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Extraction of daily activity pattern and vertical migration behavior from the benthic fish, *Lophius americanus*, based on depth analysis from data storage tags.

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ABSTRACT

Depth (pressure) and temperature measurements recorded on a data storage tag were examined from a single goosefish, *Lophius americanus*, tagged on Georges Bank on 9 December 2003 and recaptured 192 days and 113 km away off Cape Cod, Massachusetts on June 18, 2004. The monkfish exhibited a strong pattern of periodic vertical movements ranging from 4 to 209 m (mean=75 m) with durations of 48 to 864 minutes (mean 177 minutes). A total of 43 vertical movements were recorded averaging 1.6 movements per week. Two periods of frequent daily movements were recorded. The first period occurred over six weeks in February and March during a transition from deep (180 m) to shallow water (150 m), while the second period apparently occurred as the fish descended into the Great South Channel and then ascended up the western slope into the inshore waters of Cape Cod over a five week period in May and June. Vertical movements during the second period were consistently longer in duration (mean = 198 minutes) and higher in elevation (132 m), than those in the first period (mean duration = 131 minutes, mean height = 41 m, respectively). The rate of ascent and descent were similar with means of 1.0 m/minute and 1.2 m/minute, respectively. Vertical movements occurred primarily between 0000 h and 1200 h (81 %), with peaks at 0300 h and 1000 h. This data suggests that goosefish exhibit at least three modes of movements: 1) gradual movements along the bottom contour, 2) short vertical hops of less than 10 m height, and 3) large vertical movements involving vertical jumps of 10-200 m and durations averaging 6.5 h hours. The latter pattern suggest extensive use of tidal transport mechanisms. We suggest that future studies that use advanced geolocation techniques promise to provide valuable insight into goosefish activity and migration patterns, as well as the environmental factors that may trigger them.

INTRODUCTION

The American goosefish, *Lophius americanus*, also known as monkfish or angler, is an important fishery species in the northeast region of the United States and was ranked seventh in value for the region in 2004 and 17th nationally with a value of over 33 million dollars (Barbara Rountree, Northeast Fisheries Science Center, Personal Communication). Despite its economic importance relatively little is known about the behavior and ecology of the species. Behavioral studies have been largely limited to observations of its unique predatory behavior involving the use of its angling appendage which is composed of a modified dorsal spine (the illicium) from which it dangles a lure (esca) to attract prey (Bigelow and Schroeder 1953; Steimle et al., 1999; Caruso 2002). goosefish have been reported to make seasonal inshore-offshore migrations based on catch distribution patterns (Jean, 1965), but to our knowledge no tagging studies have yet been conducted to confirm that migrations do occur. The lack of a swim bladder and the body morphology of the goosefish suggests it is ideally suited to a benthic lifestyle with its large, dorsoventrally-flattened head, and strong, leg-like pectoral fins. The species is usually described as a slow moving solitary bottom fish that sits in wait of prey to ambush. There are anecdotal observations of individuals occurring at the surface (Connolly, 1920; Steimle et al., 1999), but this behavior has been thought to be unusual for the species. More recently European researchers have suggested that the closely related *Lophius piscatorius* sometimes occurs near the surface over deep depths (Hislop et al., 2000), and Laurenson et al. (2005) has hypothesized that the species uses selected tidal stream transport to undertake inshore migrations.

In this study we report on movements of a single adult goosefish tagged with a data storage tag that recorded depth (pressure), temperature and salinity. Our observations confirm that this individual did migrate inshore between the winter and early summer, and that it underwent periodic vertical migrations. These observations reveal that the species is capable of staying in the water column for many hours and provide support for the selected tidal stream transport hypothesis (sensu Laurenson et al., 2005).

MATERIALS AND METHODS

Thirteen goosefish ranging from 22 to 75 cm total length (TL), were tagged in November and December 2003 (ten on 9 December) on Georges Bank in the western north Atlantic (Fig. 1). Fish were tagged with conventional t-bar anchor tags, as well as with data storage tags (DST) made by Star-Oddi (Reykjavik, Iceland). The tags were 49 mm in length and 18 mm in diameter and recorded depth (pressure), temperature and salinity every 48 minutes. The temperature resolution was +0.1 C and the depth resolution was 1.2 m. The attachment method was similar to that used successfully in an earlier study of Atlantic cod, *Gadus morhua*, (Groeger et al. in press). The tags were attached using two 7.7 cm stainless steel pins that were first inserted through the tag and then through the dorsal musculature and finally were anchored in place by earring backings. One 62 cm TL individual, tagged at 02:20 h on 9 December 2003 in 174 m (95 fm) of water on the northern slope of Georges Bank, was recaptured by a commercial gill net fishermen on June 18th 2004 inshore near the tip of Cape Cod, Massachusetts (Fig. 1). Assuming a straight-line migration, the fish had traveled 113 km in 192 days, averaging 0.6 km/day.

