Pairing AIS data and underwater topography to assess maritime traffic pressures on cetaceans: Case study in the Guadeloupean waters of the Agoa sanctuary

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Title

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Abstract

Maritime transportation forecasts project an increase in shipping. In this context, interactions with cetaceans are of growing concern especially when relevant biological data are not available to monitor the impacts. The Agoa sanctuary in the Wider Caribbean region faces this situation. To overcome this issue, we used AIS data to estimate three pressure types from maritime traffic associated with known impacts for cetaceans: (1) "intensity" corresponding to the frequency of vessel presence, (2) "occupancy" corresponding to the duration of ship presence, known to lead to disturbance and noise-related impacts and (3) "speed" presenting the risk of physical injuries from collisions. A simplified approach of the Cumulative Effect Assessment framework was used. We mapped species underwater topographic preferences as a proxy for their distribution to link habitat features with traffic pressure maps to evaluate pressure levels and types. Results showed that three species were more at risk from intensity and speed in the plains: the bottlenose dolphins, the Fraser's dolphins and the short-finned pilot whales. The speed pressure had the highest score over the habitat types slopes, canyons and valleys, placing sperm whales, Cuvier, Blainville's and Gervais's beaked whales at higher risk of collision in these areas. Humpback whales and pantropical spotted dolphins faced a higher risk of disturbance over the continental shelf along the West coast. We recommend a precautionary approach in the Agoa sanctuary: speed reduction in the Pointe-à-Pitre-Marie-Galante route and displacement of shipping lanes to move maritime traffic away from the West Coast.

Keywords

Automated Information System (AIS), underwater topography, maritime traffic, shipping, marine mammals, cetaceans, pressure, habitat, cumulative effect assessment (CEA), Marine Protected Area (MPA), marine spatial planning, Agoa sanctuary, Wider Caribbean Region.

1.Introduction

Maritime transportation accounts for about 80% of the world trade, and forecasts under different global economic scenarios project an increase of vessel movements between 240 and 1,290% by 2050 (Sardain et al., 2019). This intensification of ship traffic should logically be accompanied by an amplification of the interactions between shipping activities and the marine environment. For marine biodiversity, these interactions are of growing concern (Jung & Madon 2021). Shipping noise, grounding and anchoring, ship-generated oil discharge and exhaust emissions, persistent organic pollutant, sewage and debris, introduction of alien species are among the main threats that have been identified (Trozzi, 2003; Abdulla & Linden, 2008; Carlton, 2010; Jägerbrand et al., 2019). A growing body of literature focuses on measuring and estimating the extent of these impacts on the marine communities (e.g. Clark et al., 2009; Parks et al., 2011; Nedelec et al. 2015; Broad et al., 2020; Ivanova et al., 2020; Jung & Madon 2021). On cetaceans specifically, maritime traffic has been shown to have short and long-term impacts, direct or indirect, such as causing deaths (e.g. by collision due to vessel speed), hearing impairment or loss (due to noise emitted by vessels), physiological stress and modification of behaviour due to the prolonged or recurrent exposure to ship presence with additional long-term impacts on fitness and survival (e.g. Lusseau et al., 2009; Formigaro et al., 2017; Erbe et al., 2019; Garcia-cegarra & Pacheco, 2019; Smith et al., 2020; Arranz et al., 2021; Hausner et al., 2021; Jung & Madon, 2021). The impacts of maritime traffic on some charismatic top vertebrate predators, such as cetaceans, have also started to be used as a lever for financial support and to try to establish relevant mitigation measures (Pirotta et al., 2019). However, the term “impact” implies that the effect of the maritime traffic can be measured on the studied biological marine systems (organisms, populations, ecosystems…). In many cases, relevant biological data or results of impact studies are not available to infer an impact and the so-called impact is therefore doomed and remains as a potential threat.

The French marine mammal sanctuary named Agoa in the French exclusive economic zone (EEZ), around the Guadeloupean and the Martinique waters faces this situation. Located in the Wider Caribbean regions and characterized by a complex underwater topography that contributes to its high marine biodiversity, the area was declared a sanctuary for marine mammals in 2010, in agreement with the Guadeloupean authorities and the French government in order to reinforce the conservation of ca. 25 species of cetaceans that inhabit it (Ward and Carlson, 2001; Coché et al. 2021). The area has been shown to be already highly impacted by human activities (Halpern et al., 2008) and is in particular under pressure from an intense maritime traffic (Foulquier et al., 2021; Foulquier et al., *in prep*). However, efforts to evaluate the potential impacts of maritime traffic on cetaceans and design measures to mitigate them are hampered by the lack of relevant data in a region where governance and protection of biodiversity are complex (Fanning et al., 2021). Nevertheless, the first comprehensive, collaborative and open database for cetacean occurrences in Agoa, named ‘Kakila’, was initiated in 2021 and holds promises to support cetacean conservation (Coché et al., 2021).

The assessment of the impacts of maritime traffic on cetaceans implies first to have a realistic comprehension of the spatio-temporal distribution of the maritime traffic. For this aspect of the problem, data are far from being scarce and uncertain (Metcalfe et al., 2018). Indeed, the International Maritime Organisation (IMO) requires the use of the Automatic Identification System (AIS) for all vessels of >500 gross tonnage (GT), any vessels >300GT on an international voyage and all passenger vessels (SOLAS Convention, Chapter V, Regulation 19). In addition, the European Directive 2002/59/EC[1] requires AIS transmitters for all ships of 300-gross tonnage or more that were built after 01.07.2002. For any equipped ship (more than 60 000 after Ball, 2013), theoretically AIS data can be transmitted every 2-10 s creating this incredibly-rich source of data to describe ship movement and behaviour at a very fine scale (e.g. Le Guyader et al., 2017; Svanberg et al. 2019; Yang et al., 2019).

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[1] Directive 2002/59/EC of the European Parliament and of the Council of 27 June 2002 establishing a Community vessel traffic monitoring and information system and repealing Council Directive 93/75/EEC, https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32002L0059&from=FR

With AIS, it becomes therefore possible to measure the pressures or stressors maritime traffic places *de facto* on marine biological systems. Providing indicators of maritime traffic pressures to managers and decision-makers in Marine Protected Area (MPA) is paramount to open a discussion for designing measures to prevent advert impacts and move towards a sustainable use of the areas by maritime traffic. As a case study, and focusing on the Guadeloupean waters in the Agoa sanctuary, the aim of this study was to estimate and map key anthropogenic pressures that maritime traffic places on cetaceans. We used a complete dataset of 2019 AIS data and a simplified approach of the Cumulative Effect Assessment (CEA) framework (Halpern et al. 2008). We estimated maritime traffic pressures on the marine ecosystem and on cetaceans by calculating: (1) the “intensity” that corresponded to the frequency of vessel presence, (2) the “occupancy” that corresponded to the duration of ship presence and (3) the “speed” that was deduced from vessels speed. First, we explored these so-called pressures at various scales: (1) at the annual scale, (2) for vessel category and (3) at seasonal, night-day and individual scales. We used underwater topographic preferences of cetacean species as a proxy for cetacean distribution and we mapped species habitat topographic preferences using the benthic position index approach to characterize marine ecological habitat features (e.g. Azzellino et al., 2008; MacLeod and Zuur, 2005; Podestà et al., 2016). Using the Kakila database, we illustrated the relevance of the use of such proxy before overlaying habitat features with maps of traffic pressures to assess the types and levels of pressure and to identify areas of particular concern in the Guadeloupean waters of the Agoa sanctuary (Lundblad et al., 2006; Walbridge et al., 2018).

