OCEANOGRAPHIC RESEARCH INSTITUTE, DURBAN, SOUTH AFRICA, AFFILIATED WITH THE UNIVERSITY OF KWAZULU-NATAL

A retrospective analysis of shark catches made by pelagic longliners off the east coast of South Africa and biology and life history of shortfin mako shark, *Isurus oxyrinchus*

Submitted in fulfillment of the academic requirements for the degree of Master of Science in the Oceanographic Research Institute, affiliated with the School of Biological and Conservation Sciences, University of KwaZulu-Natal, Durban.

By Alan Foulis

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i. Abstract

Oceanic pelagic shark species are under threat worldwide as fishing effort increases and they are taken as both targeted and bycatch. It is widely recognized that the life history characteristics of sharks make them inherently susceptible to over-exploitation and as a result many shark-directed fisheries have collapsed. It is therefore essential that good-quality data are collected and analyzed in order to provide fisheries managers with the right information to manage these species sustainably.

South Africa has a pelagic longline fishery which includes tuna-, swordfish-, and shark-directed vessels. This study analyzed logbook (1998 – 2010) and observer data (2002 – 2010) provided by the Department of Agriculture, Forestry and Fisheries in order to assess the catch composition and standardized catch-per-unit-effort (CPUE) of sharks captured as both targeted catch and bycatch. The study area consisted of four zones moving east of the 20°E meridian: the Agulhas Bank (20°E – 24°E), South Coast (25°E – 29°E), East Coast 1 (30°E – 32.8°E), and East Coast 2 (32.9°E – 36.5°E).

The majority of fishing effort targeted at tuna was focused on the Agulhas Bank and consisted of foreign vessels which operated over the winter months, whereas local vessels targeted swordfish with consistent year-round effort along the upper east coast. Sharks made up 13% of total catches according to logbook data and catch composition was dominated by blue shark (*Prionace glauca*) and shortfin mako shark (*Isurus oxyrinchus*). Observer data identified a larger number of shark species than shown by logbooks, and notably, the crocodile shark (*Pseudocarcharias kamoharai*) made up 22.5% of shark bycatch on swordfish-directed vessels operating along the upper east coast. In addition, the observer data showed that although blue and mako shark dominated catches in the Agulhas Bank and South coast zones, carcharhinid sharks were more prevalent further east.

Generalized linear models explained 54% of the variation in CPUE of shark bycatch, with year and target species being the two most important explanatory variables. The standardized CPUE index based on logbook data suggested a slightly increasing shark abundance trend between 1998 and 2010, but conversely, the index based on observer data suggested a decline between 2002 and 2010. Assuming that the observer data best reflected the actual CPUE trend (i.e. a declining trend), the increasing trend shown by logbooks over the same period most likely stems from initial under-reporting of shark capture events by skippers, followed by improved reporting in later years, thus masking the declining trend. Catch by target species revealed that swordfish vessels caught significantly more sharks per 1000 hooks than tuna vessels. The shortfin mako shark was one of the most common bycatch species, and also the primary target species of the shark-directed fishery. Generalized linear models of shortfin mako shark CPUE using the delta method produced similar trends than models of total shark bycatch; i.e. trends based on logbook data appeared stable but observer data showed a declining trend over time. Shortfin mako sharks were more abundant in the Agulhas Bank and South coast zones than along the East coast.

A total of 817 shortfin mako shark samples were collected onboard a South African shark-directed pelagic longline vessel operating out of Cape Town and by the KwaZulu-Natal Sharks Board bather protection nets, set close inshore. Sharks collected inshore (from nets) were significantly larger than those collected offshore. More males than females were collected from the nets (2.3 males : 1 female), whereas the ratio for offshore samples was 1.1 : 1.

Age and growth parameters were estimated from 89 sectioned vertebral samples consisting of 43 females and 46 males ranging in size from 90 cm to 299.4 cm fork length (FL). Annual band-pair deposition was assumed and growth was analyzed by fitting 3-parameter von Bertalanffy and Gompertz growth models. Parameter estimates for the Gompertz model were: K = 0.152 $year^{-1}$ for males and 0.127 $year^{-1}$ for females; L0 = 85 cm; L∞ = 295 cm for males and 315 cm for females; and longevity was 17 and 21 years for males and females respectively. Estimates for the von Bertalanffy model were: K = 0.08 $year^{-1}$ for both sexes; L0 = 85 cm; L∞ = 354 cm for males and 321 cm for females; and longevity was 34 and 31 years for males and females respectively.

Using these data, age and length at 50% maturity were calculated at 7 years and 199.1 cm FL for males, and 14 years and 252.8 cm for females. Litter size was in agreement with previous studies (9 to 14 pups). The gestation period was not estimated but parturition may be in late winter to spring. The stomach contents of 817 sharks showed that shortfin mako sharks are opportunistic feeders; elasmobranchs dominated in stomachs collected from sharks caught in nets near the shore (%F = 63.54%) whereas shark stomachs collected from the offshore contained mainly teleosts (70%). Length-frequency analyses revealed that large and reproductively active shortfin mako sharks were more common along the upper east coast and in the inshore environment, whereas juveniles and subadults preferred the oceanic environment, particularly over the Agulhas Bank and South Coast zones. The findings from the present study are a significant step forward towards developing a management strategy for protecting shortfin mako sharks in the South West Indian Ocean region.

Keywords: bycatch; fisheries management; pelagic longline; pelagic sharks; generalized linear model; abundance; distribution; growth; shark; shortfin mako; *Isurus oxyrinchus*

ii. Preface

The experimental work described in this dissertation was carried out in the School of Biological & Conservation Sciences, University of KwaZulu – Natal, Durban, from April 2010 to September 2012, under the supervision of Prof. Johan Groeneveld (Oceanographic Research Institute), Dr Sheldon Dudley (KwaZulu – Natal Sharks Board) and Dr D. Glassom (University of KwaZulu – Natal).

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others it is duly acknowledged in the text.

iii. Declaration – plagiarism

I, Alan Foulis, declare that:

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

4. This thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

    a. Their words have been re-written but the general information attributed to them has been referenced
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5. This thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

Signed: _______________ Date: 29 October 2012
Alan Foulis

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v. Acknowledgements

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To my friends and the gentlemen in “the office”, thank you for a super couple of years, the long days and even longer nights were never short of entertainment and I am grateful for the advice and support you gave me.

I would like to thank my parents for their love and support, not only during my MSc but throughout my life as they have always taught me to follow my passions, to work hard, and to persevere, I love you both.

Finally, I would like to thank my lovely girlfriend, and partner in crime, for not only supporting me and pushing me throughout, but for blessing me with a perfect son who I love and adore.

“Champions do not become champions when they win the event, but in the hours, weeks, months and years they spend preparing for it. The victorious performance itself is merely the demonstration of their championship character” *- Alan Armstrong*

"Today, more than ever before, life must be characterized by a sense of Universal Responsibility, not only nation to nation and human to human, but also human to other forms of life."—His Holiness The Dalai Lama

Elasmobranchs are widely recognized as having life history traits such as slow growth, late onset of maturity and few offspring relative to teleosts, and these characteristics make them vulnerable to over-fishing (Bonfil 1994; Sminkey and Musick 1995; Kroese and Sauer 1998; Musick *et al.* 2000; Dulvy *et al.* 2003; Compagno 2008; Blaber *et al.* 2009). Shark populations worldwide are in decline and evidence of this has increased substantially over the last decade (Ellis *et al.* 2005; Baum *et al.* 2005; Robbins *et al.* 2006; Dulvy *et al.* 2008). Baum *et al.* (2003) found declines of 60% to 89% in some North Atlantic shark populations, and Ferretti *et al.* (2008) reported a population crash of blue (*Prionace glauca*), hammerhead (*Sphyrna* spp.), mackerel (Lamnidae) and thresher sharks (*Alopias* spp.) in the Mediterranean sea. The FAO estimated that 0.72 million t of sharks were captured in 2009, slightly less than a peak of 0.9 million t in 2003 (FAO 2010). These catches resulted from shark-directed fisheries and from retained or discarded bycatches made by commercial fisheries for other fishes (Romanov 2002; Lewison *et al.* 2004; Petersen *et al.* 2009; Bensley *et al.* 2010). Additionally, Clarke *et al.* (2006) reported that actual global shark catch could be up to four times higher than the reported catch. The above statistics suggest that fishing has contributed significantly to the reduction of sharks as apex predators in parts of the world's oceans (Baum *et al.* 2003; Ferretti *et al.* 2008).

Large pelagic sharks are caught by several line-fisheries off the coast of eastern South Africa, and in the wider South West Indian Ocean (SWIO) (Petersen *et al.* 2009). The total shark catch recorded by pelagic longline vessels in South Africa is approximately 43 000 sharks per year (<1% of the global pelagic shark catch), (Petersen *et al.* 2009). An unknown proportion of sharks taken as incidental bycatch by these fisheries is discarded, and is not reported (IOTC 2009). Recreational line fishers catch negligible quantities of pelagic sharks in the region. One of the most common shark species taken as both incidental and directed catch in pelagic longline fisheries, and as a recreational catch (Cliff *et al.* 1990), is the shortfin mako shark, *Isurus oxyrinchus*.

The shortfin mako shark is fast-swimming (Mucientes *et al.* 2009) and is one of five members of the Lamnidae. The Lamnidae have highly evolved physiological adaptations such as hearts with similar cardiac physiology to that of birds and mammals (Chin Lai *et al.* 1997), rete mirabile or vascular heat exchangers, and elevated stomach temperatures (Lowe and Goldman 2001). Together with two other members of this family, salmon (*Lamna ditropis*) and porbeagle sharks (*Lamna nasus*), it is commercially exploited in various regions around the world (Natanson *et al.* 2002; Weng *et al.* 2005; Saunders and Clarke 2010). Shortfin mako sharks have been studied extensively over the past decade, resulting in several peer-reviewed publications worldwide (Campana *et al.* 2005; Ribot-Carballal *et al.* 2005; Natanson *et al.* 2006), but none of these studies dealt with the SWIO region.

The Food and Agriculture Organization of the United Nations (FAO) has designated the Western Indian Ocean (WIO) as fisheries statistical area 51 (FAO 2010) and this area includes 24 countries that border on the WIO. The South West Indian Ocean (SWIO) region, however, consists of only nine countries: Seychelles, Comoros, Madagascar, Mozambique, Kenya, Tanzania, France (La Reunion Island), Mauritius, and South Africa, located in the southern hemisphere. The oceanographic features of the SWIO influence a number of fisheries and animal distribution patterns (van der Elst *et al.* 2009). The major ocean currents within the SWIO are the Southern Equatorial Current, Mozambique Channel eddies, East Madagascar Current and Agulhas Current (Brunnschweiler *et al.* 2009). A number of fisheries are found in this region, including artisanal fisheries made up of handlines, spearguns, gillnets and seine nets and industrial fisheries further offshore (IOTC 2009).

The primary regional fisheries management organization is the Indian Ocean Tuna Commission (IOTC) which oversees the management of pelagic purse seines, artisanal gillnets, and pelagic longline fisheries. Industrial vessels target tuna and swordfish as the primary target species. A recent study on shark bycatches of pelagic longline fisheries in the South African component of the SWIO found a decline in shark abundance, and recommended that there was an urgent need for further research and the implementation of a National Plan of Action (NPOA) for shark conservation (Petersen *et al.* 2009).

Contents of this study

This thesis aims to assess bycatch of large pelagic sharks taken by industrial longline fisheries targeting tuna and swordfish, and catches taken by those targeting sharks. It also addresses the distribution, abundance and life history characteristics of one of the most important shark species captured by these fisheries, the shortfin mako shark (*Isurus oxyrinchus*), east of the 20° E meridian in South African waters.

Chapter 2 reviews historical catch trends of sharks in longline fisheries within the SWIO region of the South African fishery relative to target species, area, season, year, flagstate, and temperature in order to produce standardized catch indices to assess the status of stocks impacted by the tuna/swordfish-directed and shark-directed fisheries.

Chapter 3 focuses on shortfin mako sharks specifically with regard to their distribution, abundance and the mean size of animals captured in the South African pelagic longline fisheries and in the near-shore bather-protection nets along the coast of KwaZulu-Natal (KZN). Chapter 4 continues with the investigation, by assessing shortfin mako shark age, growth, reproductive biology and diet. This thesis is concluded by integrating the newly obtained fisheries and biological information into a series of recommendations for mitigating shark bycatches of pelagic longline fisheries, and providing information towards the development of a sustainable exploitation strategy for shortfin mako sharks.

CHAPTER 2 RETROSPECTIVE ANALYSIS OF INCIDENTAL AND TARGETED SHARK CATCHES IN SOUTH AFRICAN PELAGIC LONGLINE FISHERIES IN THE SOUTH WEST INDIAN OCEAN

2.1 Introduction

Open ocean pelagic sharks are commonly caught in commercial fisheries as a bycatch or targeted catch, yet they remain under-researched at a global level (FAO 1999; Francis *et al.* 2001; Pikitch *et al.* 2008a). Their life history strategy is ill-suited to fisheries exploitation (slow growth, low fecundity and late onset of maturation), however the management of shark stocks has received far less attention than that of the more valuable teleosts (Pikitch 2008b). Nevertheless, large pelagic sharks are apex predators within oceanic ecosystems, and their reduction or loss may have long-term ecological consequences (Ferretti *et al.* 2008).

The status of pelagic shark populations in the South West Indian Ocean (SWIO) region is unknown in most cases, and data reporting is incomplete (Barnett 1997; Herrera and Pierre 2009). Factors such as incorrect species identification, insufficient onboard observers, illegal fishing activities, lack of legislation, poor enforcement and inadequate environmental education of fishers contribute to the lack of information on shark populations in this region (Kroese and Sauer 1998). Some countries in the SWIO region record information on shark bycatches in commercial longline fisheries (Petersen *et al.* 2009). At a regional level, the Indian Ocean Tuna Commission (IOTC) reports bycatches made by tuna longline, gillnet and purse-seine fishing fleets, however their data on sharks are incomplete (IOTC 2010).

The Food and Agriculture Organization of the United Nations (FAO) annually summarizes catch statistics provided by member countries by species or species group in their global production database, and the information is available online (http://faostat.fao.org/site/339/default.aspx). The tonnages of sharks reported by the FAO for area 51 (Western Indian Ocean) and by the IOTC (http://www.iotc.org/English/data/databases.php) for its member states are shown in Figure 2.1. Although these databases are not directly comparable as a result of different reporting standards, species groups and areal boundaries, they do suggest an increase in reported shark catches in the Western Indian Ocean since the 1950s. The FAO data furthermore suggest a decline in shark catches over the last decade, although this trend is not visible from the IOTC data.

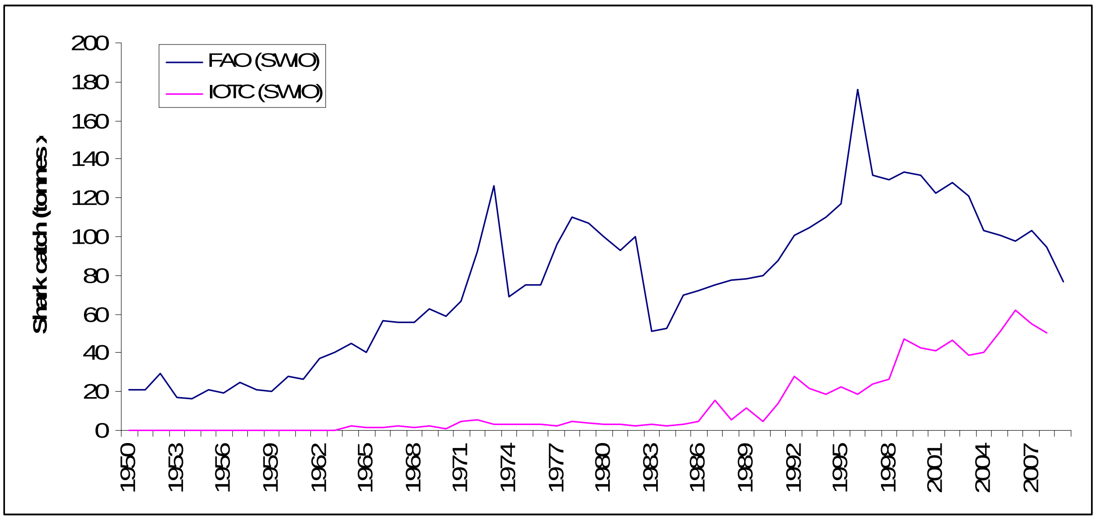

Figure 2.1. Total shark catch in the Western Indian Ocean as recorded in the FAO and IOTC databases respectively, from 1950 to 2009.

The industrial longline fishery for large pelagic fishes in South Africa consists of three distinct fishing sectors directed at tuna, swordfish and sharks, respectively. In the tuna and swordfish directed sectors, sharks are a bycatch that can be either retained for their fins and meat (Petersen *et al.* 2009), or discarded at sea. Discarded sharks may either be cut loose next to the vessel, in which case they may survive, or injured sharks or carcasses may be thrown overboard. It is unclear whether finning has been occurring in these fisheries and if so, to what extent. Fowler and Séret (2010) defined finning as the removal of the fins of a shark and returning the carcass to the sea, and this activity, together with other discards, complicates efforts to quantify shark fishing mortality using historical data (Clarke *et al.* 2006).

The South African pelagic longline fishery is currently in an experimental phase, with 26 vessel permits reissued in 2010 out of a total of 30 originally issued in 1997. Of these, some 15 - 21 are active based on reported catch in 2010, consisting of South African (approximately 60% of the fleet) and foreign fishing vessels, mainly from Japan and Korea. Whereas the South African vessels target mainly swordfish (*Xiphias gladius*) for fresh (iced) export, the foreign vessels target bigeye- (*Thunnus obesus*) and yellowfin (*Thunnus* *albacares*) tuna for the Japanese sashimi market. Many vessels fish on or near the edge of the continental shelf, where bycatches of sharks can be high. The most commonly caught sharks are blue- (*Prionace glauca*) and shortfin mako sharks (*Isurus oxyrinchus*). Local fishers often discard blue sharks, however the Japanese and Korean tuna fishing vessels retain shark bycatches, particularly the higher value shortfin mako sharks (Petersen *et al.* 2009).

The longline fishery directed at pelagic sharks in South Africa is much smaller than the tuna and swordfish directed fisheries (only three vessels, two of which are active) and it targets primarily shortfin mako sharks, which yield high quality fins and excellent meat for export (Compagno 1990; Kroese and Sauer 1998; IUCN 2007). Blue sharks are also targeted, primarily for their fins. These two species are generally more fecund than their coastal relatives (Compagno 1990), but it is unkown whether current levels of exploitation are sustainable. The shark-directed fishery was closed in 2007 by the South African government but fishers have continued to target sharks under temporary permits.

The management of shark bycatch in the South African pelagic longline fishery has three primary tools. The first of these is the limitation placed on the amount of shark bycatch landed, which stipulates that shark catch can be no more than 10% (by dressed weight) of the total catch of the target species. Secondly, although fins may be landed detached from the body, the ratio of fin to carcass cannot be higher than 8% of the total weight of shark trunks. The third tool is the stipulation of species specific no-landing rules which apply to all thresher sharks (*Alopias* spp). In addition, fishers are encouraged to release sharks alive, instead of killing them and discarding carcasses (DAFF 2011).

The catches of longline fisheries in South Africa are monitored in two ways: firstly, using logbook information completed by the skippers of fishing vessels and submitted to the Department of Agriculture, Forestry and Fisheries (DAFF) at the conclusion of each fishing trip; and secondly by deploying fisheries observers onto vessels to report detailed information on fishing effort, catches and species composition (DEAT 2005; 2007; 2009; MCM 2007; 2008). The collection and analysis of historical information sourced from logbooks and from fisheries observers remains of critical importance for the assessment and management of shark populations (Clarke *et al.* 2006; Cortes 2008; Dulvy *et al.* 2008).

The aims of this chapter were to investigate the spatio-temporal trends in fishing effort, catches and catch rates of pelagic shark species, in longline fisheries off the eastern coast of South Africa, based on logbook data (1998 – 2010, and 2004 – 2009 for shark directed data) and on fisheries observer data (2002 – 2010). Fishing sectors directed at tuna, swordfish and pelagic sharks were considered individually, and the effects of fleet nationality, season, year, fishing area, and target species were investigated. The results were compared with information available from the IOTC and FAO for the South West Indian Ocean region.

2.2 Methods and materials

Study Area

The landward boundary of the study area off southern and eastern South Africa extended eastwards from 20° E (western boundary of FAO area 51; Western Indian Ocean), to the Mozambique border at approximately 27° S, and the area extended 200 nm offshore to the boundary of the exclusive economic zone (EEZ). Four sampling areas were defined, based on a previous study by Petersen *et al.* (2009): the Agulhas Bank (20°E – 25° E), South Coast (25°E – 30° E), East Coast 1 (30° E – 32.8° E), and East Coast 2 (32.9° E – 36.5° E). (Figure 2.2)

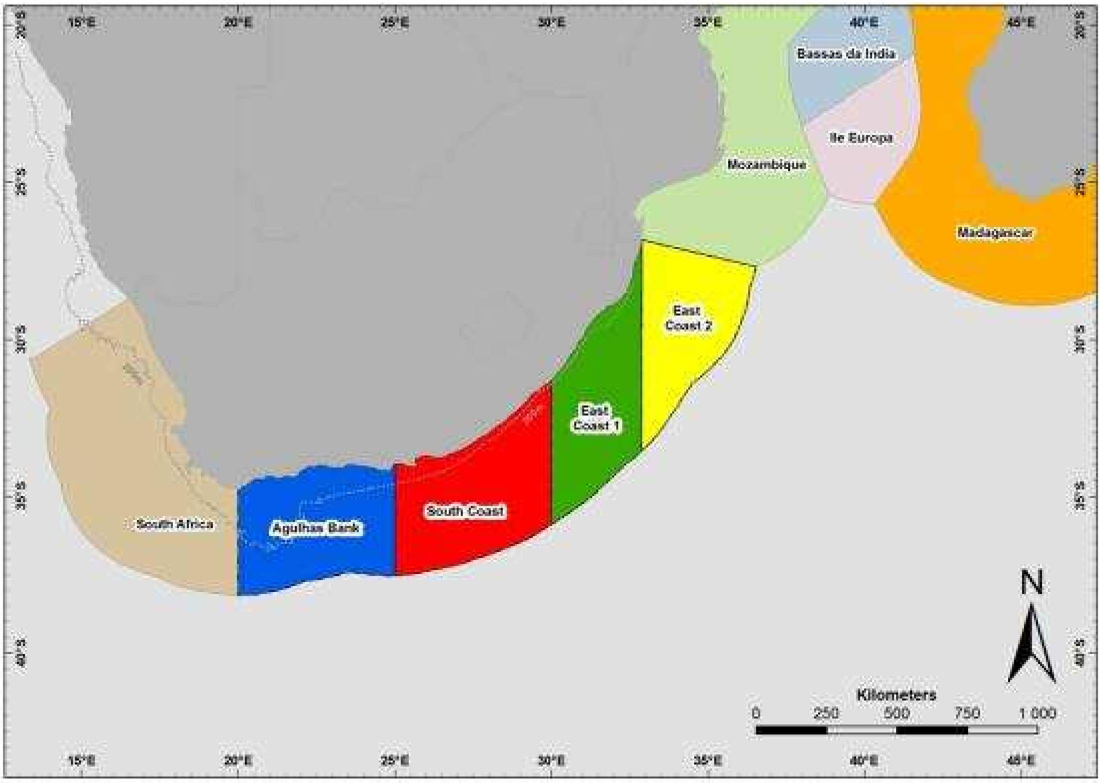

Figure 2.2 The four areas of the eastern coast of South Africa: (a) Agulhas Bank, (b) South Coast, (c) East Coast 1, and (d) East Coast 2.

Pe , but within the longitudinal boundaries of an area, was included in the data for that area.

Data collection

Existing databases

DAFF has a data collection system that includes both logbook data (catch and effort information reported by skippers of fishing vessels) and observer data (detailed information recorded by fisheries observers deployed on fishing vessels). Specifically, when referring to logbook or observer data, this referred to tuna and swordfish data where as shark directed data was referred to as such. The analyses conducted in this chapter examined the trends in shark catch and bycatch over the available time series for each dataset for fisheries targeted at tuna, swordfish and sharks, respectively (Table 2.1). Additional data on shark bycatches reported by countries in the broader Western Indian Ocean region were sourced from the online IOTC and FAO databases.

Table 2.1. Database name, period and main data fields. The geographic location is that portion of the South West Indian Ocean, east of 20°E, that occurs within and immediately offshore of South Africa's Economic Exclusion Zone.

Database name	Period	Main data fields	Comments/ Data resolution
1. Tuna and swordfish observer data	2002-2010	Date, target species, temperature, GPS position, no. of hooks, depth, shark species (14 species), and weight.	Temperature and depth information incomplete
2. Tuna and swordfish logbook data	1998-2010	Species, date, GPS position, depth, temperature, flagstate, vessel ID., target species, no. of hooks, shark species (3 species), weight.	Shark bycatches grouped. Few sharks identified to species level
3. Shark directed logbook data	2004-2009	Shark species (4 species), vessel ID., date, GPS position, weight.	Lack of operational information.

Logbook data

Logbook data were sourced from the DAFF for the period 1998 to 2010 (Table 2.1). These data were recorded by the skipper of each vessel and submitted to the fisheries officials at the conclusion of each trip. Shark bycatches were often grouped on this database, with only a small proportion identified to species level. It is not known to what extent discarded bycatches of sharks were recorded, if at all.

Observer data

Catch and effort data were recorded by fisheries observers deployed on board pelagic longline vessels operating in the South African fishery between 2002 and 2010. Observers collected operational information such as date, time and GPS co-ordinates at the start and end of set and haul, number of hooks deployed, line material and configuration, flagstate and water temperature. The target species of each set was recorded and the 14 shark species recorded were identified as reported by Petersen *et al.* (2009) and placed into categories for blue shark (*Prionace glauca*), shortfin mako shark (*Isurus oxyrinchus*), thresher shark (*Alopias sp.*), carcharhinids, and total number of sharks. Sharks cut loose alongside the fishing vessel were not always reported. Random samples of selected shark species were measured (fork or total length).

Shark directed logbook data

These data were collected in the same way as the logbook data for tuna and swordfish fisheries, except that the target species were shortfin mako and blue sharks. Data supplied by the DAFF for this fishery was from 2004 to 2009 as this was what was made available.

Statistical analysis

Fishing effort (numbers of longline sets and hooks), catches (numbers of sharks reported) and catch per unit effort (CPUE; number of sharks / number of hooks × 1000) were calculated from logbook and observer data sets. Spatial and temporal information on catch and effort were plotted in 50 × 50 km grid blocks, using GIS programmed ArcEditor 9.3™.

The statistical programs SigmaPlot 11.0™, GenStat Discovery™ and R™ were used for statistical tests and model fitting. Generalized linear models (GLMs) were fitted to ascertain which explanatory variables (EVs) accounted for the largest proportion of variance within the data (Bennet 2007; Petersen *et al.* 2009).

Selection of explanatory variables

To ensure that only the best-fitting set of explanatory variables was included in the final GLM, all variables seen in Table 2.2, and the combinations thereof, were initially modelled using a forward-stepwise selection for initial sorting (Minami *et al.* 2007). Those with the smallest Akaike's Information Criterion (AIC) (Akaike 1974) values were selected for the final model. Elimination of spurious variables avoided over-fitting which sometimes occurs when many variables are considered (Götz 2006).

Table 2.2: Candidate factors hypothesized to affect catch rates of sharks caught in pelagic longline fisheries off eastern South Africa

Variable	Type	Dataset	Description
Year	Categorical	Logbook	1998-2010 (13 levels)
	Categorical	Observer	2002-2010 (9 levels)
	Categorical	Shark-directed	2004 - 2009 (6 levels)
	Categorical	Observer (length)	2002-2009 (8 levels)
Month	Categorical	Logbook and observer	January - December (12 levels)
Season	Categorical	All three	Autumn = February - April Winter = May - July Spring = August - October Summer = November - January
Target Species	Categorical	Logbook	Tuna Swordfish
Area	Categorical	All three	4 levels: Agulhas Bank (20°E – 24° E) South Coast (25°E – 29° E) East Coast 1 (30° E – 32.8° E) East Coast 2 (32.9° E – 36.5° E).
Flagstate	Categorical	Observer	ZAR – South Africa JPN – Japan KOR - Korea NAM – Namibia PAN – Panama PHI – Philippines SEY – Seychelles STV – St. Vincent and the Grenadines ICE – Iceland

Model selection

Petersen *et al.* (2009) analyzed the same datasets as those used in the present study but with a shorter period (1998 – 2005) and looking at the entire South African EEZ, having selected a Poisson error distribution together with the log link function based on count data.

Previous studies which made use of GLMs to standardize catch data suggest that perhaps the negative binomial distribution would handle the large proportion of zero counts better (Pusineri and Ravier 2002; Anon. 2009; Whoriskey *et al.* 2011). For this study the Poisson and the negative binomial, both with log link functions, were used for comparative purposes. The exploratory variables were then fitted in a forward - stepwise manner, and to avoid redundancy in the model, the month and season variables were not modelled together. Only those which were significant in the final models were included. Notably, vessel ID was not divulged and random names were assigned to each vessel to maintain anonymity.

A series of tests were conducted in SigmaPlot 11.0™, which automatically conducts a Normality test (Kolmogorov – Smirnov) when analyzing data. The data, once standardized, were testing using Dunn's Method as a post-hoc multiple comparisons procedure.

