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Onshore–offshore movement of jumbo squid (*Dosidicus gigas*) on the continental shelf

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ABSTRACT

Jumbo squid (*Dosidicus gigas*) have greatly extended their range in the California Current System, where they forage on a variety of ecologically and economically important species that inhabit both coastal and offshore mesopelagic regions. Swimming abilities and behavior are important factors in assessing the impacts of this range expansion, particularly in regard to foraging in conjunction with onshore–offshore movement over the continental shelf. Here we describe a study of horizontal movements by jumbo squid along and across the continental shelf off Washington, USA, using acoustic tags in association with the Census of Marine Life's Pacific Ocean Shelf Tracking Program (POST) receiver arrays. We detected frequent movements along the shelf break, movement onto the shelf at night, and no evidence of movement as a cohesive school. Our results demonstrate feasibility of using acoustic tags and arrays to document horizontal movements of jumbo squid along and across the continental shelf. This is important in order to determine how those movements overlap with those of other ecologically and commercially important fish species.

1. Introduction

Jumbo squid (also called Humboldt squid, *Dosidicus gigas*) have been undergoing a large range expansion in the California Current System, as documented through scientific sampling (Cosgrove, 2005; Pearcy, 2002; Zeidberg and Robison, 2007), commercial and recreational fishing effort, and popular media coverage. These sources, combined with demographic data, suggest a seasonal foraging migration to the northeastern Pacific with potentially significant impacts on local ecosystems (Field et al., 2013). Studies with pop-up archival transmitting (PAT) tags that tracked movements of individual animals have provided estimates of sustained horizontal velocities of ~40 km/day, and movement up to ~160 km offshore (Bazzino et al., 2010; Gilly et al., 2006; Stewart et al., in review). Although some of these tagging studies have suggested onshore–offshore horizontal migrations over the course of several days, no study to date has unequivocally demonstrated movements of jumbo squid on the continental shelf.

In all of the above tagging studies several (n=2–4) squid were tagged at the same place and time (within several hours), but no evidence was found that the tagged animals traveled in any sort of tight association on a time scale of days to weeks. Active acoustic surveys in the Gulf of California, Mexico have identified spatially extensive aggregations of jumbo squid at shallow nighttime depths with densely packed groups (3–18 individuals/m^3) across up to 10 m of depth, but neither the function nor longevity of these aggregations is known (Benoit-Bird and Gilly, 2012). These studies have also identified much smaller groups of animals (<40 individuals) that ascend from the dense aggregations and engage in bouts of highly coordinated, presumptive foraging behavior, but it is not known how long these smaller schools remain coherent.

Acoustic transmitter-tags have been deployed on jumbo squid (Yatsu et al., 1999), but these preliminary studies were carried out in the open ocean with a tracking vessel 15 years ago, and the results were inconclusive. Here we report the first use of acoustic transmitters on jumbo squid in conjunction with a fixed array of acoustic receivers in a continental shelf environment, using the Pacific Ocean Shelf Tracking (POST) network. We demonstrate the feasibility of this technology to map horizontal movements of jumbo squid on and along the continental shelf and discuss the nature of movements in relation to migration and schooling.

2. Materials and methods

Twenty-four jumbo squid (58–71 cm dorsal mantle length) were tagged with Vemco (Halifax, Nova Scotia, Canada) V13-1H acoustic tags during midday hours on September 22, 2009 on the

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shelf break (~200 m isobath), ~56 km off Westport, Washington, USA (46.93°N–124.55°W). The tags transmit at 69 kHz with an acoustic output of 156 dB re 1 μPa at 1 m. Tags were attached to the dorsal surface of the mantle several cm from the gladius and ~2 cm from the anterior edge of the mantle, similar to previously described methods (Markaida et al., 2005). Sharpened nylon bolts (10–24) were epoxied to the end of each tag, and the sharpened end was passed through the mantle and secured with a nylon washer and nut on the inside of the mantle. Squid were caught with weighted jigs and brought on board the private sport-fishing vessel *Time Warp* for tagging in a live-well on the deck. Tagged squid were gently released back into the sea within minutes. Each tag transmitted a unique identification code once per minute on average, and the nominal life of the tags was about six months. Although subsequent efforts were made to extend this pilot study, an absence of squid throughout the northern California Current System during the summer and fall of 2010 (and their continued scarcity through 2011) prevented additional deployments.