2. Material and Method

2.1. Regional context and study area

The Wider Caribbean region (WCR) is defined, in the 1983 Convention for the Protection and Development of the Marine Environment (i.e. the Cartagena Convention), as an ocean management area encompassing “the marine environment of the Gulf of Mexico, the Caribbean Sea and areas of the Atlantic Ocean adjacent there to, south of 30° north latitude and within 200 nautical miles of the Atlantic coasts of States referred to in article 25 of the Convention’’ (Article 2, paragraph 1). This maritime area faces the growing pressure of the maritime traffic with major shipping routes utilizing the WCR, while being a biodiversity hotspot, especially for marine mammals with 29 recorded species (Ward and Carlson, 2001; UNEP-Wider Caribbean Region)[2].

[2] https://www.unep.org/explore-topics/oceans-seas/what-we-do/working-regional-seas/regional-seas-programmes/wider

The WCR is also bordered by 28 sovereign states and 18 overseas territories of France, United Kingdom, United States of America and the Netherlands. As such, it presents a high degree of socio-economic and geopolitical inequalities that ultimately hinder efforts towards the development of a regional ocean governance of the shared living marine resources. In 2010, the French government contributed to the effort for cetacean protection and sustainable development by creating the Agoa Sanctuary (Fig.1). This MPA encompasses 143,256 km² of the French West Indies EEZ and presents an innovative governance shared by all stakeholders: local governments (Guadeloupe, Martinique, Saint-Martin and Saint-Barthelemy Islands and their environmental departments), the French MPA Agency, the French Ministry of Environment, and the local socio-economic partners, including environmental NGOs, universities and scientific bodies. This collaborative effort to protect cetaceans and their critical habitats in the French EEZ was illustrated in 2020 by the creation of the first collaborative and open database. Named “Kakila” (“Who is there” in Creole language), it gathers all cetacean occurrences recorded by NGOs, whale watchers and scientific bodies between 2001 and 2019 around the Guadeloupean waters (Coché et al., 2021). In the present study, we used the spatial extent of Kakila to provide topographic habitat and pressure maps to the Guadeloupean local authorities and managers.

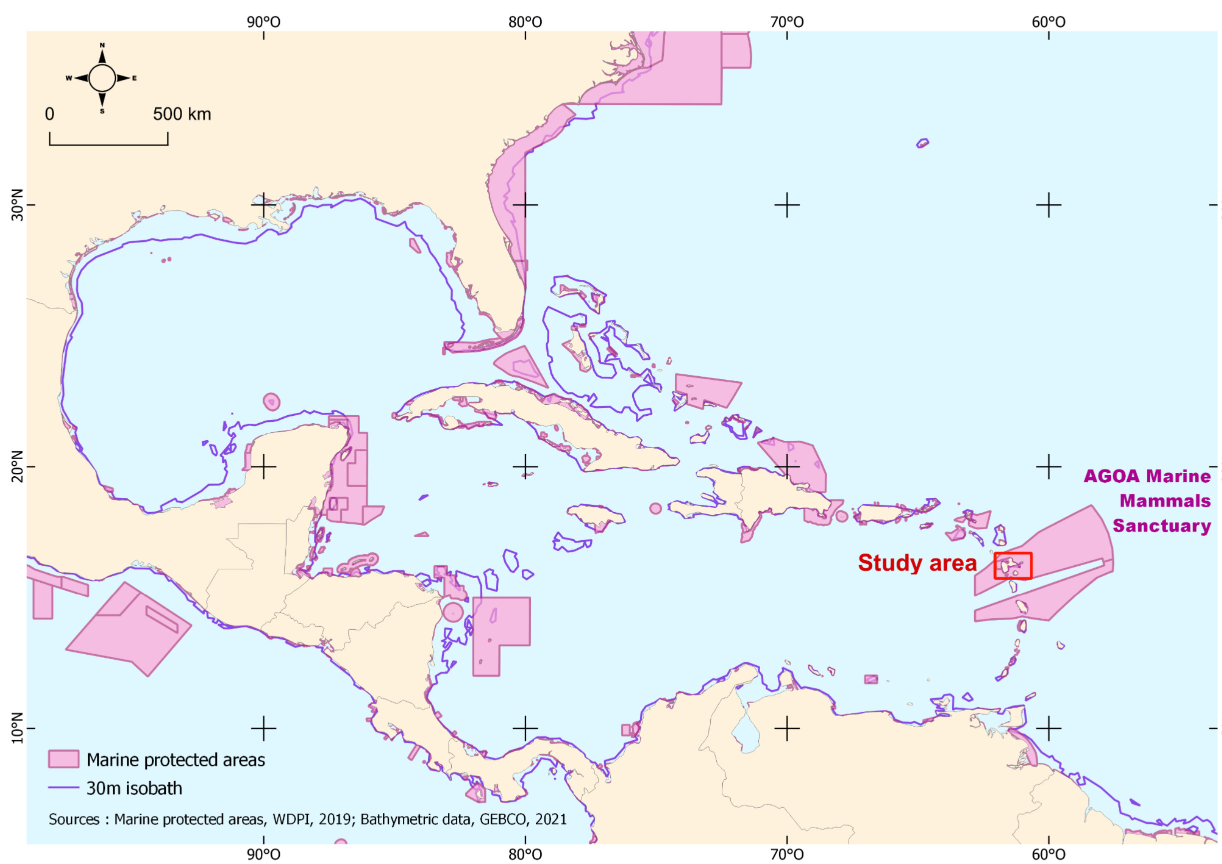


Fig.1- Marine protected areas in the wider Caribbean region and study site within the Agoa sanctuary.

2.2. Habitat description: topographic data processing

Topography can be described by various morphometric variables (slope, aspect, roughness, etc.). These variables are easy to calculate using commonly used GIS (such as QGIS, SAGA, ArcGIS, etc.), as long as a digital terrain model (DTM) of sufficiently fine resolution is available. Among the most commonly used indices, the topographic position index (TPI) allows for a comparison of the value of each cell with the average value of its neighborhood, according to a defined dimension window. Conceptualised by Guisan et al (1999), the TPI distinguishes between ridges and breaks (positive values of relatively high positional surfaces), canyons and valleys (negative values of relatively low positional surfaces), and flat areas or constant slopes (values close to zero). Depending on the scale of analysis, the TPI allows the identification of local forms (crevasses, pinnacles) and macro-forms (canyon, slope, abyssal plains) nested within each other. Weiss (2001) has shown that the combination of TPIs at two scales allows generic landforms to be classified. Many applications of this approach have been developed to characterise both terrestrial and marine ecological habitats (Lundblad et al., 2006; De Reu et al., 2013; Mata et al., 2021; Skentos, 2017; Walbridge et al., 2018; Wilson et al., 2007). In the latter cases, the TPI becomes the BPI: Benthic Position Index.

Based on the bathymetric DTM of Guadeloupe and Martinique produced by the French Hydrographic service (SHOM, 2018), the BPI was developed within the spatial extent of the Kakila database. The DTM has a spatial resolution of approximately 100 m (0.001°). Its bathymetric accuracy corresponds to the IHO S-44 standard, i.e. a vertical uncertainty of 5% with the survey data. In order to smooth out the pixel effect of the DTM, we generalised it to a resolution of 300m using SAGA GIS's *Simple filter* function. The *TPI based Landform classification Tool* was then applied to this raster to delimit morphological entities. In a first step, TPIs of several spatial resolution levels (300, 500, 600, 800, 1000, 2000, 3000, 5000, 10 000m) were compared with the DTM. The distances of 600 and 2000m were considered the most optimal for classifying landforms. In addition, three kinds of flat zones were distinguished according to their depth: shelf (depth < 100m), plains (100-700m) and abyssal plains (> 700m).

2.3. Cetacean habitat preferences

Cetacean habitat preferences depend on a variety of factors. The most important one is the underwater topography that conditions prey availability, water temperature, marine current conditions, *etc* (e.g. Davis et al., 2002; Guidino et al., 2014; MacLeod and Zuur, 2005).

