Supporting Information

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SI Materials and Methods

Terminology. The ability to maintain slow-twitch, aerobic RM warmer than ambient water in tunas and some sharks is called RM endothermy in this paper, following the frequent use of the term endothermy for these fishes in previous studies (1–3). However, we are aware that the term endothermy may refer exclusively to birds and mammals (where relatively high and more or less constant internal body temperatures are maintained, with high resting metabolic rates as the main source of heat; ref. 4), and that the thermal strategy of tunas and some sharks may be called heterothermy (4) or mesothermy (5). Some teleosts, including billfishes (Xiphiidae and Istiophoridae), the opah *Lampris guttatus*, and possibly the butterfly mackerel *Gasterochisma melampus*, do not have warmed RM but have warmed eyes and brain, a thermal strategy called cranial endothermy (2, 6).

Swim Speed from Acoustic Tracking Studies. A difficulty associated with extracting swim speed data from acoustic tracking studies was that the authors often reported only the horizontal speed of the fish (as "rate of movements") calculated from the horizontal track. Horizontal speed can be an underestimate of the true speed in the water column because fishes generally move vertically as well. To attain the best balance between the quantity and quality of the data collection, we grouped the acoustic tracking studies into those made in coastal or inland waters, and those made in pelagic waters. For the studies made in coastal or inland waters, horizontal speed of the fish was accepted as its true speed ("Acoustic tracking 2D" in the method column of Table S1), assuming that vertical movement is sufficiently small compared with horizontal movement in those shallow environments. In the pelagic waters, in contrast, many fishes show large, frequent vertical movement (7), and, thus, horizontal speed was not accepted as the true speed of the fish. Instead, we only accepted studies that estimated the speed of the pelagic fish in the 3D coordinates by combining the horizontal track and depth record of the fish ("Acoustic tracking 3D" in Table S1).

Body Mass and Body Temperature. In our comparative analyses of swim speed, body mass was used as a measure of body size of the animals (Table S1), although body length was normally easier to measure in fishes and, thus, more frequently reported. This choice is because fishes in our dataset vary greatly in body shape (e.g., ocean sunfish, flounder, and eel), presumably making body length a poor predictor of swim speed. Body mass is likely a better predictor of the amount of locomotory muscle and, hence, swimming performance. Moreover, the collection of body mass data for the fishes in our datasets allowed the direct comparison of allometric relationships of swim speed between fishes (this study) and nonfish vertebrate swimmers reported (8). When body mass was not reported in the data source for swim speed (9–22), it was estimated from body length by using published length–mass relationships for the species or a closely related species. Length–mass relationships have not been published for the whale shark, the largest fish species in the world. The mass for this species was set on the basis of catch records for an individual of a similar length (2.2 tons for a 5.7-m individual; ref. 23).

Body temperature was also estimated for each species in the swim speed dataset (Table S1). For fishes with RM endothermy, it was set at the value reported for the species (24–29). For fishes without RM endothermy, body temperature was set as the mean water temperature experienced by the fish at their swimming depth. When such data were unavailable (9, 10, 15, 19, 20, 22, 30–32), it was estimated by using global water temperature maps available for each month at various depths, provided by the National Oceanic and Atmospheric Administration (33).

In our comparative analyses of migration range, body mass was used as a measure of body size (Table S2). When only body length was reported in the data source (34–46), body mass was estimated by using the length-mass relationships for the species or a closely related species. When neither body mass nor length was reported (47–54), an average body mass for the species was used.

1. Block BA, Finnerty JR, Stewart AFR, Kidd J (1993) Evolution of endothermy in fish: Mapping physiological traits on a molecular phylogeny. *Science* 260(5105):210–214.
2. Dickson KA, Graham JB (2004) Evolution and consequences of endothermy in fishes. *Physiol Biochem Zool* 77(6):998–1018.
3. Carlson JK, Goldman KJ, Lowe CG (2004) Metabolism, energetic demand, and endothermy. *Biology of Sharks and Their Relatives*, eds Carrier JC, Musick JA, Heithaus MR (CRC, Boca Raton, FL), pp 203–224.
4. Clarke A, Pörtner H-O (2010) Temperature, metabolic power and the evolution of endothermy. *Biol Rev Camb Philos Soc* 85(4):703–727.
5. Grady JM, Enquist BJ, Dettweiler-Robinson E, Wright NA, Smith FA (2014) Dinosaur physiology. Evidence for mesothermy in dinosaurs. *Science* 344(6189):1268–1272.
6. Runcie RM, Dewar H, Hawn DR, Frank LR, Dickson KA (2009) Evidence for cranial endothermy in the opah (*Lampris guttatus*). *J Exp Biol* 212(Pt 4):461–470.
7. Humphries NE, et al. (2010) Environmental context explains Lévy and Brownian movement patterns of marine predators. *Nature* 465(7301):1066–1069.
8. Watanabe YY, et al. (2011) Scaling of swim speed in breath-hold divers. *J Anim Ecol* 80(1):57–68.
9. Barnett A, Abrantes KG, Stevens JD, Bruce BD, Semmens JM (2010) Fine-scale movements of the broadnose sevengill shark and its main prey, the gummy shark. *PLoS ONE* 5(12):e15464.
10. Sims DW (2000) Filter-feeding and cruising swimming speeds of basking sharks compared with optimal models: They filter-feed slower than predicted for their size. *J Exp Mar Biol Ecol* 249(1):65–76.
11. Carlisle AB, Starr RM (2010) Tidal movements of female leopard sharks (*Triakis semifasciata*) in Elkhorn Slough, California. *Environ Biol Fishes* 89(1):31–45.
12. Ruggerone GT, Quinn TP, McGregor IA, Wilkinson TD (1990) Horizontal and vertical movements of adult steelhead trout, *oncorhynchus mykiss*, in the Dean and Fisher channels, British Columbia. *Can J Fish Aquat Sci* 47(10):1963–1969.
13. Quinn TP, Terhart BA, Groot C (1989) Migratory orientation and vertical movements of homing adult sockeye salmon, *oncorhynchus nerka*, in coastal waters. *Anim Behav* 37:587–599.
14. Olson AF, Quinn TP (1993) Vertical and horizontal movements of adult Chinook salmon *oncorhynchus tshawytscha* in the Columbia River estuary. *Fish Bull* 91(1): 171–178.
15. Løkkeborg S, Skajaa K, Fernö A (2000) Food-search strategy in ling (*Molva molva* L.): Crepuscular activity and use of space. *J Exp Mar Biol Ecol* 247(2):195–208.
16. Fernö A, Jørgensen T, Løkkeborg S, Winger PD (2011) Variable swimming speeds in individual Atlantic cod (*Gadus morhua* L.) determined by high-resolution acoustic tracking. *Mar Biol Res* 7(3):310–313.
17. Marsac F, Cayre P (1998) Telemetry applied to behaviour analysis of yellowfin tuna (*Thunnus albacares*, Bonnaterre, 1788) movements in a network of fish aggregating devices. *Hydrobiologia* 372:155–171.
18. Metcalfe JD, Arnold GP, Webb PW (1990) The energetics of migration by selective tidal stream transport: An analysis for plaice tracked in the southern North Sea. *J Mar Biol Assoc U K* 70(1):149–162.
19. Kerwath SE, Goetz A, Attwood CG, Sauer WHH, Wilke CG (2007) Area utilisation and activity patterns of roman *Chrysoblephus laticeps* (Sparidae) in a small marine protected area. *Afr J Mar Sci* 29(2):259–270.
20. Luo J, Serafy JE, Sponaugle S, Teare PB, Kieckbusch D (2009) Movement of gray snapper *Lutjanus griseus* among subtropical seagrass, mangrove, and coral reef habitats. *Mar Ecol Prog Ser* 380:255–269.
21. Hanson KC, et al. (2007) Assessment of largemouth bass (*Micropterus salmoides*) behaviour and activity at multiple spatial and temporal scales utilizing a whole-lake telemetry array. *Hydrobiologia* 582:243–256.
22. Starr RM, Sala E, Ballesteros E, Zabala M (2007) Spatial dynamics of the Nassau grouper *Epinephelus striatus* in a Caribbean atoll. *Mar Ecol Prog Ser* 343:239–249.
23. Doiphode P (1986) On the landing of a whale shark *Rhincodon typus* Smith at Anjuna, Goa. *Mar Fish Inf Serv Tech Ext Ser* 66:29.
24. Goldman KJ (1997) Regulation of body temperature in the white shark, *Carcharodon carcharias. J Comp Physiol B Biochem. Syst Environ Physiol* 167(6):423–429.
25. Goldman KJ, Anderson SD, Latour RJ, Musick JA (2004) Homeothermy in adult salmon sharks, *Lamna ditropis*. *Environ Biol Fishes* 71(4):403–411.

