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New Insights into Marine Migration and Winter Habitat of Gulf Sturgeon

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Abstract.—Migrations and movements of Gulf sturgeon *Acipenser oxyrinchus desotoi* were determined using satellite pop-up archival transmitting (PAT) tags and acoustic telemetry. Adult Gulf sturgeon from four rivers in northwestern Florida were caught with gill nets and were tagged with PAT and acoustic tags in the fall of 2001 and 2002. PAT tags were programmed to release in early February 2002 and 2003 to provide information about location of late-winter marine habitats. However, only 5 of 25 provided meaningful location information. Three of the PAT-tagged fish were relocated acoustically near the PAT tag pop-up locations, one of which was in Choctawhatchee Bay. Acoustic searches near Gulf of Mexico pop-up locations led to acoustic relocation of one nonreporting PAT-tagged fish and five fish tagged with acoustic transmitters only. Many of these fish were relocated on several dates in late winter, and many (including fish from the Yellow, Choctawhatchee, and Apalachicola rivers) were concentrated in a 25-km stretch of the Florida Panhandle coast, within 2 km from shore, and in depths less than 6 m. A fish that had been tagged with a PAT tag in the Yellow River was acoustically relocated in the concentration area and then in the Choctawhatchee River the following summer. It returned to the concentration area again the next winter and returned to the Choctawhatchee for the second summer. An acoustic-tagged fish was relocated very near a PAT tag pop-up location about 30 km south of the Suwannee River, within 12 km from shore, and in depths of 3–4 m. Pop-up locations and acoustic relocations showed that the Gulf sturgeon had migrated distances of at least 30–180 km. These findings indicate a pattern in which Gulf sturgeon migrate considerable distances along the coastline, sometimes to specific areas of concentration, sometimes mixing with other populations, and primarily utilizing shallow (2–6 m), nearshore areas as late-winter habitats. This pattern is similar to that reported by others in this volume for Atlantic sturgeon *Acipenser oxyrinchus* and for green sturgeon *A. medirostris*.

Introduction

Adult Gulf sturgeon *Acipenser oxyrinchus desotoi* from major Gulf of Mexico rivers east of the Mississippi River emigrate in the fall (Foster and Clugston 1997; Edwards et al. 2003) to marine habitats, where they feed and grow until returning to rivers in the spring. These winter marine habitats are of particular importance because Gulf sturgeon do not feed

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during their approximately half year of freshwater residency (Mason and Clugston 1993) and hence must acquire all energy reserves for growth, maintenance metabolism, and reproduction from marine habitats. Gulf sturgeon is listed as threatened under the Endangered Species Act, and critical habitat has been designated (USFWS and NMFS 2002) but, largely due to lack of information about marine habitats, not completely.

Until recently, little was known about Gulf sturgeon migrations and winter habitats. Fox et al. (2002) suggested that many adults emigrated from the Choctawhatchee River to the Gulf of Mexico, while others remained in Choctawhatchee Bay during winter. Edwards et al. (2003) reported that Gulf sturgeon emigrate from the Suwannee River around October to 2–4-m-deep nearshore areas of the open Gulf just offshore of Suwannee Sound, a very shallow (<2 m), semi-enclosed estuarine area immediately outside the Suwannee River. Edwards et al. (2003) found that Gulf sturgeon remained in this area for many weeks before further emigrating in late December or early January to heretofore unknown late-winter habitats. Parkyn et al. (2007, this volume) relocated Gulf sturgeon within or very near Suwannee Sound as the fish emigrated in the fall and returned in the spring.

Edwards et al. (2003) found that Gulf sturgeon migrated to late-winter habitats during periods of storms and rough seas and that continual tracking or relocation of acoustic-tagged fish to determine the location of these habitats was infeasible. However, recent development of the new technology of pop-up, archival, satellite tags (Block et al. 1998), combining satellite tracking and data transmission, micro- processor controlled sensors for depth, temperature and light, and nonvolatile memory for archiving data, offered a new way of determining Gulf sturgeon migration and marine habitat. We now report information, collected by a combination of pop-up, satellite, archival tags and conventional acoustic telemetry, on late-winter habitats and migrations of Gulf sturgeon. We discuss this information relative to parallel findings for Atlantic sturgeon *A. oxyrinchus* (Laney et al. 2007, this volume) and green sturgeon *A. medirostris*, (Erickson and Hightower 2007, this volume).

Methods

The study included two areas: (a) the northwestern Florida Panhandle region, and (b) the northwestern peninsular Florida area near the Suwannee River mouth (Figure 1). Adult Gulf sturgeon were collected in the fall of 2001 and 2002 using large-mesh gill nets deployed in the Yellow, Choctawatchee, Apalachicola, and Suwannee rivers (Figure 1).

