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Tracking seabirds to identify potential Marine Protected Areas in the tropical western Indian Ocean

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ABSTRACT

We conducted a regional tracking program on seabirds in order to identify major foraging hotspots and potential Marine Protected Areas in the tropical western Indian Ocean. Thirty-one species of seabirds breed in the region, totaling 7.4 million pairs. The main breeding grounds are in the Seychelles, in the Mozambique Channel and in the Mascarene. Seven pelagic species have been tracked so far from eight different islands of the region. Using count per sector analysis we identified five major oceanic foraging hotspots, among which three include the breeding colonies and two are oceanic areas not connected to a breeding island. We found important overlaps between most of these seabird foraging hotspots and potential threats (industrial fishery targeting surface dwelling tunas and marine pollution due to maritime routes) suggesting that in these regions seabirds may be at risk when foraging. Although this analysis is based on a limited number of tracking studies, the knowledge on seabird distribution at sea has increased tremendously in the last 6 years in the tropical western Indian Ocean, and this trend will continue, as research is ongoing. The data, we present here for the first time in a single synthesis show clear spatial patterns that identify high priority locations for designation as Marine Protected Areas in the tropical western Indian Ocean.

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1. Introduction

Tropical pelagic ecosystems of the western Indian Ocean are a marine hotspot of biodiversity, with major concentrations of emblematic or economically important species such as cetaceans (Balance and Pitman, 1998), turtles (Lauret-Stepler et al., 2007), tunas and billfish (Worm et al., 2005) and seabirds (Le Corre and Jaquemet, 2005). In spite of this, Marine Protected Areas (MPAs) cover less than 1% of the oceanic and coastal surface of the region (figure derived from WIOMSA, 2010), and, except for the ongoing project of implementing a large MPA around the Chagos Archipelago (Koldewey et al., 2010; De Santo et al., 2011), there are currently no specific tools to protect pelagic ecosystems of the region (Game et al., 2009).

Although industrial fisheries have historically had less impact on the tropical Indian Ocean than in other oceans, since the late 1980s this is no longer the case. In the tropical western Indian Ocean, annual catches of tunas have increased 30-fold, from less

than 40 thousand tons in the early 1950s, to more than 1200 thousand tons in 2007 (IOTC, 2008a). When top predatory fish like tunas are targeted, their collapses can lead to meso-predator releases and cause cascading effects throughout the food chain (Baum and Worm, 2009). In the tropics, most catches are made by industrial fisheries (long liners and purse seiners) and in the Indian Ocean, all purse seine catches and more than 80% of long line catches occur in the western basin (Ménard et al., 2007; IOTC, 2008), indicating that this region supports great productivity and is at risk from concentrated fisheries.

Fisheries impact seabirds in various ways, the main impacts include direct mortality by fishing gear (by catch) and competition when fisheries and seabirds target the same prey (e.g., Okes et al., 2009; Trebilco et al., 2010). Although these interactions can have large impacts on many seabird populations throughout the world (see Furness, 2003 for a review), our observations in the western Indian Ocean indicate that they do not have major impacts on seabirds in this region. There is little bycatch of seabirds in the tropical western Indian Ocean (Anderson et al., 2009 and pers. obs.), likely because seabirds in the western Indian Ocean community tend not to be attracted to fishing vessels. Fisheries and

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seabirds do not compete directly for a shared prey community because most tropical seabirds feed upon small epipelagic prey (Le Corre et al., 2003; Jaquemet et al., 2008; Catry et al., 2009a), whereas the tropical industrial fisheries target top predators such as tunas and swordfish, which are also predators of epipelagic fauna (Potier et al., 2007). Therefore, because fisheries-induced mortality of top predatory fish may lead to a release of epipelagic fauna (see for instance Polovina et al., 2009), it might be expected that industrial fishing would benefit seabirds. However, because tropical seabirds are strongly dependent on surface dwelling top-predators, we suggest this is not the case. Tropical seabirds rely on surface seizing and plunge diving (Harrison, 1990) to acquire prey, and very few are able to dive deeper than a few meters. Because epipelagic prey are distributed within the upper 50 meters of the water column, they are only accessible to seabirds when surface dwelling predators like tunas and dolphins pursue epipelagic prey and force them to flee toward the surface. Tropical seabirds take advantage of this phenomenon by frequently foraging over schools of tunas or dolphins to catch the evading prey. This interaction is so important for tropical seabirds that it has been termed a “near-obligate commensalism” between seabirds and marine top predators (Au and Pitman, 1986). At-sea studies in the Indian Ocean have confirmed that most seabirds are associated with surface dwelling tunas (Jaquemet et al., 2004, 2005).

Because fisheries of the western Indian Ocean target mostly surface dwelling tunas, including skipjack (*Katsuwonus pelamis*) and yellowfin tunas (*Thunnus albacares*) (IOTC, 2010a), this commensalism faces a high risk of disruption if tunas become overfished. The consequence of this disruption has never been quantified but may be very important for seabirds. Indeed, the depletion of surface dwelling tuna may reduce the foraging efficiency of many tropical seabirds, which could have cascading effects on their population dynamics (Le Corre and Jaquemet, 2005).

Offshore MPAs could potentially benefit species targeted by industrial fisheries (tuna and billfish) and help to sustain these fisheries (Worm et al., 2009; Koldewey et al., 2010), although the conservation of highly migratory fish like tuna is more challenging (Steffansson and Rosenberg, 2006) and may require the implementation of dynamic MPAs (see for instance Hobday and Hartmann, 2006). Increased protection of resources targeted by fisheries could also afford increased protection for untargeted species vulnerable to bycatch (sharks, rays, turtles, marine mammals) and for the species associated with tuna, like seabirds (Le Corre and Jaquemet, 2005).

The second major threat, which may impact marine biodiversity of the Indian Ocean, is oil pollution. Thirty-six percent of the world's oil is produced in the Middle East, and most of it is exported via maritime routes throughout the Indian Ocean (figures extracted from http://www.nationmaster.com/graph/ene_oil_pro-energy-oil-production). Intensive maritime traffic increases the risk for low-level chronic pollution and potentially catastrophic oil spills (Vethamony et al., 2007; Sivadas et al., 2008). The impact of oil pollution on seabirds has been widely documented and most studies have shown that oil spills invariably produce massive seabird mortality (e.g., Ford et al., 1996; Votier et al., 2008; Munilla et al., 2011). The level of mortality is variable however and depends on various parameters including size of spills, weather conditions, seabird foraging behavior and seabird density (Tan et al., 2010). Seabird mortality associated with oil pollution is poorly documented in the Indian Ocean (but see Evans et al., 1993). However, given the intensity of the maritime traffic and the density of seabirds in this part of the world, there is a high risk of additive seabird mortality due to chronic or accidental oil pollution.

