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Assessing marine traffic and related pressures and threats to cetacean populations to support vessel management in the Mascarene Important Marine Mammal Area

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ABSTRACT

The global growth of marine traffic, among many growing anthropogenic threats, is of particular concern for marine mammals. Assessing the co-occurrence of marine traffic and cetacean distributions provide useful information for understanding the spatial extent and level of pressures and threats posed by vessels. Regional and local marine traffic is increasing within the territorial waters of Réunion Island, included in the Mascarenes Important Marine Mammal Area. This study provides the first description of the spatial distribution of vessels within these waters using Automatic Identification System (AIS) data and provides an assessment of the pressures and threats vessels may pose to five cetacean species (the spinner dolphin, the Indo-Pacific bottlenose dolphin, the common bottlenose dolphin, the pantropical spotted dolphin and the humpback whale). We found that vessels occurred in all Réunion waters and identified two highly-used shipping corridors on either side of the island. Our results highlighted areas of potential threats from marine traffic for each of the five species. These areas mostly mirrored their preferential core habitats, which raises concerns, especially for the resident and most vulnerable species. Given the increase in marine traffic in the western Indian Ocean region, this study provides additional information in support of an ongoing French initiative to implement an "Area to Be Avoided" in Réunion waters, in order to improve safety and security while also benefiting to cetacean conservation.

1. Introduction

Anthropogenic pressures on marine life are growing, reaching critical points for marine ecosystems and their biodiversity [1,2]. Marine traffic represents one of the pressures that contributes most anthropogenic impact to the marine realm [3,4]. Yet in order to meet the growing global demand for maritime trade, shipping traffic, vessels' size and shipped volumes have increased over recent decades, a trend that is predicted to continue [2,5–8]. In addition, as a result of geopolitic crises, nautical accidents or other global changes, new shipping routes have emerged, with direct consequences for marine traffic routeing and volumes in some areas [8–12].

Marine traffic is acknowledged to generate pressures with non-negligible detrimental effects on marine wildlife, particularly on cetaceans (whales and dolphins). Vessel collisions with cetaceans can result in serious injuries or deaths of affected animals [13–17]. Collisions with large whales are frequently reported, but collisions with small cetaceans like dolphins are also of concern [15,16,18,19]. Many types of vessels have been involved in collision with cetaceans [15,20], and vessel strike rate has been linked to vessel density, vessel size (length, width and hull height) and vessel speed [16,20–24]. Large vessel size and/or high vessel speed may impair manoeuvrability, making the avoidance of cetacean difficult [15]. If collisions occur, vessel speed has been reported to be positively correlated to collision impact force and the probability of lethal injury [24–28]. Additionally, marine traffic is considered the most dominant and primary source of anthropogenic underwater noise [29]. Vessel noise emissions can disrupt behaviour, compromising vital functions (communication, echolocation) and the

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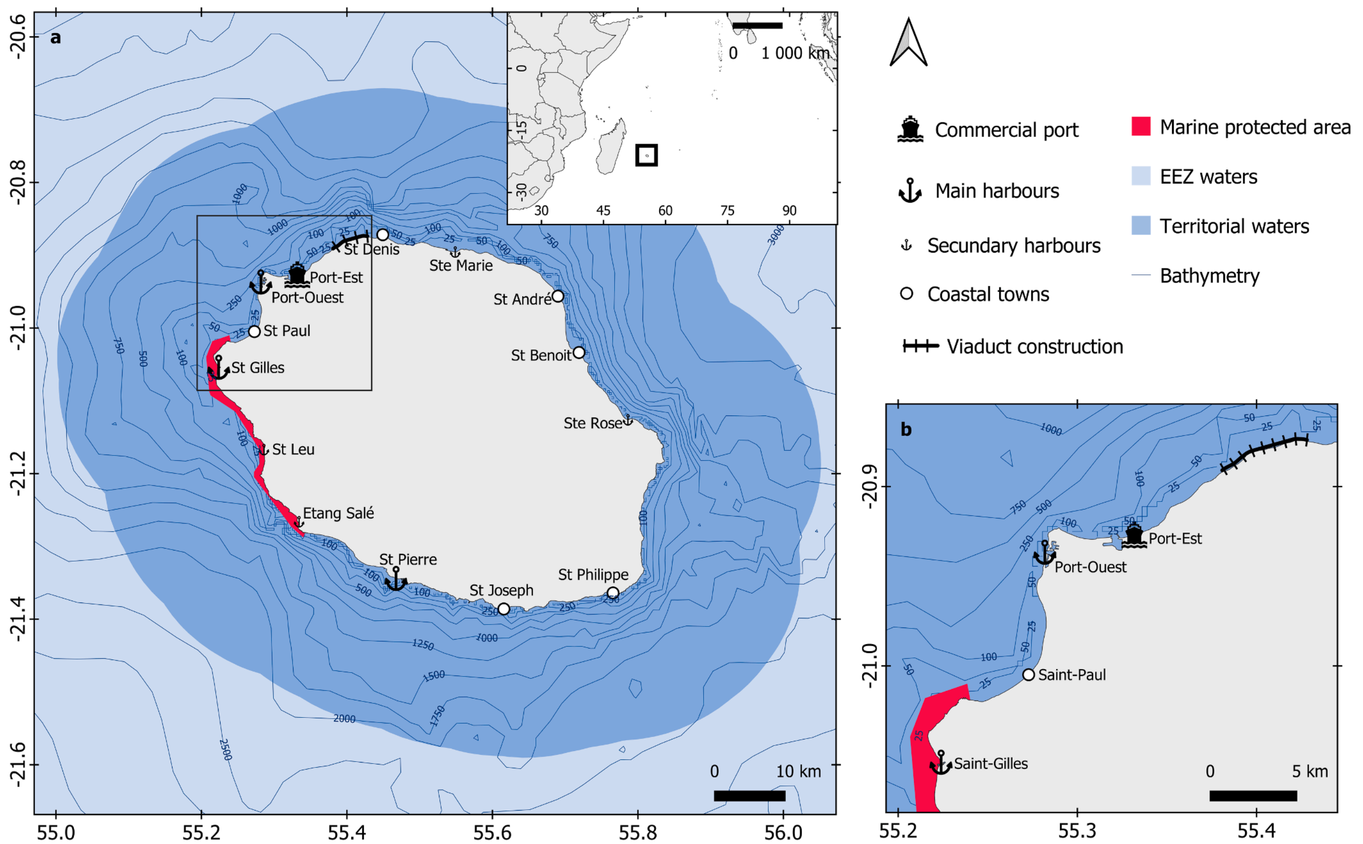

Fig. 1. Map of the study area. Marine activities are hosted by the eight harbours mostly distributed on the west coast. The territorial waters of Réunion Island (*i.e.*, the study area; in darker blue) are delimited by the 12 NM limit (source of the spatial layer: Shom 2018). Source of the bathymetry data: GEBCO 2014.

performance of vital activities (feeding, resting, socializing, breeding), can affect coordination within a group, or decrease the navigation and orientation abilities of individuals [30–34]. The potential threats posed by underwater noise depends on vessel characteristics, with noise levels varying by engine type, hull shape and vessel speed [32,35–37]. Marine traffic can also generate chemical pollution, linked to routine ship operations (tank washing, degassing) or accidents, which compromise the health, reproduction and/or survival of affected species [4,31]. All these threats can have deleterious consequences in the short and long term, at both the individual-level (behavioural alterations resulting in reduced individual fitness; *e.g.*, [30,34,38–40]) and the population-level (population displacement, population decline; *e.g.*, [41,42]).

The recent availability of vessel Automatic Identification System (AIS) data to the scientific community has improved understanding of the spatio-temporal distribution and operating characteristics of marine traffic [43–45]. AIS is a ship-to-ship and ship-to-shore vessel tracking system intended to enhance the safety of life at sea and the efficiency of navigation. Since 2002, AIS devices have been mandated by the International Maritime Organization (IMO) for all commercial passenger vessels and shipping vessels of 300 gross tons or more, and 500 gross tons (GT) for vessels dedicated to domestic coastal navigation [46]. These measures entered into force in Europe through two directives agreed in 2002 and 2009 and also include fishing vessels $\geq$ 15 m in length [47,48]. Although pleasure-craft are not bound by this measure, they are often equipped with AIS for safety purposes.

Assessing the co-occurrence of marine traffic and cetacean distributions provides useful information for understanding the spatial extent and level of pressures and threats posed by vessels [49–64] and can support the development of management actions. The IMO provides multiple tools for improving maritime safety and managing the impacts of marine traffic on the environment (*e.g.*, traffic separation schemes, areas to be avoided (ATBA) or particularly sensitive sea areas; [65]). Successful implementation of such ship's routeing measures to benefit cetacean conservation has been reported in the northeastern USA/Scotia-Fundy region, the Strait of Gibraltar, California, the Bering Strait, the Lombok Strait (Indonesia) and the Gulf of Panama [65–69].

The Indian Ocean region is a strategic crossroads for maritime trade [70]. Considering increased demand for merchant traffic related to the growing economies of Indian Ocean coastal states, the recent regional maritime trade agreements (African Continental Free Trade Area) and the geopolitical tensions in Yemen (reduced traffic through the Gulf of Aden), traffic flows within the Indian Ocean are predicted to increase by 2030 [8,71]. A major shipping route crosses from the Cape of Good Hope to the Strait of Malacca (*i.e.*, the South Africa/Asia route) and concentrates the traffic transiting to/from the Atlantic Ocean [5,72,73]. The remote oceanic island of Réunion (an overseas territory of France), is located along this busy shipping route. Traffic flows within Réunion waters have soared over the recent years [72,73], and continued increases are expected, given the regional context and the local authorities' strategy plan for maritime development [74,75]. Marine traffic in the waters of Réunion is constantly monitored by the 'Centre Régional Opérationnel de Surveillance et de Sauvetage' (the French Maritime Rescue Coordination Centre, MRCC) under its mandate to prevent shipping accidents and manage hazards when accidents occur. In order to manage accident risks and other security threats in Réunion waters and to improve maritime safety and security [72,73], the MRCC and the French Authorities have proposed new ship's routeing measures, including an Area To Be Avoided (ATBA) around the island, to be endorsed by the International Maritime Organization (IMO).

