

Size, sex and reproductive biology of seven pelagic sharks in the eastern Arabian Sea

SIJO P. VARGHESE, N. UNNIKRISHNAN, DEEPAK K. GULATI AND A. E. AYOOB

Cochin Base of Fishery Survey of India, Kochangadi, Kochi – 682005, India

*Studies on reproduction in sharks are important for their management, since the attainment of sexual maturity has a substantial impact on their distribution, behaviour and biology. However, reproductive biology of large oceanic sharks is poorly studied in the Indian seas. In this study, the size structure, sex and maturity of pelagic thresher (*Alopias pelagicus*), bigeye thresher (*A. superciliosus*), oceanic whitetip shark (*Carcharhinus longimanus*), tiger shark (*Galeocerdo cuvier*), shortfin mako (*Isurus oxyrinchus*), longfin mako (*I. paucus*) and blue shark (*Prionace glauca*) in the eastern Arabian Sea are described based on 1449 specimens collected from gillnet-cum-longline landings at the Cochin fisheries harbour during 2013–2014. Sex ratios of sampled specimens were biased to males in pelagic thresher, bigeye thresher, tiger shark and blue shark, while females dominated in the specimens of oceanic whitetip shark. Females matured at greater lengths than males in all species except oceanic whitetip shark. Lengths at maturity for males were in the range of 189.05–286.56 cm, whereas those of females were in the range of 187.74–310.69 cm. Litter sizes of both the thresher shark species were always two, while in oceanic whitetip shark, litter size was 3–9 and 22–51 in tiger shark. Seasonal reproduction was noticed in oceanic whitetip shark and tiger shark. Pregnant females were not found in the blue shark, shortfin and longfin makos sampled during the study period. Reproductive aspects of pelagic thresher, bigeye thresher, oceanic whitetip shark, tiger shark, shortfin mako, longfin mako and blue sharks in the eastern Arabian Sea are generally consistent with earlier reports from other regions of the world's oceans. These preliminary findings should be useful to identify suitable management measures for the above shark species.*

Keywords: length at maturity, pelagic thresher (*Alopias pelagicus*), bigeye thresher (*Alopias superciliosus*), oceanic whitetip shark (*Carcharhinus longimanus*), tiger shark (*Galeocerdo cuvier*), shortfin mako (*Isurus oxyrinchus*), longfin mako (*Isurus paucus*), blue shark (*Prionace glauca*)

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INTRODUCTION

Pelagic sharks are important components of the oceanic pelagic ecosystem, functioning as apex predators and scavengers, exerting significant impact on other species of the marine food web (Cortés, 1999; Kitchell *et al.*, 2002). The population dynamics of most of these sharks are characterized by slow growth, late maturity and low fecundity and therefore they can withstand only modest level of fishing without depletion and stock collapse (Camhi *et al.*, 1998). Due to increasing demands for shark flesh for human consumption, fins for shark fin soup, liver oil for vitamin extraction and hides for leather (Compagno, 2002), sharks are increasingly exploited both by targeted fisheries and as by-catch of fisheries targeting tunas and swordfish (Stevens *et al.*, 2000). Scientists have documented growing concern over the widespread decline of shark populations due to this increased fishing mortality and had advocated for immediate adoption of management measures for arresting the rapid depletion of sharks (Stevens *et al.*, 2000). Detailed information on the life history traits is essential for identifying suitable management measures for a given species. Studies on the maturity on sharks are of high

importance in their management, since the attainment of sexual maturity has substantial impact on their distribution, behaviour and biology (Francis & Duffy, 2005).

The pelagic thresher (*Alopias pelagicus* Nakamura, 1935), bigeye thresher (*A. superciliosus* Lowe, 1841), oceanic whitetip shark (*Carcharhinus longimanus* (Poey, 1861)), tiger shark (*Galeocerdo cuvier* (Péron & Lesueur, 1822)), shortfin mako (*Isurus oxyrinchus* Rafinesque, 1810), longfin mako (*I. paucus* Guitart, 1966) and blue shark (*Prionace glauca* (Linnaeus, 1758)) constitute a significant proportion of oceanic sharks harvested in India (Varghese *et al.*, [in press](#)). Sarangdhar (1943, 1949) described the pregnant tiger sharks and their embryos collected from the shark landings at Bombay, India. However, there is a dearth of detailed information on the reproductive aspects of these oceanic pelagic sharks in Indian seas. In this perspective, the present study aimed to describe the size, sex and maturity of seven pelagic sharks caught in the oceanic fishery of the eastern Arabian Sea.

MATERIALS AND METHODS

Pelagic shark specimens for this study were collected from the sharks landed at the Cochin fisheries harbour (south-west India, 9°56'N 76°15'E) during January 2013 to December 2014. Monthly samplings were made on the shark landings by mechanized drift gillnet-cum-longline fleet based at

Corresponding author:
S.P. Varghese
Email: varghesefsi@hotmail.com

Cochin. This fishery deploys about 210 mechanized boats of 10–20 m overall length (L_{OA}), targeting large pelagics. The drift gillnets operated by this fishery are of maximum 2000 m length and 11 m hung depth with mesh size 100–350 mm, whereas monofilament longlines with steel wire leaders and circle, 'J' or tuna hooks, usually with live baits are used in longline operations, deploying 500–1000 hooks in a day's operation. The fishing area spans the entire western Indian Exclusive Economic Zone (EEZ, Figure 1). Fishing operations were suspended in June and July every year due to the closed fishing season.

The total lengths (L_T) of individual sharks were measured using a measuring tape and sexes were discriminated by examining the presence of claspers. In males, the outer clasper length (C_{LO}) was measured from the clasper tip to the edge of pelvic fin and the condition of the claspers were noted before the fish was eviscerated at the harbour. Males were classified as immature (claspers are non-calcified or semi-calcified, testes are soft, elongated and not lobated or starting to lobate) and mature (claspers are fully calcified and can be rotated 180 degrees, rhipidion can be splayed easily and testes lobated). Similarly, female specimens were classified as immature (ovary small, oocytes white or translucent, thin oviducts, oviducal glands and uteri poorly developed) and mature (well developed ovary, uteri, oviducal glands and egg capsules, fertile eggs or embryos present in the uteri). Testes from males and ovary, eggs, oviducal glands and uteri from females were measured and weighed. In pregnant females, the embryos were extracted from the uteri, enumerated, sexed, measured and weighed. Following the method from Harry *et al.* (2013), a logistic regression was fitted to binomial maturity data (0 = immature; 1 = mature) vs total length using GLM procedure in R with the argument family 'logit' (R Core Team, 2013) to predict the lengths at which 50% (length at maturity, L_{T50}) and 95% (L_{T95}) of the individuals are

mature. The length at birth (L_b) was estimated from the maximum size of embryos recovered from the uterus and the minimum size of free-swimming specimens captured (Liu *et al.*, 1999).

RESULTS

Overall, 1449 specimens of pelagic sharks in the L_T range of 65–361 cm were subjected for biological studies during the study period (Table 1). Sex ratio was biased to males in blue, threshers, longfin mako and tiger sharks, while females dominated in the specimens of oceanic whitetip shark. The length frequency distributions indicated variations in the total lengths of male and female specimens in all the species. However, a Kolmogorov–Smirnov test did not reveal any statistically significant differences in the length frequencies. The length at maturity, litter size and size at birth varied widely among different species studied. However, reproductive strategy in both the thresher shark species was similar, including litter size (always two), mode of nutrition to embryos (oophagy) and seasonality and periodicity in reproduction (non-seasonal reproduction with annual reproductive cycle).

Alopias pelagicus

A total number of 656 pelagic threshers, in the L_T range of 142–319 (248.16 ± 31.92 ; mean \pm standard deviation) cm were studied. The overall sex ratio (F:M) was 1:1.61, which significantly varied from the expected ratio of 1:1 ($\chi^2 = 36.15$, $P < 0.05$). Male specimens collected were in the L_T range of 142–312 (249.98 ± 29.95) cm, whereas the L_T of females ranged between 144 and 319 (245.02 ± 34.37) cm (Figure 2). However, the length frequencies distributions of males and females did not show significant differences (Kolmogorov–Smirnov test: $D = 0.22$; $P > 0.05$).

The C_{LO} of smallest male was 2.3 cm while that of largest specimen was 18.7 cm and noticeable increase in the C_{LO} starts with the size class 230–235 cm (Figure 3). Smallest mature male specimen was 245 cm while the largest immature male was L_T 270 cm. The L_{T50} estimated was 254.96 cm (Figure 4) and the L_{T95} estimated was 278.04 cm (Table 2). The females start maturing at 268 cm L_T and all the females larger than 286 cm were mature. The immature specimens had ovaries in the weight range of 10.7–323 g, whereas those of mature specimens were in the range of 185.3–1215.7 g, and the ovary weights of pregnant females were in the range of 480.3–2834 g. In females, the L_{T50} estimated was 271.39 cm and the L_{T95} was 287.18 cm. In pelagic threshers, only two eggs are fertilized; these are then enclosed in egg capsules, reach one uterus each and develop there. Overall, 21 pregnant females, in the L_T range of 282–319 cm were recorded, almost throughout the year. All pregnant females carried two embryos, one in each uterus. The sex ratio of embryos did not vary significantly from parity ($\chi^2 = 0.381$, $P > 0.05$). The embryos were in the L_T range of 16.8–137.8 cm and the temporal analysis of mean length of embryos could not reveal seasonal reproduction of pelagic threshers in the eastern Arabian Sea. The largest embryo of L_T 137.8 cm was recorded during May 2014, and had the typical colouration and features of free-swimming specimens. The smallest free-swimming specimen was a 142 cm (L_T) male recorded in September 2013. It is therefore

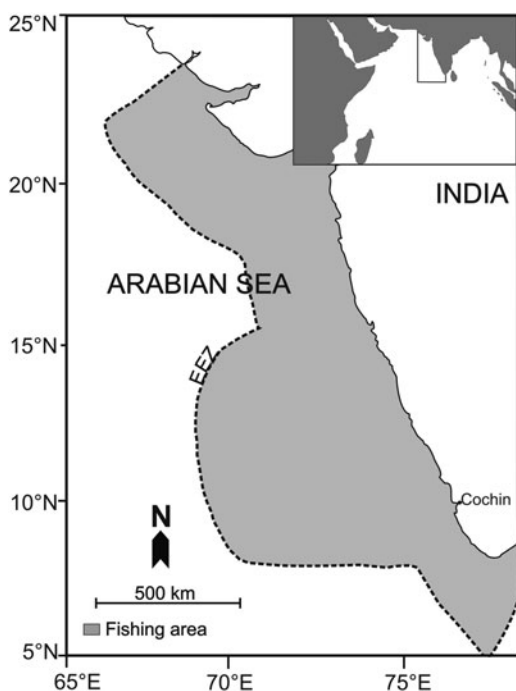


Fig. 1. Map of the study area, the western Indian Exclusive Economic Zone (eastern Arabian Sea).