Using the underwater topographic morphology of Guadeloupe defined previously and habitat references of the IUCN Red List of threatened species, we can characterise the topographic habitat preferences of 6 cetacean species (and an additional group of 3 species known to inhabit the same habitat) within the study area.
We illustrated the relevance of the use of topographic habitat features as a proxy for cetacean species distribution in our study area using the Kakila database. The Kakila database comprises a total of 4,704 records of 21 cetacean species collected in the Guadeloupe Archipelago from 2000 to 2019 during daily-boat excursions related to citizen science data acquisition or related to tourism (Coché et al., 2021). We used the 3 most recorded species, which accounted for up to 75% of the observations in Kakila: the pantropical spotted dolphin, *Stenella attenuata* (723 observations, 30% of all observations); the sperm whale, *Physeter microcephalus* (622 observations, 26% of all observations), and the humpback whale, *Megaptera novaeangliae* (457 observations, 19% of all observations), to display the matching rate between the topographic habitat features of the observations with the IUCN topographic habitat preferences. The density maps were produced using the Heat Map tool in QGIS from the observations by species selected in the KAKILA database.

2.4. AIS data processing for shipping description

The AIS database contains more than 400 million ship positions registered during the whole year 2019 at 2-min median intervals. Satellite and terrestrial AIS raw data for 2019 were obtained from exactEarth Ltd[3] and were imported into a PostgreSQL/PostGis database. A pre-processing phase consisted in the removal, from the raw data, of duplicates, invalid Maritime Mobile Service Identity - MMSI (i.e. codes without 9 digits), MMSI outside the correct numerical range (i.e. MMSI codes with first digits between 2 and 7 are those intended for individual ships), positions located on land and MMSI with less than 50 positions over the year. AIS data also contained aberrant vessel characteristics (e.g. no vessel name, several vessel types for the same vessel). Therefore, a typological enrichment was conducted from the Lloyd's Register of Ships purchased from the IHS Markit Company[4]. Vessels were classified into 4 categories based on the IHS Markit typology (level 4): shipping/commercial vessels (cargos and tankers), cruise ships (passenger cruise ships), inter-island ferries (passenger ships) and others (all other vessel types). Fishing boats were not included in the analyses as AIS was not mandatory for this category. A second phase consisted in geoprocessing of AIS positions which included segment interpolation of ship trajectories (Fig.2). A segment corresponded to the shortest line joining two consecutive positions. Then ship speed was computed for each segment. Inconsistent segments were removed based on

[3] http://www.exactearth.com/
[4] https://ihsmarkit.com

several criterions: segment entirely or partly located on land, segment for which the travel time is greater than 6 hours or segment for which the speed was greater than 60 kn. The criterion of travel duration was retained in order to restrict the potential interpolation errors of the vessel tracks in cases of low AIS signal quality (transmission and/or reception).

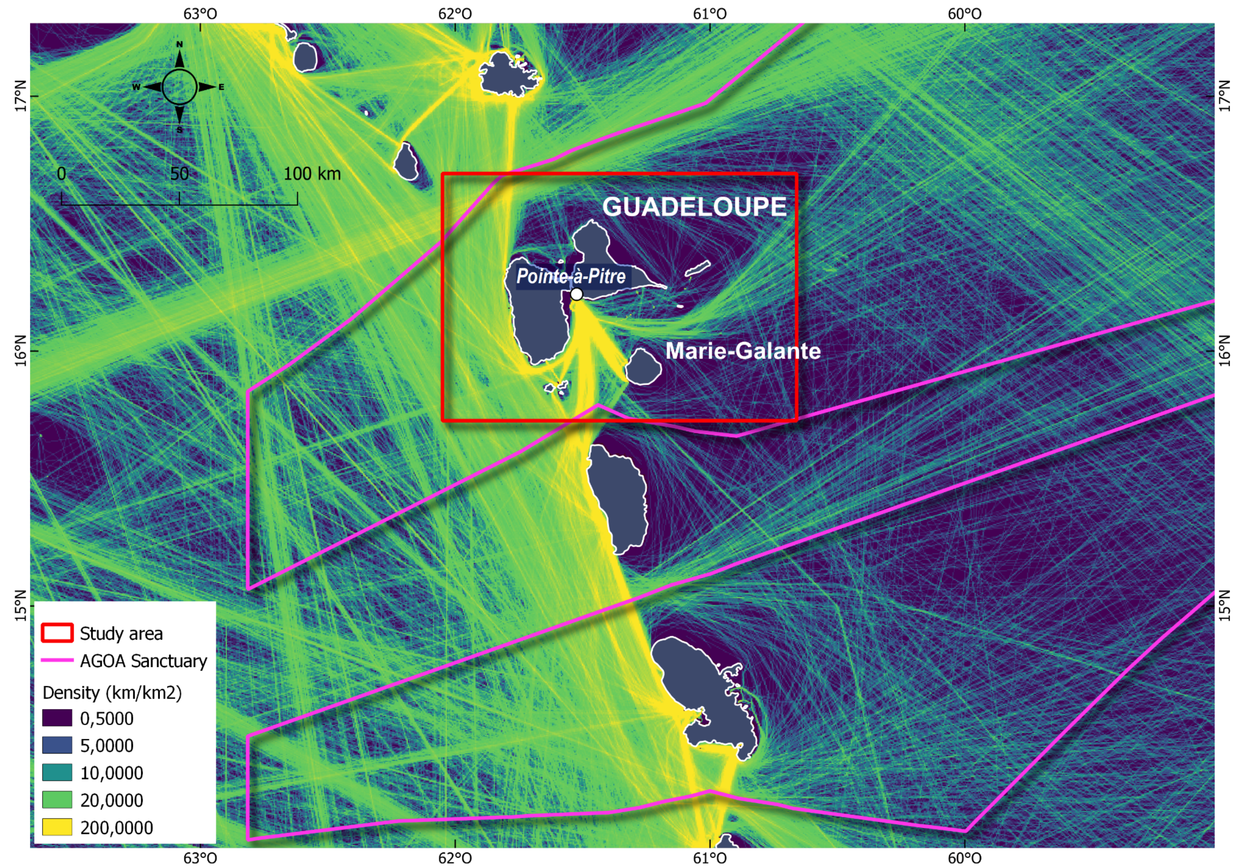


Fig.2- Shipping trajectories around Guadeloupe and the Agoa sanctuary in 2019 (source : ExactEarth, 2019; Produced by Geo4Seas).

To evaluate the pressure shipping exerts on its environment, we calculated 3 metrics with a cell resolution of 500 * 500m in an area corresponding to the spatial extent covered by the Kakila database (Coché et al 2021): (1) intensity (*I*), (2) occupancy (*O*) and (3) speed (*S*). Intensity (in $km.km^{-2}$) was generated as the total distance covered by ships, i.e. the sum of all segment lengths in the cell at the chosen temporal scale. Occupancy (in hr) was the total duration of ship presence at the chosen temporal scale, i.e. the total time spent in the cell. Speed (in *kn*) was the median of ship speed in the cell. These pressure indexes were calculated for global maritime traffic, by ship categories, and at biologically-relevant temporal scales for cetaceans: seasonally (wet season: June to November; dry season: December to May) and night and day temporal scale (day: 6h-18h, night: 18h-6h). Following the methodology of Halpern et al. (2008), we developed layers for each of the 3 pressure types D_i and combined them to obtain cumulative pressure (F_g) maps of maritime traffic on cetaceans such that:

$F_g = \sum_{i=1}^{n} D_i$ where D_i is the log-transformed (for *I* and *O*) and normalized (so that values are between 0 and 1) value of the anthropogenic stressor *i* (i.e. *I*, *O*, *S*), in a given cell and at a given temporal scale. As such, the cumulative pressure in 2019 was the cumulative scores of the individual pressures (i.e. *I*, *O*, *S*) at the wet and dry seasons in 2019. The day and night pressures were the cumulative scores of the individual pressures (i.e. *I*, *O*, *S*) at day and night time in 2019. For all pressure types, we only kept values between the 1th and 99th percentiles and we used the lowest 1th and highest 99th percentiles at each level (i.e. ship type, season, day/night) to rescale the pressures such that $D_i = {(d_i - p_1)}/{(p_2 - p_1)}$ where d_i was the log-transformed value of the anthropogenic pressure *i* (for *I* and *O*), p_1 was the lowest 1th percentile and p_2 the highest 99th percentile. Such transformation and rescaling processes are common in CEA to enable comparison and addition of stressors measured in different units and reduce the effects of outliers (Halpern and Fujita, 2013). All analyses were carried out with the software R (R Core Team, 2020) and maps were developed with QGIS v.3.18.