Salinity data obtained from the DST exhibited a strong electronic creep and is not presented, herein, because it was not considered reliable. However, failure of the salinity (conductivity) sensor does not affect the reliability of the temperature or pressure sensors (Baldur Sigurgeirsson, Star-Oddi). A comparison of the depth reported at tag release with that recorded on the DST when the fish reached the bottom (174 m versus 175-183, respectively) suggested that the DST was recording depth (i.e., pressure) properly at that time. We initially thought that a 23 m error in the depth recorded at the surface on recapture indicated a minor offset in the depth recording. However, on consultation with the manufacturer we found the readings in air at the surface were erroneous as the tag was not designed to record in less than 1 m depths, so all other depth records are reliable (Baldur Sigurgeirsson, Star-Oddi).

We therefore, proceeded to examine the depth (pressure) and temperature record for evidence of vertical movements (Fig. 2). Periods where fish appeared to remain on the bottom could usually be recognized by a low depth variation over short to long time periods (Fig. 3), during which time the tidal signal in depth was observed. Unfortunately, the long time interval between recordings (48 minutes) and the low depth resolution of the DST tags (1.2 m), prevented us from statistically resolving the tidal signal. It is also for these reasons that attempts to use the tidal signal to geolocate the daily position of the fish (sensu Groeger et al., in press) during its migration was not possible.

We measured several parameters for all apparent vertical migrations of at least 4 m. Total duration was estimated as the number of records from the start to end depth (Fig. 3) minus 2, multiplied times the sampling interval of 48 minutes. Therefore, in the example in Figure 3, the total duration was estimated as 48(11-2) = 482 minutes. The peak height was measured as the highest elevation reached by the fish, and the total height of the movement was measured as the difference between the peak height and starting depth (Fig. 3). A height plateau was observed during some events where the fish remained in the water column for some time after its ascent. The plateau duration was measured as the number of sampling intervals minus one multiplied times the sampling interval (which would be 48(9-1)=384 minutes in Fig. 3). The plateau height was measured as the mean height during the plateau period. The height and duration of the ascent was measured from the time and depth at the start of the ascent to the beginning of the plateau period, or to the peak height when no plateau occurred. The rate of ascent was then estimated as the ascent height divided by the ascent duration. Descent height, duration and rate were similarly calculated from the end of the plateau, or peak height, to the end of the event (end depth, Fig. 3). A measure of the change in bottom depth resulting from a vertical migration event was determined as the difference between the ending and starting depths (end depth- start depth) and could be positive (drop in elevation as in Fig. 3) or negative (rise in elevation). The absolute bottom depth change was also calculated.

Bottom events were determined as the periods between measurable vertical events, when the fish was assumed to be on the bottom because of the long duration and the presences of a clear tidal signal in the depth recording. The duration and depth range (maximum depth - minimum depth) of each bottom event was measured. Linear regression was used to test for significant changes in depth during bottom events. A positive slope indicated a gradual rise in the bottom depth, while a negative slope indicated a gradual decline in the bottom depth. It should be noted, that there were indications of vertical movements that were too short and low to be clearly resolved in the DST record due to the low sampling resolution, therefore, some of the depth changes observed during bottom events may have been due to unresolved short-duration vertical movements.

We categorize vertical movements into one of four types for descriptive purposes, but recognize them as being purely arbitrary. Drops occurred as a rapid change in depth that lacked any apparent rise in depth from the starting point. Hops were vertical rises of less than 10 m and 240 minutes duration. Jumps were rapid rises of 10 m or more that lacked a plateau, or for which the plateau was shorter than the sampling time interval. Glides were prolonged jumps with duration of over 240 minutes that usually exhibited a clear plateau stage. To illustrate seasonal differences in vertical movements we describe data from recording weeks 1, 9, 13, and 24 (labeled in Fig. 2) in detail in Figure 4.

RESULTS

A total of 43 vertical movements (averaging 1.6 per week) and a corresponding 41 bottom periods were indicated in the DST record (Fig. 2; Table 1 and 2). Vertical movements averaged 75 m in height with a maximum height of 209 m (Table 1). Duration averaged 177 minutes (2 h 57 minutes) and ranged from 48 to 864 minutes (14 h 24 minutes). The rate of ascent and descent were similar at 1.0 m per minute and 1.2 m per minute, respectively (Table 1). A plateau occurred at an average height of 108 m with an average duration of 70 minutes. Movements occurred primarily between the hours of midnight and noon (81 percent), with peaks at 3 am and 10 am (Fig. 5). The bottom depth changed an average of -1 m (or 6 m for absolute magnitude) between the start and end of the vertical events (range -41 to 24 m; Table 1; Fig. 6). Depths of bottom events were often stable, with low variation (Table 2), however, significant depth gradients were found in 16 (39 %) of the bottom events (Table 2). Most of these occurred in the second half of the recording when the goosefish migrated down the eastern wall of the Great

South Channel (GSC) and up the western wall (when a 0.74 m/hr slope was measured).