Table 1. Length, sex ratio, maturity and litter size of pelagic sharks in the eastern Arabian Sea (L_T , Total length; SD, standard deviation).

Species	<i>A. pelagicus</i>	<i>A. superciliosus</i>	<i>C. longimanus</i>	<i>G. cuvier</i>	<i>I. oxyrinchus</i>	<i>I. paucus</i>	<i>P. glauca</i>
No of specimens	656	217	212	217	96	25	26
Sex ratio (F:M)	1:1.6	1:1.4	1:0.9	1:1.1	1:1.0	1:1.3	1:5.5
L_T (cm)	142–319	135–361	65–265	85–398	97–269	140–258	186–280
L_T Mean \pm SD (cm)	248.16 \pm 31.92	254.35 \pm 38.92	155.43 \pm 38.32	198.23 \pm 59.54	168.73 \pm 37.56	167.57 \pm 35.05	218.93 \pm 20.30
Size at birth (cm)	137.8–142	118–135	64.2–65.0	79.6–85.2	^a	^a	^a
Litter size	2	2	3–9 (5.8 \pm 2.39)	22–51 (35.25 \pm 8.94)	^a	^a	^a

^aPregnant females were absent in the specimens collected.

inferred that the size at birth of pelagic threshers in the eastern Arabian Sea will be 137.8–142 cm. Only the right ovary was functional and pregnant females had huge ovaries, containing thousands of vitelline eggs which were supplied to the embryos in the form of nutritive egg capsules. Nutritive egg capsules contained varying numbers of eggs (12–62) and a steady increase in the size and number of eggs in the nutritive egg capsules were noticed with increasing embryo size (linear regression, nutritive egg capsule length = 0.058 embryo length + 2.628; $R^2 = 0.947$ and number of eggs in egg capsule = 0.385 embryo length + 5.293; $R^2 = 0.931$).

Alopias superciliosus

A total of 217 specimens of bigeye threshers, in the L_T range of 135–361 (254.35 \pm 38.92) cm were sampled. The overall sex ratio (1F:1.44M) significantly varied from the expected ratio of 1:1 ($\chi^2 = 7.01$, $P < 0.05$). Male specimens collected were in the L_T range of 135–327 (250.89 \pm 32.68) cm, whereas the L_T of females ranged between 145 and 361 (259.33 \pm 46.20) cm (Figure 5). However, the total lengths of males and females did not show significant differences (Kolmogorov–Smirnov test: $D = 0.15$; $P > 0.05$).

The outer clasper lengths of males were in the range of 3.2–22.4 cm and noticeable increase in the C_{LO} starts when L_T reaches 224 cm (Figure 6). Smallest mature male specimen was 247 cm while the largest immature male was of L_T 280 cm. The L_{T50} estimated was 263.50 cm and the L_{T95} was estimated to 282.98 cm. The females start maturing at 282 cm L_T and all the females larger than 322 cm were mature. Total number of immature females recorded was 76, number of mature females excluding pregnant was 5 and the number of pregnant females was 8. The immature specimens had ovaries in the weight range of 1.9–325.5 g, whereas those of mature specimens were in the range of 870.3–1112.9 g, while the ovary weights of pregnant females were in the range of 1823.4–2615 g. In females, the L_{T50} estimated was 310.69 cm (Figure 7) and the L_{T95} was estimated to 345.13 cm. Similar to pelagic threshers, only two eggs become fertilized in bigeye threshers, which are then enclosed in egg capsules, reach one uterus each and develop there. Eight pregnant females, in the L_T range of 283–361 cm were recorded, almost throughout the year. All pregnant females carried two embryos, one in each uterus. The sex ratio of embryos (1F:0.78M) did not vary significantly from parity ($\chi^2 = 0.25$, $P > 0.05$). The embryos collected were in the L_T range of 19.0–118.0 cm and the temporal analysis of mean length of embryos could not reveal seasonal reproduction in this species either. The largest embryo of L_T 118.0 cm weighing 3.5 kg was recorded during March 2014, which had the typical colouration and features of free-swimming specimens. The smallest neonate was a male specimen of L_T 135 cm recorded during April 2013. The size at birth of bigeye threshers in the eastern Arabian Sea will be 118–135 cm. Similar to the pelagic threshers, in bigeye threshers the functional right ovary of pregnant females was huge, containing thousands of vitelline eggs which were supplied to the embryos in the form of nutritive egg capsules. Nutritive egg capsules contained varying number of eggs and, similar to pelagic threshers, the size and number of eggs in the egg capsules increased with increasing embryo length in this species (Figure 8).

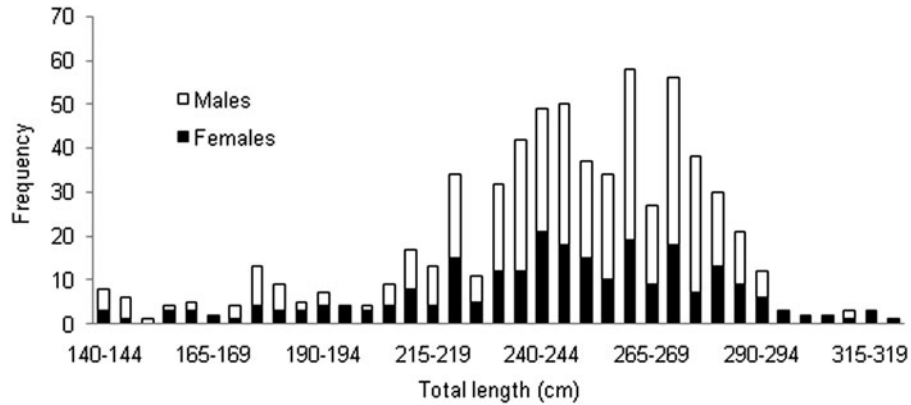


Fig. 2. Total length frequency of pelagic threshers sampled from the eastern Arabian Sea.

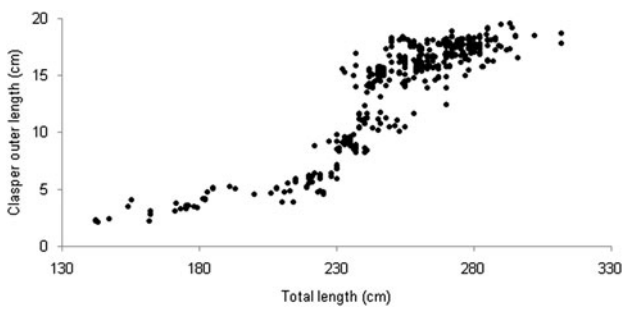


Fig. 3. Total length and clasper length of male pelagic threshers sampled from the eastern Arabian Sea.

Carcharhinus longimanus

The total lengths of 212 oceanic whitetip shark specimens sampled during the study were in the range of 65–265 (155.43 ± 38.32) cm. The overall sex ratio was near to parity (1:0.93; F:M) ($\chi^2 = 0.30, P > 0.05$). Male specimens collected were in the L_T range of 65–265 (164.30 ± 44.03) cm, whereas the L_T of females ranged between 69 and 246

(147.20 ± 30.08) cm (Figure 9). Statistically significant differences in the length frequencies of males and females were also absent in the species (Kolmogorov–Smirnov test: $D = 0.17; P > 0.05$).

The C_{LO} of the smallest male was 1.5 cm while that of the largest specimen was 17.2 cm and a noticeable increase in the C_{LO} starts when L_T reaches 187 cm (Figure 10). The smallest mature male specimen was 202 cm while the largest immature male was of L_T 225 cm and the length at maturity (L_{T50}) estimated was 207.19 cm while the L_{T95} was estimated to 226.74 cm. The females start maturing at 185 cm L_T and all the females longer than 203 cm were mature. The oviducal gland widths of immature specimens were in the range of 0.5–2.2 cm, those of mature specimens were in the range of 4.0–5.5 cm, and in pregnant females the oviducal gland widths were in the range of 5.6–6.4 cm. The uterus widths in immature specimens were in the range of 0.8–2.3 cm, mature specimens in the range of 4.9–5.7 cm, and in pregnant females the uterus widths were in the range of 12.2–16.2 cm. In females, the L_{T50} estimated was 187.74 cm (Figure 11) and the L_{T95} estimated was 203.27 cm. Only five pregnant females, in the L_T range of 183–246 cm were recorded, during the months February, May and September. A total number of

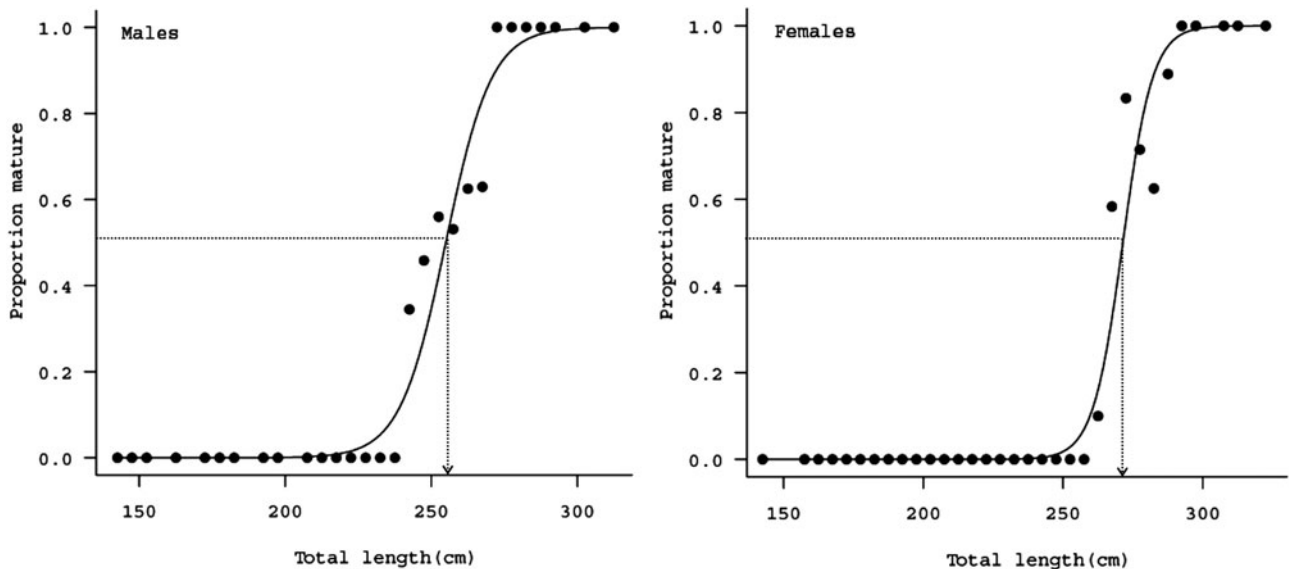


Fig. 4. Logistic curves fitted to maturity in relation to total lengths of pelagic threshers of the eastern Arabian Sea. Dashed lines indicate length at maturity.

