence of detectability-related variables on Time to Potential Collision (TPC) of all whale sightings. I – Insular. DC – NRP Almirante D. Carlos I. GC – NRP Almirante Gago Coutinho. L – Lagoa. MB – Monte Brasil. MG – Monte da Guia.

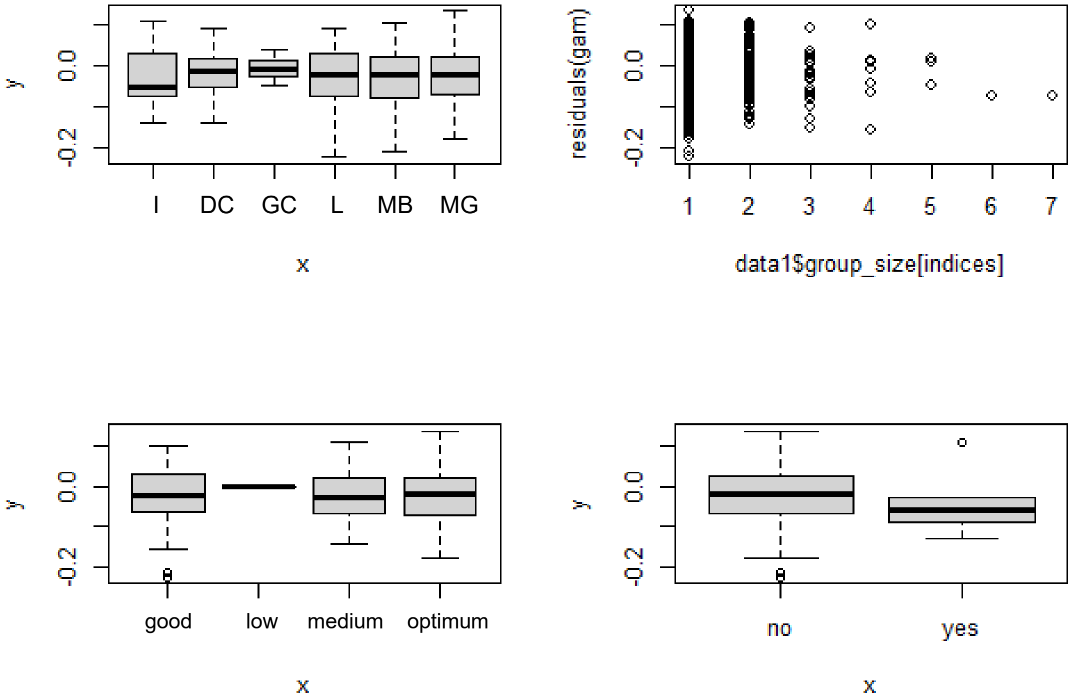


Figure A19. Residuals plots of the explanatory variables included in the Generalised Additive Model (GAM) developed evaluate the influence of detectability-related variables on Time to Potential Collision (TPC) of baleen whale sightings. I – Insular. DC – NRP Almirante D. Carlos I. GC – NRP Almirante Gago Coutinho. L – Lagoa. MB – Monte Brasil. MG – Monte da Guia.