The vertical movements were highly aggregate by time of year, with 81% occurring in two periods. The first period occurred over six weeks in February and March during a transition from deep (approximately 180 m) to shallow water (approximately 150 m), while the second period occurred as the fish descended into the GSC and then ascended up the western slope into the inshore waters of Cape Cod over a five week period in May and June (Fig. 2). Vertical movements during the first period were shorter in duration, lower in height (Table 3), and exhibited low temperature variation, suggesting a homogenous water column (Fig. 4). In contrast, vertical movements during the second period were longer, higher, and exhibited strong temperature variations indicative of movement through a thermocline (Fig. 4). A long period lacking obvious vertical movements (except for one jump) occurred for over 100,000 minutes (approximately 70 days) between these two periods. During this time the depth averaged 146 m and ranged from 143 to 155 m. Linear regression indicated a gradual rise of 12 m (0.008 m/h; R^2=0.81) before a 95 m jump occurred, followed by an equally gradual descent of 6 m (0.006 m/h; R^2=0.57).

Week 1 after release. – For the first two days after release, the fish exhibited an unusual movement patterns compared to the rest of the recording (Fig. 4a). It is uncertain whether the fish ever actually reached the bottom during these first two days, because the depth never stabilized long enough to observe a tidal signal. It dropped rapidly towards the sea floor to a maximum depth of 183 meters immediately after release, then wobbled between 175-183 m for 288 minutes before undertaking a short (13 m high, 144 minutes duration) vertical glide followed immediately by a long vertical glide of 151 m and 864 minutes (>14 h). It is notable that this second vertical rise lasted much longer than any subsequent vertical movement, and was the only vertical movement in which the fish passed through a thermocline prior to May. This second glide included the longest plateau period of 576 minutes which occurred at an average depth of 46 m. At the end of the plateau the fish descended to an average depth of 185 m (range 185-186 m) where it remained for 2,928 minutes (approximately 2 days) before undertaking two jumps about 12 hours apart. The bottom depth changed after each jump, 3 m for the first to 12 meters for the second, so that after the second jump the bottom depth had risen to 170 m. A strong tidal signal in the temperature field was noted just prior to the jumps (Fig. 4a). The fish then remained at an average depth of 170 m for 36,384 minutes (25 days) before the next vertical event.

Week 9 after release. – One of the three drop events observed occurred during the 9th week after release (Fig. 4b). In this event the depth dropped 14 m in 288 minutes without any indication of an initial rise in the water column. It is likely that the fish either made a very short hop into the water column that was not recorded due to the long sampling interval, or that the fish actually descended down a steep gradient in the sea floor. It is notable that a strong tidal signal in the temperature record was recorded just prior to the drop.

Week 13 after release. – A peak frequency of seven vertical movements, including five jumps and two glides, occurred in the 13th week after release (Fig. 4c). During this period the bottom depth appeared to gradually decline as the fish transitioned from a depth of approximately 180m to a depth of approximately 150 m. Note that the temperature remained stable at about 4^{o}C throughout this period, despite vertical movements of up to 112 m.

Week 24 after release.– The 24^{th} week after release occurred during the second period when the frequency of vertical movements again peaked at 7 (or 1 per day; Fig. 4d). During this period the fish appeared to have moved down the eastern wall of the GSC and then up the western wall in the five weeks prior to its capture west of the GSC (Fig. 1, 4d). During this week 5 glides, one jump and a hop were recorded. The height and duration of the movements tended to be greater than in period 1 (Table 3). In addition, the fish appeared to pass through a strong thermocline during five of the events, and experienced temperature increases as great as 5 ^{0}C. Most of the vertical movements occurred as the fish moved down the eastern wall of the GSC, with only 3 events recorded as the fish moved up the western wall. The first three vertical movements (together with the last from week 23) occurred at 24 hour intervals starting at approximately 0300-0400 h and had durations of 6-8 h. In contrast three of the last five vertical movements (including the first from week 25) started at 1000 h, but were interrupted by two short hops at 2100 h (1^{st} and 3^{rd} events, Fig. 4d).

