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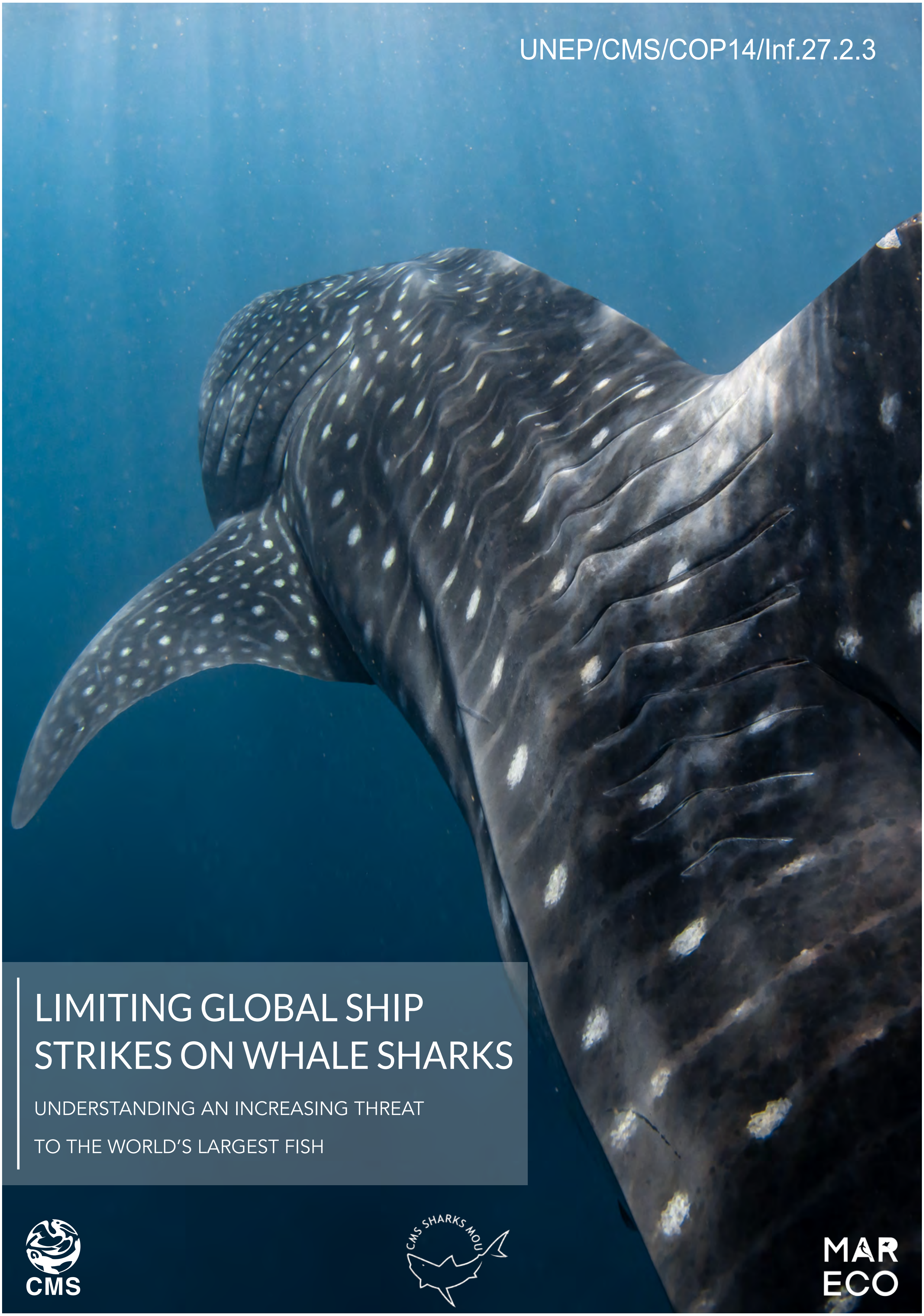

# LIMITING GLOBAL SHIP STRIKES ON WHALE SHARKS

## UNDERSTANDING AN INCREASING THREAT TO THE WORLD'S LARGEST FISH

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# Limiting Global Ship Strikes on Whale Sharks:

## Understanding an increasing threat to the world's largest fish

**Gonzalo Araujo, Christoph A. Rohner & Freya C. Womersley**

### About the authors

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### Contributors

We would like to thank all of our collaborators and colleagues for their invaluable contribution, expert knowledge and insight, which were critical for this report. Contributors in alphabetical order: Katya Abrantes, Shin Arunrugstichai, Shir Bar, Adi Barash, Peter Barnes, Adam Barnett, Ginevra Boldrocchi, Noemie Buffat, Tom Canon, Clara Canovas Perez, Metavee Chuangcharoendee, Jesse Cochran, Tyler Clavelle, Rafael de la Parra, Stella Diamant, William Driggers, Christine Dudgeon, Mark V. Erdmann, Richard Fitzpatrick, Anna Flam, Gemma Francis, Beatriz Eugenia Galvan, Rachel Graham, Sofia Green, Jonathan R. Green, Ya'ara Grosmark, Hector M. Guzman, Royale S. Hardenstine, Jessica-Lily Harvey, Maria Harvey, Abdi Wunanto Hasan, Alexander Hearn, Jill Hendon, Mochamad Iqbal Herwata, Mahardika Rizqi Himawan, Eric Hoffmayer, Jason Holmberg, Hua Hsun Hsu, Ashlee Jansen, Christy Judd, Muhammad Moazzam Khan, David A. Kroodsma, Baraka Kuguru, Emily Lester, Kirsty Magson, Rossana Maguiño, Mabel B. Manajaji-Matsumoto, Stacia Marcoux, Travis Marcoux, Jennifer McKinney, Mark Meekan, Alejandra Mendoza, Emily Monacella, Brad Norman, Cameron Perry, Simon Pierce, Clare Prebble, Dení Ramírez Macías, Holly Raudino, Samantha Reynolds, David Robinson, David Rowat, Jennifer Schmidt, Chad Scott, Abraham Sianipar, Conrad Speed, Ismail Syakurachman, See S. Tian, Julian Tyne, Kelly Waples, Timothy D. White, Chloe Winn, Ranny R. Yuneni and Irthisham Zareer.

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### Disclaimer



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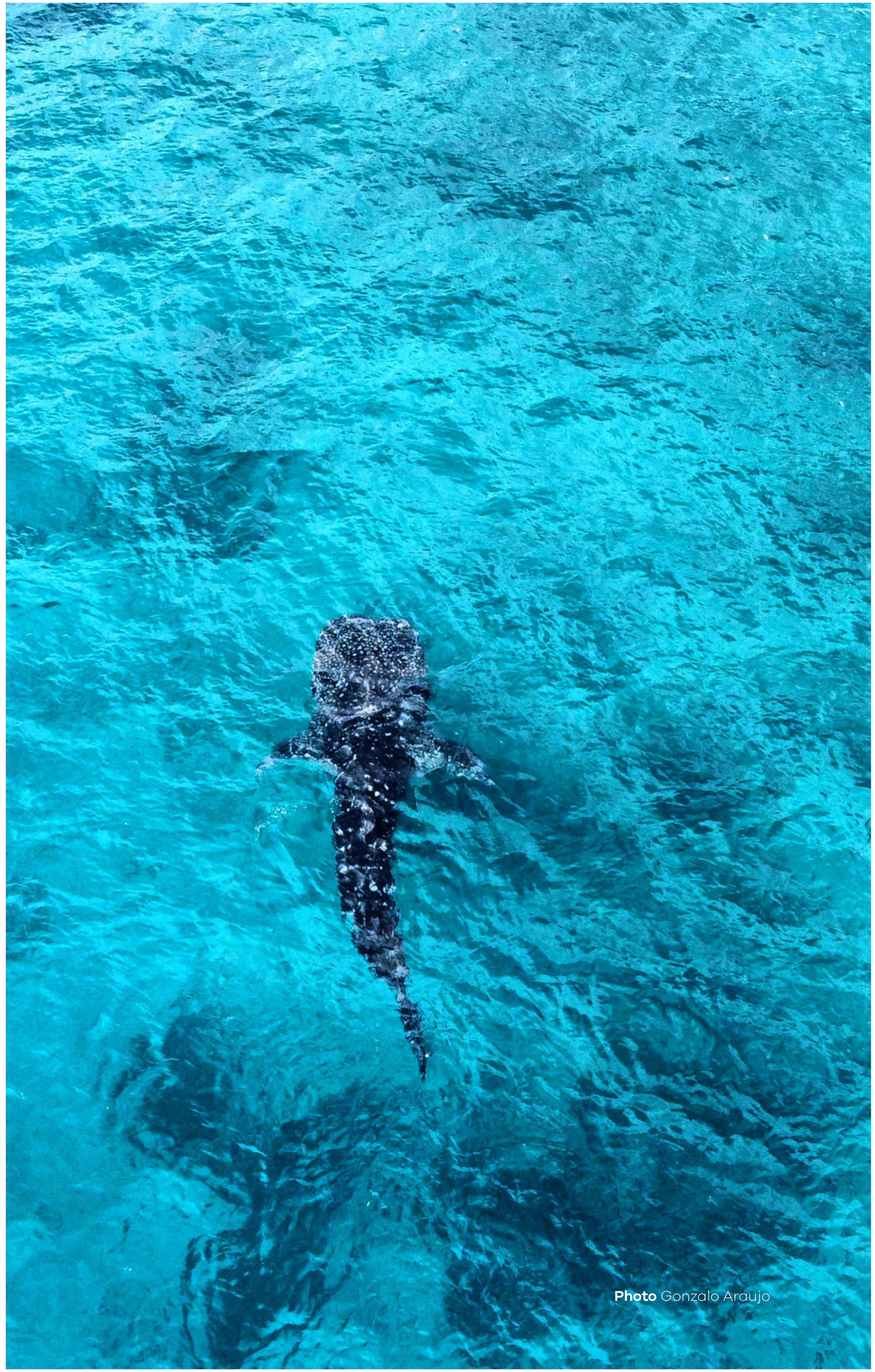

**Photo** Gonzalo Araujo

Photo Chris Rohner

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# EXECUTIVE SUMMARY

The whale shark is the world's largest fish and is globally assessed as Endangered on the International Union for the Conservation of Nature (IUCN) Red List, and Largely Depleted on the IUCN Green Status of Species. This negative outlook is largely the consequence of targeted fisheries and non-targeted fisheries induced mortality across much of their tropical to warm-temperate distribution. With long generation times, they are susceptible to anthropogenic threats. While direct fisheries have now largely stopped, an additional source of cryptic mortality that could be hindering the recovery of the species was recently attributed to ship strikes.

Whale sharks spend around half of their time in the top 20 m of the water column, and as such are prone to vessel collisions. Collisions with large vessels are likely fatal, yet due to the negative buoyancy of their cartilaginous skeletons, dead whale sharks sink and thus go unreported. To ensure the species recovery, we need to mitigate their main threats, including ship strikes.

Whale sharks are likely to be most at risk from ship strike in major shipping routes as they travel far distances across the ocean, and within small, predictable hotspots where up to 400 individuals aggregate, often to feed. Over 340 satellite tracks have identified the key areas where whale sharks are at high risk from shipping during their migrations. These included areas in all oceans, such as in the Gulf of Mexico, the Gulf of Panama, between Australia and Indonesia, and in the Red Sea. Some of the tagged whale sharks also revealed potential mortality events, where the tracks stopped right in the middle of busy shipping lanes.

Here, we focus on the second aspect, the small, predictable key aggregation sites where high densities of whale sharks can be found. Through expert elicitation, we defined the known global core habitats for the species (>40 'hotspots' cover >12,000 whale sharks) and overlapped those with shipping traffic data from 2017–2019. Our results show that many whale shark hotspots, particularly in the Arabian Sea and adjacent waters, the Gulf of Mexico, the Gulf of California, and in Southeast and East Asia, are at relatively higher risk from ship strikes within the core whale shark habitat zone. Not only is there spatial overlap, but there are temporal concerns when shipping is highest at the same time as the whale shark hotspots are at their peak aggregation times. Management is therefore required by Range States to ensure mitigation of ship strikes.

Focusing on global whale shark core habitats is an important first step as mitigation measures here can have a positive impact on a large number of sharks, and costs to shipping are low because of the small size of these hotspots. Better whale shark protection could be achieved through the designation of Areas To Be Avoided or vessel exclusion zones, even if temporarily assigned; through Traffic Separation Schemes that concentrate ships and reduce the area of overlap with whale sharks; through vessel speed reduction within these critical areas; and through the use of alert networks that can complement these or be used at local levels. Further work to develop site-specific mitigation mechanisms is required in collaboration with industry, government and research stakeholders. Our work supports the Concerted Action for the Whale Shark under CMS proposed by the government of the Philippines and adopted in 2017 during COP12.

**Photo** Chris Rohner

Photos Chris Rohner





# 1. BACKGROUND

Whale sharks share their circumglobal habitat with an expanding fleet of vessels that is important in global trade. Whale sharks are Endangered and vessel strike poses a threat to the species, particularly in areas with high densities of whale sharks that overlap with high vessel traffic. Lessons learned from dolphins and whales, which are also impacted by vessels, may guide mitigation measures that help protect whale sharks in key areas.

## 1.1 WHALE SHARK ECOLOGY AND CONSERVATION

Sharks and rays are some of the most endangered animal groups on the planet (Dulvy *et al.* 2021). They often grow slowly, reach maturity at an old age, and have few offspring – life history traits that make them particularly vulnerable to anthropogenic threats. Whale sharks follow this pattern. They are born at ~60 cm long and males reach maturity only ~25 years later, while for females it is likely to be 30+ years until they first reproduce (Pierce *et al.* 2022). This strategy means that they cannot cope with added, unnatural mortality. As a result, whale sharks were assessed as 'Endangered' on the International Union for Conservation of Nature (IUCN) Red List and as 'Largely Depleted' in the IUCN Green Status of Species. Population declines have been mainly driven by past targeted fisheries in the Indo-West Pacific region, and ongoing non-targeted fisheries induced mortality in purse-seine and gillnet fisheries across the species range (globally in tropical and warm-temperate seas) (Rowat *et al.* 2021). The species was listed on the United Nations Convention on the Conservation of Migratory Species of Wild Animals (CMS) Appendix II in 1999, and in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) in 2002. The species was further listed on Appendix I of CMS in 2017 and is covered by the CMS Memorandum of Understanding on the Conservation of Migratory Sharks (also known as the Sharks MOU). A recent source of cryptic mortality in whale sharks was highlighted that warrants further investigation to understand the species' road to recovery. Collisions with large vessels, most of which go unreported and unnoticed due to the negative buoyancy of the sharks' bodies, could be playing a significant negative role hindering the species' recovery, noting that even though targeted fishing has been prohibited across most Range States, numbers continue to dwindle.

## 1.2 WHALE SHARK CONSTELLATIONS

Whale sharks are the largest fish in the world and have a circumglobal distribution, yet surprisingly little was known about them until the 1990's. Over the last three decades, the whale shark has become one of the best-studied shark species, largely due to the discovery of sites where many individuals predictably aggregate and are accessible to researchers. These whale shark hotspots, termed constellations (Norman *et al*. 2017), are scattered throughout the tropics and sub-tropics (Fig. 1). There are three characteristics of whale shark constellations that are most pertinent to the mitigation of ship strikes: their predictability, the extensive use of surface waters by whale sharks, and the population segregation observed in the species:

**Constellations are predictable in time and space.** While the wider movements of whale sharks vary considerably among individuals, without clear migration patterns like in some whale or turtle species, constellations are small, defined areas. Some constellations have whale sharks present throughout the year and others are seasonal. Constellations bring together individuals that are otherwise solitary, and are of high importance to the

### WHAT IS A WHALE SHARK?

Whale sharks, *Rhincodon typus*, are true sharks. They have a cartilaginous skeleton and breathe water through their gills. Their name reflects the similarities they share with baleen whales: a large body size and a filter-feeding lifestyle. Whale sharks are gentle giants, popular with marine tourists, and a charismatic flagship species that resonates with the public.

**Class:** Chondrichthyes
**Order:** Orectolobiformes
**Family:** Rhincodontidae
**Genus:** *Rhincodon*
**Species:** *Rhincodon typus*

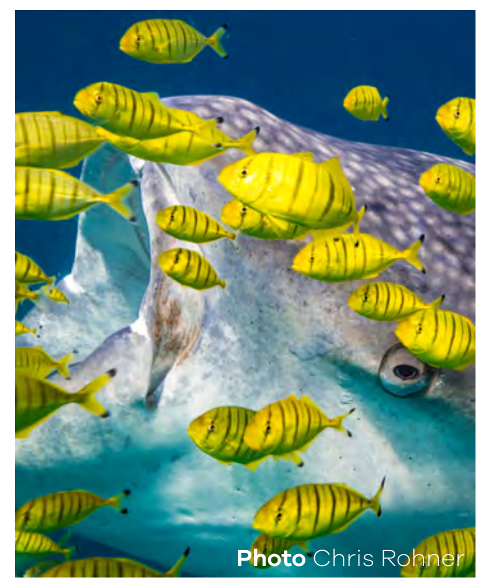


Photo Chris Rohner

# BACKGROUND

species. The small size, predictable nature, and high importance of constellation areas makes them ideal targets for protecting whale sharks from anthropogenic threats.

In most constellations, **whale sharks feed at the surface**, where they are also at risk from ship strike. In these areas, many whale sharks congregate to feed in concentrated patches of zooplankton, which is otherwise often too diffuse to be a target for whale sharks. For example, up to 400 individuals feed together on fish eggs that are floating at the water surface off the Yucatán Peninsula in Mexico (de la Parra Venegas *et al.* 2011). Visual observations are made during the day, so we know that whale sharks spend a lot of their day-time at the surface when they are feeding within constellations.

**Whale sharks segregate by sex and size.** Many constellations consist of large juvenile individuals and most are male. Small juveniles and adults are rarely seen, and large juvenile females only make up ~15-25% of the sharks in constellations (Rohner *et al.* 2022). The habitat of neonates, females, and large mature whale sharks is poorly characterised at present. This means that conservation measures within constellations are important, but that they only benefit part of the overall whale shark population.

Globally, ~18,000 individual whale sharks have been identified and logged on the global database www.sharkbook.ai. Almost all logged encounters are from the constellations in Figure 1. Considering the sex and size segregation, and the migratory nature of the species, there are clearly more whale sharks present in the ocean, but the same reasons make it difficult to estimate a total number of individuals globally. Instead, researchers have recorded individual whale shark sightings within constellations over many years to examine trends in abundance. For example, whale shark sightings off Praia do Tofo in southern Mozambique have steeply declined (Rohner *et al.* 2013) and population models have estimated an 89% decline in abundance from 2005–2019 (Auditore *et al.* 2022). No long-term study has reported an increase in abundance so far. It is possible that less-recognised threats, such as non-targeted fisheries induced mortality, ship strike, or marine pollution, are at a level that hinders recovery. It is also possible that the life history of the species means that populations will take more time to recover from recent bans on fishing. Given that whale sharks are Endangered, a precautionary approach is warranted to address all recognised threats to their survival, including ship strikes, before it is too late.

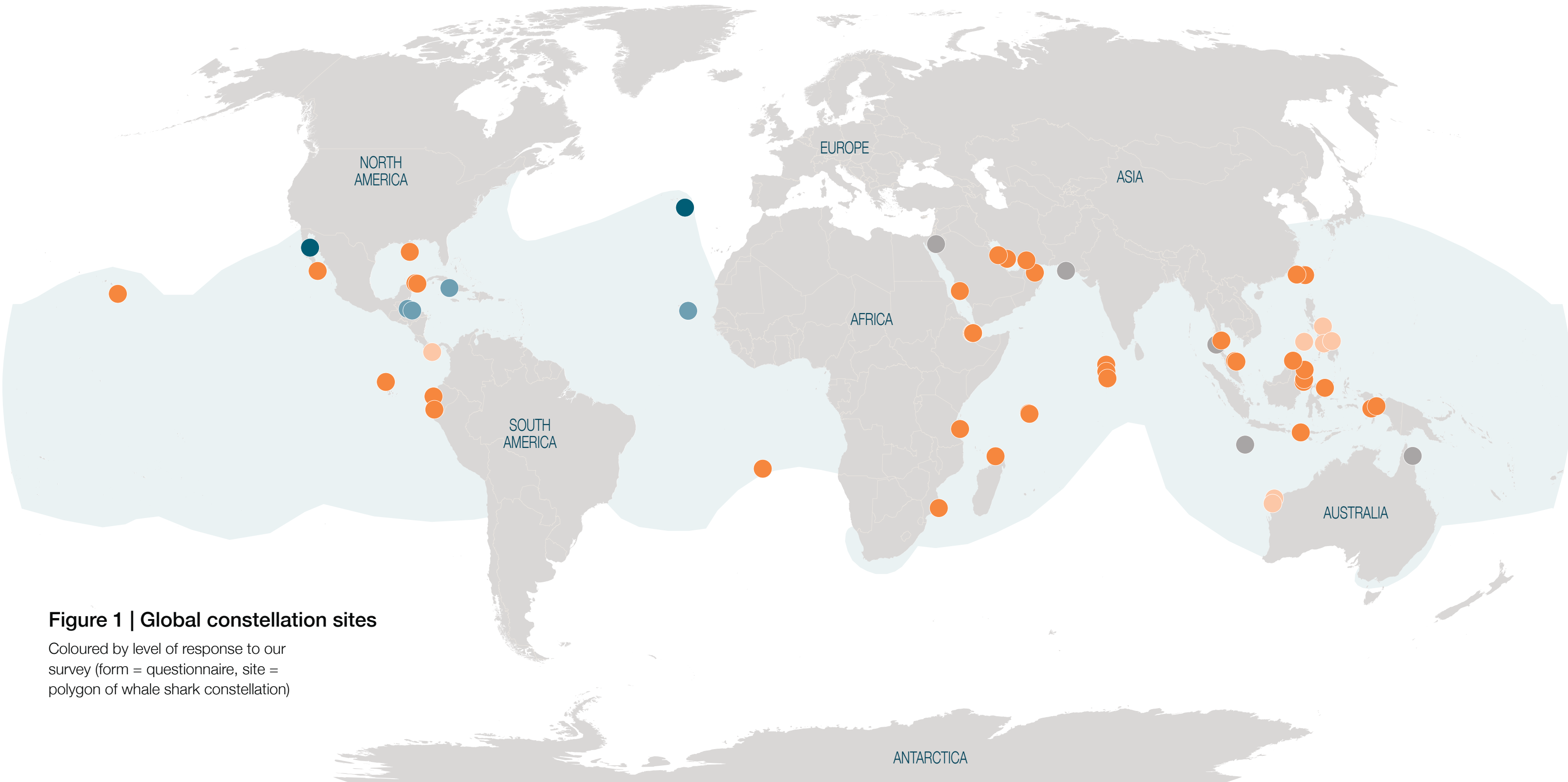



**Figure 1 | Global constellation sites**

Coloured by level of response to our survey (form = questionnaire, site = polygon of whale shark constellation)

Photo Chris Rohner

### 1.3 WHALE SHARK MOVEMENTS AND MIGRATIONS

Constellations play an important role for whale sharks, particularly for the nutrition of large juveniles that make up most of the world's known hotspots. However, individual whale sharks move in and out of these sites and likely spend a significant portion of their time in offshore waters. The other parts of the population (small juveniles, females, adults), largely absent from constellations, are also likely to be oceanic (Rohner *et al.* 2022). Whale sharks tracked with satellite tags have moved 1,000's of kilometres through the ocean (reviewed in Hearn *et al.* 2022). Short tag retention (typically <6 months) relative to the life-span of the species means that we do not fully understand their movements yet. However, juveniles and adults spend much of their time away from the coast. No clear pattern in their habitat use away from the coast has emerged yet, so protection measures at localised constellations (Fig. 1) likely have the best chance of improving the species' conservation at present.

Whale sharks have been tracked to a depth of almost 2,000 m (Tyminski *et al.* 2015). Current tags break beyond this depth and have a failsafe release triggered by the pressure at depth. Tagged whale sharks regularly initiate this release, so they likely dive even deeper. Despite these dives into cold, dark, deep waters, they spend most of their time at or near the surface. A global dataset of 348 tracked whale sharks showed that they spend almost half of their time in depths <20 m, where they are susceptible to the draft and hydrodynamic draw of large moving vessels (Womersley *et al.* 2022).

### 1.4 EMERGING THREAT: SHIP STRIKE

Fishing is the single-largest threat to sharks in general. Whale shark numbers suffered an estimated decline of >50% during the past 75 years (Pierce and Norman 2016), largely driven by targeted fisheries. Most of these fisheries have now stopped following species-level protection measures in many countries (e.g. Philippines, 1998). Remaining targeted fisheries, non-targeted fisheries induced mortality and ship strikes are the three most pertinent threats to whale sharks at present (Rowat *et al.* 2021). A recent study highlighted that the risk from ship strike is likely to be higher than previously thought (Womersley *et al.* 2022).

Large vessels travel much faster than whale sharks. At high speeds, vessels cannot avoid a collision even if they see a whale shark in their path. Similarly, whale sharks cannot out swim an approaching vessel. The main causes of mortality or severe injury are:

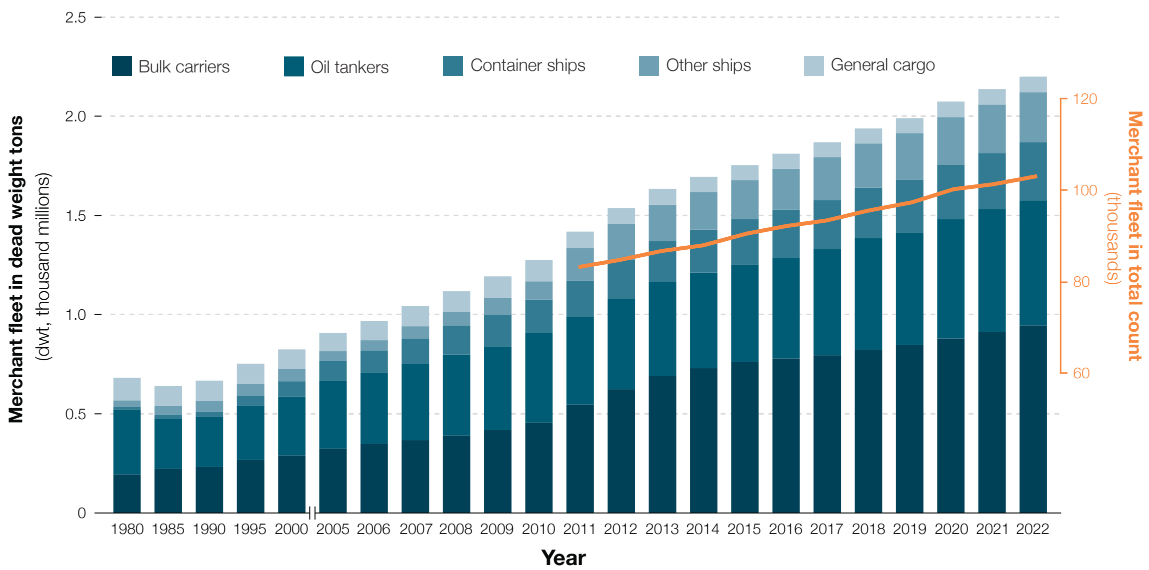
- **Collision with the hull (blunt trauma)**
- **Cuts by propellers (lacerations, amputations)**

Additionally, shipping noise may impact habitat use with indirect consequences but further investigation is needed

Photo Fabio Maria Lopes Costa

# BACKGROUND

**Figure 2 | Shipping is on the rise**
Data sourced from United Nations Conference on Trade and Development (UNCTAD) reports




Reports of whale sharks getting hit by ships date back to the earliest whale shark literature over a hundred years ago. Marine traffic has increased since, and continues to expand (Fig. 2). Ships are bigger and travel faster, meaning that this threat has likely amplified too. The reason why it has not gotten more attention until recently is that ship strikes go unnoticed and/or are unreported. Whale sharks are negatively buoyant and quickly sink if dead, unlike whale carcasses that float, making it more difficult to quantify mortality due to vessel collisions. The recent analyses by Womersley *et al.* (2022) show that the risk of ship strike varies spatially, but can be high and may hinder the recovery of the species.