26. Sepulveda CA, Kohin S, Chan C, Vetter R, Graham JB (2004) Movement patterns, depth preferences, and stomach temperatures of free-swimming juvenile mako sharks, *Isurus oxyrinchus*, in the Southern California Bight. *Mar Biol* 145(1):191–199.
27. Marcinek DJ, et al. (2001) Depth and muscle temperature of Pacific bluefin tuna examined with acoustic and pop-up satellite archival tags. *Mar Biol* 138(4):869–885.
28. Block BA, et al. (2001) Migratory movements, depth preferences, and thermal biology of Atlantic bluefin tuna. *Science* 293(5533):1310–1314.
29. Carey FG, Teal JM, Kanwishe JW, Lawson KD, Beckett JS (1971) Warm-bodied fish. *Am Zool* 11(1):137–145.
30. Gleiss AC, Norman B, Wilson RP (2011) Moved by that sinking feeling: Variable diving geometry underlies movement strategies in whale sharks. *Funct Ecol* 25(3):595–607.
31. Mitamura H, et al. (2012) Short-range homing in a site-specific fish: Search and directed movements. *J Exp Biol* 215(Pt 16):2751–2759.
32. Mitamura H, et al. (2012) Movements of lumpsucker females in a northern Norwegian fjord during the spawning season. *Environ Biol Fishes* 93(4):475–481.
33. NOAA National Oceanographic Data Center. Available at www.nodc.noaa.gov. Accessed Jan. 1, 2015.
34. Stehfest KM, Patterson TA, Barnett A, Semmens JM (2014) Intraspecific differences in movement, dive behavior and vertical habitat preferences of a key marine apex predator. *Mar Ecol Prog Ser* 495:249–262.
35. Weng KC, et al. (2008) Migration of an upper trophic level predator, the salmon shark *Lamna ditropis*, between distant ecoregions. *Mar Ecol Prog Ser* 372:253–264.
36. Campana SE, Joyce W, Fowler M (2010) Subtropical pupping ground for a cold-water shark. *Can J Fish Aquat Sci* 67(5):769–773.
37. Bonfil R, et al. (2005) Transoceanic migration, spatial dynamics, and population linkages of white sharks. *Science* 310(5745):100–103.
38. Howey-Jordan LA, et al. (2013) Complex movements, philopatry and expanded depth range of a severely threatened pelagic shark, the oceanic whitetip (*Carcharhinus longimanus*) in the western North Atlantic. *PLoS ONE* 8(2):e56588.
39. Svedang H, Righton D, Jonsson P (2007) Migratory behaviour of Atlantic cod *Gadus morhua*: Natal homing is the prime stock-separating mechanism. *Mar Ecol Prog Ser* 345:1–12.
40. Childers J, Snyder S, Kohin S (2011) Migration and behavior of juvenile North Pacific albacore (*Thunnus alalunga*). *Fish Oceanogr* 20(3):157–173.
41. Loher T, Seitz A (2006) Seasonal migration and environmental conditions of Pacific halibut *Hippoglossus stenolepis*, elucidated from pop-up archival transmitting (PAT) tags. *Mar Ecol Prog Ser* 317:259–271.
42. Hunter E, Metcalfe JD, Reynolds JD (2003) Migration route and spawning area fidelity by North Sea plaice. *Proc Biol Sci* 270(1529):2097–2103.
43. Hawkes LA, et al. (2012) Migratory patterns in hawksbill turtles described by satellite tracking. *Mar Ecol Prog Ser* 461:223–232.
44. The Guy Harvey Research Institute www.nova.edu/ocean/ghri/tracking/. Accessed Jan. 1, 2015.
45. Vandeperre F, et al. (2014) Movements of blue sharks (*Prionace glauca*) across their life history. *PLoS ONE* 9(8):e103538.
46. Block BA, et al. (2011) Tracking apex marine predator movements in a dynamic ocean. *Nature* 475(7354):86–90.
47. James MC, Ottensmeyer CA, Myers RA (2005) Identification of high-use habitat and threats to leatherback sea turtles in northern waters: New directions for conservation. *Ecol Lett* 8(2):195–201.
48. Broderick AC, Coyne MS, Fuller WJ, Glen F, Godley BJ (2007) Fidelity and over-wintering of sea turtles. *Proc Biol Sci* 274(1617):1533–1538.
49. Thiebot J-B, et al. (2013) A space oddity: Geographic and specific modulation of migration in *Eudyptes* penguins. *PLoS ONE* 8(8):e71429.
50. Rasmussen K, et al. (2007) Southern Hemisphere humpback whales wintering off Central America: Insights from water temperature into the longest mammalian migration. *Biol Lett* 3(3):302–305.
51. Ream RR, Sterling JT, Loughlin TR (2005) Oceanographic features related to northern fur seal migratory movements. *Deep Sea Res Part II Top Stud Oceanogr* 52(5-6):823–843.
52. Urbán-Ramírez J, et al. (2003) A review of gray whales (*Eschrichtius robustus*) on their wintering grounds in Mexican waters. *J Cetacean Res Manag* 5(3):281–295.
53. Mate B, Mesecar R, Lagerquist B (2007) The evolution of satellite-monitored radio tags for large whales: One laboratory's experience. *Deep Sea Res Part II Top Stud Oceanogr* 54(3-4):224–247.
54. Quakenbush L, et al. (2012) Seasonal movements of the Bering-Chukchi-Beaufort stock of bowhead whales: 2006–2011 satellite telemetry results. *Report to the Scientific Committee of the International Whaling Commission*, SC/64/BRG61.