Table 2. Length at 50% maturity (L_{T50}) and the length at 95% maturity (L_{T95}) of pelagic sharks in the eastern Arabian Sea (SE, standard error).

Species	Males		Females	
	L_{T50} (SE)	L_{T95} (SE)	L_{T50} (SE)	L_{T95} (SE)
<i>Alopias pelagicus</i>	254.96 (1.25)	278.04 (2.63)	271.39 (1.45)	287.18 (3.09)
<i>Alopias superciliosus</i>	263.50 (2.03)	282.98 (4.22)	310.69 (6.44)	345.13 (13.03)
<i>Carcharhinus longimanus</i>	207.19 (3.66)	226.74 (6.26)	187.74 (3.11)	203.27 (6.96)
<i>Galeocerdo cuvier</i>	286.56 (5.62)	306.87 (13.37)	300.31 (9.69)	347.26 (21.58)
<i>Isurus oxyrinchus</i>	189.05 (6.84)	222.88 (14.23)	266.42 (7.46)	289.14 (28.75)
<i>Prionace glauca</i>	207.11 (4.42)	228.56 (9.69)	^a	^a
<i>Isurus paucus</i>	206.77 (34 704.51)	209.07 (36 163.03)	^a	^a

^aLength at maturity could not be estimated due to inadequate sample size.

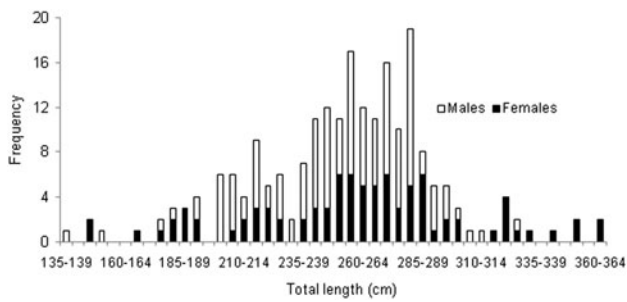


Fig. 5. Total length frequency of big eye threshers sampled from the eastern Arabian Sea.

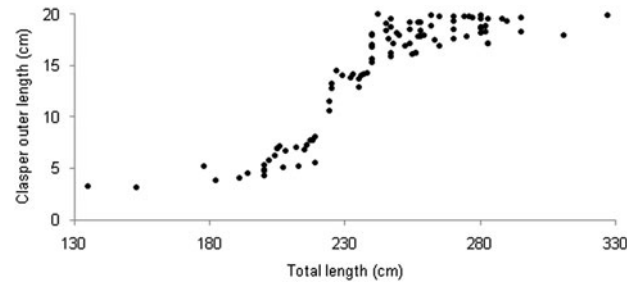


Fig. 6. Total length and clasper length of male bigeye threshers collected from the eastern Arabian Sea.

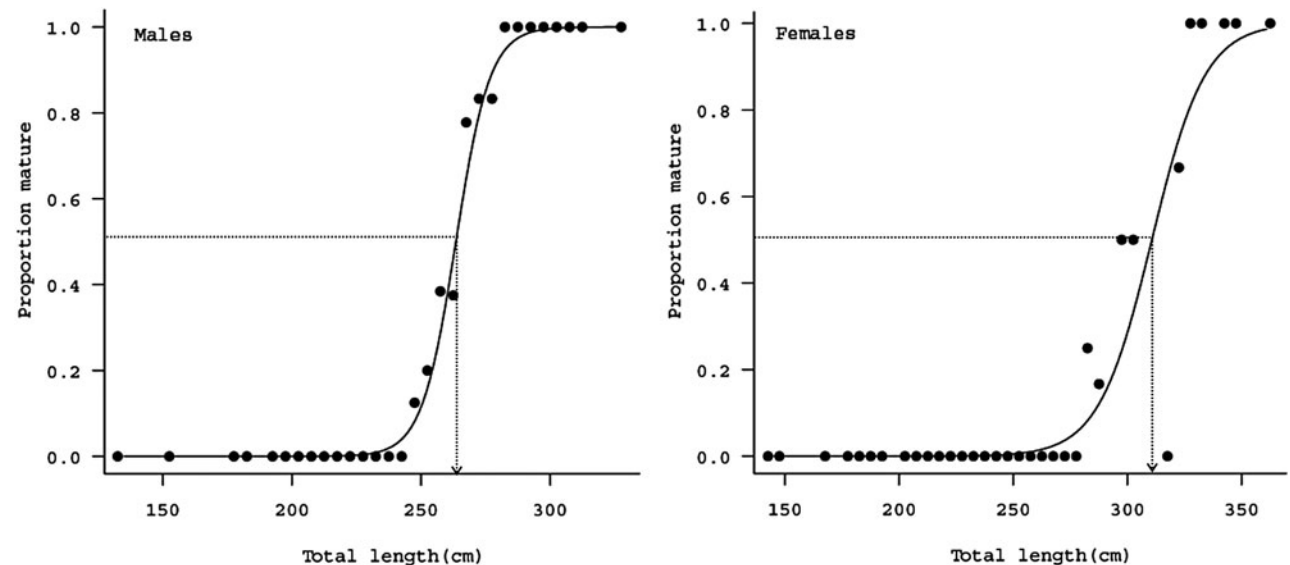


Fig. 7. Logistic curves fitted to maturity in relation to total lengths of bigeye threshers of the eastern Arabian Sea. Dashed lines indicate length at maturity.

29 embryos, in the L_T range of 7.2–64.2 cm were recovered from the uteri. Numbers of embryos in females were in the range of 3–9 (5.8 ± 2.39) and the relationship between the L_T of mothers and number of embryos was given by $y = 0.0697x - 8.524$ ($R^2 = 0.55$), indicating a moderate relationship between the mother's length and litter size. No significant differences in the number of embryos in left and right uteri (Student's t-test, $P > 0.05$) were observed. The sex ratio of embryos (1F:0.81M) did not vary significantly from parity ($\chi^2 = 0.31$, $P > 0.05$). The near term embryo of L_T 64.2 cm was recorded during February 2014, and considering the smallest neonate was 65 cm, the size at birth will be 64.2–65.0 cm. Since the near term embryo was recorded during February and the smallest neonate was recorded during March, it is concluded that the parturition will be taking place during March–May. Considering the record of smallest embryo during May and the largest in February, it is postulated that the gestation period may be little less than one year.

Galeocerdo cuvier

A total of 217 specimens of tiger sharks, in the L_T range of 85–398 (198.23 ± 59.54) cm were sampled. The overall sex ratio was 1F:1.09M, which did not significantly vary from the expected ratio of 1:1 ($\chi^2 = 0.37$, $P > 0.05$). Male specimens collected were in the L_T range of 89–355 (199.39 ± 54.06) cm,

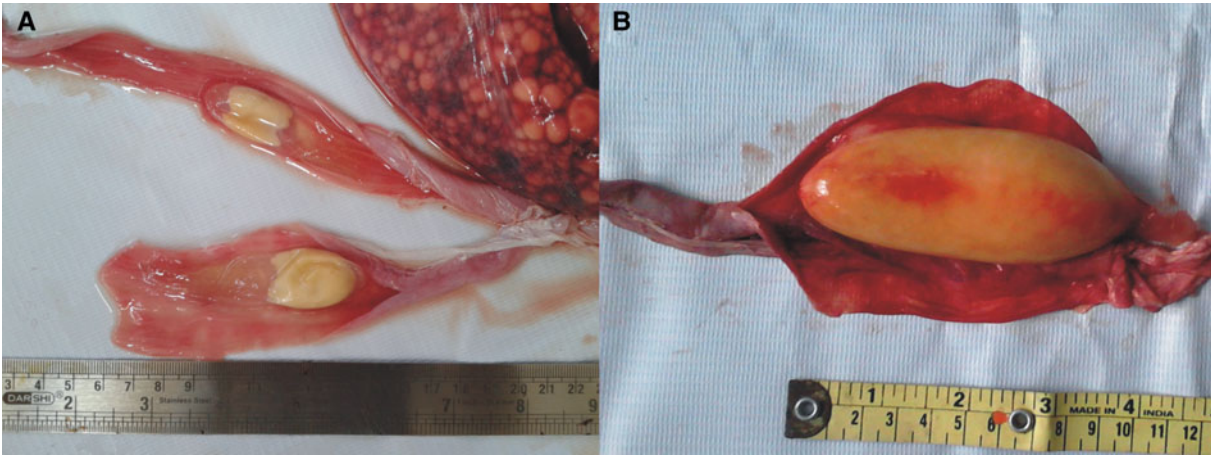


Fig. 8. Nutritive egg capsules supplied to bigeye thresher embryos of 34 cm L_T (A) and 118 cm L_T (B).