DISCUSSION

The remarkable periodic vertical movements made by an individual goosefish observed in this study challenge previous assumptions about the behavior of the species and have important management implications. However, the reason or reasons for the vertical movements are unknown at this time, but Hislop et al. (2000) suggested three hypotheses: 1) migration mechanism, 2) spawning behavior, and 3) foraging behavior. We suggest that predator avoidance (including disturbance by human predators) may be another reason for some of the vertical migrations exhibited by goosefish, particularly for the movements we characterize as short hops. For example, disturbance by a passing trawl may cause a sudden upward hop to avoid the passing ground cables, doors or other trawl component. Perhaps the strongest of these hypotheses is that vertical movements are a mechanism for accomplishing short or long-range migrations. These can be directed such as in selected tidal stream transport, or undirected where the fish simply seeks to move to a potentially more favorable location with relatively little effort. Our observations of relatively long duration vertical movements that appear to be on a tidal scale would support the selected tidal stream transport hypothesis advanced by Laurenson et al. (2005) for *L. piscatorius*. However, we lacked sufficient data to formally test this hypothesis. We note, that at several times vertical movements were preceded by strong tidal variation in the temperature field (Fig. 4a, b), and suggest that future studies test the hypothesis that such events trigger migrations. It was also notable that the longer duration glide events tended to occur when the fish passed through a thermocline, while jumps usually occurred within a homogeneous water column. If the liver mass aids in vertical movements as Hislop et al. (2000) speculates, then the presence of a pycnocline may allow the fish to remain in the water column longer (indeed, durations were four times greater when the fish passed through a thermocline, e.g., 2^{nd} glide in Fig. 4a and first 3 glides in Fig. 4d). Alternatively, lack of a thermocline and occurrence of shorter vertical movements prior to May, followed by their occurrence in May and June might suggest that the presence of a thermocline may serve as a migration trigger for goosefish.

Another likely reason for the vertical movements might be that they occur as part of the fish's spawning behavior. Vertical movements might aid the female to shed the large buoyant egg veil produced by the species, and spawning high in the water column or near the surface might enhance veil dispersal. The fact that the second period of frequent vertical migrations observed during this study (Fig. 2, 4d), corresponds with the beginning of the spawning season in the Georges Bank area (Caruso 2002) and that the individual was certainly mature at over 60 cm (Almeida et al. 1995), would support the hypothesis. However, the high frequency of vertical movements that occurred in late February and March suggests that spawning is not likely the primary cause. Of course, it is possible that the different vertical movement characteristics (Fig. 4c,d; Table 3) exhibited between the two periods reflects different behaviors and causes for the movements (i.e., the fish makes vertical movements for different reasons at different times).

Hislop et al. (2000) suggest that the behavior is unlikely to be related to foraging behavior, but they do note that two individuals were caught on pelagic long lines. However, in the western North Atlantic, squid and pelagic fish make up 4-11% and 3-5% of the diet of the goosefish, respectively (Rountree 1999), so the importance of pelagic feeding may be understated for the species.

Regardless of the underlying cause of the vertical migration, we believe that they do in fact result in changes in fish location. We suggest that once measurement error and tidal variations in depth have been accounted for, that the residual changes in bottom depth can be used in future studies as an proximate index the fish's activity pattern. Temporal patterns in vertical movements, including the smallest resolvable hops, can be studied in relationship to tidal dynamics, celestial events (e.g., time of day) and other factors. In addition, since changes in bottom depth during the bottom periods can be inferred as changes in location, they can be used as an index of the fishes movements across the bottom (however, since movement can occur without a change in bottom depth, it would be a conservative index).

Future studies using DST tagging technology promise to provide important new insights into the behavior and ecology of the goosefish. With improved data resolution and an increased sampling frequency we expect that geolocation techniques (Groeger et al., in press) can be effectively applied to the species. Geolocation using tidal modeling can be enhanced by locating the fish only during the bottom event periods. However, if hydrographic models can be incorporated together with the tides, then vertical event parameters such as those measured, herein, can be used to better model the fish's movements. Besides the obvious usefulness of these new techniques for determining the migration patterns of benthic fishes, they are also a powerful new tool for use in behavioral ecology studies that can provide insight into activity patterns, as well as the environmental triggers for vertical and horizontal movements.

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Table 1. Summary statistics for vertical movement events.

Event attribute	N	Minimum	Maximum	Mean	Standard deviation
Duration (minutes)	43	48	864	177	162
Total height of movement (m)	43	0	209	75	73
Rate of ascent (m/minute)	40	0.079	3.958	0.994	0.915
Plateau height (m)	40	26	216	108	59
Plateau duration (minutes)	40	0	576	70	130
Rate of descent (m/minute)	43	0.014	4.208	1.199	1.295
Bottom depth change (m)	43	-41	24	-1	10
Absolute bottom depth change (m)	43	0	41	6	8
Rate of bottom change (m/hour)	43	0.000	7.5	1.7	1.604

Table 2. Summary statistics for bottom period events.

Event attribute	N	Minimum	Maximum	Mean	Standard deviation
Duration (minutes)	41	384	64368	6413	12687
Absolute depth range (m)	41	0	91	6	16
Slope (m/hr)	41	-0.69	0.74	0.02	0.19
Absolute slope (m/hr)	41	0.00	0.74	0.07	0.18
Events with significant gradients					
Duration (m)	16	912	64368	13472	18372
Depth range (m)	16	-18	91	12	26
Absolute depth range (m)	16	3	91	17	23
Slope (m/hr)	16	-0.69	0.74	0.06	0.03
Absolute slope (m/hr)	16	0.00	0.74	0.18	0.25

Table 3. Comparison of summary statistics for vertical movements between period 1 (week 8-13) and period 2 (week 23-27).