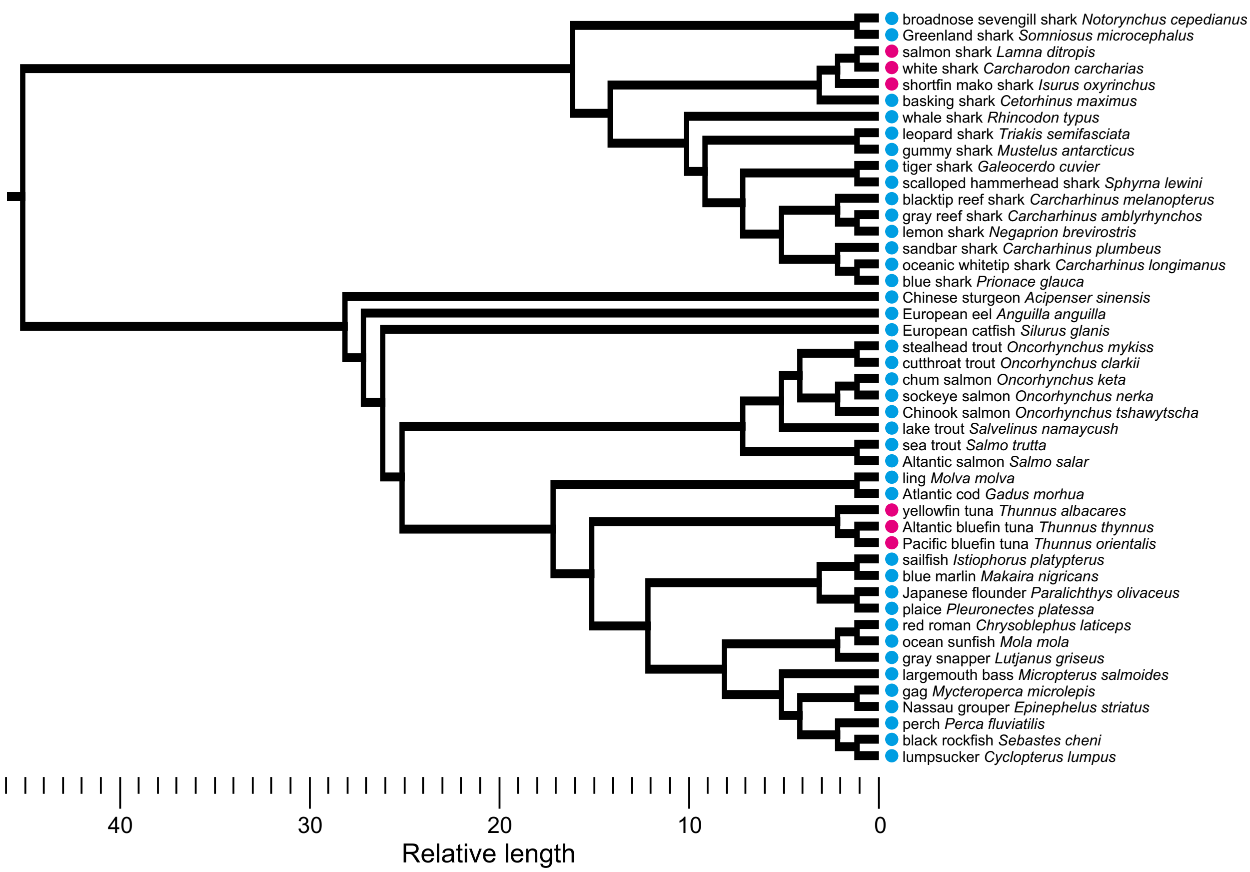

Fig. S1. Phylogenetic tree used in the comparative analysis of swim speed and the cost of transport. Pink and light blue circles represent fishes with and without RM endothermy, respectively.

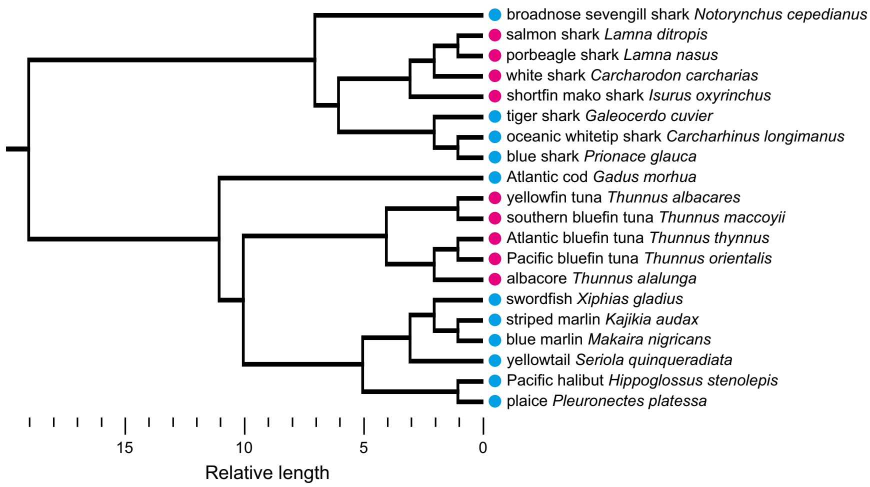

Fig. S2. Phylogenetic tree used in the comparative analysis of migration range. Pink and light blue circles represent fishes with and without RM endothermy, respectively.