We then overlaid the topographic habitat features with the individual pressure maps to estimate the mean score of each pressure type (*I*, *O* and *S*) for the 6 topographic habitat features (abyssal plains, canyons and valleys, continental shelf, plains, ridges and breaks and slopes) and used *t-tests* to infer statistical differences (p<<0.05) in the mean pressure scores between the topographic habitat features We finally assessed the maritime traffic pressures likely placed over the different cetacean species of the Agoa sanctuary in 2019 and areas of concern, based on their topographic habitat preferences.

3. Results

3.1. Maritime traffic pressures

3.1.1. Cumulative pressure of maritime traffic

The cumulative pressure of maritime traffic for cetaceans in 2019 was illustrated in Fig.3. The highest pressures for cetaceans from maritime traffic were concentrated in routes originating from Pointe-à-Pitre and splitting towards Marie-Galante, southward and westward. The west part of the study area was quite homogeneously subject to a medium-level global pressure score while this medium-score pressure was more scattered in the east side. This is most likely due to the contrast in sailing conditions between windward and leeward coasts.

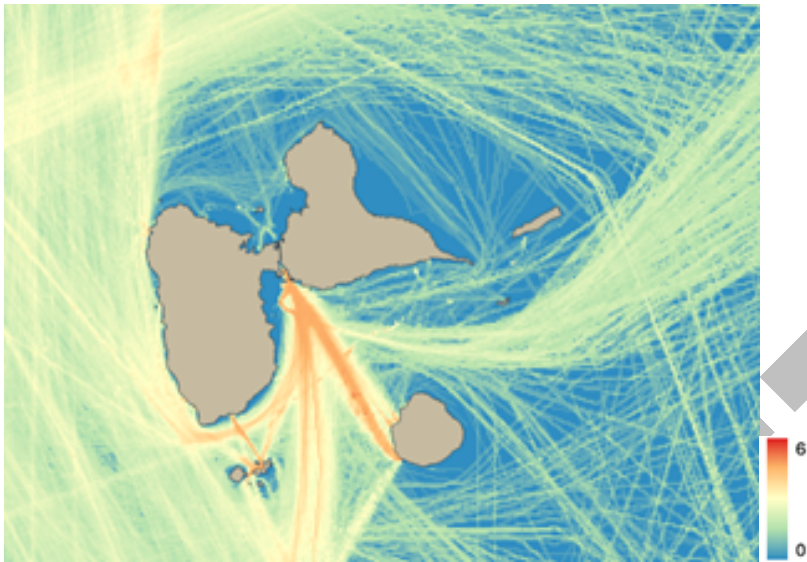


Fig.3- Cumulative pressure of the maritime traffic in 2019 as the cumulative score of the intensity, occupancy and speed pressures summed over the dry and wet seasons 2019 (maximum score of 6 as 3 normalized pressure scores x 2 seasons).

3.1.2. **Seasonality**

We found that maritime traffic cumulative pressure was higher at the dry season with a clear increase on the west coast compared to the wet season (Fig.4). As the dry season is the “touristic” season, the increase observed on the West coast is probably related to the increase in recreational boat traffic along the West coast. The Pointe-à-Pitre - Marie Galante route presented a similar cumulative pressure score at both seasons (Fig.4).

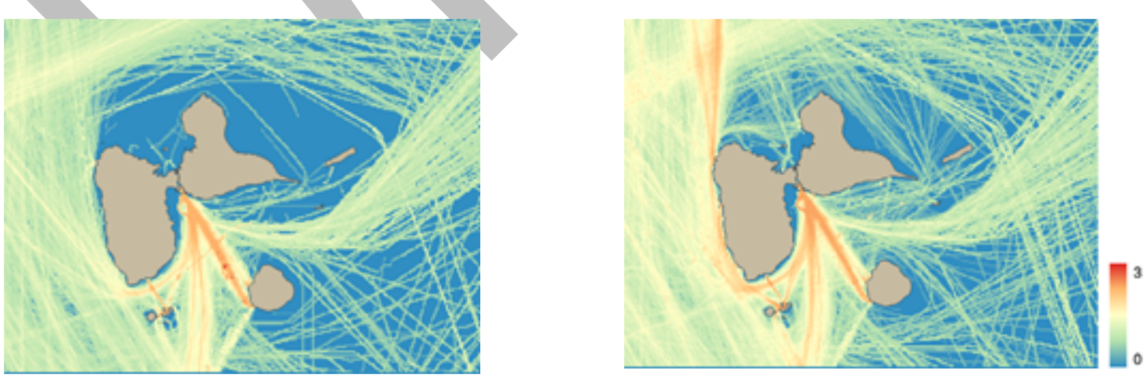
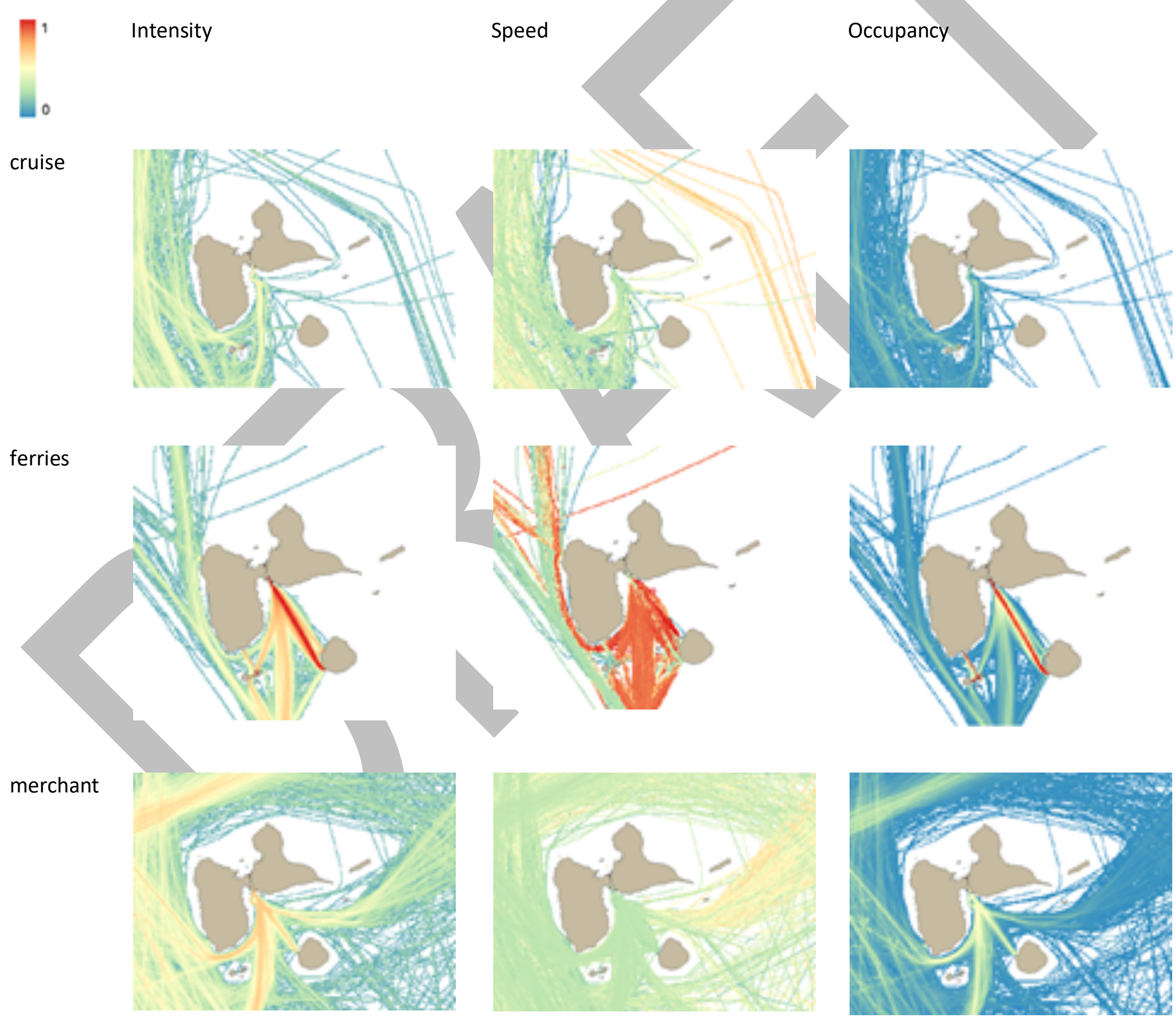