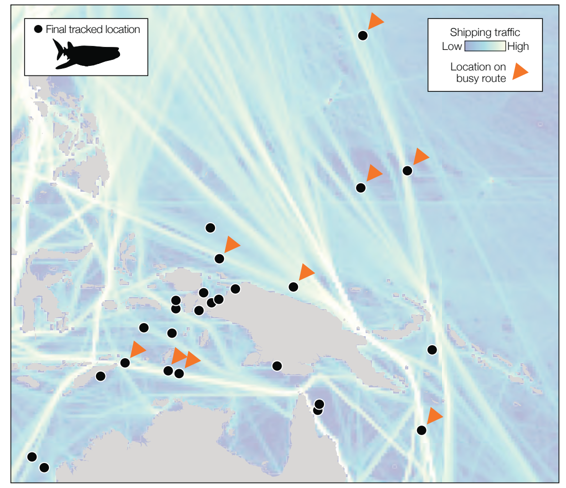
Womersley *et al.* (2022) combined whale shark movement tracks to establish high-use areas of whale sharks to overlay with ship traffic data and assess relative collision risk. Large vessels were present in over 90% of the areas they moved through, meaning there are few places in the ocean where whale sharks are completely undisturbed by shipping. Away from coastal aggregations, during movements in both territorial waters and Areas Beyond National Jurisdiction (ABNJs), tracked whale sharks often crossed busy shipping routes where the potential for ship strike is high (Fig. 3). Some of the areas of high risk included the Arabian/Persian Gulf, Red Sea, Gulf of Mexico, and the Gulf of Panama which are also home to several key constellation sites (Fig. 4). Cargo vessels posed the greatest threat globally due to their extensive coverage of the ocean and many persistent, heavily-used routes passed close to or through whale shark high-use areas all year round providing little respite to sharks during their long-distance migrations.

Tracks with highly accurate locations further demonstrated that whale sharks and ships routinely pass very close to each other. Ships travelled more than 10 times the speed of whale sharks, and, worryingly, the whale sharks in this case did not show any avoidance behaviour to ships. Using information on where some of these tracks ended, this study was also able to identify several potential cases of collision-related mortality. Almost a quarter of tags attached to whale sharks stopped transmitting in highly dense shipping areas (Fig. 3) and several cases were identified where depth recording tags slowly sunk to the seafloor and popped off in some of the most heavily used shipping areas in the world.

This recent study explored collision risk from a number of angles using data from satellite-tracked whale sharks as they move throughout the ocean. Here, we build on these findings and provide an additional layer of analyses specifically focussed on

**Photo** Chris Rohner

**Figure 3 | Final whale shark tracking locations**
Potential mortality from ship strike reproduced from Womersley *et al.* (2022)



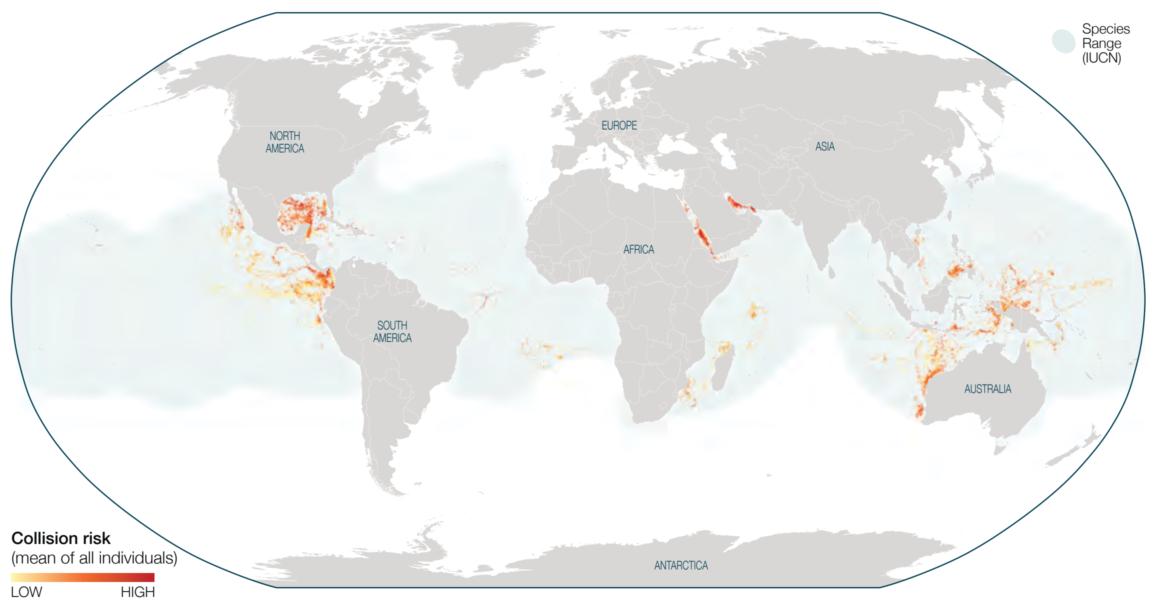

whale shark constellations. The main benefit is that a constellation-based approach can capture much more detail about shipping impacts at a scale local enough to inform management, and more data are available from observations than from the relatively few satellite tracks currently available. Since constellations are particularly important to the species, managing threats within these areas will have a disproportionately large positive impact on their conservation as a whole.

### *1.4.1 What influences the risk of ship strike?*

Several factors influence the risk of vessels colliding with whale sharks. Blue bullets indicate that we examined the factor in our analyses, grey bullets mean that more data are needed to include the factor in quantitative analyses:

- **Ship density:** Areas with high densities of ships pose a higher risk for whale sharks.
- **Whale shark habitat use:** Areas where whale sharks aggregate in high numbers have a higher risk of ship collisions.
- **Whale shark migrations:** Whale sharks enter and leave aggregation sites on their wide movements, so areas surrounding immediate hotspots likely have more vessel strikes.
- **Whale shark behaviour:** Feeding whale sharks pay less attention to their surroundings, elevating the risk of vessel collision.
- **Whale shark vertical movement:** Whale sharks are only susceptible to vessel collision in the top ~20 m of the water column. They generally spend much of their time in surface waters, but localised differences in their depth use can influence the risk.
- **Avoidance behaviour:** Whale sharks are generally not known to show avoidance behaviour towards boats, but it is not yet known if localised adaptations exist.
- **Vessel speed:** At normal vessel speeds, collision risk is higher than when vessels slow down, giving both parties more time to evade a collision.
- **Vessel size and maneuverability:** Large vessels have deeper drafts and thus, a larger strike zone and are less likely to be able to avoid whale sharks if they happen to see them due to their slow turning speeds.

**Figure 4 | Global collision risk based on satellite-tracked whale shark movements**
Averaged monthly risk to individual transiting sharks (n = 348) reproduced from Womersley *et al.* (2022)



# BACKGROUND

### 1.5 LESSONS LEARNT FROM OTHER MARINE MEGAFAUNA

Vessel strike is a major threat to other marine megafauna, particularly to marine mammals. Like whale sharks, dolphins and whales also spend much of their time in surface waters and cover large distances in coastal and oceanic waters, leaving them vulnerable to vessel strike. Unlike whale sharks, however, whales and dolphins tend to float when they die, so there is more information available on causes of their mortality, and thus their threats are better defined. For example, 17 of 20 Bryde's whale deaths in the Hauraki Gulf of New Zealand had injuries from ship strike (Constantine *et al.* 2015). Generally, vessel strike has long been identified as a key threat to marine mammals (Laist *et al.* 2001), but the risk appears to have increased with increasing ship traffic over the past decades (Ritter and Panigada, 2019). The resulting mitigation measures developed to better protect dolphins and whales from ships can now inform the steps we need to take to quickly turn things around with whale sharks.

The main management strategies developed to reduce vessel collisions with whales are area-based management, such as moving shipping routes away from critical whale habitat, vessel speed reduction, early warning systems, acoustic deterrents, and observers spotting whales ahead (see details in the policy section below). When managers know where and when to implement targeted collision mitigation strategies they can be a success. For example, off Cape Cod in the north-eastern USA, North Atlantic right whales, *Eubalaena glacialis*, are threatened by busy ship traffic moving into and out of nearby ports, such as Boston. North Atlantic right whales are also one of the most endangered whale species, with <400 individuals left. Mortalities have been mainly attributed to ship strikes and entanglement in fishing gear. To improve their conservation, a seasonal management area with vessel speed restrictions to <10 knots and mandatory reporting was established, and the main shipping route was moved to avoid the most important feeding zones in the area (Wiley *et al.* 2013; Silber *et al*. 2015). Here, fines were more effective in enforcing the rules than reprimanding letters or on-water radio contact with offending vessels. The measures have led to a decrease in vessel collisions in this area, although whale numbers in the full population are still low. Whale shark populations could also benefit from the same evidence-based approach to mitigation, through a reduction in ship strike-induced mortality.

**Photo** Chris Rohner


Photo Chris Rohner





# 2. ASSESSING THE RISK

of ship strike in whale shark constellations and in their overall distribution

We collated data on whale shark distribution and timing of constellations, and overlaid shipping data to examine the risk of vessel strike in each of the global whale shark hotspots. Local experts from around the world shared their knowledge of whale sharks within key constellation sites, allowing us to develop risk metrics specifically for each site.

## 2.1 METHODS

We set out to quantify the risk whale sharks face from large vessels at each of their global hotspots. We focus on large vessels (>300 gross tons) here because they have an Automatic Identification System (AIS) beacon that allows us to track their movements, and because collisions are likely to be fatal for whale sharks (Womersley *et al.* 2022). Although smaller vessels can also have detrimental effects on whale sharks (e.g. Penketh *et al.* 2020; Lester *et al.* 2020), they cannot be tracked on a global scale, and we could only include a qualitative measure of their threat (see below).

### *2.1.1 Expert elicitation*

The whale shark is one of the most studied species of shark globally, with a great expert network and research studies spanning over two decades. We developed an online, semi-structured questionnaire (Appendix 5.1) to elicit experts' knowledge of their whale shark constellations (Fig. 1) to understand the level of threat large vessels pose to whale sharks. Topics such as the number of whale sharks, seasonality in sightings, perception of threats, and local policy were included. To gain a better understanding of global whale shark trends, we also asked whether their respective constellations were increasing, stable or decreasing. The experts were asked to map the area where they see most whale sharks (core habitat) and where they see any whale sharks (buffer zone). For sites where no expert spatial information was available (which included the Azores, Ningaloo, Bahía de Los Angeles, Panama and the Philippines), constellation boundaries were drawn from the literature (Ramírez-Macías *et al.* 2012; Afonso *et al.* 2014; Anderson *et al.* 2014; Araujo *et al.* 2014, 2017, 2019; McCoy *et al.* 2018; Guzman *et al.* 2022). In total, 100 core and buffer areas were compiled and, for the first time, spatial data from almost all global constellations were combined in a worldwide analysis. We then analysed the answers and maps to evaluate the spatially-explicit risk whale sharks face from shipping at each constellation.

### *2.1.2 Shipping analysis*

Gridded shipping data were provided by Global Fishing Watch (GFW, https://globalfishingwatch.org) at a 0.1 x 0.1° cell resolution scale which equates to approximately 11.1 km at the equator. Each cell provided the count of uniquely identified vessels within a ~123 km² area for every month in 2017 through to 2019. This information was provided for 8 different classes of vessel: 'bunker or tanker', 'bunker', 'cargo or reefer', 'cargo or tanker', 'cargo', 'container reefer', 'passenger' and 'specialised reefer' (Fig. 5). Shipping data were overlaid with each constellation site and cropped to include cells that fell within or intersected the site boundary. Then, shipping activity was summarised within the area. We summarised activity monthly using shipping data averaged between 2017 and 2019 for each month and then annually by averaging each month from the 2017–2019 aggregates. For each vessel class the minimum, maximum and mean count of vessels within each cell in a constellation area was calculated. These calculations were also performed for all vessel classes combined to reflect total vessel activity. Core habitats of each constellation were ranked between 1–5 by sorting mean total vessel activity into 5 quantiles. This 'Danger Rank' reflects the relative localised risk based on shipping density within each site.

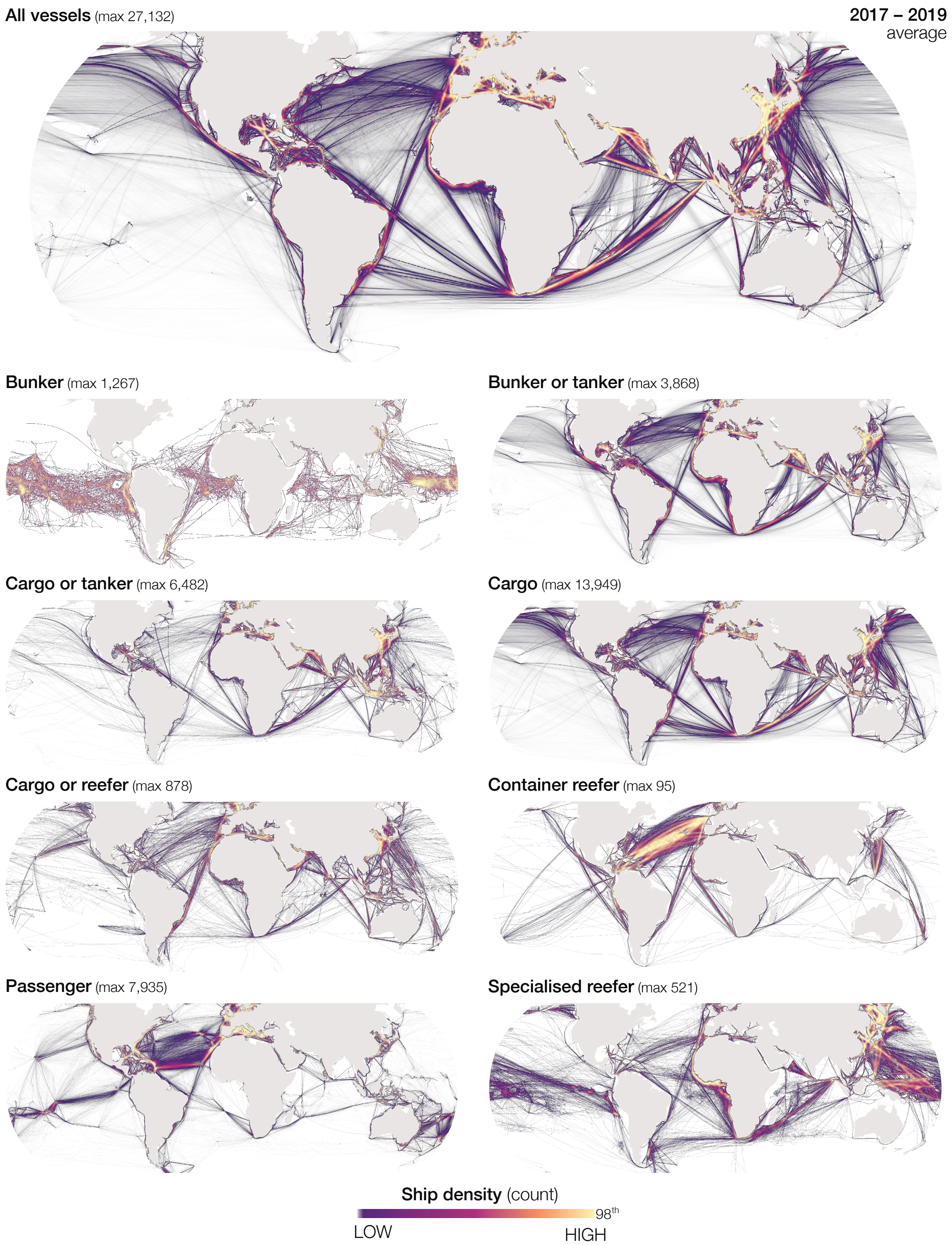
To examine the risk whale sharks face as they enter or leave the immediate constellation area (core habitat and buffer zones), we added "peripheral zones" reaching up to 100 km around each core site and analysed shipping activity in these surrounding waters. Here, mean total vessel activity within the peripheral zone was sorted into 5 quantiles, providing each site with a quantifiable 'Danger Rank' between 1–5 which represents the relative risk based on where each site is positioned globally; higher vessel count is interpreted as higher danger. Months of higher or lower shipping activity were calculated based on positive or negative differences from the annual average for each constellation and the ship type posing the greatest relative threat was determined from the highest mean count from the annual average.


Photo Simon Pierce

# ASSESSING THE RISK

Figure 5 | Global shipping distribution

Data sourced from Global Fishing Watch showing count of vessels per month within 0.1° resolution cells




### 2.2 RESULTS

#### *2.2.1 Expert elicitation*

Scientists from most global whale shark constellation sites rated threats, injuries, and the risk posed by vessels based on their in-water observations over many years of whale shark surveys. Experts were mostly concerned about the impact of tourism and small vessels affecting whale sharks at these sites, but they also greatly agreed that large vessel collisions are likely to be a major threat to whale sharks in general.

We received questionnaire responses from 40 global whale shark hotspots in 23 countries (Fig. 1). The number of whale sharks in constellations varied widely, but overall, experts reported observations from ~12,800 individuals. This is over 70% of all identified whale sharks on the global database (shakbook.ai). The sites with the largest number of individuals identified were Ningaloo Reef in Australia, the Mexican Caribbean, Arabia, and southern Mozambique (Table 1; Fig. 6). Although more than half (56%) of constellations reported that whale sharks can be seen throughout the year, only two locations (Hawai'i and the South Ari Atoll in the Maldives) did not have a defined peak season (Fig. 7). On average, the whale shark peak season lasts between 3 to 4 months. For example in Honda Bay, Philippines whale sharks are mostly seen from June to September, and in Coiba, Panama the peak season is from December to February (Fig. 7). Some constellations had a short peak season of 1 month, such as Shib Habil in the Red Sea or Saleh Bay in Indonesia, and others had longer peak seasons, including, for example, Baa Atoll in the Maldives with six months. The relatively short peak seasons overall mean that temporally-restricted management measures, tailored to the respective peak season in each location, could enhance protection of whale sharks within their constellations. Before designing particular management strategies, however, it will be important to work with local experts to derive quantitative measures of seasonality, rather than relying on these survey results alone. Nevertheless, our results do show that seasonal management could be a feasable and efficient option within whale shark constellation areas.

Whale shark core habitat zones were generally small, with a median area of 116 km² (Table 1). For example, the core whale shark zone in southern Mozambique was 144 km², and in St Helena it was 98 km². The smallest core zones were at two provisioning sites in Gorontalo (<0.1 km²) and Oslob (0.1 km²), and off Darwin Island in the Galápagos (1.1 km²). By far the largest core zone was in the northern Gulf of Mexico (~91,000 km²; Table 1), although it is possible that further examinations of whale shark habitat use there will be able to identify smaller hotspots within this large area.

**Photo** Chris Rohner

**Table 1 | Whale shark constellation site population summary based on information received from experts working at each of the known areas globally.** Constellation size relates to the total number of encounters (column 3) and total number of individuals identified (column 4) per site during the defined monitoring period. The five largest sites are coloured in column 4. Population trend status represents a local estimate based on data and expert perception. Constellation areas are given in km² for each core site and were summed when more than one area was submitted.

| County code | Constellation site | Constellation size: # Encounters | Constellation size: # Individuals | Population trend: Status | Constellation size: Area/ km² |
|---|---|---|---|---|---|
| AUS | Christmas Island | 100 | 45 | - | - |
| | Ningaloo Reef | 44,607 | 1,473 | Neutral | 157.9 |
| | FarN Queensland | 50 | 15 | Neutral | - |
| DJI | Djibouti | 3,229 | 762 | Neutral | 20.8 |
| ECU | Galápagos | 953 | 626 | Neutral | 1.1 |
| | Mainland Ecuador | 45 | 7 | Neutral | 58.2 |
| GBR | St Helena | 860 | 483 | Slightly Increasing | 98.1 |
| IDN | Cenderawasih Bay | 538 | 153 | Neutral | 260.6 |
| | Kaimana | 439 | 76 | Increasing | 214.3 |
| | Saleh Bay | 459 | 108 | Neutral | 387.1 |
| | Gorontalo | 891 | 33 | Slightly Decreasing | 0.002 |
| | Derawan Island | 44 | 23 | Neutral | 209.2 |
| | Talisayan | 178 | 75 | Neutral | 44.1 |
| ISR | Bay of Aqaba | - | - | Decreasing | - |
| MDG | Nosy Be | 1,800+ | 497 | Slightly Decreasing | 606.4 |
| MDV | South Ari Atoll | 6,488 | 404 | Decreasing | - |
| | Thaa Atoll | 245 | 42 | - | 116.3 |
| | Baa Atoll | 280 | 94 | - | 82.8 |
| MEX | Caribbean & GoM | 10,600 | 1,335 | Slightly Decreasing | 974.2 |
| | La Paz Bay | 1,039 | 623 | Neutral | 212.7 |
| MOZ | Mozambique | 3,788 | 806 | Decreasing | 144.2 |
| MYS | Malaysian waters | 750 | 206 | Increasing | 663.6 |
| PAK | Pakistani waters | ~400 | 150 | Neutral | - |
| PAN | Coiba | - | 25 | Slightly Decreasing | 899.4 |
| PER | Northern Peru | 750 | 224 | Slightly Decreasing | 20.5 |
| PHL | Donsol | 4,985 | 614 | Slightly Increasing | 40.2 |
| | Honda Bay | 506 | 321 | Increasing | 396.8 |
| | Oslob | 42,732 | 423 | Slightly Increasing | 0.1 |
| | Pintuyan | 1,976 | 321 | Slightly Increasing | 51.1 |
| QAT OMN | Al Shaeen, Daymaniyat Islands, Musandam | - | 819 | Neutral | 111.8<br>64.5<br>4,452.9 |
| SAU | Saudi Arabian Gulf | 135 | 5 | Neutral | 2.9 |
| | Shib Habil | 403 | 154 | Neutral | 17.0 |
| SYC | Mahe | - | 550 | Decreasing | 23.6 |
| THA | Koh Tao | 249 | 178 | Slightly Increasing | 674.0 |
| | West Thailand | 228 | 52 | Neutral | - |
| TWN | Taiwan waters | >507 | ~315 | Increasing | 7,570.0 |
| TZA | Mafia Island | 2,300 | 222 | Neutral | 80.9 |
| USA | Northern GoM | 800 | 109 | Decreasing | 90,797.1 |
| | Hawai'i | 643 | 416 | Neutral | 752.3 |
| **Responses** | | 35 | 38 | 36 | - |
| **Summary** | | Min 44 | Min 5 | + + 11.1% | Sum 110,206.6 |
| | | | | + 13.9% | |
| | | Max 44,607 | Max 1,473 | : 47.2% | Mean 3,148.8 |
| | | | | - 13.9% | |
| | | Sum 133,997 | Sum 12,784 | - - 13.9% | Median 116.3 |

(++) Increasing, (+) Slightly Increasing, (:) Neutral, (-) Slightly Decreasing, (--) Decreasing

**Figure 6 | Global constellations coloured by number of individual whale sharks identified**

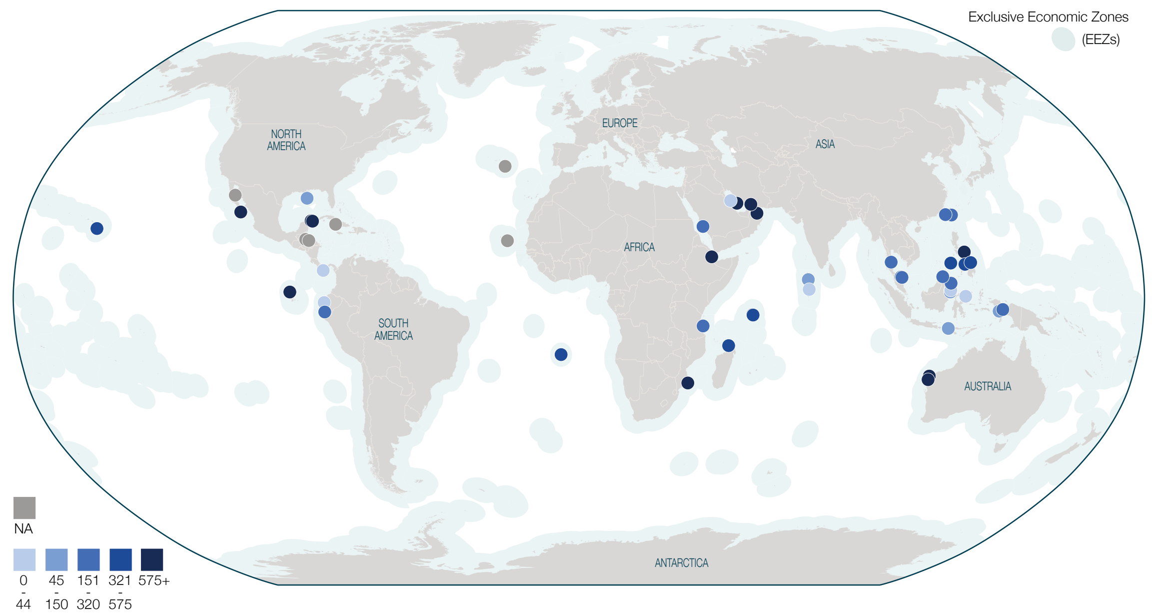
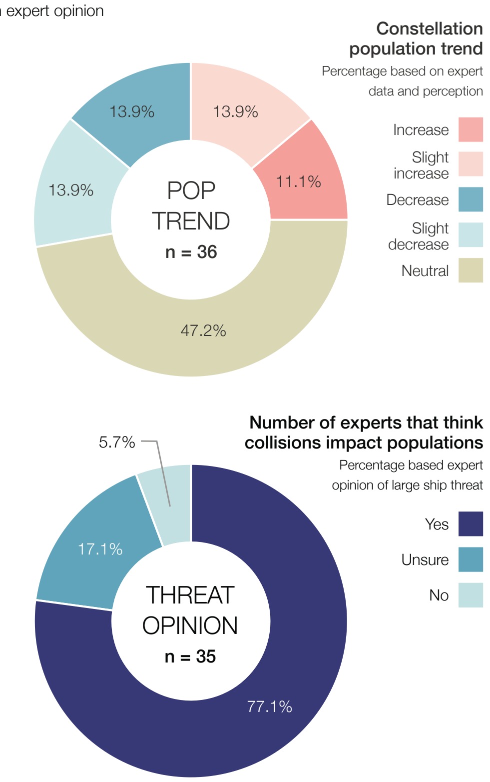



**Figure 7 | Constellation seasons**
Based on expert knowledge


Experts thought that the whale shark numbers in their constellations are mostly stable (47% of answers), with about equal responses for increasing (25%) or decreasing (28%; Table 1; Fig. 8). It is important to note that the median duration of surveys that contributed to the expert's opinion was 11 years, which is less than the generation time of whale sharks (25 years). Increases may thus simply be driven by experts starting to discover more of the population, rather than the population itself actually increasing. Quantitative population models exist for this reason, and these can calculate population trends based on parameters such as the resighting rate of individuals over time (Rohner *et al.* 2022). However, so far these models have been limited by the short time-series of data available compared to the long lifespan of whale sharks. Most studies failed to calculate a trend, and most of the others found a stable or decreasing population (Rohner *et al.* 2022). Only one model reported a small increase in whale shark numbers in Ningaloo, however, confidence in the result is low because the study was based on just 4 years of data and included only a subset of individuals (Holmberg *et al.* 2009). The current view suggests that a precautionary approach to whale shark conservation is needed, considering their old age at maturity, the scarcity of data, and the clear threats that impact whale shark numbers. More data are presently being collected, allowing more accurate trends to be calculated in the future to track the success of conservation measures that are implemented now. Therefore, whilst at first glance the the expert opinions from the survey might seem optimistic for an Endangered and Largely Depleted species, these perceptions are not empirical to infer the population status of the species. Indeed, a small percentage population increase in a Largely Depleted species, would still remain a Largely Depleted population.