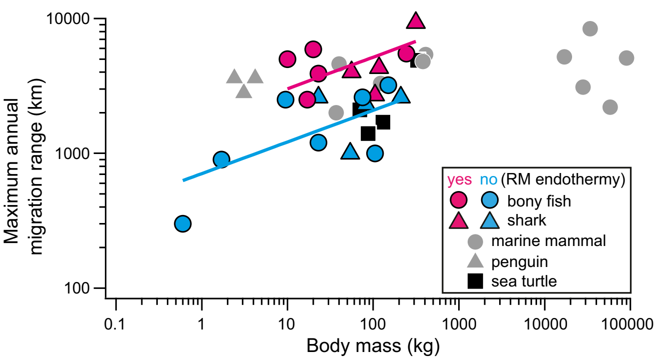

Fig. S3. The maximum annual migration ranges of various vertebrate swimmers as a function of body mass. Fishes with and without RM endothermy (pink and light blue, respectively) are shown with their phylogenetically informed regression lines (see main text for equations). For comparison, marine mammals, penguins (gray), and sea turtles (black) are also shown.

Table S1. Cruising speed of fishes recorded in the wild, and their energetics estimated for that speed

Group	Species	RM endothermy	Body length, m	Body mass, kg	Swim speed, $m \cdot s^{-1}$	Body temp, °C	Basal metabolic rate, W	Routine metabolic rate, W	Cost of transport, $J \cdot kg^{-1} \cdot m^{-1}$	Method	Source
Shark	Broadnose sevengill shark *Notorynchus cepedianus*	No	2.13	50	0.48	16	5.4	8.2	0.34	Acoustic tracking 2D	1
	Greenland shark *Somniosus microcephalus*	No	2.98	263	0.34	2	11.5	14.6	0.16	Speed sensor	2
	Salmon shark *Lamna ditropis*	Yes	2.15	155	1.09	25 (13)†	38.1	82.5	0.49	Speed sensor	This study
	White shark *Carcharodon carcharias*	Yes	3.60	428	2.25	26 (15)†	102.9	250.7	0.26	Acoustic tracking 2D	3
	Shortfin mako shark *Isurus oxyrinchus*	Yes	1.10	16	1.86	22 (18)†	6.7	32.5	1.09	Acoustic tracking 3D	4
	Basking shark *Cetorhinus maximus*	No	4.00	400	1.08	13	29.0	46.9	0.11	Boat	5
	Whale shark *Rhincodon typus*	No	6.00	2200	0.85	25	236.3	313.3	0.17	Pitch	6
	Leopard shark *Triakis semifasciata*	No	1.19	7.7	0.34	18	1.2	1.9	0.73	Acoustic tracking 2D	7
	Gummy shark *Mustelus antarcticus*	No	0.88	2.3	0.33	16	0.36	0.67	0.89	Acoustic tracking 2D	1
	Tiger shark *Galeocerdo cuvier*	No	3.57	266	0.69	26	38.8	56.0	0.31	Speed sensor	8
	Scalloped hammerhead shark *Sphyrna lewini*	No	0.57	0.76	0.46	26	0.23	0.64	1.84	Tailbeat	9
	Blacktip reef shark *Carcharhinus melanopterus*	No	1.20	11.9	0.52	29	2.9	5.9	0.95	Speed sensor	This study
	Gray reef shark *Carcharhinus amblyrhynchos*	No	1.57	26.1	0.59	28	5.6	10.4	0.67	Speed sensor	This study
	Lemon shark *Negaprion brevirostris*	No	1.71	27	0.63	22	4.2	7.9	0.46	Speed sensor	10
	Sandbar shark *Carcharhinus plumbeus*	No	0.83	5.2	0.42	22	1.0	2.2	0.99	Acoustic tracking 2D	11
	Oceanic whitetip shark *Carcharhinus longimanus*	No	2.09	97	0.71	25	15.2	27.1	0.39	Speed sensor	This study
	Blue shark *Prionace glauca*	No	2.52	105	0.44	22	14.0	19.7	0.43	Speed sensor	12
Bony fish	Chinese sturgeon *Acipenser sinensis*	No	2.97	198	1.10	20	22.2	41.0	0.19	Speed sensor	13
	European eel *Anguilla anguilla*	No	0.81	1.18	0.42	13	0.17	0.38	0.76	Acoustic tracking 2D	14
	European catfish *Silurus glanis*	No	1.21	10.3	0.36	18	1.5	2.5	0.68	Acoustic tracking 2D	15
	Stealhead trout *Oncorhynchus mykiss*	No	0.79	5.0	0.71	13	0.61	1.9	0.53	Acoustic tracking 2D	16
	Cutthroat trout *Oncorhynchus clarkii*	No	0.49	1.01	0.22	12	0.14	0.29	1.32	Acoustic tracking 2D	17

Table S1. Cont.

