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Satellite tracking the world's largest jelly predator, the ocean sunfish, *Mola mola*, in the Western Pacific

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ABSTRACT

Twelve ocean sunfish, *Mola mola*, were tagged with pop-up satellite archival tags off the coast of Kamogawa, Japan during the spring of 2001 and 2003–2006. Transmitted data were obtained from seven tags. An eighth tag was recovered and provided a highly detailed four-month dataset from which several recognizable diving patterns emerged. This *M. mola* spent considerable time at the surface, possibly warming itself. These apparent basking events were punctuated by regular deep dives below the thermocline to depths as great as 600 m and temperatures as low as 2 °C. The vast majority of dives occurred during the day, with relatively little vertical movement at night. Geolocation estimates were possible between tag and release for five individuals. No large, basin-scale movements were apparent with most molas remaining relatively close to their initial tagging location over a six to nine month period. Seasonal movements were apparent for some molas and corresponded to regional shifts in oceanography. Northward movements from the Kuroshio Current into the Kuroshio–Oyashio transition zone and the Oyashio Current during the summer months coincided with an increase in temperature and reduction in chlorophyll a concentrations in waters near central Japan. In the fall, most molas returned inshore to the coast of Japan. Molas are targeted and incidentally captured by fishermen in these waters, and the information presented here is vital for effective fisheries management and to forecast changes in mola behaviors associated with environmental variability.
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1. Introduction

Ocean sunfish [*Mola mola* (Linnaeus, 1758)] are found in all tropical and temperate ocean basins and are the world's heaviest bony fish, reaching more than 2200 kg (Carwardine, 1995; Roach, 2003). According to fossil evidence, the family Molidae diverged from their puffer fish relatives approximately 40 million years ago, abandoned life on the reef, and took to the open sea (Tyler and Bannikov, 1992; Tyler and Santini, 2002). Currently, three species are recognized (Nelson, 1994), all of which lack a true tail (Bigelow and Welsh, 1924; Fraser-Brunner, 1951; McCann, 1961): *M. mola* (common mola), *Masturus lanceolatus* (Liénard 1840) (sharp tailed mola) and *Ranzania laevis* (Pennant 1776) (slender mola). The English common name of the group, ocean sunfish, stems from the fish's characteristic behavior of lying at the sea surface, apparently basking (Norman and Fraser, 1938).

Molas forage near the base of the food web like most of the largest whales, sharks, and rays. They may consume krill and other crustaceans (Aflalo, 1904), but their primary food source appears to be a mixed assemblage of gelatinous zooplankton, referred to here as jellies (Fraser-Brunner, 1951). One of the few large pelagic organisms that share this unique trophic niche is the leatherback sea turtle, the largest of the extant marine turtles. Jellies comprise one of the most dominant yet poorly understood assemblages of pelagic fauna (Mills,

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1995; Mills, 2001), and their global abundance and distribution may be changing due to a number of factors including climate change, pollution, and overfishing, (Brodeur et al., 1999; Purcell et al., 2007; Richardson et al., 2009). In turn, the changes in the abundance and distribution of jellies may be impacting the organisms that rely on them, such as the mola.

While general distribution patterns are known, information on the movements of *M. mola* is based on relatively few studies. In 2004, Cartamil and Lowe (2004) reported on the horizontal and vertical movements of eight acoustically tracked molas off Southern California for periods ranging from 24 to 72 h. More recently, Hays et al. (2009) published a study comparing the geographical movements and vertical tracks of four *M. mola* to those of leatherback sea turtles (*Dermochelys coriacea*) off Capetown, South Africa, with results supporting the claim that molas are deep divers (Norman and Fraser, 1938; Wheeler, 1969). In a similar study, Sims et al. (2009) provided evidence for seasonal migration of three *M. mola* in the northeast Atlantic, and highly variable dive patterns. These studies suggest that molas likely alter their vertical behavior in response to environmental conditions and prey distribution (Hays et al., 2009; Sims et al., 2009). While research to date has provided important insights into their geographic and vertical habitat use, previous studies have been limited in time, space, and/or sample size and there is currently no information available for the western Pacific where molas are captured in fisheries.

Although caught and sold in only a few locations worldwide, such as Japan and Taiwan, *M. mola* are taken incidentally in a large number of fisheries. They are the most common bycatch of the broadbill swordfish drift gillnet fishery off California and Oregon. According to reports from the National Marine Fisheries Service (NMFS) Southwest Region, between 1990 and 1998, 26.1% of the drift net catch consisted of *M. mola*. This translates to a catch of more than 26,000 individuals (Rand Rasmussen, NMFS Southwest Fisheries Science Center, pers. comm.). In the Mediterranean, *M. mola* constitute up to 90% of the catch of the illegal Spanish driftnet swordfish fishery off the Gibraltar Straits (Silvani et al., 1999). Off the coast of South Africa, ocean sunfish bycatch rates from the tuna and swordfish longline fishery are estimated at 340,000 sunfish annually (Petersen, 2005; Sims et al., 2009). Unfortunately, without even crude estimates of the population structure, connectivity, or size, the impact of these fisheries is difficult to assess. Also, while molas are considered to be highly fecund (Fraser-Brunner, 1951), recruitment is unknown.