# ASSESSING THE RISK

**Figure 8 | Constellation population summary**
Based on expert opinion




Experts thought that unregulated tourism (30% of answers) and small vessel strikes (27%) were the leading most pertinent threat to whale sharks within constellations (Fig. 9; Table 2). Large vessel collisions followed with 18%, while bycatch (12%) and fishing-related injuries (9%) were mentioned less often. By contrast, on a global level encompassing all whale shark habitat (not only constellation sites), fishing, bycatch and shipping are the main threats (Rowat *et al.* 2021)). Tourism and small vessel strike likely have mostly sublethal impacts, indicating that most experts think that whale sharks are relatively well protected inside constellations. It is worth noting that experts were not asked to rank solely sources of mortality (Appendix 5.1).

However, ~50% of respondents thought small vessel strikes posed a high (4) or very high (5) threat within constellations. The most mentioned types of vessels that threaten whale sharks within constellations were also small: tourist vessels (included in 78% of responses), recreational vessels (75%), and artisanal fishing vessels (71%; Fig. 10). Additionally, a mean of 15% of whale sharks had major injuries from vessel collisions (Fig. 10; Table 3), most likely from small boats as collisions with larger vessels are likely to be fatal. This warrants further investigation of small vessel strike and underlines the need for effective boating regulations within constellation areas. Management action to reduce ship strike should include both large and small vessels within constellation areas, but focus on large vessels away from these coastal hotspots.

More than half (53%) of respondents thought that large vessel strike is a threat in their constellation. Combined with what the experts thought was the most pertinent threat, large vessel collisions appear to be a concern, but not the main issue within constellations on a global level. The constellations that listed large vessel collisions as their main concern included the northern Gulf of Mexico, the Seychelles, far north Queensland and Ningaloo Reef in Australia, Donsol in the Philippines, and mainland Ecuador. Over their whole distribution, not only inside constellation areas, 77% of experts thought that large vessels affect whale shark populations (Table 3; Fig. 8). Our quantitative analyses of ship traffic in whale shark core zones and the peripheral area surrounding them (below) show that the threat from large vessels can be underestimated in some locations. It will be interesting to track how experts feel about large vessel strikes over time as this threat gains more scientific spotlight.

Specific policy to manage ship strike on whale sharks is largely lacking in global whale shark hotspots (Table 4). Perhaps the best positive example is the Tubbataha constellation in the Philippines, which is listed as an Area To Be Avoided (ATBA), meaning that vessels cannot transit through the area under normal circumstances to protect the coral reefs (not whale sharks specifically). Some other areas had a recommended speed limit for vessels in place, for example a maximum of 10 knots is advised in all three whale shark aggregation areas in the Maldives. In other areas, such as in Indonesia,

**Figure 9 | Activities posing a threat within each constellation**
Based on expert knowledge

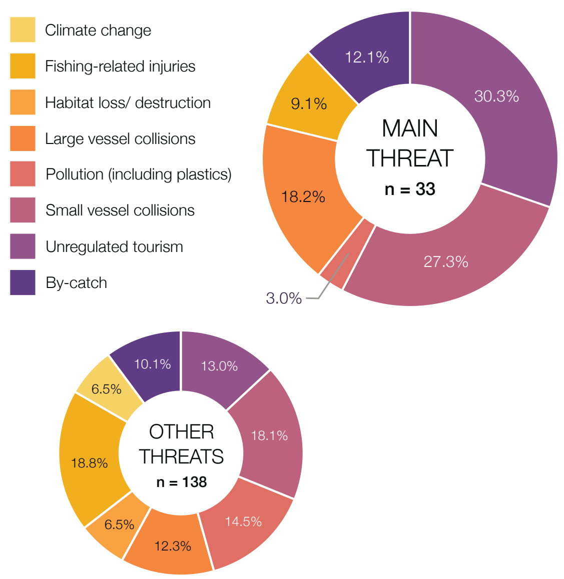


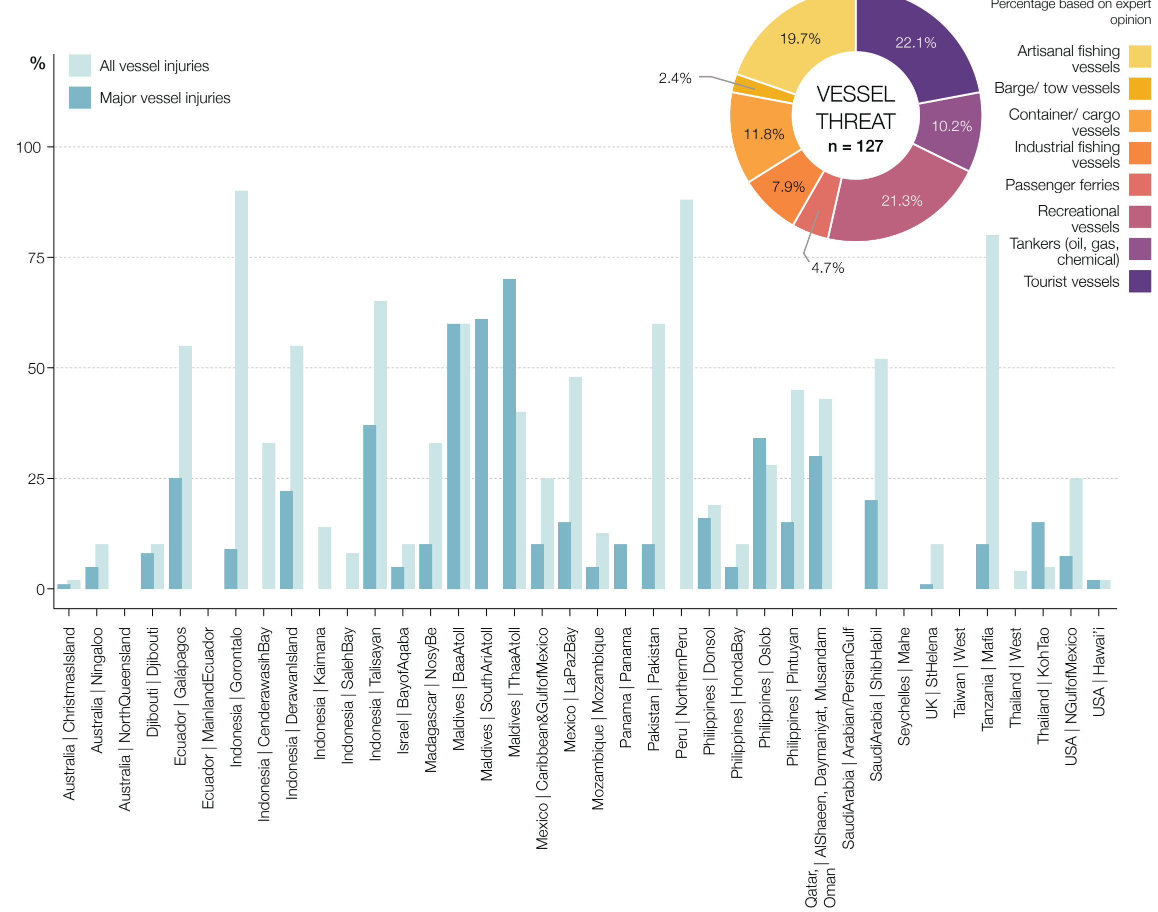

**Table 2 | Whale shark constellation site threat summary based on information received from experts working at each of the known areas globally.** Leading local threats represent the single most pressing issue for whale sharks at each constellation. Experts were asked to list other threats occurring in the area. If large vessels were listed as either a leading or other threat we noted this in column 4. Threat levels are a ranked perception from each expert as to how much of a threat they think both small (column 5) and large (column 6) vessels pose locally based on a rank of 1 – 5.

| County code | Constellation site | Local threats: Leading | Local threats: Large vessels included | Threat level: Small vessels | Threat level: Large vessels |
|---|---|---|---|---|---|
| AUS | Christmas Island | Unknown | No | 1 | 1 |
| | Ningaloo Reef | Large vessel collisions | Yes | 3 | 4 |
| | FarN Queensland | Large vessel collisions | Yes | 1 | 3 |
| DJI | Djibouti | Fishing-related injuries | No | 3 | 1 |
| ECU | Galápagos | None locally | Yes | 1 | 1 |
| | Mainland Ecuador | Large vessel collisions | Yes | 5 | 3 |
| GBR | St Helena | None locally | No | 2 | 2 |
| IDN | Cenderawasih Bay | Fishing-related injuries | Yes | 4 | 3 |
| | Kaimana | Unregulated tourism | No | 2 | 1 |
| | Saleh Bay | Unregulated tourism | Yes | 4 | 2 |
| | Gorontalo | Small vessel collisions | No | 4 | 1 |
| | Derawan Island | Unregulated tourism | No | 4 | 1 |
| | Talisayan | Unregulated tourism | No | 4 | 1 |
| ISR | Bay of Aqaba | Pollution | No | 4 | - |
| MDG | Nosy Be | Small vessel collisions | Yes | 4 | 3 |
| MDV | South Ari Atoll | Small vessel collisions | Yes | 5 | 4 |
| | Thaa Atoll | Unregulated tourism | Yes | 3 | 2 |
| | Baa Atoll | Small vessel collisions | Yes | 4 | 3 |
| MEX | Caribbean & GoM | - | No | 2 | 5 |
| | La Paz Bay | - | No | 3 | 2 |
| MOZ | Mozambique | By-catch | Yes | 2 | 2 |
| MYS | Malaysian waters | By-catch | No | 3 | 2 |
| PAK | Pakistani waters | By-catch | No | 2 | 2 |
| PAN | Coiba | Unregulated tourism | No | 4 | 2 |
| PER | Northern Peru | - | No | 3 | - |
| PHL | Donsol | Large vessel collisions | Yes | 4 | 3 |
| | Honda Bay | Small vessel collisions | Yes | 4 | 3 |
| | Oslob | Unregulated tourism | Yes | 5 | 3 |
| | Pintuyan | Small vessel collisions | Yes | 5 | 5 |
| QAT OMN | Al Shaeen, Daymaniyat Islands, Musandam | By-catch | Yes | 3 | 3 |
| SAU | Saudi Arabian Gulf | Unregulated tourism | No | 1 | 1 |
| | Shib Habil | Small vessel collisions | Yes | 4 | 3 |
| SYC | Mahe | Large vessel collisions | Yes | 4 | 5 |
| THA | Koh Tao | Unregulated tourism | No | 3 | 2 |
| | West Thailand | Small vessel collisions | - | 3 | - |
| TWN | Taiwan waters | Fishing-related injuries | No | 1 | 1 |
| TZA | Mafia Island | Small vessel collisions | Yes | 4 | 3 |
| USA | Northern GoM | Large vessel collisions | Yes | 2 | 2 |
| | Hawai'i | Unregulated tourism | No | 4 | 2 |
| **Responses** | | 36 (33 threats) | 38 | 39 | 36 |
| **Summary** | | By-catch 12.1% | Yes 52.6% | 1: 12.8% | 1: 25.0% |
| | | Fishing-related injuries 9.1% | | 2: 15.4% | 2: 30.6% |
| | | Large vessel collisions 18.2% | No 47.4% | 3: 23.1% | 3: 30.6% |
| | | Pollution 3.0% | | 4: 38.5% | 4: 5.6% |
| | | Small vessel collisions 27.3% | | 5: 10.3% | 5: 8.3% |
| | | Unregulated tourism 30.3% | | | |

(1) Low threat, (5) High threat




**Figure 10 | Constellation based vessel injury frequency**
Based on expert knowledge






a framework to limit vessel speed and routes inside MPAs and other important habitats exists, but it has not yet been applied to whale shark constellation sites. Largely though, there are currently no management measures in place to safeguard whale sharks from large vessel strike in most of their constellation areas. We have a great opportunity to improve whale shark conservation with targeted, small-scale and temporally-explicit rules for vessels at these sites.

Experts from most of the known global whale shark constellations rated threats, injuries, and the risk posed by vessels based on their in-water observations over many years of whale shark surveys. Therefore, these are observer/researcher based results. Tourism and small vessels were important considerations, likely because injuries and scars from these smaller boats are apparent, and conflict with tourism operations can be observed. However, whale sharks heal relatively quickly from small injuries (see Penketh *et al.* 2020; Womersley *et al.* 2021), and the high percentage of returning individuals suggests that these local threats do not keep them from occupying constellation areas. Considering that collisions with large vessels will likely be fatal, and that dead whale sharks sink, local experts are unlikely to see much evidence from this threat in the form of injuries. Our quantitative analysis overlaying shipping traffic with whale shark constellation areas below addresses this gap.

**Table 3 | Whale shark constellation site vessel threat summary based on information received from experts working at each of the known areas globally.** Experts were asked to relay the number of individuals with any form of vessel-related scarring at the constellation site (column 3) and the number with major vessel-related injuries such as blunt force trauma or propeller induced lacerations (column 4). They were also asked their opinion as to whether large vessel collisions impact whale shark populations generally (column 5) and whether they were aware of any other species that might be at risk of collision with large vessels within the constellation site.

| County code | Constellation site | Vessel-related scarring %: Any | Vessel-related scarring %: Major | Opinion: Do collisions impact populations | Other species at risk |
|---|---|---|---|---|---|
| AUS | Christmas Island | | 1 | Yes | No |
| | Ningaloo Reef | 10 | 5 | Yes | Yes: C, E ,S |
| | FarN Queensland | 0 | 0 | Yes | - |
| DJI | Djibouti | 10 | 8 | Yes | Yes: C, T |
| ECU | Galápagos | ~50-60 | 25 | Yes | Yes: E, T |
| | Mainland Ecuador | - | - | Yes | Yes: C, E ,S, T |
| GBR | St Helena | 10 | 1 | Yes | Yes: C, E |
| IDN | Cenderawasih Bay | 33 | 0 | Unsure | Yes: C, S |
| | Kaimana | 14 | 0 | Unsure | Yes: C, S |
| | Saleh Bay | 8 | 0 | Unsure | Yes: C, S |
| | Gorontalo | 90 | 9 | - | No |
| | Derawan Island | 55 | 22 | - | - |
| | Talisayan | 65 | 37 | - | - |
| ISR | Bay of Aqaba | 10 | 5 | Unsure | - |
| MDG | Nosy Be | 33 | 10 | Yes | Yes: C, E |
| MDV | South Ari Atoll | - | 61 | Yes | Yes: C, E ,T |
| | Thaa Atoll | 40 | 70 | Yes | Yes: C, E ,T |
| | Baa Atoll | ~60 | ~60 | Yes | Yes: C, E ,T |
| MEX | Caribbean & GoM | 25 | 10 | Yes | Yes: C, E ,T |
| | La Paz Bay | 48 | 15 | Yes | Yes: C,T |
| MOZ | Mozambique | 10-15 | <5 | Unsure | Yes: C, S |
| MYS | Malaysian waters | 0 | 0 | Yes | Yes: C, S, T |
| PAK | Pakistani waters | - | >10 | Yes | Yes: C |
| PAN | Coiba | 60 | 10 | Yes | Yes: C |
| PER | Northern Peru | 88 | - | Yes | Yes: C |
| PHL | Donsol | 19 | 16 | Yes | - |
| | Honda Bay | 10 | 5 | Yes | - |
| | Oslob | 28 | 34 | Yes | - |
| | Pintuyan | 45 | 15 | Yes | - |
| QAT OMN | Al Shaeen, Daymaniyat Islands, Musandam | 43 | 30 | Unsure | - |
| SAU | Saudi Arabian Gulf | - | - | No | Yes: C |
| | Shib Habil | 52 | 20 | Yes | Yes: C, E ,S, T |
| SYC | Mahe | - | - | Yes | Yes: C |
| THA | Koh Tao | 5 | 15 | Yes | Yes: C, T |
| | West Thailand | 4 | - | - | - |
| TWN | Taiwan waters | 0 | 0 | No | No |
| TZA | Mafia Island | 80 | 10 | Yes | No |
| USA | Northern GoM | ~25 | ~5-10 | Yes | Yes: E |
| | Hawai'i | 2 | 2 | Yes | Yes: C |
| Responses | | 35 | 34 | 35 | 29 |
| Summary | | Mean 31.5% | Mean 15.3% | Yes 77.1% | Yes 86.2% |
| | | | | Unsure 17.1% | C 79.3% |
| | | | | No 5.7% | E 37.9% |
| | | | | | S 27.6% |
| | | | | | T 37.9% |
| | | | | | No 10.3% |

(C) Cetaceans, (E) Elasmobranchs, (S) Sirenians, (T) Turtles

**Table 4 | Whale shark constellation site management summary based on information received from experts working at each of the known areas globally.** Experts were asked whether there was any form of monitoring framework in place within the constellation site to monitor vessel activity (column 3), whether there was any form of large vessel activity management within the site (column 4), and whether there was any management specifically targeted at protecting whale sharks from vessel impacts (column 5).

| County code | Constellation site | Monitoring framework: Vessel focussed | Management framework: Vessel focussed | Management framework: Vessel & whale shark focussed |
|---|---|---|---|---|
| AUS | Christmas Island | No | No | No |
| | Ningaloo Reef | Yes | Yes | No |
| | FarN Queensland | No | Unknown | No |
| DJI | Djibouti | No | No | No |
| ECU | Galápagos | Yes | Yes | No |
| | Mainland Ecuador | Yes | No | No |
| GBR | St Helena | No | Yes | No |
| IDN | Cenderawasih Bay | No | Yes | No |
| | Kaimana | No | Yes | No |
| | Saleh Bay | No | Yes | No |
| | Gorontalo | Yes | Yes | Yes |
| | Derawan Island | Yes | Yes | Yes |
| | Talisayan | Yes | Yes | Yes |
| ISR | Bay of Aqaba | No | No | No |
| MDG | Nosy Be | Yes | No | No |
| MDV | South Ari Atoll | No | No | Yes |
| | Thaa Atoll | No | No | Yes |
| | Baa Atoll | Yes | Yes | Yes |
| MEX | Caribbean & GoM | Yes | No | No |
| | La Paz Bay | Yes | Yes | Yes |
| MOZ | Mozambique | No | Yes | No |
| MYS | Malaysian waters | Yes | Yes | No |
| PAK | Pakistani waters | No | No | No |
| PAN | Coiba | No | Yes | No |
| PER | Northern Peru | No | No | No |
| PHL | Donsol | Yes | Yes | No |
| | Honda Bay | No | No | No |
| | Oslob | No | Yes | No |
| | Pintuyan | No | Yes | - |
| QAT OMN | Al Shaeen, Daymaniyat Islands, Musandam | No | Unknown | Yes |
| SAU | Saudi Arabian Gulf | No | No | No |
| | Shib Habil | No | No | No |
| SYC | Mahe | Yes | No | No |
| THA | Koh Tao | No | No | No |
| | West Thailand | - | - | - |
| TWN | Taiwan waters | No | No | No |
| TZA | Mafia Island | No | No | No |
| USA | Northern GoM | No | No | No |
| | Hawai'i | - | Yes | No |
| Responses | | 37 | 38 | 37 |
| Summary | | Yes 35.1% | Yes 47.4% | Yes 21.6% |
| | | No 64.9% | No 47.4% | No 78.4% |

# ASSESSING THE RISK

### *2.2.2 Shipping analysis*

Overlaying ship traffic data with whale shark constellation core and peripheral zones showed that the risk of ship strike varies among sites, but is almost ubiquitous. Constellations with high ship densities in the core habitat of whale sharks require urgent development of mitigation strategies to reduce this threat locally.

#### *2.2.2.1 Ship traffic globally*

Shipping traffic comprised of large vessels was prevalent globally (Fig. 5). Large vessels transited in all constellation sites assessed here, with the exception of some core habitats in Djibouti that are located in a narrow bay. The scale of global shipping, and the almost ubiquitous overlap of at least some large vessel traffic with whale shark constellations, again underlines the magnitude of this threat. Whale sharks are not only at risk during their large-scale migrations, when they sometimes swim in and across shipping lanes (Womersley *et al.* 2022), but also when they are within small, localised aggregation sites. This result shows that targeted measures to reduce the risk from vessel collisions within constellation areas is needed, and has the potential to greatly improve the conservation of whale sharks.

**Measuring risk**

Throughout this report, we use the term "risk" as a relative measure. This means that we compared the risk among different areas in a relative way. For example, we make statements such as "the risk from ship strike is higher in area A than in area B". Often, we quantified different levels of this relative risk, for example with the danger rank, by sorting the data into quantiles or equal intervals.

We did not calculate the absolute risk, or how likely a whale shark is to collide with a ship. This is not possible at the moment, mainly because we do not know how many whale sharks are hit by large vessels.

**Figure 11 | Global constellation danger rank**

Map based on 100 km peripheral zone and pies based on questionnaire

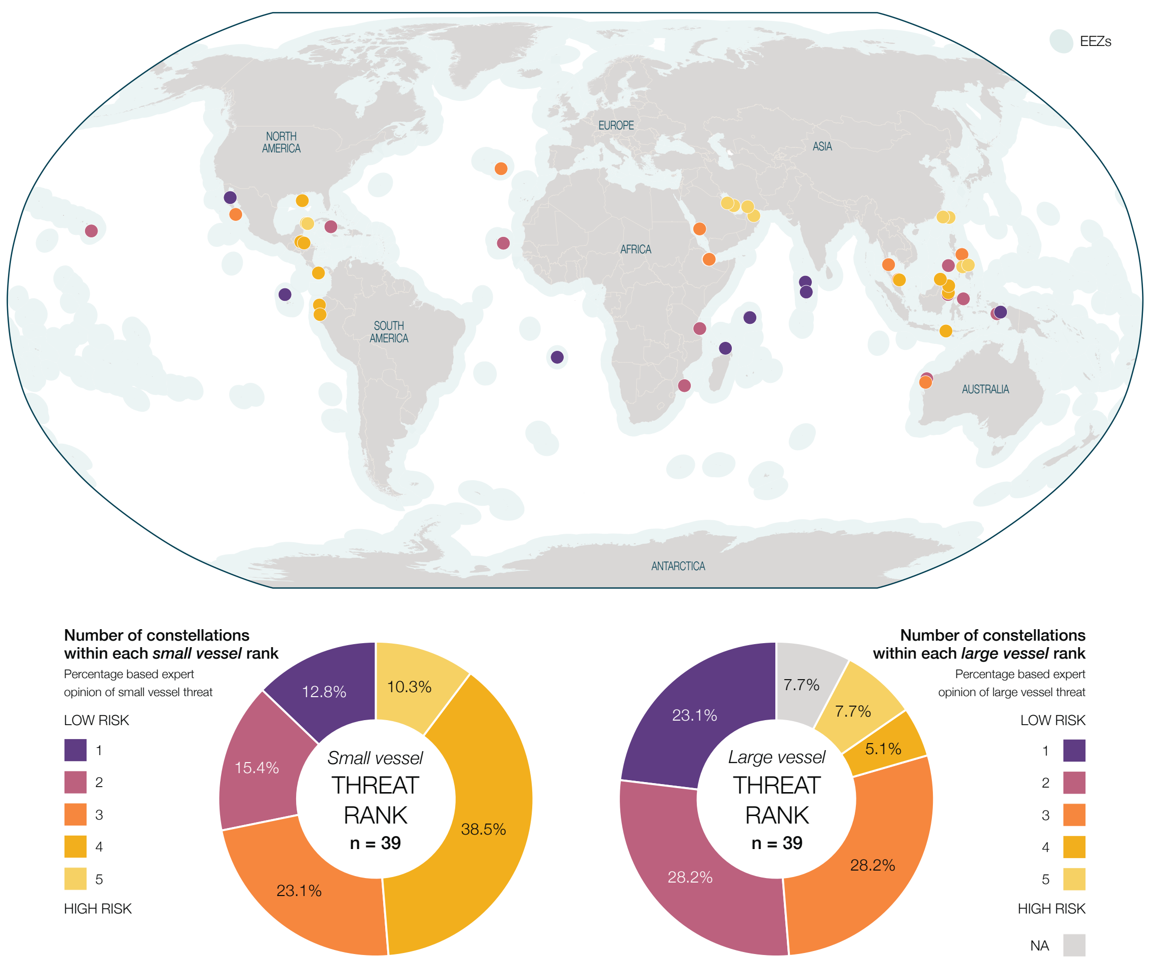



**Table 5 | Whale shark constellation site analysis summary based on core habitat polygons received from experts or drawn from the literature and three years (2017 – 2019) of global shipping count data.** The vessel class with the highest occupancy was determined from the highest mean ship density from the annual average within each site (column 3), and the month with the highest mean ship density from the average of all vessel classes within each site was also determined (column 4). Ship density summary stats were calculated based on cells within the core habitat area from the annual average (columns 5 – 7). Relative danger rank was determined by subsetting mean ship density from the annual average into 5 percentiles to provide a rank between 1 and 5 for the core habitat (column 8) and the 100 km peripheral zone surrounding it (column 9). Ranks 4 and 5 are coloured in column 8 to highlight constellations with the highest relative danger rank.

| County code | Constellation site | Most occupied by: Vessel type | Most dense in: Month | Ship density: min | Ship density: max | Ship density: mean | Danger rank: Core | Danger rank: 100km |
|---|---|---|---|---|---|---|---|---|
| AUS | Ningaloo Reef 1 | Passenger | MAY | 1.9 | 27.8 | 11.9 | 3 | 2 |
| | Ningaloo Reef 2 | Passenger | MAY | 1.0 | 7.9 | 3.5 | 2 | 3 |
| BLZ | Gladden | Cargo | MAR | 1.9 | 3.6 | 2.8 | 2 | 4 |
| CPV | Boa Vista | Cargo | NOV | 2.9 | 61.5 | 24.7 | 4 | 2 |
| DJI | ArtaBeach | Cargo | MAR \| JUN | 0.2 | 0.2 | 0.2 | 1 | 3 |
| | Goubeth | NA | NA | 0.0 | 0.0 | 0.0 | 1 | 3 |
| | LaPass | Cargo \| Tanker | MAR | 0.0 | 0.1 | 0.0 | 1 | 3 |
| | RasEiro | Cargo | MAR \| JUN | 0.2 | 0.2 | 0.2 | 1 | 3 |
| | RasKorali | Cargo \| Tanker | MAR | 0.1 | 0.1 | 0.1 | 1 | 3 |
| ECU | Galápagos | Passenger | MAY \| JUN | 0.4 | 0.4 | 0.4 | 1 | 1 |
| | Mainland Ecuador | Cargo | AUG | 25.9 | 87.6 | 48.4 | 5 | 4 |
| GBR | St. Helena | Passenger | JAN | 0.8 | 12.5 | 6.2 | 3 | 1 |
| HND | Utila | Cargo | DEC | 20.4 | 80.2 | 46.7 | 4 | 4 |
| IND | Cenderawasih Bay | Passenger | OCT | 0.1 | 2.1 | 1.0 | 1 | 1 |
| | Derawan Island 1 | Cargo | NOV | 0.6 | 19.3 | 7.2 | 3 | 3 |
| | Derawan Island 2 | Cargo | NOV | 19.3 | 33.5 | 23.8 | 4 | 4 |
| | Gorontalo | Cargo \| Tanker | MAR \| APR \| JUL | 0.1 | 0.1 | 0.1 | 1 | 2 |
| | Kaimana | Passenger | OCT | 0.0 | 37.8 | 5.6 | 3 | 2 |
| | Saleh Bay | Cargo | MAY | 0.6 | 4.1 | 2.3 | 2 | 4 |
| | Talisayan | Cargo | FEB | 1.7 | 20.2 | 9.2 | 3 | 2 |
| MDG | Nosy Be | Passenger | SEP | 1.7 | 15.8 | 6.2 | 3 | 1 |
| MDV | Thaa Atoll | Passenger | DEC | 3.1 | 8.5 | 4.7 | 2 | 1 |
| | Baa Atoll | Cargo \| Tanker | APR | 0.8 | 2.8 | 1.8 | 2 | 1 |
| MEX | Bahia Los Angeles | Passenger | JUL | 0.5 | 1.2 | 0.9 | 1 | 1 |
| | Holbox | Cargo | DEC | 8.0 | 71.3 | 23.1 | 4 | 5 |
| | Isla Mujeres | Cargo | MAR | 36.3 | 76.4 | 56.3 | 5 | 5 |
| | La Paz Bay | Passenger | DEC | 0.2 | 516.1 | 132.1 | 5 | 3 |
| MOZ | Mozambique | Passenger | JUL | 0.2 | 3.4 | 1.7 | 2 | 2 |
| MYS | Kota Kinabalu | Passenger | JUL | 7.8 | 312.2 | 107.3 | 5 | 4 |
| | Perhentian Archipelago | Cargo | JUL | 16.8 | 28.8 | 22.3 | 4 | 3 |
| | Redang Island | Cargo | DEC | 29.8 | 58.6 | 48.2 | 5 | 4 |
| | Sipidan | Cargo | OCT | 3.3 | 12.4 | 7.8 | 3 | 4 |
| PAN | Coiba | Passenger | JAN | 0.1 | 4.3 | 1.1 | 2 | 4 |
| PER | Northern Peru | Cargo | JAN | 0.4 | 0.9 | 0.6 | 1 | 4 |
| PHL | Donsol | Cargo | MAR | 0.6 | 14.1 | 4.3 | 2 | 3 |
| | Honda Bay | Cargo | NOV | 0.1 | 24.7 | 7.0 | 3 | 2 |
| | Oslob | Cargo | AUG | 37.9 | 37.9 | 37.9 | 4 | 5 |
| | Pintuyan | Passenger | MAY | 11.7 | 144.0 | 75.4 | 5 | 5 |
| PRT | Azores | Passenger | JUL | 3.1 | 84.6 | 16.8 | 4 | 3 |
| QAT | Al Shaeen, | Bunker \| Tanker | NOV | 18.9 | 48.9 | 32.2 | 4 | 5 |
| OMN | Daymaniyat Islands | Cargo | DEC | 2.2 | 24.6 | 10.6 | 3 | 5 |
| | Musandam | Cargo | MAY | 0.4 | 2429.5 | 518.5 | 5 | 5 |
| SAU | Jana | Bunker \| Tanker | NOV | 1.7 | 8.8 | 5.2 | 3 | 5 |
| | Shib Habil | Passenger | JAN | 0.0 | 2.1 | 1.0 | 1 | 3 |
| SYC | S Mahe | Specialis. Reefer | APR | 4.7 | 135.4 | 70.0 | 5 | 1 |
| | NW Mahe | Passenger | MAR | 3.8 | 249.1 | 78.1 | 5 | 1 |
| THA | Koh Tao | Bunker \| Tanker | JAN | 4.7 | 36.8 | 17.5 | 4 | 3 |
| TWN | E Taiwan | Cargo | DEC | 0.8 | 204.0 | 53.3 | 5 | 5 |
| | W Taiwan | Cargo | MAY | 15.9 | 307.8 | 102.5 | 5 | 5 |
| TZA | Mafia Island | Passenger | NOV | 0.6 | 2.3 | 1.5 | 2 | 2 |
| USA | Northern GoM | Cargo | JAN | 2.6 | 714.1 | 47.7 | 4 | 4 |
| | Hawai'i | Passenger | DEC | 0.1 | 47.1 | 14.3 | 3 | 2 |

(1) Low threat, (5) High threat

# ASSESSING THE RISK

### *2.2.2.2 Peripheral danger rank*

The risk of vessel collisions to whale sharks is not uniform among constellations throughout the world because ship traffic is also not uniform. There are some well-defined shipping lanes that concentrate vessel traffic, such as through the Strait of Hormuz, in the Gulf of Mexico, or through the East China Sea (Fig. 5). Constellations that are located near such shipping lanes received a higher peripheral zone danger rank, from 1 = low to 5 = high, based on the number of ships that transited through the 100 km radius peripheral zone around whale shark areas. We used this peripheral danger rank considering that whale sharks have to enter, and leave, the aggregation site from surrounding waters that can be heavily used by ships. Their residency time within core zones is often shorter than the duration of the peak season (Araujo *et al.* 2022), which shows that whale sharks commonly travel through these peripheral zones.