Period 1	Number	Minimum	Maximum	Mean	Standard deviation
Duration (minutes)	19	48	480	131	106
Plateau duration (minutes)	19	0	240	19	60
Total height (m)	19	0	112	41	40
Period 2					
Duration (minutes)	16	48	432	198	143
Plateau duration (minutes)	16	0	384	108	129
Total height (m)	16	4	209	132	77

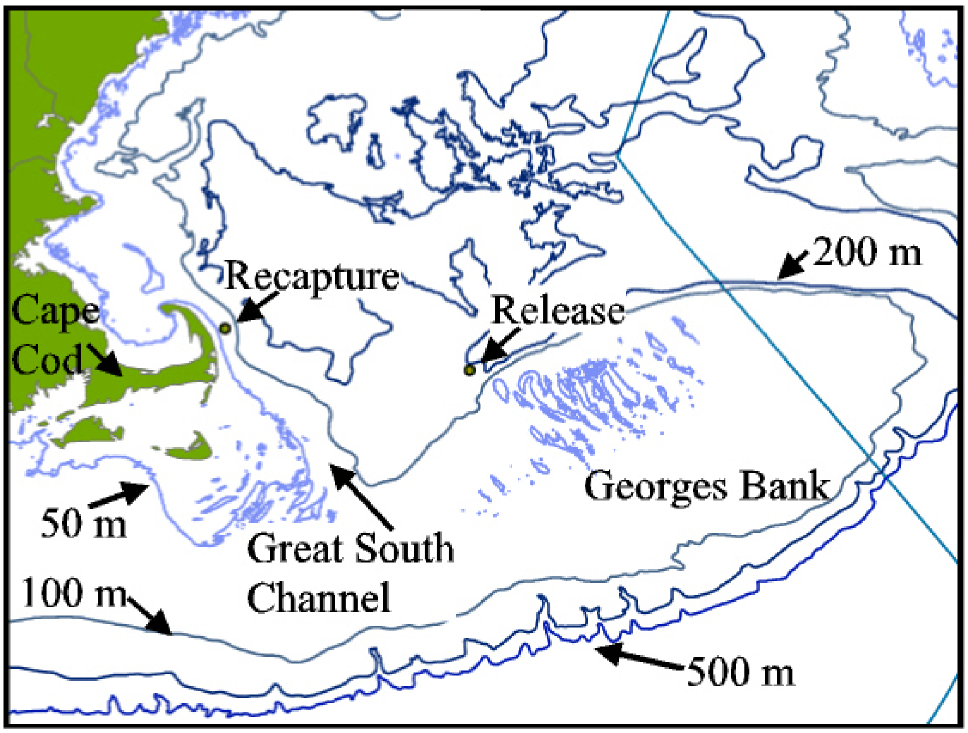

Fig. 1. Tag and release location of an goosefish tagged on Georges Bank on 9 December 2003 and recaptured inshore off Cape Cod, Massachusetts on June 18th 2004.

