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An approach to describe depth-specific periodic behavior in Pacific halibut (*Hippoglossus stenolepis*)

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ABSTRACT

Correspondence between patterns of occupied depth and environmental cycles, called "depth-specific periodic behavior", has been used to inform management of several flatfishes. However, little is known about depth-specific periodic behavior of Pacific halibut (*Hippoglossus stenolepis*), an important species in recreational, commercial and subsistence fisheries in the eastern North Pacific Ocean. To evaluate depth-specific periodic behavior of Pacific halibut, an approach was developed in which depth data from electronic tags were used to produce four types of complementary plots, including two-dimensional time series of depth, activity level derived from differencing adjacent depth recordings, periodograms, and wavelet transform coefficients. From a visual examination of the plots, daily depth-specific periodic behavior types, including diel, tidal, spawning, semi-lunar and lunar, were assigned to 37 individual Pacific halibut. Overall, the approach used in this study was useful for describing relatively short term depth-specific periodic behavior, but was less informative for understanding relatively long term behavioral patterns. The results suggest that patterns in occupied depth may be related to seasonal activities of Pacific halibut. Specifically, during the summer feeding season, fish most commonly behaved periodically on a diel scale or inactively laid on the seafloor, which was manifested as tidal periodicity as the height of the water column fluctuated above the fish. Both active swimming and inactivity on the seafloor may be related to different foraging strategies. During fall and spring migratory periods and the winter spawning season, no periodicity in depth-specific behavior was most common, which may correspond to directed movement over irregular bathymetry between feeding and spawning locations or to reproductive behaviors. Evidence of an additional reproductive behavior, spawning rises off the seafloor, was also observed during the winter spawning season. This approach for understanding the periodicity of occupied depth of Pacific halibut provides additional insight into the behavior of this iconic species. This knowledge perhaps may be used in the future to inform this species' management, such as refining estimates of susceptibility to capture and examining timing of movement among regulatory areas.

1. Introduction

Behavior patterns of animals often correspond to fixed periodic environmental cycles, including diel, tidal, semi-lunar and lunar cycles. When correspondence between fixed environmental and behavioral cycles of animals exists, it is typically termed "periodic behavior" (Li et al., 2012). In fishes, periodic behavior is frequently studied by examining changes in occupied depth measured by electronic tags, hereafter referred to as "depth-specific periodic behavior". Fisheries scientists and managers are frequently interested in understanding depth-specific periodic behavior of fishes because it can be useful for informing fisheries science and management (Hunter et al., 2004a; Schaefer and Fuller, 2010; Subbey et al., 2008). For flatfishes, analyses of depth-specific periodic behavior have been used for assessing abundance and understanding movement. Specifically, periodic changes in depth may indicate flatfish such as Greenland halibut (*Reinhardtius hippoglossoides*) leaving the sea floor (Albert et al., 2011). Information about pelagic behavior of flatfishes can be useful for understanding susceptibility to capture by benthic survey gear (Albert et al., 2011), which in turn can be used to improve stock assessments. Additionally, periodic changes in depth may provide insight into movement states of flatfishes, specifically, when they are relatively sedentary versus mobile, which may be used to understand effectiveness of Marine Protected Areas (Nielsen, J.K. and Seitz, A.C., unpublished data). Finally, periodic changes in depth can be used to determine when and where a fish migrated (Hunter et al., 2004b), which can be used to understand population structure of flatfishes (Hunter et al., 2004c).

Descriptions of depth-specific periodic behavior in fishes have been accomplished by using a variety of analytical methods. Relatively simple methods include qualitatively examining two-dimensional time series of depth (Teo et al., 2013) and activity level derived from differencing

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adjacent depth recordings (Godø and Michalsen, 2000). Relatively more complex methods involve transforming depth data and qualitatively examining periodograms (Hunter et al., 2004a) and wavelet transform coefficients (Subbey et al., 2008). Each individual analytical method has strengths and liabilities, and clear conclusions can only be drawn when multiple methods are used simultaneously. For example, a periodogram may provide evidence that the depth record of a flatfish changes on a tidal scale. However, this method is not able to discern whether the flatfish tends to actively change depth during certain phases of the tidal cycle, or whether the flatfish merely remains motionless on the seafloor regardless of tide stage while the water column height above the flatfish fluctuates with the tide.

One particularly important species of flatfish in the Pacific Ocean is the Pacific halibut (*Hippoglossus stenolepis*), which is captured in subsistence, commercial, and recreational fisheries throughout the US Pacific Northwest, Gulf of Alaska and Bering Sea. To understand several aspects of the behavior of Pacific halibut which may be used to inform this species' management, scientists have studied individual fish using depth-sensing electronic tags. Qualitative analysis of summarized depth records that contain maximum and minimum depths for 12-hour periods has been used to infer seasonal migration (Loher, 2008; Loher and Blood, 2009; Loher and Seitz, 2006; Seitz et al., 2011). Typically, adult Pacific halibut occupy relatively shallow continental shelf areas (50–200 m) during the summer feeding season and relatively deep continental slope areas (200–750 m) during the winter spawning season. Individual Pacific halibut typically move between these two habitats during spring and fall migrations. In addition to analyzing summarized depth data, continuous data recorded at two min intervals have been qualitatively examined for evidence of spawning behavior of Pacific halibut. For this species, spawning behavior is thought to be manifested as 6–10 serial rises of 39–324 m conducted December through March, with a periodicity averaging just under 4 days (92 $\pm$ 1.8 h, 71–133 h; mean $\pm$ standard error, range; Seitz et al., 2005; Loher and Seitz, 2008; Loher, 2011).

