Cetaceans and tuna purse seine fisheries in the Atlantic and Indian Oceans: interactions but few mortalities

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ABSTRACT: Fisheries bycatch is considered to be one of the most significant causes of mortality for many marine species, including vulnerable megafauna. In the open ocean, tuna purse seiners are known to use several cetacean species to detect tuna schools. This exposes the cetaceans to encirclement which can lead to incidental injury or death. While interactions between fishers and cetaceans have been well documented in the eastern tropical Pacific Ocean, little is known about these interactions and potential mortalities in the tropical Atlantic and Indian Oceans. Here, we provide the first quantification of these interactions in both oceans by analyzing a large database of captain's logbooks (1980 to 2011) and observations collected by onboard scientific observers (1995 to 2011). Distribution maps of sightings per unit effort highlighted main areas of relatively high co-occurrence: east of the Seychelles (December to March), the Mozambique Channel (April to May) and the offshore waters of Gabon (April to September). The percentage of cetacean-associated fishing sets was around 3% in both oceans and datasets whereas 0.6% of sets had cetaceans encircled. Of the 194 cetaceans encircled in a purse seine net (122 baleen whales, 72 delphinids), immediate apparent survival rates were high (Atlantic: 92%, Indian: 100%). Among recorded mortalities, 8 involved pantropical spotted dolphins *Stenella attenuata* and 3 involved humpback whales *Megaptera novaeangliae*. These high survival rates suggest that setting nets close to cetaceans has a low immediate apparent impact on the species involved. Our findings will contribute to the development of an ecosystem approach to managing fisheries and accurate cetacean conservation measures.

KEY WORDS: Apparent survival · Bycatch · Marine mammals · Fishery impact · Marine conservation · Megafauna

INTRODUCTION

Worldwide, large numbers of many marine mega-fauna species are declining, including mammals, turtles, and elasmobranchs (Lewison et al. 2004, 2014, Read et al. 2006, Wallace et al. 2011, Dulvy et al. 2014). A wide range of human activities impact their populations, including direct and indirect harvesting (i.e. bycatch mortality), habitat destruction, ship traffic, pollution, climate change, and

non-lethal fisheries interactions. Fisheries bycatch (i.e. the capture of non-targeted species) is considered to be one of the main threats, particularly for marine mammals (Lewison et al. 2004, Schipper et al. 2008, Brown et al. 2013, Weir & Pierce 2013). Late maturity and low reproductive rates make marine mammals particularly vulnerable to these impacts, while their large body sizes along with high metabolic and food consumption rates indicate their important roles in the structure and dynamics of marine ecosystems (Bowen 1997). Thus, quantifying their incidental mortality rates is important not only for species-based conservation and management but also to understand their broader roles in ecosystem functioning (Bowen 1997, Estes et al. 1998).

In tropical tuna purse seine fisheries, vessels actively search for clues indicating the presence of tuna schools at the sea surface, including flocks of birds, cetaceans, whale sharks *Rhincodon typus*, and natural and artificial floating objects, such as drifting Fish Aggregating Devices (FADs, i.e. artificially constructed rafts) (Ariz et al. 1999, Gaertner & Medina-Gaertner 1999, Hallier & Parajua 1999, Hampton & Bailey 1999, Romanov 2002, Capietto et al. 2014). Given the risk of encirclement by nets when fishing close to cetaceans, there is concern that this fishing practice may potentially impact their survival (Hall 1998, Gilman 2011). In particular, 2 cetacean groups are known to interact with these fisheries: dolphins and baleen whales. Species interacting with purse seiners are listed by the International Union for Conservation of Nature, in Appendix II of the Convention of Migratory Species of Wild Animals (IUCN; www.redlist.org), as well as in Appendix I or II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES; www.cites.org).

In the eastern tropical Pacific Ocean, the pantropical spotted dolphin *Stenella attenuata* and the spinner dolphin *S. longirostris* are known to associate with schools of large-size yellowfin tuna *Thunnus albacares* (Hall 1998, Scott et al. 2012). Historically, tuna purse seine fisheries in this region have provoked unsustainable dolphin mortalities. Indeed, purse seine vessels chased, then encircled dolphin groups during fishing operations, potentially leading to the capture of large amount of tunas but also of dolphins (Hall 1998). In the 1960s and early 1970s, when the practice was the most widespread, dolphin mortality was estimated at hundreds of thousands of animals per year in the eastern tropical Pacific Ocean (Hall 1998). However, there has been a 98% reduction of dolphin mortality due to fishing gear modifications and changes in fishing practices, leading to sustainable bycatch levels (Hall 1998, Schipper et al. 2008, Gilman 2011).

In the western tropical Indian Ocean and the eastern tropical Atlantic Ocean, while dolphin–tuna associations have been observed (Levenez et al. 1979, Ballance & Pitman 1998), existing studies suggest scarce interactions between dolphins and purse seine fisheries (Levenez et al. 1979, Romanov 2002, Weir & Pierce 2013). In contrast, whale-associated sets (i.e. nets set close to or around one or more baleen whales) are the major interaction between purse seine fisheries and cetaceans in the western Pacific Ocean (Hampton & Bailey 1999, Molony 2005). A few mortality events have been recorded in this area (Molony 2005, Gilman & Lundin 2009, WCPFC 2012). While whale-associated sets have been previously reported in the Atlantic and Indian Oceans (Gaertner & Medina-Gaertner 1999, Romanov 2002, Amande et al. 2010), including a single mortality event in the Indian Ocean (Romanov 2002), there are no detailed studies investigating the specific whale–tuna associations and the resulting potential impact of purse seine fisheries on the species involved.

Megafauna associated with tuna schools can be encircled intentionally, such as in the eastern tropical Pacific Ocean where this is a fishing strategy consisting of chasing and encircling dolphins in order to catch tuna (Hall 1998), or accidentally, as is the case for whale sharks which are (most of the time) only seen after the net has been set (Capietto et al. 2014). In the eastern Atlantic and western Indian Oceans, while the practice of keeping baleen whales inside purse seine nets as long as possible has been reported (Romanov 2002), no studies have specifically investigated intentional setting of nets in the vicinity of cetaceans.

In view of the potential impacts on cetaceans and the lack of data on purse seine interactions with these species in the eastern Atlantic and western Indian Oceans (Lewison et al. 2014), this study aimed to (1) assess the spatial and temporal distributions of cetacean–purse seine fishery co-occurrence (i.e. regions with high numbers of cetacean observations standardized by the sighting effort), (2) identify and quantify the nature of cetacean observations (e.g. sightings during tuna searches, fishing sets associated with cetaceans and their encirclements), and (3) determine the fate of encircled individuals (i.e. mortality or apparent survival after release).

MATERIALS AND METHODS

Datasets

The European tropical tuna purse seine fishery (i.e. France and Spain) began in the late 1960s in the eastern Atlantic Ocean and in the 1980s in the western Indian Ocean (Fonteneau 2009, 2010). For each of these 2 regions, we separately analyzed 2 complementary datasets to assess the impact of fisheries: (1) logbook records filled out by vessel captains, and (2) data from scientific observers onboard fishing vessels. While records from these 2 sources are made on the same vessels and from the same fishing trips (i.e. when an observer is onboard a vessel, logbooks are still filled by captains), the datasets are independent as they come from 2 different sources (i.e. scientific observers and vessel captains), and present their own advantages and limitations (see below). Logbooks and observer datasets have specific scientific purposes: estimating fishing effort and catch composition of targeted species for logbook data, and assessing the amount of bycatch for observer data. Among all the data contained in these datasets, we only used the data that pertained to cetacean–purse seine interactions.