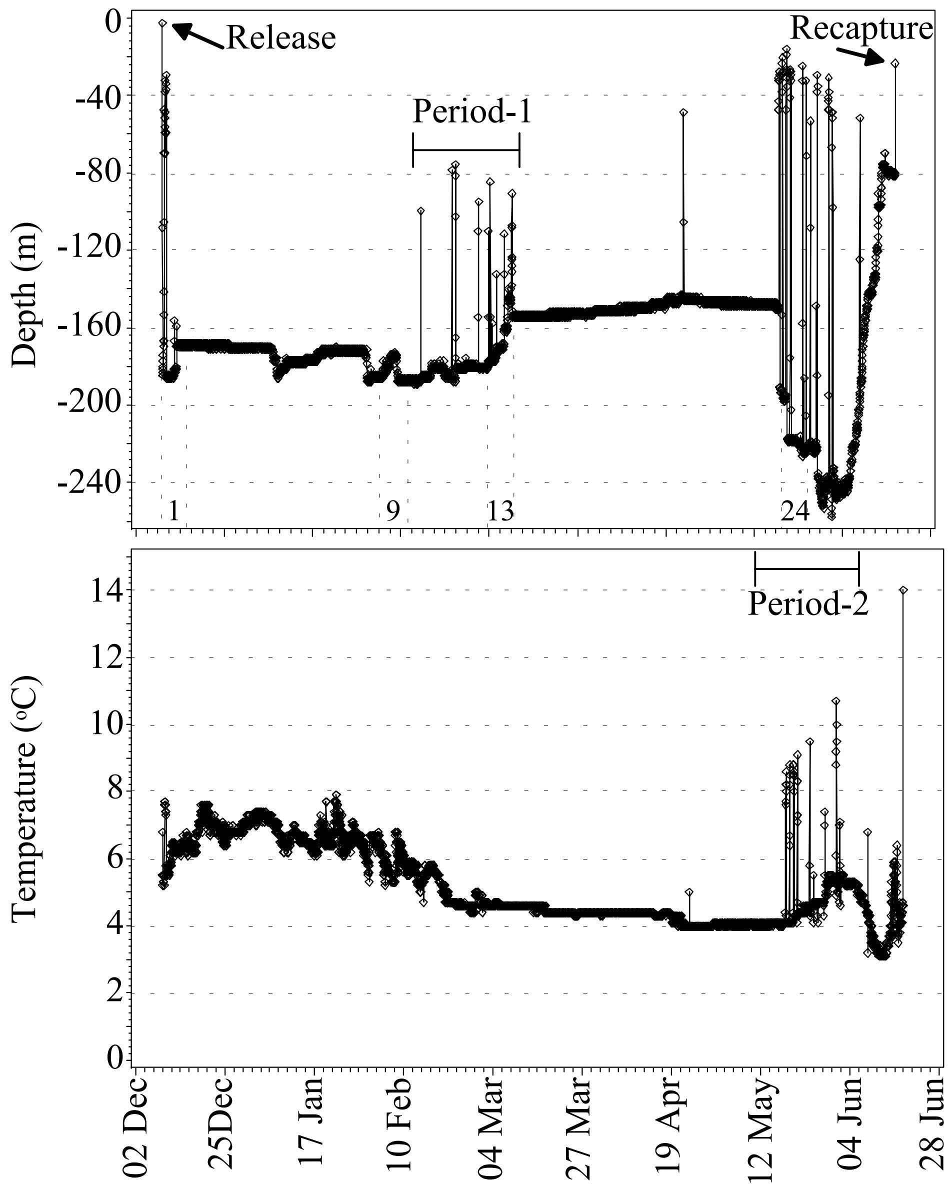

Fig. 2. Temperature and depth recorded for a tagged goosefish at large for 192 days from December 2003 through June 2004. Two periods of frequent vertical migrations are labeled as period-1 and period-2. Labels for the weeks 1, 9, 13, and 24 after release are provided for reference in Figure 4.