As seabirds are relatively easy to track at sea compared to most other marine top predators, we propose that their foraging distributions and movements can be used to identify oceanic areas of

particular importance for seabirds and associated marine community assemblages. Indeed, there is a worldwide interest in using seabird telemetry data and at-sea surveys to identify marine Important Bird Areas (IBAs, BirdLife International, 2011) and potential MPAs (e. g. Hyrenbach et al., 2006; Louzao et al., 2009). The validity of determining protected areas from top-predator distributions has similarly been demonstrated in terrestrial areas (Sergio et al., 2005). Tracking data can also help to identify oceanic areas where seabirds are at risk of oil spills (Montevicchi et al., 2011).

BirdLife International has defined a set of criteria to define a zone as a marine IBA (BirdLife International, 2011) one of them being that the area must hold a least 1% of the global population of a given seabird species (BirdLife International, 2011). In this paper, we did not calculate such proportions with our tracking dataset. Instead we used our tracking data to identify “population hotspots” (BirdLife International, 2011) whatever the size of the populations studied, because we considered that these hotspots are indicators of important marine ecological processes. Thus we consider a “population hotspot” as an area where individuals of a given seabird population concentrate to forage.

In this paper, we analyze all tracking data available for seabirds of the tropical western Indian Ocean to identify these hotspots. Because seabirds forage mostly at places of great productivity and of important ecological processes, we propose to ultimately use these foraging areas as indicator of potential Marine Protected Areas in the tropical western Indian Ocean. In order to identify areas where seabirds may be at risk when at sea, we also compiled all spatially explicit data on industrial fisheries and on maritime trade routes in the tropical Indian Ocean, and we conducted an overlap analysis of these threats with our tracking data.

2. Material and methods

2.1. Seabird datasets

2.1.1. Breeding colonies

The abundance and distribution of seabirds at sea depend primarily on where they breed. We compiled all existing data on seabird colonies of the western tropical Indian Ocean. We define the western tropical Indian Ocean as the part of the Ocean located between the coasts of East Africa and the longitude 70°E and between the latitudes 10°N and 30°S. This compilation includes Mozambique (Parker, 2001), Tanzania (Baker and Baker, 2001), Kenya (Bennun and Njoroge, 2001), Somalia (Anonymous, 2001), Madagascar (ZICOMA, 2001), Comoros (Safford, 2001a), the Seychelles (Rocamora and Skerret, 2001), Mauritius (Safford, 2001b), Reunion and Iles Eparses (Le Corre and Safford, 2001). We compiled all areas of these countries identified as Important Bird Areas (IBA) because of their seabird breeding colonies (see references above). We also included in this compilation all other seabird breeding sites of the region, which are not yet classified as IBAs (Louette, 1988; Rocamora et al., 2003; Rocamora, 2004; Crawford et al., 2006; Anonymous, 2008; McGowan et al., 2008; Le Corre and Bemanaja, 2009).

2.1.2. Tracking data

Since 2003, we conducted a regional tracking program on seabirds of the tropical western Indian Ocean (see Weimerskirch et al., 2004, 2005, 2010; Catry et al., 2009b; Pinet et al., 2011). As far as we know this represents all the tracking data available for seabirds of the region, except the work of Asseid et al. (2006) conducted on masked boobies (*Sula dactylatra*) of Latham Island, and our own work on the migration of a great frigatebird (*Fregata minor*, Weimerskirch et al., 2006). We haven't included these data in

our analysis because of the small sample size (two masked boobies in Asseid et al., 2006, and one great frigatebird in Weimerskirch et al., 2006).

Although most data herein have been reported previously (see references above), we also include six original unpublished datasets (see Table 1 for details). From September 2003 to July 2011, seven species of seabirds from 13 different populations have been tracked using Argos transmitters or archival tags (Global Positioning Systems (GPS) and Global Location Sensors also termed as “geolocators” (GLS)). This represents 222 tracked birds and 3891 days of study (Table 1). Argos transmitters and GPS have short life battery duration, no (Argos) or limited (GPS) memory capacities and are relatively heavy (see below), so we used them only for short term tracking during the breeding period. GLS have a very long life battery duration, huge memory capacities and they are very light, so we used them for long term tracking to study annual cycles of the birds (breeding and post breeding migration). The field sites and methods employed to attach the loggers and process the data have been described in a number of species-specific papers (see references earlier). Broadly, Argos transmitters (PTT 100 of 18 g for great frigatebird, 12 g for masked and red-footed boobies (*S. dactylatra* and *S. sula* respectively) and 9.5 g for Barau’s petrels (*Pterodroma barau*, Microwave Telemetry, Columbia, USA) were attached to the birds on the feathers of the back (frigatebirds and Barau’s petrels) or tail (boobies) using adhesive tape (Tesa, Hamburg, Germany). GPS (NewBehavior, Zürich, Switzerland) were used on red-footed and masked boobies only and were attached to the tail, also using Tesa tape. Geolocators (GLS MK5 and MK15, British Antarctic Survey, Cambridge, UK) were used on Barau’s petrels, wedge-tailed shearwaters (*Puffinus pacificus*), red-tailed tropicbirds (*Phaethon rubricauda*) and white-tailed tropicbirds (*Phaethon lepturus*). They were attached on the tarsus to a metal ring with cable ties. Argos transmitters and GPS weighed less than 4% of the weight of the tracked bird and GLS weighed less than 1.5% of the weight of the birds. Argos transmitters were deployed for 3–30 days on a given bird, GPS for 1–3 days, and GLS for 235 days to up to 586 days.