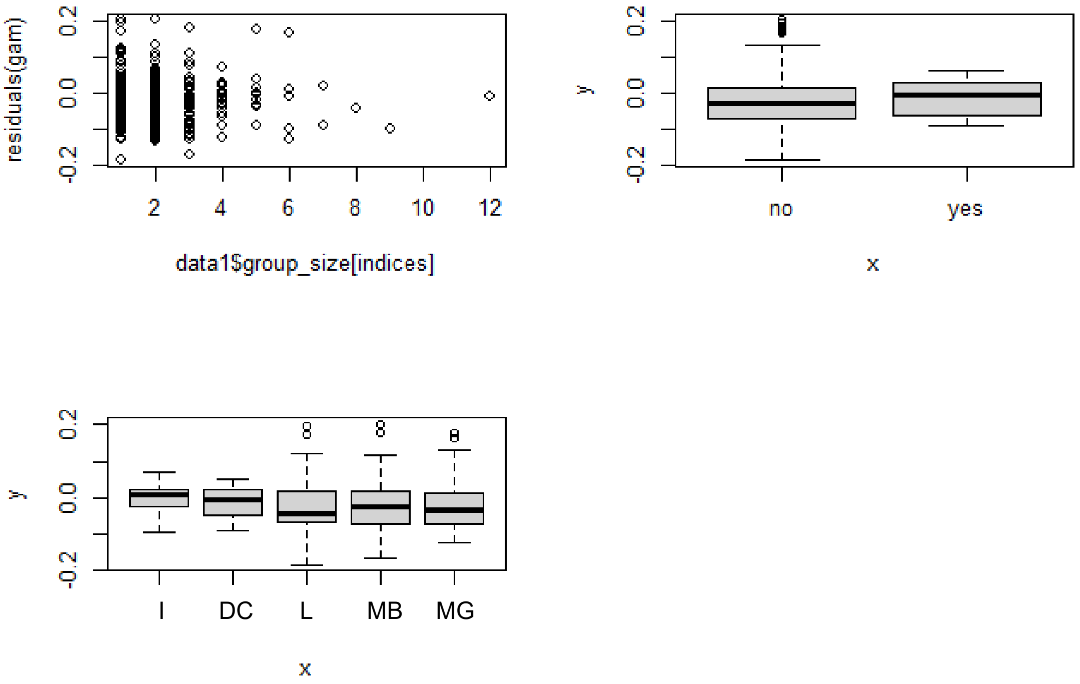


Figure A20. Residuals plots of the explanatory variables included in the Generalised Additive Model (GAM) analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of beaked whale sightings. I – Insular. DC – NRP Almirante D. Carlos I. L – Lagoa. MB – Monte Brasil. MG – Monte da Guia.