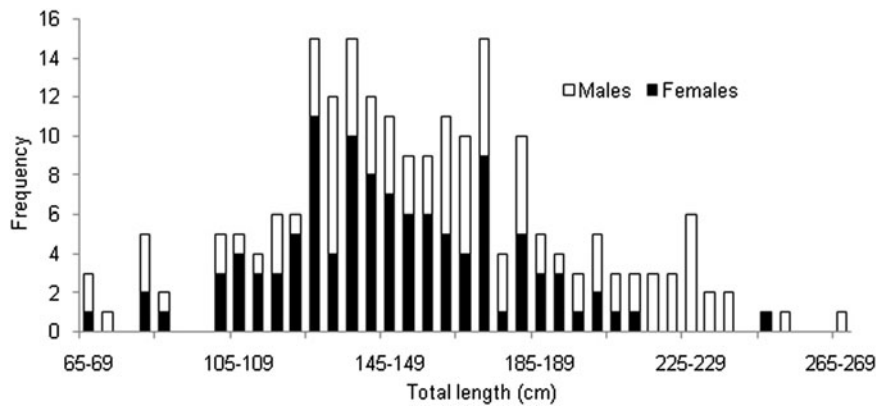


Fig. 9. Total length frequency of oceanic whitetip sharks sampled from the eastern Arabian Sea.

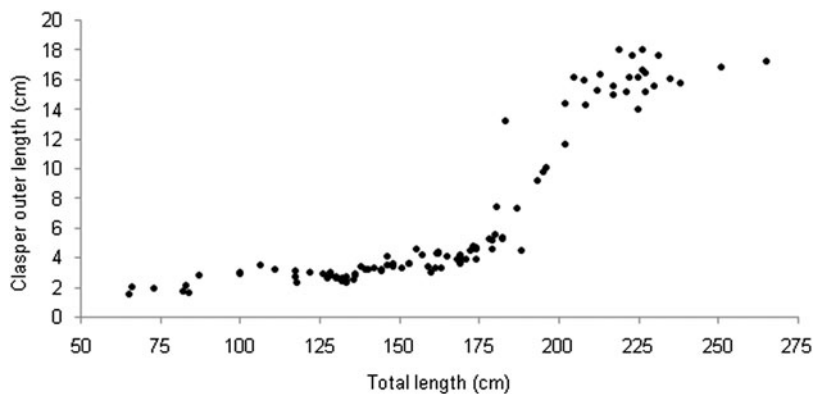


Fig. 10. Total length and clasper length of male oceanic whitetip sharks collected from the eastern Arabian Sea.

whereas the L_T of females ranged between 85 and 398 (196.97 ± 65.21) cm (Figure 12). However, the total lengths of males and females did not show significant differences (Kolmogorov–Smirnov test: $D = 0.063$; $P > 0.05$) in this species also.

The outer clasper lengths of male specimens were in the range of 1.9–24.0 cm and noticeable increase in the C_{LO} starts with the L_T 247 cm (Figure 13). Smallest mature male specimen was 272 cm while the largest immature male was

L_T 287 cm. The L_{T50} estimated was 286.56 cm (Figure 14) and the L_{T95} was 306.87 cm. The females start maturing at 274 cm L_T and all the females longer than 310 cm were mature. In females, the L_{T50} estimated was 300.31 cm while the L_{T95} was 347.26 cm.

Total number of immature females recorded was 94, the number of mature females excluding pregnant was 2 and the number of pregnant females was 8. Average number of yolked eggs in mature females was 23.4. Ovarian eggs

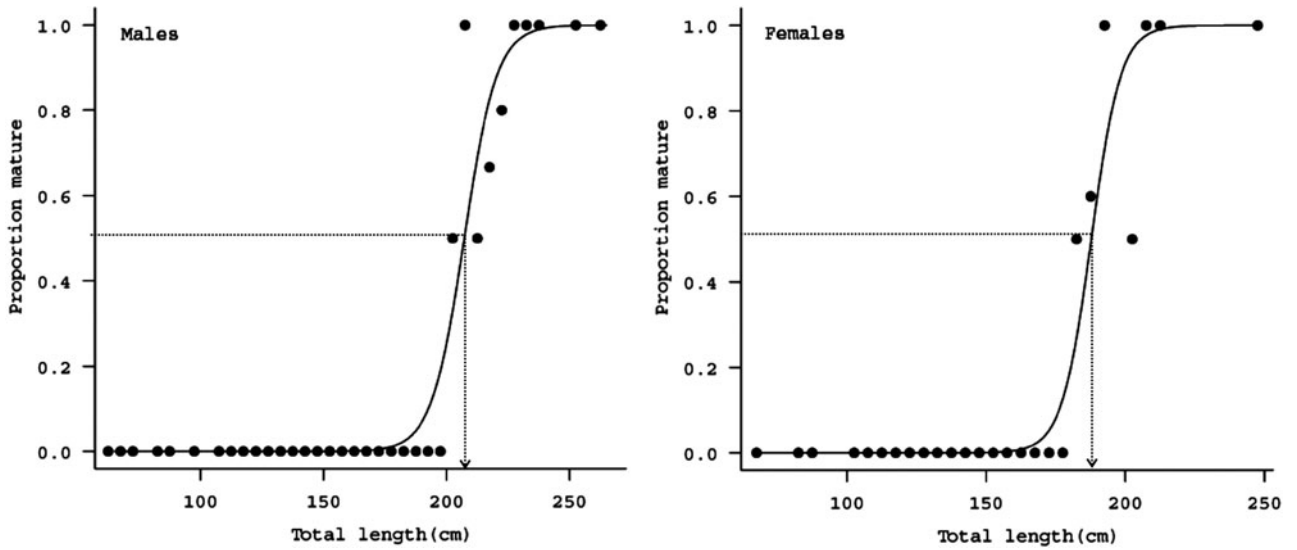


Fig. 11. Logistic curves fitted to maturity in relation to total lengths of oceanic whitetip sharks of the eastern Arabian Sea. Dashed lines indicate length at maturity.

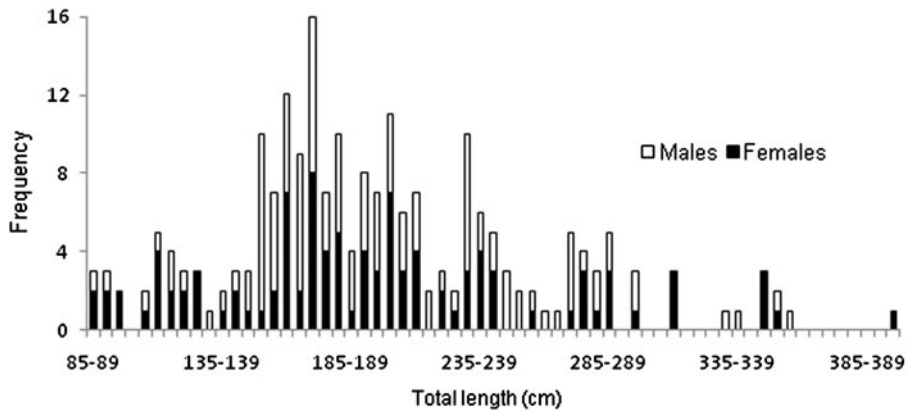


Fig. 12. Total length frequency of tiger sharks sampled from the eastern Arabian Sea.

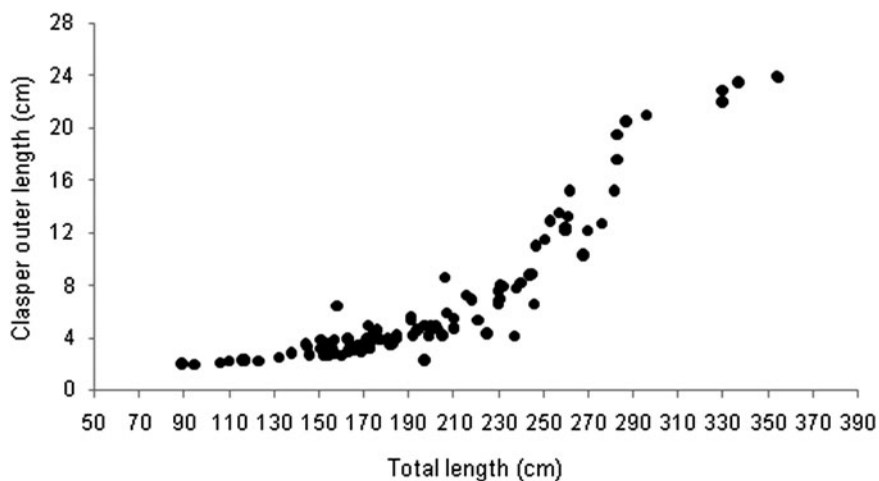


Fig. 13. Total length and clasper length of male tiger sharks collected from the eastern Arabian Sea.

measured 0.2–7.1 cm diameter and the diameters of oviducal glands were in the range of 1.3–11.2 cm. During the study, eight pregnant females were sampled, almost throughout the year. Smallest pregnant female was 285 cm (L_T) and the

mean L_T of all pregnant females sampled was 325.13 (± 38.82) cm. The oviducal glands of pregnant females were in the range of 8.8–11.2 (10.1 ± 0.89) cm. A total of 282 embryos, in the L_T range of 6.8–79.6 (37.06 ± 22.24) cm,

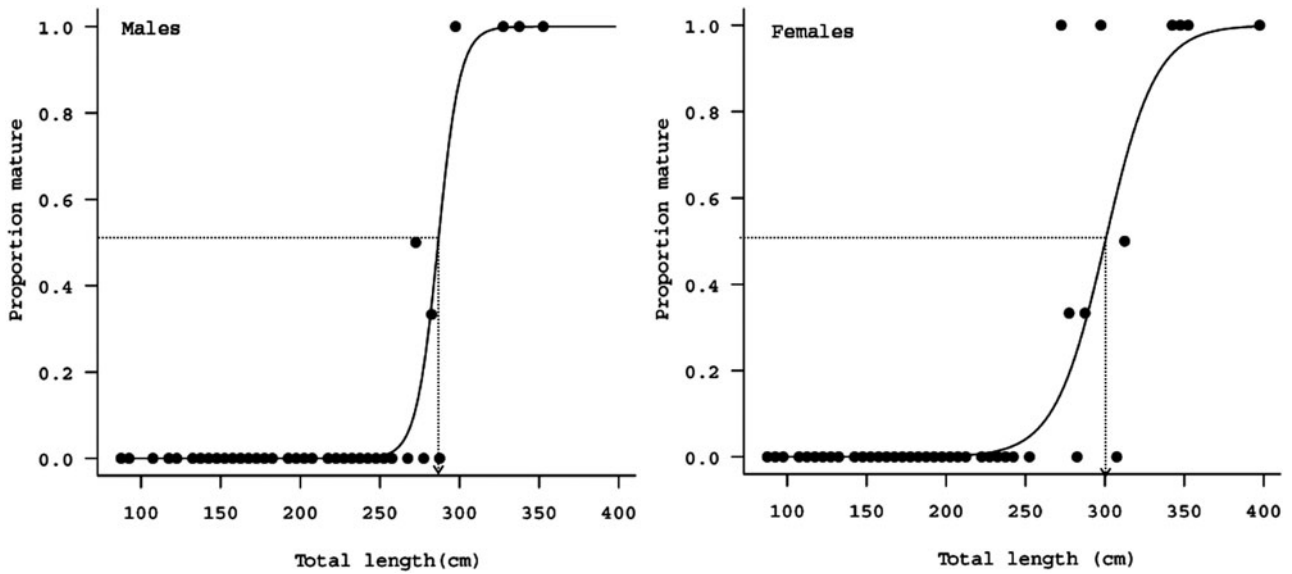


Fig. 14. Logistic curves fitted to maturity in relation to total lengths of tiger sharks of the eastern Arabian Sea. Dashed lines indicate length at maturity.