2.1.3. Filtering, smoothing procedures and count per sector analysis

The GLS measured light level every minute and logged its maximum intensity every 10 min. Positions were calculated using

TransEdit and BirdTracker (British Antarctic Survey). Sunrise and sunset times were identified based on light curve thresholds, with longitude calculated from the time of local midday relative to Greenwich Mean Time, and latitude calculated from day length (Phillips et al., 2004). Data were then filtered, unrealistic positions on continent and around equinox periods (Wilson et al., 1992) and those yielding unrealistic flight speeds (McConnell et al., 1992) were removed. Two positions per day can be inferred from the light signal with an average accuracy of 186 km (± 114 km) (Phillips et al., 2004). Argos transmitters provide about 6–10 locations per day and GPS loggers record position at 10 s intervals. Because of these very different time resolutions between devices, we used a smoothing procedure to combine the data altogether. Two locations per day were randomly sampled in Argos and GPS tracks, and the rest were not used in the count per sector analysis.

For each tracked species, we counted the number of locations (ARGOS, GPS and GLS data altogether) in cells of $1^\circ \times 1^\circ$ of a grid covering the at-sea distribution of the tracked species (from 30°E to 122°E and from 40°S to 24°N). We also added the number of locations per cell of all species in order to have a single multi-specific indicator of seabird distribution at sea (hereafter referred as the “seabird density” per sector).

In order to know if each population use a specific area or if several populations share the same foraging areas, we counted the number of populations present in each cell of $1^\circ \times 1^\circ$ (hereafter referred as the “population density” per sector). In this study, we define a “population” as a group of birds of a given species breeding in the same island. Finally we also counted the number of species present per cell in order to identify multi-specific foraging areas (hereafter referred as the “species richness” per sector).

2.2. Threats datasets

Two potential threats for seabirds were considered in the present study. The first is industrial fisheries targeting tunas (long-liners and purse-seiners). Data were downloaded from the Indian Ocean Tuna Commission databases (<http://www.iotc.org/English/data/>). We compiled the total catches of long-line and purse-seine fishing separately from 2000 to 2009.

The second major threat is oil pollution. Halpern et al. (2008) assessed the human impact on marine ecosystems through 17

Table 1
Tracking dataset used in the present study.

Species	Place	Logger	Number of equipped birds	Beginning of the study	End of the study	Duration (day)	Life stage studied	References
Red-footed booby	Europa	Argos PTT	16	18/08/2003	30/09/2003	43	B	Weimerskirch et al. (2005)
		GPS	16	18/08/2003	30/09/2003	43	B	Weimerskirch et al. (2005)
	Tromelin	Argos PTT	8	05/12/2005	02/01/2006	28	B	Kappes et al. (2011)
		GPS	14	05/12/2005	02/01/2006	28	B	Kappes et al. (2011)
Masked booby	Tromelin	Argos PTT	8	05/12/2005	02/01/2006	28	B	Kappes et al. (2011)
		GPS	17	05/12/2005	02/01/2006	28	B	Kappes et al. (2011)
Great frigatebird	Europa	Argos PTT	9	18/08/2003	30/09/2003	43	B	Weimerskirch et al. (2004)
	Aldabra	Argos PTT	14	05/10/2006	25/10/2006	20	B	Weimerskirch et al. (2010)
Wedgetailed shearwater	Arde	GLS	9	20/01/2007	17/08/2007	209	B, PBM	Catry et al. (2009a,b)
	Cousin	GLS	6	11/02/2008	03/10/2008	235	B, PBM	Kappes et al. (in preparation)
	Cousin	GLS	10	20/09/2009	14/01/2011	481	B, PBM	Kappes et al. (in preparation)
	Amirantes	GLS	13	08/09/2009	09/10/2010	396	B, PBM	Kappes et al. (in preparation)
	Reunion	GLS	8	09/12/2009	18/10/2010	313	B, PBM	Kappes et al. (in preparation)
Barau’s petrel	Reunion	Argos PTT	7	03/02/09	15/04/09	71	B	Pinet et al. (in press)
	Reunion	GLS	23	08/02/2008	16/09/2009	586	B, PBM	Pinet et al. (2011)
Red-tailed tropicbird	Europa	GLS	11	11/11/2008	15/03/2010	489	B, PBM	Le Corre et al. (in preparation)
	Madagascar	GLS	19	08/07/2010	12/07/2011	369	B, PBM	Le Corre et al. (in preparation)
White-tailed tropicbird	Cousin	GLS	14	20/09/2009	14/01/2011	481	B, PBM	Le Corre et al. (in preparation)
Total			222			3891		

global data sets of anthropogenic drivers of ecological change. Among the 17 drivers, they estimated an ocean pollution index derived from commercial shipping and port activities. These data sets can be downloaded from National Center for Ecological Analysis and Synthesis databases (<http://www.nceas.ucsb.edu/globalmarine/impacts>).

In order to perform the overlap analysis of the threats of seabirds when at sea, we expressed all threat data (industrial fishing catches and risk of marine pollution) per cells of $1^\circ \times 1^\circ$ in the same grid as that used for seabird data.

2.3. Overlap analysis

Long-line and purse seine grids were added providing a unique index of fishing threat (expressed as the weight (in tons) of tuna caught between 2000 and 2009, per cell). We then calculated a global threat index by adding fishing and pollution grids previously standardized by dividing each cell by the maximum value of the respective grid. Finally we calculated an overlap index by multiplying for each cell the global threat index with the seabird density.

3. Results

3.1. Distribution of the seabird colonies of the tropical western Indian Ocean

The tropical western Indian Ocean is a major stronghold for seabirds. The islands of the region serve as breeding habitat for 7.4 million pairs of seabirds, consisting of 31 species. The three major breeding concentrations (Fig. 1) are in the Seychelles (3.4 million pairs), in the Mozambique Channel (3.0 million pairs) and in the Mascarene Archipelago (0.7 million pairs). All large seabird colonies are located on remote, protected, oceanic islands, and few large seabird colonies exist along the coast of East Africa and Madagascar.

3.2. Patterns of seabird distribution at sea inferred from tracking data

3.2.1. Seabird density

Our tracking data revealed five major oceanic areas where seabird density is particularly high (Fig. 2A). Three are logically

located around the main breeding places: the Seychelles area, the southern Mozambique Channel and the Mascarene Archipelago area. The fourth area is a broad oceanic zone, located at the South of Madagascar, which includes the continental shelf of Madagascar and the Walters Shoals (a series of seamounts laying from 200 to 1000 km in the south of Madagascar). The last area is a massive oceanic area located in the Central Indian Ocean, on both sides of the Ninety East Ridge. Although more than 3000 km distant from all breeding sites of seabirds of the tropical western Indian Ocean, this huge area is a major foraging area for several species of migratory seabirds of the tropical western Indian Ocean (see below).

