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Short communication

Vertical movements of Pacific bluefin tuna (*Thunnus orientalis*) and dolphinfish (*Coryphaena hippurus*) relative to the thermocline in the northern East China Sea

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ABSTRACT

Pacific bluefin tuna, *Thunnus orientalis*, and dolphinfish, *Coryphaena hippurus*, are temporally sympatric top predators in the north East China Sea. To clarify their vertical habits in relation to the thermocline, we analyzed swimming depth and ambient temperature data for Pacific bluefin tuna that were obtained from animal-borne data-loggers in April, May, and November 2007. We also reanalyzed published electronic tagging data for free-ranging dolphinfish in the Tsushima Straight. When the vertical temperature structure was homogeneous, Pacific bluefin tuna made vertical excursions to the bottom layer in early May and November. When the thermocline developed in late spring, bluefin tuna made frequent dives below the thermocline, and their main distribution depth shifted to above the thermocline from the surface. During the same period, dolphinfish in this area remained near the surface and did not dive across the thermocline. However, swimming data for dolphinfish that were obtained in September and October showed that dolphinfish extended their vertical depth ranges as the thermocline depth increased.

1. Introduction

The distribution and abundance of many marine fish are often driven by physical oceanographic conditions, especially water temperature (Wildhaber and Crowder, 1990, 1991, 1995; Krause et al., 1998). Changes in water temperature with depth are believed to strongly influence the distribution of pelagic species because thermal responses vary among species (Galli et al., 2009; Hochachka and Somero, 2002; Krebs, 2009). The thermocline may play a key role in decision making about vertical habitat preferences in a variety of pelagic predatory fish (Block et al., 2005; Brill et al., 1999). Thus, understanding how such species use their habitat with regard to temperature changes with depth requires detailed knowledge about their responses. This can be used to strengthen the foundation for the spatial management of marine ecosystems.

In the northern East China Sea (ECS), Pacific bluefin tuna, *Thunnus orientalis*, and dolphinfish, *Coryphaena hippurus*, are temporally sympatric top predators. Immature Pacific bluefin tuna are distributed in temperate waters and favor water temperatures of 12–21 °C (Uda, 1957). However, dolphinfish are found mainly in subtropical and tropical waters, but migrate to the northern ECS via the Tsushima Warm Current in late spring, when the surface seawater temperature (SST) is >20 °C (Kojima, 1966; Palko et al., 1982). Hence, in late spring, the habitat of these 2 top predators can overlap along a horizontal scale near the 20 °C SST isotherm in this region. Indeed, dolphinfish are frequently captured as by-catch in bluefin tuna surface longline fisheries in the northern ECS.

In the temperate waters of the continental shelf, seasonal changes in thermocline depth and strength can be clearly observed

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(Val et al., 2006). From late autumn to spring, vertical mixing occurs; however, thermal stratification starts to develop from late spring through summer, creating a strong thermocline in the relatively shallow depths of the northern ECS. More importantly, this thermal stratification that occurs in late spring and summer is believed to influence the vertical distribution of both Pacific bluefin tuna and dolphinfish (Kitagawa et al., 2000, 2004; Furukawa et al., 2011). However, to the best of our knowledge, nothing is known regarding how Pacific bluefin tuna and dolphinfish use this vertical space when they co-occur in the north ECS during this thermal stratification period.

In general, as vertical stratification develops, bluefin tuna begin to agglomerate just above the thermocline and intermittently dive through this temperature gradient (Kitagawa et al., 2000, 2004). In stark contrast to this behavior, dolphinfish tend to constrain their swimming depth within the thickness of the surface mixed layer (Furukawa et al., 2011). Indeed, when both species occur simultaneously in the presence of thermal stratification, the thermocline may serve to separate their vertical habitat (Fig. 1). However, previous studies using electronic tags, such as archival tags and acceleration data-loggers, focused on the species-dependent diving behavior of either bluefin tuna (Kitagawa et al., 2000, 2004) or dolphinfish (Furukawa et al., 2011). In the present study, we used recordings of temperature and depth from animal-borne data-loggers to determine how the seasonal variability of the thermocline affects the vertical habitat separation of the sympatric species Pacific bluefin tuna and dolphinfish. We also reanalyzed published data from free-swimming dolphinfish in the northern ECS (Furukawa et al., 2011).

2. Materials and methods

2.1. Study site

This study was conducted in the eastern channel of the Tsushima Strait in the northern part of the ECS (Fig. 2). The SST in the northern part of the ECS was obtained from NASA/MODIS-Aqua 8-day composites (Ocean Color data set: http://oceancolor.gsfc.nasa.gov/). Although the SST near Tsushima Island in April is below 20 °C, by May, a 20 °C SST isotherm moves northeast, and can be observed just south of the island (Fig. 3a). This isotherm serves as an index for the appearance of dolphinfish (Kojima, 1966), and by late May the isotherm can generally be observed in the central region of the Tsushima Strait (Fig. 3b). By September or October, the SST around the entire Tsushima Island is typically warmer than 22 °C (Fig. 3c), and dolphinfish dominate during this period. When the SST drops below 20 °C, typically by November, dolphinfish migrate south with the 20 °C SST isotherm and Pacific bluefin tuna begin to reappear in the Tsushima Strait.