Standardization

Standardized indices of CPUE were computed using the outputs of the Poisson and negative binomial models, and the reference points used were: 1998 (year), autumn (season), Agulhas Bank (area), tuna (target species), month (December), Vessel ID (blue), and flagstate (Japan).

2.3 Results

Fishing effort

Fishing gear and vessels

A total of 12,031 longline sets comprising 25.7 million hooks were made between 1998 and 2010. Of these hooks, 3.8% were directed at sharks, 67.6 % at tunas and 28.7% at swordfish. Both swordfish- and shark-directed vessels set their lines in the early evening using the American longline system for fishing at 30-50 m depth, whereas tuna-directed vessels set longlines in the early morning, using a more complex dropper system at depths ranging between 40 and 400m (Table 2.3). The American system consisted of a monofilament mainline and droppers, and a rope upper section and 50 cm steel trace was also used on shark vessels. An average of five droppers was attached at 40 m intervals between surface buoys. The tuna system used a combination of braided monofilament, rope, and lead core to obtain optimum sinking rates. Bait types used were generally squid and mackerel for swordfish, mackerel, squid and sardine for tuna and mullet and mackerel for sharks.

Table 2.3. Operational information for the swordfish-, tuna-, and shark-directed fisheries.

	Swordfish	Tuna	Shark
Time of set	Evening	Morning	Evening
Fishing depth (m)	30-50	40-400	30-40
Buoyline (m)	15-20	30-40	15-20
Upper section (length and material)	15m: mono*	40m:rope,braided mono*, lead core rope	10m: mono*
Swivel	60-80g	-	-
Light stick	yes	no	no
Lower section	3.5m mono*	2-3m mono*	2m mono*
Steel Trace	No	No	Yes
Bait	squid	mackerel/squid/ sardine	mackerel/mullet
Line-setter	No	Yes	No
Ave. no. of hooks per line (± SD or SE?)	1556 (±514)	2382 (±629)	1275 (±685)
Target Market	Fresh (Export)	Sushi (Export), Sashimi (Export)	Fish and chips (Export), Fins (Export)

*mono = monofilament nylon line

Eight vessels operated in the tuna- and swordfish-directed fisheries in 1998, increasing to 23 in 2003. Apart from 2006, when only nine vessels fished, 19 to 25 vessels remained active in most years after 2001 (Figure 2.3). Six vessels participated in the shark-directed longline fishery in 1992, but no data were available for 1993-2003. An average of three vessels targeted pelagic sharks between 2004 and 2009.

The number of hooks set for tuna and swordfish increased from 148 488 to 3.7 million hooks between 1998 and 2010 (Figure 2.3). Fewer hooks were set in 2006, because foreign vessels were excluded from the fishery in that year. An average of 163 870 ± 63 479 (SD) hooks per year was set for sharks between 2004 and 2009 (Figure 2.3).

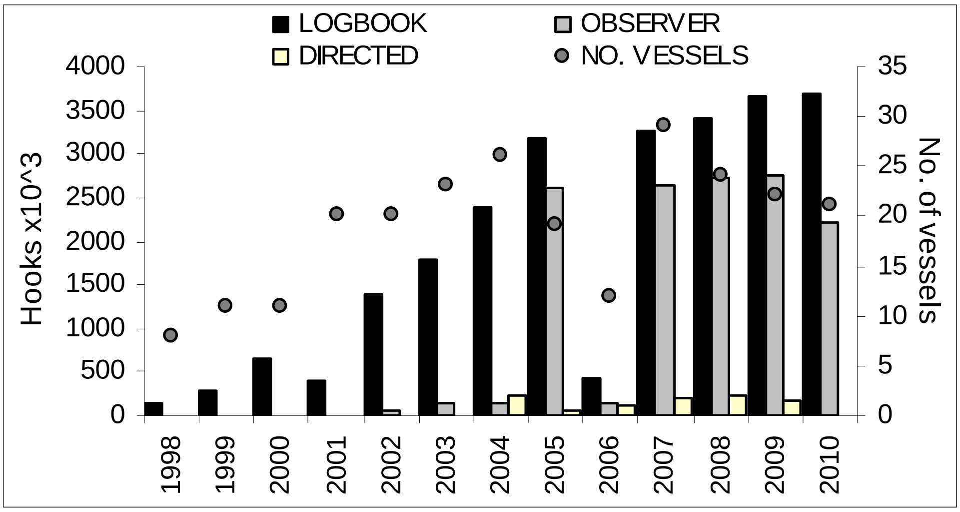

Figure 2.3. Total number of hooks deployed between 1998 and 2010 as recorded in the Logbook, Observer, and shark-directed fishery datasets.

Fisheries observers recorded data from 5316 sets (>13.4 million hooks) between 2002 and 2010. Not all fishing trips were covered by observers; therefore fishing effort reported in this way is lower than for logbooks (Figure 2.3). Observer coverage (number of hooks observed), averaged 15.81% for local vessels and 48.73% for foreign vessels (Figure 2.4). If this was split between the period 2002 -2004 and 2005 onwards, coverage was depicted in a very different manner. From 2002 to 2004, the mean coverage was 6.24% and 5.19% for local and foreign vessels respectively. However, the mean for 2005 onwards increases substantially to 20.59% and 70.51%. All local vessels carried observers during 2006, but excluding this year reduced local coverage to 5.28% between 2002 and 2010.

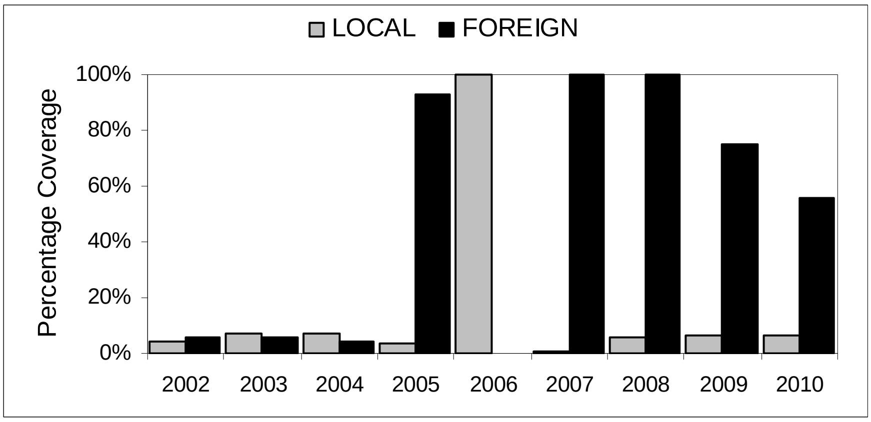

Figure 2.4 The percentage observer coverage for local South African and foreign longline fishing vessels for the period 2002 to 2010.

Flagstate

Japanese and Korean flagged vessels reported 16.5 million hook sets between 1998 and 2010, compared to 6.5 million by local vessels, and 2 million by other flagstates (Namibia, Panama, Philippines, Seychelles, St. Vincent Islands, Iceland) (Figure 2.5). Japanese vessels deployed an average of 2723 ± 784 hooks per line, compared to 2409 ± 754 by Korean-, and 1386 ± 330 by South African vessels. All foreign vessels targeted tuna, whereas 90% of local vessels targeted swordfish (90% of sets).

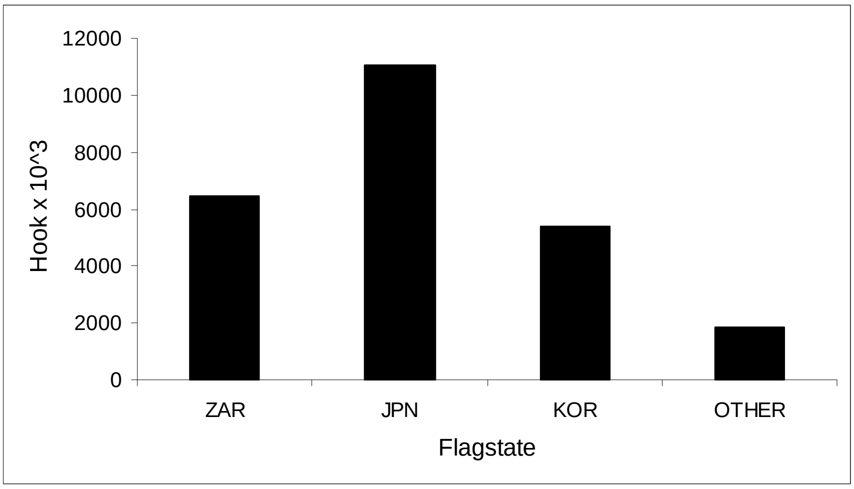

Figure 2.5. The total number of hooks set by flagstates operating in the tuna- and swordfish – pelagic longline fisheries between 1998 and 2010.

Season

Significantly more hooks were deployed in winter (29%) and spring (42%) than in other seasons (p<0.01, Kruskal-Wallis), mainly because of an influx of foreign tuna vessels during these seasons (Figure 2.6a). Local fishing vessels targeting swordfish deployed gear consistently throughout the year. Foreign vessels however, deployed significantly more hooks in spring (p<0.01; Figure 2.6b). Conversely, shark-directed effort was significantly lower in spring (p<0.01; Figure 2.6b).

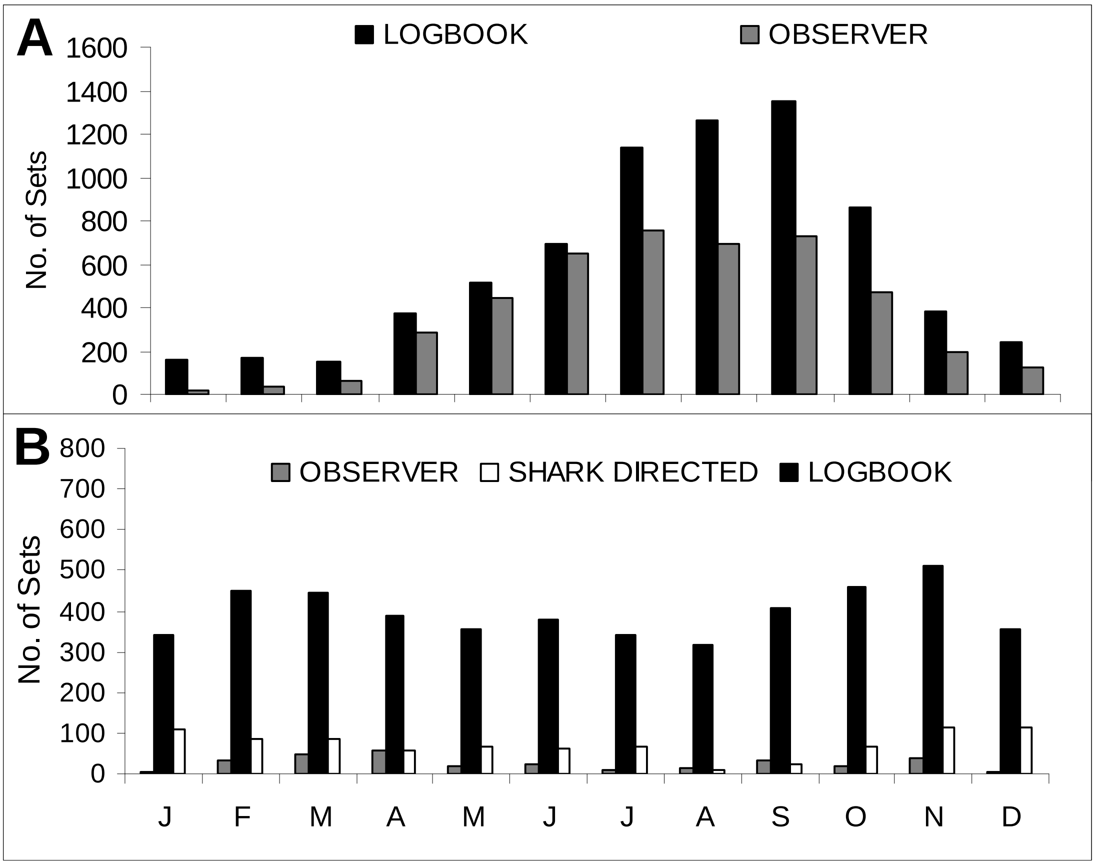

Figure 2.6. Total number of sets by month for vessels targeting: A) tuna (mainly Japanese vessels) and B) swordfish (local vessels) and shark-directed vessels. (Note: Scales on y-axes differ)

Area

Based on logbooks, most hooks were set on the Agulhas Bank, followed by the East Coast-2, South Coast, and East Coast-1 (Figure 2.7). The second East Coast zone contributed a relatively large percentage because of the large number of local vessels fishing out of Richards Bay. Few fisheries observers were placed on vessels operating out of Richards Bay in the East Coast-2 zone, possibly because of the distance between Richards Bay and Cape

Town, where the observer company is located. The shark fishery was concentrated on the Agulhas Bank with lesser effort along the South Coast and East Coast.

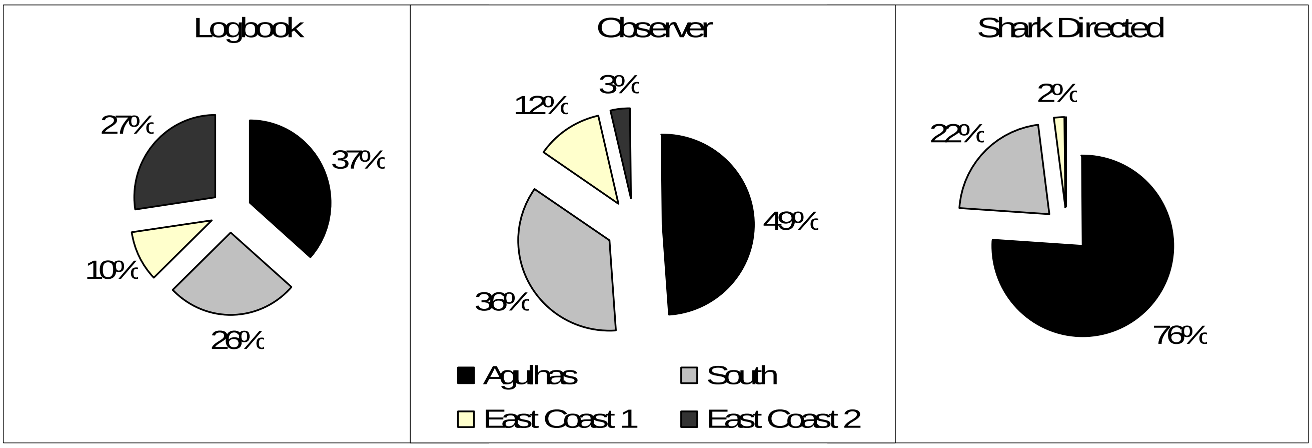

Figure 2.7. Areal distribution of effort as recorded in the Logbook, Observer, and Shark directed databases.

Catches of sharks

Bycatch of tuna and swordfish fisheries

Sharks made up 13% of the total catch by numbers recorded in logbooks. No sharks were reported for 34% of longline sets, 1-5 sharks occurred in 44%, 6-10 sharks in 14%, and >10 sharks were captured in 8% of sets. Logbooks indicated a persistent increase in shark bycatches after 2004, reaching a maximum of 17.9% of total numbers in 2008 (Figure 2.8).

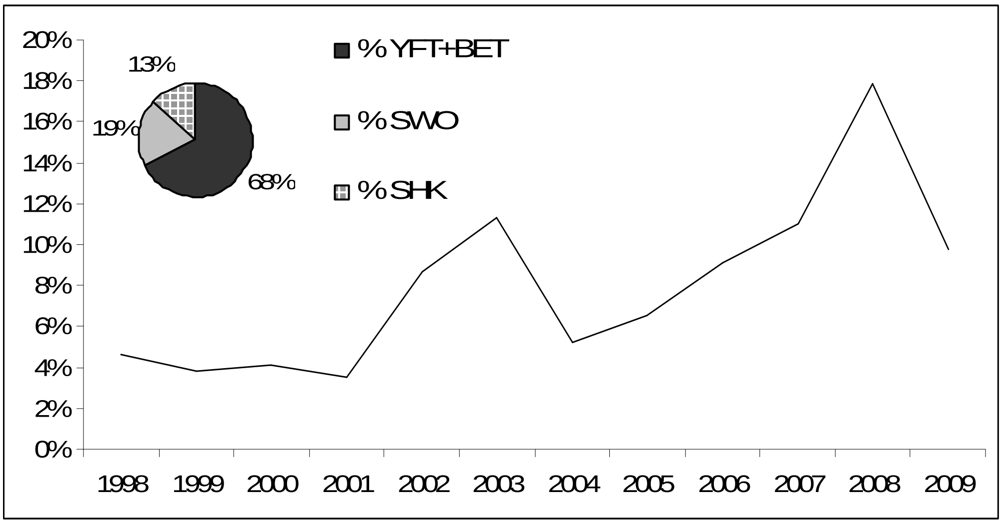

Figure 2.8. Percentages of shark bycatches by numbers by year between 1998 and 2010, as reported in logbooks. The overall catch composition is shown in the pie chart: YFT – Yellowfin tuna, BET – Bigeye tuna, SWO – Swordfish, SHK – Shark.

A total of 31677 sharks were captured by tuna vessels over the study period versus 17373 recorded by swordfish vessels. Blue sharks dominated the bycatches of swordfish and tuna directed fisheries, followed by shortfin mako sharks. Thresher (*Alopias spp.*), carcharhinid, and unidentified sharks were caught in lower numbers (Figure 2.9). The observer database showed an increase in the number of thresher sharks taken as bycatch, from 70 sharks/year between 2002 and 2006 to 138 sharks/year between 2007 and 2010.

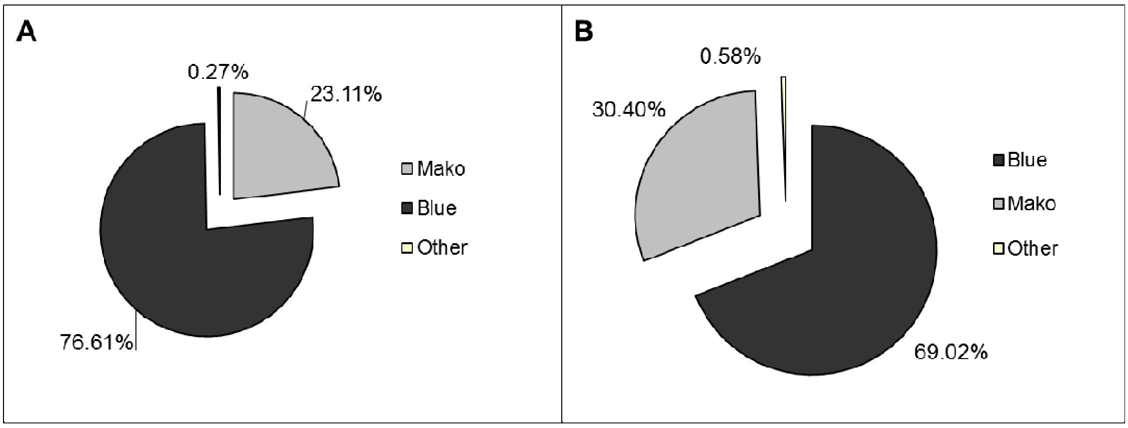

Figure 2.9. The species composition of shark bycatch as recorded in the logbook data for A) Swordfish-directed and B) Tuna-directed vessels.

Observer data reported many more shark species (15) than logbook data (4). Swordfish vessels (which operate further to the east than tuna vessels) captured similar proportions of crocodile- *Pseudocarcharias kamoharai* (22.5%) and blue sharks (21.1%), and fewer shortfin mako sharks (11.3%) (Figure 2.10). Tuna vessels captured predominantly blue (67.8%) and shortfin mako sharks (27.9%), and some thresher sharks (3.8%).

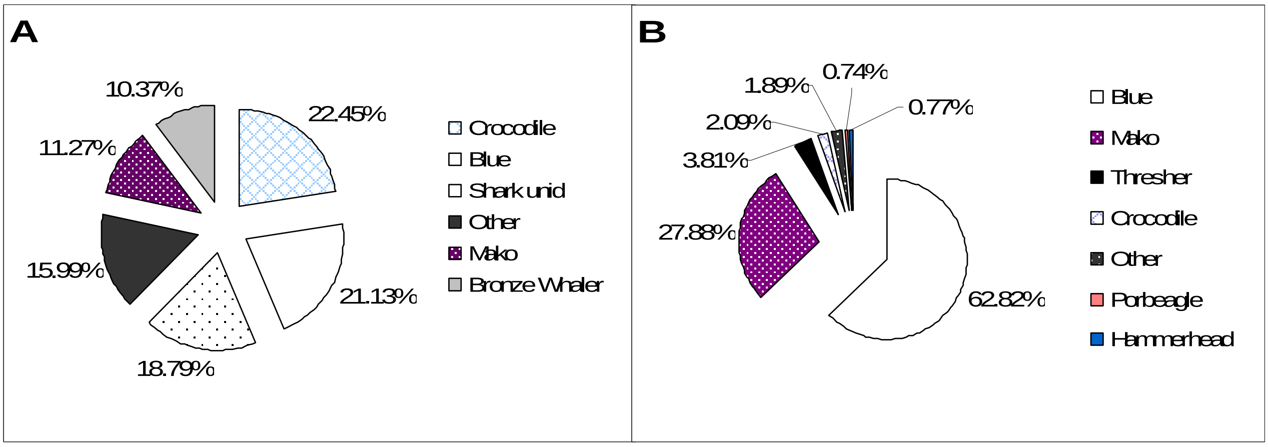

Figure 2.10. The species composition of shark bycatch as recorded in the observer data for A) Swordfish-directed and B) Tuna-directed vessels. Common names are listed in order of highest to lowest frequency.

Logbook data suggested that blue and shortfin mako sharks make up the vast majority of shark catches in all four zones (Figure 2.11). However, observer data showed that although blue and shortfin mako sharks dominate on the Agulhas Bank and parts of the South Coast, they are largely replaced by other sharks, mostly carcharhinids, towards the east. Carcharhinid sharks are virtually absent from logbook data. The discrepancy between these two databases suggests that logbooks under-report shark bycatches in categories other than blue and shortfin mako sharks.

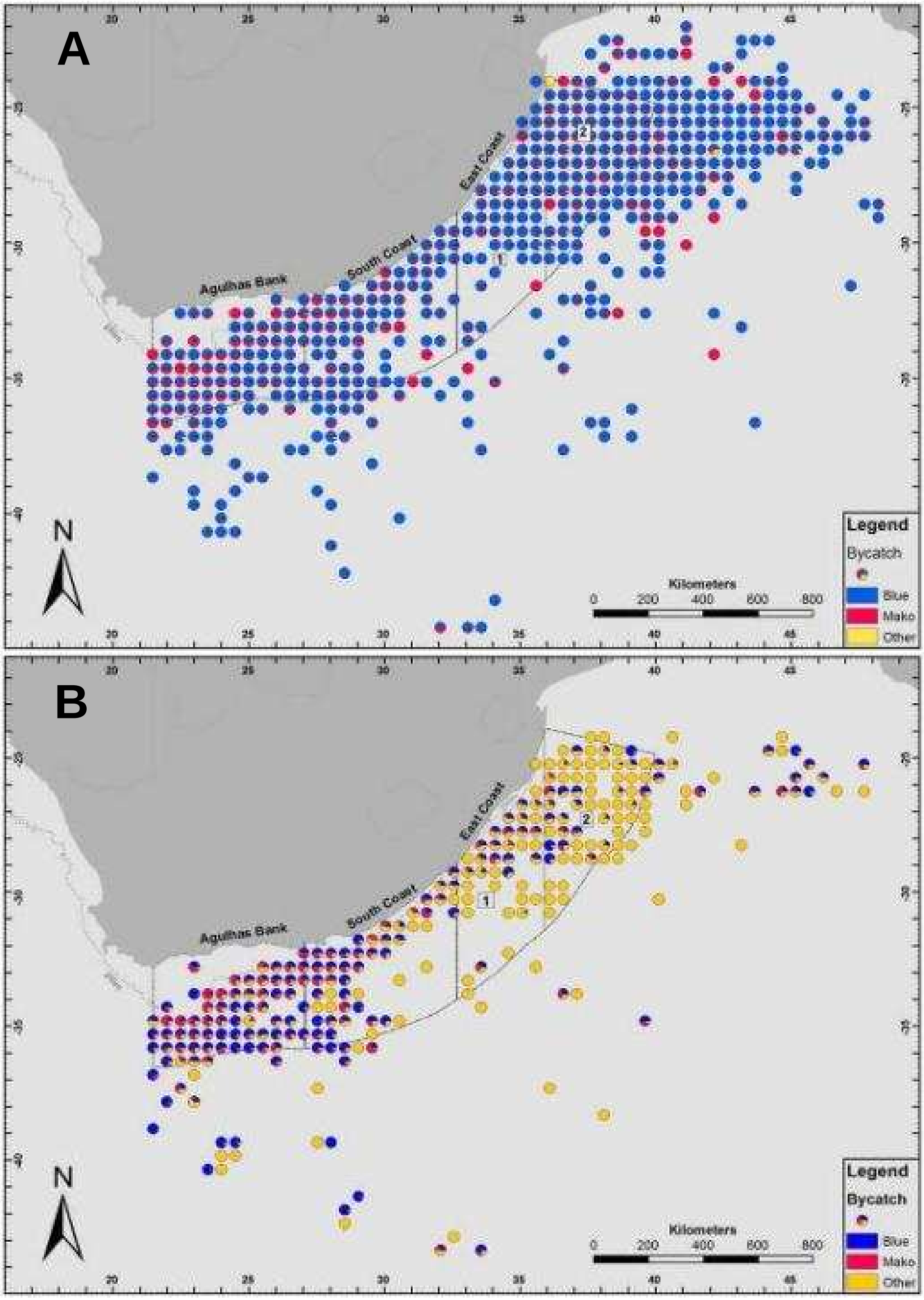

Figure 2.11. Shark bycatch composition for A) logbook, and B) observer datasets, by 50 x 50 km grids. Blue represents blue shark (*P. glauca*), red shortfin mako (*I. oxyrinchus*), and yellow carcharhinid species, unidentified sharks and *Alopias spp.*

Catches of shark-directed fisheries

Shortfin mako sharks were targeted in the shark-directed fishery and made up most of the catch by numbers (83% of catch between 2004 and 2009). The remainder of the catch comprised blue sharks (14.5%) and small numbers of thresher and carcharhinid sharks (2.5%).

Catch-per-unit-effort (CPUE)

Fisheries observers reported a much higher mean CPUE of sharks per set than was recorded in the logbook data for all areas combined for tuna-directed fishing (3.4 ± SD 4.4 versus 1.8 ± 4.3 sharks/1000 hooks) and for swordfish-directed fishing (5.9 ± 5.7 versus 1.9 ± 3.9). The mean CPUE of sharks in the shark-directed fishery was 61.5 ± 59.8 sharks/1000 hooks.

Logbook data suggested a decline in the mean CPUE of sharks caught as bycatch from west to east: 2.4 ± 4.3 sharks/1000 hooks at Agulhas Bank; 2.0 ± 5.8 at South Coast; 1.6 ± 2.7 at East Coast-1; and 1.4 ± 2.8 at East Coast-2. CPUE appeared to be highest near the 200 m depth isobath (Figure 2.12a). Observer data showed a higher CPUE than logbook data for each area; 4.9 ± 11.5 at Agulhas Bank, 3.2 ± 4.8 at South Coast; 2.2 ± 2.3 at East Coast-1; and 4.3 ± 3.9 at East Coast-2. Highest CPUE values were also concentrated in the vicinity of the 200 m isobath of the Agulhas Bank (Figure 2.12b).