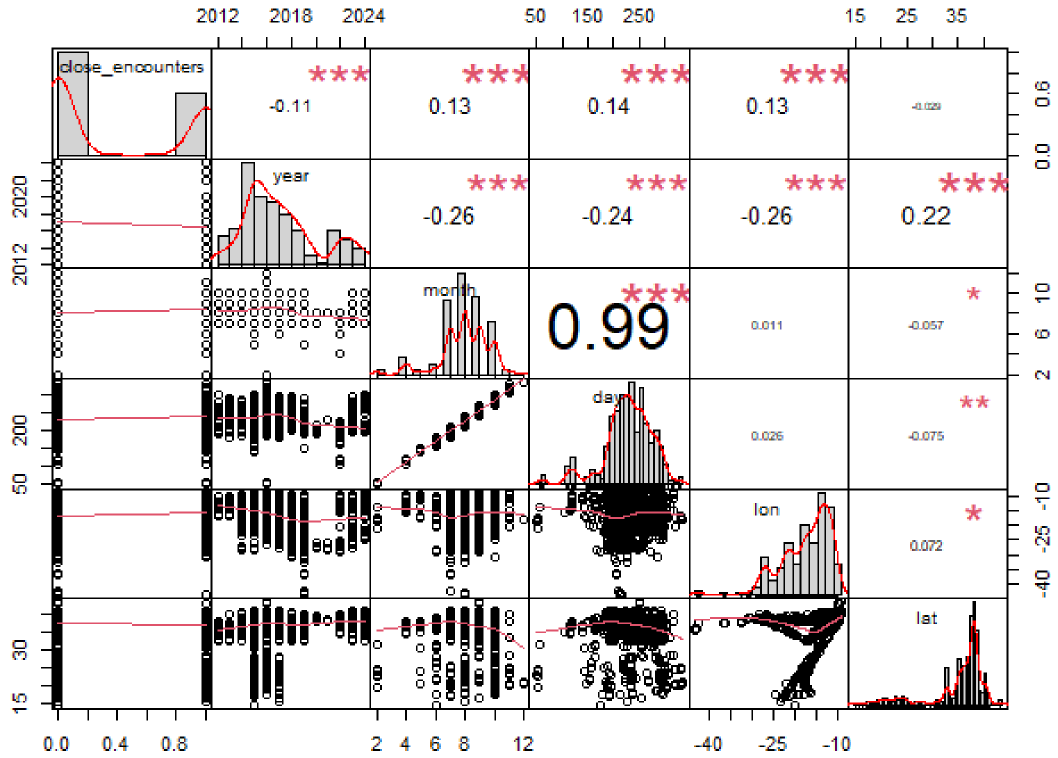


Figure A21. Correlation Matrix. Results of Pearson correlations between all pairs of explanatory variables included in the model analysing the spatio-temporal patterns of Close Encounters (CEs) across all whale sightings. Lat – Latitude. Lon – Longitude.

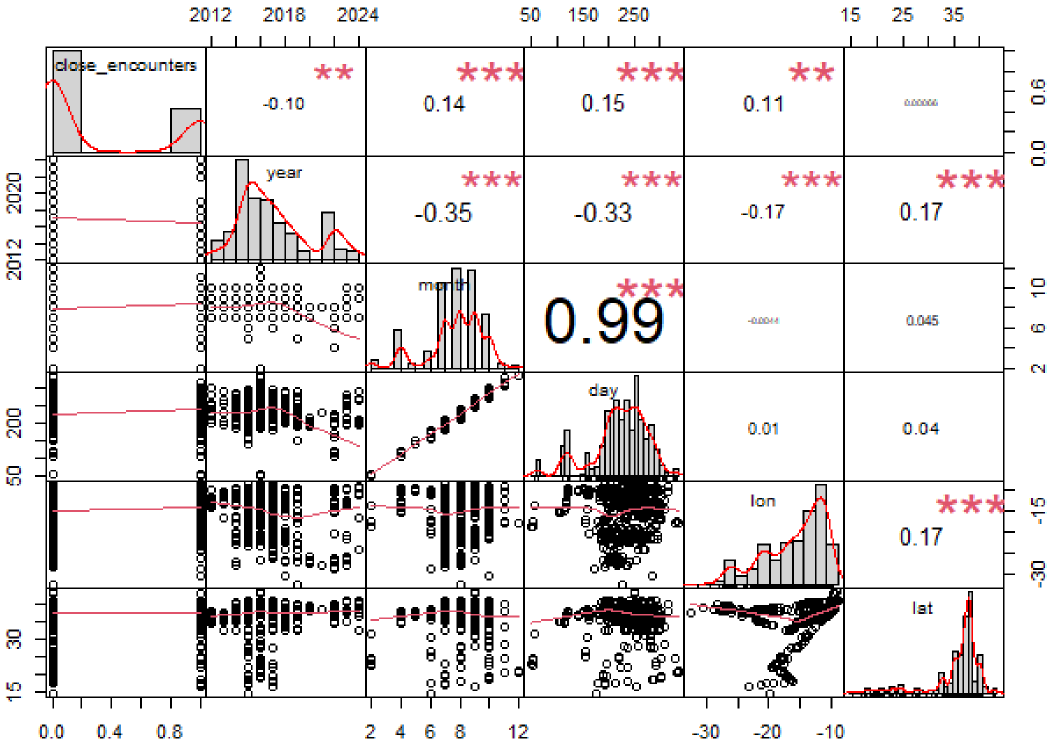


Figure A22. Correlation Matrix. Results of Pearson correlations between all pairs of explanatory variables included in the model analysing the spatio-temporal patterns of Close Encounters (CEs) across baleen whale sightings. Lat – Latitude. Lon – Longitude.