were recovered from the uteri. Numbers of embryos in females were in the range of 22–51 (35.25 ± 8.94). The uteri were obliquely compartmentalized and the embryos were individually placed in compartments of uterus. The embryos as well as the fertilized eggs in the uterus were covered with a thin fluid-filled sac, which in turn was covered by thin, soft, transparent, membranous sheath of nearly 100×30 cm. Both ends of these sheaths formed an iridescent wrinkled and highly folded structure. Smaller embryos had external yolk sacs, largest of which was 10.1 cm in diameter recorded for an embryo of 9.6 cm total length. This external yolk sac disappears in the embryos of total length 63.3 cm. Seasonal analysis of mean lengths of embryos showed pronounced seasonal change in mean embryo size. Smallest embryos were recovered from a mother of L_T 285 cm collected during January 2014. Fertilized eggs, which were also collected from the uterus of this mother, indicate that gestation in tiger sharks of eastern Arabian Sea starts in January. Largest embryo of L_T 79.6 was recovered from a 347 cm (L_T) mother caught during May 2014. The smallest free-swimming specimen of L_T 85.2 cm was caught in May 2013 (Figure 15). This shows that the parturition takes place in May and the gestation period will be about 16 months and the length at birth will be in the range of 79.6–85.2 cm. The sex ratio of embryos (1F:0.97M) did not significantly vary from the expected ratio of 1:1.

Isurus oxyrinchus

The total lengths of 96 specimens of shortfin makos sampled were in the range of 97–269 (168.73 ± 37.56) cm. The overall sex ratio (1F:0.96M) did not significantly vary from parity ($\chi^2 = 0.04$, $P > 0.05$). Male specimens collected were in the L_T range of 128–221 (161.68 ± 23.88) cm, whereas the L_T of females ranged between 97 and 269 (175.24 ± 46.06) cm (Figure 16). However, the total lengths of males and females did not show significant differences (Kolmogorov–Smirnov test: $D = 0.26$; $P > 0.05$).

The C_{LO} of the smallest male was 2.8 cm while that of the largest specimen was 18.9 cm and a noticeable increase

in the C_{LO} starts at the L_T 149 cm (Figure 17). Smallest mature male specimen was 166 cm while the largest immature male was of L_T 205 cm. Only eight mature males were recorded in the samples studied. The L_{T50} estimated was 189.05 cm and the L_{T95} was estimated at 222.88 cm. Pregnant females could not be encountered in the specimens landed at the harbour. However, three mature specimens having uterus widths greater than 4 cm were recorded during February and September 2014. These limited data indicate that females start maturing at 257 cm L_T and the largest immature was 267 cm. In females, the L_{T50} estimated was 266.42 cm and the L_{T95} was estimated at 289.14 cm (Figure 18).

Isurus paucus

The longfin mako samples for the study were collected during May–August. A total of 25 specimens, in the L_T range of 140–258 (169.72 ± 30.07) cm were sampled. The overall sex ratio was 1F:1.27M, which did not significantly vary from the expected ratio of 1:1 ($\chi^2 = 0.36$, $P > 0.05$). Male specimens collected were in the L_T range of 140–258 (167.57 ± 35.05) cm, whereas the L_T of females ranged between 149 and 227 (172.45 ± 23.61) cm (Figure 19). However, the total lengths of males and females did not show significant differences (Kolmogorov–Smirnov test: $D = 0.083$; $P > 0.05$) in this species either.

The C_{LO} of smallest male was 3.2 cm while that of largest specimen was 19 cm and noticeable increase in the C_{LO} starts with L_T 189 cm (Figure 20). Only two mature specimens, of L_T 225 and 258 cm could be sampled and due to the lack of enough mature specimens, the L_{T50} (206.77 cm) and L_{T95} (209.07 cm) estimated (Figure 21) was not reliable, since the standard errors in the estimations were too high (Table 2). However, the length distribution of largest immature (L_T 189 cm) and smallest mature specimens indicate that the length at maturity of males will be in the range of 189–225 cm. Since all the females sampled were immature, size at maturity in females also could not be estimated.

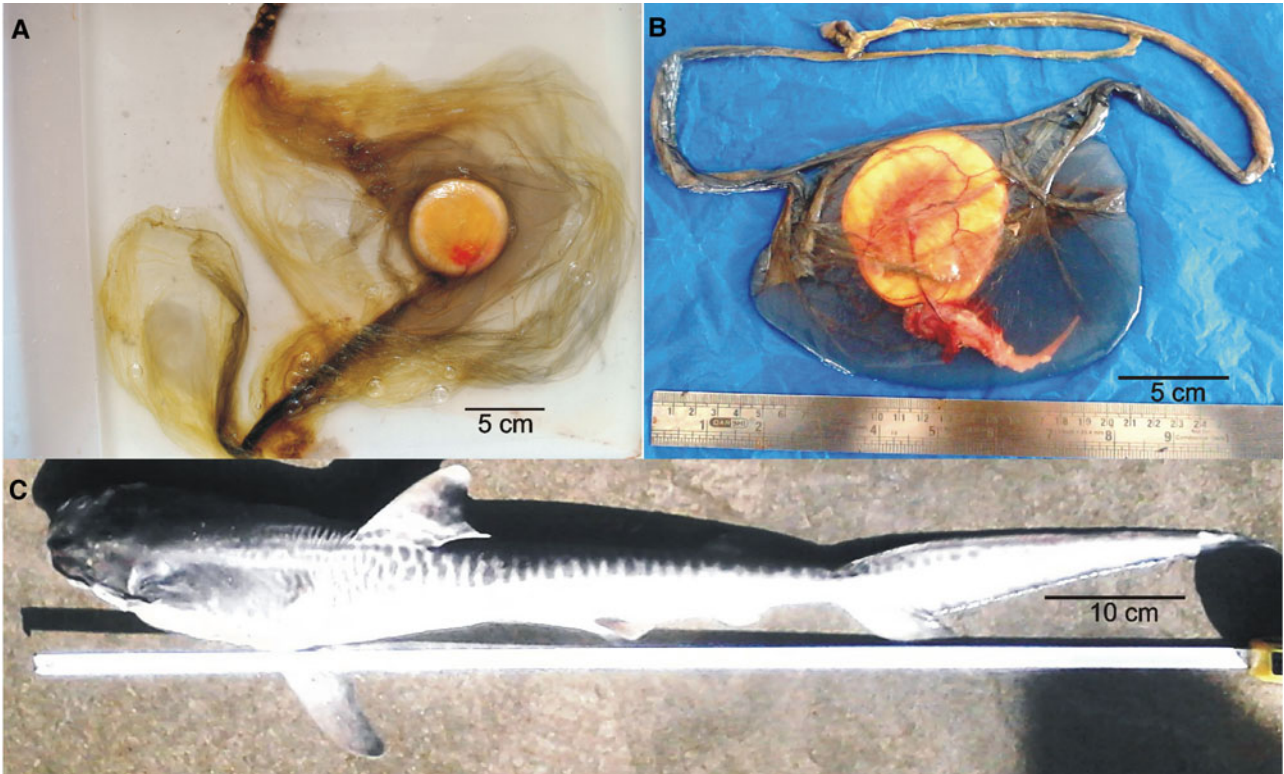


Fig. 15. Fertilized egg (A) and embryo (B) collected from a 285 cm L_T female collected during January 2014 and the smallest neonate (85.2 cm L_T) collected during May 2013 (C).

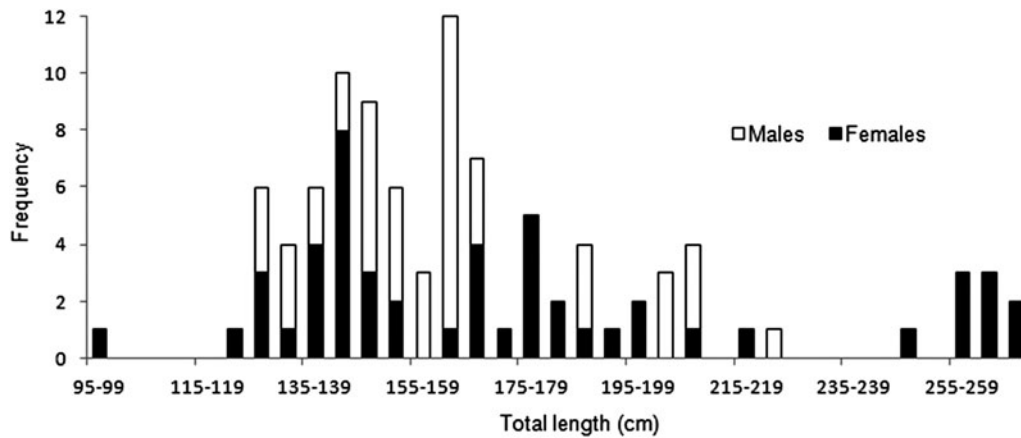


Fig. 16. Total length frequency of shortfin makos sampled from the eastern Arabian Sea.

Prionace glauca

Only 26 specimens of blue sharks, in the L_T range of 186–280 (218.93 ± 20.30) cm could be sampled during the entire sampling period. The specimens were collected during the months May and August. The overall sex ratio was 1F:5.5M, which significantly varied from the expected ratio of 1:1 ($\chi^2 = 12.46$, $P < 0.05$). Male specimens collected were in the L_T range of 186–280 (216.96 ± 21.42) cm, whereas the L_T of females ranged between 222 and 236 (229.75 ± 6.13) cm (Figure 22). However, the total lengths of males and females did not show significant differences (Kolmogorov–Smirnov test: $D = 0.4$; $P > 0.05$) in this species.