First, we analyzed data from logbook records reported by vessel captains for the 1980 to 2011 period, which covers 100% of all vessel activities since 1990 (90% before 1990) of the French and Spanish fleets (i.e. 23 and 42 purse seiners, followed by the Institut de Recherche pour le Développement, IRD, and the Instituto Espagñol de Oceanografía, IEO, respectively). Each fishing set was reported in logbooks. If no set was made during daylight hours, the main activity of the day (e.g. the search for tuna or transit between fishing areas) along with the geographical position at midday was recorded. Here, we defined an 'activity' as a record declared by the captains. Activities recorded in the logbooks included geographical position, information on associations between tuna schools and cetaceans, whale sharks, seabirds, or floating objects, and for each fishing set, the weight and catch composition of targeted tuna species. Considering that not all cetacean species occurring in the fishing areas are necessarily associated with tuna schools, there is a bias in using logbooks alone, with some cetacean species being recorded by captains less often than others. The main uncertainties in this dataset are that (1) encirclements were not discriminated from sightings, and (2) the rates at which captains declared sightings are unknown and may have varied between captains.

Complementarily, data from scientific observer programs provided more detailed information on purse seiner activities, catches of bycatch species (numbers and species involved), and discards (if any), and provided the fate of encircled individuals, including cetaceans. Scientific observer programs were conducted within the framework of specific European Union (EU) research projects in the 1990s, or since 2003, within continuous data collection programs (EU Data Collection Framework; Regulation [CE] 199/2008). We used French (IRD) and Spanish (AZTI Tecnalia and IEO) observer data collected from 1995 to 2011 (9.2% of total vessel activities in the Atlantic Ocean and 7.8% in the Indian Ocean; Bourjea et al. 2014). In this dataset, 'activities' also included fishing activities (fishing sets and searches for tuna schools), transit between fishing areas, and FAD-related operations (i.e. deployment or recovery). All activities were recorded during daylight hours. If the vessel activity did not change within 1 h, a new record of activity was systematically recorded.

Cetacean sightings were opportunistic and included any detection of one or a group of cetaceans. 'Cetacean–fishery interactions' are sightings associated with fishing sets (whether cetaceans are encircled or not), which are defined as either whale- or dolphin-associated sets. 'Sightings during cruising' include sightings during tuna school searches and transit. When cetaceans were encircled, the number of individuals and their fate was recorded by the observer as either mortality (i.e. entangled in the net) or apparent survival (i.e. alive upon release or escape from the encircling net).

During all fishing activities, members of the crew used fixed binoculars (25 × 150, 20 × 120) to detect tuna schools. Among other observations of potential indicators of tuna schools, cetacean sightings were recorded by captains and scientific observers. We assumed that captains mainly recorded cetacean sightings indicating the presence of tuna schools or made during interactions with fishing sets, while observers recorded all cetacean sightings. To check the correspondence and accuracy of cetacean sightings reported in the 2 datasets, a comparison was performed of the sightings recorded by vessel captains and observers during the same trip (Table 1).

The identification of cetacean species was not always possible. However, 3 broad species groups were defined: (1) baleen whales (i.e. Bryde's whale *Balenoptera edeni*, fin whale *B. physalus*, sei whale *B. borealis*, and humpback whale *Megaptera novaeangliae*), (2) delphinids (i.e. *Stenella* spp., common dolphin *Delphinus delphis*, common bottlenose dol-

Table 1. Comparison of cetacean sightings reported by captains (logbooks) and onboard scientific observers within the same trips from the French tuna purse seine fleet in the Atlantic and Indian Oceans

French fishing trips (n = 333)	Logbooks (1995–2011)	Onboard observers (1995–2011)
% of shared sightings[a] in both datasets	75.29	13.68
% of shared sightings[a] associated with set	85.07	24.44
% of shared sightings during ship cruising[b]	66.67	11.49

[a]Sightings at same date, hour and position; [b]Sightings during tuna searching or transit at same date and position

phin *Tursiops truncatus*, rough-toothed dolphin *Steno bredanensis*, short-finned pilot whale *Globicephala macrorhynchus*, false killer whale *Pseudorca crassidens*, melon-headed whale *Peponocephala electra*, and killer whale *Orcinus orca*), and (3) sperm whales *Physeter macrocephalus*.

In the observer dataset, we used 2 methods to identify possible intentional setting of nets in the vicinity of cetaceans. First, when cetacean sightings were associated with fishing sets, we checked if these sightings were also recorded during the activity just prior to the set, which would indicate intentional cetacean-associated sets. Second, we calculated the frequency of cetacean sightings preceding a set (French observer dataset). Thus, (1) we selected cetacean sightings not directly associated with a fishing set to avoid double counting, then (2) we calculated the number of cetacean sightings followed by a fishing set within a radius of 2 nautical miles (nmi) (i.e. the distance between the vessel position at the time of sighting and the vessel position at the time of the fishing set; 2 nmi corresponds to the average distance of cetacean detectability at sea using binoculars recorded in the observer data), and (3) we calculated the corresponding frequencies with which fishing sets were made following cetacean sightings compared to the total number of sightings.

Studied regions

Study areas covered the main fishing grounds of the European purse seiners (including transit between fishing areas) in the eastern tropical Atlantic Ocean (between 30° N and 35° S and 40° W to the African coast) and the western tropical Indian Ocean (25° N to 35° S and the African coast to 90° E). Eastern Atlantic Ocean circulation is influenced by the Benguela, Angola, Guinea and Canary Currents that generate seasonal upwellings along the coast from Gabon to Angola between July and September (Hardman-Mountford et al. 2003), and from Mauritania to Senegal between December and April (Marcello et al. 2011). Western Indian Ocean circulation reflects complex interactions of the seasonally alternating Somali Current with the South Equatorial Countercurrent and the South Equatorial Current (Schott et al. 2009). The monsoon-generated seasonal Somalian–Arabian upwelling drastically affects productivity in the northern part of the region. The area east of the Seychelles features an open-ocean equatorial upwelling zone from December to March (Hermes & Reason 2008), known as the Seychelles–Chagos thermocline ridge, while the Mozambique Channel has a complex circulation influenced by mesoscale eddies (Schott et al. 2009).

As climatic and oceanographic variability may drive the seasonal distribution of both cetaceans and fisheries, we divided the annual data into seasons that were defined differently for each ocean. In the Atlantic Ocean, we considered 4 quarters (starting from January; identified as 1 to 4) while in the Indian Ocean we followed the monsoonal pattern (Schott et al. 2009) which includes 2 monsoon periods (northeast, NE, from December to March and southwest, SW, from June to September) and 2 inter-monsoon periods (northeast, INE, from October to November, and southwest, ISW, from April to May).

Statistical analyses

To produce accurate maps of co-occurrence between cetaceans and the tuna purse seine fisheries, we first computed sightings per unit of effort (SPUE) for each 1° square of the studied areas. As cetacean sightings may be recorded during fishing sets and also during other vessel activities, the variable 'activity' was assumed to depict the most accurate unit of effort. Thus, SPUEs were computed as the number of cetacean sightings divided by the total number of purse seiner activities (i.e. fishing activities and transit) recorded in the logbooks (Sequeira et al. 2012, Capietto et al. 2014).

Then we used a Poisson kriging method (Goovaerts 2005, Monestiez et al. 2006) to account for the spatial heterogeneity in the observation effort. Cetacean sighting rates calculated for areas in which fishing activities are low will be less reliable than those calculated for densely fished areas. The Poisson kriging method addresses this problem by taking into account

sampling effort (Goovaerts 2005, Ali et al. 2006, Monestiez et al. 2006, Kerry et al. 2010). Below, we present a summary of the method following Monestiez et al. (2006).