2.2. Data-logger and fish tagging

We used fish-attached data-loggers UME-380 PD2GT (21 mm in diameter, 117 mm length, 60 g in air; Little Leonardo Co. Ltd., Tokyo, Japan) and UME-380 PD2GTL (24 mm in diameter, and 124 mm in length, 64 g in air Little Leonard Co.) to log swimming depth and ambient temperature for free-swimming immature bluefin tuna, *Thunnus orientalis*. We also analyzed dolphinfish data previously obtained by Furukawa et al. (2011). The data-loggers recorded depth and ambient water temperature every 1 s. The resolution of the depth and temperature measurements were 0.093 m and 0.02 °C, respectively, and depths could be measured to a maximum of 380 m. Detailed specifications of the data-loggers are given elsewhere (Furukawa et al., 2011).

Seven immature Pacific bluefin tuna (PBT1–PBT7) were captured by longline off the southeastern side of Tsushima Island in April, May, and November 2007. Furukawa et al. (2011) reported data for 8 mature dolphinfish (DF1–DF8), and data from 6 individuals (DF1–DF5 and DF8) were used in our analysis. We did not use the data for DF6 and DF7 because the release sites of these individuals with data-loggers were different from the cases of Pacific bluefin tuna (PBT1–PBT7) (see Fig. 2 in Furukawa et al., 2011). Each individual was measured, tagged with a data-logger, and released at the capture site immediately after tagging (Fig. 2). The tagging procedure was as described by Furukawa et al. (2011).

2.3. Data recovery system

The data-loggers needed to be recovered in order to download the data. As the recapture of tagged fish is quite improbable, we used an automatic time-scheduled release system to retrieve the data-loggers (Furukawa et al., 2011; Watanabe et al., 2004). The data-loggers were attached to a float of copolymer foam (Nichiyu Giken Kogyo Co., Saitama, Japan) that had a VHF radio transmitter (MM110 or MM120: 7 g or 10 g in air; Advanced Telemetry System Inc., Isanti, MN, USA) and ARGOS satellite transmitters (KiwiSat 202: 32.0 g in air; Sirtrack Ltd., New Zealand) embedded in the top. The logger packages (data-logger and recovery system) were attached to fish using 2 plastic cables that were connected to a time-scheduled release mechanism (Little Leonardo Co. Ltd., Tokyo, Japan). The release system included a timer that was activated 24–72 h after attachment for both Pacific bluefin tuna and dolphinfish. Once the release mechanism had been activated, the plastic cable was severed by an electric charge from a battery contained in the device, and the entire buoyant package was released from the fish. The package then floated to the surface and transmitted its general location to the ARGOS satellites. Based on the general location provided by ARGOS, a VHF receiver and a four-element Yagi antenna (Ham Center Sapporo, Hokkaido, Japan) was used to locate the package via VHF radio signals. The total weight of the system was 209–225 g in air (approx. 1.6–2.3% of the body mass of a 10 kg fish). The buoyancy offset was 11–15 g in water for the data-logger, transmitter, and time-scheduled mechanism. It is therefore unlikely that our instruments affected the swimming performance and behavior of Pacific bluefin tuna and dolphinfish in the open sea.

2.4. Data analysis

To visualize the thermal structure around the tagged fish, a temperature-at-depth matrix with 1-h time bins and 5-m depth bins was constructed by calculating the average temperature in each depth bin within each time bin, and constructing the isotherm based on the resulting temperature-depth field (Watson, 1992). Next, dive time-series data were plotted in the temperature-at-depth matrix. The start of a dive excursion from the surface (DES) was defined as the time at which a descending fish passed below 5 m. The end of a DES was defined as the time at which the fish again ascended to a depth of 5 m. DES depth was defined as the greatest depth reached during a DES. The isothermal layer depth (ILD), which is often used as a proxy for the uniform temperature layer depth, is defined as the depth at which the temperature changed by 0.8 °C relative to the surface temperature (Kara et al., 2000).

2.5. Statistical analysis

Statistical analyses were performed using R 2.13.1 Software (The R Project for Statistical Computing: http://www.r-project.org/). A generalized linear mixed model (GLMM), assuming a gamma distribution and a log-link function, was used to examine the influence of ILD on the DES depth of Pacific bluefin tuna and dolphinfish (Venables and Dichmont, 2004). Individuals were the random effect, as it was not our objective to test within-fish effects. Note