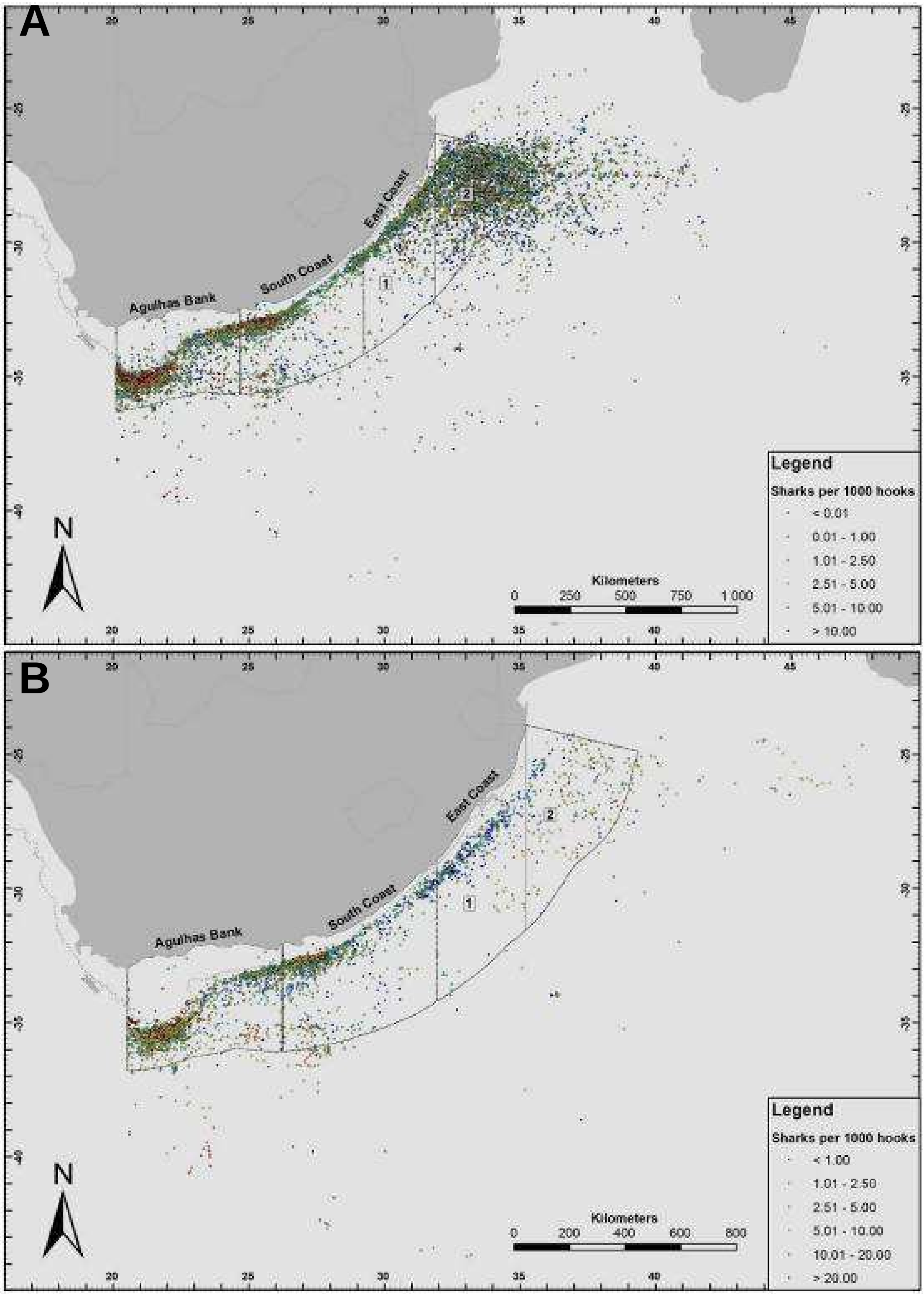

Figure 2.12 Nominal CPUE (sharks/1000 hooks) of sharks as bycatches in tuna and swordfish fisheries as reported A) in logbooks and B) by observers for the period 2002 to 2010. CPUE per set is shown in the following categories: dark blue (< 1), light blue (1.01 – 2.50), green (2.51 – 5), yellow (5.01 – 10), orange (10.01 – 20), and red (>20).

GLM of logbook-, observer, and shark-directed data

The final selected models for logbook data included area, flagstate, season, target species, vessel ID and year. The selected variables were significant (P < 0.01) for both Poisson and negative binomial (NB) distributions (Table 2.4). Vessel ID, year and flagstate explained the largest proportion of the variance encountered.

Table 2.4. Results of GLM analyses, using Poisson (P) and negative binomial (NB) distributions, of logbook shark bycatch CPUE (1998 – 2010). The top three variables, as well as the full model, are included.

Variable(s)	**DF**	**AIC**	**Explained variance (%)**	**Deviance ratio**	**P - value**
(P) Vessel ID	44	337999.2	36.11	117.7	< 0.01
(P) Year	11	408435.9	22.43	98.18	< 0.01
(P) Flagstate	7	4920.8	13.37	108.13	< 0.01
(P) All above		244126.8	54.00	112.6	< 0.01
(NB) Vessel ID	42	3923.7	32.96	50.54	< 0.01
(NB) Depth	28	5751.7	7.64	12.48	< 0.01
(NB) Year	9	6005	4.26	18.19	< 0.01
(NB) All above		3651	38.22	29.71	< 0.01

A larger percentage of the variance was explained by the model fitted to the Poisson distribution (54%) compared to the NB distribution (38%). The two models showed similar trends for logbook data, however the Poisson model showed higher values from 2002 to 2006 than the NB model (Figure 2.13a).

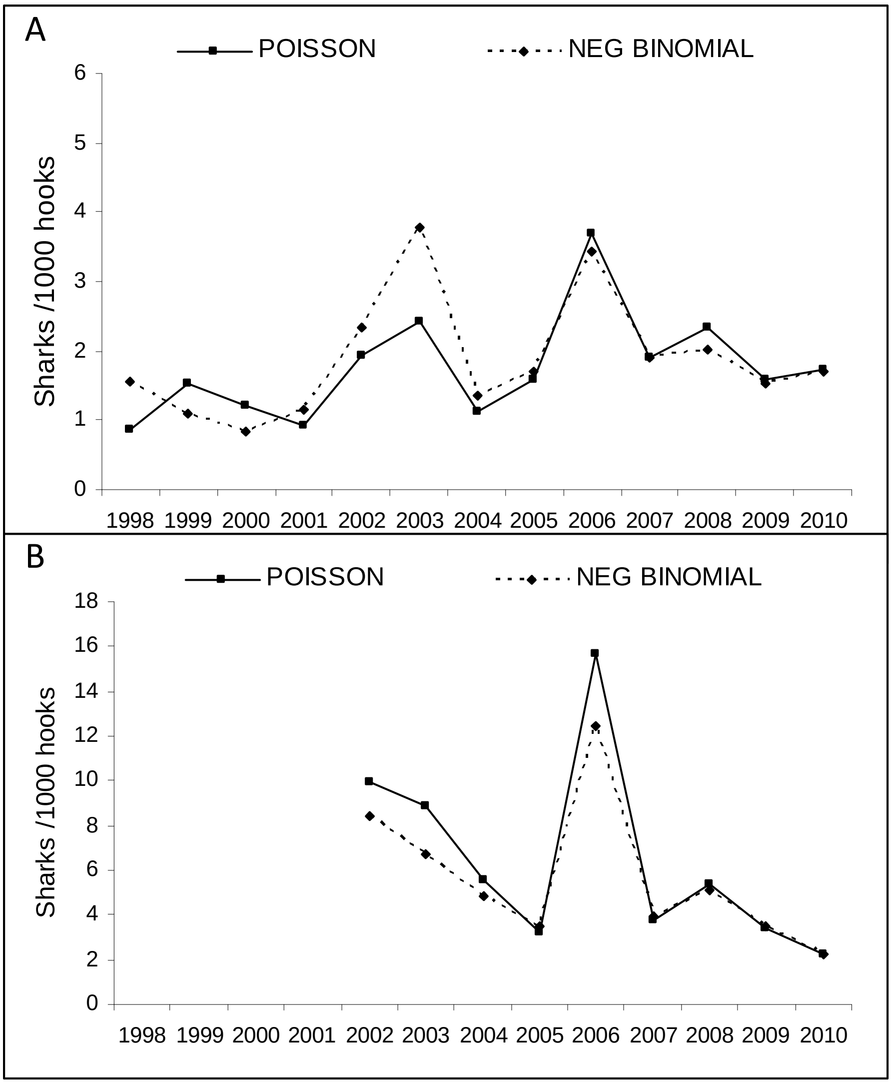

Figure 2.13. Trends in standardized CPUE of shark bycatches based on A) logbook, and B) observer datasets using the negative binomial and Poisson models.

The variables selected for the final GLMs based on observer data were target species, area and year. A number of variables included in the final GLMs for the logbook data were not significant and hence were not selected; these were flagstate, season and vessel ID. The variance explained by the full models were 33.9% (Poisson) and 32.3% (NB), and year explained the largest proportion of variance for both models (Table 2.5 and Figure 2.13b).

Table 2.5. Results of GLM analyses, using Poisson (P) and negative binomial (NB) distributions, of Observer shark bycatch CPUE (2002 – 2010). The top three variables, as well as the full model, are included.

Variable(s)	**DF**	**AIC**	**Explained variance (%)**	**Deviance ratio**	**P - value**
(P) Year	7	6034.3	20.94	264.74	<0.01
(P) Target species	3	7014.9	7.96	124.04	<0.01
(P) Area	4	7121.8	6.58	221.54	<0.01
(P) All above	20	5075	33.88	187.32	<0.01
(NB) Year	7	6073.5	18.44	228.31	<0.01
(NB) Area	4	6738.7	9.40	200.79	<0.01
(NB) Target species	3	6755.5	9.15	99.71	<0.01
(NB) All above	20	5078	32.27	133.43	<0.01

Interannual trends

Standardized CPUE based on logbook data differed significantly between years (Figure 2.13). Based on the analysis using the Poisson distribution, CPUE was significantly higher in 2003 (2.43 ± 0.15 sharks/1000 hooks) and in 2006 (3.70 ± 0.59) than the remaining years (Kruskal – Wallis, $P < 0.01$, Dunn's Pairwise comparison, $P < 0.05$) (Figure 2.13). The lowest CPUE recorded was 0.87 ± 0.13 sharks/1000 hooks in 1998, and there is an overall trend towards an increasing CPUE over time (Figure 2.14).

The standardized CPUE trend based on observer data revealed a consistently higher CPUE than the logbook data (Figure 2.14), as did the nominal CPUE (Figure 2.13). CPUE values were significantly higher in 2002, 2003, and 2006 than in other years (Kruskal – Wallis, $P < 0.01$, Dunn's Pairwise comparison, $P < 0.05$), and lower in 2010 ($P < 0.05$). A gradual decline in shark CPUE over time shown by observer data contrasted with an increase shown by the logbook data.

The standardized CPUE of the shark-directed fishery decreased substantially between 2005 and 2006, but it was followed by an increase in 2007 and 2008 (Figure 2.14). The time series is still short, and no conclusions on overall trend in CPUE have yet been drawn.

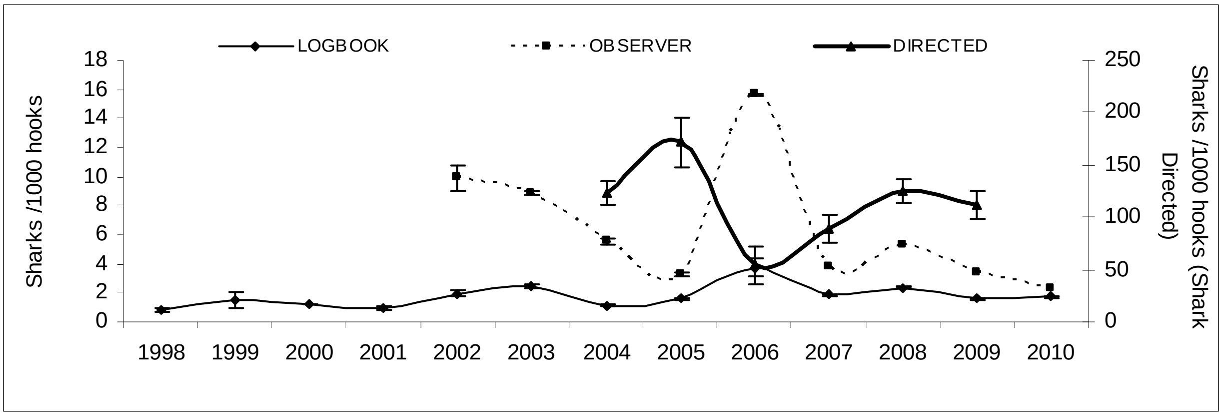

Figure 2.14. Trends in standardized CPUE of shark bycatches based on logbook (1998-2010), observer (2002-2010) and shark-directed (2004-2009) datasets.

Area

CPUE declined by area moving eastwards from the Agulhas Bank, for all three datasets (Figure 2.15), with the Agulhas Bank and South Coast zones significantly higher than the other two zones (Dunn's Pairwise comparison, P < 0.05).

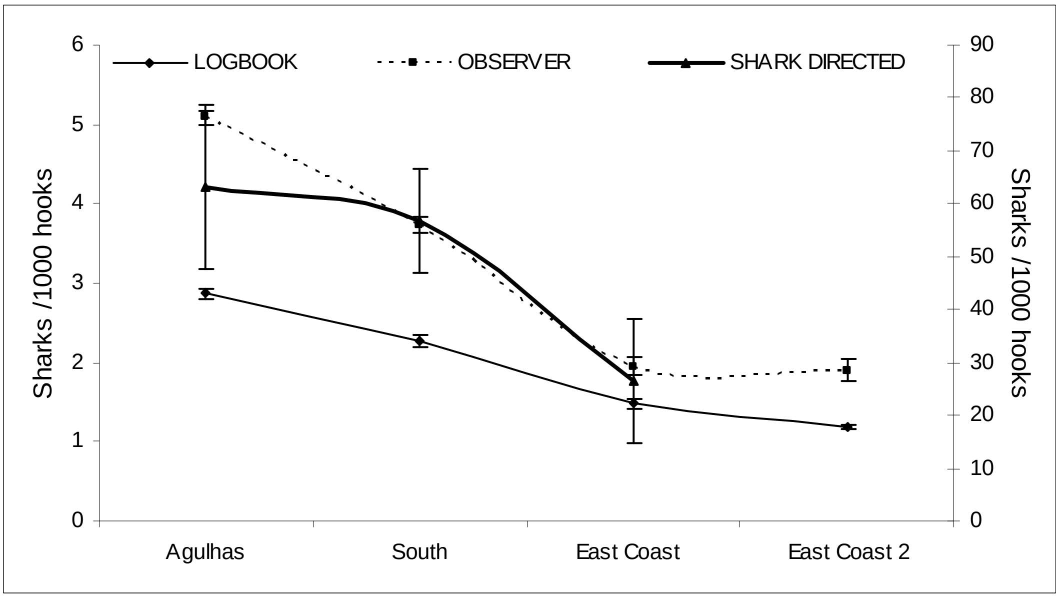

Figure 2.15. Mean standardized CPUE for the four areas for the three datasets analyzed: logbook data (1998-2010), observer data (2002-2010), and shark-directed data (2004-2009). Shark-directed CPUE is depicted using a secondary Y-axis (right).

Season

Overall trends for all three datasets showed an increase in CPUE in autumn and winter, with spring having the lowest mean CPUE. Autumn and winter had significantly higher CPUE than spring and summer (Kruskal – Wallis, P < 0.01, Dunn's Pairwise comparison, P < 0.05) (Figure 2.16) for both logbook and observer data sets. Shark directed CPUE, however, showed much larger variation between seasons with only autumn having a significantly higher CPUE than spring (P<0.05).

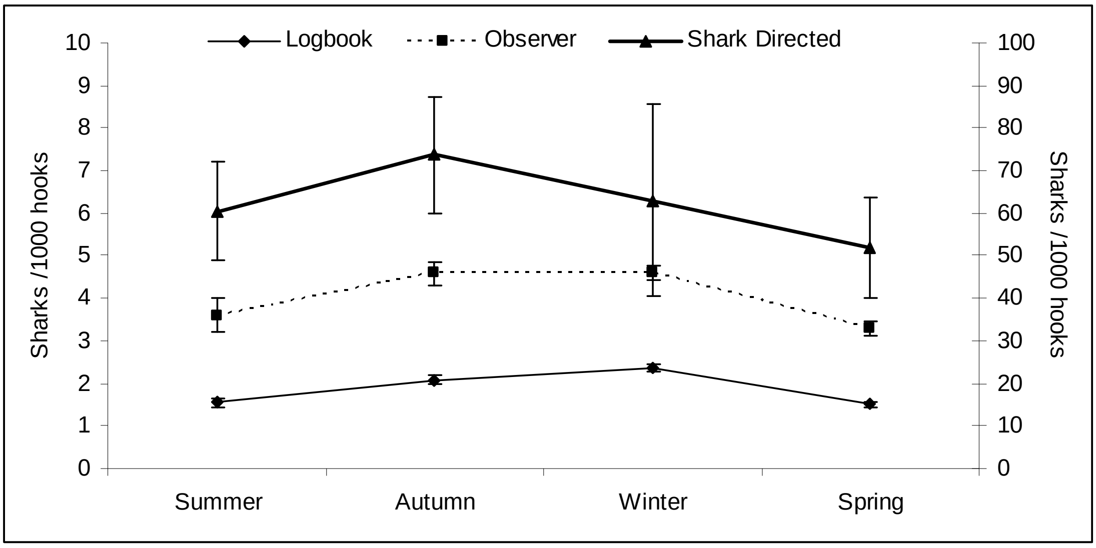

Figure 2.16. The seasonal CPUE of all sharks for each of the three databases. Shark-directed CPUE is depicted using a secondary Y-axis (right)

Fleet trends

Swordfish-directed vessels had significantly higher standardized shark CPUE than tuna vessels based on observer data (4.8 ± 0.3 versus 3.6 ± 0.1 shark/ 1000 hooks) (Kruskal – Wallis, P < 0.01, Dunn's Pairwise comparison, P < 0.05) and logbook data (2.2 ± 0.3 versus 2.0 ± 0.1 shark/ 1000 hooks) (P < 0.05), and this trend extended across all four areas (Figure 2.17).

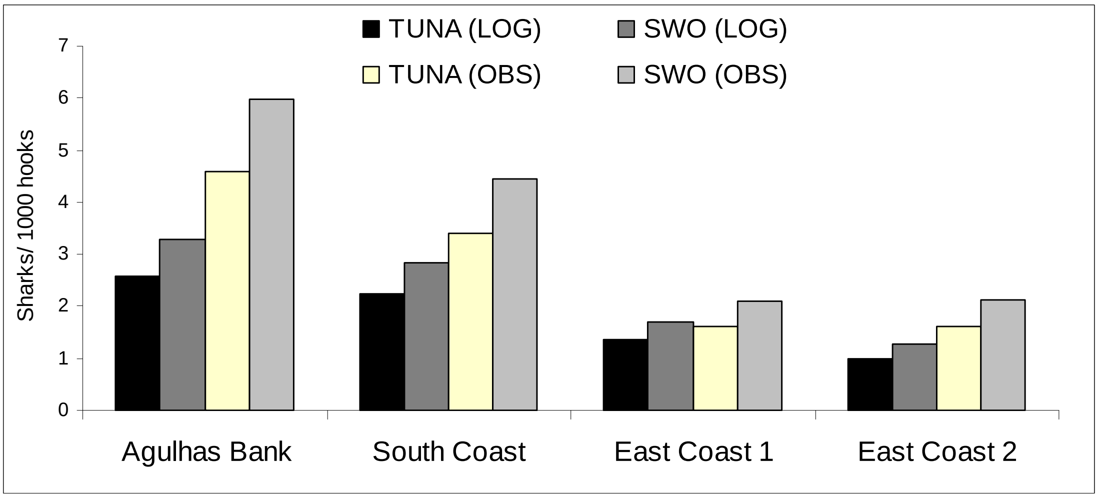

Figure 2.17. Mean CPUE based on logbook and observer data of sharks caught by vessels targeting tuna and swordfish.

Flagstate

Most vessels (40) operated under a South African flag, followed by Japanese (21) and Taiwanese (15) vessels. The mean standardized shark CPUE for both logbook and observer data was, however, highest for “other” countries (Figure 2.18).

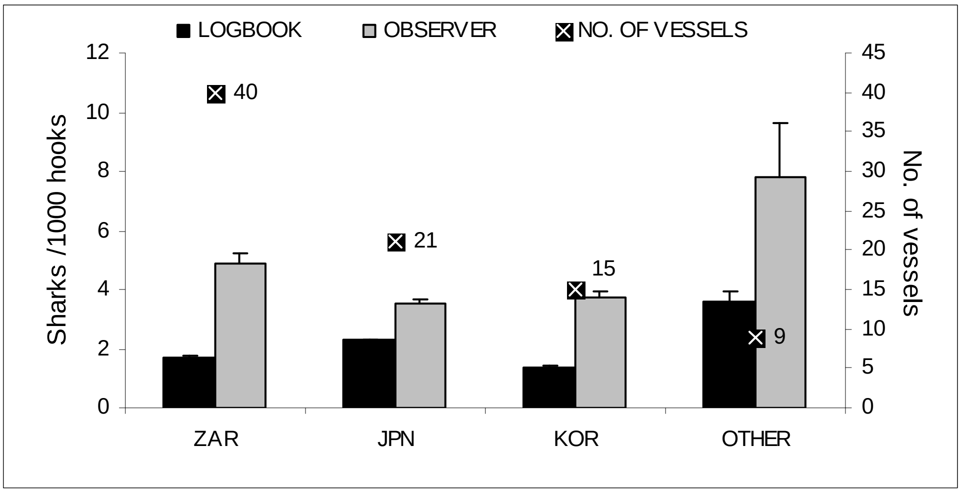

Figure 2.18: The number of vessels and mean standardized CPUE of shark bycatches by flagstate in the tuna and swordfish longline fisheries, based on logbook (1998-2010) and observer data (2002-2010). The “other” category includes vessels from Namibia, Seychelles, Iceland, Panama, Philippines, St. Vincent islands and unknown or unrecorded vessel flagstate.

2.4 Discussion

Participation of South African stakeholders in the pelagic longline fisheries (excluding the shark-directed fishery) is a relatively recent development. From 1998 to 2002 the fishery was dominated by Asian-flagged vessels and the fishing effort was comparatively low at <200 000 hooks/year. The plan of the South African government to increase South African participation in the fishery was implemented when bilateral agreements allowing the Japanese and Taiwanese to fish in South African waters were renegotiated in 2007 (DEAT 2007). South African crew were to be employed as well as the presence of a South African fisheries observer were prerequisites for the agreement. This in turn would result in a larger quota being granted by the IOTC and therefore the increased potential for South African vessels to participate in the fishery. Fishing effort, in terms of number of hooks set, increased over the 13 year dataset with the exception of 2006, when no Asian-flagged vessels participated (DEAT 2007). The smaller number of active vessels in 2006 allowed for a

100% observer coverage of local vessels. Fishing effort recovered to its former levels when Asian-flagged vessels returned in 2007 (DEAT 2007).

The databases used for the assessment of shark catches made by longline fisheries were obtained from several different sources, and were analyzed using a generalized linear model (Maunder and Punt 2004). The data included a large number of zero values (i.e. no sharks recorded on a longline targeting tuna or swordfish), which had to be taken into account in selecting the error distributions. The error distributions chosen were based on the AIC values produced by the models, and the Poisson distribution was used because the variance in catch rate was proportional to its square (Maunder and Punt 2004) and it is considered robust enough to handle a large proportion of zero values (Petersen *et al.* 2009). In addition, the negative binomial (NB) which produced lower AIC values, was also used. The use of both models provided a simple comparison in which the NB provided slightly smaller AIC values however the Poisson modelling data were represented as to allow for comparison with Petersen et al. (2009). Prior to modelling, the exploration of effort and catch data provided interesting observations.

The large numbers of hooks deployed over the winter months by Asian-flagged vessels in the Agulhas Bank and South Coast zones can be attributed to the target species of these vessels. Bigeye and yellowfin tuna aggregate in these zones during winter, where they are associated with the warm Agulhas Current water running along the edge of the continental shelf (Penney and Griffiths 1999). Conversely, local fishing vessels pursue swordfish in the warm waters along the east coast, between Durban and the Mozambique border. The occurrence of eddies and gradients in water temperature make this region favourable for swordfish (Stillwell and Kohler 1985), and skippers believe that swordfish are often found at the warm-cold water interface occurring in this area (pers. obs.).

Fishing effort of the shark-directed fishery was the most consistent of the three pelagic longline fisheries over time. Seasonal effort varied slightly with a decrease in the number of hooks deployed in spring, and this was attributed to less favourable sea and weather conditions prevalent over the Agulhas Bank area during that time of the year (pers. obs.).

Shark bycatches reported in logbooks comprised only the most commonly caught species; blue shark (*P. glauca*), shortfin mako shark (*I. oxyrinchus*), thresher sharks (*Alopias* spp.), and grouped carcharhinids, however not all species within that group were carcharhinids, e.g. crocodile shark. By contrast, the observer data listed 16 species of sharks, some in low numbers. The higher resolution of the observer data compared to logbook data assisted in identifying several shark bycatch species that were grouped in logbooks under 'carcharhinids' or 'sharks'. One such species was the crocodile shark (*Pseudocarcharias kamoharai*) which was the most commonly observed shark species in the swordfish fishery and the fourth most observed in the tuna fishery, but was not separated into its own category in the logbook data. Little is known about crocodile shark populations (IUCN Red List, 2011; www.iucnredlist.org), but it is the only member of the Pseudocarchariidae. It is slow-growing with a low fecundity, and may be at risk as a common bycatch species in longline fisheries (Musick *et al.* 2000; Camhi *et al.* 2009; Petersen *et al.* 2009). This example illustrates the value of higher resolution data provided by fisheries observers, compared to grouped logbook information.

Observer data also proved valuable in refining the geographical composition of shark bycatches by taxon. Logbooks created the impression that blue and shortfin mako sharks dominated shark catches in all four zones, whereas observer data showed that these two species were most common only in the Agulhas Bank and South Coast zones. Further eastwards bycatches were dominated by crocodile sharks *(P. kamoharai*) thresher sharks (*Alopias* spp.), carcharhinid and unidentified shark species. The carcharhinid group most likely includes spinner sharks (*Carcharhinus brevipinna*), silky sharks (*C. falciformis*), oceanic whitetip sharks (*C. longimanus*), dusky sharks (*C. obscurus*) and bignose sharks (*C. altimus*) (IOTC 2010).

Thresher sharks are sought after on a global scale for their fins and meat, and common thresher sharks (*Alopias vulpinus*) constitute 2.3% of the fins identified in the Hong Kong fin market, which translates to a potential 3.9 million individual sharks per year (Clarke *et al.* 2006). The increase in thresher shark bycatches found in this study may indicate an improvement in population status, or else increased targeting or processing of captured animals. There is insufficient information to support either of the possibilities, but considering that bigeye thresher (*A. superciliosus*) has a high risk of over-exploitation in the Atlantic (ICCAT 2009), improved data collection of the congeneric *A. vulpinus* should be a priority. As of 2010, the IOTC instituted a condition for thresher sharks that stipulated that there be no retention or sale by commercial or recreational fleets by the member countries (IOTC 2011).

The standardized CPUE of sharks taken as bycatches based on logbook data suggests a stable or slightly increasing abundance trend between 1998 and 2010. Conversely, the standardized trend based on observer data suggests a decline in shark abundance between 2002 and 2010. Two separate processes may account for the apparent contradiction; i) for logbook data, increased attention to shark bycatch and improved species identification by skippers over time may have resulted in better reporting of shark capture events, and ii) for observer data the observers sole duty on board is to record the fishing practice and species captured which results in a more accurate representation of actual fishing activity where bycatch is concerned. In practice, skippers focus on gear set-up and catch information of target- and valuable bycatch species (Francis *et al.* 2001). Consequently, they are less likely to record sharks that are cut loose next to the vessel, as they may be released before the skipper becomes aware of their capture (Walsh *et al.* 2002). Additionally, as a result of the low value of sharks compared to the target species (Clarke *et al.* 2006), their capture is a low priority event on board. The capture of blue sharks was often seen as a nuisance by the crew and was regularly not recorded, further supporting the hypothesis that under-reporting occurs in logbook data. The slight increase in the logbook index may be as a result of improved reporting in latter years, following several programmes on responsible fishing by governments and NGOs (Grantham *et al.* 2008). Walsh *et al.* (2002) found a modest amount of non-reporting in the Hawaiian pelagic longline fishery, and concluded that some vessels, even without an observer on board, carried out their duties with regard to data collection

Fisheries observers do not take part in fishing operations and are thus able to report comprehensively on the catches and bycatches taken at sea. The standardized index based on observer data is therefore less likely to suffer from the inherent bias introduced by logbook data, and is presumably a better reflection of actual shark abundance. The present study shows a slight decline in shark abundance based on bycatches, and compares with the downwards trend shown by Petersen *et al.* (2009), which included both Atlantic and Indian Ocean data. Five years of additional data included in the present study, compared to Petersen *et al.* (2009), shows a continued decline of shark bycatch rates in pelagic longline fisheries off southern and eastern South Africa. Notably however, Jolly (2011) reported contradictory results to those reported by Petersen *et al.* (2009) with regard to blue shark catch trends. Petersen *et al.* (2009) reported a decline in catch and decrease in mean size of blue shark on South African waters but Jolly (2011) showed that shark bycatch restrictions had in fact resulted in a decrease in blue sharks caught and not a decrease in population size.

Shark bycatch rates standardized for target species (i.e. fleet) showed that swordfish (local) vessels had higher bycatch rates than the tuna-directed vessels. On closer observation, however, it appeared that tuna (foreign) vessels were substantially under-reporting shark catches – to the extent that <20 sharks were reported by the entire fleet in 1998. Even with this in mind, Petersen *et al.* (2009) found that swordfish vessels accounted for 61% of the sharks with 25% of the effort. The IOTC (2008) reported that swordfish vessels were responsible for higher shark catches due to gear configuration for night fishing, targeting areas in the Southwest Indian Ocean (SWIO) such as south Madagascar where larger shark populations are thought to exist than elsewhere in the SWIO, decreased swordfish catches, and swordfish-import bans. It is therefore possible that the targeting of sharks by these vessels has occurred.

The same may be true in the South African fishery, specifically where swordfish vessels operate along the east coast and tuna vessels operate mainly on the Agulhas Bank. The latter fishery sets lines in deeper water during the day, and did not have any bans on tuna products, and thus maintained their focus on the target species. The shallow-set night-time lines of the swordfish vessels along the east coast are apparently more likely to encounter coastal carcharhinid species, which are more active at dusk and during the night (Compagno *et al.* 2005), whereas the deeper set, tuna-directed longlines set on the Agulhas Bank are more likely to encounter shortfin mako and blue sharks.