For all sites, s (1° squares) belonging to the domain, D (in our case the eastern Atlantic and the western Indian Oceans), $z(s)$ is the number of cetacean sightings and $t(s)$ is the number of fishing activities for the corresponding sites. The observed SPUEs are calculated as $y(s) = z(s) / t(s)$. At each site s, $z(s)$ can be interpreted as a realization of a random variable $Z(s)|Y(s)$. This variable follows a Poisson distribution P with an intensity parameter (the expected number of sightings) that is the product of $t(s)$ and the SPUE $Y(s)$:

$$Z(s)|Y(s) \sim P(t(s)Y(s)) \tag{1}$$

where $Y(s)$ is a positive random field following order 2 stationarity, with mean m, variance σ^2_Y and a covariance function which depends only on the distance, h, between sites s and s': $C_Y(h)$. Following Monestiez et al. (2006), the notations were simplified; therefore, $Z(s)$, $Y(s)$ and $t(s)$ are denoted Zs, Ys and ts.

The kriging of Y_0, at any site $s_0 \in D$, is a linear predictor combining the n neighboring observed sightings, z_i, weighted by the number of fishing activities, t_i:

$$Y_0^* = \sum_{i=1}^{n} \lambda_i \frac{z_i}{t_i} \tag{2}$$

λ_i is computed to minimize the mean square error of predictions under the constraint that the estimator is unbiased. The kriging weights are the solution of the following system of the $n + 1$ linear equation:

$$\sum_{j=1}^{n} \lambda_j C_{ij} + \lambda_i \frac{m^*}{t_i} + \mu = C_{i0}, \ i \in [1, n] \tag{3}$$

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{4}$$

where λ is the Lagrange multiplier, m^* is an estimate of the mean of Y, and C_{ij} denotes the covariance function $C_Y(i-j)$. The covariance function of Y is equivalent to its variogram $\gamma^*_Y(h) = C_Y(0) - C_Y(h)$. The experimental semivariogram $\gamma^*_Y(h)$ is estimated from the data by:

$$\gamma^*_Y(h) = \frac{1}{2N(h)} \sum_{i,j} \left[\frac{t_i t_j}{t_i + t_j} \left(\frac{Z_i}{t_i} - \frac{Z_j}{tj} \right)^2 - m^* \right] 1_{d_{ij} \sim h} \tag{5}$$

where $1_{d_{ij} \sim h}$ is the indicator function of pairs (s_i, s_j) whose distance is close to h, where $N(h) = \sum_{i,j} \frac{t_i t_j}{t_i + t_j} 1_{d_{ij} \sim h}$ is a normalizing constant and where m^* is an estimate of the mean of Y. A model $\gamma_Y(h)$ is then fitted to $\gamma^*_Y(h)$ in order to derive the semivariogram for any possible

distance h. Detailed calculus can be found in Monestiez et al. (2006, p. 618–621) and in Goovaerts (2005, p. 8).

The experimental variograms for the entire logbook datasets were computed for each ocean (Fig. 1). Initially, we checked that no directional effect was present in the experimental variograms. Then we fitted the variogram models to the experimental variogram using a weighted least-square regression procedure. The nested semivariogram models selected were 2 Gaussian variogram models for the Atlantic Ocean, and a Gaussian variogram model for the Indian Ocean. Nugget models were also added for each ocean. For each model, the sills and distance range were calculated (Table 2). The input parameters used to conduct the kriging included a minimum of 1 and a maximum of 32 observations and a radius of 500 km.
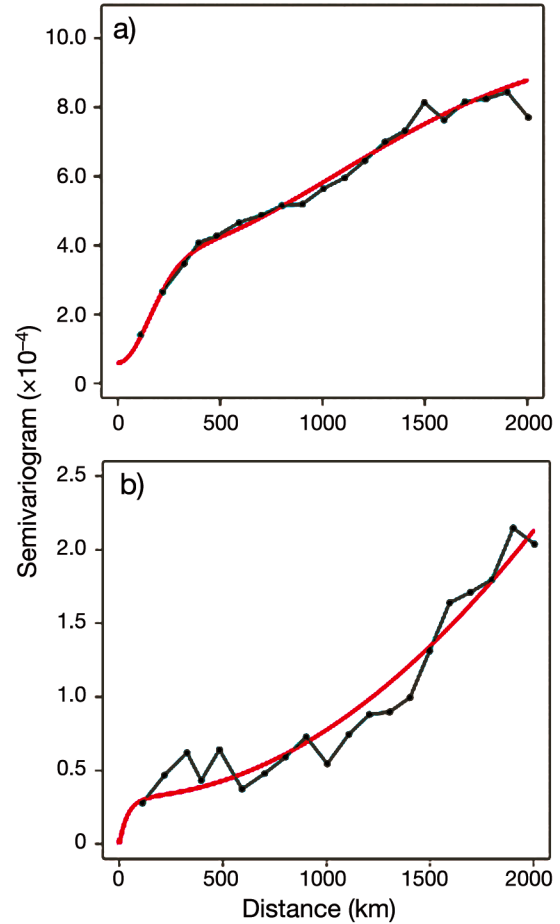

Fig. 1. Experimental (black dots and black line) and fitted (red line) semivariograms from the (a) Atlantic Ocean (weighted residual sum of squares: 2.8×10^{-4}) and (b) Indian Ocean (weighted residual sum of squares: 3.91×10^{-9})

Table 2. Nested fitted variogram parameters

Ocean	Variogram	Sill	Range (km)
Atlantic	Nugget	5.98×10^{-5}	–
Atlantic	Gaussian	3.00×10^{-4}	151
Atlantic	Gaussian	6.28×10^{-4}	1070
Indian	Nugget	1.00×10^{-7}	–
Indian	Exponential	3.15×10^{-5}	410
Indian	Gaussian	4.61×10^{-3}	7060

It was not possible to separately map SPUEs by season or cetacean group as the low numbers of sightings precluded the computation of the experimental variogram (see Fig. 2 for SPUE maps). All analyses were conducted using R software v.2.15.2 (R Development Core Team 2014). Poisson kriging was performed using the R script of Monestiez et al. (2006).

RESULTS

A comparison of cetacean sightings reported in both datasets during the same trip was performed (Table 1). About 75% of all sightings and up to 85% of sightings associated with fishing sets declared by captains were also recorded by observers. On the contrary, only 14% of all sightings recorded by observers were also found in logbooks (24% for sightings associated with fishing sets only). Overall, on-board observers reported cetacean sightings more frequently than captains, especially sightings during ship cruising (i.e. tuna search and transit).

Of the total 861 585 activities recorded in the logbook dataset, 487 272 were fishing sets (Table 3). This dataset also included 19 003 records of cetacean sightings, most of which were baleen whales (17 802), followed by delphinids (1165) and sperm whales (38). While cetacean sightings were recorded during 2.2% of all activities and 3.1% of all fishing sets (Table 3), almost 80% of all cetacean sightings were associated with fishing sets.