The POST array (www.postprogram.org) comprises over 400 receivers between California and Alaska, deployed in long lines across major straits or running across the continental shelf from the shoreline out to the shelf break. Vemco receivers can detect a V13-1H tag over a range of ~800 m under good conditions, and detected animals may be shallower or deeper (for receivers near the shelf break) than the depth of the reporting receiver. Tagged squid were released in an area with relatively sparse receiver coverage, with the closest receiver line being the Willapa line that lies ~45 km south of the deployment site at 46.57°N and runs in an east–west direction from the shelf break nearly to shore (Fig. 1). The line had 22 receivers operational from the time of tag deployment through early 2010, and these receivers spanned a depth range from <50 m to ~230 m. The Willapa line is the southern-most line to extend to the shelf break, although a central California array (just north of Point Reyes, ~38°N, max depth ~100 m, about half-way across the shelf at that location) was operational.

3. Results

Ten of 24 tagged squid were detected a total of 977 times by 17 receivers on the Willapa line 6–56 days after tag deployment (Fig. 2 and Table 1). No detections were reported at the two shallowest receivers, and none were reported on other receiver lines in the POST array.

Individual tagged squid were detected by 1–9 different receivers on one or two different days each. When individual tagged squid were detected by multiple receivers (seven out of 10 cases, Table 1), two or more contiguous receivers detected the squid in a back-and-forth manner, indicative of movement of the squid along the receiver line. Such movements are consistent with an estimated horizontal velocity of up to several meters per second based on archival tags (Gilly et al., 2006; Stewart et al., in review) and a detection range for the receivers of ~800 m.

Nearly 80% of all detections occurred near the shelf break where receivers are 150–250 m deep, and these detections occurred throughout the day as well as night (Fig. 3). Eight tagged squid were only detected at these deeper locations (receivers 35–44; Table 1). Only two tagged squid (1, 8) were detected by shallow inshore receivers that were 50–100 m deep and <13 km from shore, and all of these detections occurred between sunset

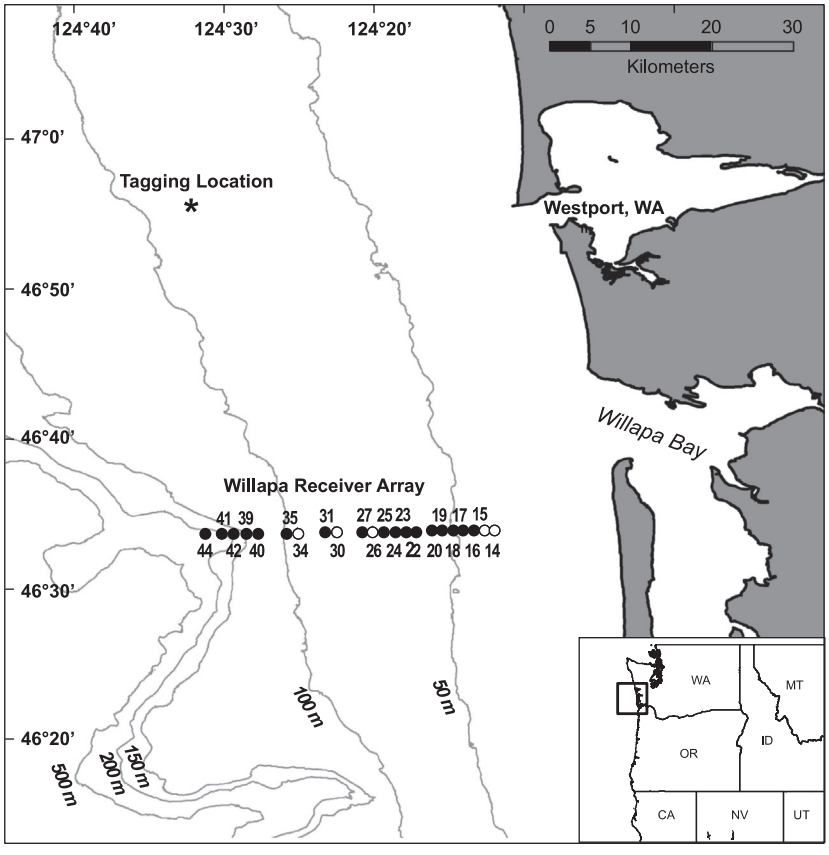

Fig. 1. Map of the tagging area off the coast of Washington, USA. The deployment location for twenty-four acoustic transmitting tags (*) is ~45 km from the array of numbered receivers along the Willapa line. Filled circles indicate receivers that detected squid; open circles represent functioning receivers that did not detect squid. Receiver 16 is ~12 km offshore (~45 m depth) and Receiver 44 is ~35 km offshore (~230 m depth). Isobaths are marked.