The life history strategies and migratory nature of pelagic sharks taken as bycatch by longline fisheries make the development of regional management plans particularly important (Simpfendorfer *et al.* 2002; ICCAT 2009). The International Convention for the Conservation of Atlantic Tuna (ICCAT) has developed a pioneering approach to shark bycatch management, including: banning of finning; regular assessments of shark populations; encouraging full use of shark carcases; promoting the release of live sharks; and increasing the accuracy and consistency of data collection (CMS 2007). The IOTC has recently made resolutions to formulate a similar management plan that would include steps such as: improved data collection; landing of sharks with fins naturally attached; refined data requirements; and the prohibition of landing certain species (IOTC 2011).

Fisheries managers can contribute to shark conservation by using new technology such as an application (app) for Android devices introduced by the NOAA Fisheries' Atlantic Highly Migratory Species Management Division that allows anglers to share information about releasing North Atlantic shortfin mako sharks (Website 1).

The vulnerability of large pelagic sharks to overfishing due to slow growth and late onset of sexual maturation cannot be disregarded when planning and implementing management plans (Gubanov 1978; Hoenig and Gruber 1990; Kroese and Sauer 1998; Lack and Sant 2006). Developed countries such as Canada (Aires-da-Silva and Gallucci 2007) and Australia (Bensley *et al.* 2010) have efficiently constructed and implemented bycatch management plans. These are executed with the input of fisheries stakeholders, scientists and managers. The developing countries of the SWIO region face different challenges, however, such as food security and prohibitively high financial costs of implementing fisheries management strategies. In order for the sustainable management of shark bycatch to be successful in the developing world, management skills and effective data collection need to be developed, and even if these factors are in place, management strategies cannot succeed without effective policing (Lewison *et al.* 2004).

Fisheries management in the SWIO region generally suffers from inadequate and insufficient data (Kroese and Sauer 1998; IOTC 2009). For this reason a region-wide observer programme, such as the SWIO Fisheries Project observer program can contribute greatly, because it can provide high resolution species specific information on shark catches made by longline fisheries (see Camhi *et al.* 1998; 2009; Musick *et al.* 2000a; 2000b; Cavanagh *et al.* 2005; 2008; Pikitch *et al.* 2008a). The implementation of management measures relies directly on the level of responsibility assumed by permit holders and skippers of fishing vessels, and it is therefore important to educate the fishing industry on the importance of correct reporting of all bycatches (WCPFC 2005). This has been particularly effective for the management of bird catches in pelagic longline fisheries (Petersen *et al.* 2009), where the use of bird-scaring lines (i.e. tori lines) is now compulsory, and the education of crew on the need for management measures and accurate reporting has resulted in a positive response from industry (Grantham *et al.* 2008). The investigation and implementation of efficient means for reduced shark bycatch may therefore also be well received by fishers. These could include: incentives to release sharks alive where possible, and spatio-temporal closures to fishing when shark captures are traditionally highest.

Conclusion

The major findings of this chapter included; the discrepancy in the standardized CPUE indices based on logbook- and observer data, respectively; the decreasing trend in shark bycatch rates in longline fisheries based on observer data; the prevalence of crocodile sharks as the most abundant shark species in bycatches off eastern South Africa; and that vessels that target swordfish record higher shark bycatch rates than those that target tuna. These results provide crucial information for the development of shark bycatch management plans for longline fishing vessels that take bycatch, species composition, fleet fishing strategy and spatio-temporal abundance of bycatch species into account.

CHAPTER 3: ABUNDANCE AND SIZE OF SHORTFIN MAKO SHARKS CAPTURED BY PELAGIC LONGLINE FISHERIES AND BATHER-PROTECTION NETS

3.1 Introduction

The shortfin mako shark *Isurus oxyrinchus* is a circumglobal oceanic species that occurs in temperate and tropical waters, where it has a preferred temperature range of 17° to 22°C (Compagno 2001). It occurs predominantly in the epipelagic zone (0 – 200 m) (Compagno 2001), but has been encountered down to 500 m depth (Casey and Kohler 1992; Holts and Bedford 1993; Loefer *et al.* 2009). Although oceanic in nature, shortfin mako sharks also occur close to the coast, where they are sometimes caught in bather-protection nets set < 1 km from the shore off eastern South Africa (Cliff *et al.* 1990).

The commercial shark longline fishery off South Africa operates both in the South East Atlantic Ocean (west coast) and the South West Indian Ocean (SWIO, South and East coasts). In the SWIO, the swordfish-directed vessels operate mainly from Durban northwards to the Mozambique border, whereas tuna-directed vessels operate further to the south west, from Mossel Bay westwards, around Cape Point and along the west coast of South Africa (Figure 3.1). The shark-directed vessels concentrate their fishing effort along the 200 m isobath of the southern Agulhas Bank, and operate as far east as Port Elizabeth. Longline characteristics vary according to the target species, and generally consist of 12 - 120 km of longline and 500–2000 hooks. For swordfish, gear is generally set at sunset and allowed to soak overnight before hauling in the morning; for tuna, gear is set in the early morning and hauled later in the day (He *et al.* 1997); and for the shark-directed fishery, gear is set just before midnight and hauled between 07h00 and 08h00 (Petersen *et al.* 2009, Jolly 2011).

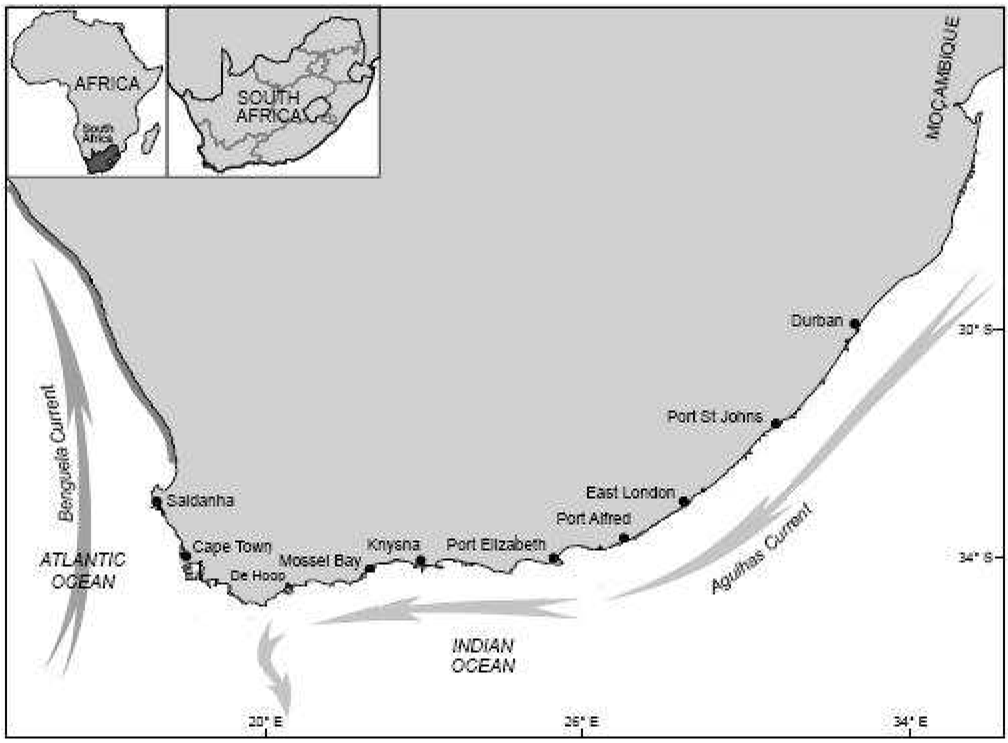

Figure 3.1 Map of South African coastline showing both oceans and major currents.

Shortfin mako sharks are also captured in the bather-protection nets along the coast of KwaZulu-Natal (KZN) South Africa. The nets were first introduced in 1952 and by 1990 a total of 44 km of nets had been installed at more than 40 beaches. The quantity of netting per beach, and therefore total effort, was reduced from the late 1990s onwards as a measure to reduce catches (Cliff and Dudley 2011). To reduce bycatches in the nets, some of them were replaced by baited hooks (drumlines) in 2007 (Cliff and Dudley 2011). The numbers of shortfin mako sharks taken by the nets are far lower than those taken by the longline fisheries.

Catch rates are generally assumed to be proportional to abundance and hence provide an abundance index (Airesdasilva *et al.* 2008; Montealegre-Quijano and Vooren 2010; Carlson *et al.* 2012). The relationship may, however, be influenced by variations in fishing strategy, gear design and selectivity, or fluctuations in catchability. A generalized linear model (GLM) framework is commonly used to quantify the effects of these factors on catch rates, and to calculate standardized catch rate indices (Maunder and Punt 2004; Carlson *et al.* 2012). Petersen *et al.* (2009) provided standardized indices for shortfin mako sharks, showing declines in catch rates and median size off South Africa, and Campana *et al.* (2005) found a decline in the median size of shortfin mako sharks in Atlantic Canadian waters. Jolly (2011) however, when looking at the same data analyzed by Petersen *et al.* (2009) for blue shark in South African waters, found that there was no evidence to support the claims that blue shark populations were decreasing and questioned the methodology applied with regard to the 10% bycatch limit which was not taken into account when analyzing blue shark CPUE. The concerns mentioned by Jolly (2011) were taken into account when analyzing these data for shortfin mako shark abundance trends.

In this study, a GLM approach was used to quantify the effects of year, sampling area, longitude, season and fleet on the abundance and size of shortfin mako sharks caught along the southern and eastern coasts of South Africa, within FAO fisheries statistics area 51 (Western Indian Ocean). Standardized indices of abundance and size were subsequently used to assess spatio-temporal trends in the population abundance and the size of shortfin mako sharks.

3.2 Methods and materials

Data

Three long-term datasets were used in this study: (i) shortfin mako shark catches taken by pelagic longline fisheries in the offshore environment (i.e. over the continental shelf and upper slope); (ii) shortfin mako shark catches taken by bather-protection nets (or shark nets) set close (< 1 km) to the KZN coastline; and (iii) shortfin mako shark length frequency data collected from both the offshore and nearshore fishing operations.

a) Offshore catch database

The Department of Agriculture, Forestry and Fisheries (DAFF) provided fisheries data specific to shortfin mako sharks, recorded both by skippers (logbook: 1998 – 2010) and observers (observer: 2002 – 2010) on board pelagic longline vessels operating within the South African fishery. Information provided included co-ordinates of longline sets, number of hooks deployed, flagstate of vessel, target species, and date of activity. Chapter 2 contains a more detailed description of the data.

b) Nearshore catch database

The KwaZulu-Natal Sharks Board (KZNSB) provided data on shortfin mako sharks collected in shark nets between 1978 and 2010. Shark nets were set approximately 400 m from shore off beaches between Richards Bay (28°48’ S, 32°06’ E) in KZN and Mzamba (31°06’ S, 30°10’ E) in the Eastern Cape. The nets were made of polyethylene braid, were approximately 214 m long and 6.3 m deep, with a stretched mesh size of 51 cm (Cliff and Dudley 2011). At some beaches, drumlines were used in addition to one or more nets, each with a single Mustad 4480DT 14/0 J hook (Gjøvik, Norway) suspended beneath a large, anchored float. The gear was checked an average of 18 times per month. The nets were deployed in fixed locations, but were sometimes removed in winter to reduce catches of predators associated with the annual sardine run (Dudley and Cliff 2010).

c) Length frequency data

Length frequency data were collected by fisheries observers on board pelagic longline vessels targeting tuna and swordfish in the SWIO between 2002 and 2009. These data were sourced from DAFF, and contained details such as the date and co-ordinates of longline sets, and the fork lengths (FL) of shortfin mako sharks, but sharks were not sexed. Additional length frequency data of shortfin mako sharks caught in shark nets between 1978 and 2010 were collected by the KZNSB, and the sex of these specimens was recorded. Length recorded by the KZNSB was generally the precaudal length and this was converted to fork length (Mejuto *et al.* 2008).

Data analysis

a) Catch per unit effort (CPUE)

Following the methods of Dudley *et al.* (2005), fishing effort of shark nets was defined as kilometres of net per year (km-net year^{-1}), and nominal CPUE was calculated as

$$CPUE = \left(\frac{y}{x}\right)/z$$

for each beach, where:

y = total catch of shortfin mako sharks in numbers
x = number of years the beach had nets
z = average annual effort (km-net) at the beach

For the pelagic longline fisheries, CPUE was calculated as number of sharks / number of hooks × 1000. A generalized linear model approach (GLM) in the freely available statistical software package R (version 2.14.0, R Development Core Team, 2011) was used to assess variability in shortfin mako shark CPUE. The dataset comprised a large proportion of zeroes and therefore the delta method, that involves fitting two sub-models to the data (Maunder and Punt 2004, Shono 2008), was selected. In the first sub-model the probability of a non-zero catch was modelled, assuming a binomial error distribution, and in the second sub-model only the positive catches were modelled using the log-normal, Poisson, negative binomial or gamma distribution.

Where longline CPUE was the response variable, year, area, season, month, target species and flagstate were considered as explanatory variables (Table 3.1). Target species within the logbook and observer data sets were recorded both on tuna and swordfish vessels and therefore this was used as an explanatory variable. Shark-directed vessels did not have target species as an explanatory variable.

Table 3.1: Candidate factors hypothesized to affect catch rates and size (FL) of shortfin mako shark caught in pelagic longline fisheries off eastern South Africa

Variable	Type	Dataset	Description
Year	Categorical	Logbook	1998-2010 (13 levels)
	Categorical	Observer	2002-2010 (9 levels)
	Categorical	Shark-directed	2004 - 2009 (6 levels)
	Categorical	Observer (Length)	2002-2009 (8 levels)
Month	Categorical	Logbook and observer	January – December (12 levels)
Season	Categorical	All three	Autumn = February - April Winter = May - July Spring = August - October
Target Species	Categorical	Logbook	Tuna Swordfish
Longitude	Categorical	Observer (length)	Location of longline sets 20 - 21°S 21 - 22°S 22 - 23°S 23 - 24°S … 40°S
Area	Categorical	All three	4 levels: Agulhas Bank (20°E – 24° E) South Coast (25°E – 29° E) East Coast 1 (30° E – 32.8° E) East Coast 2 (32.9° E – 36.5° E).
Flagstate	Categorical	Observer	ZAR – South Africa JPN – Japan KOR - Korea NAM – Namibia PAN – Panama PHI – Philippines SEY – Seychelles STV – St. Vincent and the Grenadines ICE – Iceland

The probability of non–zero catch was modelled with binomial error distribution and a logit link function (Table 3.2). The positive catches were then modelled assuming Poisson and gamma error structures, and in both cases a log link function was used. Fishing effort (number of hooks) was used as an offset variable (Cooke and Lankester 1996; Punt *et al.* 2000). The most parsimonious models were selected based on Akaike's Information Criterion (AIC) (Akaike 1974) and models were validated by visual assessment of residual plots.

Table 3.2: Factors retained in the final generalized linear models (GLM) of catch rates and size of shortfin mako *Isurus oxyrinchus* off eastern South Africa. Delta models used for catch rates comprised a submodel of the proportion of sets with a positive shark catch (binomial) and a submodel of positive sets only (gamma). AIC is the Akaike Information Criterion.

Model	Error	Link	Factors	AIC
Logbook catch rate	Binomial	Logit	Target + year + season + area	14379*
	Gamma	Log	Target + year + season + area	10612*
	Poisson	Log	Target + year + season + area	Inf
Observer catch rate	Poisson	Log	Target + year	6148
	Poisson	Log	Target + year + season	5731
	Poisson	Log	Target + year + season + area	5188
	Poisson	Log	Target + year + season + area + flagstate	5087*
Logbook shark-directed	Poisson	Log	Year + season	986
	Poisson	Log	year + season+ area	881*
Size	Gamma	Log	Year + longitude	59489
	Gamma	Log	Year + longitude + season	50373*
	Gaussian	Log	Year + longitude + season	50617

* Final size and sex ratio models chosen

The standardized catch rate indices were computed as the product of the binomial and gamma (or Poisson) model outputs, using the following reference points: 1998 (year), autumn (season), and Agulhas Bank (area). Indices for size distribution used the following reference points: 2002 (year), 20°S (longitude), and autumn (season).

b) Length frequency analysis

The mean lengths of shortfin mako sharks caught in 50 x 50 km grid blocks in the pelagic longline fishery were plotted using GIS software (ArcEditor 9.3™). Length classes were: 0 – 100 cm; 100.1 – 150 cm; 150.1 – 200 cm; 200.1 – 250 cm; and > 250 cm FL. A GLM framework was further used to explore the response of shortfin mako shark size (FL, cm) relative to the explanatory variables longitude, year and season (Table 3.1). Haddon (2001) described the gamma distribution as appropriate for length-based models in fisheries, and preliminary tests showed that the relationship between the logarithms of the mean and variance of length was larger than two (data highly dispersed). Consequently a gamma model with a log link function was selected for the size analysis, and fork length was treated as continuous, rather than categorical, in order to maintain the variability between samples. To ensure that the variables included in the final model were all significant, they were fitted using a forward-stepwise selection function (Table 3.2). Models with the smallest AIC were selected, and validated as above (Minami *et al.* 2006). One-way ANOVA and Tukey post-hoc analyses were used to compare mean lengths where needed.

3.3 Results

Longline fisheries

Catches in the longline fishery

A total of 12028 longline deployments were reported in logbooks over the 13 year period between January 1998 and December 2010. Of those, 7331 (60.9 %) recorded no shortfin mako shark catches. Fisheries observers reported on 5316 longline sets while aboard commercial tuna and swordfish longline vessels, and on 1790 of these (33.7 %) they reported no shortfin mako shark catches. Based on the percentages of longline deployments in which no shortfin mako sharks were reported in logbooks versus fisheries observers, and assuming that fisheries observers reported all shortfin mako sharks captured, skippers failed to record shortfin mako sharks in 27.2% of longlines in which they were actually present.

On average, 2057 ± 712 (SD) hooks were set per line with an average soak time of 11.4 ± 1.2 hours. The percentages of lines directed at tuna, swordfish and sharks were 65.1%, 56.6% and 6.6%, respectively. Logbook records showed that 61237 shortfin mako sharks were landed during this period; of these 12640 (20.6 %) were landed as a bycatch of the tuna and swordfish fisheries between 1998 and 2010, and 48597 (79.4%) as a targeted catch of shark directed fisheries between 2004 and 2009.

Shortfin mako shark catches made by tuna and swordfish vessels increased substantially between 1998 and 2010 based on logbook data (Figure 3.2). The mean number of sharks per year reported between 1998 and 2001 was 159 ± 42 individuals, whereas the mean between 2007 and 2010 was 1868 ± 201. Few shortfin mako sharks were reported by the fishery in 2006, because Asian-flagged vessels did not participate in the fishery in that year (DEAT 2007). The Asian-flagged vessels tend to target tuna rather than swordfish, and also tend to retain (and hence record) more of the shortfin mako shark bycatch than do the locally-flagged vessels (see Chapter 2). Between 2007 and 2010, tuna-directed vessels reported far more shortfin mako sharks per year than the smaller fishery for swordfish; the mean numbers were 1530 ± 227 for tuna vessels compared to 338 ± 32 for swordfish vessels.

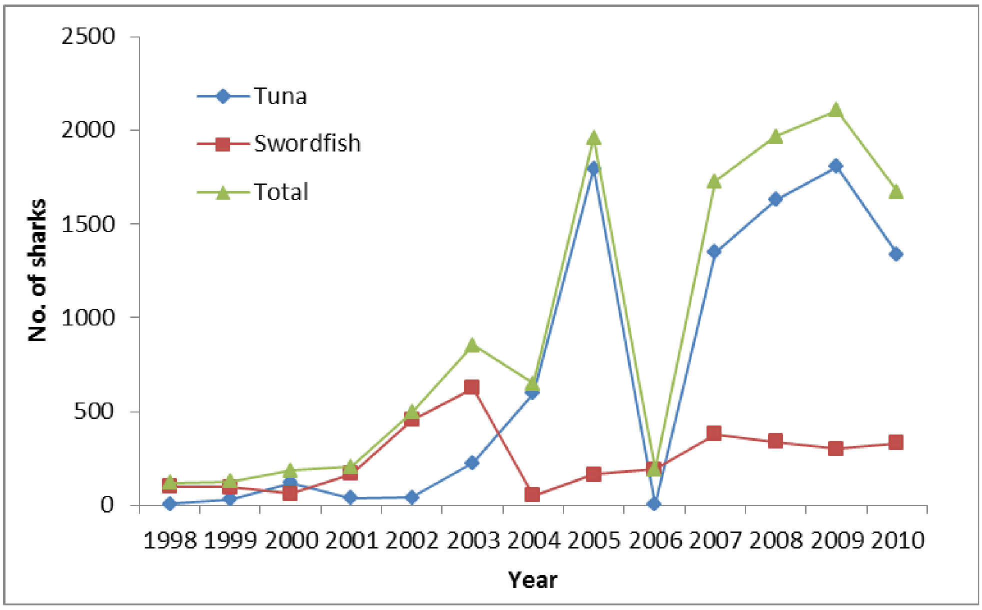

Figure 3.2. Total shortfin mako catches recorded in logbooks (1998-2010), comprising bycatches made by tuna- and swordfish-directed fisheries.

Logbook CPUE model

Year, target species, season and area were significant explanatory variables in the binomial sub–model based on logbook data. The binomial model showed that the probability of encountering a shortfin mako shark was highest between 2005 and 2010, in the Agulhas Bank zone, and during winter months (Table 3.3). The residuals of the second sub-model, the conditional gamma model for positive catches, was validated visually using diagnostic plots for logbook data (Figure 3.3), and the fit was considered to be acceptable. In this model the same explanatory variables were significant as in the binomial model (Table 3.3), but the highest CPUE by year occurred in 1998, 1999 and 2003, and CPUE after 2004 was visibly lower than in the years before.

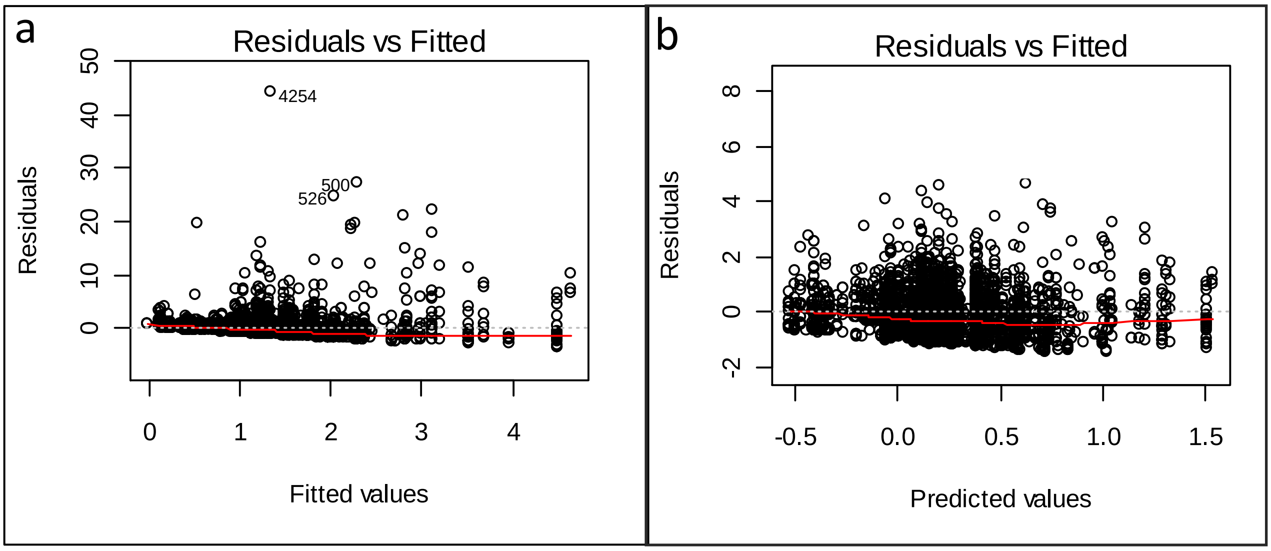

Figure 3.3. A plot of the residuals against the fitted values for the final model chosen as the best fit, the gamma error distribution for logbook data.

Table 3.3: Coefficients (± SE) of the parameters in the different generalized linear models that describe catch rates.

	Logbook bycatch				Observer bycatch		Logbook shark	
Error	Binomial		Gamma		Poisson		Poisson'	
Link	Logit		Log		Log		Log	
N	12028		4702		5316		853	
AIC	14379		10612		3446		881	
Df	12027		4701		5115		852	
Intercept	-0.81772		1.52388		1.782		3.842	
	Estimate	SE	Estimate	SE	Estimate	SE	Estimate	SE
Swordfish	0	0	0	0	1.3428	0.0358		
Tuna	0.03258*	0.05322	-0.33042	0.04897	0.4073	0.0307		
1998	0	0	0*	0				
1999	-0.30373	0.28821	-0.21342*	0.28302				
2000	-0.48711	0.26204	-0.48877	0.25889				
2001	0.38209	0.26721	-0.50848	0.26028				
2002	0.62082	0.24188	-0.75811	0.23806	8.2486*	0.343		
2003	0.70837	0.23802	-0.32212*	0.2347	5.1798*	0.2304		
2004	-0.57195	0.24042	-0.63453	0.24034	0.7167	0.2491	65.08*	1.16424
2005	1.06918*	0.23396	-1.0203	0.22788	0.9539	0.0335	78.341*	2.42844
2006	0.93945*	0.25852	-0.73549	0.25375	7.3*	1.2488	25.549*	1.08192
2007	0.77204	0.23232	-1.08311*	0.22711	0.7621	0.0322	41.699	1.078
2008	0.94184*	0.23373	-0.93134	0.22799	1.3403	0.044	55.085	1.1172
2009	0.82523*	0.23224	-1.05497	0.22703	0.9747	0.0333	45.883	1.10348
2010	0.66036	0.23229	-1.05086	0.22782	0.744	0.0368		
Autumn	0	0	0	0	2.6857*	0.245065	53.59667	12.9948
Spring	0.33185	0.06888	0.01037	0.06573	1.0681	0.071997		
Summer	0.27346	0.07813	-0.0154*	0.07825	1.1478	0.241995	47.93	10.682
Winter	0.47832*	0.07046	0.12409*	0.06602	1.118167	0.084933	66.2767*	21.67106667
Agulhas	0*	0	0*	0	0.8868*	0.047824	52.18*	4.4688
EastCoast1	-1.32921	0.07767	-0.65228	0.07553	0.2591	0.073108	16.1*	22.9908
EastCoast2	-1.3646*	0.06205	-0.58869	0.06221	0.097	0.056448	NA	NA
South	-0.1311	0.05413	-0.18131*	0.04329	0.7547	0.06076	49.16	7.3108
ZAR					4.1936	0.1579		
JPN					3.5542	0.0422		
KOR					3.7622	0.0819		
NAM					7.2294*	1.0794		
SEY					8.7444*	1.5644		
P < 0.05 indicated by *; NA – Not available								

Standardised CPUE of shortfin mako sharks (i.e. the product of the binomial and gamma sub-models; Figure 3.4) decreased between 1998 and 2000, where after it increased to a peak of 1.05 ± 0.7 sharks per 1000 hooks in 2003. A gradual decline was observed between 2006 and 2010. Combining the results of the two models highlights two separate trends (Table 3.3): that the probability of occurrence (or reporting) of shortfin mako sharks increased over time shown with results of the binomial model (looking at catch versus zero catch); but conversely, that the CPUE (i.e. numbers caught per longline) decreased over the same period.

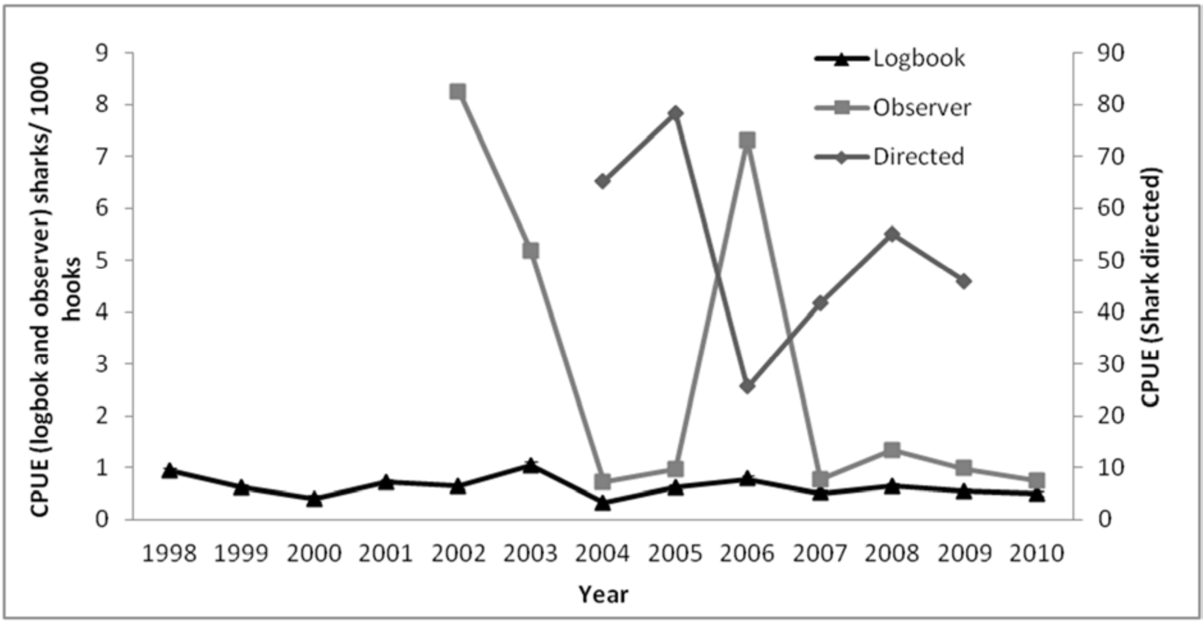

Figure 3.4. Standardized shortfin mako shark CPUE according to logbook (1998 – 2010), observer (2002 – 2010), and shark-directed fishery (2004 – 2009) datasets.