Fig.4- Cumulative pressure scores of the maritime traffic during the wet (left) and dry (right) seasons (maximum score of 3 as sum of 3 normalized pressure scores for *I, O* and *S*).

3.1.3. Ship-type pressure score

Ferries presented the highest score for the 3 pressures on localized areas, i.e., on the 3 routes originating from Pointe-à-Pitre and going westward, southward and towards Marie-Galante (Fig.5). Unsurprisingly, the strongest pressure came from the ferries because of their relatively high speed and their high spatial concentration: median speed was of 19.65*kn* (*sd*= 8.29), max intensity of 1,943km.km^{-2} and a maximum occupancy of more than 11hr per day. In comparison, Merchant ships presented a moderate level for intensity of traffic and speed (median speed = 12.49*kn* (*sd* = 4.22); median intensity: 6.72km.km^{-2} (*sd*=12.91,) but their pressures had a larger spatial coverage.



Other

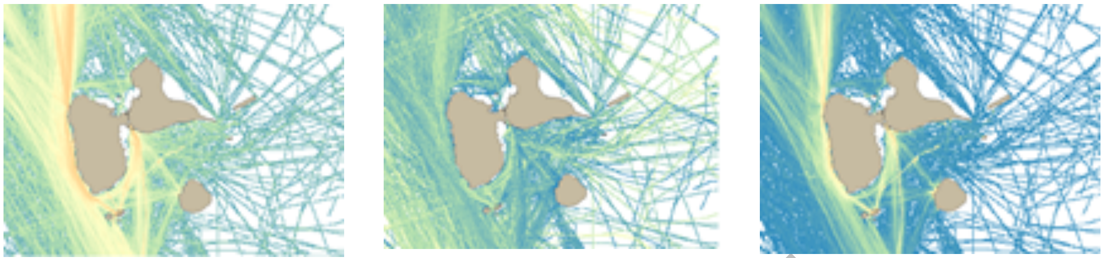


Fig.5- Pressure score by ship-type (maximum score of 1 as individual normalized pressure scores).

Pressure maps and results for each pressure type and at the night-day scale are available in Appendix A.

3.2. Maritime traffic pressures on cetacean habitats

3.2.1. Topographic Features of the study area

The topographic characteristics of the study area (Fig.6) displayed a chaotic underwater relief and a highly-fragmented landscape with a short and shallow continental shelf (with a maximum depth of 20 to 100m and a maximum extension of 15 km) around the Guadeloupe islands separated from abyssal plains by an escarpment of several hundred meters drop, fragmented by valleys and canyons (Augris and Clabaut, 2001).

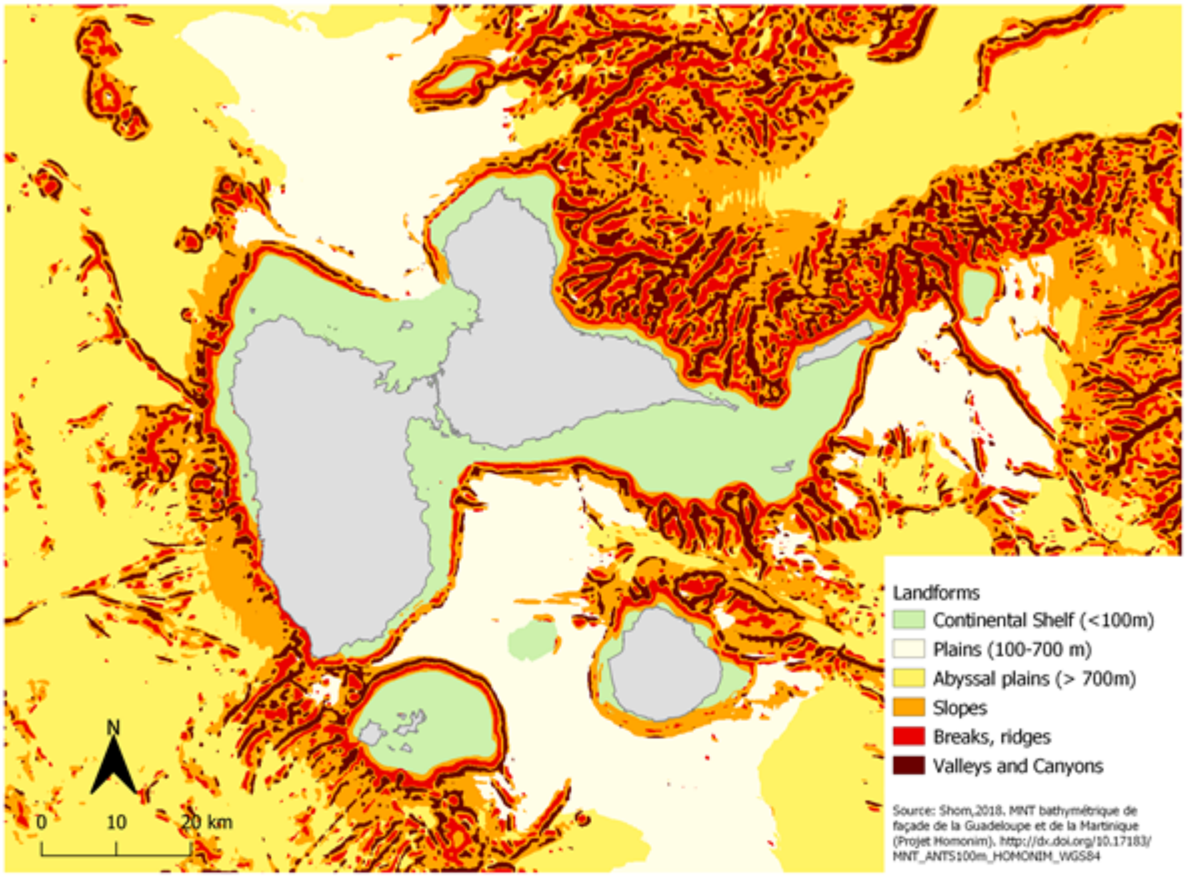


Fig.6 - Underwater topography of the study area based on the Benthic position index to characterise marine ecological habitat features for cetaceans.

3.2.2. Cetacean topographic habitat feature preferences

The complexity of the underwater topography provides different generic habitats, i.e. the plains and abyssal plains shared by most species of cetaceans but also specific habitats, i.e. the canyons favoured by the beaked whale species (Table 1).

Table 1- Preferred topographic habitat features for 9 species of cetacean inhabiting the Agoa sanctuary (after IUCN Red List, 2021).