For both oceans, logbook records indicated areas and periods with high cetacean–fishery co-occurrence. Main areas with high SPUE were located in the Indian Ocean (1) east of the Seychelles (0° N to 15° S, 55° E to 65° E), especially baleen whales during the NE monsoon; and (2) in the Mozambique Channel, mainly baleen whales during the ISW period (Figs. 2 & 3a). Two other areas with relatively high baleen whale SPUE were also identified: (1) in the Atlantic Ocean, especially in the coastal waters of Gabon between April and September; and (2) in the

Table 3. Main statistics of logbook and scientific observer datasets on the French and Spanish tuna purse seine fleets in the eastern tropical Atlantic Ocean and in the western tropical Indian Ocean. Data are presented for broad cetacean groups: baleen whales (WHA), delphinids (DEL), and sperm whales (SPW)

|	Logbooks (1980–2011)			Observers (1995–2011)		
	Atlantic	Indian	Total	Atlantic	Indian	Total
No. of activities	468 181	393 404	861 585	169 546	114 581	284 127
Cetacean sighting events	7443	11 560	19 003	1932	1449	3381
WHA	6865	10 937	17 802	1118	610	1728
DEL	561	604	1165	734	784	1518
SPW	18	20	38	80	55	135
% cetacean sightings by activities	1.59	2.94	2.21	1.14	1.26	1.19
No. of fishing sets	238 172	249 100	487 272	9969	6129	16 096
% sets among activities	50.87	63.32	56.56	5.88	5.35	5.67
Cetacean sightings associated with sets	5794	9391	15 185	363	183	546
WHA	5623	9301	14 924	299	150	449
DEL	175	83	258	55	30	85
SPW	6	7	13	9	3	12
% cetacean sightings associated with set	77.84	81.2	79.91	18.79	12.63	16.15
% sets with cetacean associated	2.43	3.77	3.11	3.64	2.99	3.39
No. of sets with cetaceans encircled				74	22	96
% sets with cetacean encircled				0.74	0.36	0.60
% sets with cetacean encircled by total no. of sighting events				3.83	1.52	2.84
No. of cetaceans encircled				155	39	194
No. of cetaceans fate known				153	37	190
No. of cetaceans apparent survival				142	37	179
% cetacean apparent survival				92.81	100.00	94.21
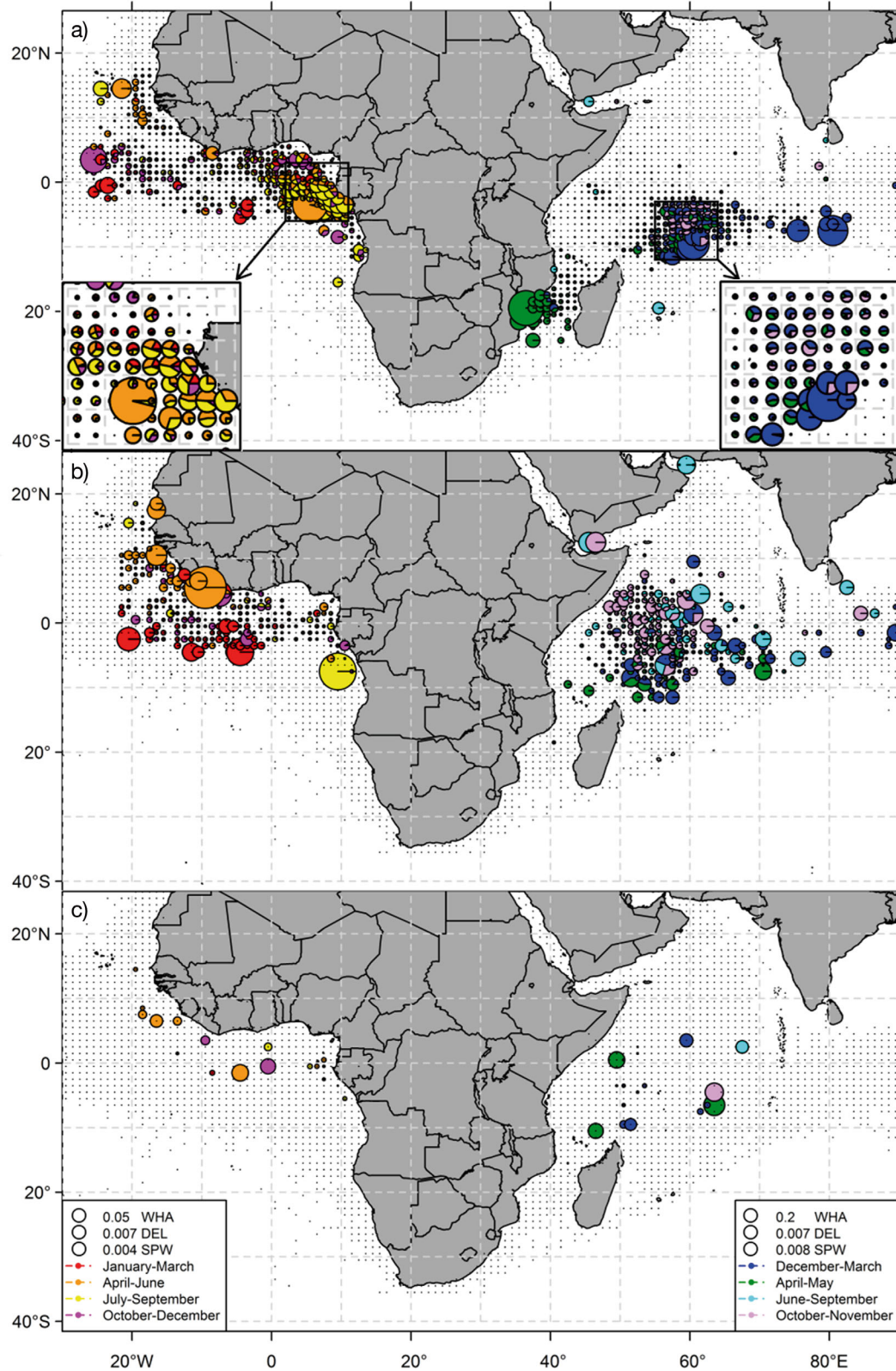
Fig. 2. Seasonal distribution of sightings per unit of effort (SPUE; number of cetacean sightings divided by the total number of purse seiner activities per 1° square) from logbook data (1980–2011) of the French and Spanish tuna purse seine fleets for (a) baleen whales (WHA), (b) delphinids (DEL), and (c) sperm whales (SPW), in the eastern tropical Atlantic and western tropical Indian Oceans
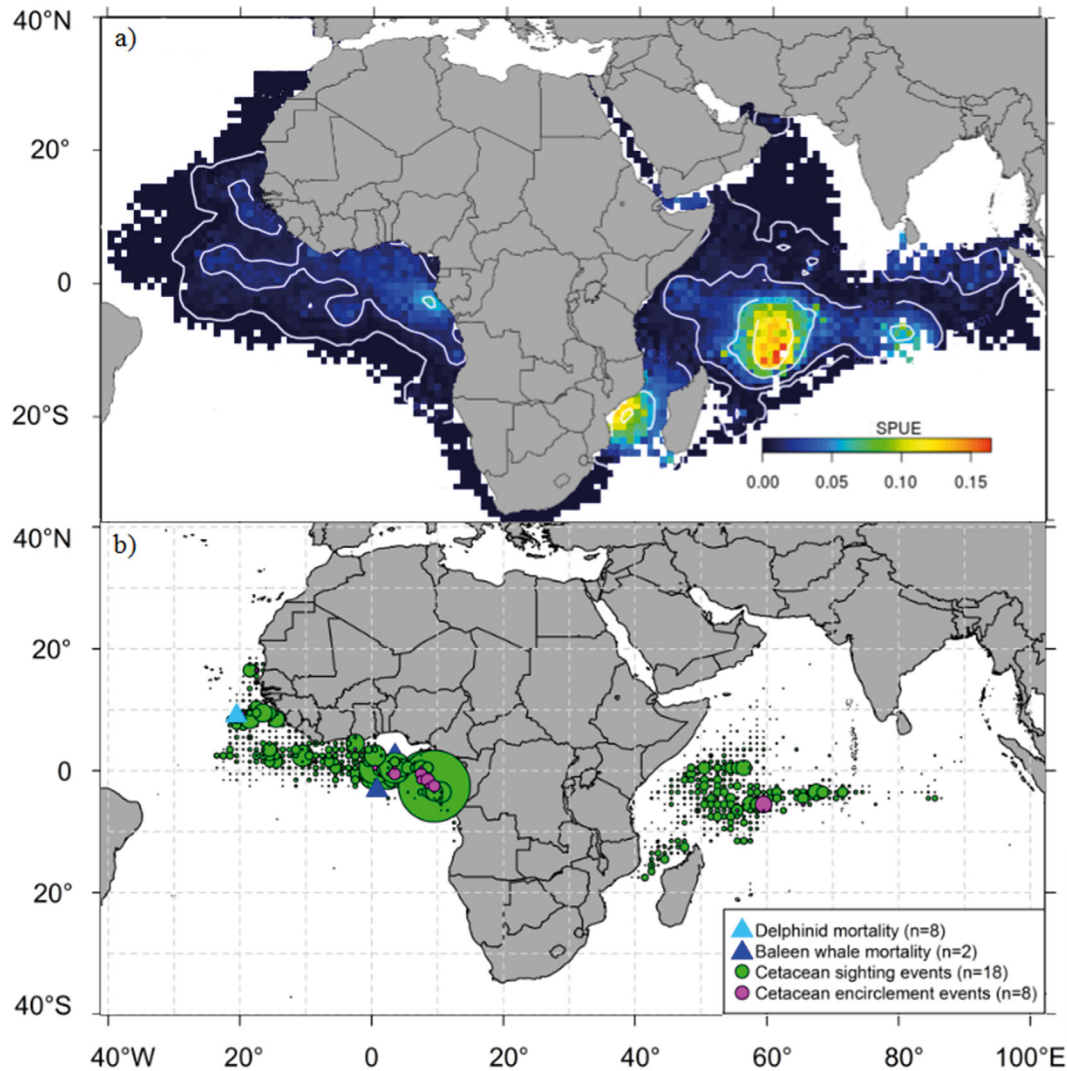
Fig. 3. (a) Distribution maps of calculated sightings per unit of effort (SPUE; number of cetacean sightings divided by the total number of purse seiner activities) from the French and Spanish logbook data (1980–2011) for all cetacean groups combined, using a Poisson kriging method. (b) Distribution of sightings, encirclements, and mortalities of cetaceans (French and Spanish scientific observers′ data, 1995–2011) per 1° square, in the Atlantic and Indian Oceans. Symbol size is proportional to the number in brackets (n); small dots also represent sightings (n ≥ 1)