Group	Species	RM endothermy	Body length, m	Body mass, kg	Swim speed, $m \cdot s^{-1}$	Body temp, °C	Basal metabolic rate, W	Routine metabolic rate, W	Cost of transport, $J \cdot kg^{-1} \cdot m^{-1}$	Method	Source
	Chum salmon *Oncorhynchus keta*	No	0.65	3.3	0.75	15	0.47	1.7	0.70	Speed sensor	18
	Sockeye salmon *Oncorhynchus nerka*	No	0.67	2.5	0.67	11	0.30	1.0	0.60	Acoustic tracking 2D	19
	Chinook salmon *Oncorhynchus tshawytscha*	No	0.84	6.2	0.64	15	0.82	2.3	0.57	Acoustic tracking 2D	20
	Lake trout *Salvelinus namaycush*	No	0.58	2.14	0.69	21	0.44	1.6	1.10	Acoustic tracking 2D	21
	Sea trout *Salmo trutta*	No	0.20	0.062	0.14	11	0.012	0.030	3.50	Acoustic tracking 2D	22
	Altantic salmon *Salmo salar*	No	0.15	0.025	0.09	11	0.0053	0.012	5.68	Acoustic tracking 2D	23
	Ling *Molva molva*	No	0.60	0.6	0.08	8	0.074	0.10	2.02	Acoustic tracking 2D	24
	Atlantic cod *Gadus morhua*	No	0.40	0.8	0.29	5	0.082	0.22	0.95	Acoustic tracking 2D	25
	Yellowfin tuna *Thunnus albacares*	Yes	0.80	11.7	1.24	28 (23)†	4.2	19.4	1.34	Acoustic tracking 3D	26
	Altantic bluefin tuna *Thunnus thynnus*	Yes	2.46	240	2.00	25 (13)†	50.9	146.0	0.30	Acoustic tracking 3D	27
	Pacific bluefin tuna *Thunnus orientalis*	Yes	1.00	22.6	1.37	25 (16)†	7.4	30.8	0.99	Acoustic tracking 3D	28
	Sailfish *Istiophorus platypterus*	No*	1.34	20	0.64	22	3.3	6.9	0.54	Acoustic tracking 2D	29
	Blue marlin *Makaira nigricans*	No*	2.20	85	0.50	28	15.7	23.9	0.56	Speed sensor	30
	Japanese flounder *Paralichthys olivaceus*	No	0.52	2.2	0.31	14	0.31	0.75	1.09	Speed sensor	31
	Plaice *Pleuronectes platessa*	No	0.42	0.68	0.24	7	0.079	0.18	1.12	Acoustic tracking 2D	32
	Red roman *Chrysoblephus laticeps*	No	0.32	0.48	0.14	19	0.11	0.21	3.16	Acoustic tracking 2D	33
	Ocean sunfish *Mola mola*	No	1.15	87	0.60	16	8.8	19.4	0.37	Speed sensor	34
	Gray snapper *Lutjanus griseus*	No	0.33	0.69	0.57	29	0.24	1.2	3.04	Acoustic tracking 2D	35
	Largemouth bass *Micropterus salmoides*	No	0.40	0.93	0.12	6	0.10	0.17	1.50	Acoustic tracking 2D	36
	Gag *Mycteroperca microlepis*	No	0.66	3.8	0.14	18	0.62	0.92	1.74	Acoustic tracking 2D	37
	Nassau grouper *Epinephelus striatus*	No	0.73	6.0	0.53	27	1.5	3.9	1.22	Acoustic tracking 2D	38
	Perch *Perca fluviatilis*	No	0.26	0.26	0.10	18	0.059	0.11	4.26	Acoustic tracking 2D	39

Table S1. Cont.

Group	Species	RM endothermy	Body length, m	Body mass, kg	Swim speed, $m \cdot s^{-1}$	Body temp, °C	Basal metabolic rate, W	Routine metabolic rate, W	Cost of transport, $J \cdot kg^{-1} \cdot m^{-1}$	Method	Source
	Black rockfish *Sebastes cheni*	No	0.21	0.157	0.06	21	0.044	0.073	7.71	Acoustic tracking 2D	40
	Lumpsucker *Cyclopterus lumpus*	No	0.43	3.2	0.20	8	0.32	0.67	1.05	Acoustic tracking 2D	41

*These species have cranial endothermy, in which eye and brain temperatures are elevated. See the terminology section in *SI Materials and Methods* for details.
†Body temperature is different from the ambient water temperature (shown in parentheses) in fishes with RM endothermy.