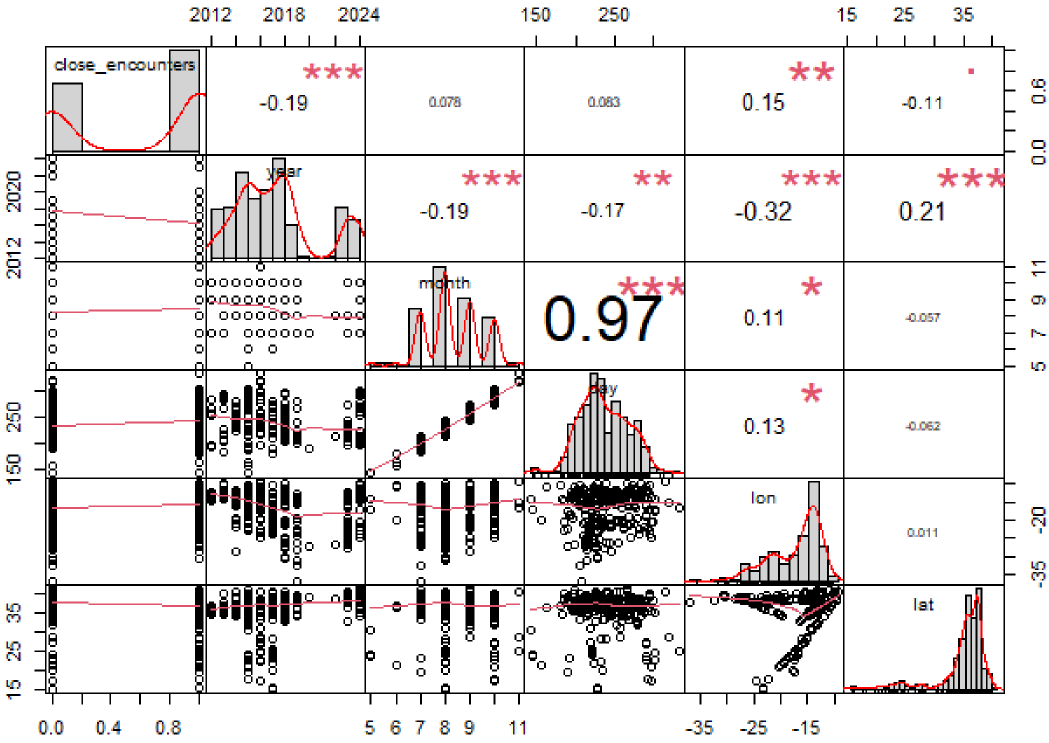


Figure A23. Correlation Matrix. Results of Pearson correlations between all pairs of explanatory variables included in the model analysing the spatio-temporal patterns of Close Encounters (CEs) across beaked whale sightings. Lat – Latitude. Lon – Longitude.

Table A6. Variance Inflation Factor (VIF) results of explanatory variables of the model analysing the spatio-temporal patterns of Close Encounters (CEs) across all whale sightings.

Year	Longitude	Latitude
1.141600	1.090827	1.071900

Table A7. Variance Inflation Factor (VIF) results of explanatory variables of the model analysing the spatio-temporal patterns of Close Encounters (CEs) across baleen whale sightings.

Year	Longitude	Latitude
1.075643	1.072468	1.074213

Table A8. Variance Inflation Factor (VIF) results of explanatory variables of the model analysing the spatio-temporal patterns of Close Encounters (CEs) across beaked whale sightings.