Based on observer data, autumn had the highest standradized CPUE of shortfin mako sharks. The logbook and shark-directed fishery datasets had marginally higher CPUE values in winter than in autumn (Figure 3.5).

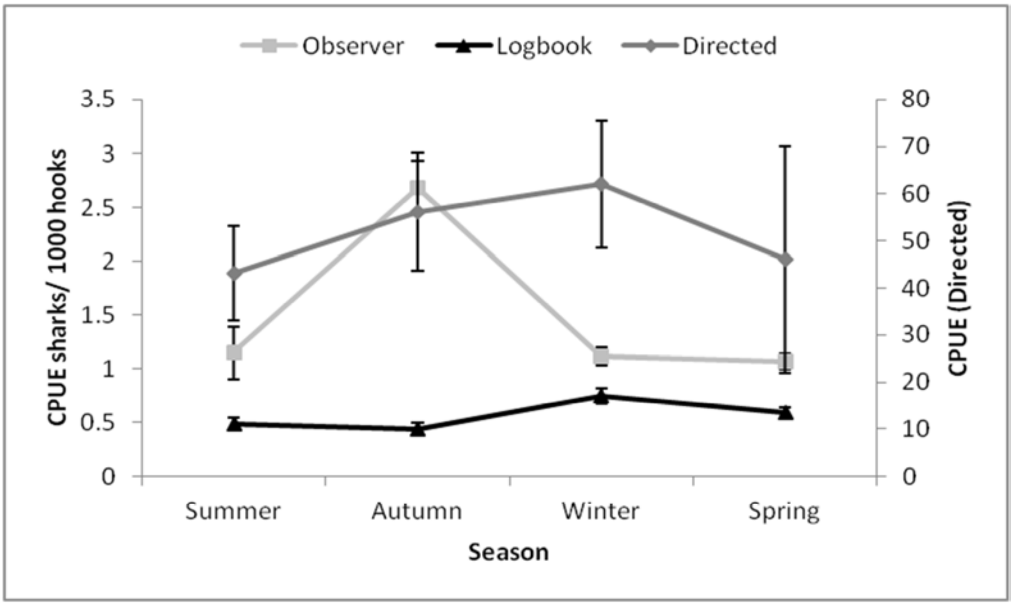

Figure 3.5. The standardized seasonal CPUE for shortfin mako sharks based on the shark-directed, observer, and logbook datasets.

The standardized CPUE was highest at Agulhas Bank (P < 0.01, Dunn's Pairwise comparison, df = 3) decreasing towards the South and East Coast zones (Figure 3.6).

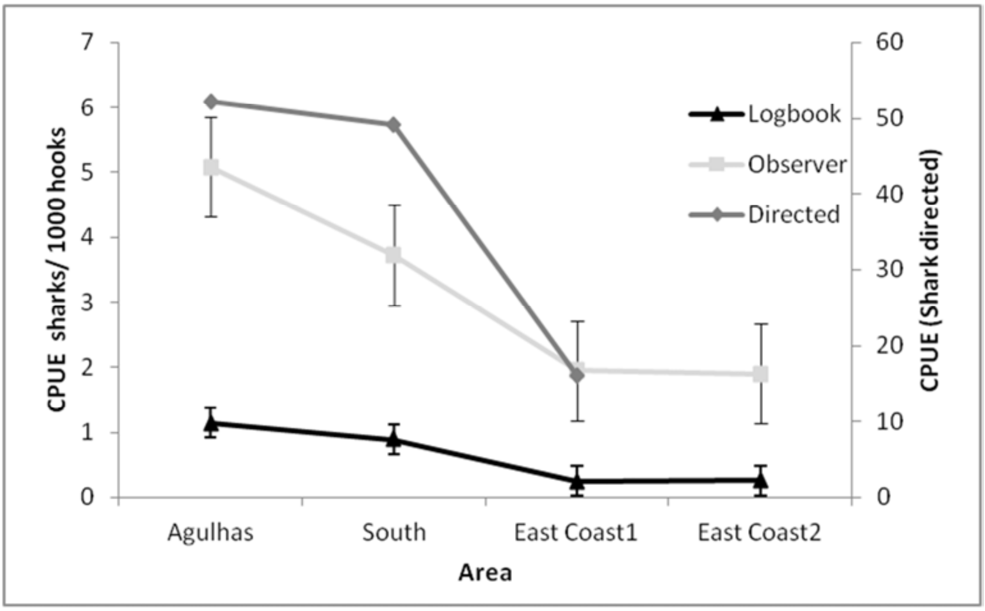

Figure 3.6. Standardized CPUE by area, based on logbook (1998 – 2010), observer (2002 – 2010), and shark-directed (2004 – 2009) datasets.

Observer CPUE model

Target species, year, area, flagstate and season were significant explanatory variables for predicting shortfin mako shark CPUE by observers. Observer data showed two peaks in standardized CPUE; 8.2 and 7.3 shortfin mako sharks/1000 hooks in 2002 and 2006 respectively (Figure 3.4). These were significantly different to the remaining years which had a mean CPUE of 0.92 ($P<0.05$, Dunn's Pairwise comparison, df = 3). The 2006 peak coincided with the exclusion of Asian vessels from the tuna fishery, and not only was fishing effort much lower in this year but most active vessels were local, and were therefore targeting swordfish. Observer coverage during 2006 was 100% and included amongst those vessels were two particularly high shark catches which, when removed, reduced the CPUE to 3.4 sharks/ 1000 hooks.

Autumn was estimated to have the highest shortfin mako shark CPUE ($P<0.05$, Dunn's Pairwise comparison, df = 3) when recorded by observers (Figure 3.5) and area mirrored that of the logbook results (Figure 3.6). Target species was a significant predictor explaining 27% of the variance. Swordfish-directed vessels recorded higher shortfin mako shark catches than did tuna-directed vessels ($P<0.05$, Dunn's Pairwise comparison, df = 1).

In terms of flagstate, Namibia and Seychelles flagged vessels produced the highest CPUE with 8.74 and 7.23 sharks/1000 hooks ($P<0.05$, Dunn's Pairwise comparison, df = 5), respectively, however only took part in the fishery for one year each. Following those two nations, South African vessels were third highest with a mean of 4.19 (± 0.15) sharks/1000 hooks.

Shark-directed CPUE model

Year, season and area were significant predictors of shortfin mako shark CPUE in the shark – directed fishery. The highest standardized CPUE was recorded in 2005 ($P < 0.01$, Dunn's Pairwise Comparison, df = 3) followed by a sharp decline in 2006 before reverting to the second highest CPUE in 2008 (Figure 3.4). As in the logbook catch model, winter and the Agulhas Bank were the season (Figure 3.5) and area (Figure 5) where the highest shortfin mako shark CPUE could be expected ($P < 0.01$, Dunn's Pairwise Comparison, df = 3).

Shortfin mako shark catch in the KwaZulu-Natal bather protection gear

A total of 391 shortfin mako sharks have been captured in the KZN bather protection gear since 1978, two of these by drumlines and the rest by shark nets. The nominal CPUE of nets fluctuated between 0.05 and 0.69 sharks/ km net/ year (Figure 3.7); smoothing over three time periods suggest a general decline in CPUE, the mean for 1978 to 1990 was 0.38 ± 0.14 sharks/ km net/ year, declining to 0.32 ± 0.08 between 1991 and 2000 and to 0.19 ±0.12 between 2001 and 2010.

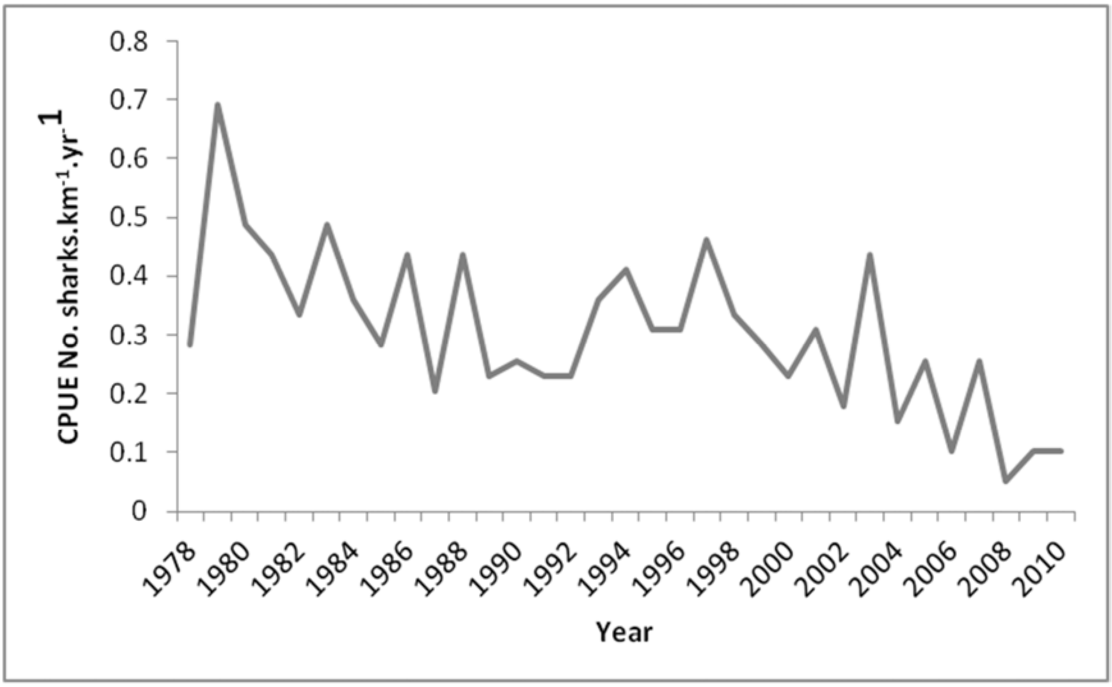

Figure 3.7. The nominal CPUE of shortfin mako sharks captured in the KwaZulu-Natal shark nets from 1978 to 2010. (n = 389)

KZN Bather Protection gear

Monthly catch

There was a clear increase in the number of sharks captured from May onwards with a peak in September, followed by a rapid decline thereafter (Figure 3.8). Both males and females were caught in higher numbers over the winter and spring periods.

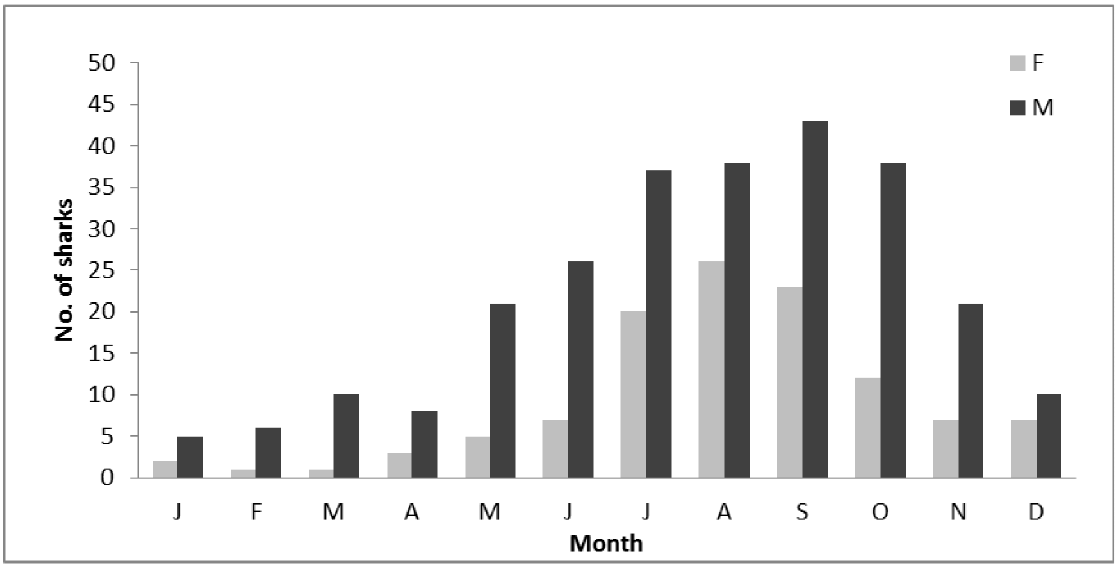

Figure 3.8. The total number of male and female shortfin mako sharks captured monthly in KZN bather protection gear (1978 – 2010).

Area

When analyzing CPUE by beach with bather protection gear on the KZN coast, there were two visible modes; between Blythedale and Umdloti, and between Uvongo and Glenmore (Figure 3.9). The highest CPUE was 1.1 ± 0.05 sharks/ km net/ year) at Brighton Beach and the lowest was 0.04 ± 0.001 sharks/ km net/ year at Richards Bay.

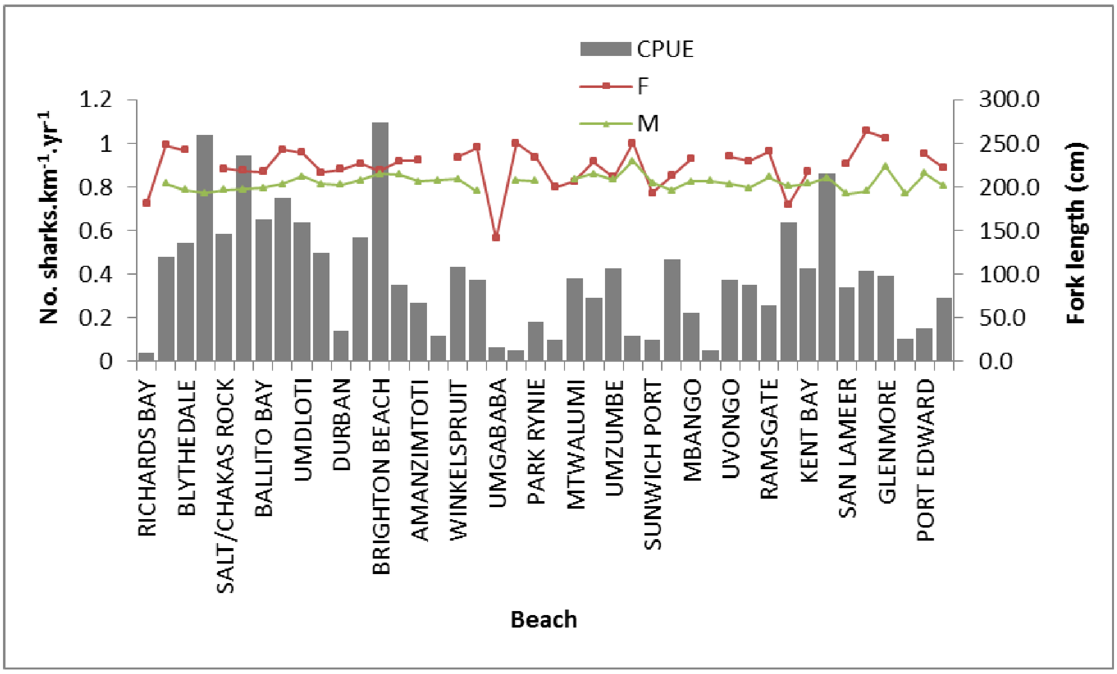

Figure 3.9. Nominal CPUE and mean fork length of shortfin mako sharks captured at each net installation, from north to south along the east coast (1978 – 2010).

Mean length information

No obvious trends in length-frequency were observed when plotting mean FL by netted beach (Figure 3.9). The highest mean length of captured sharks was recorded at Scottburgh, 229 cm (± 29.7), and the lowest was 141 cm, at Umgababa, which was a single specimen.

SWIO observer mean length data

Mean FL of shortfin mako sharks, when plotted by season, revealed the concentration of individuals between 100.1 cm and 150 cm on the Agulhas Bank in winter with more individuals between 150.1 cm and 200 cm present in spring in the same area (Figure 3.10). Summer and spring were the only seasons to contain blocks with mean FL of over 250.1 cm.

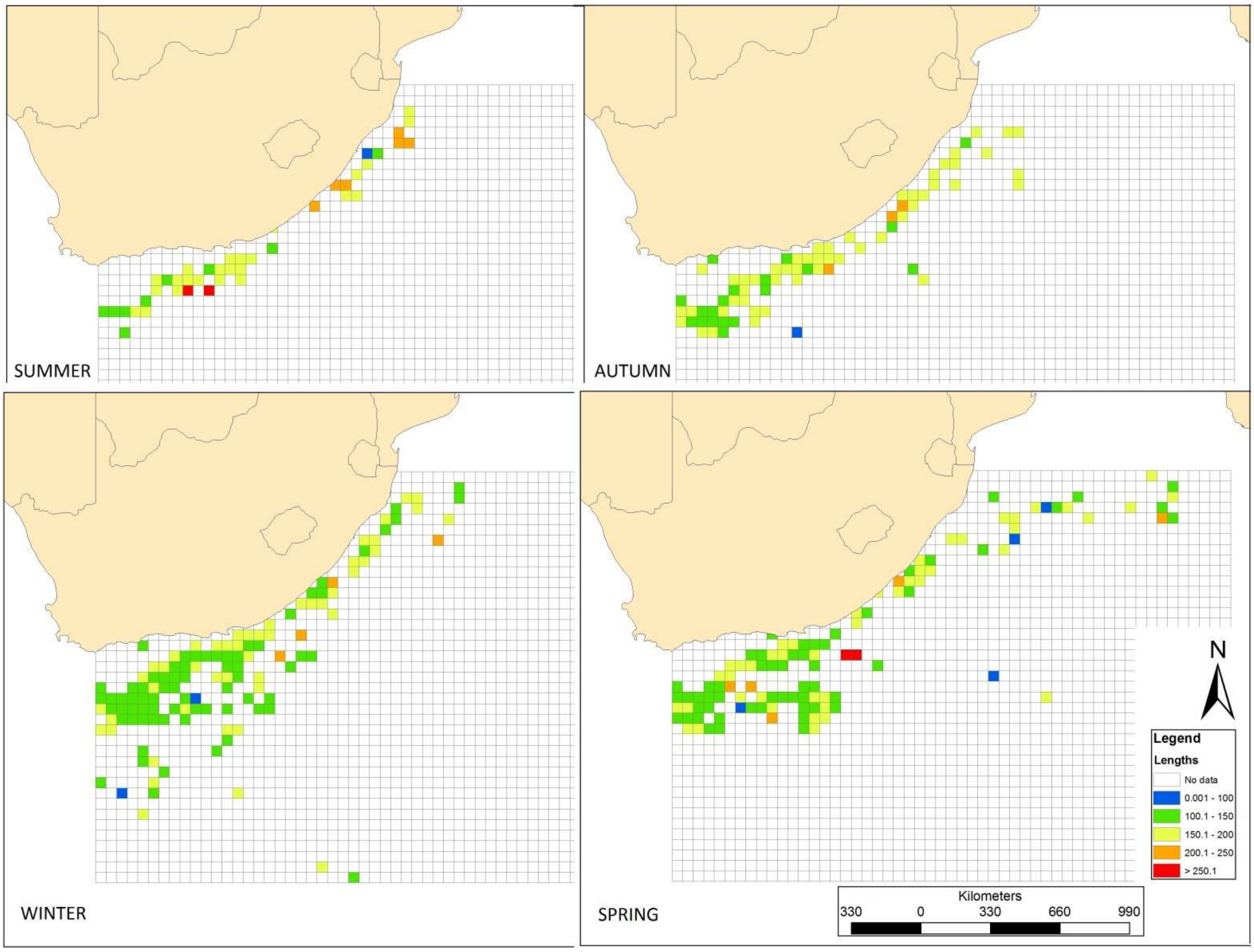

Figure 3.10. The mean FL of shortfin mako sharks measured by SWIO fisheries observers from 2002 – 2009, in 50 x 50 km blocks.

Observer length model

A total of 5329 shortfin mako shark length observations were available, and year, target species, longitude and season were significant explanatory variables in the GLM (Table 3.4).

Table 3.4. Coefficients (± SE) of the parameters in the different generalized linear models that describe size.

Error	Gamma
Link	Log
n	5329
AIC	967
Df	5328
Intercept	4.8582

	Estimate	SE
2002	0	0
2003	-0.047711	0.06083
2004	-0.094898*	0.135066
2005	0.213139	2.86E-02
2006	0.114269	7.06E-02
2007	0.186707	2.88E-02
2008	0.157118	0.028827
2009	0.194126	0.029136
Autumn	0*	0
Spring	-0.082464	0.012098
Summer	-0.050729	0.014497
Winter	-0.059851	0.011212
20° E	0	0
21° E	-0.022197	0.007975
22° E	0.00417	0.012016
23° E	0.04584	0.018242
24° E	0.022507	0.013291
25° E	0.04768	0.007926
26° E	0.05049	0.010431
27° E	0.105712	0.02231
28° E	0.08025	0.04121
29° E	0.119257	0.026415
30° E	0.133221	0.02183
31° E	0.067438	0.02712
32° E	0.109939	0.048636
33° E	0.07615	0.036046
34° E	0.250409	0.047555
35° E	0.041357	0.108227
36° E	0.121429	0.075258
37° E	0.265722	0.109877
39° E	0.423556*	0.189058
40° E	0.55467*	0.097491
41° E	0.334011*	0.082831

$P < 0.05$ indicated by *

The diagnostic plots showed that the residuals were distributed normally around the mean (Figure 3.11).

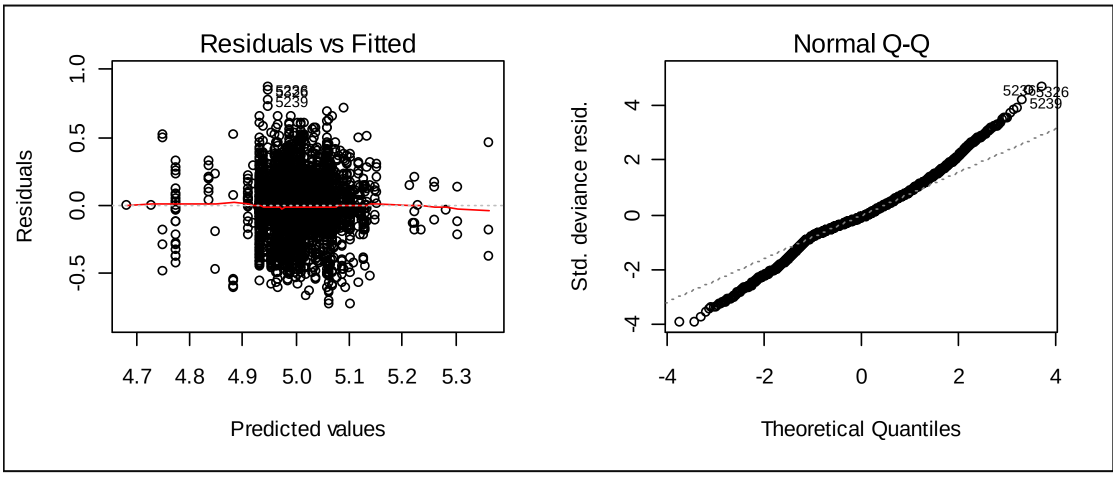

Figure 3.11. Diagnostic plots from the gamma error distribution shown as a) residuals vs. fitted, and b) Normality Quantile plot for FL of shortfin mako sharks from the SWIO data set (n = 5340).

No trend was evident on an annual basis (Figure 3.12). The estimated mean FLs recorded over the eight year period showed slight fluctuations. For example, from 2002 to 2004 mean FL fluctuated between 129.2 cm and 142 cm, and from 2005 to 2009 it fluctuated between 159.2 cm and 175.8 cm. These differences were not significant.

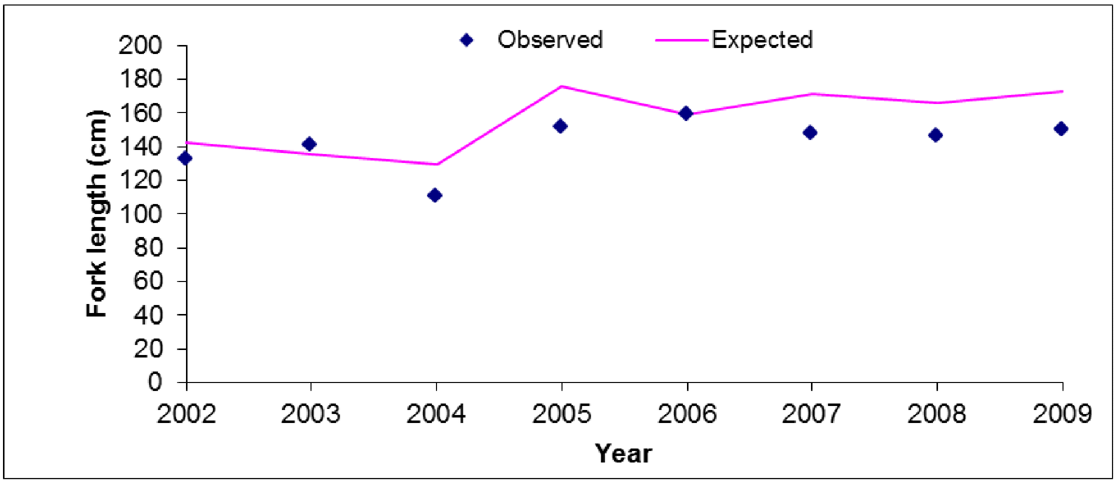

Figure 3.12. The observed and estimated annual mean FL of shortfin mako sharks sampled by the South African observer program throughout the SWIO region (2002 – 2009).

The most effective method of describing geographical distribution by mean length was by grouping by degrees of longitude. An increase in mean size from west to east was observed, with significantly larger animals occurring from 38° to 41° E (Figure 3.13; One-Way ANOVA, Tukey Post-hoc test, $P < 0.05$). From 20° S to 37° E the mean FL was 145.8 cm versus a mean of 201.7 cm from 38° S to 41° E.

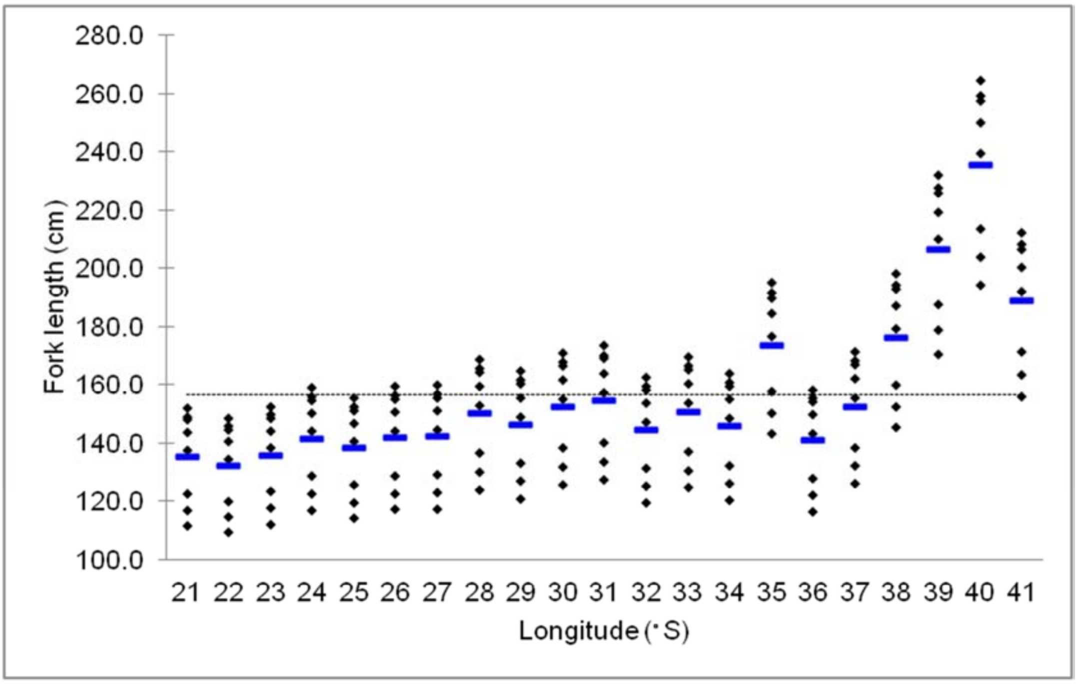

Figure 3.13. The estimated mean FL of shortfin mako sharks by longitude, in the SWIO region (2002 – 2009), with means shown as solid lines.

3.4 Discussion

The binomial sub-model based on logbook data showed an increase in the probability of encountering shortfin mako sharks after 2005, however over the same time period, the gamma sub-model showed a decline in the numbers of shortfin mako sharks caught. This suggests that while reporting rate may have increased, the abundance of shortfin mako sharks has shown a slight decline. Petersen *et al.* (2009) also found a declining trend in CPUE of shortfin mako sharks caught by longlines and concluded that overfishing was the main cause. Furthermore, Petersen *et al.* (2009) found that swordfish–directed vessels had a higher CPUE than tuna–directed vessels and cited differences in fishing strategy (as described in Chapter 2) as the explanation; this was also the case in the present study.