The waters of Réunion have been recognised as an Important Marine Mammal Area since 2020, sustaining a high species diversity and representing suitable habitats for key life cycle activities (*i.e.*, the Mascarenes IMMA [76,77]). Twenty-five species of cetaceans have been recorded around the island, among which five species are commonly

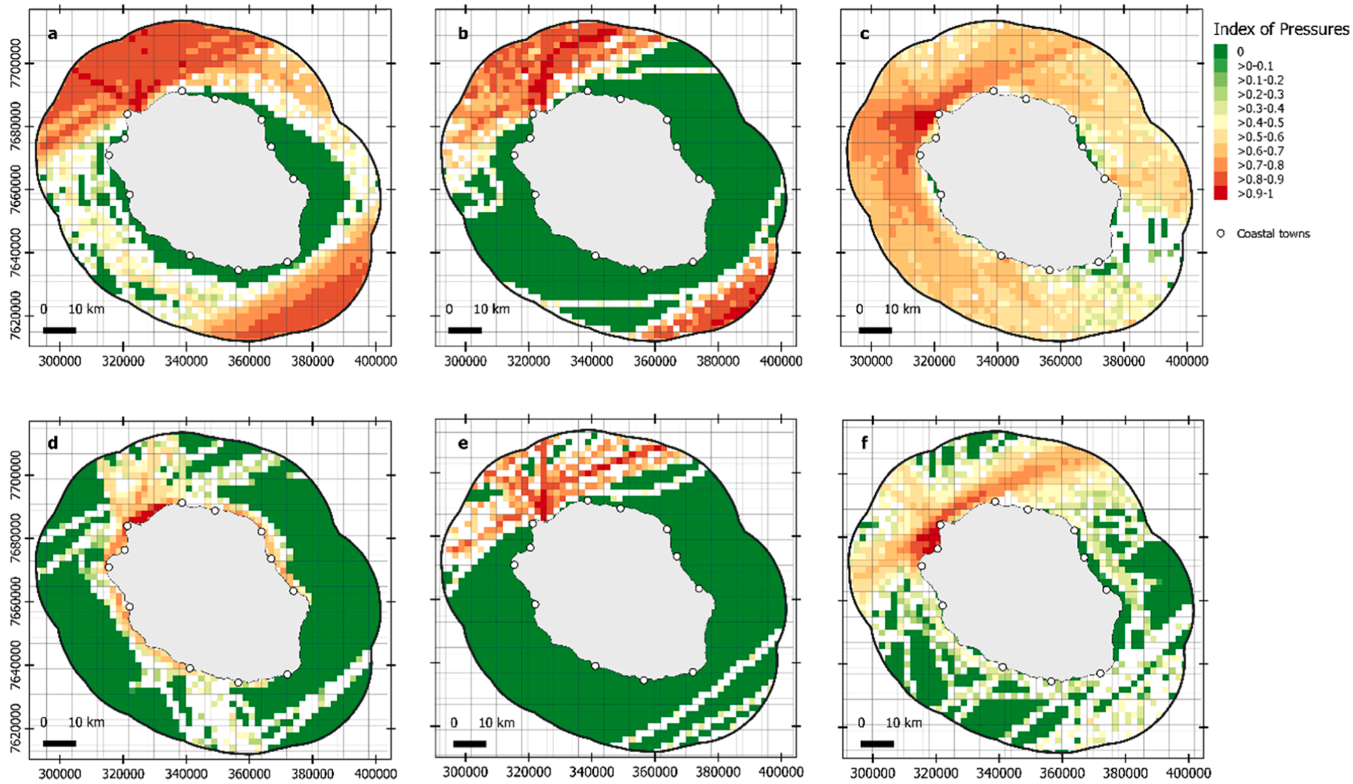

Fig. 2. Index of vessel pressures (I_P) by vessel types within the territorial waters of Réunion Island. **a)** cargo vessels; **b)** tanker vessels; **c)** fishing vessels; **d)** marine works vessels; **e)** passenger vessels; **f)** recreational vessels. I_P was calculated with the whole AIS dataset (July 2017-August 2019). The limit of the territorial waters (12 NM) is illustrated by the solid black line.

sighted within territorial waters ([78]; GLOBICE, unpublished data). These include the spinner dolphin (*Stenella longirostris*), the Indo-Pacific bottlenose dolphin (*Tursiops aduncus*), the pantropical spotted dolphin (*Stenella attenuata*) and the common bottlenose dolphin (*Tursiops truncatus*), all of which are considered to be year-round residents [79–81]; as well as the humpback whale (*Megaptera novaeangliae*), which migrates to Réunion waters to breed during the austral winter [78,82,83]. These five species are protected under French law and are subjected to local conservation plans [84,85]. Due to their small population size, restricted habitat and high level of residency, the two coastal dolphin species (spinner and Indo-Pacific bottlenose dolphins) are particularly vulnerable to anthropogenic disturbances, including the increasing pressures associated with marine traffic [79–83,86]. Being capital breeders [87], humpback whales, and mothers with calves in particular, are expected to exhibit low-energy expenditure behaviours [88,89] and are likely to be particularly vulnerable to repeated disturbances induced by marine traffic.

Our understanding and assessment of marine traffic threats to cetaceans around Réunion are hindered by a general lack of knowledge on the spatial extent and density of marine traffic within the island's waters. Considering the regional and local context of ongoing and projected marine traffic growth [8,9,12,71–74], providing baseline information on the level of co-occurrence of cetaceans and vessels and the associated level of threats is needed. The objectives of this study were to address these gaps by (1) providing the first description of the spatial distribution of vessels within the territorial waters of Réunion; and (2) assessing and mapping the pressures generated by these vessels and the potential threats they may pose to five cetacean species sharing these waters; (3) supporting initiatives led by French authorities at the IMO, by proving supplementary information on the environmental risk of traffic, and in particular on cetacean populations around Réunion Island.

2. Materials and methods

2.1. Study area and context

Réunion Island (55°33′E, 21°07′S), is a small (2500 km^2) oceanic island in the southwest Indian Ocean, located 700 km to the east of Madagascar and 170 km to the west of Mauritius (Fig. 1). The geographic extent of the study area was limited to the territorial waters of Réunion Island (12 nautical miles (NM)), in consistency with the spatial coverage of cetacean survey effort and the ATBA proposed by the French authorities, representing an total surface area of 5900 km^2 (Fig. 1). The study area encompassed the insular shelf and the slope, to a depth of 2500 m. Water depth increases rapidly from the coast (Fig. 1) except on the western side of the island, where the outer part of the insular shelf extends to 12 km off Saint-Paul and 7 km off Saint-Gilles, where depths remain relatively shallow (*ca.* 200 m).

Réunion Island has one commercial port, located on the northwest side of the island, and seven harbours distributed mainly on the west coast (Fig. 1). The island economy is dependent on the imports of goods (food, construction material, fuel, medical products), for which the commercial port (Port-Est) and the harbour of Port-Ouest play key roles. Recently, the local authorities have designed a strategic plan for maritime development, including improving and expanding several of Réunion harbours and the commercial port, which is intended to become a transhipment and cruise vessel hub [74,75]. Industrial fishing activity is mainly supported by the harbour of Port-Ouest, whereas the small-scale fishery is scattered among all harbours. Industrial fishing vessels in Réunion are mainly represented by longliners targeting tuna-like species and billfish operating in waters beyond 20 NM, a few tuna purse-seiners that mostly operate in the northern Mozambique channel, a few longliners targeting toothfish operating in French Exclusive Economic Zones (EEZ) in the subantarctic (Crozet and Kerguelen), and one lobster trap vessel in French EEZs around Saint Paul