3.2.2. Population density

As shown in Fig. 2B, seabirds of the thirteen populations tracked so far occupy widely the tropical Indian Ocean. However two major areas concentrate an important number of populations. The first one is the Seychelles Archipelago with numerous sectors simultaneously used by birds of six populations or more. The second one, already identified as an area with high seabird concentration (see above), is in the central Indian Ocean, particularly between the equator and 15°S and between 70°E and 85°E .

3.2.3. Species distribution and species richness

The distribution of the seven tracked species is presented in Fig. 3 and the species richness in Fig. 2C. The species have contrasted distribution patterns.

The two species of boobies are restricted to an oceanic area of less than 200 km from their breeding places, resulting in a patchy distribution around their breeding colonies (Fig. 3A). The great frigatebirds (Fig. 3B) have a wider foraging distribution but still centered at their breeding places, Europa and Aldabra (but see Section 4).

The four other species in contrast have very wide distributions. The Barau's petrels occupy the southern part of the tropical Indian Ocean (Fig. 3C). Although seasonal changes in the distribution are not detailed in the present paper, we have shown elsewhere that Barau's petrels migrate from west to east after their breeding season (Pinet et al., 2011, in press). When breeding, they forage to the south of Reunion Island (their breeding ground), in the south of Madagascar and along the east coast of South Africa (Pinet et al., in press and see Fig. 3C). After breeding, they migrate eastward

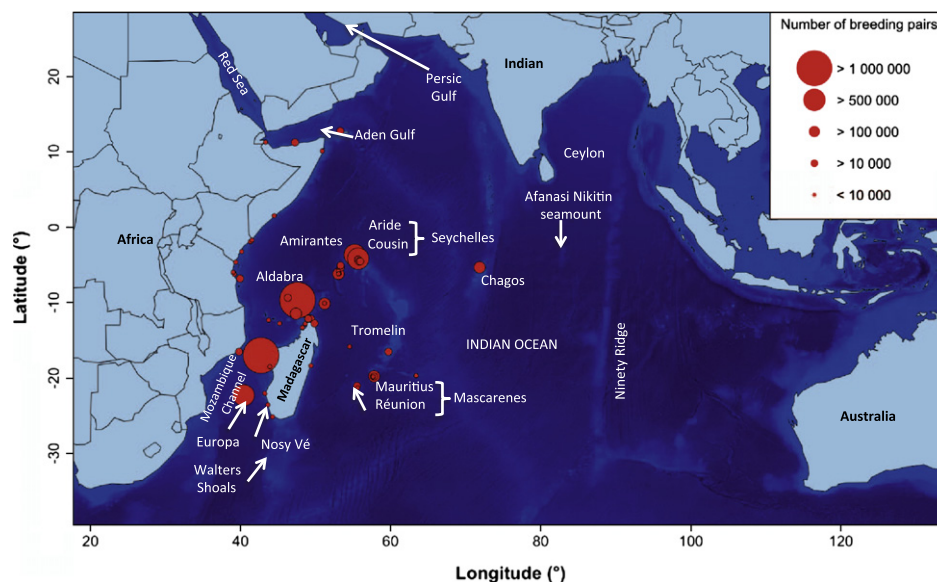


Fig. 1. Distribution of the seabird breeding colonies in the western Indian Ocean. The names represent the places cited in the text.

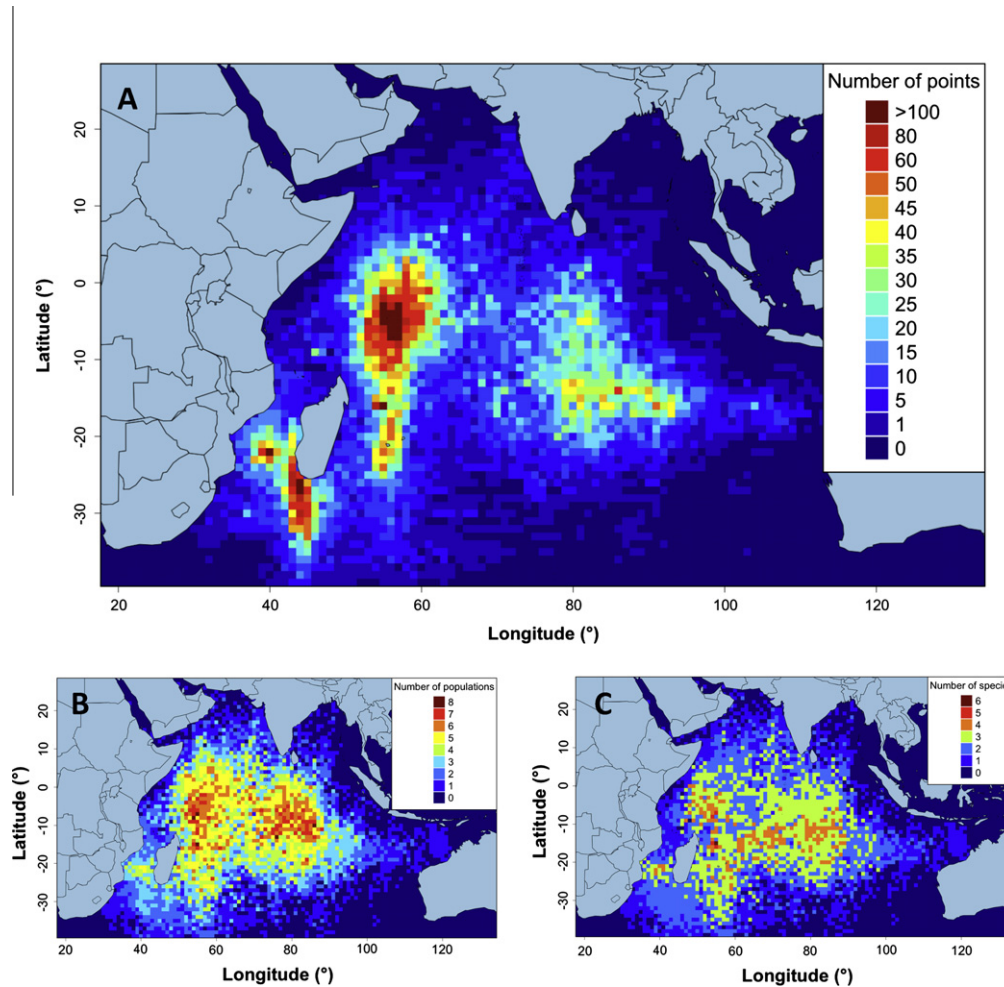


Fig. 2. Seabird hotspots of the western Indian Ocean, based on tracking data. (A) Seabird density, (B) population density and (C) species richness. All these indicators are calculated per cell of $1^\circ \times 1^\circ$.

to the central and eastern Indian Ocean. Their core migration area is located between 10° and 20° S and between 78° E and 95° E (Pinet et al., 2011 and see Fig. 3C).

