

## **Supplemental information**

### **Similar circling movements observed**

### **across marine megafauna taxa**

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## 1 Supplemental Information

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### 3 Transparent Methods

#### 4 Sampling behavioural Data

5 Fine-scale 3D movements data of tiger sharks (*Galeocerdo cuvier*, N = 4), a whale shark  
6 (*Rhincodon typus*, N = 1), green turtles (*Chelonia mydas*, N = 3), king penguins (*Aptenodytes*  
7 *patagonicus*, N = 6), Antarctic fur seals (*Arctocephalus gazella*, N = 4) and a Cuvier's beaked  
8 whale (*Ziphius cavirostris*, N = 1) were obtained by deploying multi-channel data loggers  
9 (3MPD3GT, Little Leonardo, Japan) that recorded depth, temperature, swim speed and 3-axis  
10 magnetism at 1 Hz and 3-axis acceleration at 8 - 16 Hz.

11 Two male and two female tiger sharks were captured using demersal longline set off the  
12 north-east coast of Oahu Island, HI, USA (21° 26' N, 157° 58' W) in 2013. Captured sharks were  
13 tail-roped alongside of a research boat and inverted to induce tonic immobility. Data loggers were  
14 attached to each shark following Nakamura et al. (2011). A male whale shark incidentally captured  
15 by a set-net in Yomitan (Okinawa Island, Japan, 26° 28' N, 127° 55' E) was equipped with a data  
16 logger package and released (see Nakamura et al. 2020 for the details).

17 For green turtles, displacement experiments were conducted for adult females nesting at  
18 oceanic islands: one nesting female at Moheli Island, Comoro (12°22'S, 43°52'E) in 2010 and two  
19 nesting females in Chichijima Island, Japan (27°04'N, 142°12'E) in 2012. The turtles were  
20 captured before laying eggs and individually confined in wooden crates at their nesting beach. On  
21 the following day, the turtles were transferred to oceanic release sites that were 150 km southwest  
22 and 20 km east from their nesting beaches in 2010 and 2012, respectively. Turtles were equipped  
23 with 3MPD3GT data loggers and Argos-linked Fastloc GPS tags (MK10, Wildlife Computers, USA  
24 in 2010 and F4G 371A, Sirtrack Ltd., New Zealand in 2012). All instruments were retrieved from  
25 the turtles when they returned to their nesting beaches 2 – 5 days after the release.

26 For king penguins, data were collected from chick-rearing penguins (sex unknown) at  
27 Possession Island (46° 25' S, 51° 45' E), Crozet Archipelago, South Indian Ocean, from late  
28 January to early March in 2011. For field procedures, see Shiomi et al. (2016) for the details.

29 For Antarctic fur seals, the fieldwork was conducted at Bird Island (54° 00' S, 38° 03'  
30 W), South Georgia during breeding season in 2009. All data was collected from females. For details,  
31 see Iwata et al. (2012).

32 A Cuvier's beaked whale was equipped with data loggers off the Ogasawara Islands  
33 (27°04'N, 142°12'E) in the western North Pacific Ocean during September in 2010. The whale  
34 was estimated as adult-size, but its sex was unknown. We approached the whale with a 20-m long  
35 fishing boat and deployed a suction-cup-attached tag using a 6 m pole. The weight of the whole tag  
36 was 410 g (see Type B tag in Aoki et al. 2012). After deploying the tag, we tried to follow the

37 tagged whale to observe its behaviour while maintaining >300 m distance from the whale to avoid  
38 any disturbances.

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#### 40 *Data analysis and extraction of circling events*

41 Time-series data obtained from 3MPD3GT were analysed using IGOR Pro. ver. 6.37  
42 (WaveMetrics, Lake Oswego, OR, USA) and 3D movements of each tagged animal was  
43 reconstructed using data on swim speed, acceleration and magnetism, as described in Narazaki et  
44 al. (2009). In this study, we defined a circling event as a consecutive same-direction circling  
45 movement lasting for more than two times. To extract circling events, angular speed ( $\text{deg s}^{-1}$ ) was  
46 calculated from heading data and smoothed by 3 – 20 s to remove the effect of instantaneous noises.  
47 Clockwise/anticlockwise circling events began when accumulated angular speed for 30s exceeded  
48 mean angular speed plus/minus standard deviation multiplied by 1.5 – 2.0. Circling events ended  
49 when the sign of angular speed changed (e.g., positive angular speed turn to negative in clockwise  
50 event) and when mean angular speed for next 30 s reached zero (i.e., no constant turning occurred  
51 in next 30s). All detected circling events were visually inspected to remove any false events. For  
52 each circling event, cross-spectral density of sine of smoothed heading was computed using  
53 DSPPeriodogram function in IGOR Pro to obtain dominant circling cycle of each event.

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#### 55 *Ethics statement*

56 This study was performed in accordance with the guidelines of the Animal Ethic Committee of the  
57 University of Tokyo, and the protocol of the study was approved by this committee (Permit No.10-  
58 26 for king penguin, No. P12-5 for green turtles in Ogasawara, No. P16-8 for sharks, No. P12-6  
59 for beaked whales). The study of green turtles in Comoro was conducted as a part of the project  
60 ESTVOI (ANR-07-BLAN-0220). The study of whales was carried out under a permit from the  
61 Ogasawara Whale Watching Association (No.10-07). The studies of Antarctic fur seals were  
62 approved by the British Antarctic Survey and the University of Cambridge Animal Welfare Review  
63 Committee. Tiger shark handling and tagging activities were carried out in accordance with the  
64 animal use protocols of the University of Hawaii Institutional Animal Care and Use Committee  
65 (IACUC) and were approved under IACUC protocol #05-053.

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#### 68 **Supplemental References**

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