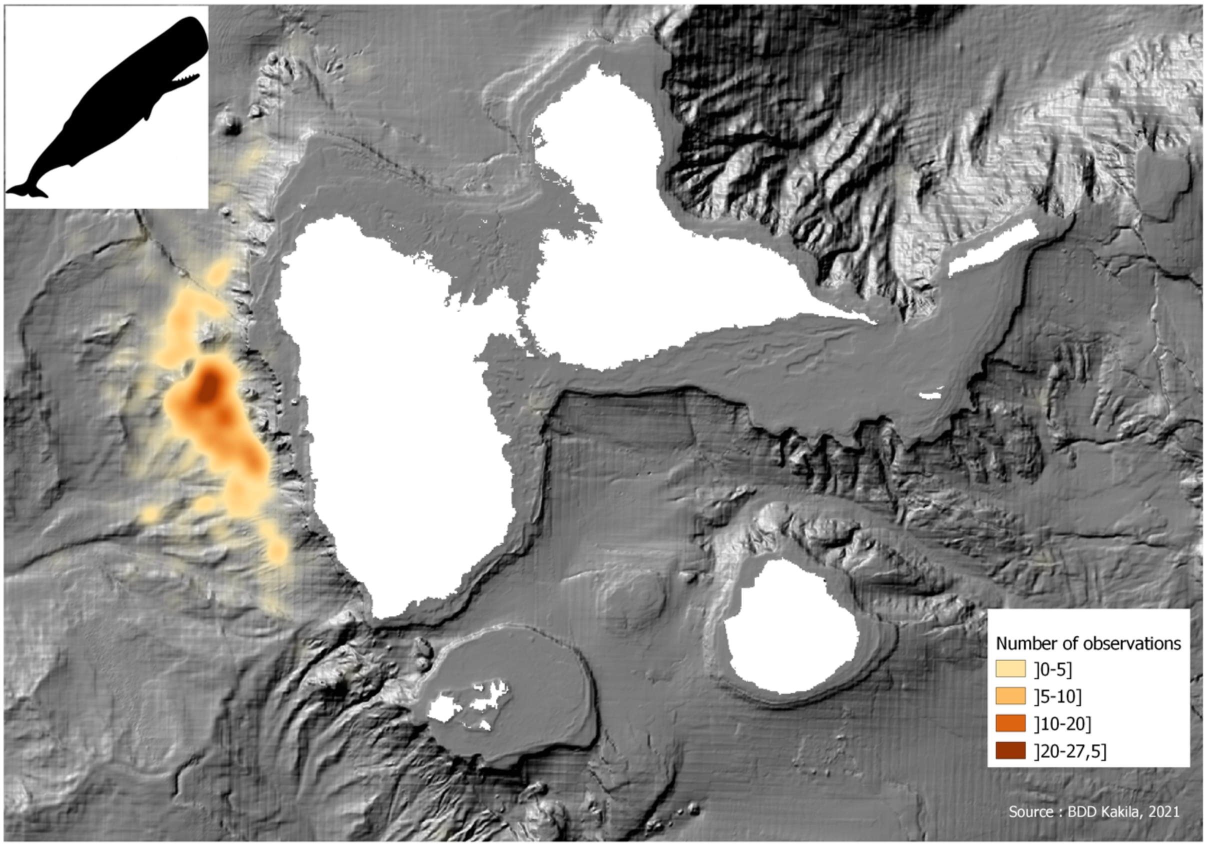
Common name	**Scientific name**	**Valleys and canyons**	**slope**	**Continental shelf**	**Plains**	**Abyssal plains**	**Ridges and breaks**
Humpback whale	*Megaptera novaeangliae*		**X**	**X**	**X**		
Sperm whale	*Physeter macrocephalus*		**X**			**X**	**X**
Short-finned pilot whale	*Globicephala macrorhynchus*				**X**	**X**	

Fraser's dolphin	*Lagenodelphis hosei*				X	X	
Pantropical spotted dolphin	*Stenella attenuata*		X	X	X	X	
Bottlenose dolphin	*Tursiops truncatus*				X	X	
Cuvier beaked whale, Blainville's beaked whale, Gervais's beaked whale	*Ziphius cavirostris,* *Mesoplodon densirostris,* *Mesoplodon europaeus*	X			X	X	X

In Fig.7, we illustrated the topographic habitat preferences for the 3 most encountered species of the Agoa Sanctuary using the Kakila database (Coché et al., 2021). Observations of pantropical spotted dolphins, sperm whales and humpback whales accounted for up to 75% of all observations in the Kakila database (respectively 30% (723 observations), 26% (622) and 19% (457)) and appeared spatially segregated (Table 2 and Fig.7). A hotspot of sperm whale observations was clearly present over slopes, ridges and breaks and abyssal plains of the West coast, matching at 84% with the preferred topographic habitat features reported in the IUCN Red List (Table 1). The pantropical spotted dolphins were encountered 80% of the time over topographic habitat features matching with the IUCN Red List and relative to the sperm whales, this species had two hotspots of occurrences spatially-distinct from the sperm whale hotspot. Finally, relative to the sperm whales and pantropical spotted dolphins, the humpback whales appeared to be most encountered closer to the coast, on the continental shelf with a 67% matching rate with the IUCN Red List (Table 2 and Fig.7). Although the Kakila database does not enable to statistically draw species distribution, the high matches between the observed and theoretically-preferred topographic habitat features for the most encountered species appeared to support the relevance of the proxy (topographic habitat features) used for cetacean distribution.

Table 2- Number of observations of sperm whales, pantropical spotted dolphins and humpback whales from the Kakila database over each topographic habitat feature (in highlight, the matches with the IUCN Red List preferred topographic habitat features (Table 1)).

Common name	Valleys and canyons	slope	Continental shelf	Plains	Abyssal plains	Ridges and breaks	Total Number of Observations
Sperm whale	98	**244**	1	1	**231**	**47**	622
Pantropical spotted dolphin	98	**225**	**1**	**7**	**346**	46	723
Humpback whale	42	**95**	**146**	**64**	28	80	457


Number of observations
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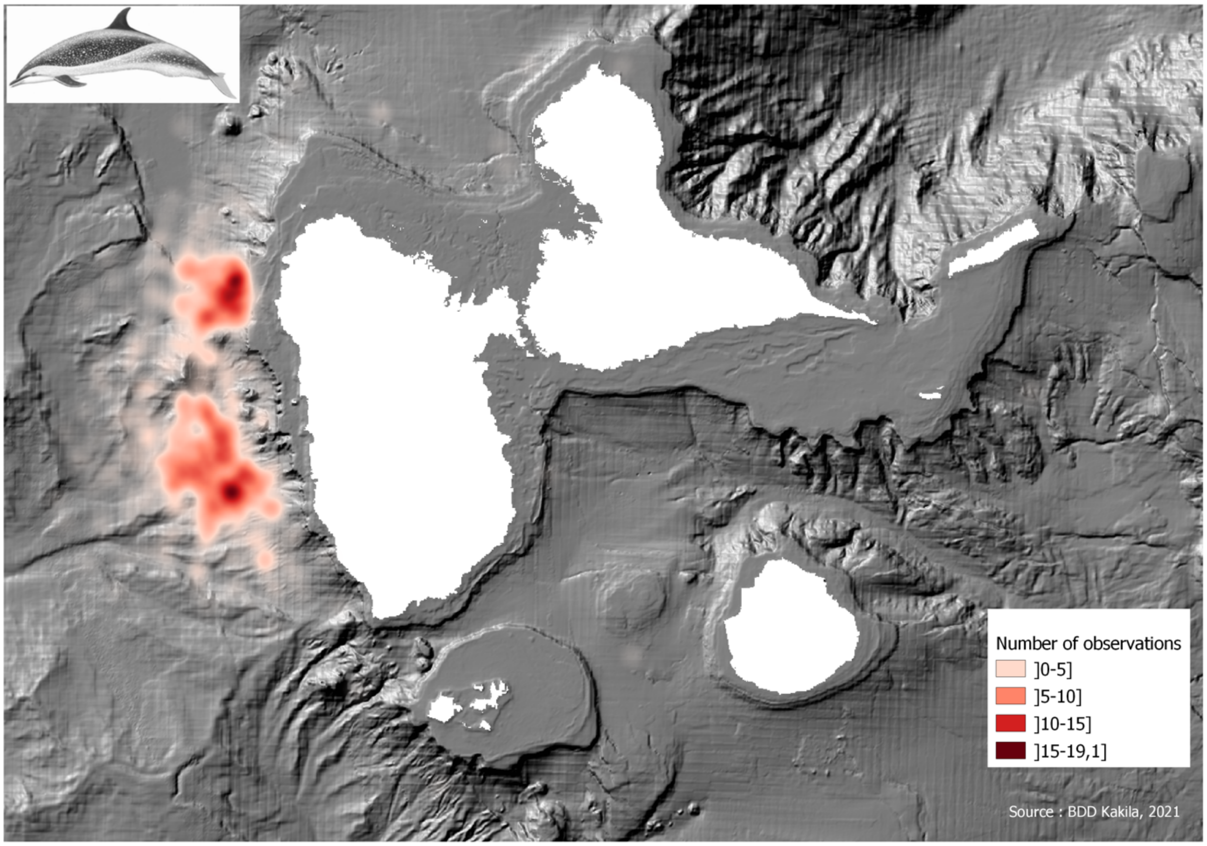
Source : BDD Kakila, 2021