The sites with the highest peripheral zone danger rank of 5 were near busy shipping lanes and included four sites in the Arabian Sea and adjacent waters, two sites in the Gulf of Mexico, two sites in the Philippines, and two sites in Taiwan (Fig. 11). Reducing the risk of ship strike in these peripheral areas may be too difficult to achieve in practice, but this peripheral danger rank shows that even with good protection inside core areas, whale sharks will still face some risk from ships. The least dangerous peripheral areas with a rank of 1 were around remote islands (e.g. St Helena, Seychelles, Maldives, and the Galápagos), or in secluded bays (e.g. Nosy Be, Madagascar and Cenderawasih Bay, Indonesia; Fig. 11). Interestingly, although Djibouti had the only core whale shark areas without any large vessel traffic, the peripheral zone was ranked as relatively dangerous (rank = 3) due to the heavy ship traffic in and out of the Red Sea.

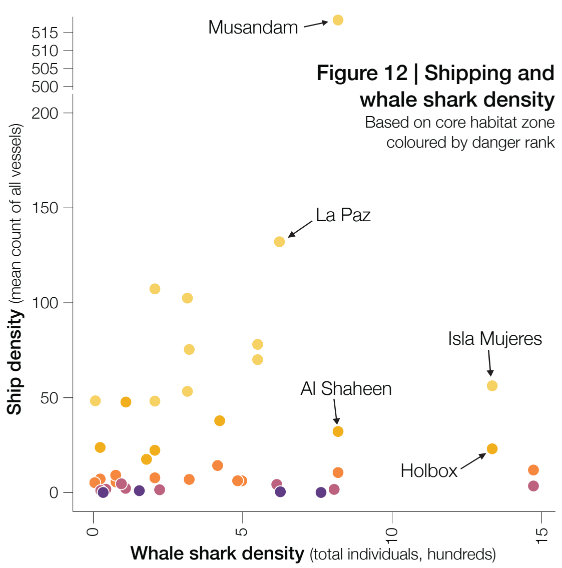



**Figure 12 | Shipping and whale shark density**
Based on core habitat zone coloured by danger rank

### *2.2.2.3 Local danger rank*

To identify the level of threats from large vessels within each constellation site, we then calculated the local danger rank based on the number of ships that transited through the whale shark constellation site core habitat. The most dangerous constellation areas for whale sharks globally were off the mainland of Ecuador, Isla Mujeres and La Paz in Mexico, Kota Kinabalu and Redang Island in Malaysia, Pintuyan in the Philippines, the Musandam in Oman, and around the Seychelles and Taiwan (Table 5). Many of these sites had areas within the constellation with over 1 vessel per km² in the core site. Localised, small-scale management of ship traffic, such as re-routing or reducing speed (see below), would greatly benefit whale sharks within constellations in general, and are particularly urgently needed within these most dangerous constellations.

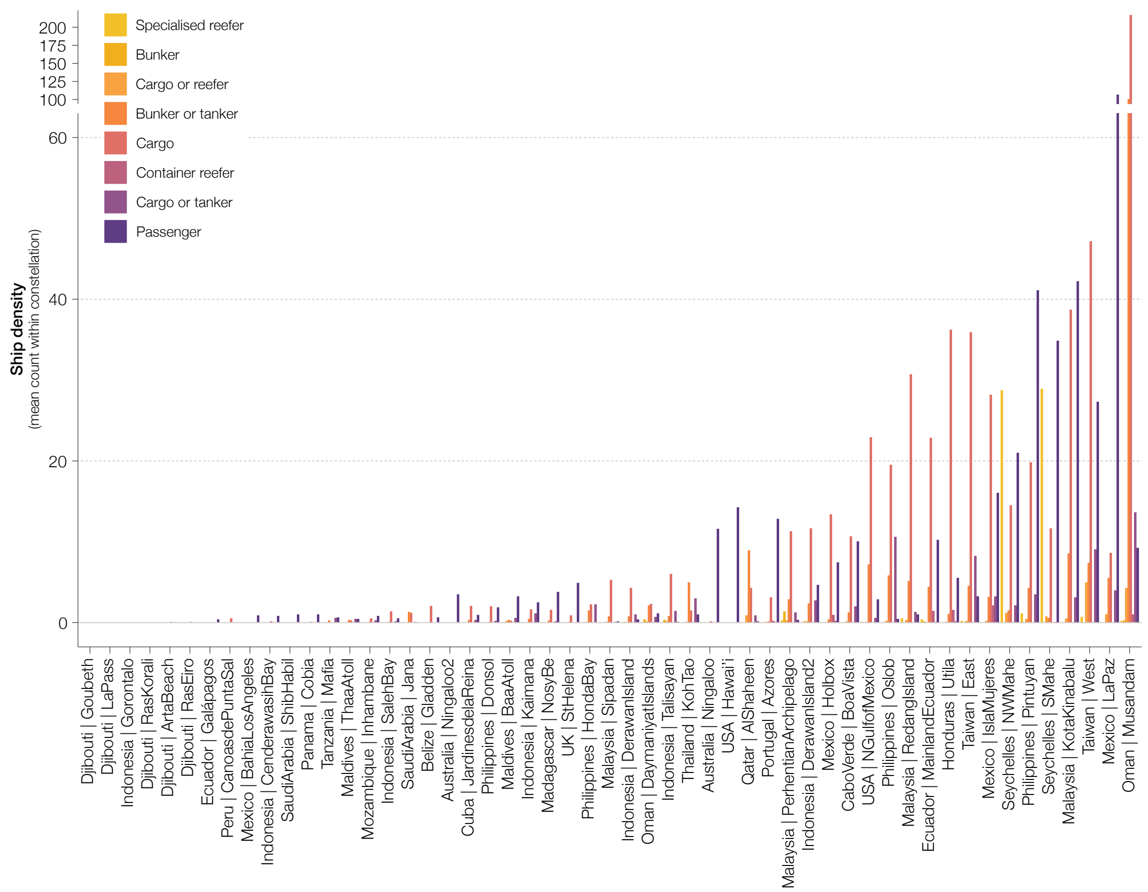
Among areas with a high threat level, there were some that had no safe areas within their spatial extent, with minimum vessel densities per ~123 km² grid cell greater than 25 (Table 5). These included Isla Mujeres, Mexico and mainland Ecuador, showing that here, vessels are spread across the entire core habitat of whale sharks. There were also sites with a low localised danger rank where whale sharks are likely to be much safer from large vessel collisions. Ship traffic was as low as a single vessel present within the site per month. Most of these relatively safe constellations were sites with a particularly small area, often comprising only ~2 grid cells. Examples include Shib Habil in Saudi Arabia or Darwin Island in the Galápagos (Table 5).

We identified some sites that had a higher danger rank inside their constellations than in the peripheral zone. It is important to remember that both indices are relative to the ship traffic elsewhere in the same zone, and so this does not mean that there were more ships in the core area than in the peripheral zone. For example, aggregations in the Seychelles had a high danger rank of 5 inside the whale shark area, and a low danger rank of 1 in the peripheral 100 km area around it. Here, local traffic of large vessels is the main concern. Other areas with a similar trend included St Helena, La Paz in Mexico, Nosy Be in Madagascar, and Boa Vista in Cape Verde (Table 5). Sites with such discrepancies are likely to provide particularly high benefit to whale sharks in their larger region if they implement measures to reduce ship strike within a relatively small, localised area.

### *2.2.2.4 Priority constellations for mitigation*

While we show that large vessels pose a risk to whale sharks in all constellations around the globe, there are some sites that require the most urgent action to reduce the threats posed by shipping activity. These sites are characterised by high numbers of whale sharks using the area and high monthly shipping activity. Constellations that stand out as requiring urgent mitigation measures within the core habitat include Holbox, Isla Mujeres and La Paz in Mexico, Musandam in Oman and Al Shaheen in Qatar. For example, Isla Mujeres has ~1,335 individual whale sharks using the site and 56.3 ships per 123 km² passing through the core habitat monthly (Fig. 12; Table 5). Targeted measures should be considered a priority for these areas with high concurrent ship and shark densities, especially those which also have a high danger rank in the peripheral zone (Table 5), including Isla Mujeres, Mexico and Musandam, Oman.

**Figure 13 | Shipping density within constellations by vessel type**
Based on core habitat zone




### *2.2.2.5 Expert elicitation*

In many cases, expert perception of the local threat posed by large vessels matched our quantified relative local danger rank (Tables 2; 5). Some areas underestimated the threat, for example Taiwan and La Paz in Mexico which had a high quantified danger rank. Others overestimated the threat posed by large vessels within the constellations, such as Shib Habil in Saudi Arabia or Ningaloo Reef in Australia. Some of these sites also reported a high level of vessel-inflicted scars and injuries on the sharks, potentially influencing their perception (Fig. 10). Further, we could not include whale shark behaviour in the quantitative analyses, but local experts may regularly observe whale sharks not swimming away from approaching ships, and thus classify the danger as higher than only the number of ships would infer.

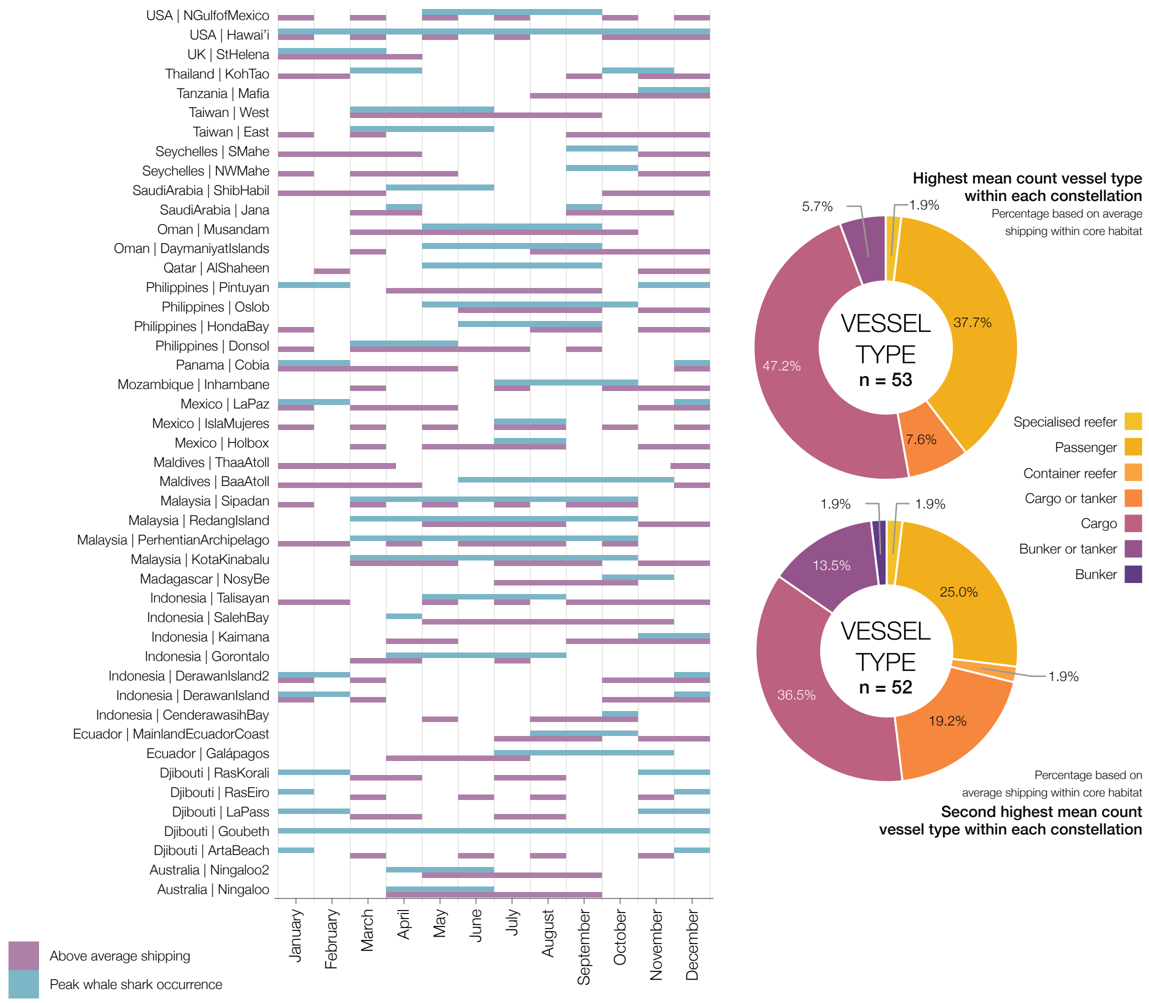
### *2.2.2.6 Vessel classification*

Overall, whale sharks in core zones of constellations were most at risk from Cargo (48%) and Passenger (38%) vessels. Other minor categories included Cargo/Tanker (8%), Bunker/Tanker (6%) and Specialised Reefer (2%; Table 5). Sites where passenger vessels posed the greatest threat include Galápagos, St. Helena, Azores, and Hawai'i, among others (Table 5). These whale shark areas are along important transit routes, with passenger vessels having the least spread and highest level of concentration among the different types of vessels (Fig. 5). Sites where cargo vessels posed the greatest threat included Mainland Ecuador, Holbox (Mexico), and northern Gulf of Mexico, among others. These whale shark hotspots are in important

# ASSESSING THE RISK

**Figure 14 | Seasonal shipping and whale shark occurrence peaks within constellations**

Based on core habitat zone and expert knowledge




maritime trade routes with heavy cargo traffic (Fig. 5). The highest ship density recorded from all vessel classes combined and all core habitats of constellations was in the Musandam, Oman, where an average of 518.5 ships were present monthly (Fig. 13). More than 200 of these were cargo vessels. The maximum density in one ~123 km² area was over 2,400 vessels per month. There were eight other core zones of whale shark constellations that had particularly high densities of ship traffic, with a mean of >50 vessels per month (Fig. 13). For example, in La Paz, Mexico, >100 passenger vessels passed through the core zone of the constellation monthly, with a comparatively low number of cargo vessels (<10). Off the west coast of Taiwan, >100 vessels were recorded as the monthly average, with peak areas having >300 vessels transiting through ~123 km² in the core whale shark zone. Other sites with high vessel traffic were in the Seychelles, Pintuyan (Philippines), Isla Mujeres (Mexico), and Kota Kinabalu (Malaysia; Table 5).

Shipping density was not consistent throughout the course of the year and 33 constellation core zones had above average vessel activity in months that were also peak whale shark occurrence seasons (Fig. 14). For example, the peak whale shark season in Coiba, Panama, is from December to February, which overlaps with above average vessel traffic in their core habitat (See Appendix 5.2 and 5.3 for summary mapped infographics of all constellation sites and seasonal trends). In these areas, whale sharks were present most during months when shipping was also at its local highest, again highlighting that seasonal management could greatly reduce the risk of ship strike in these areas.






# 3. POLICY MECHANISMS

to mitigate ship strike on Endangered whale sharks

Mechanisms that reduce the risk of ship strike have been developed for whales, and here we show how these can be applied to whale sharks. The most effective strategy is likely to be spatially separating ships from whale sharks. Considering the small size of whale shark core zones, such measures may be viable for shipping stakeholders, and will improve the conservation of this endangered species.

### 3.1 CURRENT POLICY MECHANISMS TO MITIGATE SHIP STRIKE ON MARINE MEGAFAUNA

Although some of the earliest scientific papers on whale sharks reported ship strikes (e.g. Gudger, 1937, 1938), this threat has only recently been recognised as a major concern for the conservation of the species (Pierce and Norman, 2016; Womersley *et al*. 2022). As such, no mitigation mechanisms have yet been tested for whale sharks specifically. Here, we consider current knowledge of whale shark ecology together with mitigation mechanisms developed for other marine megafauna species to assess how effective these are likely to be for whale sharks.

Ship strike mitigation strategies can be operational or technical (Sèbe *et al.* 2019; Schoeman *et al.* 2020). Operational strategies influence navigation of ships; for example moving a shipping lane around a high-use zone for whale sharks, or creating Areas To Be Avoided (ATBA) which is the main positive example that exists for whale sharks at their hotspot around Tubbataha, Philippines. Technical strategies involve ways to detect marine megafauna and then avoid collisions with them. Examples include dedicated observers looking out for animals at the surface, or predictive modelling that then influences ship navigation. We will examine the details of the most common approaches below, and discuss how effective each might be for whale sharks.

Risk reduction mechanisms can also be fixed or dynamic. Fixed management options typically involve permanent measures, such as ABTAs that are static. These can be applied to whale shark constellations that occur in a defined area, which are almost all constellations considered here. The fixed definition does not include a temporal aspect. Even seasonal restrictions on ship movement are considered fixed because they are recurring year after year. Dynamic management on the other hand involves real-time adaptive measures that are implemented when needed. For example, a monitoring system that can alert ships when a certain number of whale sharks are spotted in an area which then invokes re-routing or speed reduction.

### 3.2 JURISDICTIONS

At the international level, the International Maritime Organization (IMO) is the primary organisation responsible for establishing and enforcing rules and regulations on shipping. The IMO is a specialised agency of the United Nations (UN), and its mandate includes promoting maritime safety, security, and environmental protection. The IMO's regulations are implemented through national laws and regulations, and compliance is enforced by national and international authorities. In national waters, the relevant local and national authorities release the rules and regulations that apply to shipping. This is the pathway for local protection of whale shark areas, since almost all whale shark constellations considered in this report are located in national waters. For some constellations that are on or near borders, international collaboration will be required. Wider-scale measures to reduce ship strike on whale sharks throughout their distribution, such as in busy shipping lanes in ABNJs, fall under the IMO's responsibility.

### 3.3 FRAMEWORK FOR DEVELOPING RISK REDUCTION STRATEGIES

To be successful, a vessel strike risk reduction management system needs to consider key aspects holistically: cost, compliance, risk reduction, and regulatory system (Sèbe *et al.* 2019). It is crucial to include stakeholders from shipping, conservation, and government from the beginning in a transparent process. Management mechanisms will increase the cost to shipping, for example through more fuel consumption on a longer detour, or by employing specialist animal spotters, but the different approaches can have vastly different cost outcomes. These need to be balanced with the other factors to create a sustainable option for all parties. Compliance is paramount to avoid a situation where the management plan is theoretical only but lacks practical application. Shipping stakeholders will be more compliant if their concerns are considered in the design process, and if measures are practical and cost-effective. Risk reduction is the main factor that conservationists will be interested in. It is also a measure of the success of a management intervention for the targeted species or taxa. Finally, the regulations (laws, policies, guidelines) need to be developed with the relevant authority. When all aspects are considered under a common framework, the chance for success and compliance is higher (Silber *et al.* 2015; Sèbe *et al.* 2019). We will incorporate these four parts in the potential strategies below.

One way to standardise management approaches to reduce ship strikes on marine megafauna is to follow the Formal Safety Assessment (FSA) used by the IMO (IMO 2018). While this framework has not often been used in a biological context, it could be useful

# POLICY MECHANISMS

to assess the potential of different management strategies to reduce ship strike (Sèbe et al., 2019). For more details on the FSA approach please refer to (Kontovas and Psaraftis, 2009). Broadly, an FSA-type approach for whale shark ship strike reduction includes 5 steps:

- **Identification of hazards:** The threat of ship strike on whale sharks has been recognised for many decades, but the possible extent of this threat has only more recently emerged (Pierce and Norman 2016).
- **Assessment of risks:** This report and the recent paper by Womersley *et al.* (2022) are the first global-scale assessments of the spatial and temporal trends in relative risk of large vessel strike on whale sharks. With more data, such as numbers of whale sharks getting hit by vessels, this step can be updated in the future.
- **Risk control options:** We review relevant management strategies in this document and make suggestions on which options are likely to be best suited for whale shark risk reduction. This step also includes stakeholder engagement, which should follow the initial recommendations.
- **Cost-benefit assessment:** Close collaboration with the stakeholders in the shipping industry will be required to analyse and evaluate different options.
- **Recommendations for decision-making:** Final recommendations can then be put forward to the relevant authorities, after considering the input from all stakeholders.

## 3.4 RISK MANAGEMENT OPTIONS

### 3.4.1 Operational

#### *3.4.1.1 Re-routing, Areas To Be Avoided (ATBA), and Traffic Separation Schemes (TSS)*

Perhaps the most direct way to reduce the risk of ship strike is to spatially separate ships from whale sharks. For this to work, the target species needs to have known core habitat zones rather than be spread evenly across an area; this is certainly the case for whale sharks that aggregate in predictable areas, unlike blue whales, *Balaenoptera musculus*, off California, for example (Redfern *et al.* 2013). The predictable nature of constellations, both in time and space, also means that such measures are likely to be fixed, but seasonal in many cases. Spatial separation thus requires sound knowledge of the whale sharks' habitat use to ensure that a changed route actually reduces the overlap of ships and whale sharks. Our polygons of core habitats and buffer zones for each constellation area, drawn by local experts, are a good starting point. When developing mitigation measures, more detailed local plans will need to be designed based on scientific data and expert knowledge. Spatial separation will also incur costs for shipping stakeholders. However, the core zones of whale shark habitat use in most constellations are small (median = 116.3 km²), and routes around them will not be much further than through them in most cases. Additionally, most constellations have a relatively short peak season of ~3 months. This allows for temporally explicit management matched to the relevant months of the whale shark peak season, which means that additional costs to shipping would only incur at these times. For example, transiting through the core habitat zone of the Holbox aggregation in Mexico covers a distance of ~26.5 km. A container ship travelling at 24 knots takes 36 min for the transit. Re-routing this transit around the core whale shark zone would add 14.1 km in distance for a total transit time of 55 min. Continuing the example to include speed reduction (see below), a direct transit through the core zone would take 86 min at a speed of 10 knots, or 107 min at a speed of 8 knots. As constellation core zones are small, re-routing will often be more cost-effective than speed reduction, at least for fast vessels such as container ships.

**Photo** Sofia Green

Spatio-temporal management options like this have been implemented or suggested to reduce the risk of ship strike on whales. For example, in the Gulf of Panama, a TSS was suggested to concentrate ship traffic in narrower lanes which would reduce the area of ship and humpback whale overlap by 93% (Guzman *et al.* 2013). In the St. Lawrence Estuary in Canada, several voluntary measures were established to reduce ship strike on five species of whale that had a clear and concentrated core habitat zone. A working group consisting of stakeholders from shipping, academia, conservation, and government decided on the voluntary rules, which lead to high compliance. Among the measures was a no-go zone in the main whale habitat around which ships re-routed. Overall, the collision risk with whales reduced by 40% after four years of implementation, showing that spatial management can greatly reduce this risk (Chion *et al.* 2018).

These examples show that dividing the area for ships from that of whale sharks has a good chance of being successful for this species. Biologically, the small and predictable nature of core whale shark areas of constellations are ideally suited to measures such as ATBAs, and whale sharks are likely to directly benefit from such local measures. Economically, too, these strategies could be achievable. Although mitigation measures to reduce ship strike for other marine megafauna are still rare, ABTAs and TSSs are some of the more commonly used approaches. This indicates that the shipping sector is amenable to such strategies. Combined with positive reinforcement, perhaps via an eco-accreditation scheme, compliance can be high and risk mitigation can be a success. As a next step, Range States interested in ABTAs for reducing the risk of ship strike on whale sharks could examine if any ABTAs already exist near constellation areas, as it is likely to be easier to expand an existing ABTA rather than create a new one.

#### *3.4.1.2 Particularly Sensitive Sea Areas (PSSAs)*

Particularly Sensitive Sea Areas are designated by the IMO with the aim of reducing the impact from shipping on areas with high ecological or scientific value. At present, there are <20 PSSAs designated globally, but three sites that host key whale shark constellations are included: the Galápagos Islands, the Great Barrier Reef in Australia, and Tubbataha in the Philippines. Rules in PSSAs are often less stringent than with the previous spatial mechanisms (above); for example in the Galápagos there is a mandatory ship reporting scheme and a TSS designed to reduce the risk of ships colliding with each other (not with wildlife), and there is an ATBA within the PSSA with restrictions on what can be transported through it. The main potential benefit of PSSAs to reducing ship strike on whale sharks is that additional measures, such as speed reduction or re-routing, may be more achievable within these already-designated areas rather than creating new areas through the IMO.