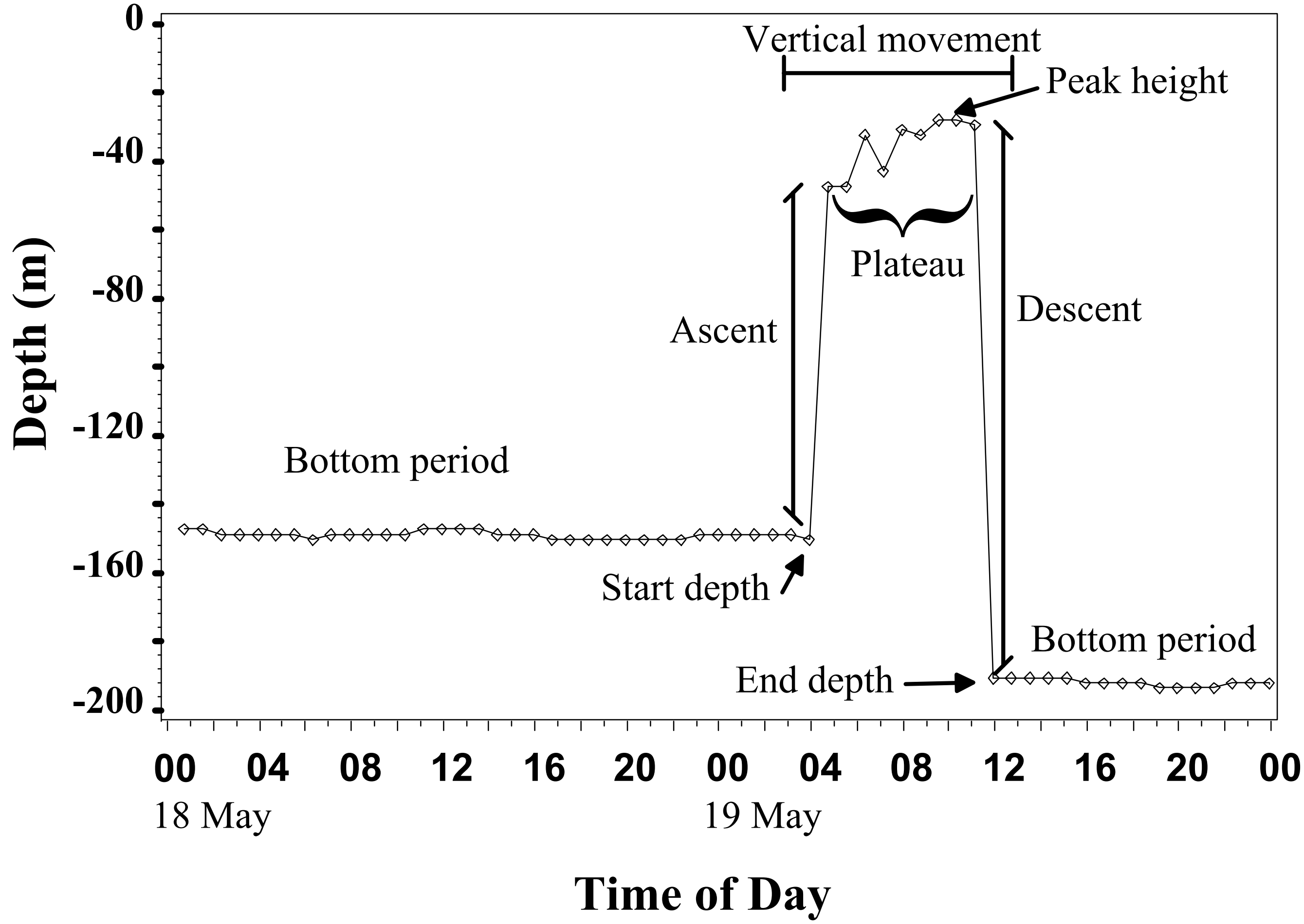

Fig. 3. Illustration of the parameters measured to define vertical events (see text for explanation).

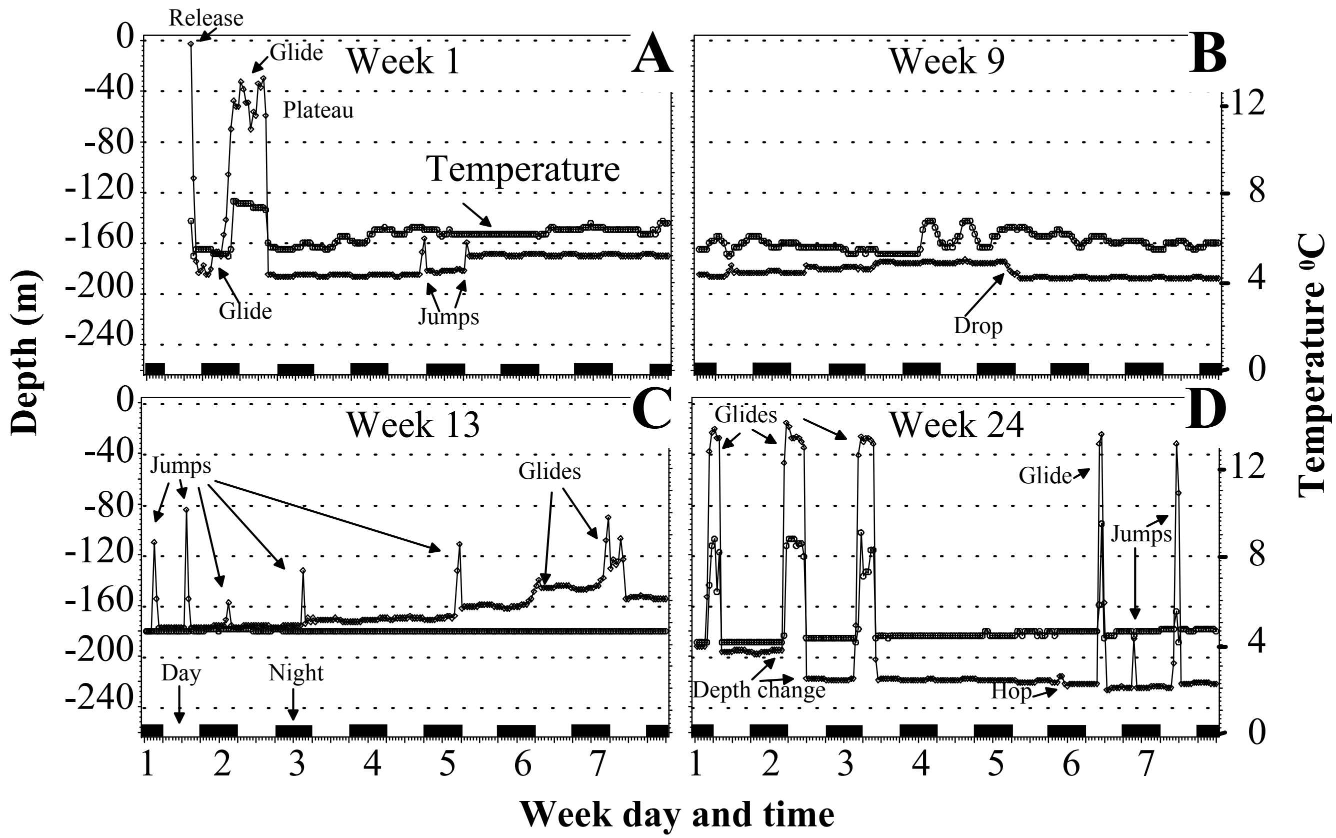

Fig. 4. Comparison of temperature and depths recorded for a tagged goosefish for the 1st, 9th, 13th, and 24th week after release. The location of these weeks are labeled on Figure 2 for reference. Day and night periods are indicated by the dark and light bars on the date-time formatted x-axis. Date labels on the x-axis have been standardized as day number.