Number of observations
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Source : BDD Kakila, 2021

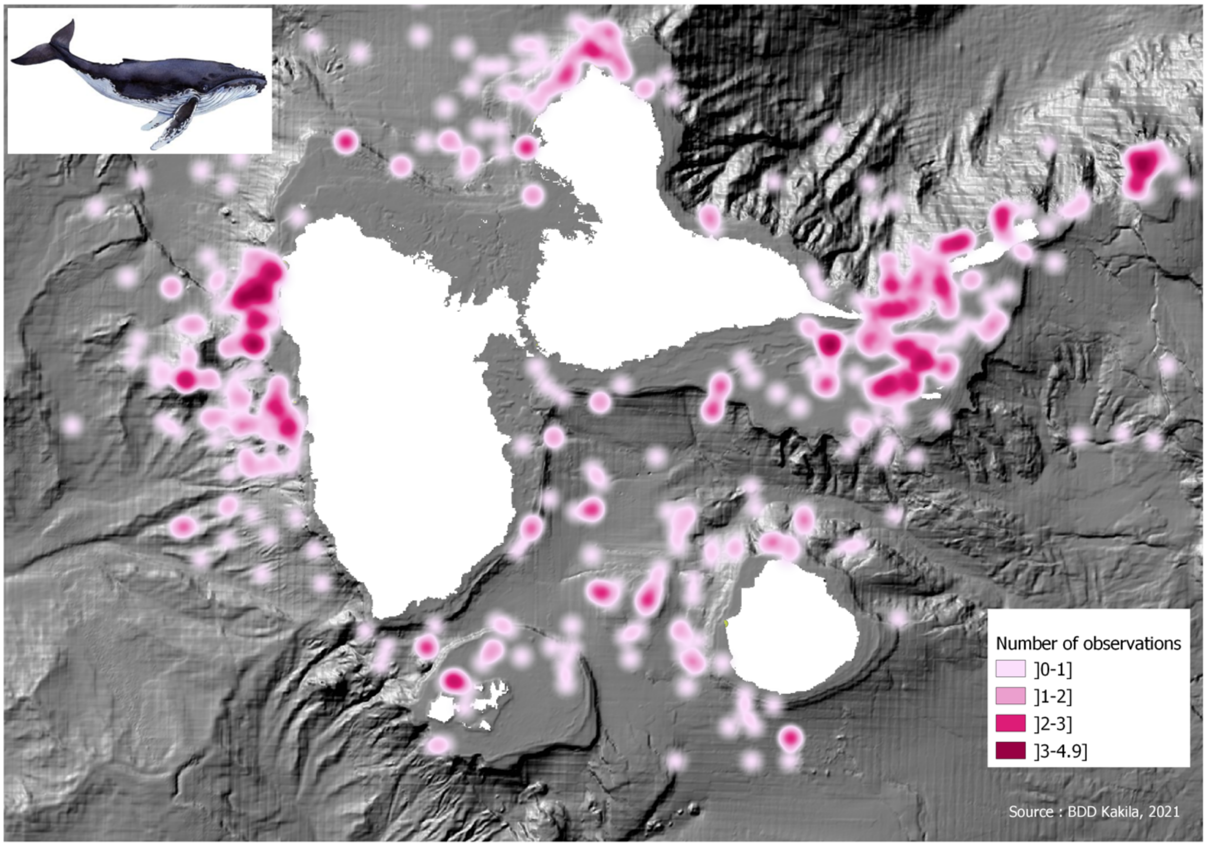

Fig.7- Heatmaps of the observations recorded in the Kakila database, of sperm whales (Physeter macrocephalus)(top), pantropical spotted dolphins (*Stenella attenuata*)(middle), and humpback whales (*Megaptera novaeangliae*)(bottom).

3.2.3. Pressure scores on the topographic habitat features

When looking at the pressure score per topographic habitat feature, the plains were subject to the statistically highest mean scores for the intensity and speed and the second highest mean score for occupancy (Table 3). This is unsurprising as approximately 2/3 of the traffic lanes between Pointe-à-Pitre and Marie-Galante cross the plains in the South. This was one of the most generic topographic habitat features (with abyssal plains), meaning that all species of cetaceans likely faced similar pressures from the maritime traffic in this habitat. However, three species were more dependent on the plains and therefore more at risk from intensity and speed: the bottlenose dolphins, the Fraser’s dolphins and the short-finned pilot whales. The speed pressure was also the highest over the slopes, canyons and valleys, ridges and breaks placing sperm whales and the group of Cuvier beaked whales, Blainville’s beaked whales, and Gervais’s beaked whales at higher risk of collision compared to the other species. Humpback whales and pantropical spotted dolphins were the species facing the highest mean occupancy over the shallow waters of the continental shelf which likely placed them at higher risk of disturbance from the maritime traffic (Table 3).

Table 3- Mean pressure scores (and associated standard error (*se*)) placed on cetacean topographic habitat features by maritime traffic in 2019 (the color scale pertains to the score level relative to the individual pressure type: the 'red' group had a statistically higher mean than the 'orange' group, than the 'yellow' group, than the 'green' group (*t*-test, *p*<<0.05)).

	Mean Intensity	**Mean Occupancy**	**Mean Speed**
Abyssal plains	0.929 (*0.003*)	0.316 (*0.002*)	0.784 (*0.002*)
Canyon and valleys	0.803 (*0.007*)	0.284 (*0.006*)	0.861 (*0.005*)
Continental Shelf	0.922 (*0.011*)	0.526 (*0.012*)	0.621 (*0.007*)
Plains	0.955 (*0.006*)	0.403 (*0.006*)	0.851 (*0.003*)
Ridges and breaks	0.797 (*0.007*)	0.278 (*0.006*)	0.865 (*0.005*)
Slopes	0.837 (*0.004*)	0.309 (*0.004*)	0.851 (*0.003*)

4. Discussion

The results from this work provide key insights on maritime traffic patterns in the Guadeloupean waters of the Agoa sanctuary. They can be used to inform management authorities and propose new conservation measures to avoid or reduce shipping impacts on cetaceans, and ultimately protect them. In this study, we propose a complementary approach to estimate the potential whale-shipping interactions, when specific impact data are not available. We used AIS data and a CEA approach, and developed metrics and scores to define individual and cumulative pressure on cetacean topographic habitats for our study area. We then overlaid the traffic pressures on the preferred habitat of several cetaceans, based on a topographic index.