#### *3.4.1.3 Speed reduction*

Speed reduction is one of the most commonly-applied risk reduction mechanisms for whales (See Sèbe *et al.* 2019). The main premise is that a reduction in ship speed reduces the impact force if collisions occur. Models show a reduction in ship strike risk of ~90% for North Atlantic right whales off the US east coast when ships travel at 10 knots or less (Conn and Silber, 2013). Models incorporating empirical ship positions and transit time, and modelling their impact at different speeds showed that 10 knots had the greatest reduction in 'predicted probability of lethality' at 57% compared to a reduction of 29% at 12 knots (Wiley *et al.* 2011). Another study estimated a probability of a lethal ship strike on North Atlantic right whales of 0.21 at 8.6 knots, compared to 0.79 at 15 knots (Vanderlaan and Taggart, 2007). A speed reduction to 10 knots is typically proposed when reducing the risk of ship strike to whales in a balance of conservation gain and ship manoeuvrability. In addition to reducing their physical impact in the case of a collision, slower ships also have more time to evade marine megafauna if they see them in time. The opposite is also technically true, but many marine megafauna species do not evade ships. For example, blue whales in California were behaviourally tolerant to ships (McKenna *et al.* 2015) and North Atlantic right whales did not respond to the sounds of approaching ships (Nowacek *et al.* 2004). Green sea turtles, *Chelonia mydas*, even showed decreased avoidance to approaching ships with increasing ship speed (Hazel *et al.* 2007). Field observations and the high rate of ship-induced scars and injuries reported in our expert survey similarly suggest that whale sharks, too, may not evade approaching vessels. Many marine megafauna species likely do not swim away from ships because they did not evolve with ship noise around, and do not consider it a threat.

# POLICY MECHANISMS

Nevertheless, reducing the overall force of the ship's impact by travelling slower can be an important conservation gain if target species are more likely to survive a collision with a ship. This is likely to be true for whale sharks, which can heal fast (Womersley *et al.* 2021), and, as field observations suggest (Norman and Morgan, 2016) seem to survive long-term even with severe injuries. Sub-lethal effects of injuries, such as fin amputations, are not well understood for whale sharks at present, but likely negatively influence the individual's fitness. However, reduced fitness is preferable to mortality, and speed reductions are likely to become a key measure within whale shark constellations. Speed reductions have the additional benefits of lowering greenhouse gas emissions and underwater noise from ships, both important considerations in the overall impact of shipping on the environment, and both are receiving increasing attention (Joy *et al.* 2019; Leaper, 2019).

Similar to re-routing, ATBAs, and TSSs, speed reduction measures can be fixed and be applied at the local scale of whale shark core habitat zones within constellations during their peak season, where and when they will provide the greatest benefit to the sharks. An important benefit of speed reduction is that its designation can also incorporate small vessels, which can achieve higher speeds than large vessels. Our expert survey suggested that small vessel strike is a major concern within constellations on a global level, and scarring data further supports this as an important threat to whale sharks (Fig. 10; Speed *et al.* 2008). Go-slow zones can also be applied to small vessels, such as tourist or fishing vessels, which can be expected to dramatically decrease the level of small ship strike at the same time. Monitoring compliance of smaller ships without AIS beacons or similar equipment will be challenging, but voluntary compliance, at least among the tourist vessels, is likely to be high based on current engagement levels.

### 3.4.2 Technical

#### 3.4.2.1 Dynamic Management Areas (DMAs)

Dynamic Management Areas (DMAs) are a mix between technical and operational mitigation mechanisms. The rules in DMAs come into effect depending on the presence or movement of the target species. In the context of whale shark hotspots, it may be possible to create an alert when researchers in the constellation see 10+ whale sharks and can relay the position of the aggregation to ships in the DMA, that then evoke certain rules, such as re-routing or speed reductions. DMAs may be a good option in constellations where fixed permanent or seasonal re-routing or speed reduction measures may not be feasible (e.g. Strait of Hormuz), or in places where the location of the constellation varies broadly over time (e.g. Honduras). However, constantly surveying the number and location of whale sharks over a season each year is likely to be expensive. DMAs could also rely on predictive modelling of the daily location of the most suitable whale shark habitat (Dransfield *et al.* 2014; Abrahms *et al.* 2019), but this would require a sound understanding of the environmental drivers that influence dynamic whale shark movement and aggregating behaviour.

**Photo** Stacia Marcoux

#### 3.4.2.2 Alert networks

Alert networks driven by the public (e.g. WhaleAlert) can provide real-time reporting of animal locations and help divert marine traffic away from them (Wiley et al., 2013). Alert networks typically require a mobile phone or a device capable of recording and transmitting a location (GPS/AGPS), as well as a software-based system able to communicate location through a network of connected users. The system can be further coupled with dedicated patrolling or active monitoring by volunteers or researchers alike. If supported by governments, the system could suggest voluntary avoidance zones for vessels and compliance could have a reward mechanism. For whale sharks, this approach would work well in high profile sites with active recreational boat users (e.g. Ningaloo Reef, Australia), as whale sharks sighted would be reported into a localised network of boat users. In the Ningaloo Reef example where they use spotter planes to locate whale sharks for their ecotourism operations, there could be associated benefits. The main objective would be to divert vessels away from where whale sharks are sighted in near-real time. However, given their popularity amongst recreational water users, this is likely to have the opposite effect and indeed attract boat activity to the area where whale sharks were sighted/reported. Whale sharks don't necessarily stay near the surface for prolonged periods and therefore a reported sighting through a network would probably be short-lived, leading to decreased user engagement. It could help general monitoring of whale sharks in specific areas (e.g. in buffer zones) but enforcement would need to be part of the network.

#### 3.4.2.3 Observers

Specially trained observers could be used as a direct approach to 'detect and alert' vessels away from whale sharks. There is a growing network of marine mammal observers which could be relied on for this potential approach, and observers do spot whales earlier than ship crew (Weinrich *et al.* 2010). However, unlike marine mammals, whale sharks don't always breach the surface of the water and as such this approach is unlikely to be effective for the species. Moreover, observers need good visibility (light and clarity) to detect animals in the water, further limiting the reliability of detection of whale sharks and its effectiveness for reducing strikes. Observer programmes to avoid whale sharks could be coupled with alert networks, wherein a reported sighting is shared with a broader network of large and small vessel users. Given the results presented here, observer programmes could also be spatially 'activated' and only apply in the peripheral zones of core whale shark habitats.

#### 3.4.2.4 Acoustic pingers

Acoustic pingers attached to ships that send out an alert sound signal may be a potential future mitigation strategy. Acoustic pingers are attractive because they would be a relatively cheap mechanism with the potential to be applicable throughout the whale sharks' distribution without much effort on behalf of the shipping industry. However, no such pingers have yet been developed for whale sharks, and may not be feasible. The premise of this technology is that marine megafauna hear the alert signal and respond by leaving the area of the approaching ship. Some acoustic pingers have been developed to deter marine mammals from stationary fishing gear, however, their effectiveness remains disputed even for their intended purpose. For whale sharks specifically, there are three additional hurdles to overcome: whale sharks have different hearing capabilities than marine mammals and would require a different sound frequency, the signal from a pinger attached to a ship may not alert them in time for a fast-approaching ship, and the whale sharks' reaction to alert signals is unknown.

Hearing capabilities of whale sharks have not yet been investigated, although their large inner ear suggests that they have good hearing in the low frequency sound spectrum (Yopak and Peele, 2021). Sharks generally have peak hearing in the 0.2–0.6 kHz range, with an overall upper limit of 1.5 kHz (Chapuis *et al.* 2019). This is much lower than the peak frequencies heard best by dolphins (~20–120 kHz) and lower also than that of large whales (1–10 kHz) (Li *et al.* 2012; Finneran, 2016). Their tuning to low frequencies means that whale sharks likely do not hear the alert signal sent via existing acoustic pingers that have been designed to deter marine mammals from fishing gear. Their likely hearing capabilities, like that of other fishes, overlap with shipping noise that is generally in the 0.01–1 kHz range, but also has higher frequencies (Erbe *et al.* 2019).

An additional consideration is the response whale sharks exhibit to an alert signal. For whales, alert signals sometimes resulted in individuals swimming strongly to the surface, which likely increases the risk of ship strike (Nowacek *et al.* 2004). Field observations suggest that whale sharks dive when startled, but a more detailed investigation would be needed to test any potential alert signals and their effectiveness. If suitable pingers can be developed, mitigation could be achieved throughout the entire species' range and therefore warrants further research.

**Photo** Chris Rohner

# 4. RECOMMENDATIONS

The work presented here highlights the urgent need for management by whale shark Range States to limit ship strikes on this Endangered and Largely Depleted species. Here, we show that, from >40 global constellations (nearly all known aggregation sites), whale sharks at some sites are under high risk of ship strike, namely, off the mainland of Ecuador, Isla Mujeres and La Paz in Mexico, Kota Kinabalu and Redang Island in Malaysia, Pintuyan in the Philippines, the Musandam in Oman, and around the Seychelles and Taiwan. Management mechanisms focused on these constellations, where whale sharks aggregate in high numbers, will not eliminate the risk of lethal ship strike for this wide-ranging species. However, it likely has the best chance of making a positive impact by reducing the risk in these key areas. Given that whale shark constellation areas are small, the cost to implement mitigation measures is also going to be lower than tackling the problem across their entire distribution. We thus focus below on mechanisms that are likely to work for these small, discrete areas of high whale shark densities:

### 1. Range States consider mitigation measures in their whale shark hotspots

We show here the pressing need for conservation action by developing mechanisms to reduce the risk of ship strike on whale sharks. We encourage all Range States to investigate the best approach in their whale shark hotspots, in transparent consultation with researchers and the shipping industry. Mitigation measures need to be based on the best available scientific data to ensure positive conservation outcomes.

### 2. Designate whale shark core zones as Areas to Be Avoided (ATBAs)

Given the relatively small size of the core zones (median ~116 km$^2$), and the limited impact on shipping time from small distance lane movements, this approach would be the most cost-effective and also have a high conservation impact.
Moreover, ATBAs would benefit other species of interest that are also at risk from ship strikes such as marine turtles and marine mammals. Whale shark ATBAs could be incorporated into wider Marine Protected Area (MPA) designations, supporting the current global effort to protect 30% of the ocean by 2030.

### 3. Consider Traffic Separation Schemes (TSSs) when ATBAs are not an option

Narrowing shipping lanes will reduce the area of high ship strike risk. This may be an alternative option in constellations with a relatively large area, such as the Gulf of Mexico, where large ATBAs are not feasible, but TSSs could greatly reduce the risk of ship strike on whale sharks in this area. They could also be used in cases where naviational or geographic restrictions prevent ATBAs.

### 4. Reduce speed in whale shark core zones

Speed reduction to 10 knots or less can potentially reduce mortality from ship strikes with whale sharks. This mechanism is also a smaller change to ship navigation than re-routing, and is thus more likely to be approved by shipping stakeholders. Go-slow zones can also be applied to all vessles, including small, which will address another facet of the ship strike threat and is a major concern of whale shark experts globally. Given the small spatial footprint of go-slow zones, similar benefits to the designation of ATBAs would also follow.

### 5. Create alert networks with temporary avoidance zones

Supported by the general public as citizen scientists, whale shark sightings could be communicated throughout a broad array of boat users to create temporary vessel exclusion zones. Similarly, satellite tracking of whale sharks within constellations could help determine and create near-real time avoidance zones. This would also help with general whale shark monitoring across larger spatial scales, providing invaluable data about seasonality, abundance and site use.

### 6. Create a centralised database for documenting ship strikes on whale sharks

Understanding the level of impact with an increasing number of large vessels will be critical for mitigation strategies. A centralised database, which could use the existing global database Sharkbook.ai, would benefit long-term monitoring of this threat. A database that could encompass all marine wildlife could be useful for holistic management in the future.

### 7. Increase awareness of this issue with the shipping sector and the public

Successful mitigation of ship strikes on whale sharks will require collaboration of stakeholders from industry, government, and conservation. As this threat is largely unknown outside the whale shark research group, awareness raising will be an important first step, particularly by instigating direct conversations with the shipping industry.

### 8. Use adaptive management and monitor & evaluate mitigation strategies

Any mitigation measures aimed at reducing ship strikes on whale sharks will need to be continually monitored and evaluated. This will include regulatory compliance (voluntary or otherwise) set by Range States, such as adherence to TSSs or ATBAs, as well as data sharing and observer reports. As shipping traffic is increasing, and species move in response to climate change, an adaptive management approach will be needed here. This means evaluating mitigation strategies put forward and reviewing and updating them over time.





# 5. APPENDICES

## 5.1 Appendix 1: Google form

Section 2 of 4

Section 2: About your constellation

For the purpose of this study, we are defining a **constellation** as an important site for whale sharks where at least **30** individual whale sharks are typically encountered annually. By important we mean a site where whale sharks are found feeding, navigating or generally spending time therein.

**Constellation Size**. How many **encounters** have you recorded at your constellation? *Please specify a number.*

Short answer text

**Constellation Size**. How many **individual whale sharks** have you identified at your constellation? *Please specify a number.*

Short answer text

**Constellation Size**. What time period does your data/information cover? *Please specify a range, for example March 1998 - February 2023.*

Long answer text

**Population trend.** Do you think there is a trend in sightings in your constellation? *Part 1 of 2.*

- Decreasing
- Slightly Decreasing
- Neutral
- Slightly Increasing
- Increasing

**Population trend.** Is this based on sighting data or your perception? *Part 2 of 2.*

- Data
- Perception
- Other...

**Seasonality.** In which months are whale sharks sighted within your constellation? *Please tick all that apply.*

- January
- February
- March
- April
- May
- June
- July
- August
- September
- October
- November
- December

**Seasonality.** Which months are peak season for whale sharks within your constellation? *Please tick all that apply.*

- January
- February
- March
- April
- May
- June
- July
- August
- September
- October
- November
- December

# Appendix 1: Google form

**Threats.** What is ***the single most pressing threat*** to whale sharks at your constellation?

- Small vessel collisions (<20 m long, <300 gross tons)
- Large vessel collisions (>20 m long, >300 gross tons)
- Direct/Targeted fishing
- By-catch
- Fishing-related injuries
- Unregulated tourism
- Pollution (including plastics)
- Habitat loss/destruction
- Climate Change
- Other..

**Threats**. What other threats exist to whale sharks at your constellation? *Please tick all that apply.*

- Small vessel collisions (<20 m long, <300 gross tons)
- Large vessel collisions (>20 m long, >300 gross tons)
- Direct/Targeted fishing
- By-catch
- Fishing-related injuries
- Unregulated tourism
- Pollution (including plastics)
- Habitat loss/destruction
- Climate Change
- Other..

**Collisions.** How would you rate the level of threat collisions from **small vessels (<20 m long, <300 gross tons)** pose to whale sharks in your constellation?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| No Threat | ○ | ○ | ○ | ○ | ○ | Great Threat |

**Collisions.** How would you rate the level of threat collisions from **large vessels (>20 m long, >300 gross tons)** pose to whale sharks in your constellation?

| | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|
| No Threat | ○ | ○ | ○ | ○ | ○ | Great Threat |

**Collisions.** What type of vessels pose a threat to whale sharks in your constellation? *Please tick all t hat apply.*

- Tourist vessels
- Recreational vessels
- Artisanal fishing vessels
- Industrial fishing vessels
- Passenger ferries
- Tankers (oil, gas, chemical)
- Container/cargo vessels
- Barge/tow vessels
- Other..

**Collisions.** Do you think vessel collisions affect whale shark populations in general?

- Yes
- No
- Unsure
- Other..

**Collisions.** What percentage (%) of whale sharks within your constellation have **any sign of vessel-related injuries**? *Please give a number from 0 to 100. An approximate number would suffice if no accurate figure available.*

Short answer text

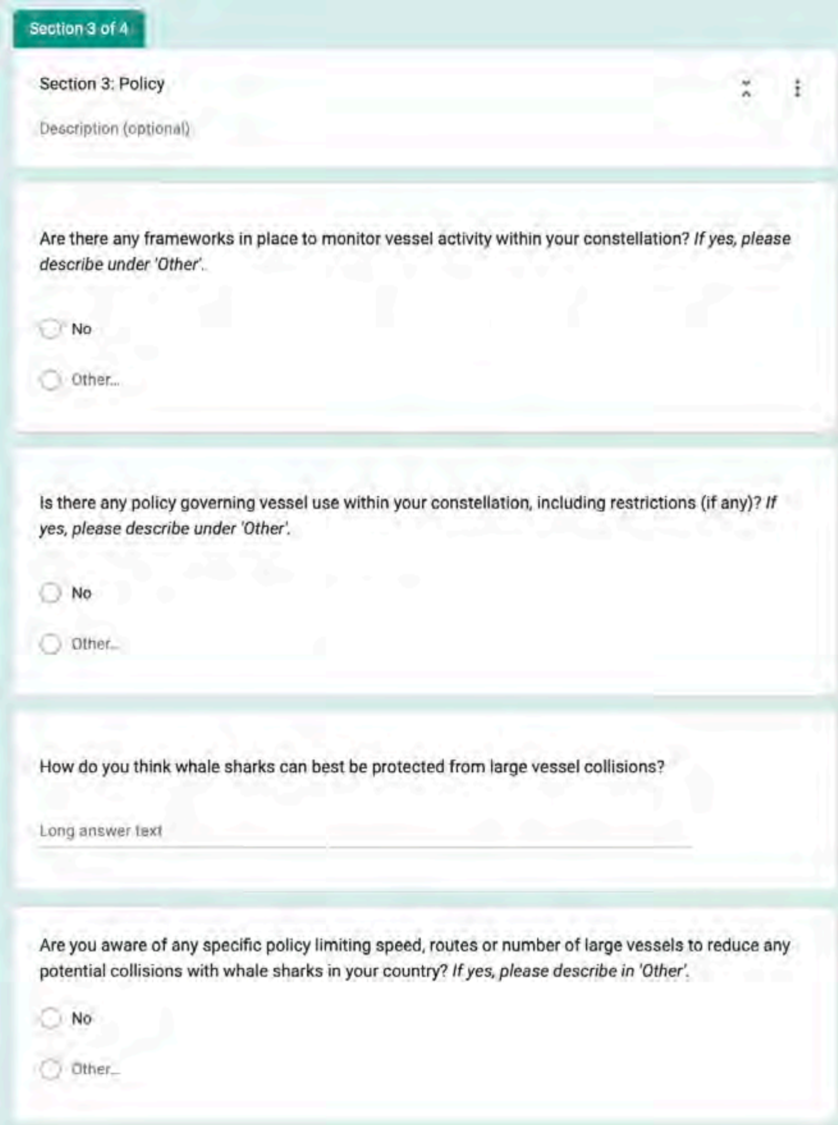
**Collisions.** What percentage (%) of whale sharks within your constellation do you consider to have **major vessel-related injuries (e.g. Large lacerations & blunt trauma, partial to full amputations)**? *Please give a number from 0 to 100. An approximate number would suffice if no accurate figure available.*

Short answer text

Do you know of any other species that may be at risk of large vessel collisions within your constellation? *If yes, please list.*

Long answer text

# Appendix 1: Google form



Section 3 of 4

Section 3: Policy

Description (optional)

Are there any frameworks in place to monitor vessel activity within your constellation? *If yes, please describe under 'Other'.*

No

Other...

Is there any policy governing vessel use within your constellation, including restrictions (if any)? *If yes, please describe under 'Other'.*

No

Other...

How do you think whale sharks can best be protected from large vessel collisions?

Long answer text

Are you aware of any specific policy limiting speed, routes or number of large vessels to reduce any potential collisions with whale sharks in your country? *If yes, please describe in 'Other'.*

No

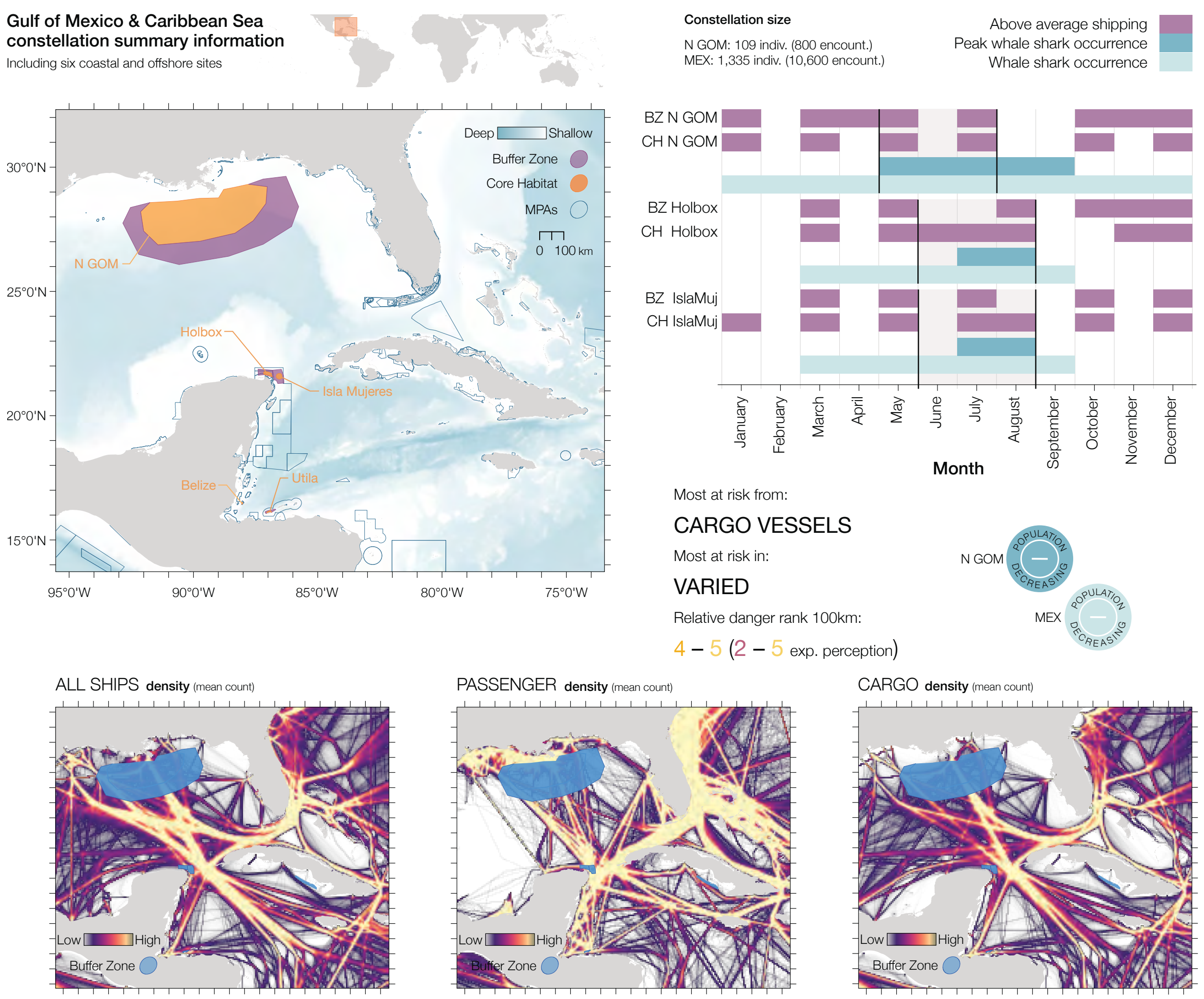
Other...

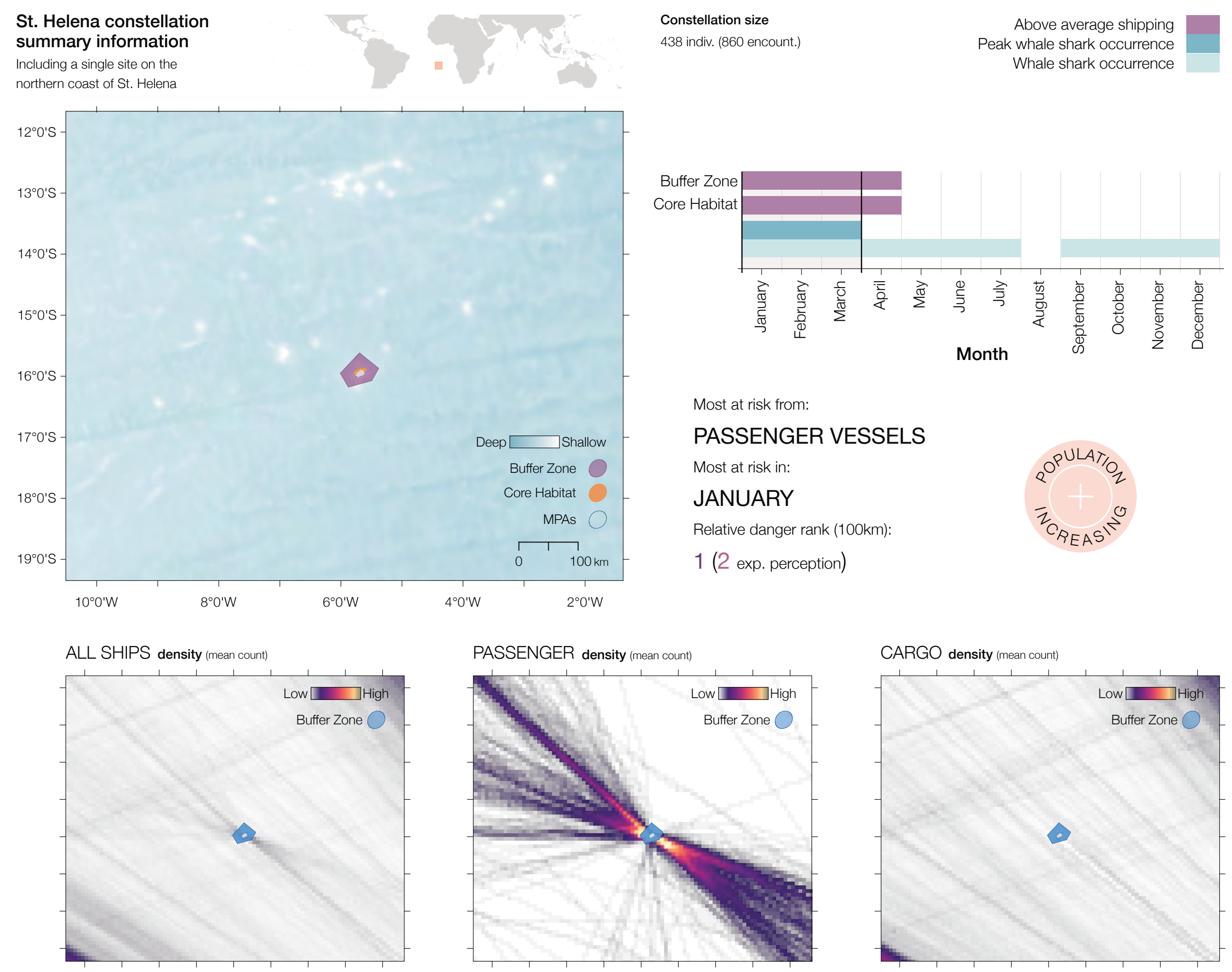


**Photo** Simon Pierce

# 5.2 Appendix 2: Regional maps

## Atlantic Ocean



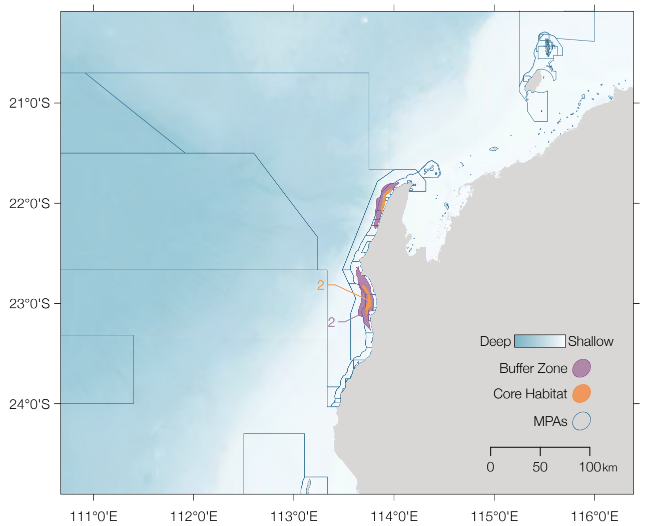
# Appendix 2: Regional maps

## Indian Ocean

**Australian constellation summary information**

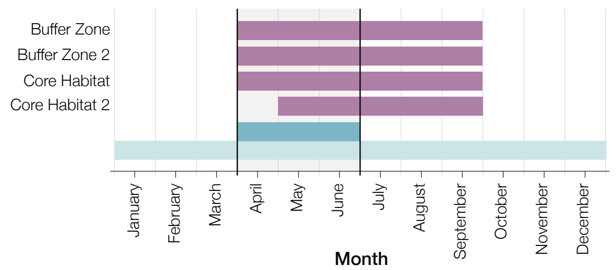
Including two Ningaloo sites on the west coast of Australia






**Constellation size**

1,473 indiv. (44,607 encount.)