In contrast to the previously described qualitative studies of Pacific halibut behavior, no information exists about the depth-specific periodic behavior of this species. Given that other flatfishes display depth-specific periodic behaviors, we hypothesize that Pacific halibut also show depth-specific periodic behaviors. Therefore, the goal of this study is to provide insight into the depth-specific periodic behavior of Pacific halibut. To accomplish this goal, two study objectives were identified. First, we developed a new approach that combines four previously existing analyses that compliment and validate each other to provide a more holistic understanding of depth-specific periodic behavior in Pacific halibut than any one single analysis can provide. Second, this approach was used to assign daily depth-specific periodic behavior types to individual fish, after which daily results were aggregated among individuals and across seasons to assess seasonal changes in Pacific halibut behavior.

2. Methods

A total of 250 Wildlife Computers Pop-up Archival Transmitting tags (PAT2, PAT4, and MK-10 versions) were externally attached to Pacific halibut in the US Pacific Northwest (Loher and Blood, 2009), Gulf of Alaska (Loher, 2008; Loher and Blood, 2009; Loher and Seitz, 2006; Seitz et al., 2003), and Bering Sea/Aleutian Islands (Seitz et al., 2011). The tags were connected to titanium darts with a tether approximately 15 cm in length and constructed of 130-kg test monofilament fishing line wrapped in adhesive-lined shrink wrap. The darts were inserted through the dorsal musculature and pterygiophores of Pacific halibut, anchoring them in the bony fin ray supports of the body. The position of the darts was about 2.5 cm medial of the dorsal fin on the eyed side of the fish where the body began to taper toward the tail (Seitz et al., 2003).

While attached to the Pacific halibut, the tags measured environmental variables, including pressure, which was converted to depth, at regularly spaced intervals of either 0.5, 1.0, or 2.0 min. The tags were programmed to release from the fish on a specified date, after which they floated to the surface and transmitted summarized data through satellites. If a tag was physically recovered, the complete detailed dataset was downloaded from the tag. Detailed datasets from recovered tags provided the depth measurements that were examined in this study.

For our analyses, changes in depth, and lack thereof, were used as proxies for active swimming behavior and remaining motionless on the seafloor. For identifying periods of active swimming behavior, it was assumed that changes in depth that occurred faster than the rate of tidal change in the study area corresponded to fish swimming on or adjacent to the bottom while tracking heterogeneous bathymetry, or to vertical swimming activity off the sea floor. For identifying periods of remaining motionless on the seafloor, it was assumed that changes in depth that occurred at approximately the same rate of tidal change in the study area corresponded to periods of inactivity by tagged Pacific halibut, during which the height of the water column above the fish fluctuated with the tidal cycle. Periods of remaining motionless on the seafloor were also identified as times where there was no change in depth, as the tidal amplitude in some locations in the Gulf of Alaska is relatively small and may not be detected by the tags. However, if a fish remained at a relatively constant depth while actively swimming either on or adjacent to relatively flat bathymetry, or at a constant depth in the water column, periodic behavior would not be detected because active swimming behavior would be mistaken for inactivity.

To examine the complete detailed depth records for depth-specific periodic behavior, four figures were created for each tag's depth dataset, using MATLAB R2012b: 1) a two-dimensional time series of depth plot, 2) an activity level plot, 3) a periodogram plot and 4) a wavelet transform coefficient plot. First, the surface plot of depths called a "2-d time plot" was created using recorded depth readings represented by a continuous color gradient plotted on the z-axis, day of year on x-axis and time of day on the y-axis (sensu Teo et al., 2013). This type of figure allowed visualization of patterns in occupied depth with durations around 24 h (i.e., tidal and diel periods), and was a tool for examination of longer patterns such as variations in intensity of diel behavior patterns.

The remaining three figures for each depth record did not directly display raw depth recordings, but instead displayed functions that operate on the depth time series and produced outputs that were then plotted and used to infer information about periodicity in the raw data. The second plot, called the "activity level" plot (Godø and Michalsen, 2000), displayed the rate of depth change between successive depth readings (depth change rate = Δdepth/Δtime). In all cases, data were kept in their native temporal resolution (i.e., the temporal resolution was not standardized among datasets), to maintain as much detail as possible in the depth datasets. In general, the activity level figures were used to provide greater detail about periodic behaviors that occur at different time scales, such as those that occur in a 24-hour cycle.

The third figure was a plot of periodogram values, which indicate the relative degree to which data repeats itself for specified lengths of time (the period). This plot is another surface plot that displays the power spectral density (PSD) estimate on the z-axis, day of year on the x-axis and period length on the y-axis. Periodograms were calculated for periods from 500–3500 min to examine potential tidal (745 min) and diel (1440 min) periods and multiples of those periods. To examine whether each fish was behaving periodically during specific dates, periodograms for continuous 10 day (14,400 min) sub-samples of tag data were calculated, sliding the 10 day sample in 60 min increments through the tag data. Periodic behavior was visually identified as relatively sharp peaks that were continuous through time. Overall, peak values of the period (z-axis) are indicators that the corresponding