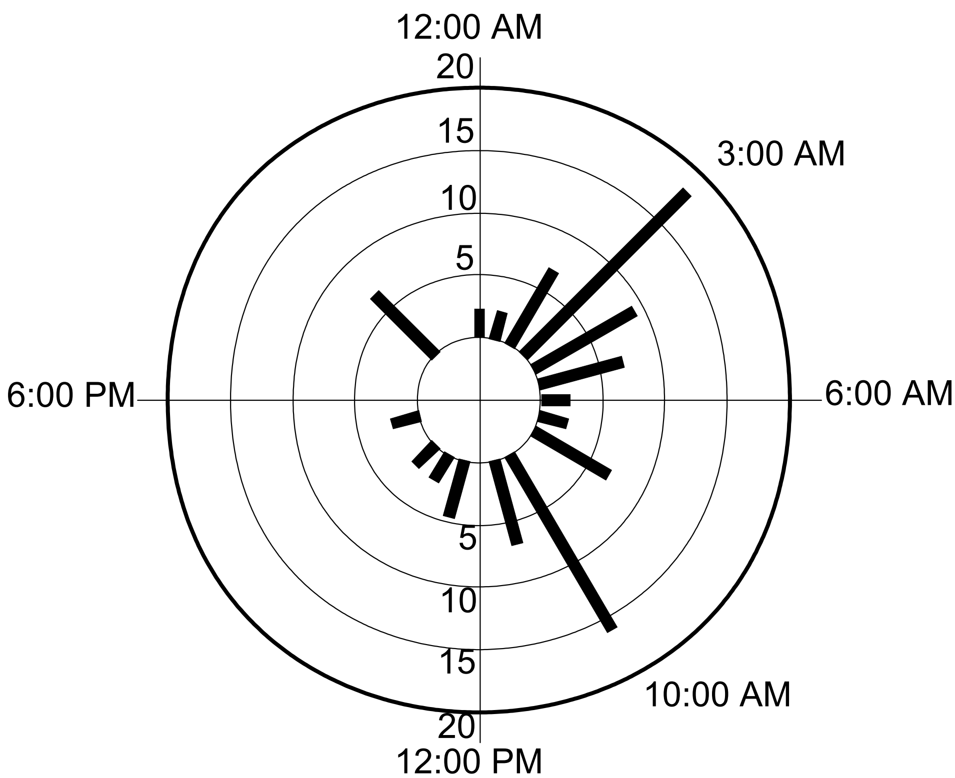

Fig. 5. Circular histogram of the percent frequency of vertical movements by hour of the day. Concentric circles are at 5 % intervals.

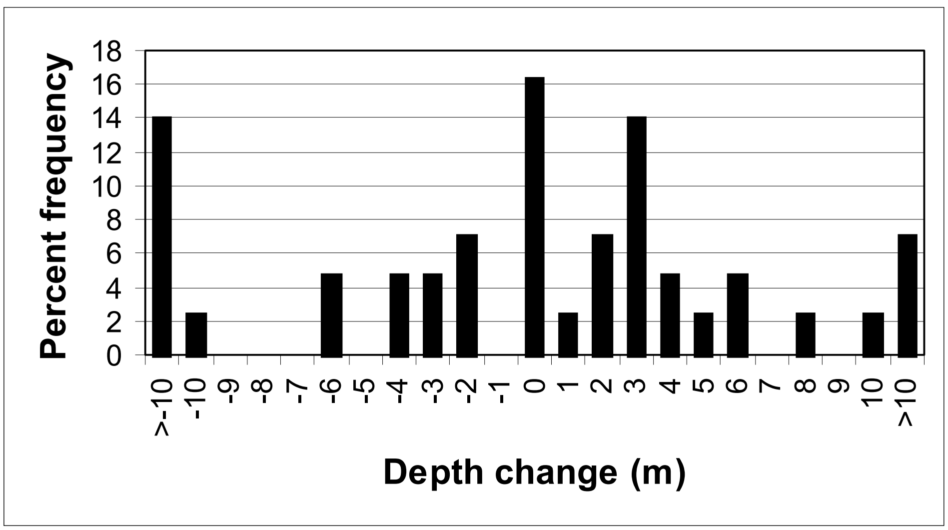

Fig. 6. Histogram of the change in bottom depth between the start and end of vertical movements.