Most at risk from:

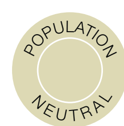
PASSENGER VESSELS

Most at risk in:

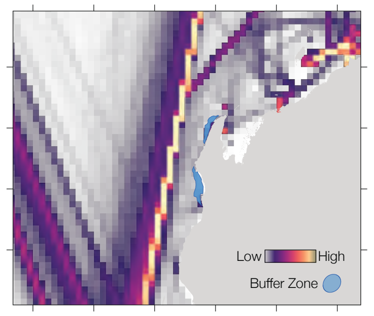
MAY

Relative danger rank (100km):

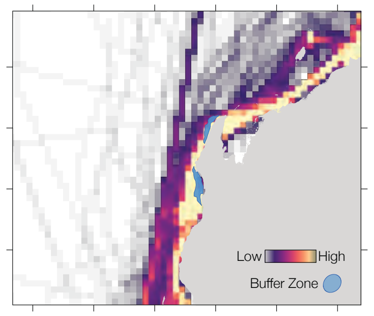
2 – 3 (4 exp. perception)



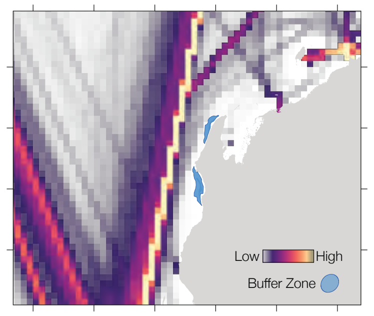

ALL SHIPS **density** (mean count)




PASSENGER **density** (mean count)



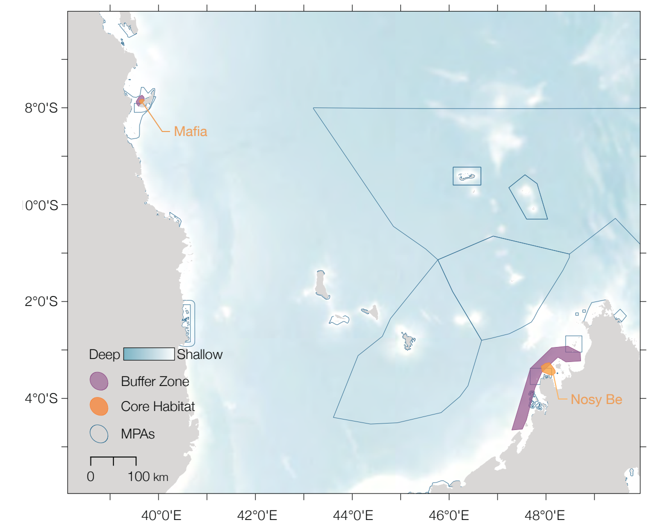

CARGO **density** (mean count)




**Southwest Indian Ocean constellation summary information**

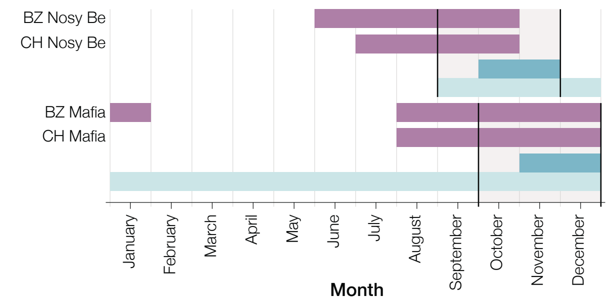
Including sites in Tanzania and Madagascar






**Constellation size**

Nosy Be: 497 indiv. (1,800+ encount.)
Mafia: 222 indiv. (2,300 encount.)




Most at risk from:

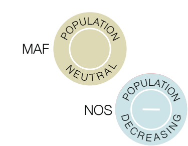
PASSENGER VESSELS

Most at risk in:

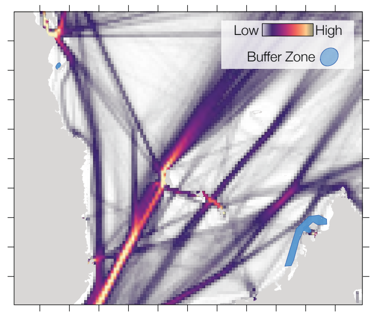
VARIED

Relative danger rank (100km):

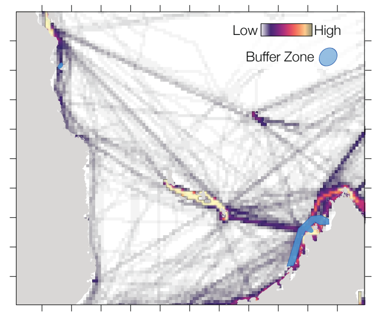
1 – 2 (3 exp. perception)



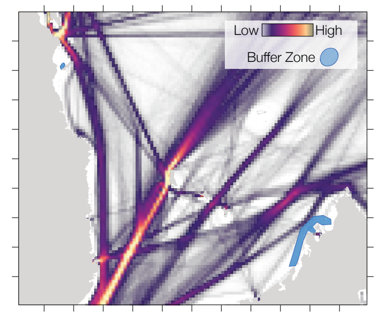

ALL SHIPS **density** (mean count)




PASSENGER **density** (mean count)

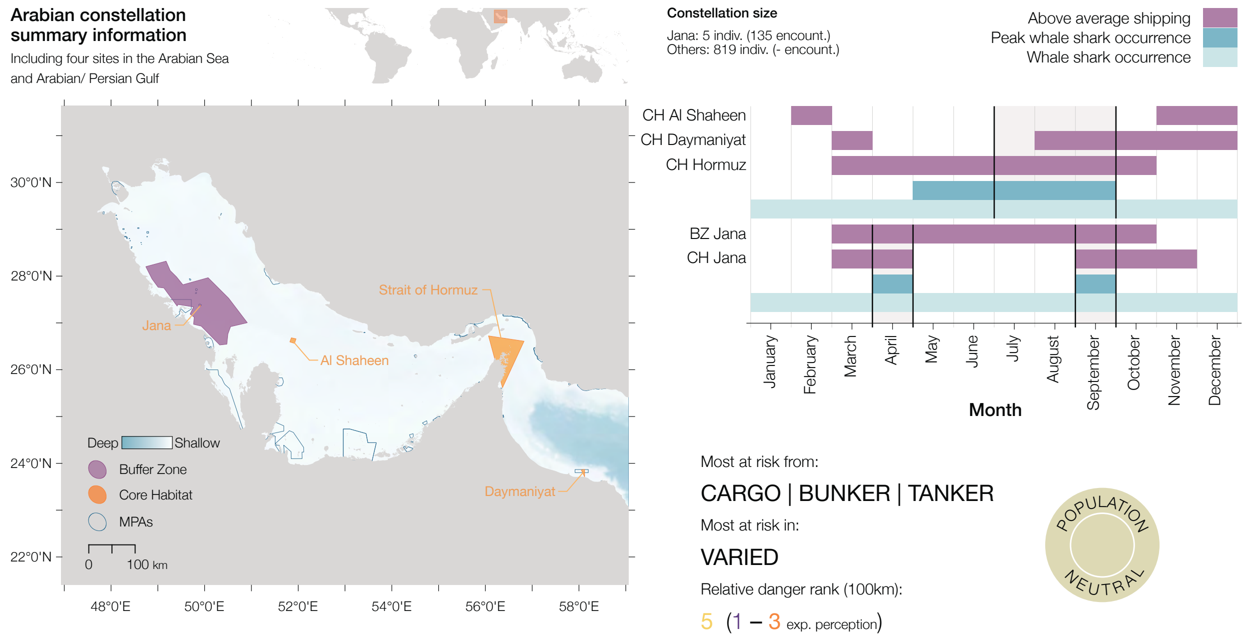


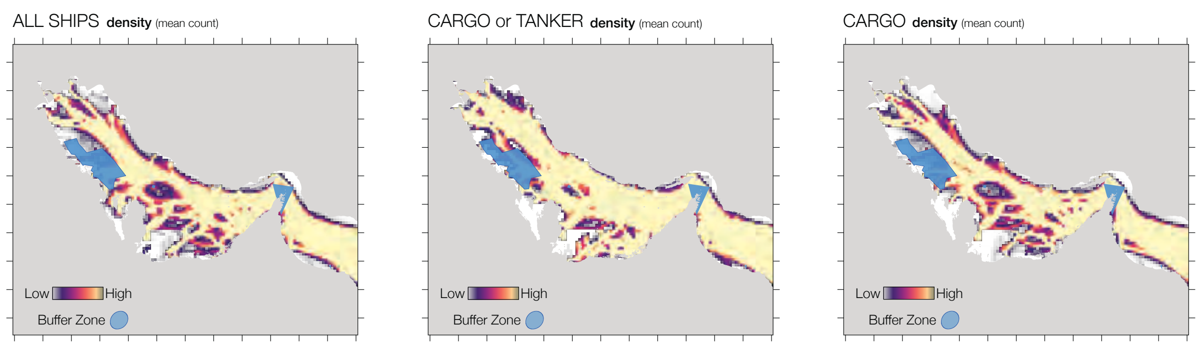

CARGO **density** (mean count)

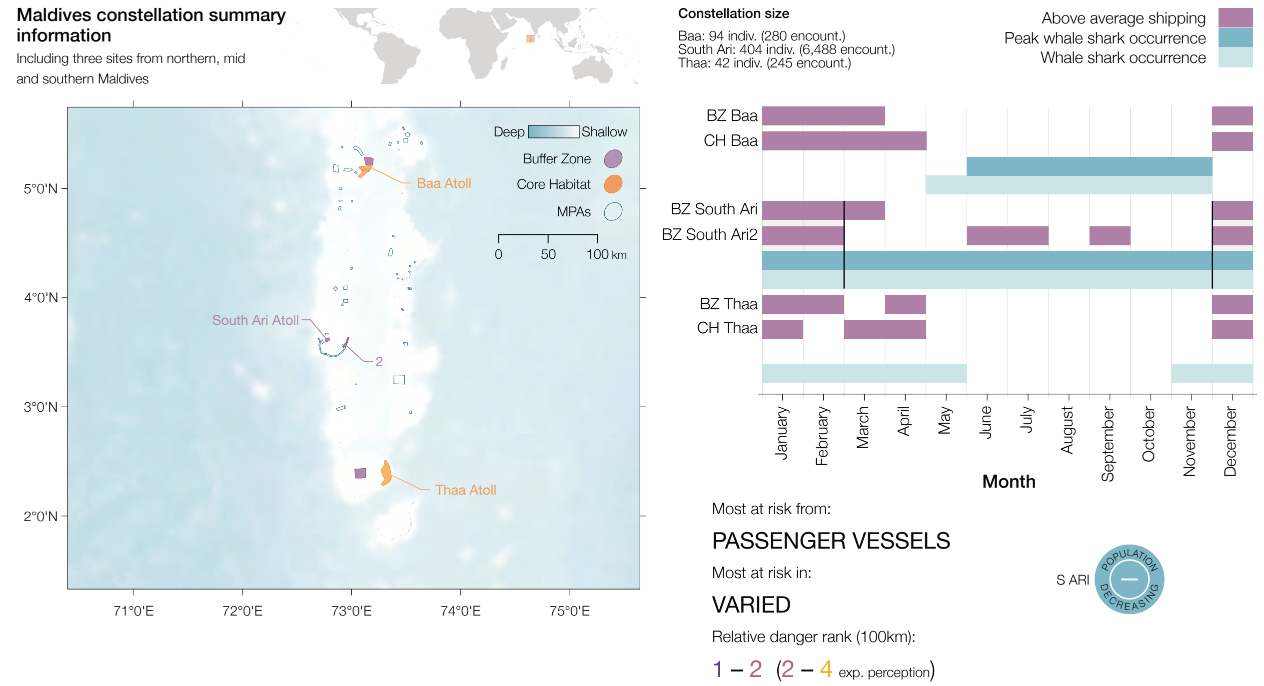


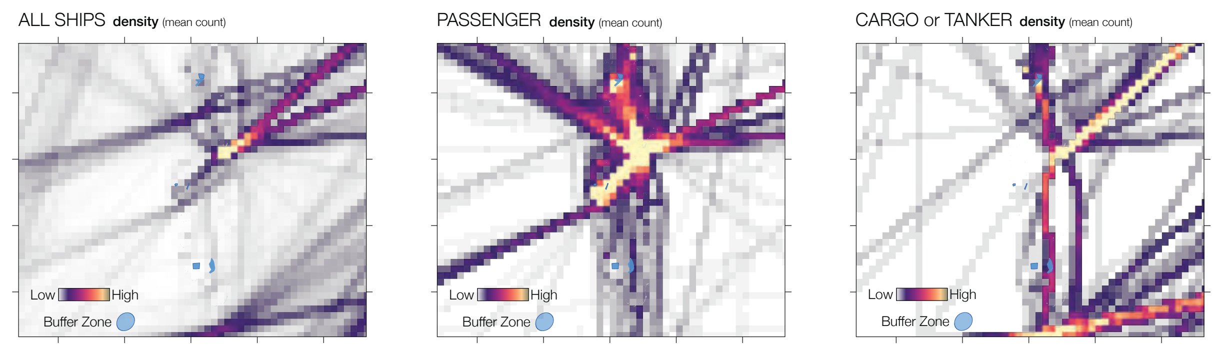
# Appendix 2: Regional maps

## Indian Ocean



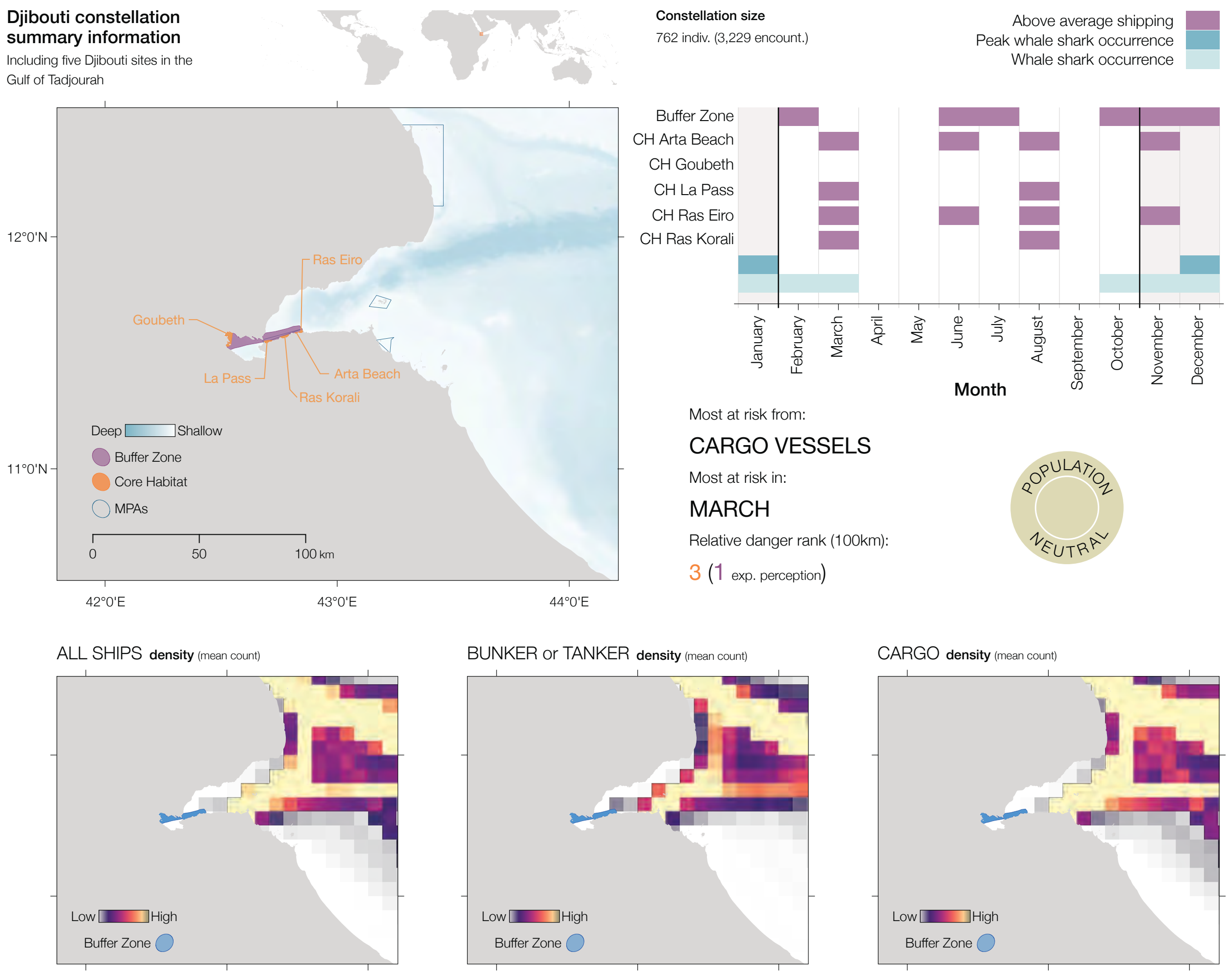



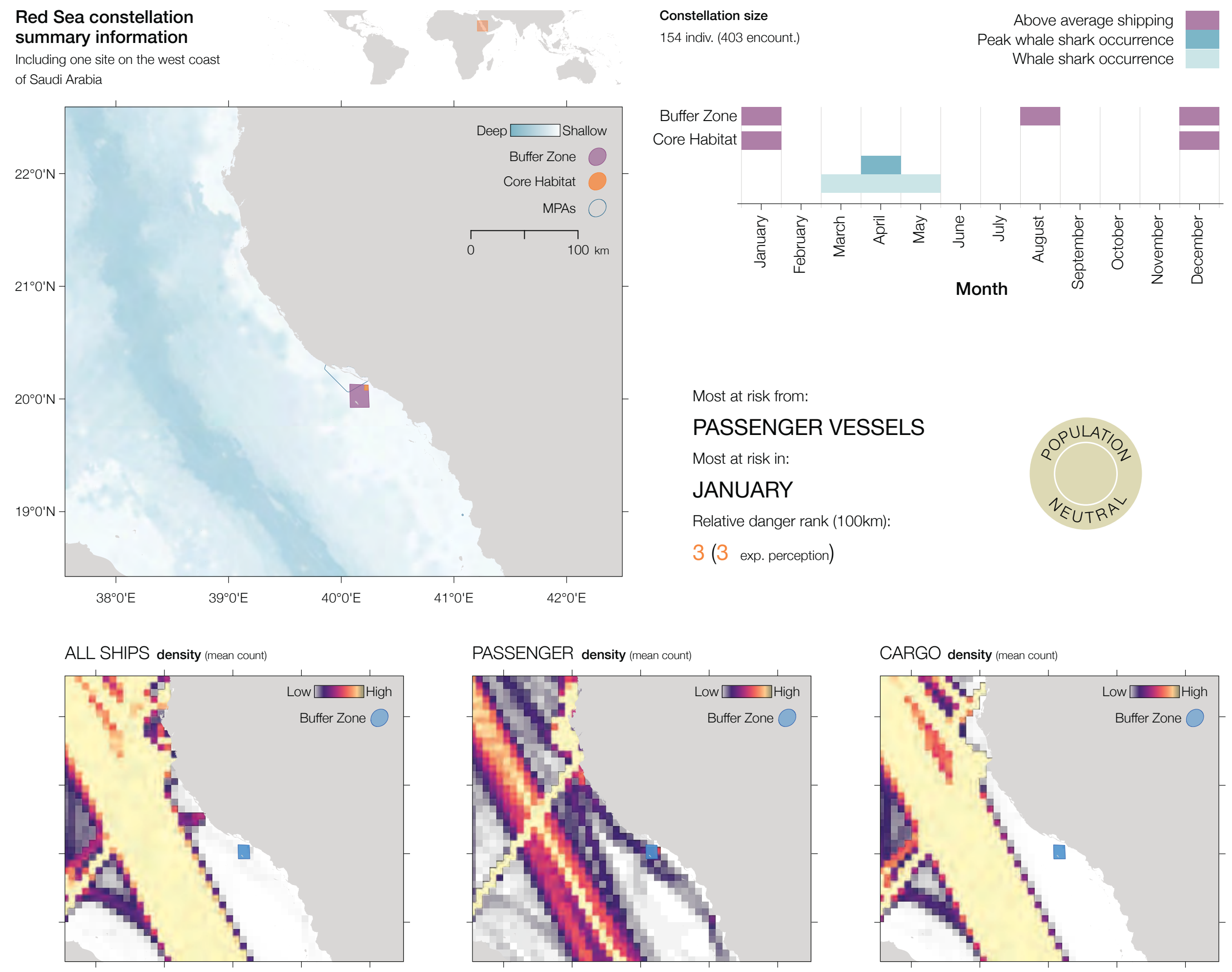



# Appendix 2: Regional maps

## Indian Ocean



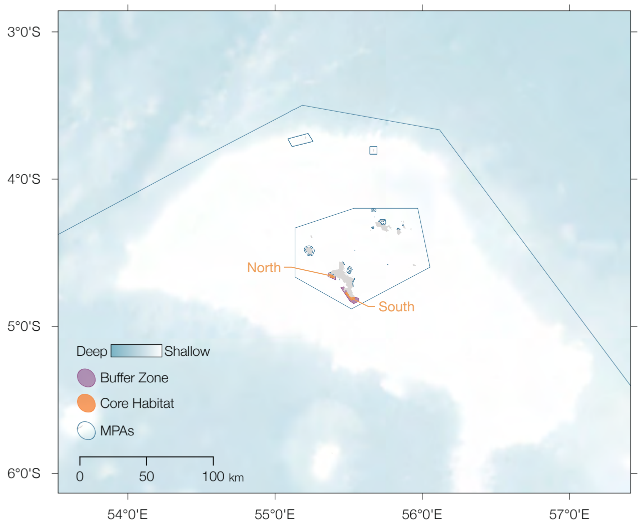
# Appendix 2: Regional maps

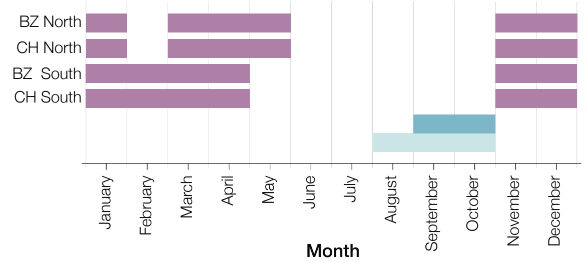
## Indian Ocean

**Seychelles constellation summary information**
Including two sites on the northwest and south coast of Mahe



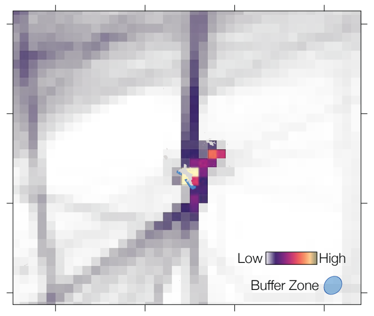
**Constellation size**
550 indiv. (- encount.)



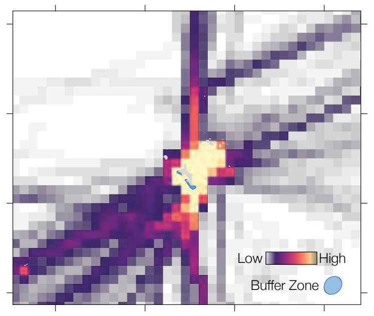




Most at risk from:
PASSENGER | SP. REEFER
Most at risk in:
MARCH | APRIL
Relative danger rank (100km):
1 (5 exp. perception)

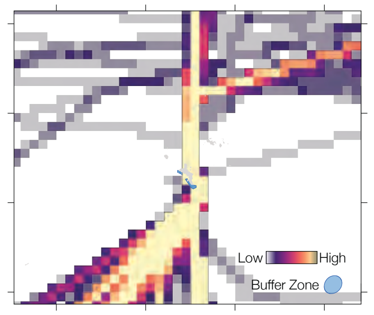

ALL SHIPS **density** (mean count)




PASSENGER **density** (mean count)




SPECIALISED REEFER **density** (mean count)

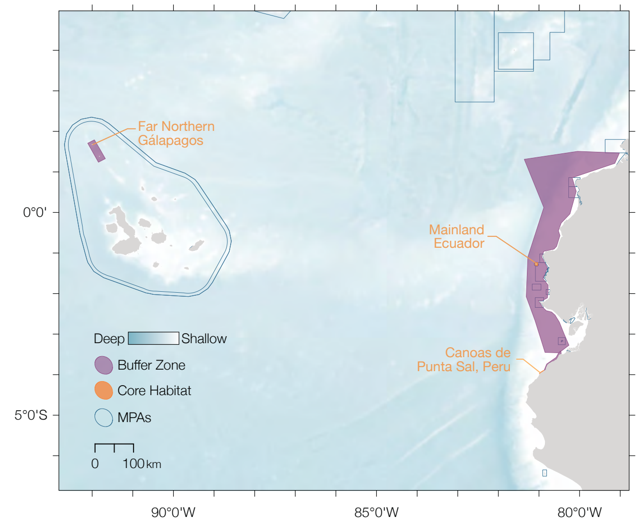


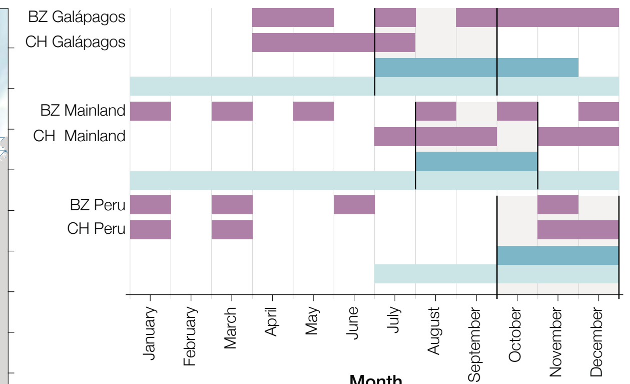

## Pacific Ocean

**Ecuador and Peru constellation summary information**
Including three sites in mainland Peru and Ecuador, and Galápagos

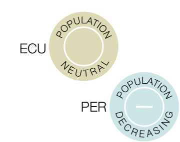


**Constellation size**
Galapagos: 626 indiv. (953 encount.)
Mainland Ecuador: 7 indiv. (45 encount.)
Peru: 224 indiv. (750 encount.)