eastern part of the studied area in the Indian Ocean (around 8° S and 80° E; Figs. 2 & 3a) during the NE monsoon. In this latter area, relatively high SPUE resulted from a low number of cetacean sightings and a low number of vessel activities.

The observer dataset contained a total of 284 127 activities, of which 16 096 were fishing sets (Table 3). A total of 3381 cetacean sightings were recorded in this dataset, including 1728 baleen whales, 1518 delphinids, and 135 sperm whales (Tables 3 & 4, Fig. 4). As with the logbook data, cetacean sighting rates were relatively low in both oceans, making up 1.2 % of all recorded activities or 3.4 % of all fishing sets (Table 3). Interactions between fishing operations

and baleen whales were more commonly recorded than those involving delphinids (26 versus 5.6 %). Within these set-associated sightings, over half of the interactions with baleen whales (52 %) had been previously recorded as a sighting while the ship was searching for tunas, compared to only 14 % for delphinids. Furthermore, the frequency of fishing sets being made following baleen whale sightings (within a radius of 2 nmi) was 0.23, compared to 0.05 for delphinid sightings and 0.02 for sperm whale sightings.

Of all cetacean sightings recorded by observers in both oceans, only 546 (16 %) were associated with sets. The percentage of fishing sets with cetaceans encircled was 0.74 % in the Atlantic and 0.36 % in the
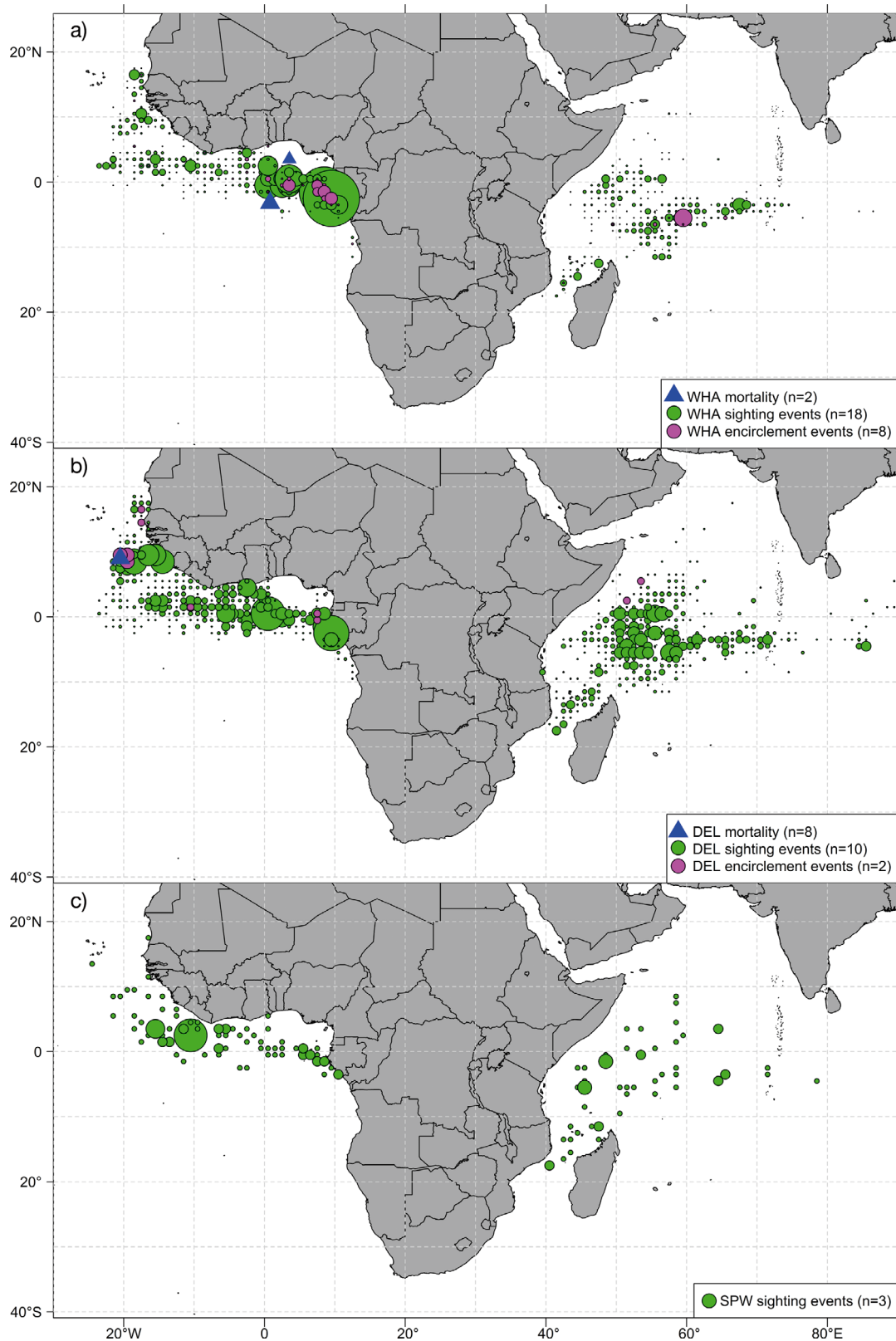
Fig. 4. Distribution of sighting, encirclement, and mortality records from scientific observer data (1995−2011; French and Spanish tuna purse seine fleets) of (a) baleen whales (WHA), (b) delphinids (DEL), and (c) sperm whales (SPW) in the eastern tropical Atlantic and western tropical Indian Oceans. Circle size is proportional to the number in brackets (n)

Indian Ocean (Table 3). Indeed, 96 sets were recorded as having encircled cetaceans (194 individuals) which can be related to the possible intentional setting of nets in the vicinity of cetaceans: in 70% of encirclements, observers had already recorded the sightings during the previous activity (i.e. prior to the net being set). Only baleen whales (122) and delphinids (72) were recorded as encircled, and the majority of these incidents occurred in the Atlantic Ocean (Tables 3 & 4, Figs. 3b & 4). Out of 155 individuals encircled in the Atlantic, 3 humpback whales in 2 separate sets and 8 pantropical spotted dolphins in 3 separate sets were incidentally killed (Tables 3 & 4, Figs. 3b & 4). In the Indian Ocean, 39 individuals were encircled but no mortalities were recorded. Thus, the apparent survival rates for cetaceans following encirclement were 93% (142 apparent survivals out of 153 known fates) in the Atlantic Ocean and 100% (37 apparent survivals out of 37 known fates) in the Indian Ocean (Table 3).