The wedge-tailed shearwaters also have a wide distribution in the Indian Ocean (Fig. 3D). Tracking data indicate two major areas. The first one is in the western Indian Ocean and includes most known breeding grounds of the species, in particular the Seychelles and the Mascarenes. This area represents the foraging distribution of the species during its breeding period (Kappes et al., 2011). The second area is located further east, to the south of Indian and Sri Lanka. It represents the foraging distribution of the species when migrating although some birds remain in the western Indian Ocean between two breeding seasons (see Catry et al., 2009b; Kappes et al., 2011 and Fig. 3D).

The red-tailed tropicbirds (breeding at Europa Island and Nosy V ) forage to the south of the Mozambique Channel and to the south of Madagascar, particularly around the Walters Shoals during the breeding season (Fig. 3E). After breeding they migrate eastward to reach their non-breeding area in the central Indian Ocean (Fig. 3E). The core of the non-breeding range overlaps considerably with that of Barau's petrels (Le Corre et al., in preparation and see Fig. 3E).

Finally, the white-tailed tropicbird of Cousin Island (Seychelles) forage around the Seychelles Archipelago during the breeding season and disperse eastward after breeding (Fig. 3F). The core of the non-breeding area is similar to that of the wedge-tailed shearwa-

ter, although some birds remain in the Seychelles after breeding (Fig. 3F and Le Corre et al., in preparation).

3.3. Threat distribution

3.3.1. Industrial fisheries

The two main industrial fisheries operating in the oceanic ecosystems of the tropical Indian Ocean have very clear geographical distribution (Fig. 4A and B). The purse seine fishery (Fig. 4A) operates mostly in the northwest Indian Ocean, in a wide area influenced by the Somalia upwelling that occurs seasonally during the South West monsoon, along the south-equatorial countercurrent and in the northern Mozambique Channel. The long line fishery (Fig. 4B) operates more widely throughout the western Indian Ocean and particularly along the latitude 30° S, to the south of Madagascar, around the Seychelles Plateau and around the Mascarenes.

3.3.2. Marine pollution risk

The risk of marine pollution is directly linked to maritime trade. The main risk of marine pollution is located in the northern Indian Ocean, particularly along the maritime line between South-East Asia, Aden Gulf and the Red Sea and along the coasts of western India (Fig. 4C). Major traffic and potential risk of pollution also exist across the Indian Ocean, along the line between South-East Asia and South Africa via the Mascarene Archipelago and the southern