Year	Longitude	Latitude
1.175863	1.122705	1.055289

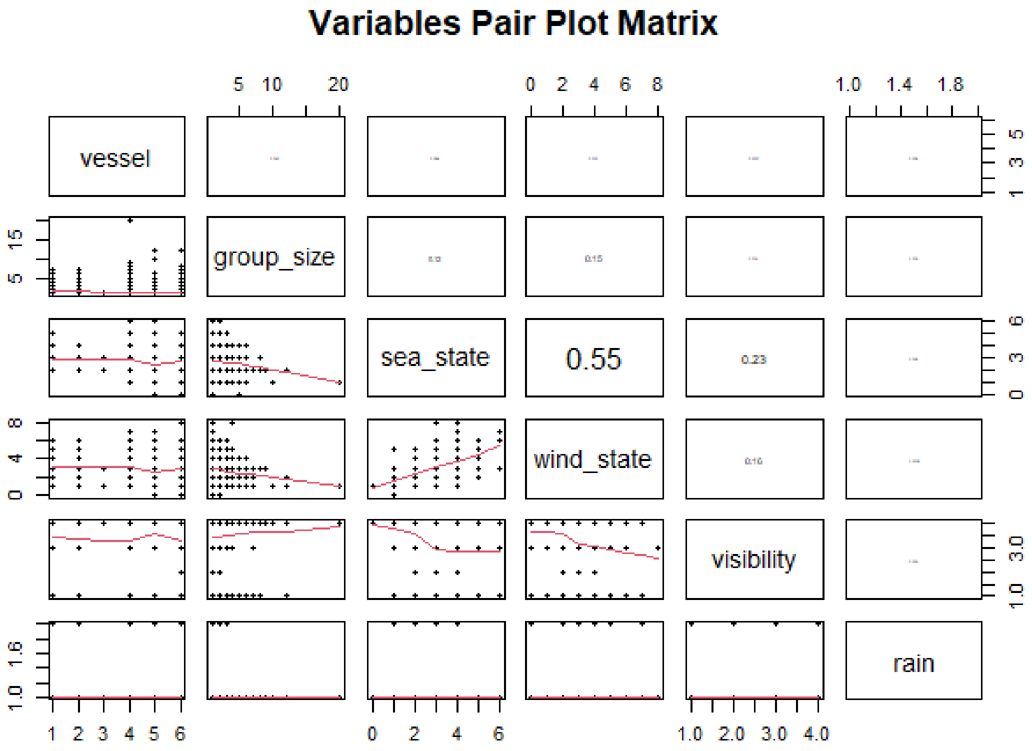


Figure A24. Correlation Matrix. Results of Pearson correlations between all pairs of explanatory variables included in the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of all whale sightings.

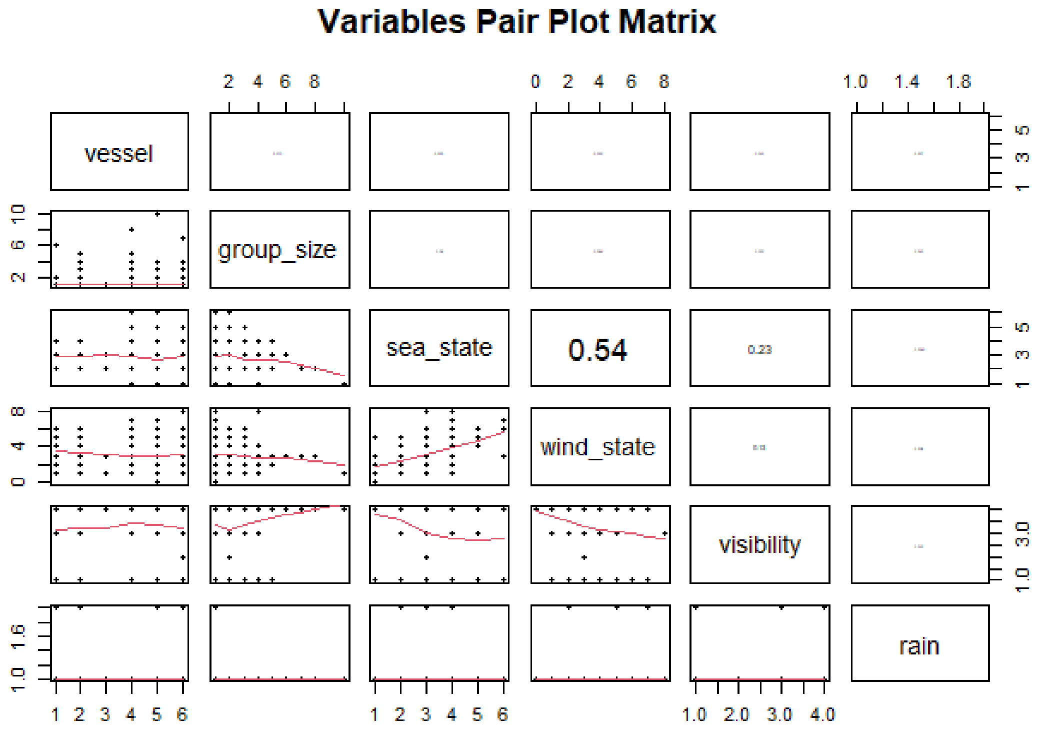


Figure A25. Correlation Matrix. Results of Pearson correlations between all pairs of explanatory variables included in the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of baleen whale sightings.