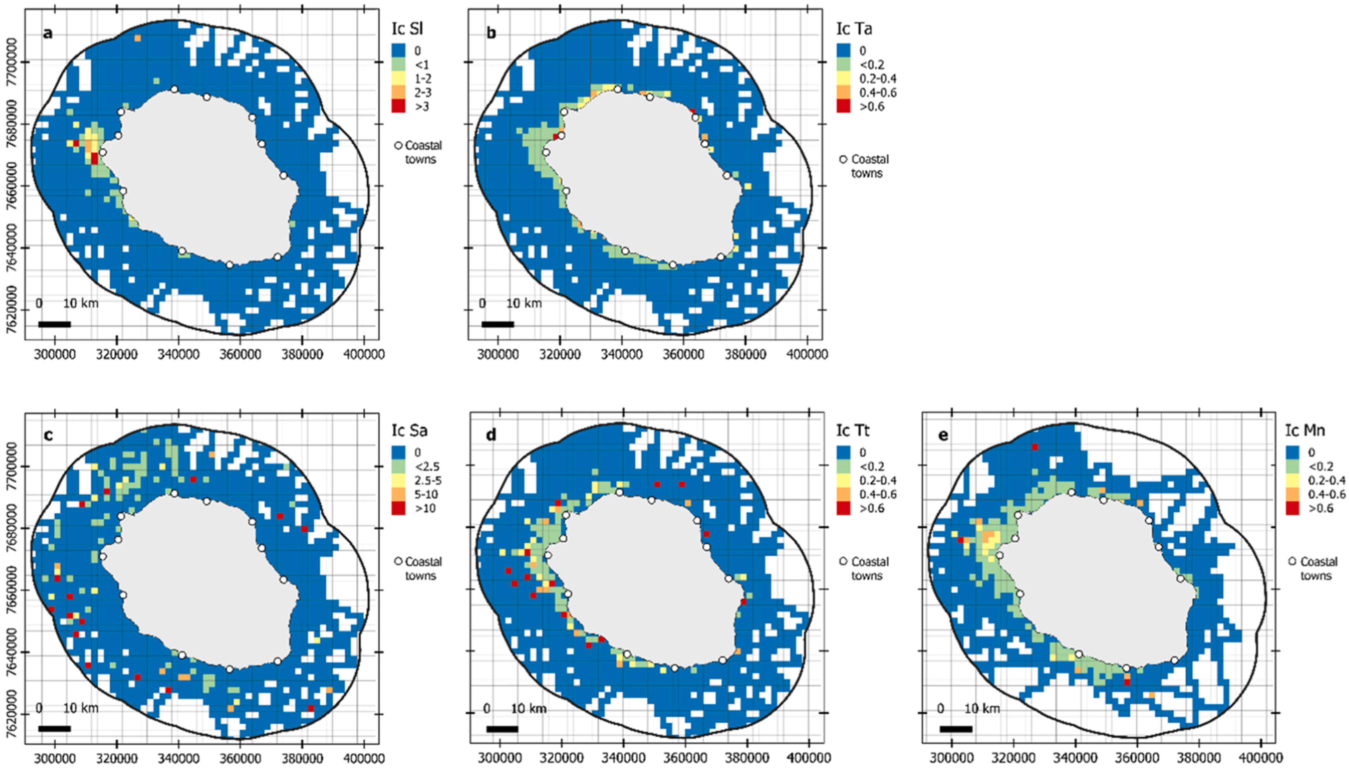

Fig. 3. Index of occurrence (I_C) of the five species of cetaceans commonly observed within the territorial waters of Réunion Island. **a)** the spinner dolphin, Sl (*Stenella longirostris*), **b)** the Indo-Pacific bottlenose dolphin, Ta (*Tursiops aduncus*), **c)** the pantropical spotted dolphin, Sa (*Stenella attenuata*), **d)** the common bottlenose dolphin, Tt (*Tursiops truncatus*), and **e)** the humpback whale, Mn (*Megaptera novaeangliae*). The surveys conducted to prospect for the presence of cetaceans did not cover all the study area, hence the empty cells. Among the prospected cells, cetacean were observed ($I_C > 0$, cells green to red) or not ($I_C = 0$, blue cells). The limit of the territorial waters (12 NM) is illustrated by the solid black line.

and Amsterdam Islands. The small-scale fishery fleet consists of small longliners (≤ 12 m in length, named 'mini-longliners') operating between 12 and 20 NM, and small boats (5–9 m in length) fishing in territorial waters but mostly within 5 NM. Recreational and tourism activities mainly take place from the harbour of Saint-Gilles, and to a lesser extent from the harbour of Port-Ouest and the harbours of Saint-Leu and Saint-Pierre. From 2014 to 2022 a 12.5 km long road viaduct along the north coastline of the island was constructed above the sea (see Fig. 1b). Operations related to this construction have involved the use of various vessels (*e.g.*, maritime works vessels, security vessels, research vessels) transiting from the Port-Ouest to the different work site locations, which have led to an increased marine traffic in the area. A marine protected area (*i.e.*, National Natural Marine Reserve of La Réunion) was created in 2007 [90] to preserve the fringing reef located on the west coast of the island (Fig. 1), providing a mean to manage nautical and fishing activities within a 35 km² area (*i.e.*, authorizing, restricting or prohibiting recreational and professional activities).

2.2. Marine traffic

An existing AIS dataset, comprising data from September 1st 2017 to August 31st 2019 and acquired from Marine Traffic (www.marinetraffic.com) as part of a previous research project, was used to investigate marine traffic within the territorial waters of Réunion. In addition to the geographical position (latitude, longitude) of the vessels, recorded at 2-min median intervals, the AIS included the following data: the identity of the vessel (*i.e.*, Maritime Mobile Service Identity, MMSI; one unique ID per vessel), the date and time, the speed (in knots; kn) and the heading. Vessel type was inferred *a posteriori*, as vessel type associated with MMSIs was provided separately from the AIS data. Based on the number of vessels represented per vessel type within the dataset and the context of the study, we chose to investigate the following vessel types: 1) cargo vessels (CA; *e.g.*, container vessels, bulk carriers); 2) tanker vessels (TA; *e.g.*, vessels carrying crude oil, chemicals); 3) fishing vessels (FI; industrial fishing vessels and small longliners, see 2.1); 4) passenger vessels (PA; cruise vessels); 5) recreational vessels (RE; *e.g.*, yachts, sailing vessels); and 6) maritime works vessels (MW; *e.g.*, dredgers). Other vessels included in the dataset were very diverse and poorly represented and were thus discarded from the analysis when discriminating by vessel type. They were nevertheless included in the study when all vessel types were considered.

AIS data were processed following the procedure described by the Marine Management Organisation [91]. Locations were filtered by discarding erroneous positions on land, invalid and multiple MMSI numbers. Only positions of vessels underway were considered. To exclude stationary vessels, positions associated with the status "at anchor" and "moored" or with speeds ≤ 1 kn were removed from the dataset. For cargo vessels and tankers, positions associated with speeds ≤ 2 kn, most likely associated with vessels awaiting entrance into a harbour, were also discarded. AIS data were then aggregated for each unique vessel. AIS data were imported as a point-type layer into the software QGIS (v.3.12.3) and used to build daily trips for each vessel (using the points to line tool). This line-type layer was then clipped by the 12 NM limit in order to compile a database of vessel trips and vessel speeds within the territorial waters of Réunion. The two datasets (point and line layers) were then compiled: (1) the 'whole dataset', that included all available AIS data (*i.e.,* data from 01/09/2017–31/08/2019), used for the analyses of overlaps with resident dolphin populations [78,80,81] and an 'austral winter dataset' that comprised AIS data for May-October (*i.e.*, data from 01/09/2017–31/10/2017; from 01/05/2018–31/10/2018; and from 01/05/2019–31/08/2019), to account for the seasonal occurrence of

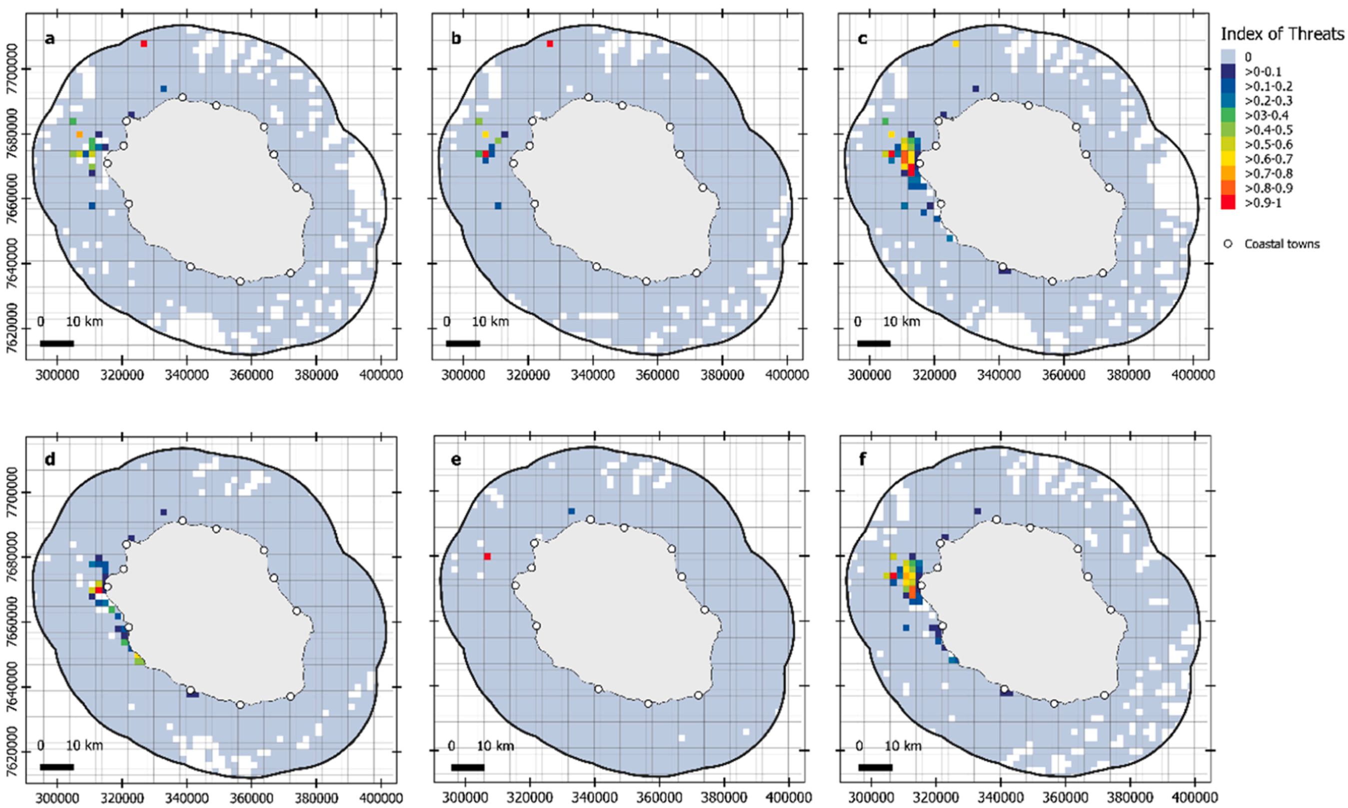

Fig. 4. Index of the potential threats (I_T) from marine traffic on the spinner dolphin (*Stenella longirostris*). I_T associated with **a)** cargo vessels; **b)** tanker vessels; **c)** fishing vessels; **d)** maritime works vessels; **e)** passenger vessels; **f)** recreational vessels. I_T was calculated from AIS data and sightings data over the period of data availability. The limit of the territorial waters (12 NM) is illustrated by the solid black line.

humpback whales [82].

AIS data were processed and mapped into a regular square grid of 2 × 2 km resolution encompassing the territorial waters of Réunion, resulting in a grid of 3250 cells. Each grid cell was associated with a unique identifier, allowing the linkage of different types of information to each cell.

Two metrics were computed from the gridded AIS data (see Section 2.2): i) the total distance travelled per cell (in km), representative of vessel density (as in *e.g.*, [23,53,55,61,63]; and ii) the mean speed recorded by cell (in kn). Vessel speed has been shown to be related to collision risk (*i.e.*, likelihood of collision and strike rate [20–22]; probability of collision lethal injury [24–27] and underwater noise [32,36]. Average speed has been previously used in studies assessing the risks for cetaceans associated with marine traffic (*e.g.*, [27,61,92,93]). We assume that a cell with high level of vessel density and high average vessel speed is subjected to greater pressures and more threats.