Although primarily aimed at supporting ship-to-ship collision avoidance, the mandatory deployment of the AIS over the last decade has facilitated our understanding and knowledge of maritime traffic. The analysis of AIS data spans nowadays, from vessel routing and operations to complex issues such as the interaction between maritime traffic and wildlife or monitoring environmental compliance (Fournier et al., 2018; Robards et al., 2016). With regard to the knowledge and conservation of cetaceans, AIS data are now commonly used alongside observation data of some species, mainly to assess collision risk and exposure to noise pollution generated by shipping (Chion et al., 2012; Guzman et al., 2013; Lagueux et al., 2011; McWhinnie etal., 2021; Priyadarshana et al., 2016; Silber et al., 2021). But for cetaceans, the effects of maritime traffic pressures are not limited to physical injuries (collisions, hearing loss) and extend to more complex advert impacts such as physiological stress (e.g., caused by the prolonged or often recurrent exposure to ship presence or to noise), the creation of barriers to their movement and communication (e.g., via masking) and the modification of their behaviour, e.g., reduced foraging, shift or decrease in social activities, with short and long-term consequences (e.g., Lusseau et al., 2009; Erbe et al. 2019; Redfern et al., 2020; Smith et al., 2020, Jung & Madon 2021). This is why our study distinguished three types of pressures that can be associated to better decipher the risks of maritime traffic for cetaceans: the pressure due to vessel speed with potential risk of physical injuries and noise-related impacts, the pressure due to occupancy and last the intensity that might lead to disturbance and noise-related impacts. Accordingly, we provided evidence that all vessel types did not contribute equally to the maritime pressures, highlighting the need for a vessel-type approach in developing management measures. These pressures were analyzed at several temporal scales to account for the circadian and seasonal cycles of cetaceans. Combined together, our results highlighted the need to better consider temporal dynamics to define regulations and regulations in MPAs (also see Izadi et al., 2018; Lemieux et al., 2018; Nelson et al., 2008).

In recent years, the application of CEA has emerged as a strategic instrument to support decision-making for the development of efficient and sustainable marine spatial planning and management of marine resources (Andersen et al., 2017; Coll et al., 2012; Hammar et al., 2020; Korpinen et al., 2021; Tulloch et al., 2015; Wyatt et al., 2017). We followed a simplified version of the method in Halpern et al. (2008) to calculate and map cumulative pressures. In our study, we assumed that the pressures and their potential response (the impacts) were additive. The three pressure types were given equal weight and their scores can be added up to produce a cumulative pressure map. However, it is unlikely that cetaceans respond linearly and uniformly between and among species (e.g. differential species and age-class vulnerability to each pressure, such as mother and calf known to be particularly vulnerable to speed) to an increase in the pressure score (Stepanuk et al., 2021). Research and empirical data are therefore needed to refine the maps by better characterising species responses to single maritime traffic pressures and to cumulative pressures. These improvements are crucial to identify critical thresholds, to provide standardized scoring scale of pressures by species and to develop appropriate key indicators in relation to maritime traffic (Harwood et al., 2014; Spitz et al., 2018). At present, the only pressure type that has an agreed critical threshold is speed, and concerns the risk of collision with large whales: below 10*kn*, the likelihood of ship strikes is believed to be significantly reduced and the probability of lethal injury for whales to be less than 50% (Laist et al. 2001; Laist et al., 2014; Vanderlaan and Taggart, 2007). Similar thresholds need to be agreed on by biologists for the pressures of occupancy and intensity in order to have comparable scores for a given species and across species. But based on the findings from this study, cetaceans seem to be at high risk of collisions with ferries in clearly-identified shipping lanes that mostly cover a habitat type (i.e. the plains) shared by most species of the sanctuary. Additional data are needed to confirm presence of cetaceans in this area and observers could be appointed to ferries in order to record cetacean presence on the traffic lanes. E-DNA and systematic-transect campaigns could also inform on the use of this area by cetaceans (Jung & Pendleton 2021, Jung et al. 2021).

Our study highlights a critical lack of robust and non-opportunistic data on cetaceans in the Agoa Sanctuary, to be able to infer the presence, distribution and critical habitats of these species with respect to maritime traffic. This gap is only partially filled by the collection of opportunistic occurrence data and by a few large-scale but scarce-in-time scientific surveys (Coché et al. 2021; Jung et al. 2021; Laran et al. 2019). Here, we used cetacean preferred topographic habitat features as a proxy for cetacean distribution to link pressure scores and species at risk from these pressures. The data from the Kakila database for the 3 most encountered species in the Agoa Sanctuary (75% of the observations in the last 20 years) seem to validate the relevance of the use of the topographic habitat features as a proxy for cetacean distribution. However, given the current limitations of the Kakila database to infer species distribution, further studies are needed to validate local habitat use and suitability for the cetacean species inhabiting the sanctuary (e.g. Jaquet and Whitehead, 1996; Naud et al., 2003; Oviedo and Solis, 2008). The recent development of the Kakila database which is based on citizen science, represents however, a stepping stone and should provide a rationale and motivation for guiding Agoa sanctuary management towards gathering additional essential data for policy guidance and conservation (Zuilan et al., 2021). Finally, in order to have a more complete picture of maritime traffic pressure in the area and develop relevant mitigation or preventative measures, data from vessels not carrying the AIS and analysis for other pressures attributable to maritime traffic are needed (Weilgart, 2007).

5. Perspectives for marine spatial planning

The findings of this study provide a baseline for developing indicators and start monitoring maritime traffic pressures on marine megafauna in the Guadeloupean waters of the Agoa sanctuary in the light of the EU Marine Strategy Framework Directive[5] needs and requirements. Unrestricted vessel activities cannot be compatible with cetacean conservation. Therefore, trade-offs have to be found between conservation goals and socio-economic needs. An adaptive management could be strategic to take into account the variation in maritime traffic patterns highlighted in this study: speed reduction in targeted areas, e.g. the Pointe-à-Pitre-Marie-Galante route; seasonal displacement of shipping lanes, e.g. with a traffic separation scheme (TSS) to move the shipping lanes away from the West Coast when humpback whales are present, and away from the canyons, valleys, breaks and ridges where Cuvier beaked whales, Blainville's beaked whales, and Gervais's beaked whales are at high risk of collision. There is a well-recognized need for fine-scale analyses of the spatial congruency between maritime traffic pressures and cetacean presence in a context of increasing anthropogenic pressures on marine ecosystems. In the Mediterranean Sea, the Pelagos sanctuary has also been registered, in 2002, as a marine mammal sanctuary and is also "under siege" from anthropogenic pressures (Coll et al., 2012). Several studies have been trying to describe there, spatial shipping distribution at different scales to help guide marine spatial planning in relation to marine mammal distribution (Coomber et al., 2016). Other studies in the Pelagos sanctuary focused on identifying collision risks from maritime traffic (e.g., Di-Meglio et al., 2019; Grossi et al., 2021) and the risk of the exposure to high intensity vessel traffic areas (Pennino et al., 2017) for specific species. From these empirical studies to move towards management strategies, many examples are available elsewhere with successful outcomes for balancing trade-offs between species conservation and human activities: the ECHO program of the Port of Vancouver, the TSS in Panama and California or the Green Alliance Certification program in North America (Laist et al. 2014; Guzman et al., 2020; Burnham et al., 2021). In the Guadeloupean waters of the Agoa sanctuary, a combination of fixed and dynamic strategies with both voluntary and mandatory measures could be envisioned for better acceptance and compliance of stakeholders and to adequately address the trade-offs between conservation and human activities.

[5] MSFD : https://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm

Credit authorship contribution statement

Bénédicte Madon, Iwan Le Berre, Damien Le Guyader, Eric Foulquier, Pascal Jean Lopez: Conceptualization.

Bénédicte Madon, Damien Le Guyader: Methodology.

Bénédicte Madon, Damien Le Guyader, Iwan le Berre: Formal analysis.

Iwan Le Berre, Eric Foulquier, Jean-Luc Jung: Funding acquisition.

Bénédicte Madon: Writing - original draft. Writing - review & editing – all authors.

Acknowledgement

This research was supported by the Fondation de France programme "The future of the coastal and sea worlds", project TRAFIC(N° 1940). It was also funded by the LabEx DRIIHM French programme “Investissements d’Avenir” (ANR-11-LABX-0010), which is managed by the ANR.

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