1. Barnett A, Abrantes KG, Stevens JD, Bruce BD, Semmens JM (2010) Fine-scale movements of the broadnose sevengill shark and its main prey, the gummy shark. *PLoS ONE* 5(12):e15464.
2. Watanabe YY, Lydersen C, Fisk AT, Kovacs KM (2012) The slowest fish: Swim speed and tail-beat frequency of Greenland sharks. *J Exp Mar Biol Ecol* 426:5–11.
3. Semmens JM, Payne NL, Huveneers C, Sims DW, Bruce BD (2013) Feeding requirements of white sharks may be higher than originally thought. *Sci Rep* 3:1471.
4. Sepulveda CA, Kohin S, Chan C, Vetter R, Graham JB (2004) Movement patterns, depth preferences, and stomach temperatures of free-swimming juvenile mako sharks, *Isurus oxyrinchus*, in the Southern California Bight. *Mar Biol* 145(1):191–199.
5. Sims DW (2000) Filter-feeding and cruising swimming speeds of basking sharks compared with optimal models: They filter-feed slower than predicted for their size. *J Exp Mar Biol Ecol* 249(1):65–76.
6. Gleiss AC, Norman B, Wilson RP (2011) Moved by that sinking feeling: Variable diving geometry underlies movement strategies in whale sharks. *Funct Ecol* 25(3):595–607.
7. Carlisle AB, Starr RM (2010) Tidal movements of female leopard sharks (*Triakis semifasciata*) in Elkhorn Slough, California. *Environ Biol Fishes* 89(1):31–45.
8. Nakamura I, Watanabe YY, Papastamatiou YP, Sato K, Meyer CG (2011) Yo-yo vertical movements suggest a foraging strategy for tiger sharks *Galeocerdo cuvier*. *Mar Ecol Prog Ser* 424:237–246.
9. Lowe CG (2002) Bioenergetics of free-ranging juvenile scalloped hammerhead sharks (*Sphyrna lewini*) in Kane'ohe Bay, O'ahu, HI. *J Exp Mar Biol Ecol* 278(2):141–156.
10. Sundstrom LF, Gruber SH (1998) Using speed-sensing transmitters to construct a bioenergetics model for subadult lemon sharks, *Negaprion brevirostris* (Poey), in the field. *Hydrobiologia* 372:241–247.
11. Rechisky EL, Wetherbee BM (2003) Short-term movements of juvenile and neonate sandbar sharks, *Carcharhinus plumbeus*, on their nursery grounds in Delaware Bay. *Environ Biol Fishes* 68(2):113–128.
12. Carey FG, Scharold JV (1990) Movements of blue sharks (*Prionace glauca*) in depth and course. *Mar Biol* 106(3):329–342.
13. Watanabe YY, Wei Q, Du H, Li L, Miyazaki N (2013) Swimming behavior of Chinese sturgeon in natural habitat as compared to that in a deep reservoir: Preliminary evidence for anthropogenic impacts. *Environ Biol Fishes* 96(1):123–130.
14. McCleave JD, Arnold GP (1999) Movements of yellow- and silver-phase European eels (*Anguilla anguilla* L.) tracked in the western North Sea. *ICES J Mar Sci* 56(4):510–536.
15. Carol J, Zamora L, Garcia-Berthou E (2007) Preliminary telemetry data on the movement patterns and habitat use of European catfish (*Silurus glanis*) in a reservoir of the River Ebro, Spain. *Ecol. Freshwat. Fish* 16(3):450–456.
16. Ruggerone GT, Quinn TP, McGregor IA, Wilkinson TD (1990) Horizontal and vertical movements of adult steelhead trout, *Oncorhynchus mykiss*, in the Dean and Fisher channels, British Columbia. *Can J Fish Aquat Sci* 47(10):1963–1969.
17. Baldwin CM, Beauchamp DA, Gubala CP (2002) Seasonal and diel distribution and movement of cutthroat trout from ultrasonic telemetry. *Trans Am Fish Soc* 131(1):143–158.
18. Tanaka H, Takagi Y, Naito Y (2001) Swimming speeds and buoyancy compensation of migrating adult chum salmon *Oncorhynchus keta* revealed by speed/depth/acceleration data logger. *J Exp Biol* 204(Pt 22):3895–3904.
19. Quinn TP, Terhart BA, Groot C (1989) Migratory orientation and vertical movements of homing adult sockeye salmon, *Oncorhynchus nerka*, in coastal waters. *Anim Behav* 37:587–599.
20. Olson AF, Quinn TP (1993) Vertical and horizontal movements of adult Chinook salmon *Oncorhynchus tshawytscha* in the Columbia River estuary. *Fish Bull* 91(1):171–178.
21. Dunlop ES, Milne SW, Ridgway MS, Condiotty J, Higginbottom I (2010) In situ swimming behavior of lake trout observed using integrated multibeam acoustics and biotelemetry. *Trans Am Fish Soc* 139(2):420–432.
22. Thorstad EB, et al. (2004) Migration speeds and orientation of Atlantic salmon and sea trout post-smolts in a Norwegian fjord system. *Environ Biol Fishes* 71(3):305–311.
23. Thorstad EB, et al. (2007) Fjord migration and survival of wild and hatchery-reared Atlantic salmon and wild brown trout post-smolts. *Hydrobiologia* 582:99–107.
24. Løkkeborg S, Skajaa K, Fernö A (2000) Food-search strategy in ling (*Molva molva* L.): Crepuscular activity and use of space. *J Exp Mar Biol Ecol* 247(2):195–208.
25. Fernö A, Jørgensen T, Løkkeborg S, Winger PD (2011) Variable swimming speeds in individual Atlantic cod (*Gadus morhua* L.) determined by high-resolution acoustic tracking. *Mar Biol Res* 7(3):310–313.
26. Marsac F, Cayre P (1998) Telemetry applied to behaviour analysis of yellowfin tuna (*Thunnus albacares*, Bonnaterre, 1788) movements in a network of fish aggregating devices. *Hydrobiologia* 372:155–171.
27. Newlands NK, Lutcavage ME, Pitcher TJ (2004) Analysis of foraging movements of Atlantic bluefin tuna (*Thunnus thynnus*): Individuals switch between two modes of search behaviour. *Popul Ecol* 46(1):39–53.
28. Marcinek DJ, et al. (2001) Depth and muscle temperature of Pacific bluefin tuna examined with acoustic and pop-up satellite archival tags. *Mar Biol* 138(4):869–885.
29. Hoolihan JP (2005) Horizontal and vertical movements of sailfish (*Istiophorus platypterus*) in the Arabian Gulf, determined by ultrasonic and pop-up satellite tagging. *Mar Biol* 146(5):1015–1029.
30. Block BA, Booth D, Carey FG (1992) Direct measurement of swimming speeds and depth of blue marlin. *J Exp Biol* 166:267–284.
31. Kawabe R, Naito Y, Sato K, Miyashita K, Yamashita N (2004) Direct measurement of the swimming speed, tailbeat, and body angle of Japanese flounder (*Paralichthys olivaceus*). *ICES J Mar Sci* 61(7):1080–1087.
32. Metcalfe JD, Arnold GP, Webb PW (1990) The energetics of migration by selective tidal stream transport: An analysis for plaice tracked in the southern North Sea. *J Mar Biol Assoc U K* 70(1):149–162.
33. Kerwath SE, Goetz A, Attwood CG, Sauer WHH, Wilke CG (2007) Area utilisation and activity patterns of roman *Chrysoblephus laticeps* (Sparidae) in a small marine protected area. *Afr J Mar Sci* 29(2):259–270.
34. Watanabe Y, Sato K (2008) Functional dorsoventral symmetry in relation to lift-based swimming in the ocean sunfish *Mola mola*. *PLoS ONE* 3(10):e3446.
35. Luo J, Serafy JE, Sponaugle S, Teare PB, Kieckbusch D (2009) Movement of gray snapper *Lutjanus griseus* among subtropical seagrass, mangrove, and coral reef habitats. *Mar Ecol Prog Ser* 380:255–269.
36. Hanson KC, et al. (2007) Assessment of largemouth bass (*Micropterus salmoides*) behaviour and activity at multiple spatial and temporal scales utilizing a whole-lake telemetry array. *Hydrobiologia* 582:243–256.
37. Biesinger Z, Bolker BM, Marcinek D, Lindberg WJ (2013) Gag (*Mycteroperca microlepis*) space-use correlations with landscape structure and environmental conditions. *J Exp Mar Biol Ecol* 443:1–11.
38. Starr RM, Sala E, Ballesteros E, Zabala M (2007) Spatial dynamics of the Nassau grouper *Epinephelus striatus* in a Caribbean atoll. *Mar Ecol Prog Ser* 343:239–249.
39. Zamora L, Moreno-Amich R (2002) Quantifying the activity and movement of perch in a temperate lake by integrating acoustic telemetry and a geographic information system. *Hydrobiologia* 483(1-3):209–218.
40. Mitamura H, et al. (2012) Short-range homing in a site-specific fish: Search and directed movements. *J Exp Biol* 215(Pt 16):2751–2759.
41. Mitamura H, et al. (2012) Movements of lumpsucker females in a northern Norwegian fjord during the spawning season. *Environ Biol Fishes* 93(4):475–481.