A marine traffic pressures index was calculated as follows: vessel pressures, P, was first calculated by multiplying the total distance travelled by the mean speed recorded for each grid cell; and a pressure index, I_P was then calculated by normalizing the resulting outputs P to a scale ranging from 0 to 1, as $I_P = [\text{Log}(P + 1) – \text{Log}(P_{min} +1)] / [\text{Log}(P_{max} + 1) - \text{Log}(P_{min} +1)]$, where P_{min} and P_{max} are, respectively, the minimum and maximum values of P over the grid). I_P were calculated for all vessel types and by vessel type, for both the whole dataset and the winter dataset.

In some cells, speed was not available because no vessel positions were recorded, even though a vessel transited through these cells. Consequently, for these cells, the index I_P could not be calculated (*i.e.*, illustrated by empty cells within the study area).

2.3. Cetacean data

Sightings data were used to infer the spatial distribution of the five cetacean species using the waters of Réunion on a regular basis: the spinner dolphin (Sl), the Indo-Pacific bottlenose dolphin (Ta), the pantropical spotted dolphin (Sa), the common bottlenose dolphin (Tt) and the humpback whale (Mn). Sightings data were collected during boat-based surveys conducted year-round over a 10-year period, from 2010 to 2019. These surveys included (1) line-transect surveys conducted annually and up to 12 NM off-shore around the island (2) line-transect surveys conducted off the northern part of the island and up to 12 NM (during the environmental assessment of the construction of the new road viaduct) and (3) coastal surveys conducted in waters up to 5 NM from the shore, without pre-defined transects [78,80,81,94]. The spatial distribution of all surveys was constrained by weather conditions, harbour location, and boat availability. Consequently, the eastern part of the study area and offshore waters were surveyed less. Survey tracks and weather conditions were recorded throughout the surveys, and for each cetacean sightings, the GPS position, the species observed, and the estimated group size were recorded. Surveys were conducted at an average speed of 6 kn and with a minimum of three observers, and only survey effort recorded in good sea conditions was considered (Beaufort <3).

Cetacean sightings data were integrated into a 2×2 km grid that matched that used for the AIS data. The total number of observed individuals, the total length of survey effort (km) and the relative abundance (number of individuals observed divided by survey effort, ind. km^{-1}) were computed for each grid cell and for each of the five species separately. Relative abundance, is a common parameter used to account for the spatial distribution of cetaceans [95,96], and was taken as an index of cetacean occurrence (I_C). To avoid over-estimating I_c in grid cells with low survey effort (for example when a transect ended in a cell

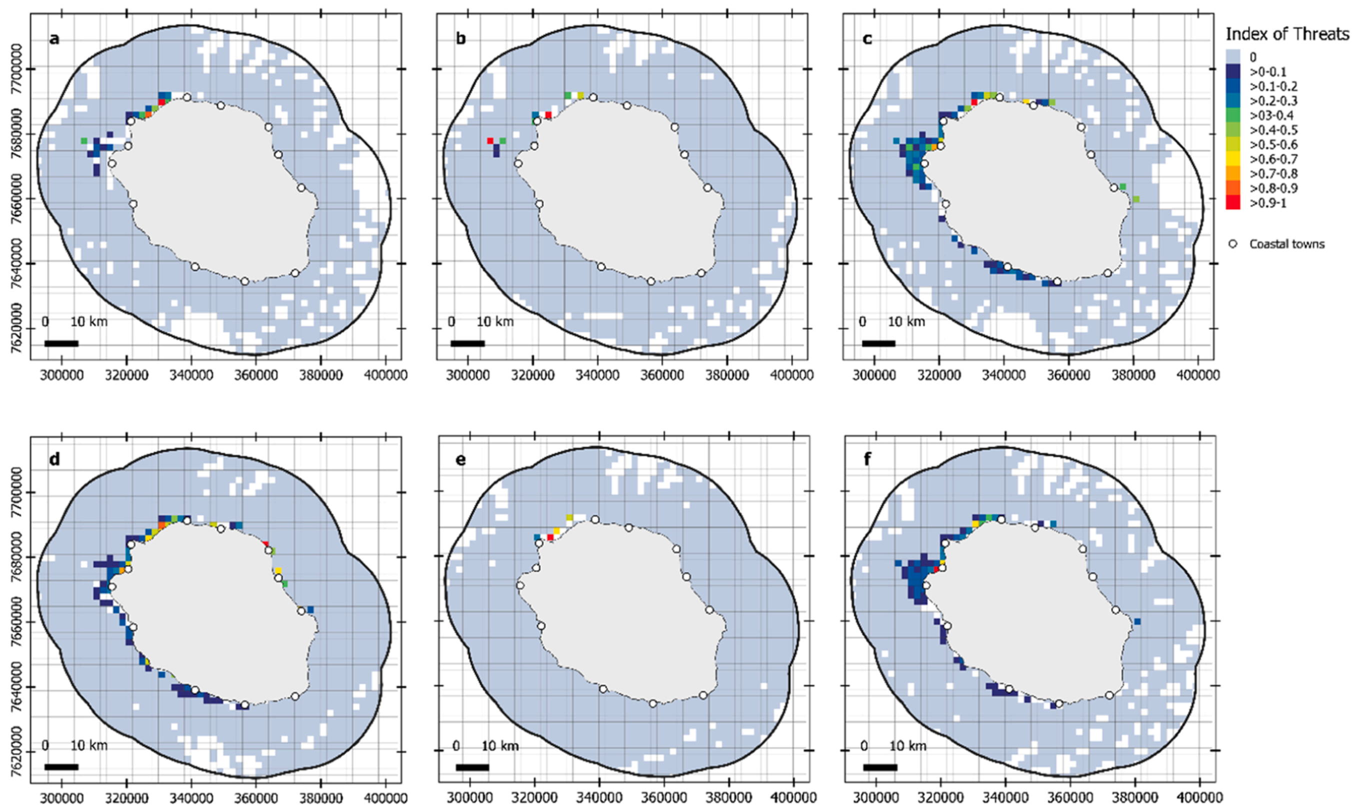

Fig. 5. Index of the potential threats (I_T) from marine traffic on the Indo-Pacific bottlenose dolphin (*Tursiops aduncus*). I_T associated with **a)** cargo vessels; **b)** tanker vessels; **c)** fishing vessels; **d)** maritime works vessels; **e)** passenger vessels; **f)** recreational vessels. I_T was calculated from AIS data and sightings data over the period of data availability. The limit of the territorial waters (12 NM) is illustrated by the solid black line.

or a small proportion of the transect crossed that cell), a threshold was established based on the recommendation that 10 % of a cell must be surveyed to be considered representative [96]. Cells with survey effort < 0.4 were not considered, based on an average detection range of 500 m on each side of the boat (1 km strip width along the track) and given the surface area of each cell was 4 km^2 [95,96]. Only one cell yielded survey effort lower than this threshold, providing reassurance for the I_C results. We assumed that using sightings data and survey effort data across a 10-yr period to calculate I_C realistically captured the spatial distribution of cetaceans at the scale of the study. For the humpback whale, the I_C index was computed using cetacean survey effort conducted during the austral winter (May 1st to October 31st) of each year, coincident with the species seasonality [82].

2.4. Co-occurrence of vessels and cetaceans and potential threats

Several approaches have been used in the literature to assess marine traffic-associated threats to cetaceans (*e.g.*, [50,53,61–64,97]) and standardised methodologies remain elusive. Here, we considered that the level of threats cetaceans may experience is mainly dependent on the level of pressures generated by vessels (represented by the pressures index I_P) and cetacean density (represented by the cetacean occurrence index I_C). The level of threat was represented spatially by computing a threats index, I_T. I_T was calculated as follows: the level of threats, T, was first calculated by multiplying the marine traffic pressures index (I_P) by the cetacean occurrence index (I_C) for each grid cell; the threats index, I_T, was then calculated by normalizing the resulting outputs T to a scale ranging from 0 to 1, as $I_T = [\text{Log}(T + 1) – \text{Log}(T_{min} +1)] / [\text{Log}(T_{max} + 1) - \text{Log}(T_{min} +1)]$, where T_{min} and T_{max} are, respectively, the minimum and maximum values of T over the grid. I_T was calculated for each species and for each vessel type, using the whole AIS dataset for the dolphin species, and with the winter AIS dataset for the humpback whale.

In cells where either I_C or I_P was unknown (*i.e.*, cells not surveyed, or cells for which I_P could not be calculated), I_T could not be calculated (*i.e.*, illustrated by empty cells within the study area). We assume that the pressures index computed to assess potential marine traffic-associated threats to cetaceans was relevant to the five species of interest in our study. Underwater noise and vessel collisions are a concern for all cetaceans species [16,18,19,30,32], and behavioural alterations in response to these stressors have been reported for large whales and delphinids [41,88,98,99].

All data processing and analyses were carried out with the software R (R Core Team, v.4.1.0). Grid analysis and mapping were performed with QGIS (v.3.12.3) using the reference coordinate system EPSG: 32740 (WGS 84, UTM 40S). Mean values are presented with their standard deviation (mean ± SD). Statistical differences in mean vessel speed among vessel types (*i.e.*, cargo, tanker, fishing vessel, maritime works vessel, passenger vessel and recreational vessel) were investigated by the non-parametric Kruskal-Wallis test, followed by Wilcox test, to compare each type *vs* each type. Differences in marine traffic-related indexes (I_P and I_T) among vessel types were also investigated by non-parametric Kruskal-Wallis tests, followed by paired Wilcox tests, to compare each type *vs* each type.