As mentioned above, one location where molas are captured for food is in the western Pacific off the east coast of Japan. Known as 'manbou', molas occupy a special place in Japanese culture. From being a tax payment to shoguns in the 17th and 18th centuries (Jingushicho, 1910) to becoming modern day town mascots (e.g. the town of Kamogawa) and the focus of ecotourism, molas have been revered and consumed in Japan for centuries. Currently, genetic and pop-up satellite telemetry data are being collected for *M. mola* to document movements, behaviors, population subdivision, and migratory rates and routes around the Pacific. Our objectives for this study were to examine the horizontal and vertical movements of molas in the western Pacific and relate changes in those patterns to changes in environmental parameters. Results are presented from satellite tagging efforts on *M. mola* off Japan in the spring of 2001 and 2003–2006.

2. Materials and methods

2.1. Pop-up satellite archival tags

The pop-up satellite archival tag (PSAT, Model PAT2, PAT3, PAT4 and Mk10, Wildlife Computers, Redmond, Washington USA) (Block et al., 1998; Lutcavage et al., 1999; Sedberry and Loefer, 2001) was used in this study. The precision of temperature measurements was 0.1 °C between 12 and 26.95 °C and for values outside this range was 0.2 °C. The precision in depth measurements was depth dependent and measured within 1, 2, 4, 8, and 16 m over ranges from −20 to 99.5, 100 to 199.5, 200 to 299.5, 300 to 499.5, and 500 to 979.5 m, respectively. Histograms and temperature/depth profiles (PDT's) were set at either 12- or 24-h intervals. Light intensity measurements, coupled with the internal clock, document the times of dawn and dusk and allow for calculation of local noon or midnight and subsequently longitude (Hill, 1994) using software provided by the tag manufacturer (WC-GPE v1.02.0005, Wildlife Computers). Latitude is determined using longitude and sea surface temperature (SST) transmitted by the PSAT (Teo et al., 2004). The SST reported by the tag is matched along the line of longitude to the SST obtained from satellite imagery. Root mean squared error estimates from previous studies are approximately $\pm 0.5^{\circ}$ for longitude and less than 2° for SST based latitudes (Hill and Braun, 2001; Musyl et al., 2001; Teo et al., 2004).

The PSAT has numerous safeguards to reduce non-reporting rates. If the tag remains at the surface or at a constant depth for a user-defined period, internal software signals the tag to release and initiate transmission. To prevent implosion at depth, a special device, the RD1500 (Wildlife Computers), severs the leader at 1500 m, releasing the tag.

2.2. Tagging

A total of 12 tags were deployed on *M. mola* off Kamogawa, Japan during April of 2001 (n = 3), 2003 (n = 2), 2004 (n = 3), 2005 (n = 2) and March 2006 (n = 2) (Table 1, Fig. 1). All molas were captured in set nets (stationary rectangular traps consisting of anchored netting) a few kilometers offshore. Four individuals were held at Kamogawa

Table 1
Summary of the deployment data for 12 pop-up satellite tags deployed off Japan between 2001 and 2006. Shown are the dates and locations of deployment and recovery when available (DR = Didn't Report), the estimated minimum distance traveled (the km between release and pop-up locations), and the total duration of the deployment.

Mola	Year	Total length of fish (cm)	PTT	Tagging latitude (°N)	Tagging longitude (°E)	Tagging date	Pop off latitude (°N)	Pop off longitude (°E)	Pop off Date	Min. Distance (km)	Duration (days)
795*	2001	93	20,020	35.01	140.17	Apr 18, 01	41.13	141.38	Oct 17, 01	689	182
758	2001	87	20,806	35.00	140.19	Apr 18, 01	36.32	146.48	May 3, 01	587	15#
833	2001	112	19,748	35.00	140.19	Apr 18, 01	37.52	151.04	Jan 22, 02	1012	279#
63	2003	99	40,561	34.97	140.27	Apr 17, 03	32.88	133.51	Nov 1, 03	665	197
64	2003	102	40,562	35.10	140.31	Apr 15, 03	36.30	140.73	Nov 1, 03	139	199
291	2004	97.5	41,769	35.03	140.15	Apr 22, 04	30.65	158.32	Dec 25 04	1763	247
218	2004	90	41,758	35.02	140.09	Apr 24, 04	DR	—	—	—	—
217	2004	130	41,757	35.02	140.09	Apr 24, 04	DR	—	—	—	—
41*	2005	92	40,561	35.03	140.22	Apr 09, 05	41.17	141.78	Oct 17, 05	696	191
42*	2005	87	40,562	35.03	140.22	Apr 09, 05	DR	—	—	—	—
288*	2006	133	64,264	35.05	140.15	Mar 15, 06	42.60	168.97	Oct 2, 06	2619	193
289	2006	113	64,265	35.05	140.15	Mar 15, 06	DR	—	—	—	—

*individuals held at Kamogawa Sea World prior to tag and release.
#tags that released early.