Anecdotal information suggests that tuna-directed vessels historically under-reported shark bycatches. Chapter Two showed that fishing effort applied by tuna-directed vessels was an order of magnitude higher than for swordfish vessels in winter and spring. However, they reported only eight shortfin mako sharks in 1998, 31 in 1999, 38 in 2001 and 41 in 2002. Thereafter, tuna-directed vessels reported an average of 1500 shortfin mako sharks per annum between 2007 and 2010. It is therefore clear that under-reporting took place prior to 2005, and this is also suggested in the binomial presence / absence GLM model of CPUE based on logbook data, in which the probability of capturing a shortfin mako shark increased over time.

The GLM model based on logbooks suggested a higher CPUE for swordfish- compared to tuna-directed vessels, but the under-reporting by tuna vessels prior to 2005 could not explicitly be taken into account in the GLM. Nevertheless, despite the obvious under-reporting, the gamma model based on positive values only (i.e. numbers of shortfin mako sharks per longline when >0 sharks were reported) showed that CPUE was higher prior to 2004 than thereafter. Given the level of under-reporting in the early years, the real decline in CPUE may have been larger than suggested in the present study, but this cannot be said with certainty.

Whereas swordfish was targeted by local vessels, the tuna fleet comprised vessels flagged in Japan, Korea, Namibia and Seychelles. The latter two nations reported the highest shortfin mako shark CPUE, but they were only present for one year each, 2003 and 2002, respectively. The fact that the Japanese and Korean fleets reported the lowest shortfin mako shark CPUE during those same years is anomalous, and difficult to explain. One possibility is that their fishing strategy was different from the strategy used by the vessels from Namibia and Seychelles; an alternative, and more likely, explanation is that shortfin mako shark catches were under-reported by the Japanese and Korean vessels. Nevertheless, based on statistics provided, the local swordfish vessels reported higher shortfin mako shark CPUE than the tuna fleet. That result is not uncommon as tuna fleets around the world report fewer shortfin mako bycatches than swordfish fleets (Thomson and Kelvin 2009; Lack and Sant 2011).

Shark-directed vessels reported higher CPUE in 2004 and 2005 than in any year since, but the time series is still too short to conclude that the local shortfin mako shark population (assuming there is only one) is declining. The highest CPUE of shortfin mako sharks (both as targeted catch and as bycatch) occurred on the Agulhas Bank. Given the intensive fishing activity by foreign tuna vessels and local shark–directed vessels in that region, a management plan needs to be developed. Lewison *et al.* (2004) suggested that areal and seasonal "hotspots" for bycatches may be considered when management plans are developed. Kitchell *et al.* (2002) reminded fisheries managers that a decade or more may be required for management strategies to reflect changes within shark populations.

The KZN bather protection gear (shark nets and, more recently, drumlines) caught shortfin mako sharks on a much smaller scale than the commercial longline fisheries. The primary function of the nets is to safeguard bathers from shark encounters, but the nets also provide an index of shark populations close to the coast. Dudley and Simpfendorfer (2006) suggested that as a result of the standardized fishing methods and fixed locations of the nets, they represent a form of fishery–independent monitoring tool. A caveat of this approach is that a decline in resident sharks might lead to the mistaken conclusion that population abundance is declining generally, whereas in reality, depletions may only be local. Dudley and Simpfendorfer (2006) reported that the potential impact of nets on local populations of coastal species such as *Carcharhinus obscurus, C. leucas* and *Carcharias taurus* was high as a result of slow growth rates and late onset of maturity. However, the potential effect of the nets on populations of oceanic species such as the shortfin mako shark was low, particularly because these nets would affect only the nearshore edge of populations that occur further offshore.

The location of the nets is at the extreme inshore limit of the distribution of shortfin mako sharks, and the individual sharks that are captured in the nets are likely part of a larger oceanic population that moves inshore to reproduce or feed. Casey and Kohler (1992) suggested that in the North Atlantic, shortfin mako sharks would remain off the continental shelf until water temperature increased to 18° C. In the nearshore waters of the SWIO, Cliff *et al.* (1990) found that the majority of shortfin mako sharks were captured when waters were cooler (19° C - 22° C), suggesting that this species may have a preferred temperature range of 18° C to 22° C. However, when considering that most shortfin mako sharks were caught in or near the Agulhas current, where the ambient water temperatures are typically warmer than 18° C to 22° C, it is clear that they prefer a broader temperature range. Therefore, it may be something other than the cooler temperatures that brings this species into the nearshore waters of KZN.

Most shortfin mako sharks were caught in nets set between Blythedale and Umhlanga, and the second most between Uvongo and Glenmore. Relatively large estuaries have outlets in those areas; such as the Tugela, Mvoti and Umzimkulu rivers. It is well documented that sharks make use of the near-shore environment for nutrient-rich waters and reproduction (Simpfendorfer *et al.* 2005; McAuley *et al.* 2007; Knip *et al.* 2010). Chapter 4 elaborates on the above suggestions with regard to the results of sexually mature individuals present inshore and stomach content.

Analysis of distribution according to size class can be useful when trying to identify areas in which a shark species may be pupping (Vélez-Marín and Márquez-Farías 2009). Although the results of the length analysis by latitude were not conclusive, it appears that larger adult sharks are more common in the East Coast 2 area in summer. This suggests that female shortfin mako sharks pup at lower latitudes (East Coast 2) in the nearshore environment in summer after which the juveniles may move south in the Agulhas Current to the Agulhas Bank (explored further in Chapter 4). Adults then move off the shelf and into the oceanic environment. This hypothesis was supported by the length data from the observer database in which the mean lengths of shortfin mako sharks sampled from 38° E to 41° E were all significantly larger than those found towards the Agulhas Bank. Furthermore, sharks caught by the nets along the northern east coast were significantly larger than those sampled offshore on the Agulhas Bank. Casey and Kohler (1992) also hypothesized that juveniles and subadults used the continental shelf as the primary feeding grounds and thereafter they moved offshore.

The standardized indices produced in this study did not show a decline in median size of shortfin mako sharks with time and showed a flat trend over the study period, contrary to the findings of Petersen *et al.* (2009). Their findings were up and to 2005 and after adding the additional four years analyzed in the present study, there appears to be a stable median size of shortfin mako sharks being caught in South African waters.

The IOTC is the regional fisheries management organisation in the SWIO region, and it has emphasized that the collection of shark bycatch data should be improved. Nevertheless, the IOTC conducts no stock assessments on shortfin mako sharks, and neither are standardized abundance indices available. South Africa possesses a reliable data source from its offshore observer programme. The programme has now been discontinued and, unless it is reinstated as a matter of urgency, South Africa's ability to monitor its mako shark population will be severely limited

The amalgamation of the three pelagic longline fisheries (tuna-, swordfish- and shark-directed, respectively) into a single sector poses several questions in relation to the management of pelagic sharks. An upper catch limit of 2000 tons of sharks was introduced in 2008 (DEAT 2009), with the understanding that all three pelagic longline fisheries would cease operations when the limit is reached. The upper limit has, however never been reached, and hence the measure may not be effective in terms of limiting shortfin mako shark catches.

Prior to 2005, shortfin mako shark catches were under-reported in logbooks of tuna-directed vessels. Reporting appeared to improve thereafter but the abundance of shortfin mako sharks appeared to decline after 2005. Observer data also suggested an overall decline in shortfin mako shark CPUE, and this database is more detailed and accurate than the logbook database. Small shortfin mako sharks may use the Agulhas Bank as a primary feeding ground and this area is intensively fished by longline vessels. The catch taken in the shark nets inshore on the KZN coast consisted primarily of large animals. Similarly, large individuals caught in longline fisheries tended to be taken further north, at East Coast 2. It is therefore hypothesized that adult shortfin mako sharks are making use of the nearshore environment as nursery grounds where young are then transported in the Agulhas current along the 200 m isobath of the Agulhas Bank. It is for this reason that spatial management measures aimed at area and seasonal closures are suggested.

CHAPTER 4 BIOLOGY AND LIFE HISTORY OF THE SHORTFIN MAKO SHARK (*ISURUS OXYRINCHUS*)

4.1 Introduction

Knowledge of the biology and life history of exploited marine species is indispensable in developing effective management strategies (Skomal and Natanson 2002; Goldman *et al.* 2006; Mollet and Goldman 2006; Natanson *et al.* 2006). Information on distribution patterns, nursery grounds and migration behaviour can be used to define the spatial and temporal boundaries of a fishery. Most fisheries assessment models include information on population size structure, age and growth, size at maturation, and reproductive strategy (Compagno 2008; Dulvy *et al.* 2008; Pikitch *et al.* 2008; Petersen *et al.* 2009) – these parameters can be used to simulate the effects of hypothetical exploitation strategies on population trends, thus assisting in the development of sustainable management strategies (Hoenig and Gruber 1990; Hilborn and Walters 1992).

The techniques used to assess age and growth in sharks differ from those used for teleosts in that sharks do not have otoliths (ear-bones) in which year-rings can be counted (Heemstra and Heemstra 2004). Instead, the primary structures used for aging sharks are the centra of the vertebrae, where calcified (opaque) and less calcified (translucent) bands are deposited alternately as the animal grows (Camhi *et al.* 1998; Campana 2001; Campana *et al.* 2002; Araya and Cubillos 2006). The techniques that have been developed to optimize the counting of bands in vertebrae include mechanical, digital and chemical methods, which are often used in tandem. Ribot-Carballal *et al.* (2005) read whole vertebrae from digital images, after staining them with 1% silver nitrate. Francis and Ó Maolagáin (2000) tested silver nitrate, alizarin red-S, and x-rays as methods to enhance vertebral bands of *Mustelus lenticulatus*, and selected x-rays. The staining of sectioned vertebrae has also been used as an optimization method (Branstetter 1987; Lessa and Santana 1998; Lessa *et al.* 1999; Carlson and Bethea 2003; Carlson and Baremore 2005). Photographs of vertebral sections were used to assess age and growth of shortfin mako sharks in New Zealand (Bishop *et al.* 2006) and the North Atlantic (Natanson *et al.* 2006). The variety of methods used and their combinations show that not all vertebrae reacted in the same manner to the methods listed above, and that the most appropriate method should be selected for a particular study or species.

Combining an assessment of age and growth with the study of reproductive biology allows for the estimation of the age at maturity of a species (Dulvy *et al.* 2008). Such an estimation enables fisheries managers to impose minimum legal size limits that consider the reproductive potential of an exploited population (Hilborn and Walters 1992), and also allows fecundity to be determined which can be used in fisheries modelling applications. Various estimates exist of size at maturity of shortfin mako sharks, ranging from 180 cm to 300 cm total length (TL), depending on sex and location. Both male and female shortfin mako sharks were initially thought to mature at 180 cm (Gubanov 1978; Stevens 1983; Mollet *et al.* 2000; Joung and Hsu 2005; Campana *et al.* 2005). In the only study of the biology of this species in the South West Indian Ocean, Cliff *et al.* (1990) estimated males to mature at 196 to 205 cm, and females at approximately 265 cm.

Reproduction in elasmobranchs can be categorized into three modes; oviparity, placental viviparity and aplacental viviparity (Compagno 1990; Camhi *et al.* 1998). Shortfin mako sharks exhibit aplacental viviparity with oophagy (Bass *et al.* 1975; Mollet *et al.* 2000; Joung and Hsu 2005). Adult females produce a large number of nutritive eggs which pups ingest; they develop swollen abdomens which store yolk for later growth (Gilmore 1993; Mollet *et al.* 2000). Litter size ranges from 4 – 14 with a suggested summer parturition (Stevens 1983; Cliff *et al.* 1990). One aim of the present study was to elaborate on the findings of a shortfin mako shark reproductive study by Cliff *et al.* (1990) with the addition of data collected subsequently.

Diet studies can assist in understanding trophic levels, and are useful for constructing food webs for ecosystem modeling (Domi *et al.* 2005; Maia *et al.* 2006a). Pelagic sharks are opportunistic feeders in the open ocean ecosystem and can have negative and positive influences on the abundance of other species across a range of trophic levels (Cortes 1999; Cox *et al.* 2002; Kitchell *et al.* 2002). While stable isotopes are a very important means of validating trophic position, due to the time consuming nature of accumulating these data, stomach content analysis remains the simplest means of gaining an insight into the trophic level of a species (Cortes 1999). Hyslop (1980) critically assessed various methods used to quantify diet composition, such as frequency of occurrence (%F), percentage by number (%N) and percentage by weight (%W) of prey items. Diet studies on sharks have regularly made use of these methods (Joyce 2002; Lucifora 2006; Maia *et al.* 2006b).

Shortfin mako sharks are apex predators in the pelagic environment (Compagno 2001; Block *et al.* 2011). A seasonal shift has been shown in their diet in the Northwest Atlantic Ocean, which correlated with the seasonal migration of bluefish *Pomatomus saltatrix,* as revealed by analysis of the $\delta^{15}N$ stable isotope (MacNeil *et al.* 2005). The stomach contents of shortfin mako sharks caught within 1 km of the KZN shore by bather protection nets revealed that coastal elasmobranch species occurred in 60.2% of stomachs (Cliff *et al.* 1990). No analyses have been conducted on stomach contents of shortfin mako sharks sampled offshore (beyond the continental shelf) in the South West Indian Ocean (SWIO) region.

Industrial longline fisheries in the SWIO catch shortfin mako sharks both as a bycatch of tuna or swordfish fisheries and as a target species in shark-directed fisheries (see Chapter 2). The aims of this study were to a) estimate the age and growth parameters of shortfin mako sharks in eastern South African waters, b) describe key reproductive parameters and c) explore the diet of shortfin mako sharks by analyzing stomach contents from both inshore and offshore samples. The information generated by this study will provide an input into assessments and the development of sustainable fisheries management strategies for shortfin mako sharks.

4.2 Materials and methods

Sample collection

Samples of shortfin mako sharks were collected on board a shark-directed pelagic longline vessel during November in 2010 and 2011. The vessel fished off the south coast of South Africa, and samples were collected between Cape Point (34°21′ S, 18°28′ E) and Plettenberg Bay (34°03′ S, 23°22′ E), over the continental shelf and slope. A total of 523 shortfin mako sharks were sampled on board the vessel. Fork length (FL, cm), sex and maturity stage (defined below) were recorded and stomach contents were analysed (see below). A total of 177 vertebral samples, each consisting of between five and eight post-cranial vertebrae, were collected and frozen on board for further processing at a laboratory.

An additional 30 vertebral samples were provided by the KwaZulu-Natal Sharks Board (KZNSB) where samples of 5-8 vertebrae anterior to the dorsal fin had been excised and preserved dried or frozen. The KZNSB furthermore provided life history data from shortfin mako sharks caught between 1978 and 2010 in the bather protection nets, set approximately 400 m from shore at beaches between Richards Bay (28° 48′ S, 32° 06′ E) and Mzamba (31° 06′ S, 30° 10′ E). The information provided by the KZNSB included precaudal, fork, and total length (cm), sex, maturity stage, inner clasper length and gonad weight (to the nearest 0.01 g). Stomach contents were identified to the lowest possible taxonomic level, and where possible counted, measured and weighed. All lengths reported in this study, unless otherwise stated, are fork length.

Processing of vertebrae

After removing muscle tissue from vertebrae, they were soaked in 4.5% sodium hypochlorite (bleach) for between 45 minutes and 12 hours to remove excess connective tissue (Yudin and Cailliet 1990; Booth *et al.* 2011). The haemal and neural arches were removed using a scalpel. Vertebrae were rinsed in distilled water, dried and embedded in polyester clear casting resin in half-pipes sealed at either end with masking tape. Dried samples were rehydrated by immersing in water for 36 hours before following the above process. After the resin had set, vertebrae were sectioned along the sagittal plane using a low speed isomet saw with two diamond-edged blades separated by a 0.8 mm spacer (Figure 4.1; Rizzo *et al.* 2004, Natanson *et al.* 2006;). Sections were dried and attached to glass slides with DPX slide adhesive. A second coat of adhesive was placed on top of each section to enhance the optical qualities of the vertebral sections.

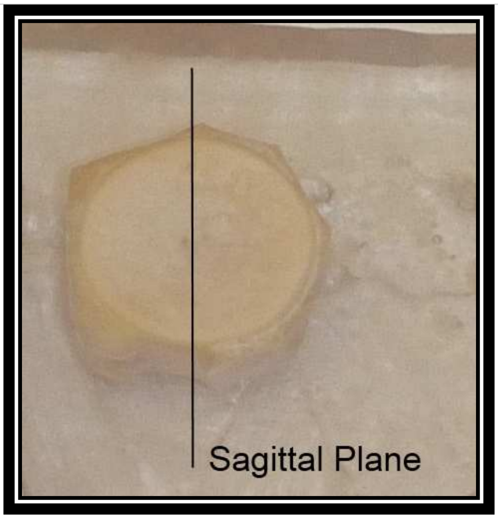

Figure 4.1. An image of the sagittal plane along which the vertebrae were sectioned.

Age determination

Vertebral sections were photographed using a Canon PowerShot S50 attached to a stereo microscope with transmitted light and a dark field. The images were digitally enhanced by adjusting brightness and contrast using the open source program, Paint.NET™. Counts of band-pairs, defined as one calcified (opaque) and one less calcified (translucent) band, (Figure 4.2) (Wintner *et al.* 2002; Cailliet *et al.* 2006), were carried out by two independent readers. The first opaque band distal to the focus was assumed to be the pre-birth ring, and the following growth band was linked with a slight angle change in the corpus calcareum, commonly labelled the “angle change” (AC) (Wintner *et al.* 2002; Goldman *et al.* 2006) or “birth band” (BB) (Natanson *et al.* 2006). The angle change is associated with the transition from fast intra-uterine growth to slower post-natal growth (Walter and Ebert 1991). The AC was considered to represent age zero and was not included in the count. Each opaque and translucent band thereafter was counted from digital images without prior knowledge of the length or sex of the specimen. Each sample was counted three times by each reader; when counts differed by >3 band pairs or produced an average percent error (APE) of more than 20%, they were discarded. Samples with consistent counts that differed between readers by 2 were re-counted. Recounts were also conducted on older animals if an individual count, within or between readers, contradicted the remaining counts as these specimens were considered more “valuable” for maximum age estimates. The mean was then calculated and the age assigned. Band pair deposition was assumed to occur annually, based on a shortfin mako shark tagged, injected with oxytetracycline (OTC), and recaptured off eastern South Africa (Natanson *et al.* 2006).

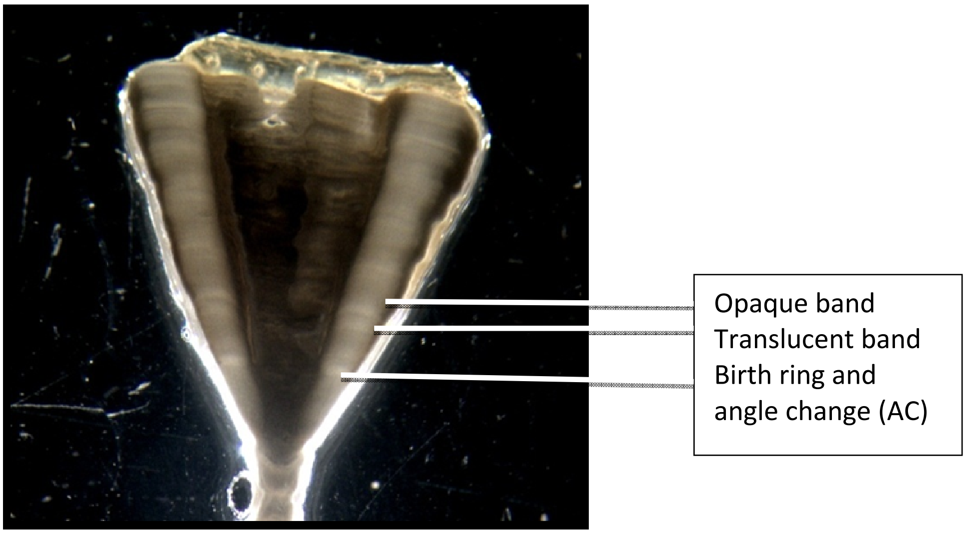

Figure 4.2 A digitally enhanced image of a vertebral section photographed using dark field lighting.

Data analysis

Regressions fitted to FL and whole weight (WW) of male and female shortfin mako sharks were of the form WW = aFL^b and consequently data were log-transformed before comparing slopes and elevations using the Megastat add-on in MS Excel 2010. Similarly, regressions were fitted to FL and vertebral radius (VR) data to assess the relationship between the two variables.

Growth curves were fitted using the von Bertalanffy growth model (VBGM) and the Gompertz model (GM) in MS Excel 2010. Three parameters were used; theoretical maximum length (L_∞), growth coefficient (k) and a theoretical age at zero length (t_0) (Neer and Cailliet 2001; Araya and Cubillos 2006). In the models, age at zero length was replaced with length at birth (L_0). Natanson *et al.* (2006) reported that the three-parameter VBGM and GM produced the most biologically acceptable values for male and female shortfin mako sharks, respectively, in the North Atlantic, and therefore the original von Bertalanffy growth model (Cailliet *et al.* 2006),

$$L(t) = L\infty\left[1 - e^{-k(t-t_0)}\right] \qquad (3.1)$$

was adapted as follows (Natanson *et al.* 2006):

$$L(t) = L\infty - (L\infty - L_0)e^{-kt} \qquad (3.2)$$

where L_t = predicted length at time t; L∞ = theoretical maximum length; k = growth rate constant (yr^{-1}); and L_0 = length at birth.

These parameters were estimated using Solver in Microsoft Excel which described the observed length-at-age data. The model was fitted by minimising the sum-of-squared-residuals (SSR). The non-linear nature of the model was accounted for by using the iterative approach of the Newton-Raphson algorithm (Cadima 2003),

$$SSR = \sum\left(L_t - \hat{L}_t\right)^2 \qquad (3.3)$$

where L_t is the observed length at age and $\hat{L}_t$ is the length at age predicted by the model. In order to provide more robust 95% confidence intervals, these were generated for the parameter estimates by generating 500 independent bootstrap samples drawn randomly (with replacement), taking the values of the original sample size. Lower and upper confidence limits were produced by selecting values at the 25th and 475th position of the sorted bootstrap estimates (adapted from Haddon 2001).

The estimated age at 95% of L_∞ (= longevity in years) was calculated by solving the VBGF growth function for t and replacing L_t with 0.95 L_∞. For the VBGF we obtained (Cailliet *et al.* 2006):

$$Longevity = \left(\frac{1}{k}\right) ln\left[\frac{L_\infty - L_0}{L_\infty(1-x)}\right] \qquad (3.4)$$

With $x = L(t)/L_\infty$

The Gompertz model was specified as follows (Natanson *et al.* 2002):

$$L(t) = L_0(e^{G(1-e^{(-kt)})}) \qquad (3.5)$$

where: $G = \ln(L\infty/L_0)$ and k is a growth rate constant (yr^{-1}).

The average percent error (IAPE) was calculated to estimate the intra-reader average error (Beamish and Fournier 1981):

$$APE = \frac{100}{N}\sum_{i=1}^{N} \left[\frac{1}{R}\sum_{j=1}^{R} \frac{(x_{ij}-x_i)}{x_i}\right] \qquad (3.6)$$

where:

N = number of sharks aged,

R = the number of readings,

x_{ij} = j^{th} count of the i^{th} shark, and

x_i = the final agreed age of the shark.

A paired t-test (Neer *et al.* 2005) , together with an age-bias plot (Natanson *et al.* 2006), was used to assess inter-reader bias at the 5% level of significance.

Due to the nature of the growth curves, the data were transformed into the linear form by taking the natural log of the variables and comparing the straight lines via multiple linear regression analyses in order to identify differences in the slope and intercept of the growth relationships of males and females at the 95% level of significance (Townend 2002).

Reproduction

The maturity of all specimens was assessed according to the criteria of Bass *et al.* (1973). In males, the inner length of the clasper was measured from the point of insertion at the cloaca, to the tip of the clasper (CL). Claspers with rigid calcification, a rhipidion (distal opening of the tube formed by the clasper) that was able to open freely exposing the spur, and anterior rotation capability were considered to be mature (Castro 1996). Fully grown but uncalcified claspers were considered to indicate adolescence, and small, soft claspers indicated immaturity. Bass *et al.* (1973) noted that the presence of semen should not be used as an indication of maturity. Bleeding claspers and swollen testes were interpreted as indicating recent mating activity.

Female shortfin mako sharks were considered mature if distinct oocytes were present in the ovary or if the uteri appeared distended, with a uterus width (UW) > 50 mm (Mollet *et al.* 2000); conversely, thin and tube-like uteri were considered to be immature. A UW of 50 mm was chosen as a knife-edge indicator of female maturity because there was a small overlap between immature and mature animals at this measurement (Mollet *et al.* 2000). The hymen was used to indicate whether female sharks were adolescent, or resting in between pregnancies, although the hymen may rupture if sharks are moved *post mortem* (Cliff *et al.* 1988). Bite marks on female sharks were also used as an indication of mating activity.

A 2-parameter logistic ogive was fitted to length and maturity data in order to calculate the length at 50% maturity, as follows (Carlson and Baremore 2003):

$$P_l = \frac{1}{1+e^{-(l-l_{50})/\delta}} \qquad (3.7)$$

Where:

P_l = Proportion of mature animals at length l
l = Length
L50 = Length at 50% maturity
delta (δ) = Inverse rate of maturity

The parameters L50 and delta (δ) were estimated using a non-linear, least squares technique in Solver, MS Excel. The confidence intervals were estimated by bootstrapping. The code was written in Visual Basic Editor for MS Excel whereby random numbers were generated based on the observed residuals, and replaced in sequence. This procedure was repeated 500 times.

Analyses of stomach contents

Stomachs sampled on board fishing vessels at sea were emptied, the prey items identified to the lowest possible taxonomic level, and counted. Prey items in stomachs examined in the laboratory were counted and weighed. Three indices for quantification of prey items were used: frequency of occurrence (F_i: percentage of stomachs which contained a particular prey i); percentage by mass (W_i: weight contribution of prey i expressed as percentage of total stomach content weight); percent by number (N_i); and the index of relative importance (Hyslop 1980; Maia *et al.* 2006; Newman *et al.* 2010).

$$\%IRI = 100 \times [F_i \times (N_i + W_i)] \qquad (3.8)$$

4.3 Results

A total of 817 shortfin mako sharks were sampled jointly from the KZNSB bather protection program (n = 292) and from the pelagic longline vessels (n = 525). Samples comprised 474 males, ranging from 66 to 292.4 cm FL and 343 females, ranging from 69 to 301 cm.

The inshore samples were significantly biased towards males (sex ratio = 2.3:1 M:F, χ^2 goodness of fit, df =1, $p < 0.001$), and females were significantly larger than males (mean 243.6 ± 34.6 cm versus 218.4 ± 20.8 cm; t-test, df =1, $p < 0.001$) (Figure 4.3a). Most (53.4%) male shortfin mako sharks caught in the nets fell within a narrow size range of 201 – 240 cm, whereas females dominated in length classes > 261 cm. The offshore samples caught by the longliner consisted of similar numbers of female and male sharks (sex ratio = 1.1:1, χ^2 goodness of fit, df =1, $p = 0.556$), and there was no significant difference between the mean length of males (144.5 ± 35 cm) and females (148.1 ± 34 cm) (t-test, df =1, $p = 0.298$, Figure 4.3b).

The mean length of shortfin mako sharks caught in nets was significantly larger than those caught by the pelagic longliner in the offshore environment (t-test, df =1, $p < 0.001$). The same was also true when testing for difference in mean lengths of males caught inshore versus offshore (t-test, df =1, $p < 0.001$), as well as females (t-test, df =1, $p < 0.001$).

A comparison between the data collected from the pelagic longliners in 2010 and 2011 (sexes combined) and unsexed observer samples collected on board the pelagic longline fishing fleet (Figure 4.3c) between 2002 and 2009 showed no significant difference in mean length (t-test, df = 1, $p = 0.199$).