Table S2. Maximum annual migration range of vertebrate swimmers

Group	Species	Elevated body core temperature	Body mass, kg	Maximum migration range, km	Distal positions on migration path	Method	Source
Shark	Broadnose sevengill shark *Notorynchus cepedianus*	No	54	1,000	S44°00′ E147°30′ S35°00′ E151°00′	Pop-up tag	1
	Salmon shark *Lamna ditropis*	Yes	117	4,300	N58°00′ W152°00′ N26°00′ W120°00′	Argos tag	2
	Porbeagle shark *Lamna nasus*	Yes	105	2,700	N44°00′ W69°00′ N20°00′ W62°00′	Pop-up tag	3
	White shark *Carcharodon carcharias*	Yes	315	9,300	S37°00′ E15°00′ S22°00′ E113°50′	Pop-up tag	4
	Shortfin mako shark *Isurus oxyrinchus*	Yes	56	4,000	N46°00′ W44°00′ N10°00′ W48°00′	Argos tag	5
	Tiger shark *Galeocerdo cuvier*	No	210	2,600	S11°00′ E132°00′ S24°00′ E111°00′	Argos tag	5
	Oceanic whitetip shark *Carcharhinus longimanus*	No	82	2,300	N30°00′ W76°00′ N18°00′ W58°00′	Pop-up tag	6
	Blue shark *Prionace glauca*	No	23	2,600	N34°00′ W46°00′ N49°00′ W22°00′	Argos tag	7
Bony fish	Atlantic cod *Gadus morhua*	No	1.7	900	N58°00′ E11°20′ N52°00′ E02°00′	Archival tag	8
	Yellowfin tuna *Thunnus albacares*	Yes	17	2,500	N33°00′ W119°00′ N17°00′ W137°00′	Archival tag	9
	Southern bluefin tuna *Thunnus maccoyii*	Yes	20	5,900	S38°00′ E140°00′ S31°00′ E75°00′	Archival tag	10
	Atlantic bluefin tuna *Thunnus thynnus*	Yes	244	5,500	N24°00′ W73°00′ N47°00′ W16°00′	Pop-up tag	11
	Pacific bluefin tuna *Thunnus orientalis*	Yes	23	3,900	N25°00′ W113°00′ N37°00′ W152°00′	Archival tag	9
	Albacore *Thunnus alalunga*	Yes	10	5,000	N30°00′ W180°00′ N45°00′ W126°00′	Archival tag	12
	Swordfish *Xiphias gladius*	No*	150	3,200	N41°50′ W65°40′ N14°00′ W75°00′	Pop-up tag	13
	Striped marlin *Kajikia audax*	No*	75	2,600	S34°10′ E172°20′ S14°00′ E158°00′	Pop-up tag	14
	Blue marlin *Makaira nigricans*	No*	105	1,000	N27°50′ W95°30′ N19°30′ W92°60′	Pop-up tag	15
	Yellowtail *Seriola quinqueradiata*	No	9.5	2,500	N28°40′ E124°10′ N46°30′ E141°00′	Archival tag	16
	Pacific halibut *Hippoglossus stenolepis*	No	23	1,200	N59°00′ W141°00′ N54°50′ W158°30′	Pop-up tag	17
	Plaice *Pleuronectes platessa*	No	0.6	300	N57°30′ E03°50′ N54°40′ E04°00′	Tidal location	18
Marine mammal	Humpback whale *Megaptera novaeangliae*	Yes	34,000	8,400	S65°21′ W64°58′ N08°39′ W83°43′	Photo ID	19
	Blue whale *Balaenoptera musculus*	Yes	90,000	5,100	N19°00′ W106°00′ N52°00′ W147°00′	Argos tag	20
	Gray whale *Eschrichtius robustus*	Yes	17,000	5,200	N26°40′ W113°20′ N54°20′ W164°50′	Radio tag	21
	North Atlantic right whale *Eubalaena glacialis*	Yes	58,000	2,200	N31°10′ W80°50′ N44°30′ W62°50′	Argos tag	22
	Bowhead whale *Balaena mysticetus*	Yes	28,000	3,100	N62°00′ W178°00′ N74°00′ W105°00′	Argos tag	23
	Northern fur seal *Callorhinus ursinus*	Yes	40	4,600	N60°00′ W171°00′ N33°00′ W122°00′	Argos tag	24
	Antarctic fur seal *Arctocephalus gazella*	Yes	37	2,000	S54°00′ W38°00′ S43°30′ W60°00′	Argos tag	25
	Northern elephant seal *Mirounga angustirostris*	Yes	410	5,400	N37°06′ W122°20′ N41°00′ E174°00′	Argos tag	26
	Southern elephant seal *Mirounga leonina*	Yes	380	4,800	S54°40′ E158°60′ S57°00′ W120°00′	Argos tag	27
	Hooded seal *Cystophora cristata*	Yes	122	3,300	N75°00′ W13°00′ N51°00′ W55°00′	Argos tag	28

Table S2. Cont.

Group	Species	Elevated body core temperature	Body mass, kg	Maximum migration range, km	Distal positions on migration path	Method	Source
Penguin	Macaroni penguin *Eudyptes chrysolophus*	Yes	4.2	3,600	S49°30′ E70°30′ S51°00′ E122°00′	Archival tag	29
	Northern rockhopper penguin *Eudyptes moseleyi*	Yes	3.1	2,800	S37°50′ E77°36′ S44°00′ E110°00′	Archival tag	29
	Eastern rockhopper penguin *Eudyptes filholi*	Yes	2.4	3,600	S49°30′ E70°30′ S49°00′ E121°00′	Archival tag	29
Sea turtle	Leatherback turtle *Dermochelys coriacea*	Yes	330	4,900	N47°00′ W55°00′ N3°00′ W47°00′	Argos tag	30
	Green turtle *Chelonia mydas*	No	130	1,700	N35°22′ E33°40′ N31°26′ E16°00′	Argos tag	31
	Hawksbill turtle *Eretmochelys imbricata*	No	87	1,400	N18°10′ W68°30′ N15°00′ W81°00′	Argos tag	32
	Loggerhead turtle *Caretta caretta*	No	70	2,100	N35°22′ E33°40′ N34°30′ E10°40′	Argos tag	31

*These species have cranial endothermy, in which eye and brain temperatures are elevated. See the terminology section in *SI Materials and Methods* for details.