The C_{LO} of males were in the range of 7.9–14.6 cm (Figure 23). Since smaller specimens were absent in the samples, point of inflection in the length of claspers could not be identified. Smallest mature male specimen was 195 cm while the largest immature male was of L_T 212 cm. More than 63% of the male specimens sampled were mature with calcified claspers. The L_{T50} estimated was 207.11 cm while the L_{T95} estimated was 228.56 cm (Figure 24). Pregnant females could not be encountered in the specimens landed at the harbour. However, all the four females sampled were mature specimens. Small sample size and absence of immature specimens in the samples precluded the estimation of size at maturity in females.

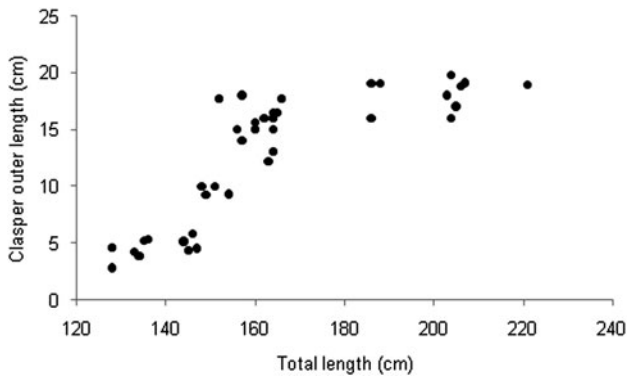


Fig. 17. Total length and clasper length of male shortfin makos collected from the eastern Arabian Sea.

DISCUSSION

Alopias pelagicus

Total lengths of pelagic threshers caught by gillnet-cum-longline fishery based at Cochin during the

years 2013 and 2014 were in the range of 144–319 cm (females) and 142–312 cm (males), which was substantially shorter than maximum sizes recorded in Taiwanese and Indonesian waters (Liu *et al.*, 1999; White, 2007a). The length of the smallest free-living specimen in the present study was similar to the length of the smallest specimen caught from the western Indian Ocean (137 cm, Compagno, 2002). Sex ratio in the present study was significantly biased to males, whereas the specimens in earlier studies conducted off Taiwan, Indonesia and Ecuador had sex ratios biased to females (Liu *et al.*, 1999; White, 2007a; Romero-Caicedo *et al.*, 2014). However, the sex ratios of embryos in all the above studies including the present study were close to parity indicating sexual segregation in free-swimming specimens.

Male and female pelagic threshers of eastern Arabian Sea become sexually mature at smaller L_T (254.96 cm and 271.39 respectively), than those in Taiwanese (267–276 cm and 282–292 cm, Liu *et al.*, 1999), Indonesian (264.8 and 285.3 cm, Drew *et al.*, 2015) and Ecuadorian (268.6 and 282.6 cm, Romero-Caicedo *et al.*, 2014) waters. Bass *et al.* (1975a) reported that a 277 cm female caught off South Africa was an immature specimen. Liu *et al.* (1999) estimated

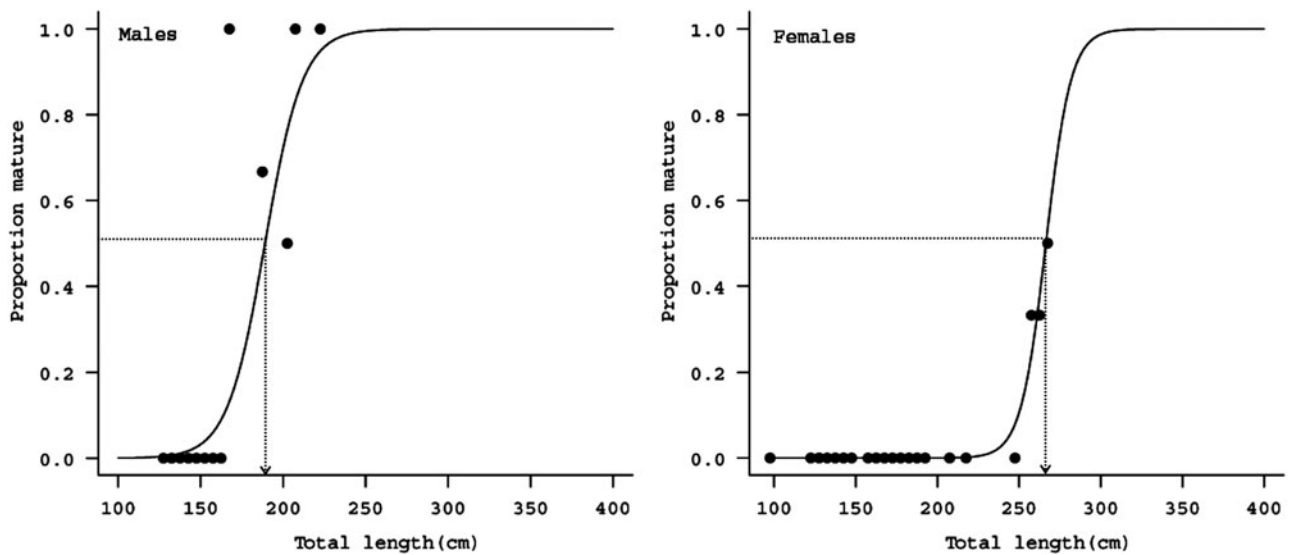


Fig. 18. Logistic curves fitted to maturity in relation to total lengths of shortfin makos of the eastern Arabian Sea. Dashed lines indicate length at maturity.

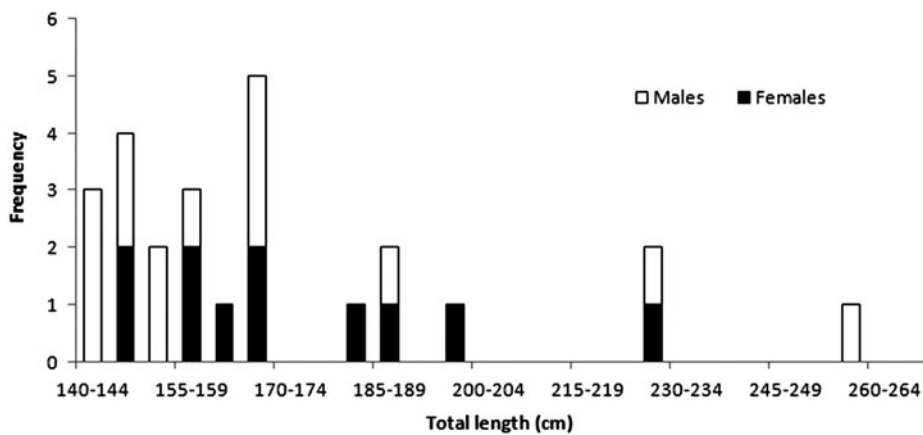


Fig. 19. Total length frequency of longfin makos sampled from the eastern Arabian Sea.

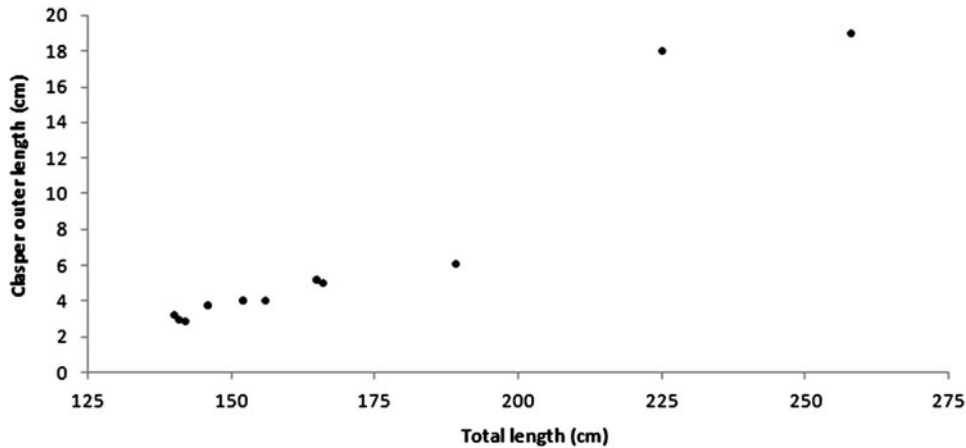


Fig. 20. Total length and clasper length of male longfin makos collected from the eastern Arabian Sea.

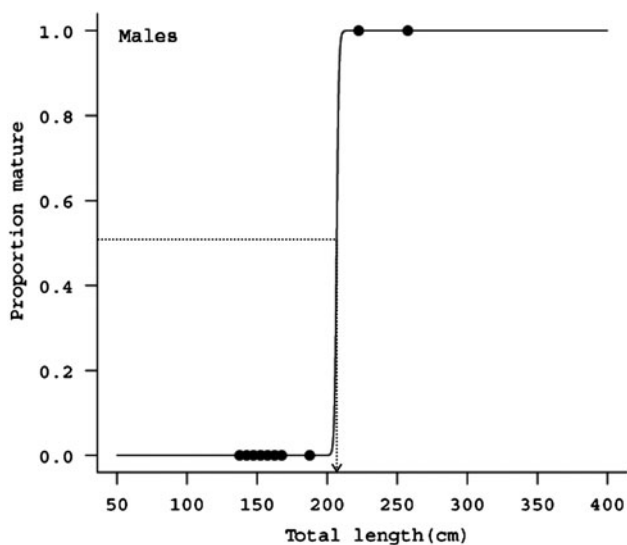


Fig. 21. Logistic curves fitted to maturity in relation to total lengths of longfin makos of the eastern Arabian Sea. Dashed lines indicate length at maturity.

the ratio of length at maturity to maximum observed length (L_{T50}/L_{max}) of pelagic threshers off Taiwan as 0.74–0.77, whereas in the present study the estimation was in the range of 0.82–0.85. The size at birth estimated in this study (139.9 cm) was similar to the estimations from Indonesian waters (130–144 cm, White, 2007a), which was smaller than estimations for population off Taiwan (159–190 cm, Liu *et al.*, 1999).