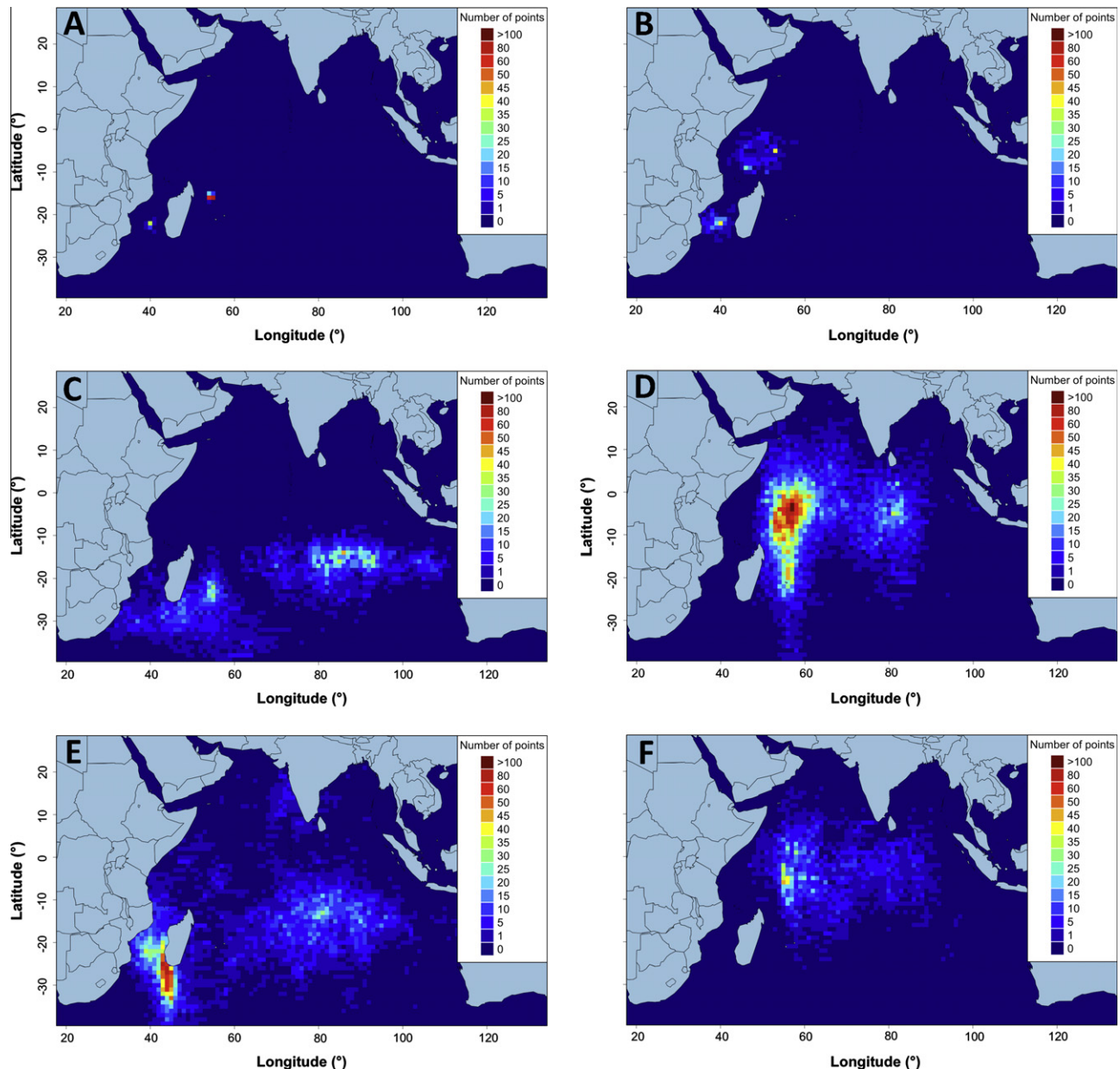


Fig. 3. Specific seabird density as inferred from tracking data. (A) Masked and red-footed boobies, (B) great frigatebird, (C) Barau's petrel, (D) wedge-tailed shearwater, (E) red-tailed tropicbird and (F) white-tailed tropicbird.

tip of Madagascar, and along the coasts of East Africa, particularly in the Mozambique Channel.

3.3.3. Overlap between seabird density and potential threats

The overlap analysis between seabird density (as inferred through our tracking data) and potential threats at sea reveals that the five seabird hotspots overlap to various degrees with potential threats (Fig. 4D). The area with the highest overlap index is the Seychelles Basin, which holds both the highest seabird density and the highest human uses of the sea (substantial purse seine fishery, important long line fishery and important maritime traffic). The Mascarene Archipelago and the south of Madagascar (including the Walters Shoals) also have a high overlap index and this is mostly due to high seabird density and high risk of pollution due to maritime traffic. Finally the southern Mozambique Channel and the central Indian Ocean have a relatively high overlap index and this is mostly due to the fact that important maritime routes cross these places of high seabird density.

4. Discussion

4.1. Seabird foraging hotspots

Our tracking data revealed the main foraging hotspots of seven seabird species of the western Indian Ocean and this should help to identify major areas where specific conservation measures should be implemented.

4.1.1. The Seychelles Basin

This area includes the Seychelles Plateau and a wide oceanic region around the Plateau. This is the main area occupied by wedge-tailed shearwaters and white-tailed tropicbirds of the Seychelles. There are 177,000 pairs of wedge-tailed shearwaters in the western Indian Ocean, of which 53% (95,000 pairs) breed in the Seychelles (Rocamora and Skerret, 2001; Le Corre et al., unpublished data). The white-tailed tropicbird population of the Seychelles is smaller (around 6500 pairs, Le Corre et al., unpublished

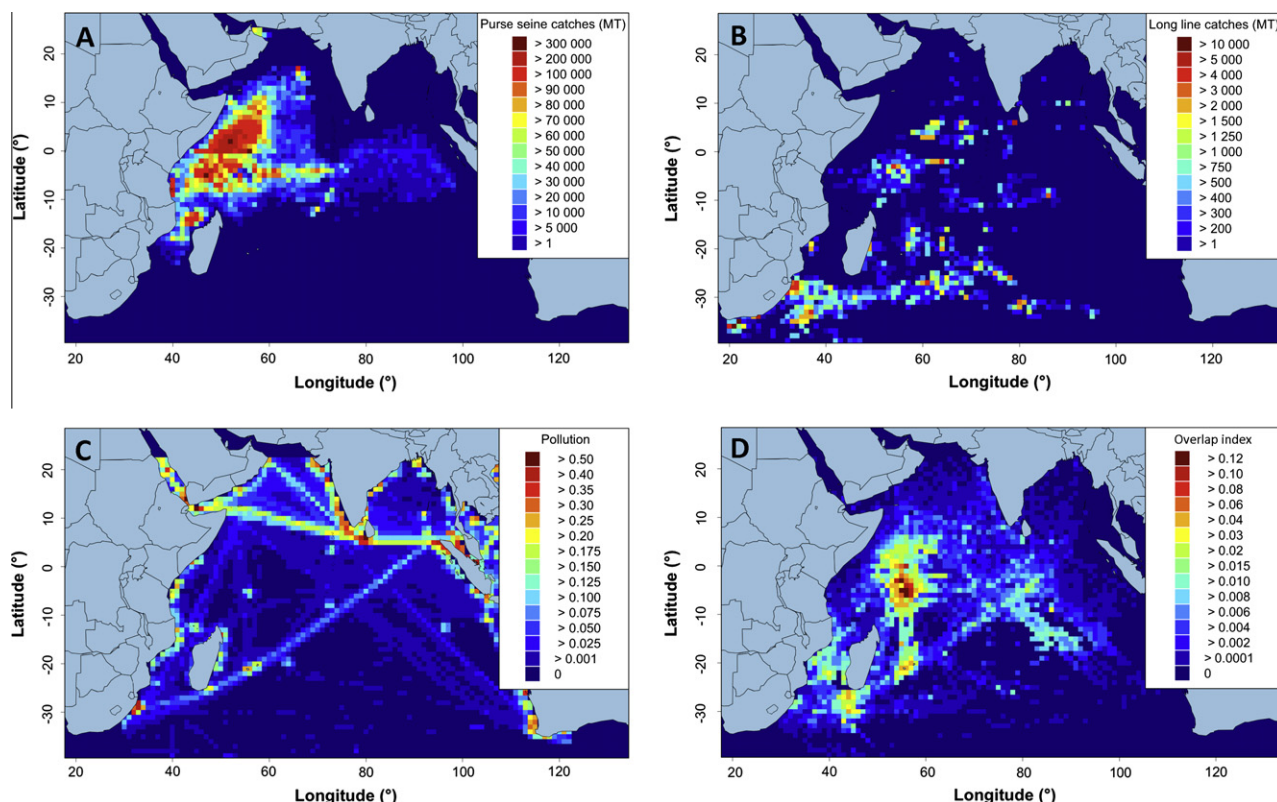


Fig. 4. Distribution of the potential threats to seabirds at sea. (A) Purse seine catches, (B) longline catches, (C) risk of maritime pollution through maritime trades, (D) overlap between seabird hotspots and potential threats. Data on purse seine and longline catches represent the total amount of catch of tunas and billfish made between 2000 and 2009 (extracted from the database of the Indian Ocean Tuna Commission). Data on risk of maritime pollution derived from Halpern et al. (2008). See text for the calculation of the overlap index.