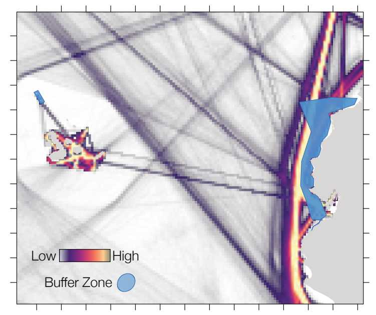


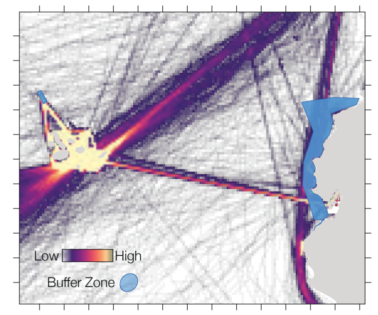

Most at risk from:
CARGO | PASSENGER
Most at risk in:
VARIED
Relative danger rank (100km):
1 – 4 (1 – 3 exp. perception)



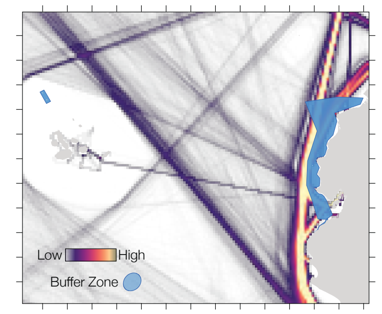

ALL SHIPS **density** (mean count)




PASSENGER **density** (mean count)




CARGO **density** (mean count)

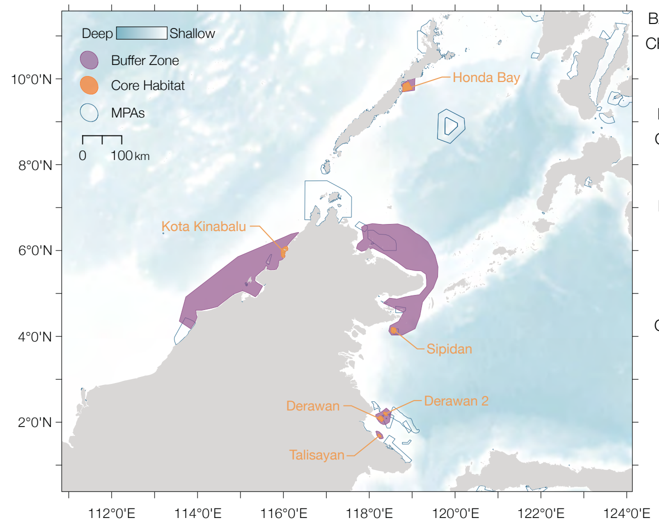


# Appendix 2: Regional maps

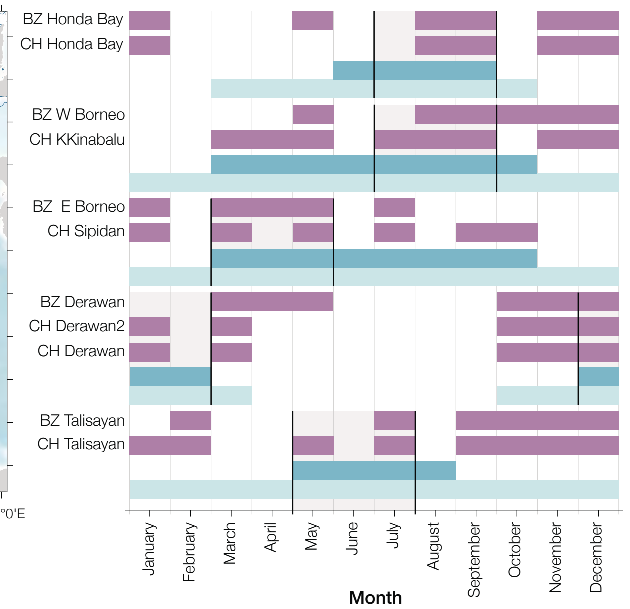
## Pacific Ocean

**South East Asia constellation summary information**
Including five sites in Malaysia, Philippines and Indonesia

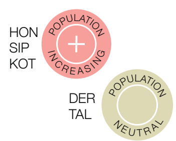




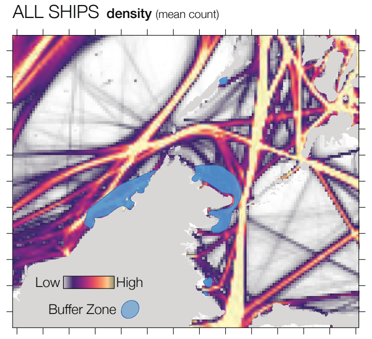

**Constellation size**
Honda Bay: 321 indiv. (506 encount.)
Malaysia: 206 indiv. (750 encount.)



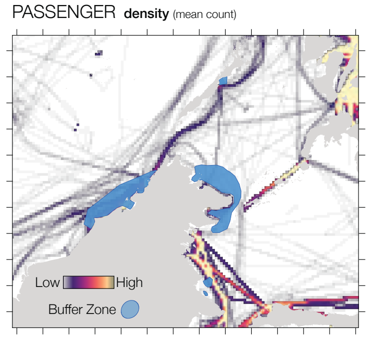

Most at risk from:
PASSENGER | CARGO
Most at risk in:
VARIED
Relative danger rank (100km):
2 – 4 (2 – 3 exp. perception)



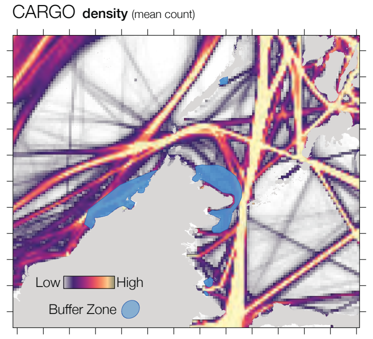

ALL SHIPS **density** (mean count)




PASSENGER **density** (mean count)

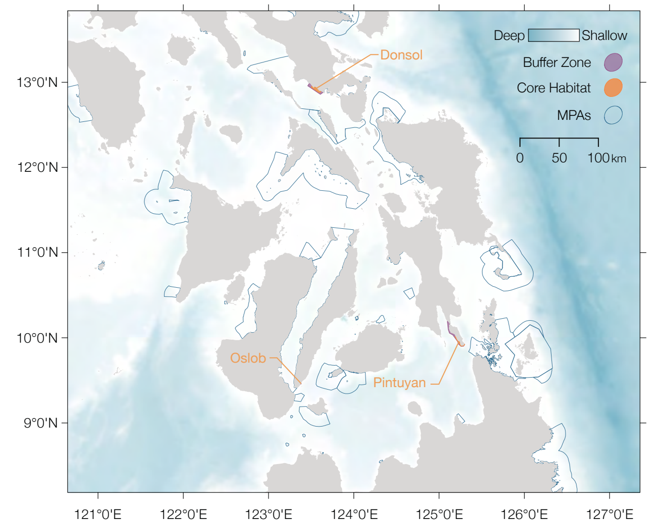



CARGO **density** (mean count)

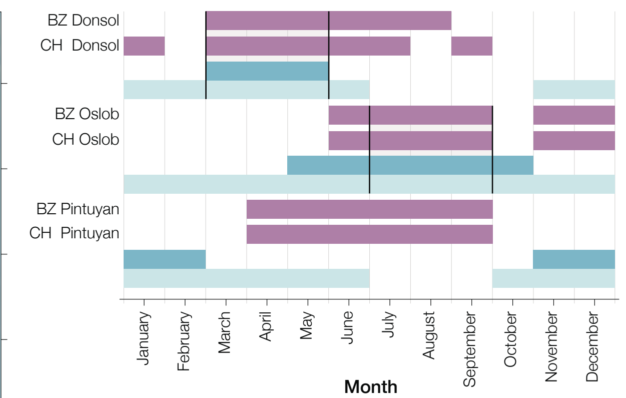



**Philippines constellation summary information**
Including three sites from northern and southern Philippines



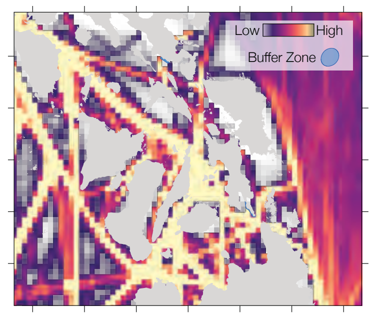



**Constellation size**
Donsol: 614 indiv. (4,985 encount.)
Oslob: 423 indiv. (42,732 encount.)
Pintuyan: 321 indiv. (1,976 encount.)

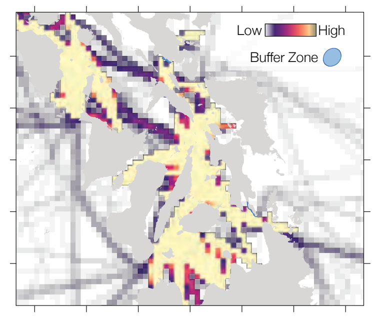



Most at risk from:
PASSENGER | CARGO
Most at risk in:
VARIED
Relative danger rank (100km):
3 – 5 (3 – 5 exp. perception)

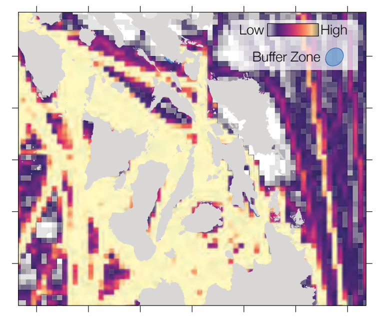

ALL SHIPS **density** (mean count)




PASSENGER **density** (mean count)

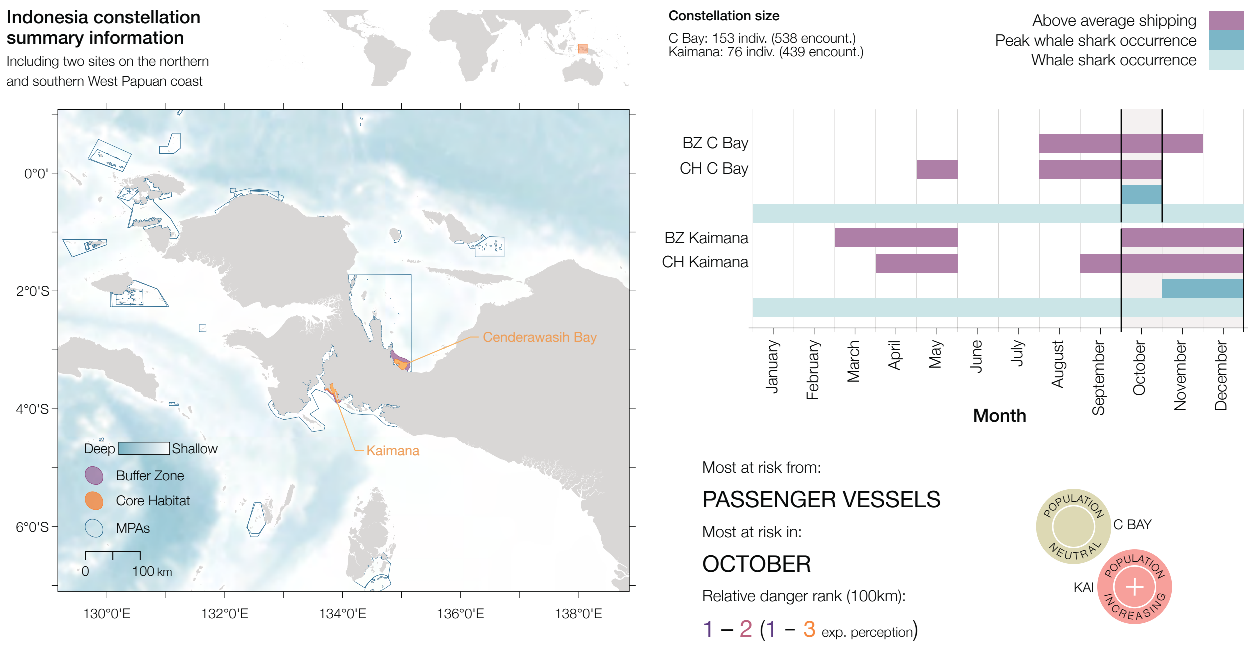


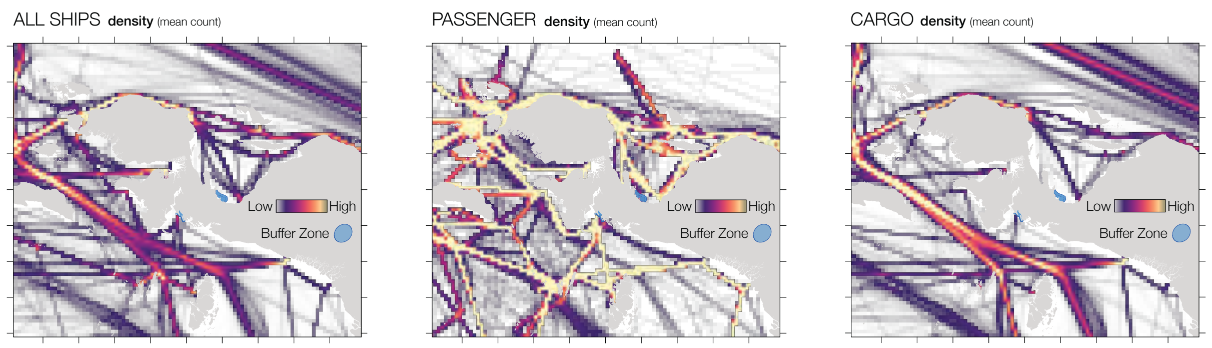

CARGO or TANKER **density** (mean count)