3. Results

3.1. Marine traffic within the territorial waters of Réunion Island

3.1.1. Overview

Overall, 2028 unique vessels (according to the MMSI) operated within the territorial waters of Réunion from September 2017 to August 2019. Most of the vessels were freighters (n = 1626), with the majority being cargo vessels and the rest petrochemical tanker vessels (92 % *vs*

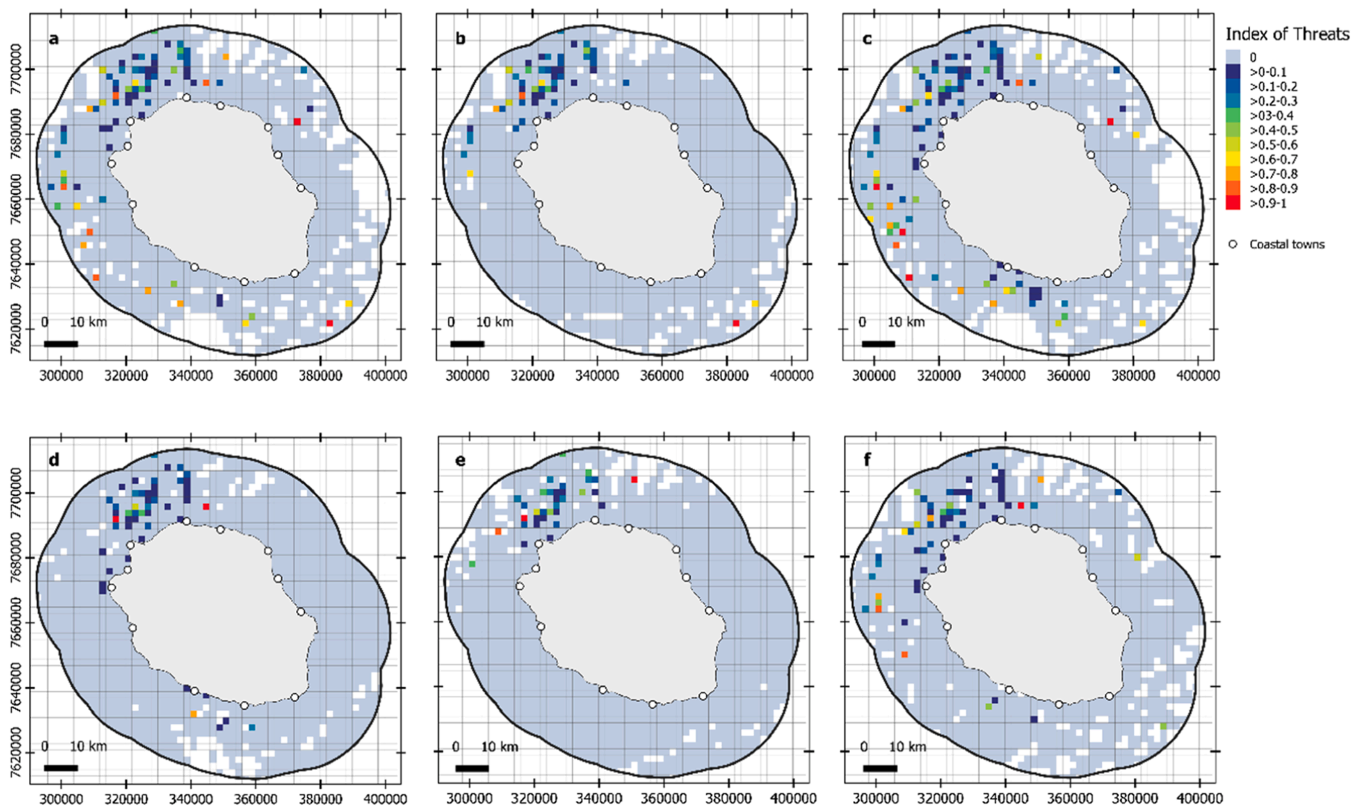

Fig. 6. Index of the potential threats (I_T) from marine traffic on the pantropical spotted dolphin (*Stenella attenuata*). I_T associated with **a)** cargo vessels; **b)** tanker vessels; **c)** fishing vessels; **d)** maritime works vessels; **e)** passenger vessels; **f)** recreational vessels. I_T was calculated from AIS data and sightings data over the period of data availability. The limit of the territorial waters (12 NM limit) is illustrated by the solid black line.

8 % respectively). A total of 180 recreational vessels, 43 fishing vessels, 29 passenger vessels and 16 maritime works vessels operated within the island's waters. Most of the freight vessels (80.6 % of all freight vessels, 80.5 % of the cargos and 81.7 % of the tankers) were only transiting through the territorial waters, whereas most of the maritime works vessels (93 %), the recreational vessels (69 %) and the fishing vessels (61 %) made a stopover in one of the harbours on the island. Half of the passenger vessels only transited through Réunion territorial waters while the other half made a stopover at the commercial port (Port-Est). Vessels' metrics are presented in Appendix A (Fig. A.1.-A.4.). Overall, vessels travelled 472,967 km within the study area. Cargo vessels travelled a total of 138,329 km, tanker vessels 12,363 km, fishing vessels 70,059 km, marine works vessels 42,241 km, passenger vessels 5531 km and recreational vessels 27,786 km. Vessels' speeds ranged widely (see vessel speed distributions in Fig. A.4, Appendix A) and average vessel speed varied among vessel types (Kruskal-Wallis test, $p < 0.01$, Kruskal-Wallis $Chi^2 = 13{,}787$). The highest average speed was recorded for passenger vessels (10.62 ± 4.32 kn) and cargo ships (10.51 ± 3.82 kn), followed by tanker vessels (9.46 ± 3.88 kn), marine works vessels (6.76 ± 5.32 kn), fishing vessels (6.60 ± 4.32 kn) and recreational vessels (4.97 ± 1.84 kn) ($p < 0.01$ for all Wilcox tests).

3.1.2. Distribution of marine traffic

Vessels were distributed all around the island but with some differences in vessel density (Appendix 1). When looking at the distance travelled by all vessel types, two major shipping corridors are clearly identified: one to the northwest of the island, with a SW-NE orientation, and the other to the southeast, parallel to that in the northwest (Fig. A.1, Appendix A). These corridors were mainly used by cargo vessels and tankers transiting through Réunion Island's territorial waters, and to a lesser extent by recreational and passenger vessels (Fig. A.2, Appendix A). An assessment of vessel headings did not allow us to distinguish any obvious patterns or preferences in the direction of traffic in each corridor (*i.e.*, toward Asia or toward South Africa). An area of high intensity of marine traffic was also observed in the direct vicinity of Port-Est and Port-Ouest, where some of the highest distances travelled by vessels were recorded per cell (Fig. A.1., Fig. A.2 Appendix A).

3.1.3. Vessel pressures

The spatial distribution of vessel pressures within the territorial waters of Réunion Island estimated using the whole dataset are presented in Fig. 2 (See also Fig. B.1 and Fig. B.2, Appendix B). The mean index of pressures I_P was significantly different according to vessel types (Kruskal-Wallis test, $p < 0.01$, Kruskal-Wallis $Chi^2 = 1704.1$). Mean I_P were also different between each vessel types (paired Wilcox tests, $p < 0.01$ in each case). The highest mean I_P was for fishing vessels, followed by cargo vessels, then recreational vessels, then tankers, then maritime works vessels and passenger vessels. Areas of highest I_P values were observed within the two identified shipping corridors, particularly for cargo vessels and to a lesser extent for tankers, and only within the northwest corridor for passenger vessels and recreational vessels (Fig. 2a,b,e,f). Highest I_P values were distributed over a large region in the northwest for fishing vessels, and near the island's coast (except to the southeast), particularly in the bay of La Possession, for marine works vessels (Fig. 2c,d).

3.2. Cetacean spatial distribution within the territorial waters of Réunion Island

3.2.1. Sightings and effort

During the ten-year survey period, a total 79,080 km of survey effort was completed within the territorial waters of Réunion. A total of 4434 sightings of the five cetacean species were recorded, with an estimated total of 54,767 individuals, including: 539 sightings of spinner dolphins

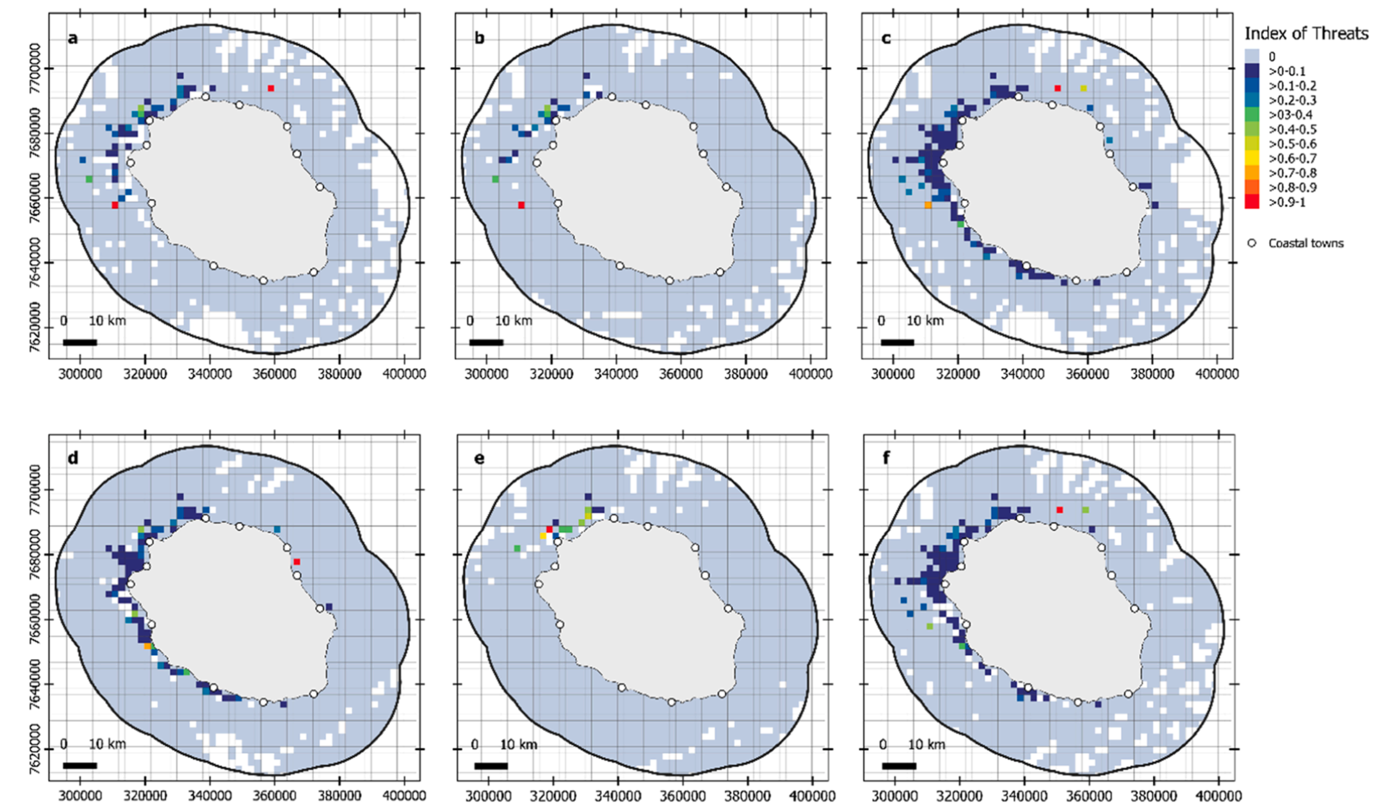

Fig. 7. Index of the potential threats (I_T) from marine traffic on the common bottlenose dolphin (*Tursiops truncatus*). I_T associated with **a)** cargo vessels; **b)** tanker vessels; **c)** fishing vessels; **d)** maritime works vessels; **e)** passenger vessels; **f)** recreational vessels. I_T was calculated from AIS data and sightings data over the period of data availability. The limit of the territorial waters (12 NM) is illustrated by the solid black line.