1. Stehfest KM, Patterson TA, Barnett A, Semmens JM (2014) Intraspecific differences in movement, dive behavior and vertical habitat preferences of a key marine apex predator. *Mar Ecol Prog Ser* 495:249–262.
2. Weng KC, et al. (2008) Migration of an upper trophic level predator, the salmon shark *Lamna ditropis*, between distant ecoregions. *Mar Ecol Prog Ser* 372:253–264.
3. Campana SE, Joyce W, Fowler M (2010) Subtropical pupping ground for a cold-water shark. *Can J Fish Aquat Sci* 67(5):769–773.
4. Bonfil R, et al. (2005) Transoceanic migration, spatial dynamics, and population linkages of white sharks. *Science* 310(5745):100–103.
5. The Guy Harvey Research Institute www.nova.edu/ocean/ghri/tracking/. Accessed January 1, 2015.
6. Howey-Jordan LA, et al. (2013) Complex movements, philopatry and expanded depth range of a severely threatened pelagic shark, the oceanic whitetip (*Carcharhinus longimanus*) in the western North Atlantic. *PLoS ONE* 8(2):e56588.
7. Vandeperre F, et al. (2014) Movements of blue sharks (*Prionace glauca*) across their life history. *PLoS ONE* 9(8):e103538.
8. Svedang H, Righton D, Jonsson P (2007) Migratory behaviour of Atlantic cod *Gadus morhua*: Natal homing is the prime stock-separating mechanism. *Mar Ecol Prog Ser* 345:1–12.
9. Block BA, et al. (2011) Tracking apex marine predator movements in a dynamic ocean. *Nature* 475(7354):86–90.
10. Bestley S, Patterson TA, Hindell MA, Gunn JS (2008) Feeding ecology of wild migratory tunas revealed by archival tag records of visceral warming. *J Anim Ecol* 77(6):1223–1233.
11. Galuardi B, et al. (2010) Complex migration routes of Atlantic bluefin tuna (*Thunnus thynnus*) question current population structure paradigm. *Can J Fish Aquat Sci* 67(6):966–976.
12. Childers J, Snyder S, Kohin S (2011) Migration and behavior of juvenile North Pacific albacore (*Thunnus alalunga*). *Fish Oceanogr* 20(3):157–173.
13. Neilson JD, et al. (2009) Investigations of horizontal movements of Atlantic swordfish using pop-up satellite archival tags. *Tagging and Tracking of Marine Animals with Electronic Devices*, eds Nielsen JL, et al., pp 145–159.
14. Domeier ML (2006) An analysis of Pacific striped marlin (*Tetrapturus audax*) horizontal movement patterns using pop-up satellite archival tags. *Bull Mar Sci* 79(3):811–825.
15. Kraus RT, Wells RJD, Rooker JR (2011) Horizontal movements of Atlantic blue marlin (*Makaira nigricans*) in the Gulf of Mexico. *Mar Biol* 158(3):699–713.
16. Ino S, et al. (2008) Migration of the adult yellowtail (*Seriola quinqueradiata*) as estimated by archival tagging experiments in the Tsushima Warm Current. *Bull Jap Soc Fish Oceanogr* 72(2):92–100.
17. Loher T, Seitz A (2006) Seasonal migration and environmental conditions of Pacific halibut *Hippoglossus stenolepis*, elucidated from pop-up archival transmitting (PAT) tags. *Mar Ecol Prog Ser* 317:259–271.
18. Hunter E, Metcalfe JD, Reynolds JD (2003) Migration route and spawning area fidelity by North Sea plaice. *Proc Biol Sci* 270(1529):2097–2103.
19. Rasmussen K, et al. (2007) Southern Hemisphere humpback whales wintering off Central America: Insights from water temperature into the longest mammalian migration. *Biol Lett* 3(3):302–305.
20. Bailey H, et al. (2009) Behavioural estimation of blue whale movements in the Northeast Pacific from state-space model analysis of satellite tracks. *Endanger Species Res* 10:93–106.
21. Urbán-Ramírez J, et al. (2003) A review of gray whales (*Eschrichtius robustus*) on their wintering grounds in Mexican waters. *J Cetacean Res Manag* 5(3):281–295.
22. Mate B, Mesecar R, Lagerquist B (2007) The evolution of satellite-monitored radio tags for large whales: One laboratory's experience. *Deep Sea Res Part II Top Stud Oceanogr* 54(3-4): 224–247.
23. Quakenbush L, et al. (2012) Seasonal movements of the Bering-Chukchi-Beaufort stock of bowhead whales: 2006–2011 satellite telemetry results. *Report to the Scientific Committee of the International Whaling Commission*, SC/64/BRG61.
24. Ream RR, Sterling JT, Loughlin TR (2005) Oceanographic features related to northern fur seal migratory movements. *Deep Sea Res Part II Top Stud Oceanogr* 52(5-6):823–843.
25. Staniland IJ, Robinson SL, Silk JRD, Warren N, Trathan PN (2012) Winter distribution and haul-out behaviour of female Antarctic fur seals from South Georgia. *Mar Biol* 159(2):291–301.
26. Robinson PW, et al. (2012) Foraging behavior and success of a mesopelagic predator in the northeast Pacific Ocean: Insights from a data-rich species, the northern elephant seal. *PLoS ONE* 7(5):e36728.
27. Schick RS, et al. (2013) Estimating resource acquisition and at-sea body condition of a marine predator. *J Anim Ecol* 82(6):1300–1315.
28. Andersen JM, Wiersma YF, Stenson G, Hammill MO, Rosing-Asvid A (2009) Movement patterns of hooded seals (*Cystophora cristata*) in the Northwest Atlantic Ocean during the post-moult and pre-breed seasons. *J Northwest Atl Fish Sci* 42:1–11.
29. Thiebot J-B, et al. (2013) A space oddity: Geographic and specific modulation of migration in *Eudyptes* penguins. *PLoS ONE* 8(8):e71429.
30. James MC, Ottensmeyer CA, Myers RA (2005) Identification of high-use habitat and threats to leatherback sea turtles in northern waters: New directions for conservation. *Ecol Lett* 8(2):195–201.
31. Broderick AC, Coyne MS, Fuller WJ, Glen F, Godley BJ (2007) Fidelity and over-wintering of sea turtles. *Proc Biol Sci* 274(1617):1533–1538.
32. Hawkes LA, et al. (2012) Migratory patterns in hawksbill turtles described by satellite tracking. *Mar Ecol Prog Ser* 461:223–232.

Table S3. Fitting of nonphylogenetic regression models

Model	R^2	AIC	ΔAIC	wAIC
Swim speed ~ Body mass + Body temp + Endothermy	0.70	−6.3	0	0.78
Swim speed ~ Body mass + Endothermy	0.67	−3.7	2.6	0.21
Swim speed ~ Body mass + Body temp	0.61	4.6	10.8	<0.01
Swim speed ~ Body mass	0.54	9.7	16.0	<0.01
Swim speed ~1	0	43.6	49.9	<0.01
COT ~ Body mass + Body temp + Endothermy	0.90	−48.1	0	0.89
COT ~ Body mass + Body temp	0.88	−43.8	4.3	0.10
COT ~ Body mass + Endothermy	0.85	−32.3	15.8	<0.01
COT ~ Body mass	0.82	−25.4	22.7	<0.01
COT ~1	0	50.4	98.5	<0.01
Migration range ~ Body mass + Endothermy	0.68	−1.7	0	>0.99
Migration range ~ Body mass	0.37	10.3	12.0	<0.01
Migration range ~1	0	17.4	19.1	<0.01

The best models are shown in bold. wAIC, Akaike weight.