data) but it is still the largest population of the western Indian Ocean (56% of the white-tailed tropicbird of the western Indian Ocean breed in the Seychelles, Le Corre et al., unpublished data). The Seychelles Archipelago (excluding Aldabra and Cosmoledo) supports the greatest abundance of seabirds in the tropical Indian Ocean with 14 breeding species totaling 2.2 million pairs. Fifteen terrestrial IBAs triggered by seabirds have been identified in the archipelago (Rocamora and Skerret, 2001). Although presently we only have telemetry data for wedge-tailed shearwaters and white-tailed tropicbirds, at-sea surveys (Le Corre and Jaquemet, unpublished data), diet analysis (Catry et al., 2009a), and stable isotope signatures (Catry et al., 2008) indicate that most birds from this community forage within this broad area. Thus, at the scale of the Indian Ocean, this first area is of major interest for the conservation of tropical seabirds.

4.1.2. The southern Mozambique Channel around Europa Island

Europa Island is one of the most important breeding places for seabirds in the western Indian Ocean (Le Corre and Jouventin, 1997; Le Corre and Safford, 2001). Europa Island supports 20%, 40% and 8% of the great frigatebirds, red-tailed tropicbirds and red-footed boobies of the western Indian Ocean respectively (Le Corre and Jouventin, 1997; Le Corre and Jaquemet, 2005, and unpublished data). Our tracking data revealed that the southern Mozambique Channel is a major foraging area for these three species. At-sea surveys (Jaquemet et al., 2005) and diet analysis (Le Corre et al., 2003; Cherel et al., 2008; Jaquemet et al., 2008) indicate that this area is also the main foraging ground of most seabirds of the island. Red-tailed tropicbirds use this area only during the breeding season (austral summer, Le Corre, 2001), whereas red-footed boobies and great frigatebirds are present all

year round. We have not done long term tracking of boobies and frigatebirds, as we used only Argos transmitters and GPS, so we do not know yet their year-round movements but field counts on the island and at sea surveys have shown that boobies remain on their breeding site all year round and very rarely venture more than a few hundreds of kilometers from their colony. So we are confident that, at the scale of the Indian Ocean, the distribution of boobies inferred from our tracking data correspond to their year-round distribution. The situation is different for great frigatebirds as we have shown with a very limited dataset (one single bird tracked with a solar powered Argos transmitter) that this species leave the southern Mozambique Channel after breeding to reach a non-breeding area in the southern Maldives (Weimerskirch et al., 2006). Further studies are needed to better understand the migration behavior of this species and to locate the different foraging areas used during a complete annual cycle.

4.1.3. The Walters Shoals (south of Madagascar)

This oceanic area is a major foraging ground of two species of seabird among the seven that we have tracked so far: the red-tailed tropicbird and the Barau's petrel. There are only nine breeding places of red-tailed tropicbird in the western Indian Ocean and the two islands of the southern Mozambique Channel (Europa and Nosy Vê) hold almost half of the regional population (Le Corre and Jouventin, 1997; Le Corre and Bemanajaja, 2009). Birds of this region consistently forage over the Walters Shoals suggesting that there are important biological processes there that improve their foraging success. Interestingly this area is also an important foraging ground of the endemic and endangered Barau's petrel coming from Reunion island (Pinet et al., in press and see Fig. 3C)). More precisely Barau's petrels forage over the Walters Shoals during

the incubation period and when they do long trips during the chick-rearing period (Pinet et al., in press). Indeed we have shown elsewhere that breeding Barau's petrels alternate long and short foraging trips when rearing their chicks (Pinet et al., in press). This dual strategy is commonly found in oceanic petrels (Chaurand and Weimerskirch, 1994; Weimerskirch et al., 1994). It is generally regarded as a behavioral strategy to feed the chick as often as possible without detrimentally depleting the body condition of the adults. During short trips, adults forage for the chick. During long trips, adults forage mainly for themselves and secondly for their chick. The oceanic area identified here is the one used between January and April by chick-rearing adults during their long trips (Pinet et al., in press). Thus this area is probably very important for the maintenance of the body condition of breeding adults, and thus on their survival. Seamounts are known to generate important upwellings and local enrichments, which are known to attract seabirds and other top predators (see for example Amorim et al., 2009). This probably explains why this area is selected by at least two seabird species in the region.

4.1.4. The Mascarene Archipelago and Tromelin Island

This area includes Reunion, Mauritius and Tromelin Islands. Reunion is the only breeding ground of two endemic petrels, the Barau's petrel (endangered) and the Mascarene petrel (*Pseudobulweria aterrima*, critically endangered). The surrounding area of Reunion island is the foraging area used by chick-rearing Barau's petrels during their short trips (Pinet et al., in press). Thus this area is probably very important for the survival of the chicks and for the breeding success of the population. This area is also used by wedge-tailed shearwaters breeding at Reunion Island (Fig. 3D and Kappes et al., 2011). At-sea surveys revealed that this area also includes most foraging grounds used by the other breeding seabirds of Reunion Island, including the critically endangered Mascarene petrel (Jaquemet et al., 2004; unpublished data). Reunion Island has three terrestrial IBAs triggered by the two endemic and endangered petrels (Le Corre and Safford, 2001). The high seabird density observed around Tromelin Island is due to the two species of boobies that breed there and that we tracked. Both species have a very limited foraging range around the island (Fig. 3A and see Kappes et al., 2011), which explain this high density. As for the red-footed boobies of Europa Island, year round census and field observations suggest that these two species remain in this area throughout their life cycle.