(31,176 ind.), 954 sightings of Indo-Pacific bottlenose dolphins (6238 ind.), 134 sightings of pantropical spotted dolphins (6160 ind.), 226 sightings of common bottlenose dolphins (5092 ind.) and 2581 sightings of humpback whales (6101 ind.). Although the majority of survey effort was distributed in western territorial waters, survey effort covered the entire study area (see Appendix C).

3.2.2. Index of cetacean occurrence

Over the study area, the index of cetacean occurrence I_C ranged from 0 to 3.74 ind.km^{-1} for the spinner dolphin, from 0 to 0.76 ind.km^{-1} for the Indo-Pacific bottlenose dolphin, from 0 to 31.21 ind.km^{-1} for the pantropical spotted dolphin and from 0 to 9.30 ind.km^{-1} for the common bottlenose dolphin. The area of highest I_C values for the spinner dolphin was located on the outer part of the insular shelf off Saint-Gilles, between 1 and 3 NM from the coast (Fig. 3a). For the Indo-Pacific bottlenose dolphin, grid cells with moderate to high I_C values were observed in close coastal waters around the island, particularly along the north coast (Fig. 3b). High I_C values were observed for the pantropical spotted dolphin in several grid cells scattered around the island between 3 NM and 12 NM offshore (Fig. 3c). For the common bottlenose dolphin, the grid cells with highest I_C values were sparsely distributed around the island except for the southeast quarter, and were mostly within 3 NM from the coast. For humpback whales, the index of cetacean occurrence I_C ranged from 0 to 1.22 ind.km^{-1}. The main area of highest I_C values was located on the outer part of the insular shelf off Saint-Paul (about 9 NM from the coast) (Fig. 3e). One cell at *ca.* 10 NM North had a high I_C value (Fig. 3e), but reflected the presence of one individual and low surveyed effort. Several areas with moderate to high I_C values were observed on the outer part of the insular shelf off Saint-Gilles, within the 3 NM of the northeast and southwest coasts (between Sainte-Marie and Saint-André, off Saint-Pierre and Saint-Joseph; Fig. 3e).

3.3. Potential threats posed by marine traffic on cetaceans within the territorial waters in Réunion Island

The potential threats posed to cetaceans by marine traffic (I_T) was computed separately for each species (Figs. 4 to 8; Fig. D.1, Appendix D). For all species, the mean index of threats I_T was significantly different according to vessel types (Kruskal-Wallis tests, $p < 0.05$ in each case; Table 1). For the spinner dolphin, mean I_T associated with fishing vessels, recreational vessels and maritime works vessels were the highest compared to other vessel types (paired Wilcox tests, $p < 0.05$) and were not significantly different from each other (paired Wilcox tests, $p > 0.05$). Mean I_T associated with cargo vessels was not significantly different from the mean I_T associated with tankers (paired Wilcox test, $p > 0.05$), but was higher than the mean I_T associated with passenger vessels (paired Wilcox test, $p < 0.01$). Mean I_T associated with tankers was not significantly different from the mean I_T associated with passenger vessels (paired Wilcox test, $p > 0.05$). For the Indo-Pacific bottlenose dolphin, mean I_T associated with fishing vessels, recreational vessels and maritime works vessels were the highest compared to other vessel types (paired Wilcox tests, $p < 0.05$) and were not significantly different from each other (paired Wilcox tests, $p > 0.05$). Mean I_T associated with tankers was not significantly different from mean I_T associated with cargos vessels and passenger vessels (paired Wilcox tests, $p > 0.05$), but mean I_T associated with cargos ships was higher than mean I_T associated with passenger vessels (paired Wilcox test, $p < 0.01$). For the pantropical spotted dolphin, I_T associated with fishing vessels and cargo vessels were higher than the other vessels types (paired Wilcox tests, $p < 0.05$) and were not significantly different from each other (paired Wilcox tests, $p > 0.05$). Mean I_T associated with the other vessel types were not different from each other (paired Wilcox tests, $p > 0.05$), excepting the mean I_T associated with recreational vessels which was higher than the mean I_T associated with passenger

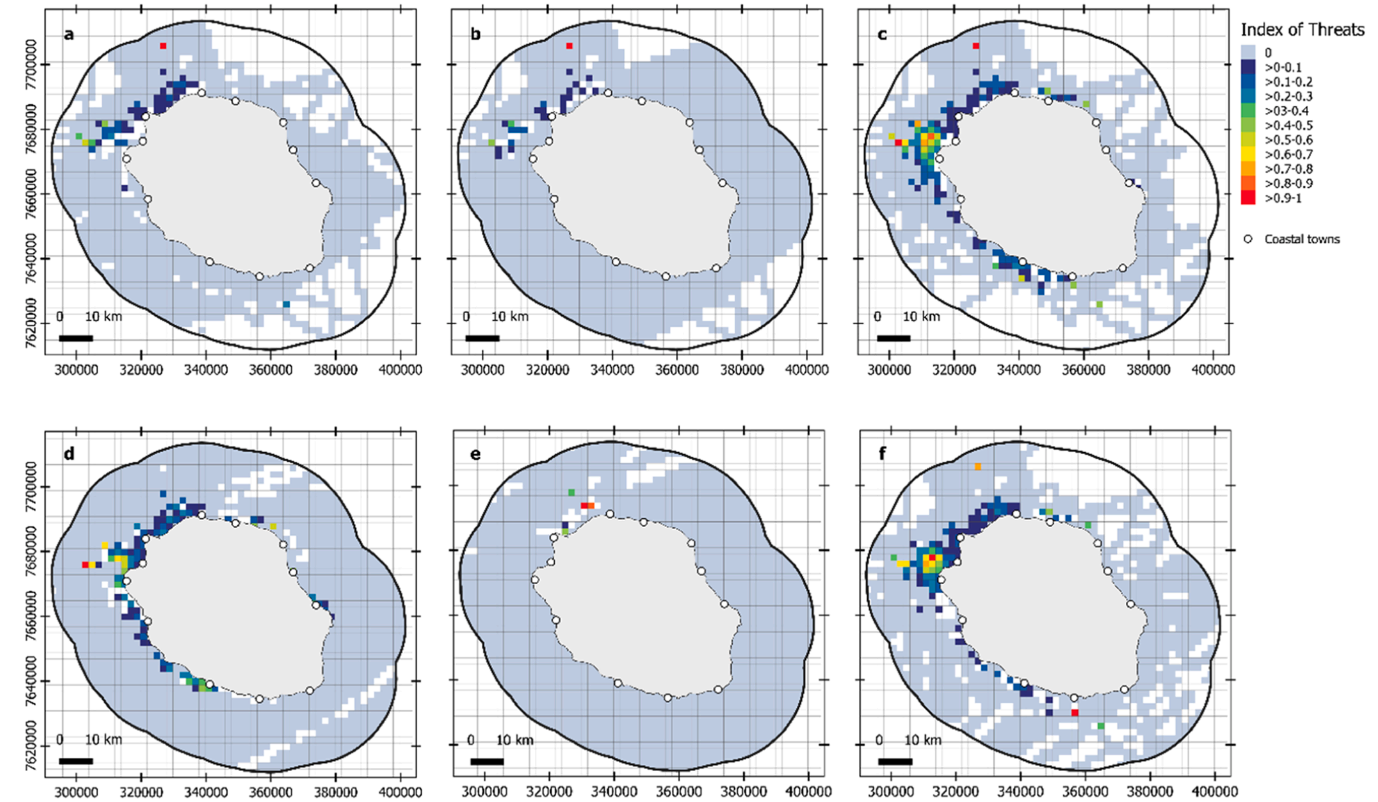

Fig. 8. Index of the potential threats (I_T) from marine traffic on the humpback whale (*Megaptera novaeangliae*). I_T associated with **a)** cargo vessels; **b)** tanker vessels; **c)** fishing vessels; **d)** maritime works vessels; **e)** passenger vessels; **f)** recreational vessels. I_T was calculated from AIS data and sightings data over the winter periods. The limit of the territorial waters (12 NM) is illustrated by the solid black line.

vessels (paired Wilcox test, $p < 0.05$). For the common bottlenose dolphin, mean I_T associated with fishing vessels, recreational vessels and maritime works vessels were the highest compared to other vessel types (paired Wilcox tests, $p < 0.05$), and were not significantly different from each other (paired Wilcox tests, $p > 0.05$). Mean I_T associated with tankers was not significantly different from mean I_T associated with cargos vessels and passenger vessels (paired Wilcox tests, $p > 0.05$), but mean I_T associated with cargos vessels was higher than mean I_T associated with passenger vessels (paired Wilcox test, $p < 0.01$). For the humpback whale, mean I_T associated with fishing vessels and recreational vessels were the highest compared to other vessel types (paired Wilcox tests, $p < 0.05$) and not significantly different from each other (paired Wilcox test, $p > 0.05$).Mean I_T associated with maritime works vessels was higher than mean I_T associated with cargo vessels, followed by mean I_T associated with tankers and then by mean I_T associated with passenger vessels (paired Wilcox tests, $p < 0.05$).