Table 4. Key statistics calculated using the scientific observer datasets of the French and Spanish tuna purse seine fleets in the tropical eastern Atlantic and western Indian Oceans for baleen whales (WHA), delphinids (DEL), and sperm whales (SPW)

Observers (1995–2011)	Atlantic	Indian	Total
Baleen whales			
WHA sighting events[a]	1118	610	1728
% WHA sightings associated with set	26.7	24.6	26.0
% sightings already recorded prior to the set	56.9	41.3	52.7
No. of WHA encircled[b]	93	29	122
No. of WHA fate known	92	27	119
% WHA apparent survival	96.7[c]	100.0	97.1
Delphinids			
DEL sighting events[a]	734	784	1518
% DEL sightings associated with set	7.5	3.9	5.6
% sightings already recorded prior to the set	16.4	10.0	14.1
No. of DEL encircled[b]	62	10	72
No. of DEL fate known	61	10	63
% DEL apparent survival	86.9[d]	100.0	87.5
Sperm whales			
SPW sighting events[a]	80	55	135
% SPW sightings associated with set	11.3	5.5	8.9
% sightings already recorded prior to the set	44.4	33.3	41.7
No. of SPW encircled[b]	0	0	0

[a]Observation of a group of cetaceans, the number of individuals could not be estimated; [b]Number of individuals encircled by the net; [c]Three humpback whale *Megaptera novaeangliae* mortalities (1 in a fishing set in 1999 and 2 in a set in 2000); [d]Eight pantropical spotted dolphin *Stenella attenuata* mortalities (in 3 different fishing sets in 1995)

DISCUSSION

Areas of relatively high co-occurrence between cetaceans and the purse seine fisheries of the Atlantic and Indian Oceans were identified for specific regions and periods. High baleen whale SPUEs were recorded east of the Seychelles during the NE monsoon (Fig. 2), as previously described by Robineau (1991) and Romanov (2002), as well as in the Mozambique Channel during the ISW monsoon. In the eastern Atlantic Ocean, significant baleen whale SPUEs were recorded in the coastal waters of Gabon between April and September. Whale-associated sets were reported earlier in Venezuelan purse seine fisheries throughout the year in the Caribbean Sea (Gaertner & Medina-Gaertner 1999).

Due to their size and high metabolic rates, baleen whales are assumed to require high densities of prey (Piatt & Methven 1992). Tuna purse seine fishing grounds are commonly characterized by oceanographic conditions that attract prey species in high densities. Thus, the interaction between cetaceans and tuna fisheries may be driven by the distribution of prey (Ballance & Pitman 1998, Mannocci et al. 2014). Areas where co-occurrence with purse seine fisheries were most frequent are highly productive zones featuring upwelling, i.e. east of the Seychelles during the NE monsoon (Hermes & Reason 2008), in the coastal waters of Gabon between July and September (Hardman-Mountford et al. 2003), and productive fronts and upwellings in the Mozambique Channel (Tew-Kai & Marsac 2009). While the observed overlap between regions of high productivity and areas of relatively high co-occurrence seems to support the assumption that cetacean–fisheries interaction is mostly driven by prey abundance, cetacean distributions may also be influenced by reproductive behavior (i.e. suitable breeding or calving habitats). More studies are needed to identify the environmental conditions linked to the co-occurrence between cetaceans and purse seine fisheries. Specific environmental variables (e.g. depth, distance to shore, sea surface temperature, primary productivity, salinity, mixed layer depth, oxygen minimum zone depth, currents, and eddies; Ready et al. 2010, Forney et al. 2012, Sequeira et al. 2012) and accurate statistical methods should be used to characterize factors which could explain the observed co-occurrence.

To improve their fishing success, fishers sometimes exploit the behavior of cetaceans foraging on the same prey species as the tuna in associated schools (Perrin et al. 1973, Clua & Grosvalet 2001) by setting nets in the vicinity of cetaceans (Romanov 2002, Amande et al. 2010). In the logbook dataset, the majority of cetacean sightings were baleen whales, while in the observer dataset the number of baleen whale sightings was similar to that of delphinids (Table 3). As the logbook sightings were mostly associated with fishing operations, the low record of delphinid sightings suggests that there is a low association between delphinids and purse seiners. Thus, captains may be less likely to record delphinid sightings since baleen whales are more often associated with tuna schools. In contrast, observers recorded sightings during all activities regardless of the cetacean group sighted, which could explain the difference in the proportion of sightings per group between the 2 datasets.

The majority of baleen whale sightings recorded by captains were associated with fishing sets, and at least 1 in every 2 whale-associated sets was intentionally set in the vicinity of baleen whales. Conversely, while delphinids were recorded as frequently as baleen whales in the observer dataset, they were rarely recorded interacting with fishing sets, which supports the low association of delphinids with fishing sets. This suggests that once sighted, captains are likely to set a net close to, or around, baleen whales but not delphinids. This assumption is further reinforced by the higher frequency of fishing sets being made following baleen whale sightings compared to delphinid sightings. Given that baleen whales and delphinids (which can form large groups of several hundred individuals) have a similar level of detectability, these figures suggest that tuna purse seiners may consider baleen whales as good indicators of the presence of tuna schools, and often intentionally set whale-associated nets in the eastern Atlantic Ocean and western Indian Ocean.

In contrast, dolphin-associated sets appear to be made relatively rarely (<10 yr^{-1}) in the studied regions. This highlights the striking difference between these tropical oceans and the eastern tropical Pacific Ocean, where dolphin-associated sets are often made by captains (from 9000 to 12 000 yr^{-1}; Hall & Roman 2013). It should be stressed that similar dolphin species were observed between our study areas and the eastern tropical Pacific Ocean, including pantropical spotted and spinner dolphins (Hall 1998, Gilman 2011), and that the same tuna species (i.e. large-size yellowfin tuna) are also present in all 3

ocean regions. The difference in the tuna–dolphin associations in the study areas and the eastern tropical Pacific Ocean is likely due to environmental differences in the respective oceans (Scott et al. 2012). Indeed, assumptions have been formulated to explain this difference, specifically because the eastern tropical Pacific Ocean presents particular oceanographic features: a shallow thermocline, warm sea surface temperatures, and a thick oxygen minimum zone (Edwards 1992, Fiedler & Talley 2006). These characteristics are thought to enhance the tuna–dolphin association in the eastern tropical Pacific Ocean by reducing the vertical movement of tunas (Edwards 1992, Scott et al. 2012). Even if some cases of tuna–dolphin association have also been observed in the tropical eastern Atlantic and western Indian Oceans in this study and in the past (Levenez et al. 1979, Ballance & Pitman 1998), using dolphins to detect tuna schools has not developed in the purse seine fisheries in Atlantic and Indian Oceans. It is unclear whether this association is less systematic and weaker than in the eastern Pacific Ocean (Scott et al. 2012), or if captains are reluctant to set on dolphins due to the potential mortality and related consequences.