4.1.5. The central Indian Ocean

This wide region of the central Indian Ocean is a major foraging area for at least four migratory seabirds: the Barau's petrel, the red-tailed tropicbird, the wedge-tailed shearwater and the white-tailed tropicbird. More precisely, this area can be further divided into two different areas. The first one is a relatively restricted zone located 1200 km to the south of Sri Lanka. This place is important for wedge-tailed shearwaters (from the four studied populations) and for the white-tailed tropicbirds of the Seychelles. The second one is a much larger area lying from 12°S to 18°S and from 78°E to 95°E. This huge area is used by Barau's petrels and red-tailed tropicbirds, and to a lesser extent by wedge-tailed shearwaters and white-tailed tropicbirds (Figs. 2 and 3). These four species use these areas during their non-breeding season only. Presently, we lack additional tracking data and at sea survey data to evaluate the importance of this region for other seabirds or other top-predators, but the fact that different species from various colonies use these wide areas clearly show that there are some oceanic processes there that enhance the foraging success of seabirds during their non-breeding season. Interestingly, these areas are both located at or near bathymetric anomalies. The northern area is just at the surface of a seamount located in the Ceylon abyssal plain

(the Afanasy Nikitin seamount) whereas the southern area is on both side of the Ninety East Ridge. Local enrichments due to upwellings induced by these seamounts may explain the high densities of seabirds there. Lévy et al. (2007) showed that a pronounced seasonal phytoplankton bloom appears in the central Indian Ocean during austral winter. Interestingly, the wintering areas of red-tailed tropicbirds and Barau's petrels co-occur with these winter blooms (Fig. 3e in Lévy et al., 2007), indicating that during winter migratory seabirds likely target prey that are more abundant as a result of local enrichments and associated food webs.

4.2. Overlap with potential threats

Most identified hotspots overlap with potential threats, at various levels but none are included in Marine Protected Areas to date. The area with the highest overlap index is the Seychelles area that combines both very high seabird density and very high human use of the sea (large catches of both purse seine and long line fisheries and important maritime traffic resulting in an important risk of marine pollution). These significant aggregations of natural and anthropogenic (fisheries) marine top predators rely on high seasonal productivity driven by the southwest monsoon in austral winter (Lévy et al., 2007). Although, the catches of surface dwelling tunas in the tropical Indian Ocean may vary from year to year in relation to oceanic conditions (Ménard et al., 2007), these catches regularly are at or above their maximum sustainable yields (IOTC, 2010a), indicating the potential for ecological impacts to tuna-associated seabirds. Although we don't know the level of these impacts on seabirds, tracking data presented here clearly show that the populations of tunas with which seabirds of the Seychelles are associated and those targeted by fisheries are the same (but see below). Between 2007 and 2010 the areas of greatest fishing pressure also have changed drastically in the Somalia Current as a consequence of Somalia piracy (Chassot et al., 2010). Risk of piracy in the Somalia Current, has displaced fishing effort several hundred km eastward and some vessels even have relocated to other oceans. As a consequence of piracy, the number of purse seiners operating in the region has decreased from 51 in 2007 to 43 in 2009 (Chassot et al., 2010). Although the long term effects of this *de facto* Marine Protected Area is unknown, it has been suggested that Somalia piracy may have just displaced the catches eastward without reducing the global amount of catches in the region (Chassot et al., 2010).

The southern Mozambique Channel, the south of Madagascar and the Mascarene Archipelago also have high overlap indices predominantly due to both high seabird density, high risk of pollution due to maritime traffic, and, to a lesser extent, to important long line catches. Several oil spills have occurred recently in the region ((Mweu Nguta, 1998; Whitefield, 2002) and the two last shipwrecks which occurred recently in the southern tip of Madagascar (shipwreck of the "Gulser Ana" in August 2010) and in Mauritius (shipwreck of the "Angel 1" in August 2011), confirmed that these areas are indeed highly at risk of major maritime pollution events in the future.

The central Indian Ocean also has a relatively high overlap index. This area of high seabird density is longitudinally crossed by the Middle East – Australia maritime line that may induce chronic or accidental marine pollution in the wintering area of several seabird species of the western Indian Ocean.

This overlap analysis shows important patterns that should help identify priority areas for the conservation of seabirds in the Indian Ocean. However these main anthropogenic uses of the sea may have consequences on seabirds not necessarily at the place where they occur. For example, tunas are known to migrate throughout the tropical Indian Ocean (Ménard et al., 2007) so that overfishing in the Somalia current for example may deplete the

stocks of tunas migrating to the central or eastern Indian Ocean, and this may threaten tuna-associated seabirds outside the Somalia current. Also, chronic oil pollution and oil spills generate large surfaces of oil that drift during days or weeks throughout the ocean, generating pollution far from the place of oil release. Thus a better understanding of the connectivity of the local tuna stocks and a better knowledge of the surface currents of the Indian Ocean are needed to improve this overlap analysis.

5. Conclusion and perspectives

The western Indian Ocean is a stronghold for tropical seabirds and our tracking studies provide the first overview of the foraging hotspots of the guild of the pelagic seabirds of the region. As far as we know this is the first attempt to identify seabird hotspots of the tropical Indian Ocean with such an extensive dataset (seven species tracked almost simultaneously at eight breeding places). However, although numerous quantitative data have been integrated for this analysis, there are several gaps that will have to be addressed before we can propose definitive and effective marine IBAs.

First, more work has to be done on smaller and more coastal species like terns and noddies which represent a very important assemblage in most tropical seabird communities and for which we do not have any available tracking data yet.

Second, there is a need to conduct studies on the seabird communities of the coastline of East Africa and of the northern Indian Ocean and the Gulf of Aden. These regions have specific seabird assemblages with several endemic species, but nothing is known of their foraging ranges, at-sea distributions and threats. For example, the map of the threats very clearly show that there is a very high risk of marine pollution (particularly through oil spills) in the northwestern Indian Ocean but no data are available on the seabird density and at sea distribution in this region. For example local populations of four species of seabirds of the Persian Gulf suffered severe mortality (22–50%) during the massive oil spill provoked deliberately by Saddam Hussein during the first Gulf War in 1991 (Evans et al., 1993).

Third, there is a need for similar studies in the eastern Indian Ocean. Although seabirds are by far less abundant in the eastern Indian Ocean compared to the western Indian Ocean, no data have been published on the foraging distribution of the birds of these populations. It would be particularly interesting to know if these birds migrate to the same broad area as those identified in this study.

Finally, once more tracking data become available, we will be able to perform multi-specific habitat modeling analysis to incorporate crucial environmental data like bathymetry, sea surface temperature, and productivity, as well as population size and foraging range, in the process of IBA identification at a more global scale.

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