When considering only the cells where vessels and cetaceans co-occurred (*i.e.*, $I_T > 0$), the highest mean I_T value were associated with passenger vessels for all species except the pantropical spotted dolphin, for which the highest mean I_T values were from cargo vessels (Table 1). The co-occurrence of cetaceans and passenger vessels was observed in only a few cells compared to other vessel types, with moderate to high I_T values.

Potential high-threat areas (*i.e.*, cells with I_T values closest to 1), were identified for each species with each type of vessel. Potential high-threat areas for the spinner dolphin were located at the outer part of the insular shelf off Saint-Gilles for fishing vessels and recreational vessels, on the outer part of the insular shelf off Saint-Paul for fishing vessels, recreational vessels, cargos and tankers, and close to the coast of Saint-Gilles and Etang-Salé for the maritime works vessels (Fig. 4). For the Indo-Pacific bottlenose dolphin, potential high-threat areas were located within the bay of Saint-Paul for fishing vessels, maritime works vessels and recreational vessels, within the bay of La Possession (from Saint-Denis to Le Port) for cargo vessels, tankers, recreational vessels and passenger vessels and sporadically along the northeast coast for maritime works vessels (Fig. 5). Potential high-threat areas for the pantropical spotted dolphin were small and remote: they were constituted of unique cells scattered across pelagic territorial waters, around the island (except for the southeast quarter) for cargo vessels, fishing vessels and recreational vessels, or within the northwest quarter for tankers, maritime works vessels and passenger vessels (Fig. 6). Potential high-threat areas for the common bottlenose dolphin were scarce and isolated within territorial waters (Fig. 7). A few cells presenting high I_T values were sparsely distributed in the northern and/or western open seas for cargo vessels, fishing vessels, recreational vessels, passenger vessels and tankers. The few cells presenting highest I_T for maritime works vessels were located along the southwest and the northeast coasts (within 3 NM; Fig. 7). For humpback whales, potential high-threat areas were located at the outer part of the insular shelf off Saint-Paul and Saint-Gilles for fishing vessels, maritime works vessels and recreational vessels, and within 3 NM at the north of Saint-Denis for passenger vessels, or further north for cargo vessels and tankers (Fig. 8).

4. Discussion

4.1. New insights on marine traffic around Réunion Island

This study presents the first investigation of the spatial distribution of marine traffic within the territorial waters of Réunion and its potential threats to cetaceans. Analyses of AIS data allowed for the identification of two major shipping corridors on the northern and southern sides of the island, both aligned along a southwest-northeast axis. These corridors are part of the major Indian Ocean shipping route between South Africa and Asia [5,73]. They are mainly used by freight vessels

Table 1
Mean values of the index of threats (I_T) from marine traffic generated by each vessel type for each species (± SD). Means were calculated considering all the grid cells and considering only the cells where there was a co-occurrence between vessels and cetaceans, *i.e.*, where marine traffic-associated threats may exist ($I_T > 0$). Vessel types are: cargo vessels (CA), tanker vessels (TA), fishing vessels (FI), maritime works vessels (MW), passenger vessels (PA) and recreational vessels (RE). All the type of vessels considered CA, TA, FI, MW, PA, RE and all the other types of vessels included in the AIS data.

Vessel type	Spinner dolphin			Indo-Pacific bottlenose dolphin			Pantropical spotted dolphin			Common bottlenose dolphin			Humpback whale		
	All grid	Areas of co-occurrence ($I_T > 0$)		All grid	Areas of co-occurrence ($I_T > 0$)		All grid	Areas of co-occurrence ($I_T > 0$)		All grid	Areas of co-occurrence ($I_T > 0$)		All grid	Areas of co-occurrence ($I_T > 0$)	
	I_T Mean ± SD	I_T Mean ± SD	Nb cells	I_T Mean ± SD	I_T Mean ± SD	Nb cells	I_T Mean ± SD	I_T Mean ± SD	Nb cells	I_T Mean ± SD	I_T Mean ± SD	Nb cells	I_T Mean ± SD	I_T Mean ± SD	Nb cells
CA	0.002 ± 0.033	0.336 ± 0.274	17	0.002 ± 0.030	0.232 ± 0.263	22	0.008 ± 0.068	0.299 ± 0.285	80	0.002 ± 0.031	0.155 ± 0.220	41	0.002 ± 0.028	0.131 ± 0.176	47
TA	0.001 ± 0.031	0.413 ± 0.338	11	0.001 ± 0.029	0.431 ± 0.338	9	0.004 ± 0.044	0.238 ± 0.241	52	0.001 ± 0.024	0.188 ± 0.228	21	0.001 ± 0.022	0.123 ± 0.202	26
FI	0.005 ± 0.054	0.345 ± 0.298	41	0.005 ± 0.044	0.215 ± 0.184	70	0.009 ± 0.070	0.266 ± 0. 272	99	0.003 ± 0.031	0.089 ± 0.138	101	0.009 ± 0.060	0.197 ± 0.203	121
MW	0.002 ± 0.031	0.224 ± 0.229	29	0.006 ± 0.050	0.220 ± 0.230	75	0.003 ± 0.034	0.153 ± 0.224	49	0.003 ± 0.031	0.114 ± 0.162	74	0.006 ± 0.046	0.194 ± 0.170	98
PA	0.0004 ± 0.0178	0.571 ± 0.606	2	0.0008 ± 0.0238	0.607 ± 0.321	4	0.003 ± 0.037	0.253 ± 0.260	33	0.001 ± 0.028	0.339 ± 0.291	13	0.001 ± 0.026	0.553 ± 0.374	5
RE	0.004 ± 0.047	0.301 ± 0.289	39	0.003 ± 0.035	0.153 ± 0.180	65	0.004 ± 0.048	0.215 ± 0.259	61	0.002 ± 0.026	0.078 ± 0.132	84	0.007 ± 0.054	0.195 ± 0.211	103
All vessels	0.006 ± 0.057	0.320 ± 0.286	49	0.008 ± 0.059	0.221 ± 0.228	95	0.010 ± 0.074	0.273 ± 0.276	101	0.003 ± 0.032	0.086 ± 0.134	108	0.008 ± 0.046	0.123 ± 0.139	157

(cargo vessels and tankers), and to a lesser extent by recreational and passenger vessels, with no clear pattern in the direction of traffic flow either side of the island. With 80 % of freight vessels transiting through Réunion waters *via* these corridors (*i.e.*, without stopover in one Réunion harbour; this study), future increases in shipping vessels using this route will result in an increased number of vessels navigating through the island's waters.

Our data also highlighted two areas of high marine traffic density flowing into the commercial port and Port-Ouest harbour. These harbours serve vital roles for the island, and their expansion is planned in the near future [74,75]. In the absence of managed traffic schemes (*e.g.*, approach channel or routeing systems), and considering maritime safety, these areas of dense marine traffic flow merit the cautious consideration of management authorities.

Although in the same order of magnitude reported in other areas (*e.g.*, [49,51,64]), the average speeds recorded in this study were slower relative to vessels' capacities. This strategy, known as 'slow-steaming', is observed when a vessel voluntarily reduces its cruising speed below its maximum speed (12–18 kn instead of 20–24 kn for a container vessel, for example), and is generally used by vessels in order to reduce fuel consumption or to adjust capacity to low demand [73]. Over the South Africa/Asia shipping route, Réunion waters are also one of the very few locations where mariners may access the mobile phone network [72], which may explain why some vessels practice slow-steaming while within Réunion waters. Consequently, on one hand, slow steaming may reduce vessel-strike risk and underwater noise, but on the other hand, vessel would spend more time within Réunion waters, which would increase the probability of vessels/cetacean interactions.

Our results are complementary to those of studies assessing maritime safety risks and security threats completed for the 2012–2019 period [72,73]. Together they provide a baseline for monitoring the expected growth of marine traffic, and associated potential threats at both regional and local scales. These should be pursued to assess marine traffic management needs in the immediate future and over the long-term.

4.2. Vessel pressures for cetaceans

Quantifying and mapping pressures associated with vessels is a key step in the assessment of anthropogenic impacts on the marine environment [100]. Here we used a broad index of pressures that accounts for traffic density and vessel speed, and addresses two of the main threats whales and dolphins are exposed to: collision risk and noise disturbance [16,18,30,32]. We believe that the pressures index (I_P), although relative, is reliable for assessing marine traffic-associated threats to the five cetacean species of this study.

Similarly to other studies, our results showed that different vessel types did not generate equal levels of pressures [51,55,58]. In the waters of Réunion, fishing vessels and cargo vessels generated the greatest levels of pressure (highest mean I_P). In terms of spatial coverage, vessel related pressures were distributed differently among vessel types. Areas with a high level of pressures (>0.7) were widespread for cargo vessels, tankers and fishing vessels, but relatively localised for the other types of vessels. These high-pressure areas were located within both identified shipping corridors for cargo vessels, but only within the northern corridor for tanker vessels, passenger vessels and recreational vessels. For maritime works vessels, high-pressure areas were located along the coastline (within 3 NM of the coast), particularly within the bay of La Possession, whereas for fishing vessels they covered a large north-western quadrant of the territorial waters. Such patterns of vessel type-specific pressures provides valuable information for the management of the marine traffic occurring around Réunion, and for potential marine spatial planning efforts [74].

4.3. Potential marine traffic-associated threats on cetaceans

Our threat assessment was based on the co-occurrence of vessel related pressures and cetacean density inferred from sightings data. As in other studies (*e.g.*, [55,58]), our methodological approach assumed that different cetacean species respond uniformly to these pressures. However, this is unlikely as they may affect species in various ways due to species-specific differences. Integrating a vulnerability metric for each species would thus improve our threats index, and could be estimated from existing studies (*e.g.*, [56,101]) or from data on diving behaviour and activity patterns, inferred from bio-loggers, at least for large whales (*e.g.*, [102]). However, our threats index is relatively easy to implement using AIS and sightings data and gives a general diagnosis of high-threat areas for cetaceans. Such a diagnosis provides valuable information for management authorities, either in terms of maritime safety and security or in terms of cetacean conservation. It also provides the basis for more in-depth assessments of collision risk and noise exposure.