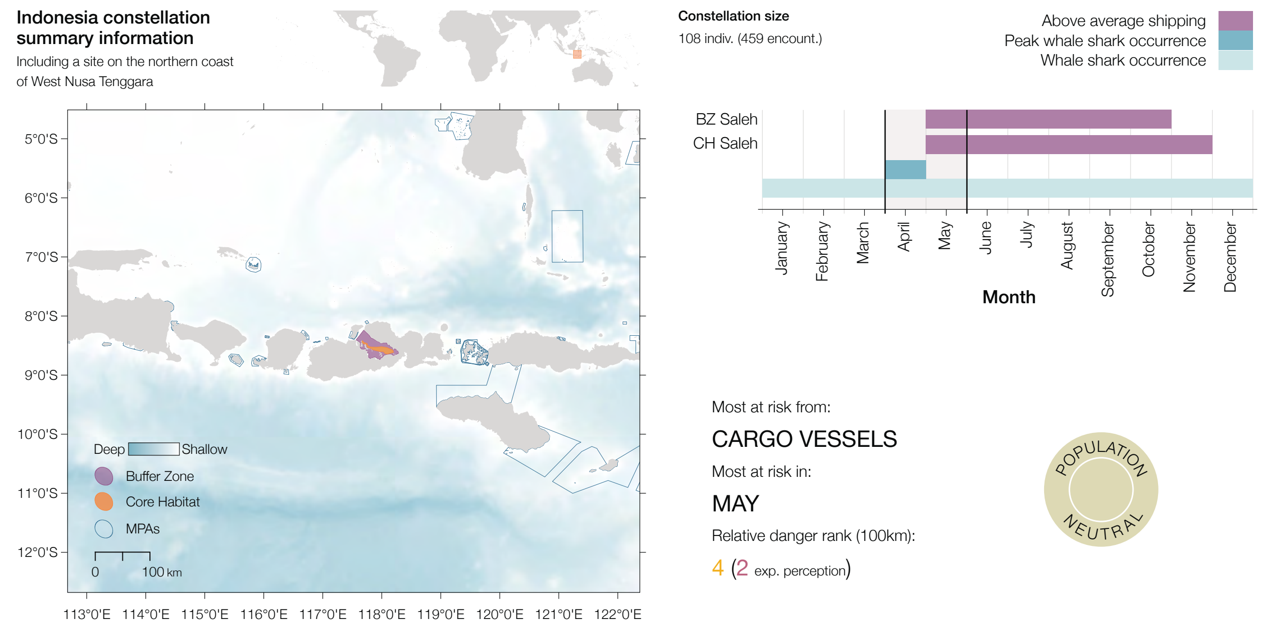


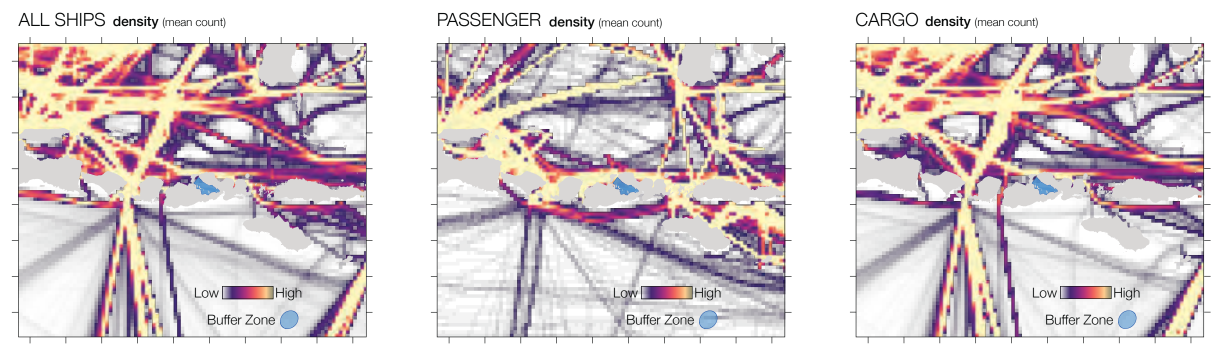
# Appendix 2: Regional maps

## Pacific Ocean



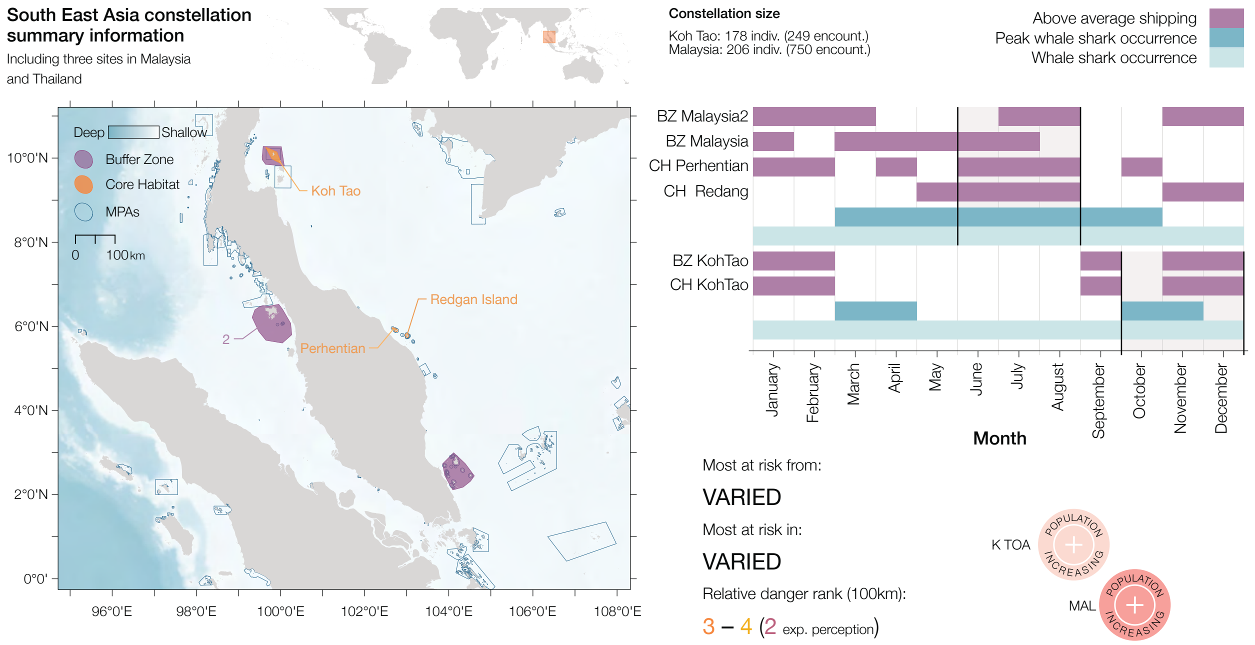



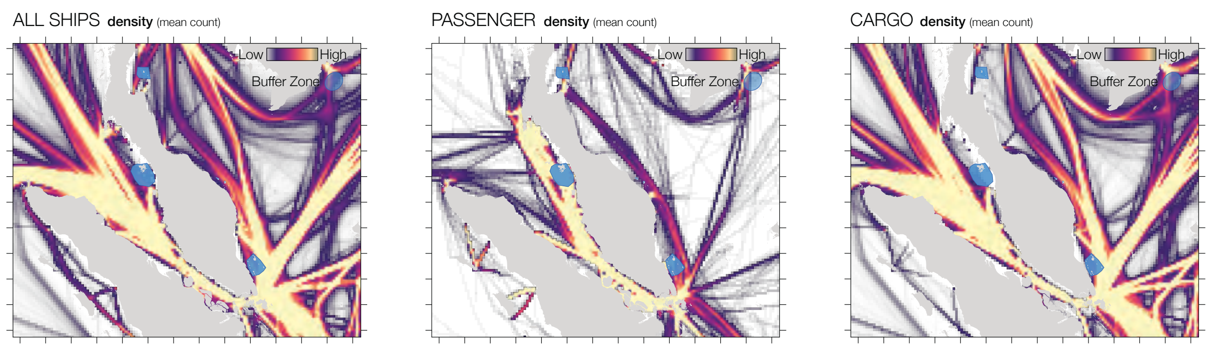



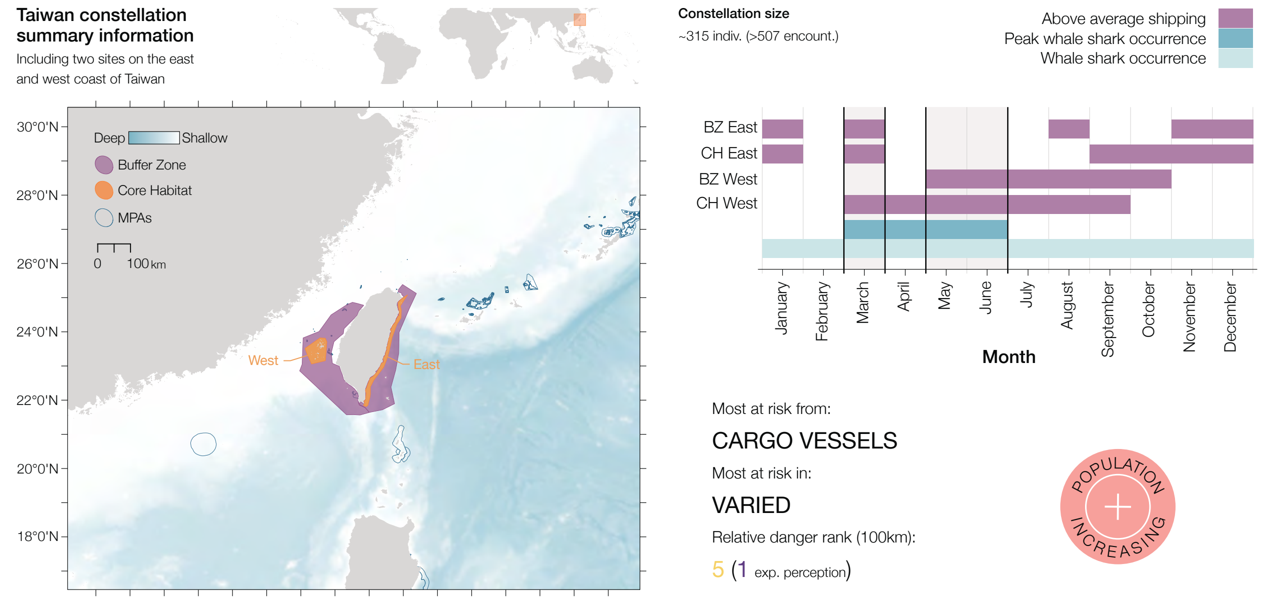



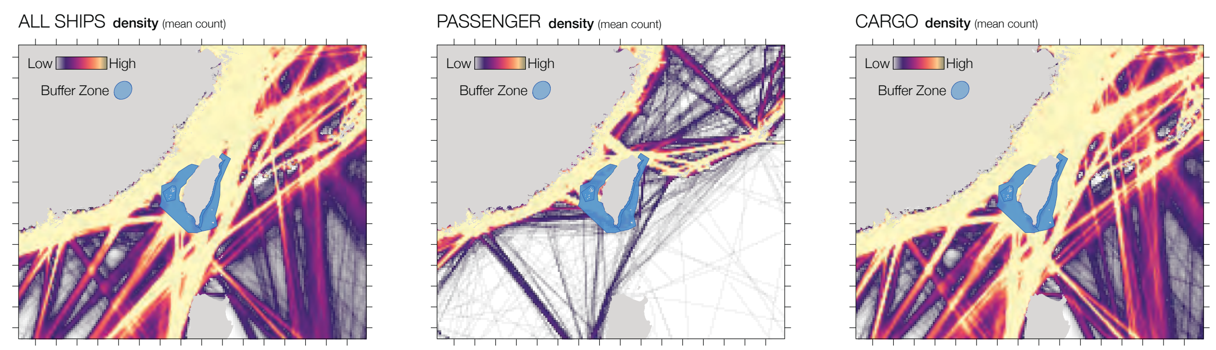
# Appendix 2: Regional maps

## Pacific Ocean



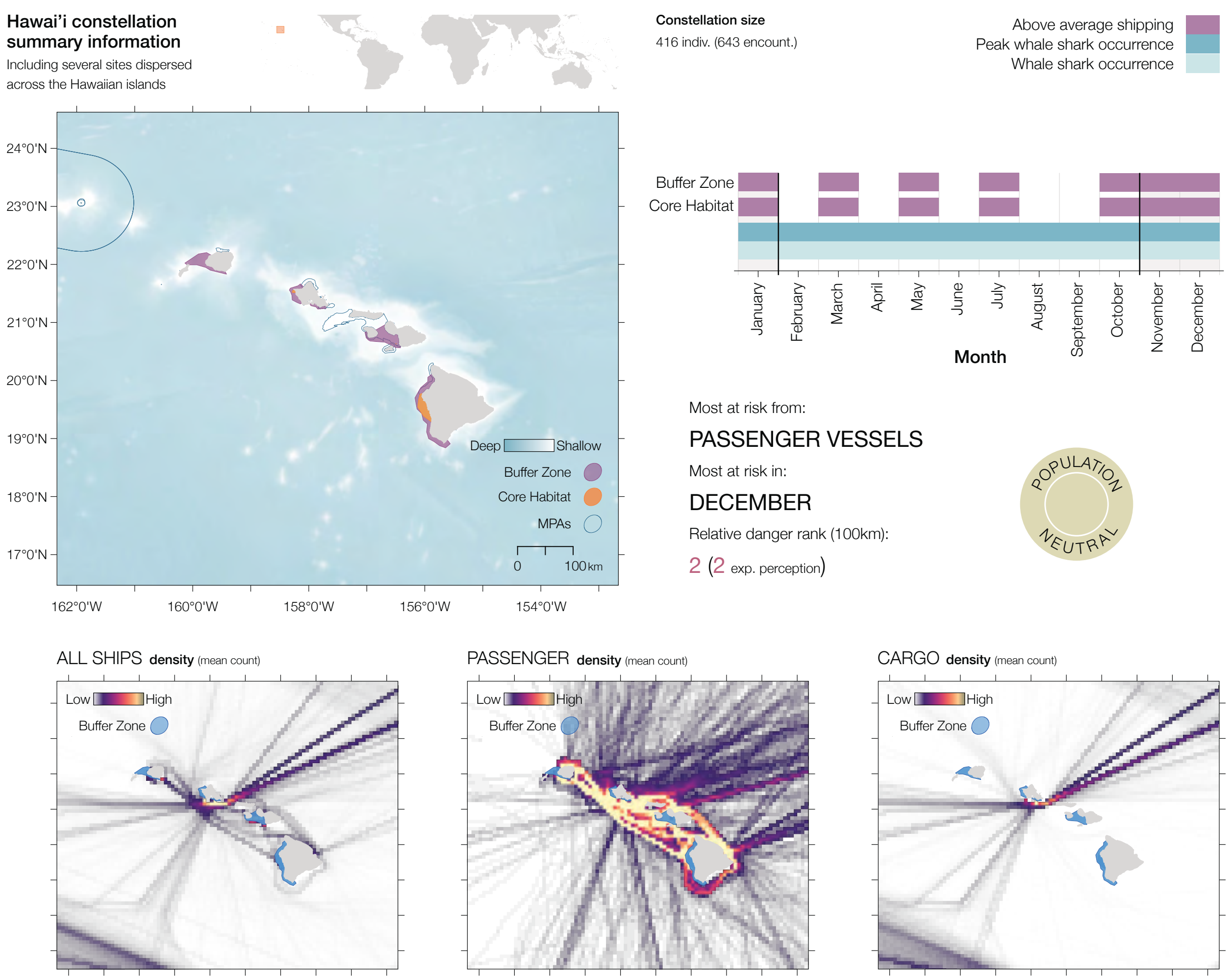



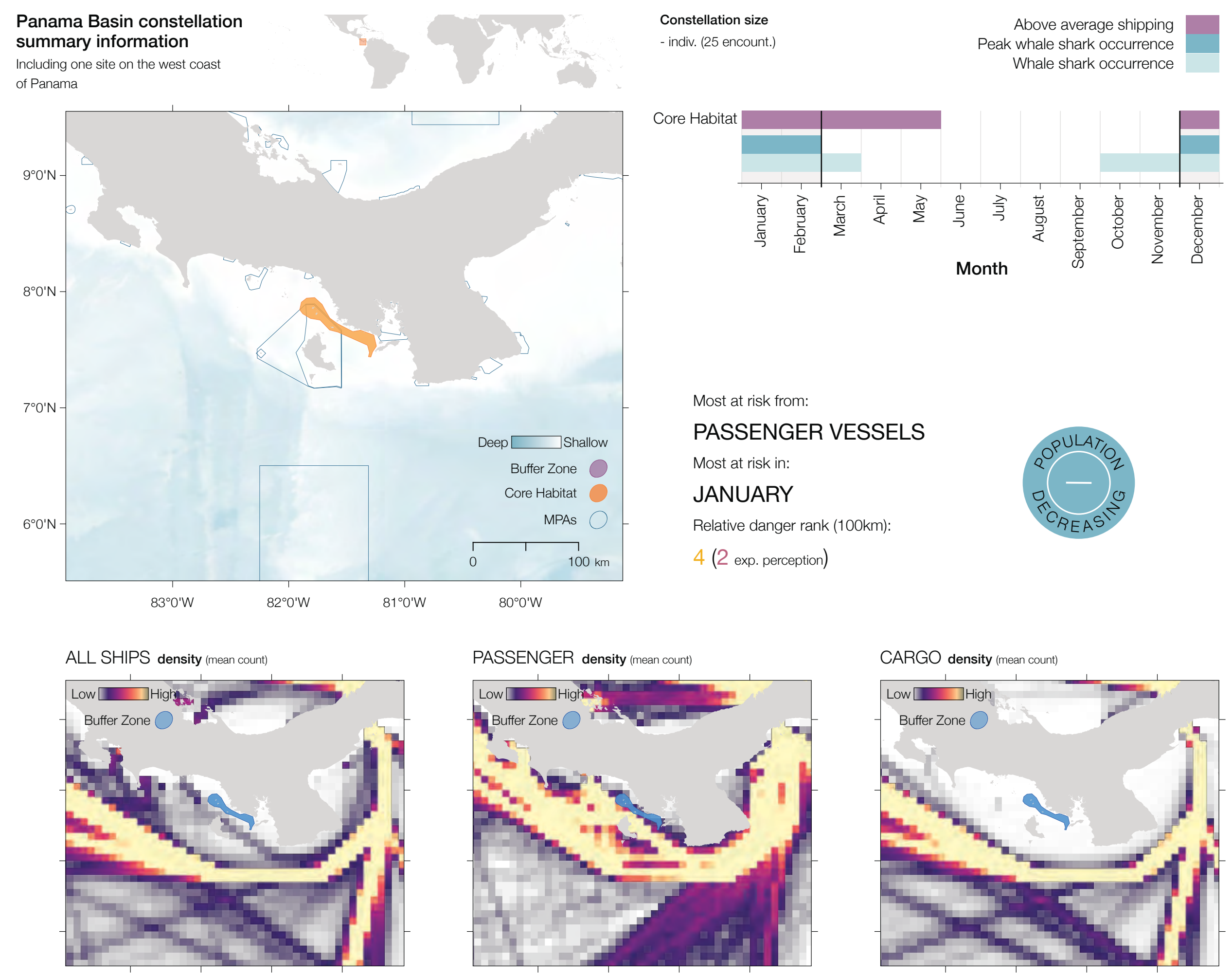



# Appendix 2: Regional maps

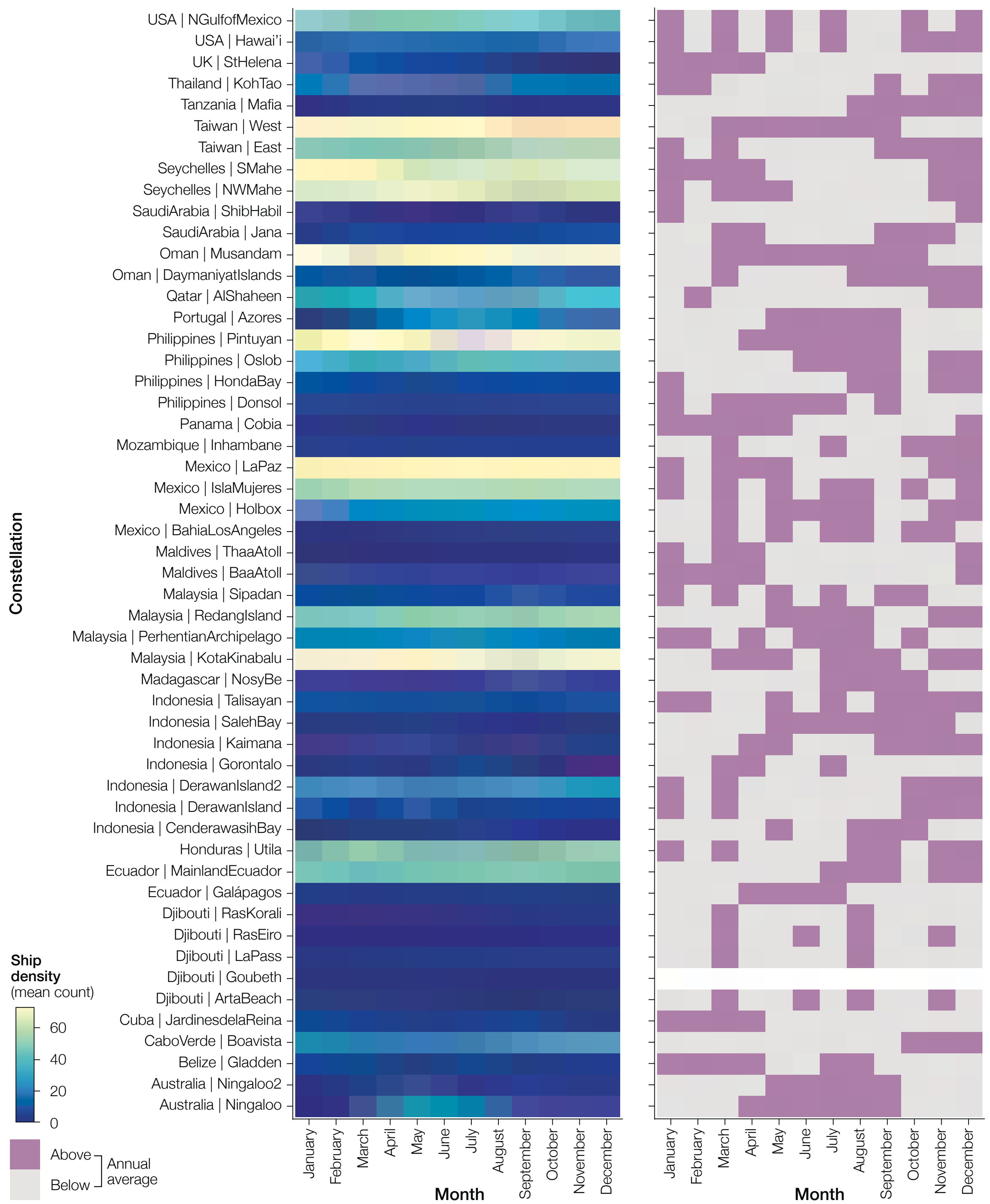
## Pacific Ocean



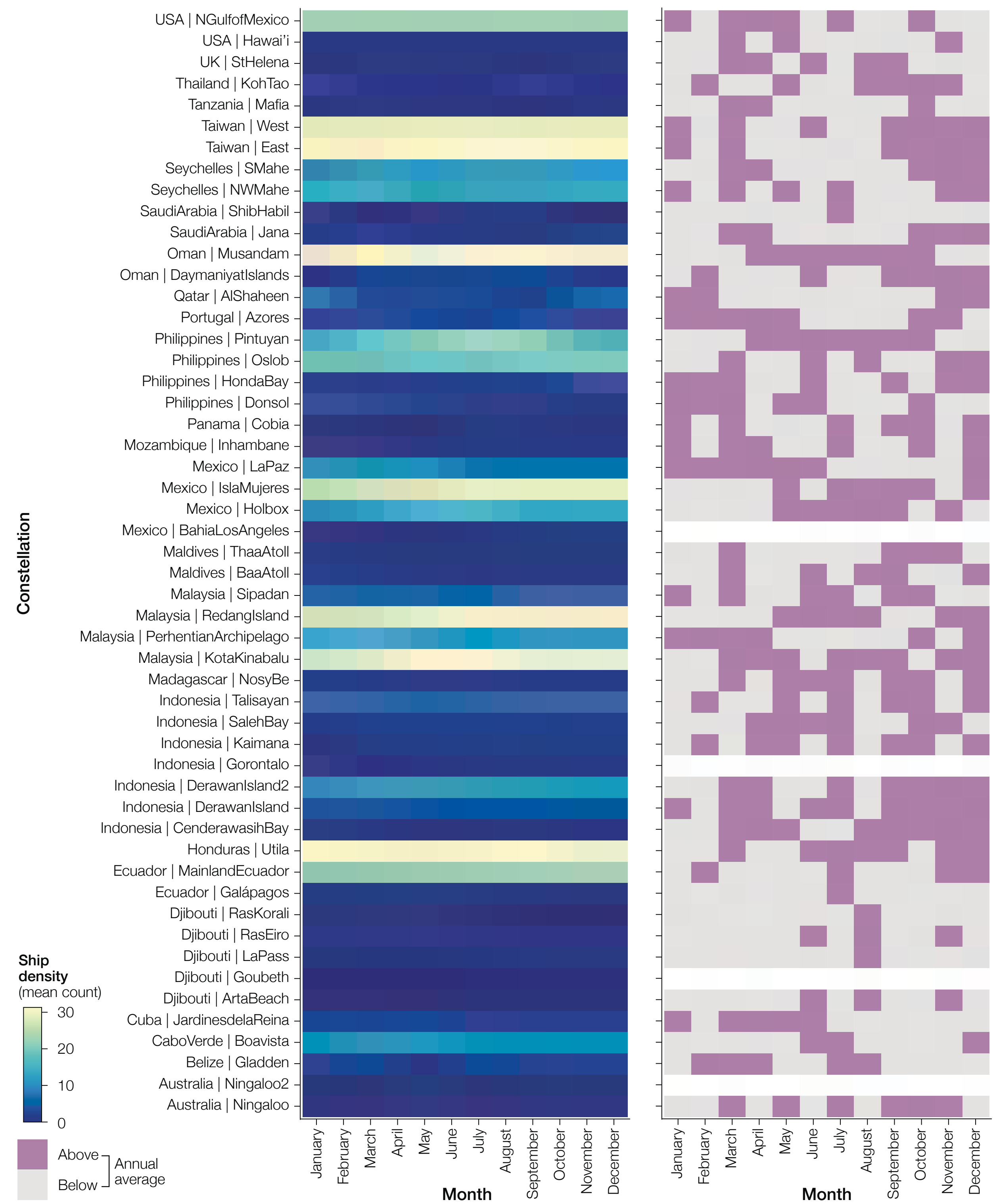



# 5.3 Appendix 3: Seasonal trends

## All vessel classes

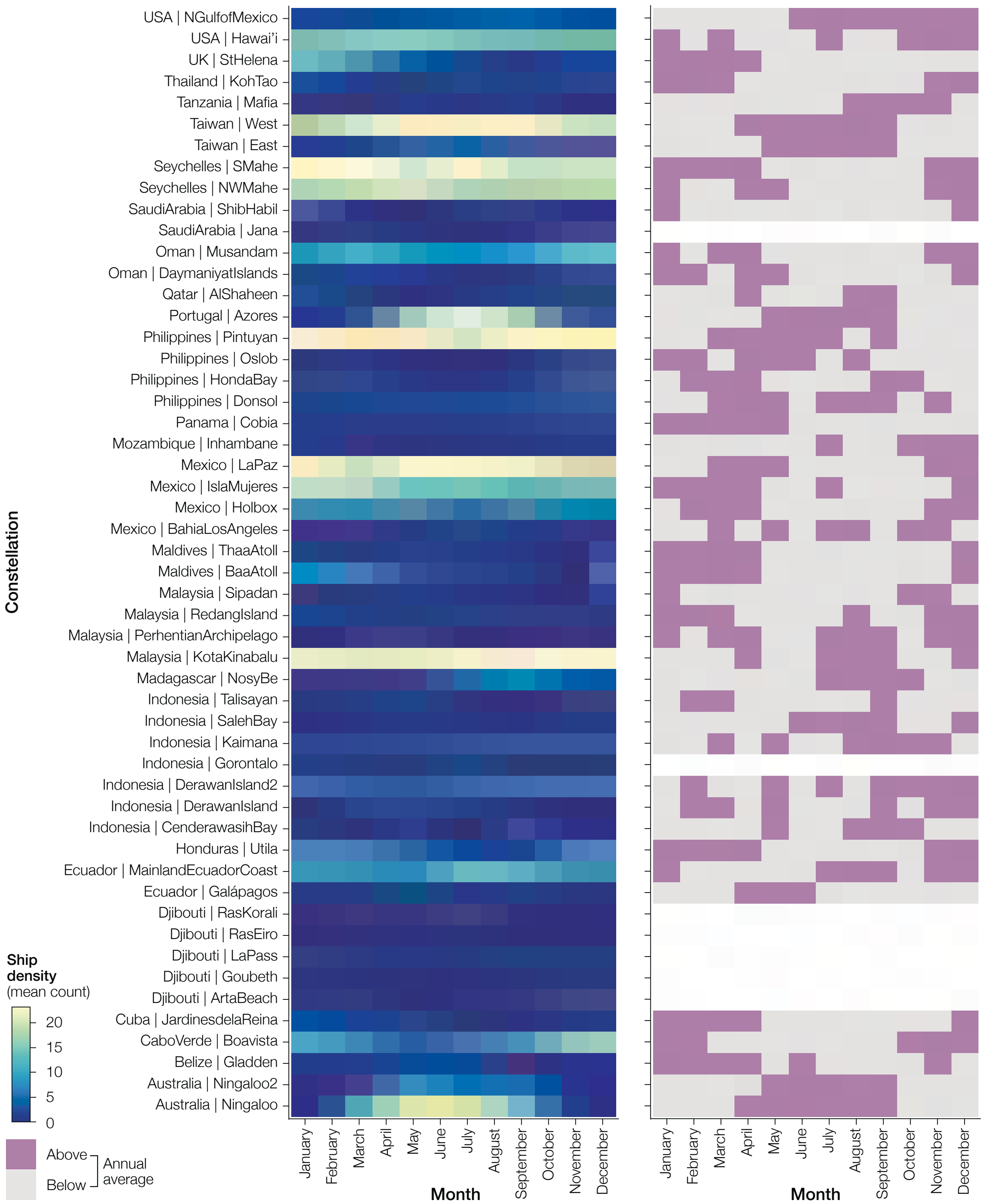



## Cargo vessels

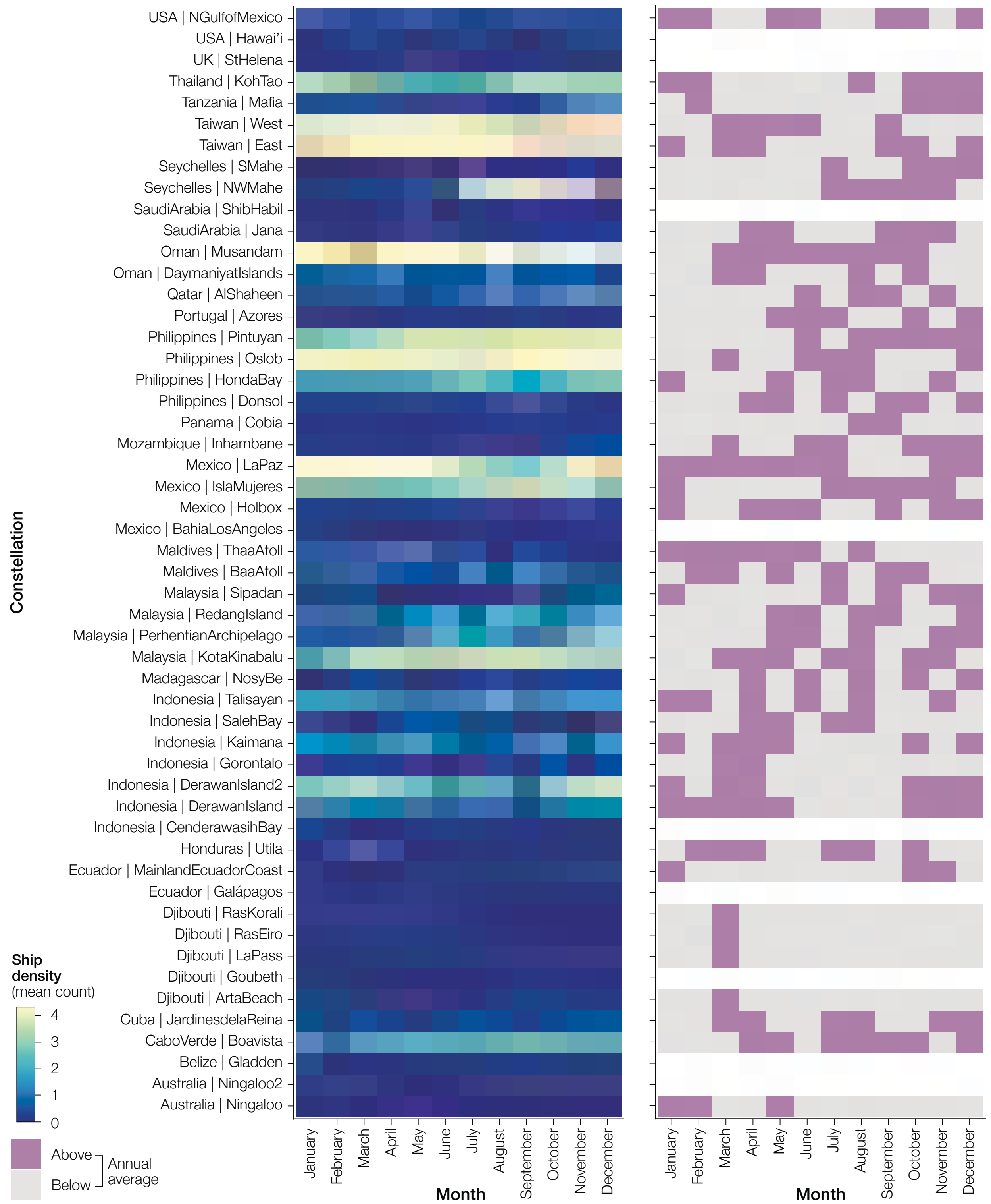


# Appendix 3: Seasonal trends

## Passenger vessels

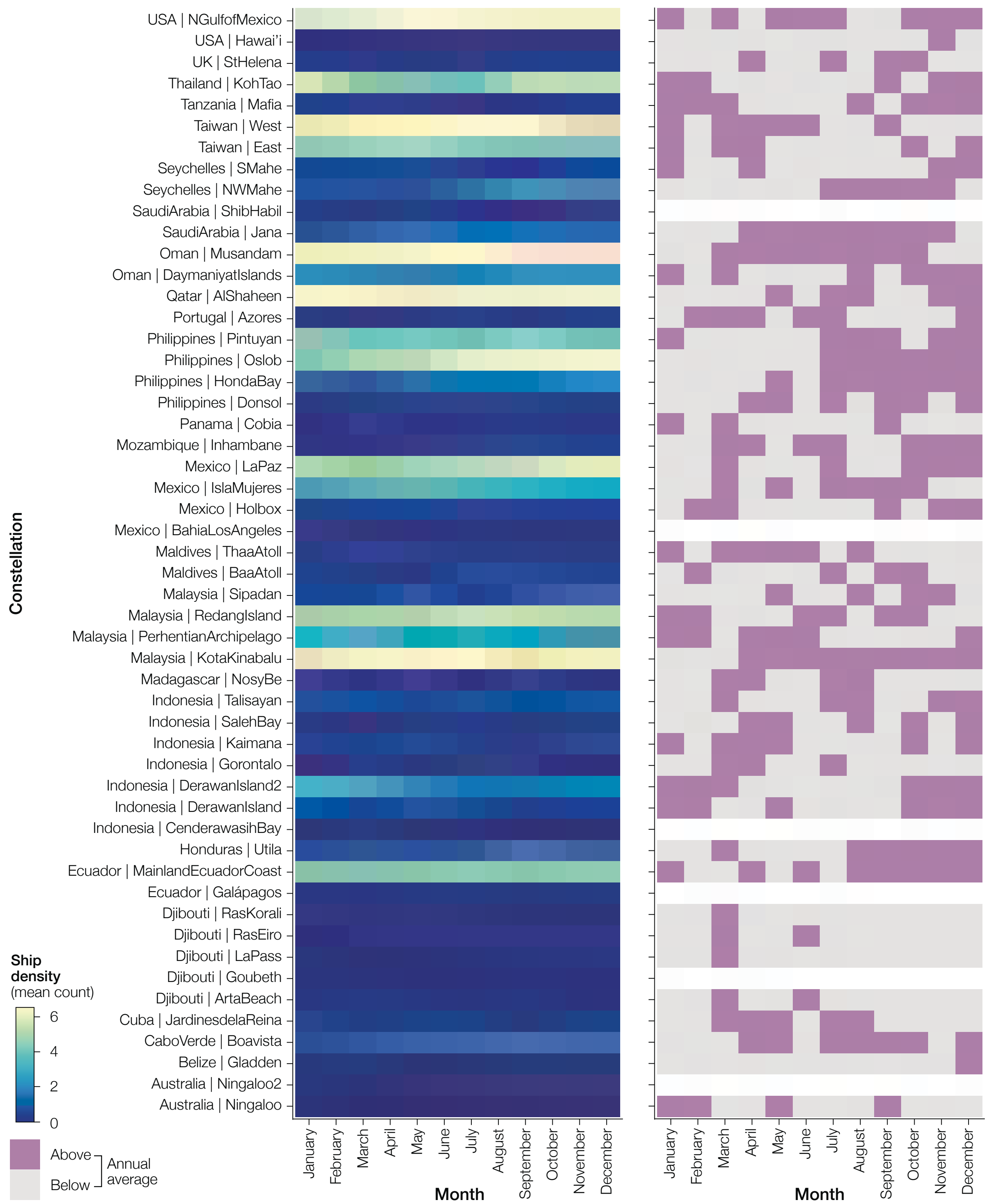



## Cargo or tanker vessels

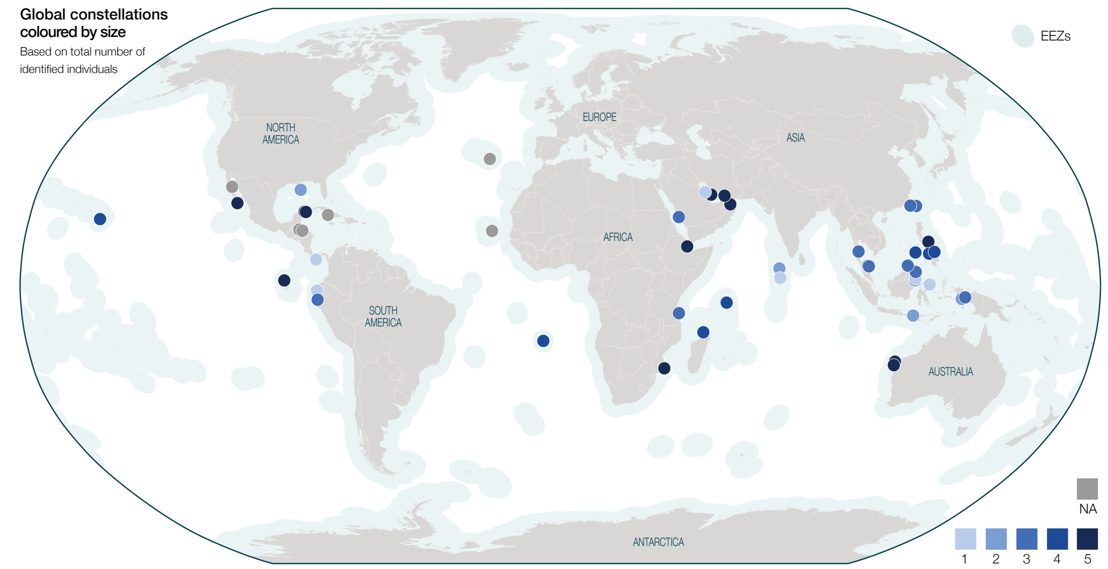


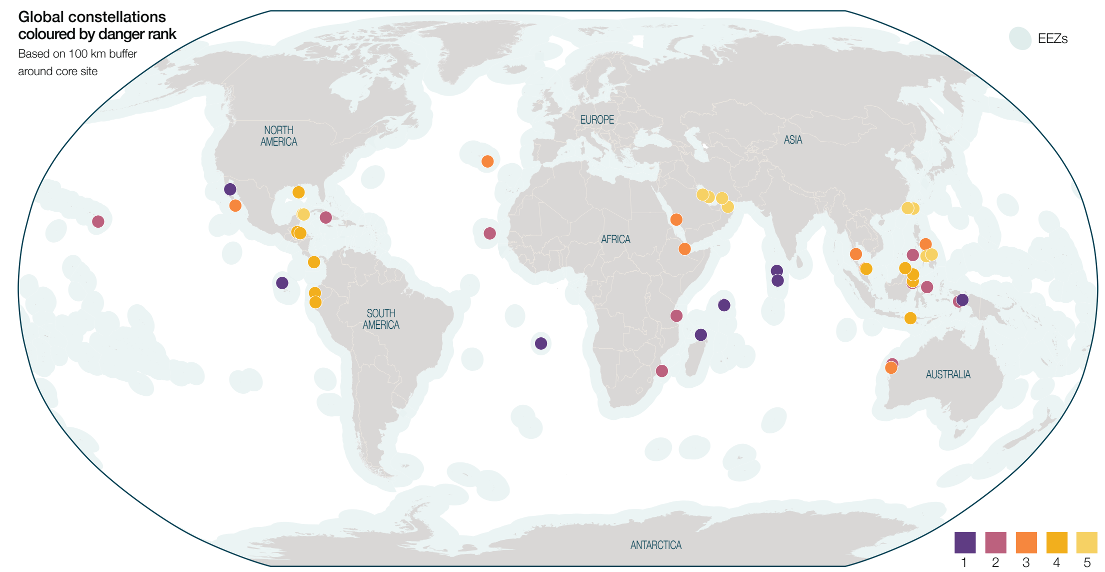
# Appendix 3: Seasonal trends

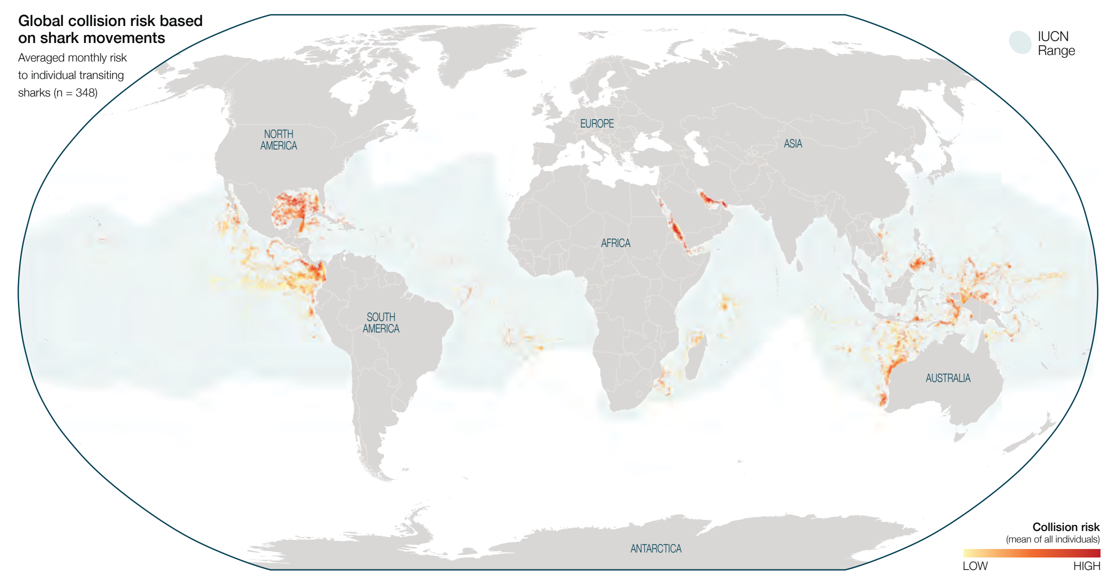
## Bunker or tanker vessels




# 5.4 Appendix 4: Global maps



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