Sperm whale sightings have been recorded in both datasets; however, it is likely that this reflects their relatively high abundance in the Atlantic and Indian Oceans (Robineau 1991, Ballance & Pitman 1998, Weir 2011, Mannocci et al. 2014) rather than their possible interaction with either tuna schools or purse seine fisheries. Indeed, tuna and sperm whales are not considered to form mixed-species associations, as they do not share similar foraging resources (Romanov 2002). Sperm whales mostly predate on large mesopelagic cephalopods (e.g. Spitz et al. 2011), and tunas in surface aggregations mainly predate on epipelagic fish, crustaceans and small cephalopods (Bashmakov et al. 1991, Potier et al. 2004).

Overall, the encirclement of cetaceans by purse seine nets was relatively rare in the Atlantic and Indian Oceans. In most cases, the data suggested that encirclement followed intentional cetacean-associated sets, but also indicated some accidental encirclements. When encircled, cetaceans usually escaped by either diving before the set was completed, swimming over the net, or escaping through the net (Romanov 2002, pers. comm. from scientific observers and vessel captains). While escaping baleen whales may cause some damage to the net, it is minor compared to the resulting amount of tuna caught.

The apparent cetacean survival rates were relatively high. In the Indian Ocean, no mortalities were

recorded in our study, although a single fatality of a young sei whale due to encirclement was previously reported by Romanov (2002) for the Soviet purse seiners. Eleven incidental mortalities were recorded in the Atlantic Ocean (8 pantropical spotted dolphins and 3 humpback whales), representing an apparent survival rate of 92%. Although these figures are heartening, it is important to note that the non-lethal impacts of cetacean-associated sets have not been assessed, and would be very difficult to measure (Wilson et al. 2014). Since 2007, encircling cetaceans has been prohibited by the EU in both the Atlantic and Indian Oceans (EU 2007). The Indian Ocean Tuna Commission introduced their own regulations for the Indian Ocean in September 2013 (IOTC 2013, resolution 13/03), but the International Commission for the Conservation of Atlantic Tunas has not yet introduced similar measures for the Atlantic Ocean. Given the lack of accurate cetacean–fisheries inter-action data that existed for the tropical Atlantic and Indian Oceans, these measures were precautionary.

Through a statistical analysis of 2 large datasets, we have shown that the magnitude of co-occurrence and interactions between cetaceans and purse-seine fisheries varies depending on factors such as the species involved, season, and area considered. Our re-sults show that while intentional setting in the vicin-ity of baleen whales seems common, few interactions between fishing operations and delphinids were observed. In addition, we found a low apparent mor-tality during sets, which suggests that purse seine fishing activities have a limited impact on cetaceans in the eastern tropical Atlantic and the western trop-ical Indian Oceans. The apparent survival rates determined here were based on the observer dataset, which covered 7 to 9% of the European fleet activi-ties during the studied period, and will be increased to 100% by 2014 (an increase to 50% has already occurred since July 2013). Overall, this research con-tributes to the development of effective measures for the sustainable management of tropical tuna fish-eries and the conservation of cetacean species.

LITERATURE CITED

Ali M, Goovaerts P, Nazia N, Haq MZ, Yunus M, Emch M (2006) Application of Poisson kriging to the mapping of cholera and dysentery incidence in an endemic area of Bangladesh. Int J Health Geogr 5:45

Amande MJ, Ariz J, Chassot E, Delgado de Molina A and others (2010) Bycatch of the European purse seine tuna fishery in the Atlantic Ocean for the 2003-2007 period. Aquat Living Resour 23:353–362

Ariz J, Delgado A, Fonteneau A, Gonzales Costas F, Pallares P (1999) Logs and tunas in the Eastern Tropical Atlantic. A review of present knowledge and uncertainties. In: Scott MD, Bayliff WH, Lennert-Cody CE, Schaefer KM (eds) Proceedings of the International Workshop on Fish-ing For Tunas Associated with Floating Objects, La Jolla, CA, 11–13 Feb 1992. Inter-Am Trop Tuna Comm Spec Rep 11:21–65

Ballance LT, Pitman RL (1998) Cetaceans of the western tropical Indian Ocean: distribution, relative abundance, and comparisons with cetacean communities of two other tropical ecosystems. Mar Mamm Sci 14:429–459

Bashmakov VF, Zamorov VV, Romanov EV (1991) Diet com-position of tunas caught with long lines and purse seines in the Western Indian Ocean. In: Collective volume of working documents presented at the workshop on stock assessment of yellowfin tuna in the Indian Ocean, Colombo, 7–12 Oct 1991. Indo-Pacific Development and Management Programme, Columbo, p 53–59

Bourjea J, Clermont S, Delgado A, Murua H, Ruiz J, Cic-cione S, Chavance P (2014) Marine turtle interaction with purse-seine fishery in the Atlantic and Indian oceans: lessons for management. Biol Conserv 178:74–87

Bowen WD (1997) Role of marine mammals in aquatic eco-systems. Mar Ecol Prog Ser 158:267–274

Brown SL, Reid D, Rogan E (2013) A risk-based approach to rapidly screen vulnerability of cetaceans to impacts from fisheries bycatch. Biol Conserv 168:78–87

Capietto A, Escalle L, Chavance P, Dubroca L and others (2014) Mortality of marine megafauna induced by fish-eries: insights from the whale shark, the world's largest fish. Biol Conserv 174:147–151

Clua E, Grosvalet F (2001) Mixed-species feeding aggrega-tion of dolphins, large tunas and seabirds in the Azores. Aquat Living Resour 14:11–18

Dulvy NK, Fowler SL, Musick JA, Cavanagh RD and others (2014) Extinction risk and conservation of the world's sharks and rays. eLife 3:e00590

Edwards E (1992) Energetics of associated tunas and dol-phins in the Eastern Tropical Pacific Ocean: a basis for the bond. Fish Bull 90:678–690

Estes JA, Tinker MT, Williams TM, Doak DF (1998) Killer whale predation on sea otters linking oceanic and near-shore ecosystems. Science 282:473–476

EU (2007) Council regulation (EC) No. 520/2007 of 7 May 2007. Laying down technical measures for the conservation of certain stocks of highly migratory species and repealing Regulation (EC) No. 973/2001. Official Journal of the European Union L123:3−13

Fiedler PC, Talley LD (2006) Hydrography of the eastern tropical Pacific: a review. Prog Oceanogr 69:143−180

Fonteneau A (2009) Atlas of Atlantic Ocean tuna fisheries. IRD, Marseille

Fonteneau A (2010) Atlas of Indian Ocean tuna fisheries. IRD, Marseille

Forney KA, Ferguson MC, Becker EA, Fiedler PC and others (2012) Habitat-based spatial models of cetacean density in the eastern Pacific Ocean. Endang Species Res 16: 113−133

Gaertner D, Medina-Gaertner M (1999) An overview of the tuna fishery in the southern Caribbean Sea. In: Scott MD, Bayliff WH, Lennert-Cody CE, Schaefer KM (eds) Proceedings of the International Workshop on Fishing for Tunas Associated with Floating Objects, La Jolla, CA, 11−13 Feb 1992. Inter-Am Trop Tuna Comm Spec Rep 11:66−86

Gilman EL (2011) Bycatch governance and best practice mitigation technology in global tuna fisheries. Mar Policy 35:590−609

Gilman EL, Lundin C (2009) Minimizing bycatch of sensitive species groups in marine capture fisheries: lessons from commercial tuna fisheries. In: Grafton Q, Hillborn R, Squires D, Tait M, Williams M (eds) Handbook of marine fisheries conservation and management. Oxford University Press, Oxford, p 150−164