Our assessment highlighted areas of potential marine traffic threats faced by selected cetacean species within the territorial waters of Réunion. Overall, potential high-threat areas mirrored preferential habitat of the considered species: the outer part of the insular shelf off Saint-Paul for humpback whales; the outer part of the insular shelf off Saint-Gilles for spinner dolphins; the shallow coastal waters for Indo-Pacific bottlenose dolphins; and pelagic waters for pantropical spotted dolphins and common bottlenose dolphins (this study, [79–82,84,85]).

Besides the direct and short term effects on the physical integrity and behaviour reported on cetaceans (reviewed in [16,32]), anthropogenic disturbances, such as those associated with marine traffic, may lead to negative population-level consequences [31,103], and have the potential to be even more significant for small populations [104]. This raises concerns about increasing marine traffic in Réunion waters [5,72,73]. The population of Indo-Pacific bottlenose dolphin around Réunion is small, resident and genetically isolated ([80], Dulau, unpublished), and thus particularly susceptible to increasing threats. This population, which qualified as locally Endangered according to the IUCN Red List criteria [105], has an estimated population size of ca. 70 individuals and its distribution is limited to shallow-water coastal habitats, preferentially waters < 60 m [79,80]. Spinner dolphins inhabiting Réunion waters include long-term residents that have highly selective habitat requirements, resting within core habitats restricted by depths, slope and substrate types [79,106], making them susceptible to chronic disturbances [79]. Relocating to a traffic-free refuge area (*e.g.*, [41,99]) is not an option for these populations, due to the lack of other suitable habitats around the Island of Réunion [79]. More generally, shifting habitats, in order to avoid disturbances, is unlikely for these two coastal island-associated populations given their geographic and genetic isolation ([106], Dulau, unpublished). Coping with increasing marine traffic-associated threats under current management schemes may thus be unsustainable for these populations, and in the medium to long term, may jeopardize the survival of these two populations.

While the cessation of commercial whaling has allowed the recovery of most humpback whale populations worldwide [107], the conservation status of the population visiting Réunion Island has been described as Vulnerable mainly due to local habitat degradation and disturbances from increased interactions with human activities [105]. The results of this study confirmed a non-negligible level of threats associated with traffic in coastal waters. Increased disturbances and stress induced by vessels on calving and nursing females in particular [98], may represent an extra reproductive cost and may ultimately be deleterious [108,109]. Examining the effects of the co-occurrence of vessel traffic and specific marine mammal populations should be prioritised and assessed over the long term, as recommended in [110].

Our results showed that high-threats areas for the five species of cetaceans may be associated with every type of vessel. However, areas of potential threats were mainly associated with fishing vessels, but also with maritime works vessels, cargo vessels and recreational vessels (depending on the species considered). Although more discrete, the potential threats from passenger vessels transiting to/from the commercial port should not be ignored, especially for the Indo-Pacific bottlenose dolphin, whose coastal habitat is subjected to high pressures.

Our study did not allow for discrimination of the nature of the threats posed by vessels. Yet threats linked to fishing operations (*i.e.*, entanglement, bycatch) are unlikely, contrary to expectations in the Indian Ocean, where the intense artisanal fishing activity and fishing grounds for high-value species (*e.g.*, tuna) by industrial fishing fleet is well recognized [111]. The fishing vessels considered in our AIS dataset were most likely transiting to/from fishing grounds because they can only conduct fishing operations outside the limit of territorial waters (see Section 2.2; www.crpmem.re). Vessel noise emissions may be one of the most pervasive threats associated with marine traffic, and concern all type of vessels, particularly if they navigate at high speed [32,33]. In addition, during operations, maritime works vessels may disturb cetaceans by elevating noise and water turbidity levels [42] (*e.g.*, dredging). Measures were taken to mitigate the impact to marine megafauna during the operations related to the construction of the road viaduct on the northwest coast [112]. These measures should also be considered during routine dredging operations for harbour maintenance, and all other potential constructions for future maritime development [74,75]. More generally, the noise generated by all vessel types within territorial water should be comprehensively assessed in order to better understand and mitigate this threat. Although collisions may occur with most type of vessels [15,20], vessel-strike rates have been shown to be positively related to vessel density, vessel size and vessel speed [16,21–23]. Even if there is no consensus on a specific vessel speed threshold, speeds above 10 kn are generally accepted to increase the probability of lethal injury [24,26]. In this study, cargo vessels, tankers and passenger vessels were large (> 50 m, up to 200 m) and travelled regularly over 10 kn and up to 33 kn, supporting the assumption that cetaceans are exposed to the threat of collision in Réunion waters. Although evidence of collisions is difficult to gather, cases have been reported within the study area for humpback whales calves and pantropical spotted dolphins (observation of propeller injuries), and suspicions of collision have been reported for stranded common and dwarf sperm whales ([94]; GLOBICE, unpublished data). As previously suggested, collisions may also occur offshore [113] and carcasses may subsequently sink or be consumed by scavengers or decomposed before reaching the shore [16]. This may explain why some collisions may go unnoticed and likely underreported [16,55, 113]. The risk of collision also depends on species-specific behavioural factors, notably the amount of time spent at or near the surface [15,16]. While in Réunion waters, humpback whales mothers and calves may be particularly exposed to vessel-strikes, as they spend a great deal of time at the surface [88]. As a precautionary measure related to collision threat, mariner outreach on marine traffic-associated threats, most particularly for cetaceans and potential risks for vessels and crews, should be initiated locally, especially prior to and during the humpback whale breeding season. The reporting of collision events should also be encouraged (for instance to the International Whaling Commission) to help quantifying the risk of vessel-strike and to better understand how collisions may threaten cetaceans at both local and regional scales.

Furthermore, the coastal waters of Réunion host an artisanal fishery fleet (see Section 2.2) and a variety of marine recreational activities, of which whale and dolphin watching activities form a main and growing part [114]. However, these vessels are small and rarely equipped with AIS or other monitoring systems and were thus not captured in this study. This gap should be addressed by monitoring and incorporating the movements of these vessel categories into future threat assessments.

4.4. Perspectives for marine traffic management and cetacean conservation

Mapping potential threats induced by different vessel types to marine wildlife is essential for developing targeted mitigation measures [100,115]. The ever-expanding vessel traffic does not portend any improvement to the pressures cetaceans are subjected to by vessels, even though some level of tolerance has been suggested [18,20,116]. Thus, the co-existence of cetaceans and vessel traffic may only be sustainable through the implementation of management measures.

Our study area may not be within the world's busiest shipping regions, but marine traffic in the Indian Ocean has increased over recent decades and will most likely keep increasing given economic demand [5,8,71–73]. Our data showed that marine traffic is significant and ubiquitous in the territorial waters of Réunion and that vessel pressures overlap significantly with the distribution of dolphins and whales. In addition to reported maritime safety issues [72,73], this study raises concerns for the conservation of local cetacean populations, particularly for those that are island-associated. In order to move towards the sustainable use of the waters around Réunion by vessel operators, trade-offs will have to be found between conservation goals and socio-economic needs [117] and could include the implementation of one or more of the management options described by the IMO and others (*e.g.*, [65]).

Reducing the risks to cetaceans from marine traffic can take various forms. Vessel Speed Reduction (VSR) is one of the most applied measures [16,118]. VSR measures can be voluntary, incentivised or mandatory, and have varying level of compliance (*e.g.*, [69,119]). VSR has been proven effective for reducing collisions with cetaceans and resultant lethal injuries [24,26]. VSR could have additional environmental benefits, including reducing ship strikes with other species (*e.g.*, sea turtles, manatees, [120–122]), reducing underwater noise, and reducing greenhouse gas emissions [123], but would have to be balanced with potential economic costs [124]. Previously applied VSR measures generally set a speed limit of 10 kn in specific areas (*i.e.*, inshore traffic zone, seasonal management areas, approaches to harbours; [69,118,125]). The results of our study suggest that a VSR of 10 kn in inshore waters (*ca.* 3 NM) would only affect transiting maritime works vessels, and passenger vessels, but would help to mitigate the potential threats for humpback whales, spinner dolphins and Indo-Pacific bottlenose dolphins.

Other modifications to vessel navigation, such as spatial management measures, which aim to reduce cetacean/vessel co-occurrence, should also be recommended. These measures may be among the most effective mitigation actions, and achieve high compliance rates when adopted by the IMO [65]. For maritime safety purposes, the South Indian Ocean MRCC (CROSS) and the French Authorities are working to implement an ATBA within Réunion waters. This ATBA would incorporate all territorial waters of Réunion, and would be applied to transiting-only freight vessels (*i.e.*, that do not make stopover at one Réunion harbour; CROSS unpublished). According to our results, such ATBA would reduce by ca. 80 % the freight vessels navigating within the territorial waters of Réunion. These vessels are most likely using the South Africa/Asia route, whose outer limit passes within Réunion territorial waters. Transiting beyond the territorial waters of Réunion is unlikely to provide any disadvantages in term of navigation (time and cost), and if the ATBA were to be established, associated economic costs would likely be negligible. Marine mammals occur at low densities beyond the territorial waters of Réunion [126], thus the potential implications for shifting freight traffic further offshore may be limited, but need to be assessed. In addition to improving maritime safety [72], the proposed ATBA would reduce underwater noise and reduce collision probability within territorial waters. The present study provides additional information in support of an ATBA, which ultimately will help reduce the threats of marine traffic on cetaceans around Réunion Island.

CRediT authorship contribution statement

Plot Virginie: Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Estrade Vanessa:** Data curation. **Martin Julie:** Funding acquisition. **Rostaing Thomas:** Resources. **Collins Tim:** Writing – review & editing, Funding acquisition. **Dulau Violaine:** Writing – review & editing, Funding acquisition, Data curation.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2025.106632.

Data Availability

The authors do not have permission to share data.

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