The present study failed to establish seasonal reproduction of pelagic threshers in the eastern Arabian Sea. Similarly, seasonal reproduction in pelagic threshers was less evident in studies conducted off Taiwan and Indonesia (Liu *et al.*, 1999; White, 2007a), whereas Romero-Caicedo *et al.* (2014) reported an annual pattern for reproduction with a gestation period of 9 months for pelagic threshers off Ecuador. Pregnant females in the present study had larger ovaries than non-pregnant specimens and continuous vitellogenesis was observed in mature and pregnant females indicating an annual reproductive cycle with concurrent vitellogenesis and gestation without any resting period. Similar observations were made by Castro (2009) and Romero-Caicedo *et al.* (2014) for pelagic threshers of the eastern Pacific. Similar to

the observations in earlier studies (Otake & Mizue, 1981; Liu *et al.*, 1999; White, 2007a; Castro, 2009; Romero-Caicedo *et al.*, 2014), this study also established oophagy in pelagic thresher embryos. The present study could establish significant linear relationship between the size and number of nutritive eggs in the nutritive egg capsules and embryo size.

Alopias superciliosus

Maximum lengths (L_T) of bigeye threshers caught by gillnet-cum-longline fishery based at Cochin during 2013–2014 were 361 cm (females) and 327 cm (males), which were substantially shorter than maximum sizes recorded in previous studies (females – 460.7 cm (Nakamura, 1935) males – 410 cm (Moreno & Moron, 1992)). Sex ratio in the present study was significantly biased to males, whereas the specimens in earlier studies conducted off Taiwan and Indonesia had sex ratios biased to females (Chen *et al.*, 1997; White, 2007a). However, the sex ratios of embryos in all the above studies including the present study were close to parity indicating sexual segregation in free-swimming specimens.

Male and female bigeye threshers of the eastern Arabian Sea become sexually mature at smaller L_T (263.5 and 310.69 cm respectively), than those in the north-eastern Atlantic (276 and 341 cm, Moreno & Moron, 1992), Taiwanese (270.1–287.9 cm and 332–341.1 cm, Chen *et al.*, 1997) and Indonesian (279–283 cm and 350.8 cm, White, 2007a) waters. Chen *et al.* (1997) estimated the ratio of length at maturity to maximum observed length (L_{T50}/L_{max}) as 0.79, whereas in the present study the estimation was in the range of 0.81–0.86. The size at birth estimated in this study (118–135 cm) was smaller than estimations for population off Taiwan (135–140 cm, Chen *et al.*, 1997).

The reproduction in bigeye threshers of the eastern Arabian Sea was non-seasonal. Similarly, seasonal reproduction in pelagic threshers was less evident in studies conducted off Taiwan (Chen *et al.*, 1997). The present study revealed an annual reproductive cycle in bigeye threshers of eastern Arabian Sea with concurrent vitellogenesis and gestation without any resting period. Similar to the observations of earlier studies (Chen *et al.*, 1997), this study also established that bigeye thresher embryos are oophagous.

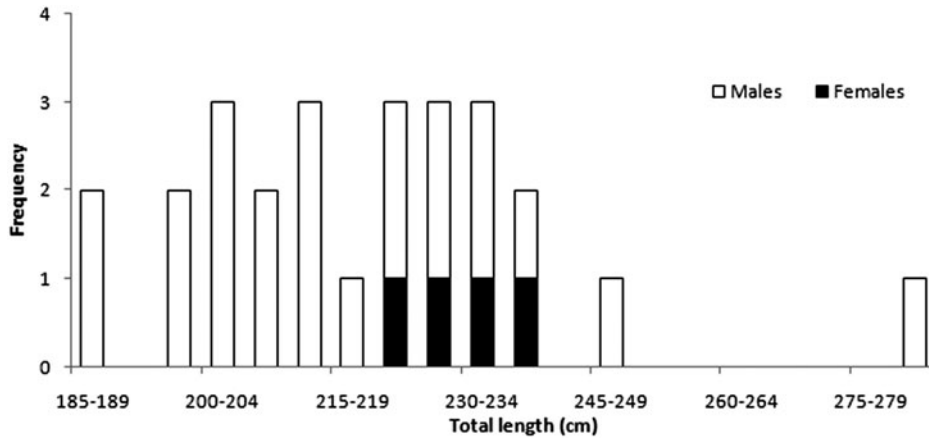


Fig. 22. Total length frequency of blue sharks sampled from the eastern Arabian Sea.

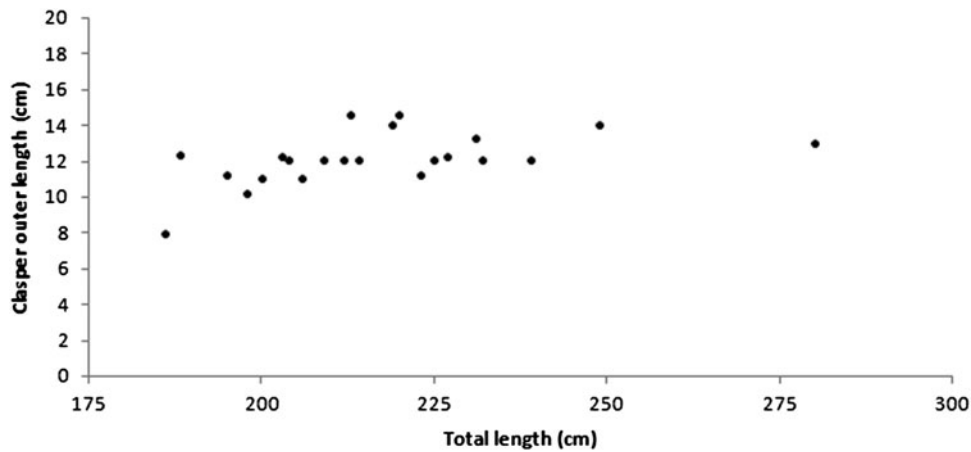


Fig. 23. Total length and clasper length of male blue sharks collected from the eastern Arabian Sea.

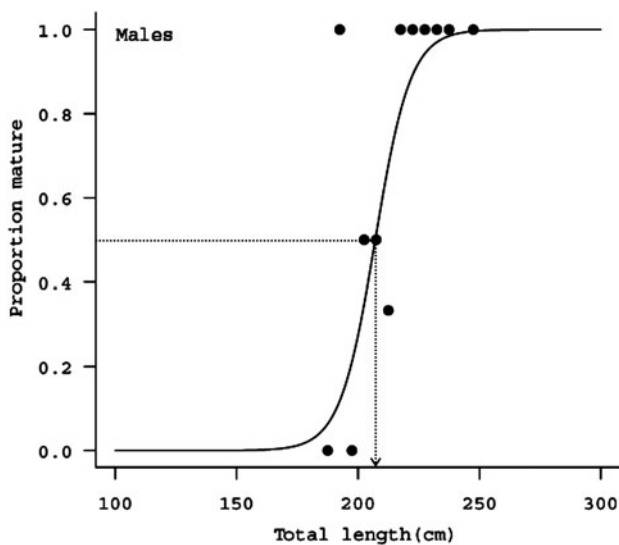


Fig. 24. Logistic curves fitted to maturity in relation to total lengths of male blue sharks of the eastern Arabian Sea. Dashed lines indicate length at maturity.

Carcharhinus longimanus

Oceanic whitetip sharks caught by gillnet-cum-longline fishery based at Cochin were in the total length range of 65–265 cm. The 65 cm specimen recorded during this study was smaller than the smallest free-swimming specimen reported in the literature (69 cm, White, 2007b). The length at birth reported for this species is in the range of 60–65 cm L_T off South Africa (Bass *et al.*, 1973) and 55–75 cm in the north-west Pacific (Seki *et al.*, 1998). The size at birth estimated in the present study was 64.2–65 cm. The sex ratio of free-swimming specimens as well as embryos of whitetip sharks in the present study was near to parity, similar to the reports in earlier studies conducted in the north-west Pacific and north-eastern Brazil (Seki *et al.*, 1998; Lessa *et al.*, 1999).

Earlier studies conducted in the Atlantic and Pacific Oceans reported lower length at maturity for males than females (Seki *et al.*, 1998; Coelho *et al.*, 2009), whereas, similar to the observations in the present study, the size at maturity was higher in males than females in the Indian Ocean stocks (Bass *et al.*, 1973; White, 2007b). Since the pregnant females could be collected during February, May and September only, gestation period could not be identified in the present study. However, the specimens with L_T less than 70 cm in this study were recorded during the month of

March which indicates that in the Arabian Sea, the parturition may be taking place during summer months (March–May). Further, considering the record of pregnant female with smallest embryos (7.2 cm) during May, largest (64.2 cm) during February and record of smallest neonates in March, it can be concluded that the gestation period may be a little less than or equal to 1 year. However, detailed studies are needed to reach a definitive conclusion. Seki *et al.* (1998) reported that the parturition period in this species is extended over a longer duration, with no distinct seasonal reproductive cycle, whereas seasonal parturition and mating occurring in spring and early summer were reported by Backus *et al.* (1956) and Gohar & Mazhar (1964). In the south-west Indian Ocean, near term foetuses were recorded during September–October, indicating early summer parturition in the whitetip sharks of the south-west Indian Ocean. Brood size of whitetip sharks in the present study was 3–9, averaging 5.8 embryos, which is in agreement with 1–14 embryos per litter reported by Seki *et al.* (1998). Bass *et al.* (1973) reported that in the south-west Indian Ocean, the brood size was 6–8, averaging 7 embryos, whereas Gohar & Mazhar (1964) reported a litter size of 10–15 for the Red Sea specimens.

Galeocerdo cuvier

During the study period, the gillnet-cum-longline fishery at Cochin fisheries harbour landed tiger sharks in the L_T range of 85–398 cm. The majority of the specimens caught were sub-adults, in the length range of 150–230 cm. The length at birth reported for this species is in the range of 51–90 cm L_T (Compagno, 1984; Randall, 1992; Simpfendorfer, 1992; Whitney & Crow, 2007) and the length at birth estimated in the present study (79.6–85.2 cm) falls in this range. The sex ratio of tiger sharks in the present study was near to parity. Similarly, the specimens caught off Indonesia and off Hawaii had sex ratios near to parity (White, 2007b; Whitney & Crow, 2007).