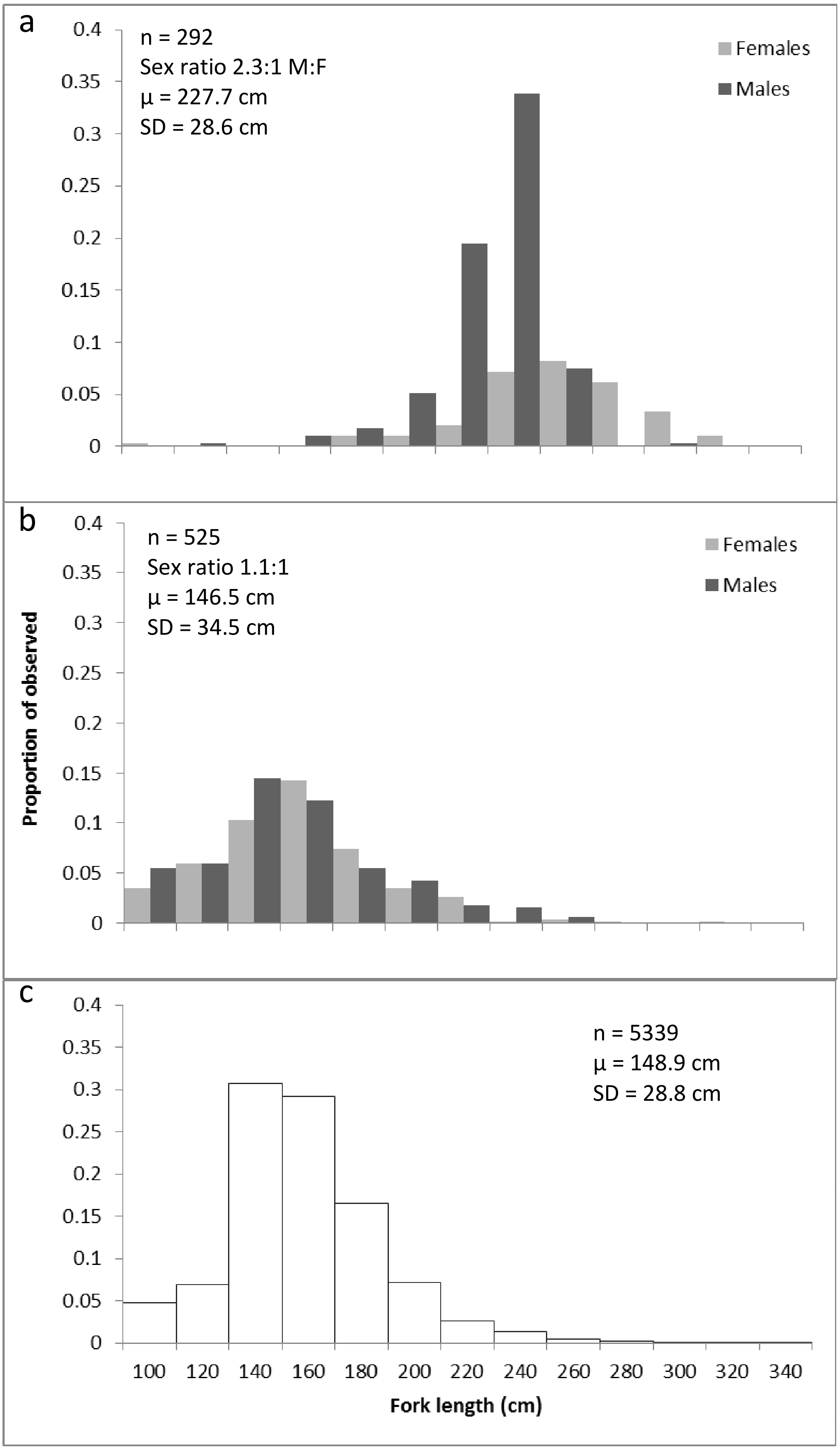

Figure 4.3. Length-frequency distributions of male and female shortfin mako sharks sampled from a) inshore KZN (1978-2010), (b) pelagic longliners in South African waters during the present study, and (c) the long-term fisheries observer programme (2002 – 2009) extending into the Southwest Indian Ocean.

Linear regressions fitted the log-transformed length and mass data well for males (n = 474, $r^2 = 0.96$, $p < 0.001$) and females (n = 343, $r^2 = 0.97$, $p < 0.001$) respectively, and the slopes and elevations differed significantly between sexes (multiple linear regression, df = 1, $p < 0.001$). Females grew significantly heavier and larger than males, and this was substantiated by the observations which showed only one male over 200 kg, whereas there were 20 females caught in excess of 200 kg (Figure 4.4).

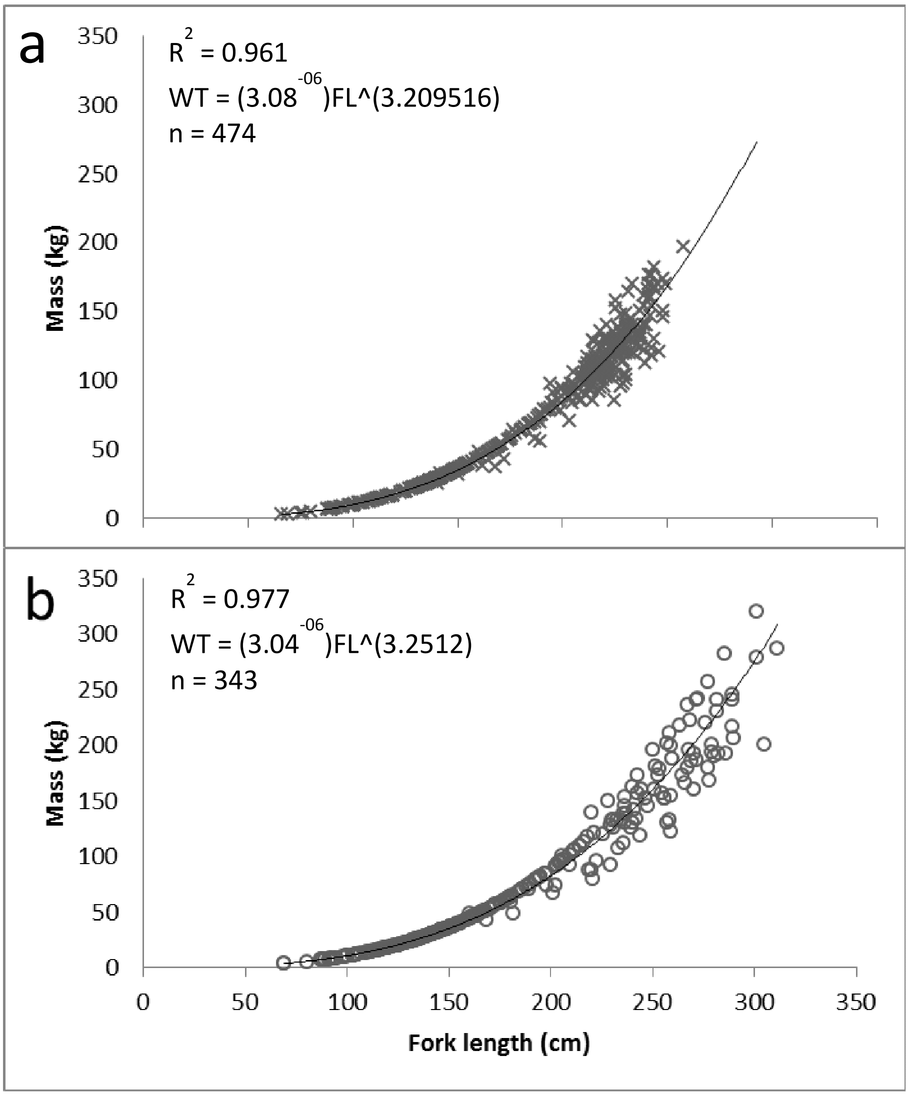

Figure 4.4. Relationships between fork length (FL, cm) and whole weight (WW, kg) of (a) male and (b) female shortfin mako sharks caught by nets and a pelagic longliner off South Africa.

4.3.1 Age and growth

The vertebrae were challenging to read, and 18 were discarded as unreadable. A further 15 vertebrae were rejected because between reader counts differed by >3 bands, or the APE was > 20%, leaving a total of 89 vertebrae. Vertebrae showed a moderately consistent presence of a pre-birth band-pair. Previous studies detected a slight angle change in the corpus calcareum coinciding with the birth band (Natanson *et al.* 2006), but this angle change was not always evident in the vertebrae used for this study. The remaining vertebrae were from 43 females (length range 91 – 297 cm) and 46 males (90 – 299.4 cm), and vertebrae from at least two male and two female sharks were available in each 10 cm length category between 130 and 230 cm (Figure 4.5).

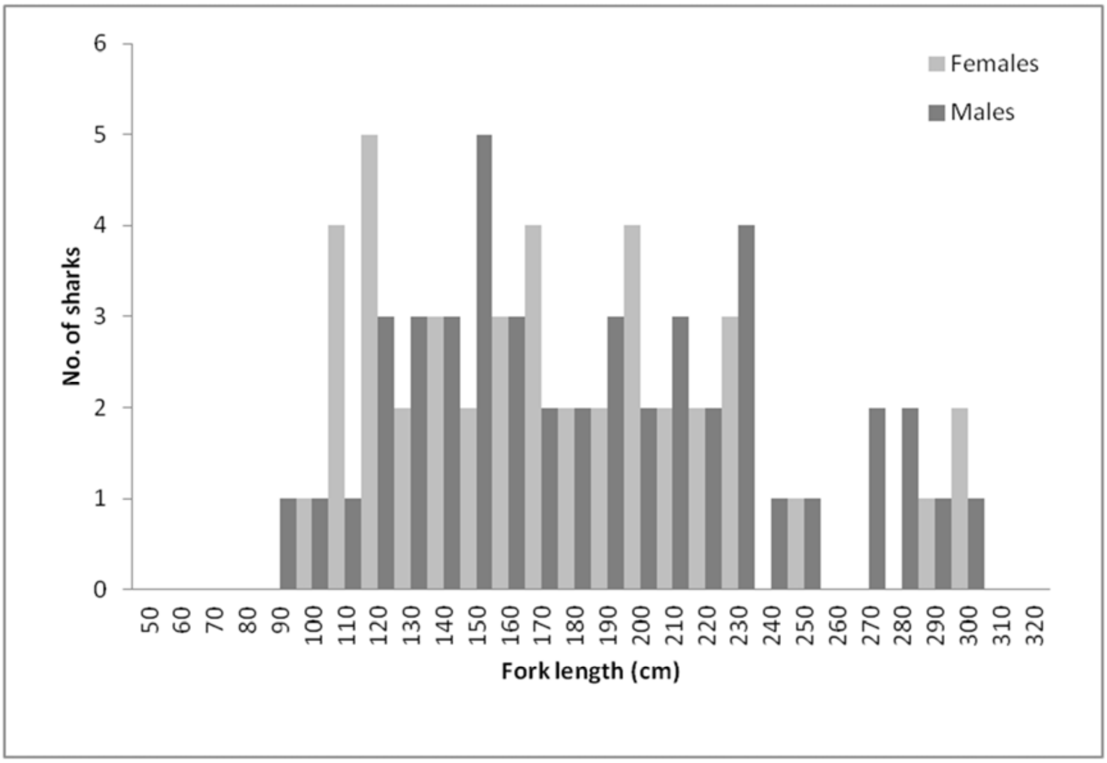

Figure 4.5. The numbers of male and female mako sharks per 10 cm FL-class used for the ageing study.

Vertebral centrum assessment

Regressions were fitted to the FL and vertebral radius (VR) of males (VR = 0.0719FL – 1.366, n=46, r^2=0.88) and females (VR = FL x (0.0796) – 2.720, n = 43, r^2 = 0.95), and the linear relationships were compared. There was no significant difference between sexes for the intercepts (p = 0.925) or slopes (p = 0.929) of the regressions, indicating that the VR increased linearly with FL, irrespective of growth rate differences between males and females. A linear regression was therefore fitted for both sexes combined (Figure 4.6).

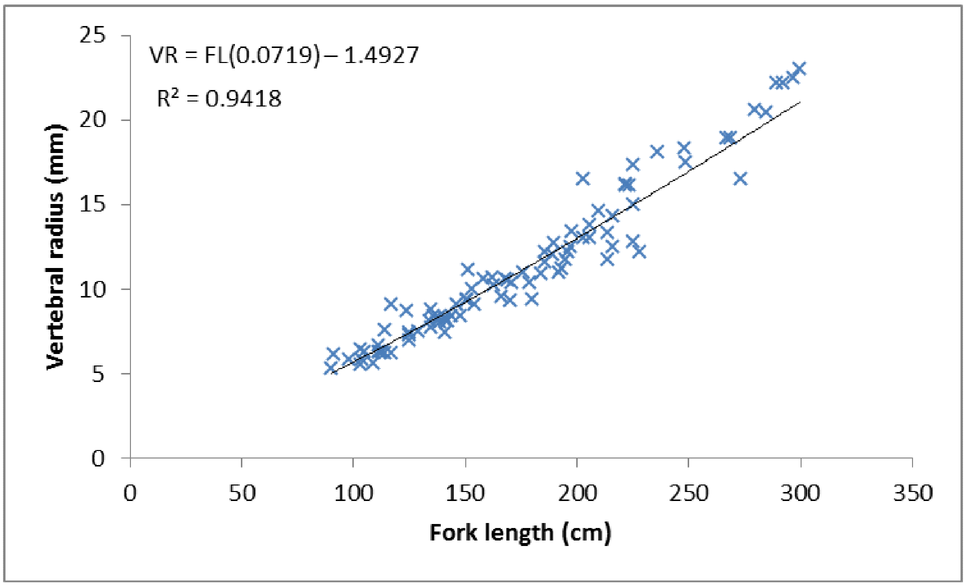

Figure 4.6. Relationship between vertebral radius and fork length for male and female shortfin mako sharks combined (n = 89)

Count reproducibility

The APE was 10.4% and 19.4% for the primary and secondary readers, respectively, which falls within the 20% margin for error suggested by Campana (2001). There was no significant difference in the accuracy of age assessments between readers (paired t-test; $p>0.05$). There was a 25% agreement on all age assessments, 87% agreement between age readings for animals up to 1 year, and 54% agreement between animals aged 2 years. There was a strong positive correlation between the mean readings of secondary versus the assigned age by the primary reader (t-test on slopes, $R^2=0.97$, $p<0.05$) (Figure 4.7).

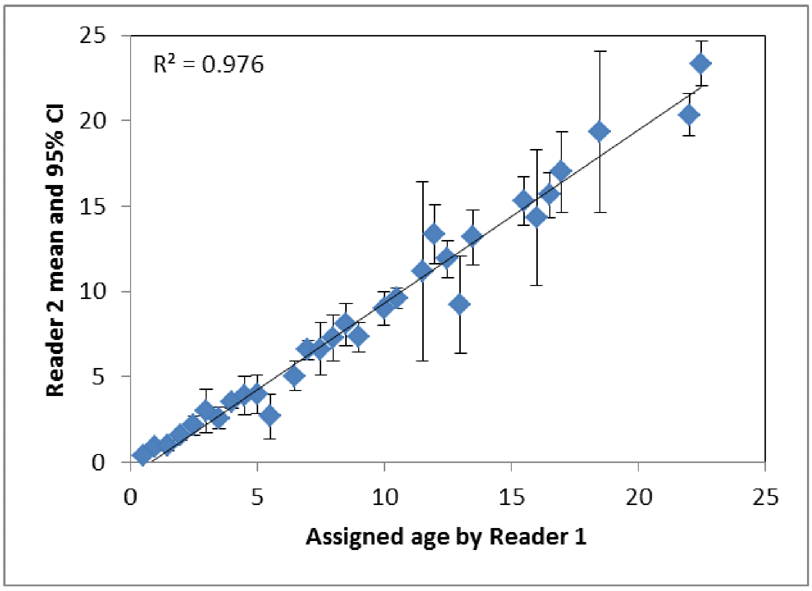

Figure 4.7. Age-bias graph comparing vertebral counts from two independent readers. Error bars represent the 95% confidence interval (CI) for the mean age assigned by reader 2 to all sharks assigned a given age by reader 1.

The smallest and largest specimens were males of 90 cm and 299.4 cm, with one band and 17 band-pairs, respectively.

Growth model application

The multiple linear regression analysis showed no significant difference ($p > 0.05$) between the slopes of males and females. However a significant difference between the intercepts showed that females grew larger than males ($p < 0.05$). Females and males grew similarly up to 150 cm, thereafter they continued to increase in size at different rates.

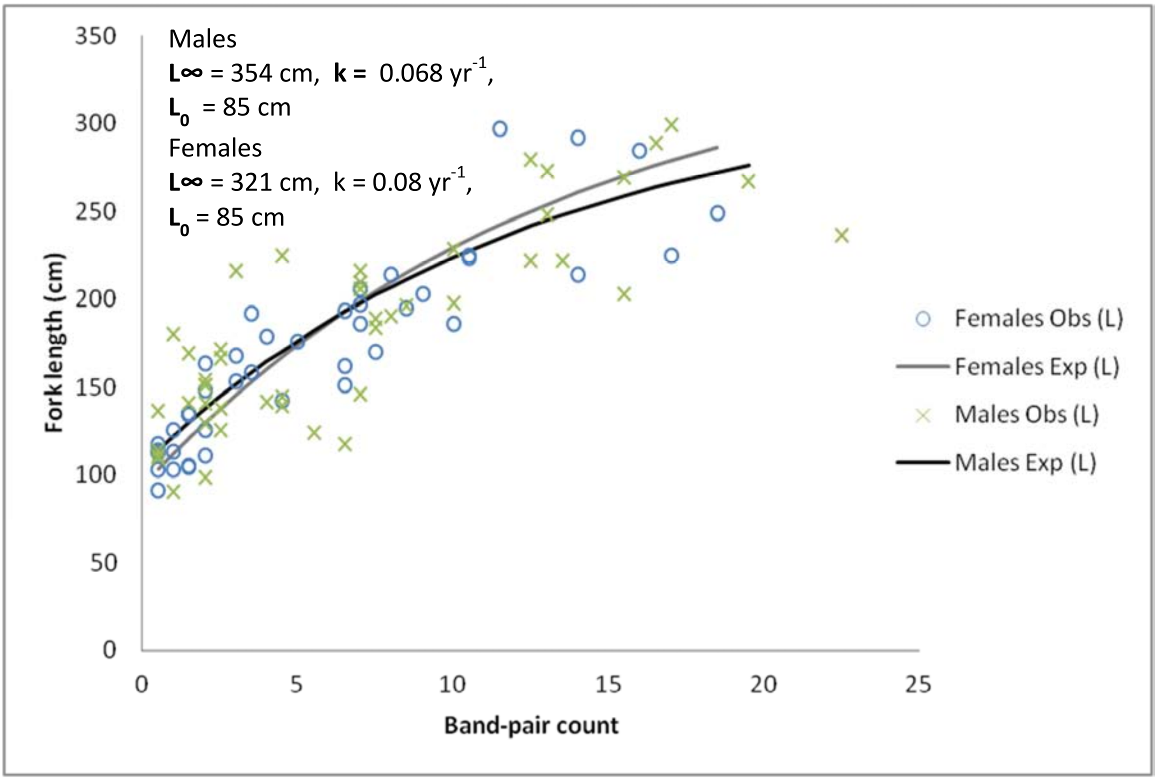

Figure 4.8. Von Bertalanffy growth curves for male and female shortfin mako sharks based on estimates of three parameters, L∞, k and L_0.

The von Bertalanffy (VBGM) and Gompertz (GM) growth models with 3-parameter estimation gave reasonable estimates of maximum length for both males and females, but sample size may have affected this parameter (Figures 4.8 and 4.9, Table 4.1). Estimates for size at birth (L_0) were in excess of 115 cm, but the smallest sharks observed were between 69 and 75 cm. Therefore L_0 was restricted to 85 cm or less, for both sexes.

Table 4.1. Boot strap results for the three parameters of the von Bertalanffy and Gompertz growth models for males and females. MLE – maximum likelihood estimate, SE – standard error, LCI – lower confidence interval, UCI – upper confidence interval. Include units for parameters

			Linf	K	Lzero
VBGM	Males	MLE	354.4411	0.068	85
		SE	109.365	0.025438	9.303884
		LCI	283.3142	0.028174	55.01111
		UCI	586.8705	0.129465	85
	Females	MLE	321.2197	0.087767	85
		SE	21.10732	0.070263	23.22891
		LCI	240.763	0.087049	0
		UCI	325.3861	0.381228	85
GPGM	Males	MLE	295.2418	0.152172	85
		SE	16.15625	0.025511	7.264482
		LCI	267.9953	0.120594	59.26122
		UCI	325.8699	0.22114	85
	Females	MLE	315.7265	0.127463	85
		SE	27.65168	0.028921	7.66392
		LCI	271.3557	0.092515	60.87639
		UCI	380.63	0.209237	85

Initial observable differences between the two models were higher k estimates for both sexes using the GPGM but the *L∞* values were higher for males and females using the VBGM (Table 4.1). In addition, the GPGM predicted notably lower longevities for males and females. Longevity estimates were 34 and 33 years for males and females respectively using the VBGM, compared to 14 and 23 years using the GPGM.

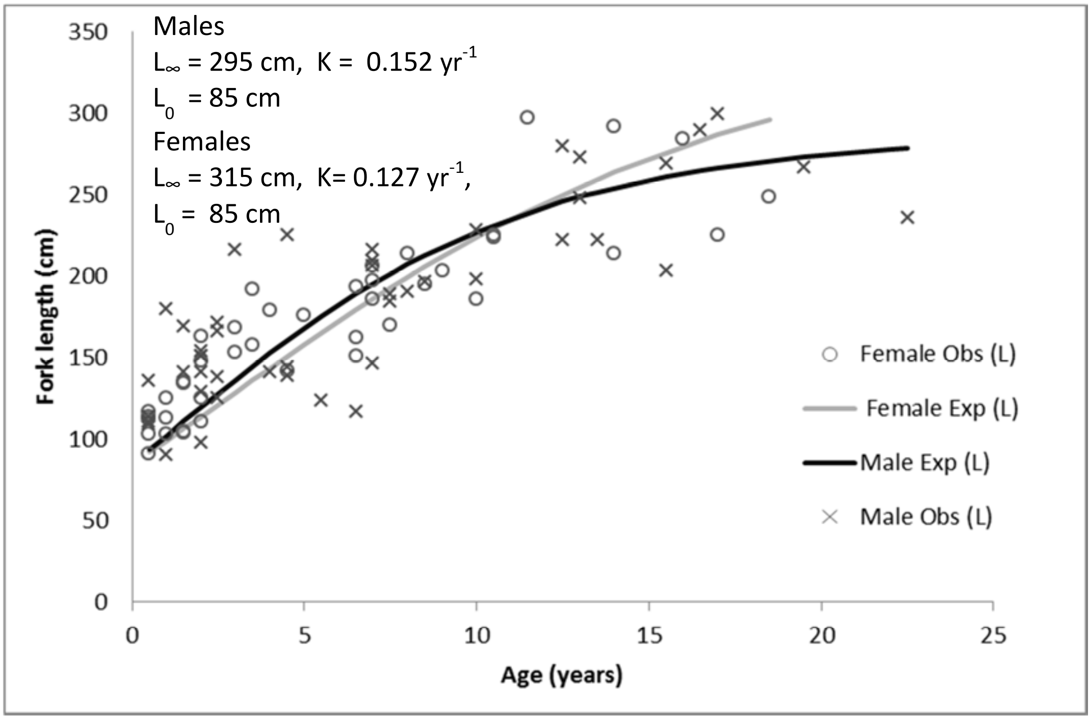

Figure 4.9. Gompertz growth curves for male and female shortfin mako sharks based on estimates of three parameters, L∞, K and L_0.

4.3.2 Reproductive biology

Ninety per cent of male and nearly 99% of female shortfin mako sharks caught offshore were immature, compared to only 45% of females and 7% of males caught inshore. Five pregnant females were sampled in this study, all captured inshore by the shark nets.

Male size- and age-at-maturity

Clasper length and calcification increased steeply after 140 cm (Figure 4.10a). Clasper articulation was not present in males below 180 cm, but it became prevalent at FL > 200 cm and all males larger than 215 cm showed full calcification and articulation. The L_{50} for male shortfin mako sharks was estimated at 199.1 cm (Figure 4.10b). Consequently, the age at 50% maturity was calculated as seven years.

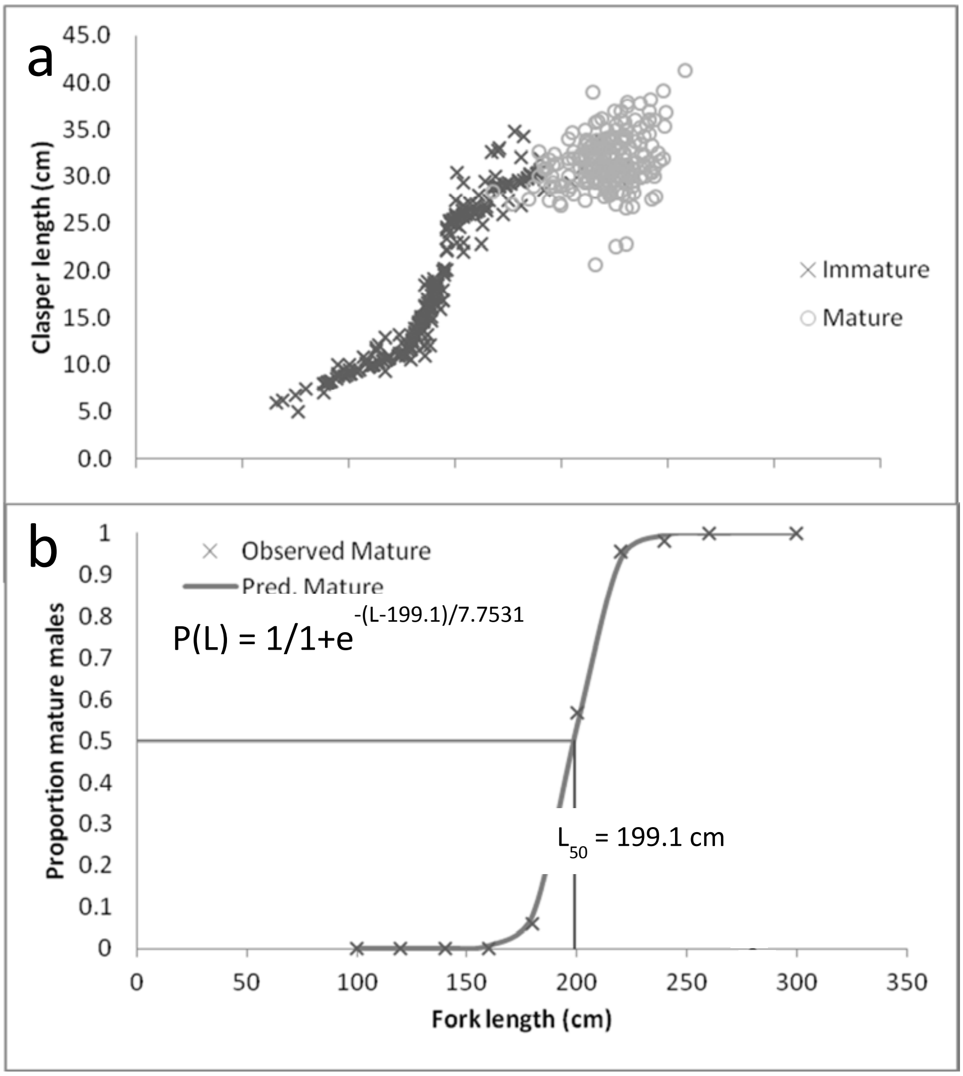

Figure 4.10. Sexual maturity of male shortfin mako shown as a) binomial maturity data relative to inner clasper (cm) and fork length (cm), (n = 476), and b) 2-parameter ogive indicating length at 50% maturity.

Female size- and age-at-maturity

A total of 44 female shortfin mako sharks were considered to be mature with a mean FL of 271.1 ± 17.3 cm. Ten females had oocytes present in the ovary, and the remaining 34 had uterus widths exceeding 50 mm. The UW of female shortfin mako sharks smaller than 250 cm did not exceed 50 mm and were considered immature (Figure 9a). The 2-parameter logistic ogive produced a L_{50} of 252.8 cm (Figure 4.11b), and the age at 50% maturity was calculated as 14 years.

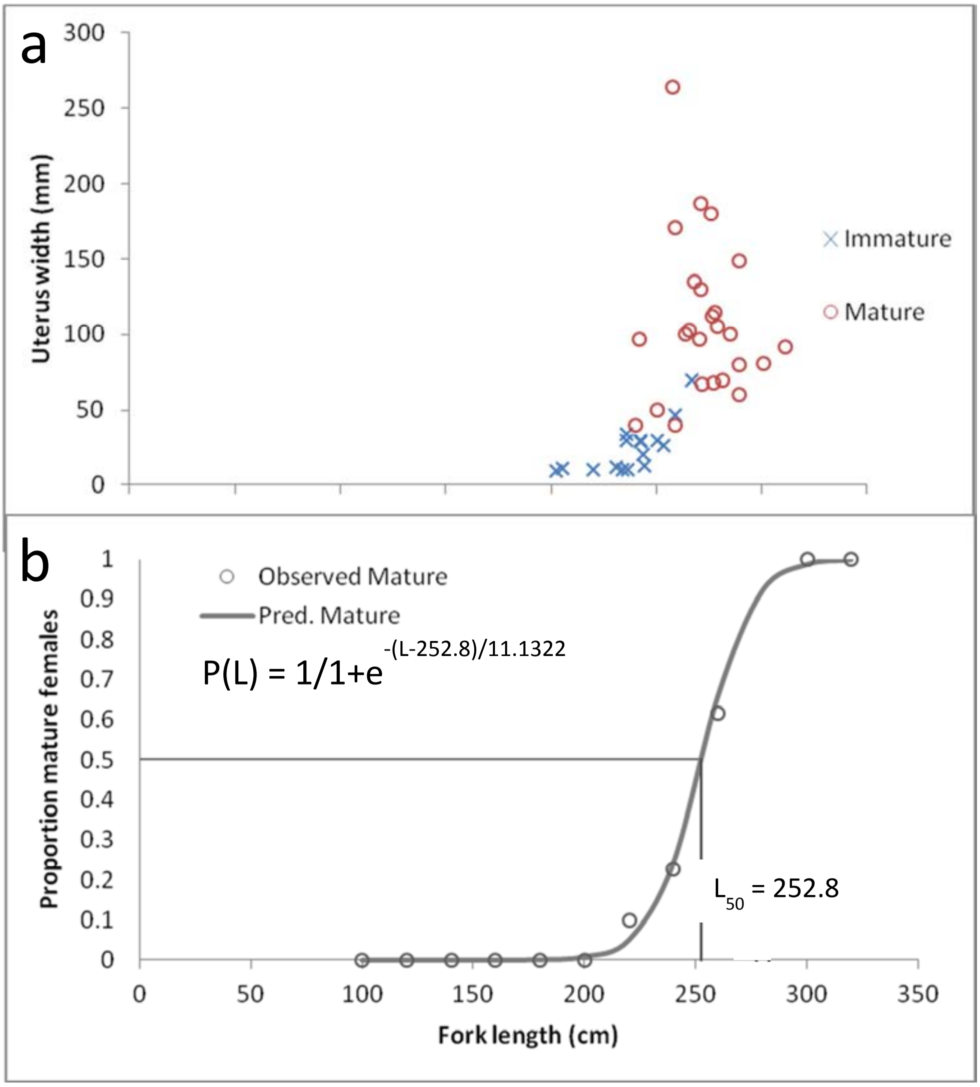

Figure 4.11. Sexual maturity of female shortfin mako sharks shown as a) binomial maturity data relative to uterus width (mm) and fork length (cm), (n = 343), and b) 2-parameter ogive indicating length at 50% maturity.