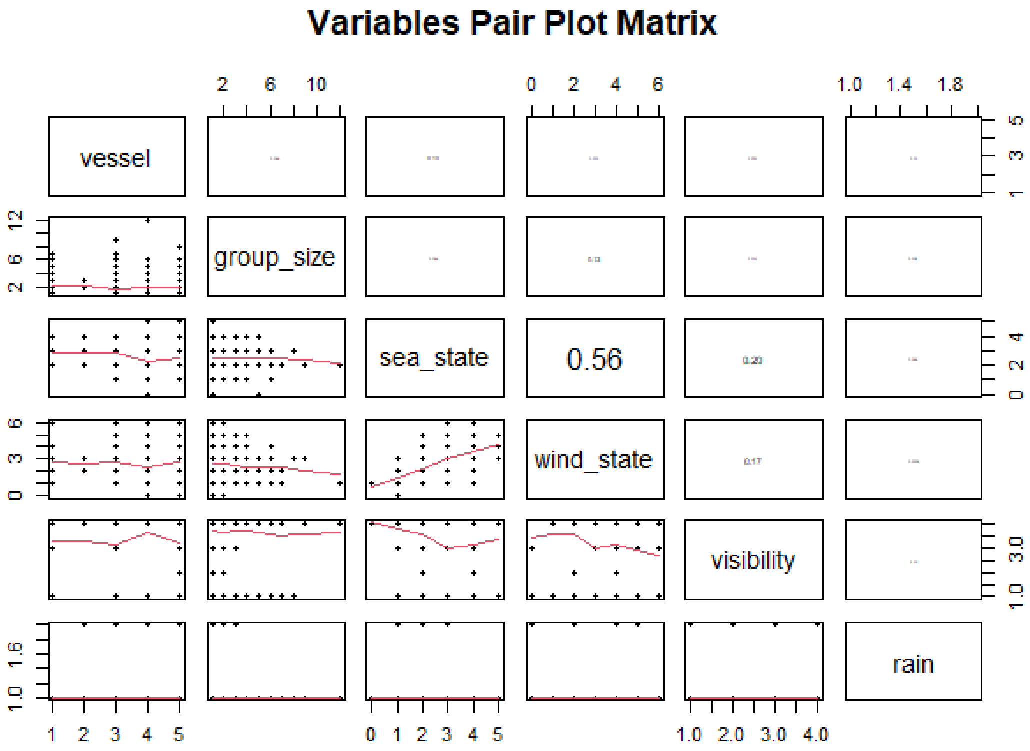


Figure A26. Correlation Matrix. Results of Pearson correlations between all pairs of explanatory variables included in the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of beaked whale sightings.

Table A9. Generalised Variance Inflation Factor (GVIF) results of explanatory variables of the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of all whale sightings.

Vessel	Group size	Sea state	Wind state	Visibility	Rain
1.100402	1.036462	1.560384	1.552342	1.127935	1.013784

Table A10. Generalised Variance Inflation Factor (GVIF) results of explanatory variables of the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of baleen whale sightings.

Vessel	Group size	Sea state	Wind state	Visibility	Rain
1.107814	1.019986	1.544498	1.523802	1.119762	1.018322

Table A11. Generalised Variance Inflation Factor (GVIF) results of explanatory variables of the model analysing the influence of detectability-related variables on Time to Potential Collision (TPC) of beaked whale sightings.

Vessel	Group size	Sea state	Wind state	Visibility	Rain
1.214820	1.052759	1.592563	1.583139	1.212918	1.098057