Size at maturity of male tiger sharks in the eastern Arabian Sea estimated in this study was 286.56 cm, which was similar to the estimations of Whitney & Crow (2007) (292 cm), Clark & von Schmidt (1965) and Bass *et al.* (1975b) (290 cm each). The smallest mature female in the samples of the present study was 274 cm L_T , whereas the total length of smallest pregnant specimen was 285 cm. Pregnant females with total lengths as small as 210 cm have been reported in Brazil (Alves, 1977). The size at maturity of females estimated in the present study is 300.31 cm, which falls within the range of 297–320 cm reported from the Atlantic Ocean (Clark & von Schmidt, 1965; Rivera-Lopez, 1970; Branstetter *et al.* 1987). However, this estimation was lower than the size at maturity reported for tiger sharks off Madagascar (340 cm, Fourmanoir, 1961), South-east Australia (330 cm, Stevens, 1984) and Hawaii (330–345 cm, Whitney & Crow, 2007), while it was higher than the value estimated for female tiger sharks off Australia (287 cm, Simpfendorfer, 1992).

In the present study, presence of pregnant females with smallest embryos (6.8 cm) along with fertilized eggs in the uterus during January indicates that the gestation starts during December–January months. Similarly, pregnant mothers with largest embryos resembling neonates were recorded during the month of May. Smallest free-swimming specimens also were appearing in the landings during May. Further, embryos of intermediate sizes were recorded during

the months February, May, September, October and January. Following Whitney & Crow (2007), it is concluded that reproduction in tiger sharks in the eastern Arabian Sea is seasonal, with gestation starting during January followed by parturition during May of the following year, and the gestation period estimated was 16 months. Considering the postulation of Whitney & Crow (2007) on the 4–5 months storage of sperm in the oviducal gland before fertilization, it is concluded that tiger shark breeding in the eastern Arabian Sea may be taking place during August–September. Sarangdhar (1943, 1949) has given detailed accounts of pregnant tiger sharks and their embryos collected from the shark landings at Bombay, India. Female with smallest embryos (6.8–7.5 cm L_T) was collected on 15 December 1941, females with embryos in the length range of 52.07–48.26 cm on 17 January 1942, whereas females with near-term embryos of 68.58–74.93 cm L_T was collected on 4 May 1943. The above findings of Sarangdhar (1943, 1949) corroborate the conclusions in the present study on a 16 months gestation period for the tiger sharks of Arabian Sea. In Hawaii, mating takes place in January–February and gestation lasts 15–16 months until parturition in September–October (Whitney & Crow, 2007). However, Castro (2009) proposed a 12 months gestation period for tiger shark. The percentage of mature females that are pregnant in the present study (80%) was substantially higher than reports in previous studies conducted off Hawaii (Whitney & Crow, 2007), the Caribbean (Rivera-Lopez, 1970), Brazil (Alves, 1977) and Australia (Simpfendorfer, 1992), which may indicate a shorter resting period for the tiger sharks than proposed by Whitney & Crow (2007) and that the tiger sharks of eastern Arabian Sea give birth once in 2 years. Castro (2009) postulated that tiger sharks may have a biennial reproductive cycle, whereas, Whitney & Crow (2007) suggested that tiger sharks in Hawaii give birth once every 3 years. However, the small sample size of mature females in the present study was a major limiting factor for drawing definitive conclusions on the reproductive cycle.

Numbers of embryos in pregnant females in the present study (range: 22–51; mean = 35.25) was in the range of litter size of tiger sharks (10–80) reported in earlier studies (Bigelow & Schroeder, 1948; Bass *et al.*, 1975b; Simpfendorfer, 1992; Whitney & Crow, 2007). Embryos collected during the present study have not shown any indication of the placenta formation. The tiger shark is the only species of the family Carcharhinidae that is ovoviviparous and aplacental (Compagno, 1988). Embryos <63.3 cm in the present study consume the yolk contained in the external yolk sac, whereas the sources of nutrition in the embryos greater than this length could not be verified, since the external yolk sacs were lost in these embryos. Sarangdhar (1943) speculated that the 'watery liquid' in the sacs covering the developing embryos has a nutritive function. Castro (1983) also postulated that embryos receive additional nourishment in the form of periembryonic fluid.

Isurus oxyrinchus

During the study period, the gillnet-cum-longline fishery at Cochin fisheries harbour landed shortfin makos in the L_T range of 97–269 cm. Shortfin makos landed in Indonesia were in the total length range of 116.7–310 cm (White, 2007a). Majority of the shortfin makos (88.54%) recorded in

the present study as well as those landed in Indonesia were immature specimens. The sex ratio of shortfin makos in the present study was near to parity. Similarly, the specimens caught off eastern Australia and Indonesia also had sex ratios near to parity (Stevens, 1983; White, 2007a), whereas the sex ratio was biased to females in the north-western Pacific (Joung & Hsu, 2005).

Female shortfin makos in the eastern Arabian Sea mature at a larger size than males, similar to the earlier reports from other regions of world oceans (Pratt & Casey, 1983; Stevens, 1983; Joung & Hsu, 2005). Size at maturity of males in the eastern Arabian Sea estimated in this study (189.05 cm) was similar to the estimations for the Baja California (Conde-Moreno & Galván-Magaña, 2006), south-east Pacific (Bustamante & Bennett, 2013), Indonesia (185.7 cm, White, 2007a) and California (Cailliet & Bedford, 1983) stocks. However, the length at maturity estimated for male shortfin makos in the western and central North Pacific (156 cm, Semba *et al.*, 2011) was smaller, while those off eastern Australia (195 cm, Stevens, 1983), southern Africa (194–206 cm, Cliff *et al.*, 1990), north-western Pacific (210 cm, Joung & Hsu, 2005) and New Zealand (180–185 cm, forklength, Francis & Duffy, 2005) were greater than the estimations in the present study.

Only 6.12% of the females were mature and pregnant specimens could not be collected in the present study. Similarly, pregnant specimens were absent in the shortfin makos sampled off Mexico (Conde-Moreno & Galván-Magaña, 2006), Indonesia (White, 2007a), and off the south-west Portuguese coast (Maia *et al.*, 2007), whereas extensive studies by Duffy & Francis (2001) and Francis & Duffy (2005) recorded a single pregnant female in the New Zealand waters. Gilmore (1993) reported that pregnant shortfin makos are usually captured in higher latitudes (between 20° and 30°N or S), which may be due to the migration of the females to these latitudes for parturition. However, none of the 640 female specimens collected from the south-east Pacific (20°S to 27°30'S) off Chile were pregnant (Bustamante & Bennett, 2013) indicating less abundance of pregnant females even in samples caught from higher latitudes. The smallest mature female in the present study was 257 cm (L_T) and the size at maturity estimated was 266.42 cm, while the size at maturity estimated in previous studies is in the range of 256–300 cm (Stevens, 1983; Mollet *et al.*, 2000; Francis & Duffy, 2005; Joung & Hsu, 2005; Semba *et al.*, 2011). However, based on a single mature female sampled, White (2007a) concluded that the female shortfin mako off Indonesia matures at a L_T of 240–250 cm, whereas Gohar & Mazhar (1964) reported a pregnant female of 263 cm with six embryos from the Red Sea and the smallest pregnant female reported by Joung & Hsu (2005) from the north-western Pacific was of L_T 272 cm. Since the size at maturity of females in the present study was estimated based on three mature specimens, results have to be considered as a preliminary estimation from the area where such reports are rare.

Isurus paucus

Reproduction in longfin mako is aplacental viviparity with oophagy and uterine cannibalism, with a litter size of 2–8 (Reardon *et al.*, 2006). Total length of smallest mature male in the present study (225 cm) was closely similar to the L_T

of smallest mature male in recorded off Indonesia (228 cm, White, 2007a). In Maldivian waters, Anderson *et al.* (2011) reported two male specimens of forklengths 177 and 181 cm assumed to be mature. Female longfin makos of the eastern Arabian Sea mature at greater lengths than males, since the largest female specimen collected in the present study (L_T 227 cm) was an immature specimen. Females of the western North Atlantic mature at >245 cm total length (Compagno, 2002).

Prionace glauca

Sex ratio of blue sharks sampled in the present study was strongly biased to males (1F:5.5M). Similarly, presence of significantly more males than females has been reported in most of the earlier studies (Stevens, 1984; Skomal & Natanson, 2003; White, 2007b; Anderson *et al.*, 2011). Spatially, blue sharks show high degrees of sexual segregation, since, in lower latitudes, the species is less common and males predominate (Compagno, 1984; Anderson *et al.*, 2011). More than 63% of the male specimens sampled in the present study were mature with calcified claspers and the length at maturity was estimated at 207.11 cm. Males become sexually mature at 184 cm total length off Baja California Sur (Carrera-Fernández *et al.*, 2010), at about 210–227 cm off Indonesia (White, 2007a), at 220–227 cm off New South Wales (Stevens, 1984) and at 221 cm off southern New England (Pratt, 1979). All the four females sampled in the present study were mature specimens. Although the length at maturity of females could not be estimated due to small sample size and absence of immature specimens in the samples, our data indicate that the female blue sharks in the eastern Arabian Sea become sexually mature at total lengths lower than 222 cm. Pratt (1979) reported that female blue sharks are fully mature at 221 cm, whereas Carrera-Fernández *et al.* (2010) estimated the length at first maturity of females at 196 cm.

Sharks have low resilience to over-exploitation by fisheries because of their K-selected life history strategy (Stevens *et al.*, 2000). In the light of the increasing fishing pressure on the sharks in the high seas, management measures are urgently needed for ensuring the long-term sustainability of oceanic shark fishery of the Indian Ocean. The biological information collected in the present study will be useful in identifying suitable management measures for these shark species.

Shark finning is prohibited in the Indian Exclusive Economic Zone (EEZ) and the export of fins of all species of shark is prohibited from India. Further, India observes an annual uniform ban on fishing in the Indian EEZ by all mechanized fishing for 61 days for the conservation and sustainable management of its marine resources. However, the annual seasonal fishing ban implemented in the Indian EEZ may not be effective for ensuring the sustainability of highly migratory stocks like sharks, unless similar management measures are adopted in the neighbouring EEZs and high seas. An ocean-wide seasonal fishing ban for the entire Indian Ocean and fleet reduction in the high seas could be useful for reducing the fishing mortality of sharks in the Indian Ocean.

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Correspondence should be addressed to:

S.P. Varghese
 Cochin Base of Fishery Survey of India, Kochangadi,
 Kochi – 682005, India
 email: varghesefsi@hotmail.com