Goovaerts P (2005) Geostatistical analysis of disease data: estimation of cancer mortality risk from empirical frequencies using Poisson kriging. Int J Health Geogr 4:31

Hall MA (1998) An ecological view of the tuna-dolphin problem: impacts and trade-offs. Rev Fish Biol Fish 8:1−34

Hall MA, Roman M (2013) Bycatch and non-tuna catch in the tropical tuna purse seine fisheries of the world. FAO Fisheries and Aquaculture Technical Paper No. 568, FAO, Rome

Hallier JP, Parajua JI (1999) Review of tuna fisheries on floating objects in the Indian Ocean. In: Scott MD, Bayliff WH, Lennert-Cody CE, Schaefer KM (eds) Proceedings of the International Workshop on Fishing for Tunas Associated with Floating Objects, La Jolla, CA, 11−13 Feb 1992. Inter-Am Trop Tuna Comm Spec Rep 11:195−221

Hampton J, Bailey K (1999) Fishing for tunas associated with floating objects: review of the western Pacific fishery. In: Scott MD, Bayliff WH, Lennert-Cody CE, Schaefer KM (eds) Proceedings of the International Workshop on Fishing for Tunas Associated with Floating Objects, La Jolla, CA, 11−13 Feb 1992. Inter-Am Trop Tuna Comm Spec Rep 11:222−284

Hardman-Mountford NJ, Richardson AJ, Agenbag JJ, Hagen E, Nykjaer L, Shillington FA, Villacastin C (2003) Ocean climate of the South East Atlantic observed from satellite data and wind models. Prog Oceanogr 59: 181−221

Hermes JC, Reason CJC (2008) Annual cycle of the South Indian Ocean (Seychelles-Chagos) thermocline ridge in a regional ocean model. J Geophys Res 113:C04035, doi: 10.1029/2007JC004363

IOTC (2013) Compendium of active conservation and management measures for the Indian Ocean Tuna Commission. Indian Ocean Tuna Commission, Mahé

Kerry R, Smit I, Goovaerts P, Ingram BR (2010) A comparison of indicator and Poisson kriging of herbivore species abundance in Kruger National Park, South Africa. In: Tate NJ, Fisher PF (eds) Accuracy 2010: Proceedings of the 9th International Symposium on Spatial Accuracy Assessment in the Natural Resources and Environmental Sciences, Leicester, 20−23 July 2010. International Spatial Accuracy Research Association, p 393−396

Levenez JJ, Fonteneau A, Regalado R (1979) Resultats d'une enquete sur l'importance des dauphins dans la pecherie thoniere FISM. Collective Volume of Scientific Papers ICCAT 9(1):176−179

Lewison RL, Crowder LB, Read AJ, Freeman SA (2004) Understanding impacts of fisheries bycatch on marine megafauna. Trends Ecol Evol 19:598−604

Lewison RL, Crowder LB, Wallace BP, Moore JE and others (2014) Global patterns of marine mammal, seabird, and sea turtle bycatch reveal taxa-specific and cumulative megafauna hotspots. Proc Natl Acad Sci USA 111: 5271−5276

Mannocci L, Laran S, Monestiez P, Dorémus G, Van Canneyt O, Watremez P, Ridoux V (2014) Predicting top predator habitats in the Southwest Indian Ocean. Ecography 37:261−278

Marcello J, Hernández-Guerra A, Eugenio F, Fonte A (2011) Seasonal and temporal study of the northwest African upwelling system. Int J Remote Sens 32:1843−1859

Molony B (2005) Estimates of the mortality of non-target species with an initial focus on seabirds, turtles and sharks. Working Paper WCPFC-SC1, 1st Meeting of the Scientific Committee of the Western and Central Pacific Fisheries Commission, Noumea, 8−19 Aug 2005. Oceanic Fisheries Programme, Secretariat of the Pacific Community, Noumea

Monestiez P, Dubroca L, Bonnin E, Durbec JP, Guinet C (2006) Geostatistical modelling of spatial distribution of *Balaenoptera physalus* in the Northwestern Mediterranean Sea from sparse count data and heterogeneous observation efforts. Ecol Modell 193:615−628

Perrin WF, Warner RR, Fiscus CH, Holts DB (1973) Stomach contents of porpoise, *Stenella* spp., and yellowfin tuna, *Thunnus albacares*, in mixed-species aggregations. Fish Bull 71:1077−1092

Piatt JF, Methven DA (1992) Threshold foraging behavior of baleen whales. Mar Ecol Prog Ser 84:205−210

Potier M, Marsac F, Lucas V, Sabatie R, Hallier JP, Ménard F (2004) Feeding partitioning among tuna taken in surface and mid-water layers: the case of yellowfin (*Thunnus albacares*) and bigeye (*T. obesus*) in the western tropical Indian Ocean. West Indian Ocean J Mar Sci 3: 51−62

R Development Core Team (2014) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Read AJ, Drinker P, Northridge S (2006) Bycatch of marine mammals in US and global fisheries. Conserv Biol 20: 163−169

Ready J, Kaschner K, South AB, Eastwood PD and others (2010) Predicting the distributions of marine organisms at the global scale. Ecol Modell 221:467−478

Robineau D (1991) Balaenopterid sightings in the western tropical Indian Ocean (Seychelles area), 1982–1986. In: Teatherwood S, Donovan GP (eds) The Indian Ocean sanctuary marine mammal technical report No. 3. UNEP, Nairobi, p 171−178

Romanov EV (2002) Bycatch in the tuna purse-seine fisheries of the western Indian Ocean. Fish Bull 100:90–105

Schipper J, Chanson JS, Chiozza F, Cox NA and others (2008) The status of the world's land and marine mammals: diversity, threat, and knowledge. Science 322:225–230

Schott FA, Xie SP, McCreary JP (2009) Indian Ocean circulation and climate variability. Rev Geophys 47:RG1002, doi:10.1029/2007RG000245

Scott M, Chivers S, Olson R, Fiedler P, Holland K (2012) Pelagic predator associations: tuna and dolphins in the eastern tropical Pacific Ocean. Mar Ecol Prog Ser 458:283–302

Sequeira A, Mellin C, Rowat D, Meekan MG, Bradshaw CJA (2012) Ocean-scale prediction of whale shark distribution. Divers Distrib 18:504–518

Spitz J, Cherel Y, Bertin S, Kiszka J, Dewez A, Ridoux V (2011) Prey preferences among the community of deep-diving odontocetes from the Bay of Biscay, Northeast Atlantic. Deep-Sea Res I 58:273–282

Tew-Kai E, Marsac F (2009) Patterns of variability of sea surface chlorophyll in the Mozambique Channel: a quantitative approach. J Mar Syst 77:77–88

Wallace BP, DiMatteo AD, Bolten AB, Chaloupka MY and others (2011) Global conservation priorities for marine turtles. PLoS ONE 6:e24510

WCPFC (2012) Summary information on whale shark and cetacean interactions in the tropical WCPFC purse seine fishery. Information Paper WCPFC8-201-IP-01, Western and Central Pacific Fisheries Commission, Tumon

Weir CR (2011) Distribution and seasonality of cetaceans in tropical waters between Angola and the Gulf of Guinea. Afr J Mar Sci 33:1–15

Weir CR, Pierce GJ (2013) A review of the human activities impacting cetaceans in the eastern tropical Atlantic. Mammal Rev 43:258–274

Wilson SM, Raby GD, Burnett NJ, Hinch SG, Cooke SJ (2014) Looking beyond the mortality of bycatch: sublethal effects of incidental capture on marine animals. Biol Conserv 171:61–72