Pregnant females

In total, five pregnant females were captured in the nets and they ranged in size from 252.4 to 263.5 cm. Three females were carrying pups; the first carried 14 pups with mean pup length of 43.5 ± 1.8 cm, the second carried 12 pups with a mean length of 47 ± 1.1 cm, and the third carried nine pups of unknown size. The two other females carried fertilized eggs in their uteri.

Mating scars

Mating scars were present on two females captured in the nets. Notably, both were pregnant and had marks on one of the two pectoral fins and abdominal area (Figure 4.12).

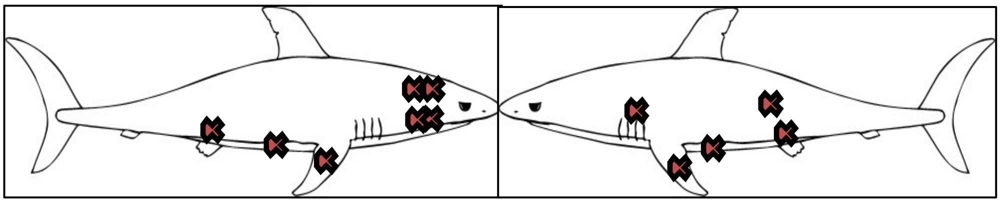

Figure 4.12. The position of the combined mating scars found on the left and right-hand-side of the two specimens captured in the nets.

4.3.3 Diet

The stomach contents of 817 shortfin mako sharks, consisting of 525 offshore (pelagic longlines) and 292 inshore (shark nets) specimens, were analyzed. An index of relative abundance (IRI) could not be calculated for prey items which were not weighed.

Inshore stomach content analyses

A total of 46 different prey items were identified; 21 to species level, 21 groupings of teleosts, elasmobranchs or invertebrates, and four items of anthropogenic origin: plastics, twine, or terrestrial refuse.

The most common prey items by weight (%W) and frequency of occurrence (%F) were elasmobranchs with 67.39% and 63.54%, respectively (Table 4.2). By frequency of occurrence, unidentified small sharks occurred in 27.62% of stomachs, followed by milk (7.18%, 65.2 IRI) and dusky sharks (4.97%, 107.6 IRI). By weight, dusky sharks made up 18.42%, followed by spotted eagle ray with 6.23% (7.7 IRI). Spotted eagle rays comprised two large individuals, and therefore contributed only 1.10% by frequency of occurrence. Prey items that only occurred once in stomachs and received an IRI of < 2 included dogfish, blacktip, smooth hammerhead and spotted ragged tooth sharks (Table 4.3).

Table 4.2. Count of individual specimens, % Weight, % Numbers, % Frequency of occurrence, and IRI of prey items in stomachs of shortfin mako sharks from inshore samples split into four categories; elasmobranchs, teleosts, cephalopods, and miscellaneous (unidentified crustaceans, man-made items, plant matter).

	Elasmobranchs	Teleosts	Cephalopods	Misc.
%W	67.39	23.58	0.11	2.46
%N	27.17	31.85	38.08	2.67
%F	63.54	43.09	39.23	7.73
IRI	6007.6	2388.8	1498.0	39.7

Teleosts were the the second most abundant group by number of but with the addition of weight, they were assigned the second highest importance according to the IRI (2388.8). A total of 13 teleosts were identified to species level and the most frequently occurring (%F) of these was spotted grunter at 2.76% (8.6 IRI). The largest group within the teleost category was unidentified teleosts (29.83%F, 976.6 IRI), with the identifiable species occurring infrequently. Squid and cuttlefish formed the majority of mollusc prey items with a combined %F of 29.83% . Cephalopods, although high in number and frequency of occurrence, only formed 0.11% by weight as these prey items were usually already digested and were therefore identified using hard part analyses (11.1 IRI). Squid were the most common mollusc and the third most frequent overall.

Table 4.3 Count of individual specimens, and percentages by number (%N), frequency (%F) and weight (%W), and the nd IRI of prey items in stomachs of shortfin mako sharks caught in nets along the inshore edge of their distribution.

	Common name	Scientific name	Count	%N	%F	%W	IRI
Elasmobranchs	unidentified small shark		50	17.92	27.62	10.76	792.3
	milk shark	*Rhizoprionodon acutus*	13	4.66	7.18	4.42	65.2
	unidentified shark		12	4.30	6.63		28.5
	dusky shark	*Carcharhinus obscurus*	9	3.23	4.97	18.42	107.6
	unidentified elasmobranch		9	3.23	4.97	0.37	17.9
	unidentified large shark		4	1.43	2.21	7.87	20.6
	requiem sharks	*Carcharhinidae*	3	1.08	1.66	3.38	7.4
	stingray	*Dasyatidae*	3	1.08	1.66	3.13	7.0
	blackspot shark	*Carcharhinus sealei*	2	0.72	1.10	4.92	6.2
	spinner shark	*Carcharhinus brevipinna*	2	0.72	1.10	3.66	4.8
	catsharks	*Scyliorhinidae*	2	0.72	1.10		0.8
	spotted eagleray	*Aetobatus narinari*	2	0.72	1.10	6.23	7.7
	dogfish	*Squalus sp.*	1	0.36	0.55	0.01	0.2
	blacktip shark	*Carcharhinus limbatus*	1	0.36	0.55	0.79	0.6
	smooth hammerhead shark	*Sphyrna zygaena*	1	0.36	0.55	2.57	1.6
	spotted raggedtooth shark	*Carcharias taurus*	1	0.36	0.55	1.38	1.0
Teleosts	unidentified teleost		54	19.35	29.83	13.38	976.6
	spotted grunter	*Pomadasys commersonnii*	5	1.79	2.76	1.33	8.6
	tunas	*Scombridae*	4	1.43	2.21	2.13	7.9
	spadefish	*Tripteron orbis*	2	0.72	1.10	0.86	1.7
	kob	*Argyrosomus japonicus*	2	0.72	1.10	1.95	2.9
	needlefishes (garfishes)	*Belonidae*	1	0.36	0.55	0.32	0.4
	sailfin rubberlip	*Diagramma pictum*	1	0.36	0.55	2.94	1.8
	blacktail	*Diplodus sargus*	1	0.36	0.55	0.13	0.3
	bronze bream	*Pachymetopon grande*	1	0.36	0.55	0.59	0.5
	german	*Polyamblyodon germanum*	1	0.36	0.55	0.52	0.5
	geelbek	*Atractoscion aequidens*	1	0.36	0.55	0.08	0.2
	cape knifejaw	*Oplegnathus conwayi*	1	0.36	0.55	0.03	0.2
	blacktip (yellowtail) kingfish	*Caranx sem*	1	0.36	0.55	0.78	0.6
	giant yellowtail	*Seriola lalandi*	1	0.36	0.55		
	chub mackerel	*Scomber japonicus*	1	0.36	0.55	0.19	0.3
	sailfish	*Istiophorus platypterus*	1	0.36	0.55		
Cephalopods	squid	*Teuthida*	29	10.39	16.02		
	cuttlefish	*Sepiida*	23	8.24	12.71		
	loligo squids	*Loligo spp.*	8	2.87	4.42		
	octopus	*Octopoda*	6	2.15	3.31		

Offshore stomach content analyses

A total of 533 stomachs were analyzed at sea and 379 (71.1%) of these were empty, presumably because shortfin mako sharks ate infrequently or everted their stomachs on capture. The remaining stomachs contained nine identifiable species of teleost. Maasbanker, *Trachurus trachurus*, occurred in 38.96% of stomachs and was the most common prey, followed by unidentified teleosts (16.23%), sardine, *Sardinops sagax* (15.58%), and loligo squid (14.94%).

Table 4.4 Frequency of occurrence (%F) and percentage by number (%N) of prey items found in the stomachs of shortfin mako sharks sampled on board a pelagic longliner in offshore waters

Common name	Scientific Name	Count	%N	%F
Maasbanker	*Trachurus trachurus*	128	46.38%	38.96%
Sardine	*Sardinops sagax*	60	21.74%	15.58%
Unidentified teleost		25	9.06%	16.23%
Loligo squid	*Loligo spp.*	22	7.97%	14.94%
John Dory	*Zeus faber*	10	3.62%	1.95%
Snoek	*Thyrsites atun*	7	2.54%	4.55%
Mackerel	*Scombridae*	6	2.17%	3.25%
Kingklip	*Genypterus capensis*	6	2.17%	0.65%
Butterfish	*Lepidocybium flavobrunneum*	5	1.81%	3.25%
Miscellaneous		4	1.45%	2.60%
Panga	*Pterogymnus laniarius*	1	0.36%	0.65%
Shortfin mako	*Isurus oxyrinchus*	1	0.36%	0.65%
Hake	*Merluccius spp.*	1	0.36%	6.49%

In contrast to the inshore stomach content analyses, only a single elasmobranch was recorded in the offshore samples (a small shortfin mako shark swallowed by a larger individual after being hooked on the longline), whereas elasmobranchs were the most frequent prey item in inshore samples. Cephalopods only made up 3.83% by numbers or 14.94% by frequency of occurrence. Both of these values were much lower than the 38.08% and 39.23% recorded for inshore samples.

Discussion

Age and growth

In this study, a key assumption of using band pair counts in vertebrae to age shortfin mako sharks was that band pairs are deposited annually. Annual deposition has been confirmed in recent studies by various methods. Campana *et al.* (2002) used radiocarbon methods and found that shortfin mako sharks deposit an annual band pair, contrary to the hypothesis put forward by Pratt and Casey (1983) that two band pairs were deposited each year. Ribot-Carballal *et al.* (2005) validated annual band pair deposition by using marginal increment analysis by analyzing the frequency of translucent and opaque edges of shortfin mako shark vertebrae by month. Natanson *et al.* (2006) injected oxytetracycline (OTC) into a shortfin mako shark which was tagged and recaptured off the east coast of South Africa; the results supported the assumption that these sharks deposit one base pair annually in the SWIO region. Use of OTC is considered to be “one of the best methods available for validating the periodicity of growth increment formation” (Campana 2001). Ideally, more than a single tagged specimen should be used for age validation and this should be an objective of further research.

A second important assumption was that the number of bands in the vertebrae of an individual shark would remain constant, irrespective of the position along the vertebral column from which the vertebrae were excised. Bishop *et al.* (2006) and Natanson *et al.* (2006) found no difference in band counts along the vertebral column of shortfin mako sharks. This finding is important within the context of the present study because vertebrae were excised from two areas of the vertebral column, immediately posterior to the head and anterior to the first dorsal fin.

Previous studies described the angle change (AC) in shortfin mako sharks as being “slight” (Natanson *et al.* 2006), or used references to other shark species (Cerna and Licandeo 2009). In the reading process of the present study, the AC could not be located consistently and therefore the first fully formed band pair was assumed to be the birth band. The AC was more apparent in some shortfin mako sharks than others, suggesting high inter-sample variability. A pre-birth band was observed in several vertebrae in this study; Ribot-Carballal *et al.* (2005) also identified this band in shortfin mako sharks from Mexico and suggested that it may be due to a feeding change from internal yolk to nutritive eggs, as this has been observed in ragged-tooth sharks *Carcharias taurus* (Branstetter and Musick 1994).

The width of the bands in younger sharks was much greater than in older sharks, where bands had become compacted towards the periphery of the corpus calcareum. It was therefore assumed that band counts of older sharks would be less accurate than those of younger sharks, possibly leading to an underestimate of the age of older sharks. Furthermore, smaller sample sizes of large sharks may have contributed to greater variability in large length classes, where fewer individuals were available for comparison. Previously, Cerna and Licandeo (2009) also attributed the larger variation observed in the reading of older sharks to the difficulty of reading and the smaller number of samples. This was also apparent in studies on *Prionace glauca* (Natanson and Skomal 2003), *Lamna nasus* (Natanson *et al.* 2002), and *Triakis megalopterus* (Booth *et al.* 2011).

In the present study, although image-enhancing software was used to assist readers to distinguish between band-pairs, several vertebral sections had to be discarded because they could not be read accurately. Campana (2001) emphasized the importance of accuracy and precision in aging studies because age and growth are amongst the most influential biological variables used in population models. To improve the accuracy of band pair counts, Campana *et al.* (2005) used enhanced digital images of vertebral sections from shortfin mako sharks from Atlantic-Canadian waters, and previous studies also used enhanced digital images and software which took measurements such as the radius of the centrum to the edge of each band, as well as the width of each band (Ribot-Carballal *et al.* 2005; Bishop *et al.* 2006; Natanson *et al.* 2006; Cerna and Licandeo 2009).

Dichotomous growth in male and female shortfin mako sharks has been documented in previous studies (Campana *et al.* 2005; Ribot-Carballal *et al.* 2005; Bishop *et al.* 2006; Natanson *et al.* 2006; Cerna and Licandeo 2009;). In the present study, growth of both sexes was similar up to the size of male maturity, whereafter the male growth rate slowed. The VBGM growth rate coefficient for females (K = 0.08 yr^{-1}) was similar to the results from recent studies from the NW Atlantic (0.087 yr^{-1}; Natanson *et al.* 2006) and the SE Pacific

(0.076 yr^{-1}; Cerna and Licandeo 2009) (Table 4.5), suggesting similar growth rates across these three ocean basins.

All eight of the ageing studies summarized in Table 4.5 reported a larger maximum size for females compared to males. In the present study, the maximum length predicted by the VBGM for males and females contradicted the previous studies by suggesting that males grow larger than females. The GPGM was, however, in agreement with the results from previous studies. Reasons for the disagreement within the VBGM could be attributed to sample size as the larger sizes were under-represented, which was also the case for Bishop *et al.* (2006). Pratt and Casey (1983) and Chan (2001) both reported biannual band pair deposition and consequently underestimated age at maturity and longevity. Several authors found that, although female shortfin mako sharks grew larger than males (larger L_∞), males grew more rapidly than females (Bishop *et al.* 2006; Natanson *et al.* 2006; Cerna and Licandeo 2009). Nevertheless, the difference in growth rates between sexes varied between studies; for instance, Cerna and Licandeo (2009) observed a much smaller difference than Natanson *et al.* (2006).

The VBGM and GPGM produced different values for longevity with the former producing a higher value for males than females (as also reported by Bishop *et al.* 2006). The estimates from the GPGM for longevity were lower than in the remaining studies in which sex – specific longevity was calculated. Based on studies completed to date, it is plausible that both males and females could reach the age of 30 as both Bishop *et al.* (2006) and Natanson *et al.* (2006) aged males of 29 years and the latter aged a female of 32 years. The difference between the models with regard to the estimated longevity may be due to the scarcity of larger individuals in samples.

Table 4.5. Growth function parameters as reported in eight previous studies together with parameters described in this study. Parameters are for the von Bertalanffy growth model unless otherwise indicated.

Study	Sex	Size Range (cm FL)	L_∞	K	T_0 (L_0)	n	Location	Age at maturity	Oldest aged	Bands/ year	Longevity (yrs)
Pratt & Casey 1983	M	69 - 328	302	0.266	-1	49	NW Atlantic	3	4.5	2	10
	F		345	0.203	-1	54	"	7	11.5	2	14
Cailliet & Bedford 1983		80.6 - 293	292.8	0.072	-3.75	44	Pacific, California (CA)	8	17	1	38
Chan 2001	M	66 - 274	267	0.312	-0.095	24	Pacific, AUS	NR	7	2	9
	F	74 - 314	349	0.155	-1.97	52	"	NR	10	2	17
Hsu 2003	M	72.6 - 250.9	321.8	0.049	-6.07	133	China	14	23.6	1	NR
	F	72.6 - 314.9	403.62	0.04	-5.27	174	"	19	30.6	1	NR
Ribot-Carballal et al. 2005		68.6	264	0.05	-4.7	109	Pacific, Baja, CA	7 M; 15 F	18	1	NR
Bishop et al. 2006	M	100 - 347	302.16	0.052	-9.04	145	Pacific, NZ	8	29	1	29
	F		732.41	0.015	-10.79	111	"	20	28	1	28
Natanson et al. 2006 *	M	72 - 260	253.3	0.125	71.6	118	NW Atlantic	8	29	1	21
Gompertz	F	64 - 340	365.6	0.087	88.4	140	"	18	32	1	38
Cerna & Licandeo 2009 *	M	76 - 285	296.6	0.087	-3.58	243	SE Pacific, Chile	NR	24	1	NR
	F	75 - 330	325.29	0.076	-3.18	304	"	NR	22	1	NR
Present Study	M	90 - 292.4	354	0.08	85	48	SW Indian Ocean, South Africa	7	22.5	1	34
	F	91 - 297	321	0.08	85	43	"	14	18.5	1	33
Gompertz	M		295	0.152	85						17
Gompertz	F		315	0.127	85						21
Validated *											
NR - Not reported											

Reproduction

The age at 50% maturity of male shortfin mako sharks was estimated as seven years (a size of 199.1 cm) whereas females achieved maturity at 14 years (252.8 cm) (Table 5). These results are similar to previous estimates for males (7 – 8 yrs) and females (15 – 20 yrs) (Bishop *et al.* 2006; Ribot-Carballal *et al.* 2005; Natanson *et al.* 2006). Male maturity is relatively easy to assess based on external criteria (clasper length and calcification) but female maturity is less straight-forward and relies on a number of internal factors that can only be observed after dissection. These include presence of embryos or egg cases in the uterus, GSI, maximum oocyte diameter (MOD), oviducal gland diameter and uterus width (Mollet *et al.* 2002 ; Ribot-Carballal *et al.* 2005; Natanson *et al.* 2006). Joung and Hsu (2005) used the same parameters for females but for males used clasper length, calcification and testes width. Francis and Duffy (2005) added terminal cartilage assessment and the presence and eruption of the spur. The inconsistency of reported parameters between studies, for age at maturation of females, reiterates what Campana (2001) reported whereby he implored researchers to improve both precision and accuracy. However, from the available literature, it is clear that that female maturity does not occur before 14 years and no later than 21 years of age in shortfin mako sharks, allowing for potential regional variation. Further in depth research is required into the age and growth methods for shortfin mako sharks, incorporating age validation, in order to establish a more precise age at maturity for females specifically.

In the present study limited data were obtained on gestation period and litter size which confirmed litter sizes of between nine and 14, consistent with the range of 8-14 pups reported in the literature (Stevens 1983; Cliff, *et al.* 1990; Mollet, *et al.* 2000; Joung and Hsu 2005). The season of parturition and the gestation period remain unclear, with a suggested peak in parturition in late winter to spring and estimates of gestation ranging from 6 to 24 months (Cliff *et al.* 1990; Mollet *et al.* 2000; Duffy and Francis 2001).

Diet

The diet of shortfin mako sharks caught inshore and offshore differed in that the former was predominantly made up of elasmobranch prey items whereas teleost prey items dominated in offshore samples. These results confirm that shortfin mako sharks are opportunists, targeting prey items with the highest abundance in a particular area (Stillwell and Kohler 1982; Cliff *et al.* 1990). MacNeil *et al.* (2005) used stable isotope analysis to reveal diet switching from cephalopods to bluefish, *Pomatomus saltatrix*, by shortfin mako sharks in the Northwest Atlantic. The stomach contents of shortfin mako sharks caught offshore in the present study were dominated by pelagic teleost species, and maasbanker (*Trachurus trachurus*) and sardines (*Sardinops sagax*) occurred in 38.96% and 15.58% of stomachs, respectively. In terms of IRI, teleosts were the most important prey group in offshore samples. This was also the finding of Maia *et al.* (2006) in a study conducted off the coast of

Portugal, where shortfin mako sharks preyed on a wide range of species but teleosts occurred in 87% of stomachs and accounted for 90% of contents by weight. Stevens (1984) found mainly teleosts, with redfish (*Centroberyx affinis*) and unidentified teleosts being the most frequently occurring items in stomachs collected off New South Wales in Australia.

Conversely, elasmobranchs were the most common prey group of shortfin mako sharks caught within 1 km of the shore in shark nets off eastern South Africa, occurring in 60.2% of stomachs and accounting for 81.7% by weight (Cliff *et al.* 1990a). In the present study, elasmobranchs occurred in 63.54 % of inshore stomach samples but in <1% of offshore samples. The identifiable elasmobranch species within the stomach samples consisted of coastal sharks, the most commonly occurring being the milk shark (*Rhizoprionodon acutus*), a continental shelf species common at 0 – 200 m depth which reaches a maximum size of approximately 1.1 m TL (Heemstra and Heemstra 2004). It is described as an abundant species in KZN. The second most frequently occurring elasmobranch was the dusky shark (*Carcharhinus obscurus*) which is also a coastal species found in warm temperate waters, and is common in KZN waters (Heemstra and Heemstra 2004).

Cephalopods were common in both inshore and offshore stomach samples with frequencies of occurrence of 39.23 % and 14.94% respectively. Maia *et al.* (2006) found a higher proportion of cephalopods than was reported by Stevens (1984) in the South Pacific but concluded that, while cephalopods were prominent in their samples, the fact that shortfin mako sharks were taken in significantly higher numbers when Atlantic mackerel (*Scomber scombrus)* were used as bait, indicated that teleosts were preferred as prey. Although loligo squid also occur offshore in the SWIO, pelagic longline fishermen who target shortfin mako sharks use mackerel as bait, either because it is easier to obtain, or because it increases shortfin mako shark catch rates.

To conclude with, growth rates and age-at-maturity of shortfin mako sharks caught off southern and eastern South Africa (SWIO region) compared well with those reported from the NW Atlantic and Pacific Oceans. Limited sample sizes and too few large individuals may have affected the growth estimates obtained from the von Bertalanffy and Gompertz growth models. Length frequency analyses showed that large adult sharks and pregnant females occur along the nearshore edge of their distribution range, whereas smaller sharks are more oceanic in character. The diet of shortfin mako sharks captured in nearshore shark nets comprised mainly elasmobranchs, whereas those in the oceanic environment fed mainly on teleosts and cephalopods.

CHAPTER 5 GENERAL CONCLUSIONS AND RECOMMENDATIONS FOR MANAGEMENT AND FUTURE RESEARCH

5.1 General conclusions

Of all hooks deployed, 67.6% were directed at tuna, 28.7% at swordfish and 3.8% at sharks. Shark-directed vessels yielded the largest catches (and highest CPUE) of sharks; vessels directed at tuna captured more sharks than swordfish vessels (31677 versus 17373 sharks reported), however swordfish vessels had a higher CPUE of sharks (1.8 ± 4.3 versus 1.9 ± 3.9 sharks/1000 hooks). Shark CPUE was influenced by fishing area, season and flagstate; the highest CPUE values were found for the Agulhas Bank, autumn season and “other” flagstates (Namibia, Seychelles, Iceland, Panama, Philippines, St. Vincent islands and unknown or unrecorded vessel flag state) based on both logbook and observer databases.

CPUE of shark bycatch decreased over time based on observer data, whereas it increased based on logbook data. The increase in logbook data suggests initial under-reporting of shark bycatches, followed by improved reporting practices in latter years. Observers reported 15 species (or species groups) of sharks, compared to only four in logbooks. Few carcharhinid sharks were reported in logbooks. Based on observer data, crocodile sharks and a higher proportion of carcharhinid sharks were captured off the East Coast compared to the Agulhas Bank and South Coast, where shark bycatches were dominated by blue- and shortfin mako sharks.

Small (mainly immature) shortfin mako sharks were captured by longliners on the offshore Agulhas Bank, whereas individuals captured by the inshore KZN bather protection nets were primarily large animals and pregnant females. Furthermore, larger shortfin mako sharks were captured by longliners operating off the east coast (East Coast 2) than at the Agulhas Bank, and the highest CPUE appeared to be concentrated around the 200 m depth isobath in all regions. Based on these observations, it is suggested that adult shortfin mako sharks use the near- and offshore environment along the eastern coast of South Africa, and that the young migrate downstream, roughly following the shelfbreak (i.e. 200 m isobath) and using the Agulhas Current, to concentrate in the Agulhas Bank region.

Gompertz and von Bertalanffy growth models based on vertebral band counts (annual deposition assumed) produced $L\infty$ estimates of 315 and 321 cm FL for males, and of 295 and 354 cm for females, and k estimates of 0.08 to 0.152 year^{-1}. Females matured at a FL of 252.8 cm (14 years old) and males at 199.1 cm (7 years old), and longevity was estimated at 17 – 34 years for males and 21 – 33 years for females. Apart from the longevity estimates, growth and maturity of shortfin mako sharks in the SWIO appeared to be similar to those in the NW Atlantic and Pacific Oceans. Sharks captured in nearshore shark nets predated mainly on other elasmobranchs, whereas those in the offshore oceanic environment fed mainly on teleosts (mostly maasbanker *Trachurus trachurus*) and cephalopods.

5.2 Management recommendations

Based on the results of the present study, the following management measures are put forward for consideration:

Development of a spatial management framework for pelagic longline fisheries that catch sharks as a targeted or bycatch.

- Research finding: The quantities and species composition of sharks in bycatches of pelagic longliners depended on area, with gradients along the northeast – southwest axis. Shark CPUE declined from west to east, but the number of shark species in catches increased in the east, particularly crocodile sharks and carcharhinids. A size gradient suggested that adult shortfin mako sharks are more common at East Coast 2, and that smaller sharks occur offshore and on the Agulhas Bank.

- Management proposals:
  a) That the South African EEZ be subdivided into management zones, and that depending on the primary target species (i.e. tuna, swordfish or sharks) shark bycatch limits be set.

b) That the spatial trends in shortfin mako shark size between the Agulhas Bank and the Mozambique border be taken into account in developing spatial management plans for this species.

Enhanced deployment of trained fisheries observers to provide accurate information on shark bycatches (species, quantities, size and location), and the incorporation of this information into assessments and management strategies.

- Research findings: Under-reporting of shark bycatches occurred in the tuna-directed fishery, to the extent that logbook and observer-based indices indicated contrasting trends in shark abundance. Logbook data combined shark bycatches into four species-groups; observer data provided a finer resolution by species.

- Management proposals:

  a) Regular deployment of fisheries observers to collect accurate fisheries and biological data;

  b) Incorporation of observer data into assessments to develop fisheries management strategies;

  c) Use observer data to do species-specific studies on the most common shark species (i.e., shortfin mako sharks; blue sharks; crocodile sharks; bronze whaler sharks).

Improved control over shark-finning practices by using landing restrictions

- Research finding: Decline in shark catches based on observer data

- Management proposals:

a) Sharks to be landed with fins naturally attached to the carcass i.e. the use of fin-to-carcass ratios should be abolished. Countries which already have successfully implemented this measure are Costa Rica, Ecuador, Oman, Colombia, Panama, El Salvador, and the United States of America waters of the Atlantic and Gulf of Mexico (Fowler and Séret 2010). Fins can be partially detached and folded against the body before freezing thus enabling efficient storage.

Tight control of shark-directed fishing operations until they have ceased, and use of population parameters for determining sustainable exploitation strategies for shortfin mako sharks:

- Research findings: Decline in shortfin mako shark catches based on observer data. Chapter 3 showed that larger shortfin mako sharks occurred inshore and further east. Chapter 2 showed that shark-directed vessels fished less often in July and August, possibly because of bad weather on the Agulhas Bank. Males and female shortfin mako sharks achieve maturity at 199.1 cm FL and 252.8 cm FL, respectively.

- Management proposals
  a) Set a realistic upper catch limit for shortfin mako sharks.

  b) Area closures to be considered, taking into account the size gradient of shortfin mako sharks along the coast and abundance of immature sharks on the Agulhas Bank.

  c) Closed fishing season to be considered, possibly using the period when bad weather disrupts fishing activities (i.e. June- September) .

  d) Total Allowable Effort (TAE) for shark-directed vessels to be maintained (or reduced) during the phase-out period.

  e) Minimum legal size limits to be considered for shortfin mako sharks. Although difficult to enforce, such a measure is used in the European Union (EU) for porbeagle sharks (*Lamna nasus*). Based on the size at maturity, a MLS of 200 cm FL can be considered.

5.3 Future research

The collection of species-specific data of shark catches by fisheries observers placed on pelagic long-line vessels is the most cost-effective and comprehensive method of obtaining good-quality fisheries and biological information that can be used in future research. This tool should be used, and enhanced, to stimulate species-specific projects on the distribution patterns, abundance and biology of the most commonly caught shark species.

It is presently unknown where shortfin mako sharks breed in the SWIO region; whether catches of shortfin mako sharks by shark-directed fishing is sustainable; what the migratory patterns of this species are; and whether shortfin mako sharks in the SWIO belong to a single genetic stock. Future research should include tagging studies, assessments to gauge trends in abundance, and a genetic study of metapopulations.

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