Satellite pop-up archival tags (PAT, Wildlife Computers) (21 mm diameter × 175 mm long excluding antenna, 75 g in air, up to 1-year battery life) were attached to selected large adult fish using two methods. In 2001, a lanyard (1.53-mm-diameter monofilament nylon) was attached through a hole drilled through a mid-dorsal scute two or three scutes anterior to the dorsal fin. In 2002, a lanyard was attached through the base of the dorsal fin (Erickson and Hightower 2007).

PAT tags measure and archive depth (pressure), temperature, and light-level data. On a user-programmed date and time, the PAT tag actively corrodes the pin to which the tether is attached, allowing the PAT tag to release from the fish and float to the surface. It then begins to transmit randomly selected (to provide a sample of data over the entire deployment period before the battery is exhausted), summarized data (frequency of depth and temperature falling within user-programmable bins for 24-h periods) via the ARGOS system of satellites. Depth bins in this study were 0–2, 2–4, 4–6, 6–9, 9–12, 12–20, 20–30, and >30 m; temperature bins were 1.5°C intervals from 7.0°C to 22.0°C. Complete archived data can only be obtained if the PAT tag is recovered. PAT tags can be programmed to begin transmitting immediately, instead of waiting until the programmed date, when depth is constant (within 2 m) for a protracted period (pro-

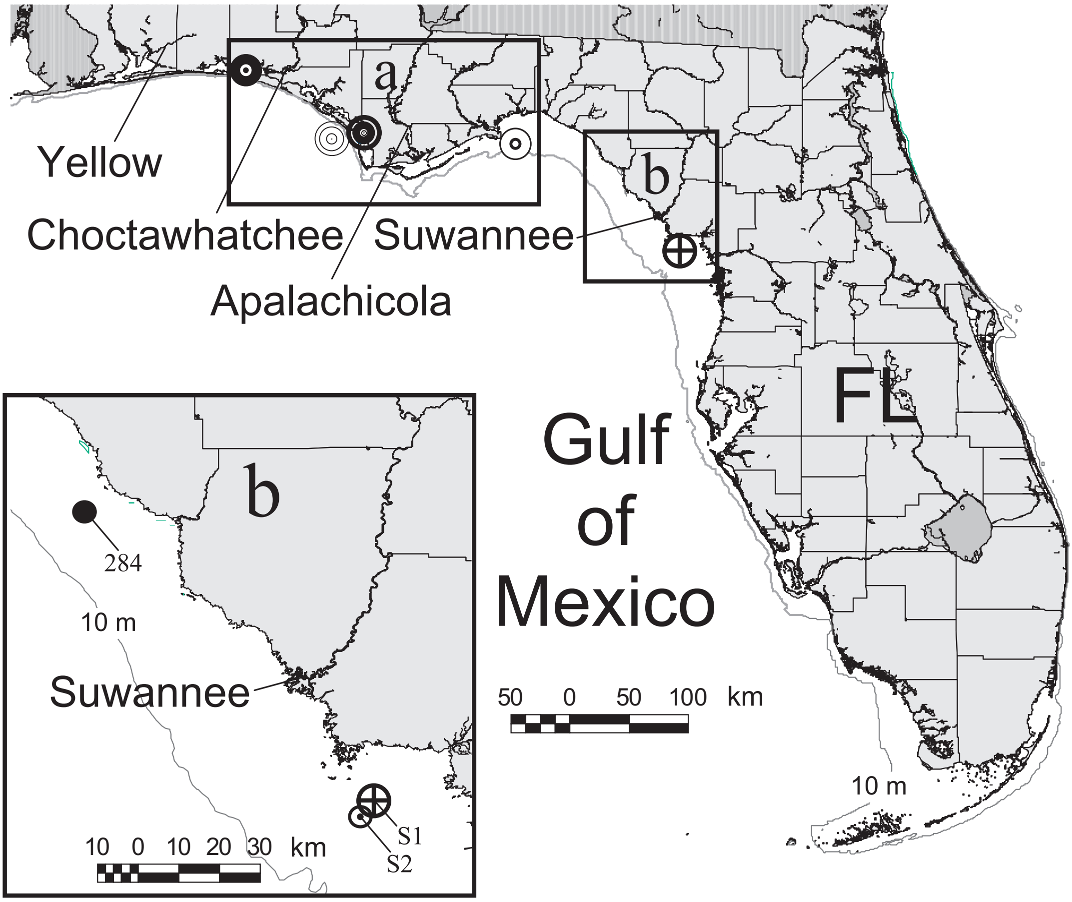

FIGURE 1. Study areas: a—Florida Panhandle area, b—Northwestern peninsular Florida. Inset area a is shown in detail in Figure 2. Inset area b is shown in detail below, including pop-up location S1, relocation S2, and Fish 284 (from Edwards et al. 2003). Pop-up locations for Y1, A2, A3, C1 (symbol legend in Figure 2), and S1 are indicated in the larger map.

grammable from 24 to 192 h). However, because Gulf sturgeon could be expected to normally remain at relatively constant depth for long periods, we were forced to disable this feature. Therefore, prematurely released or shed PAT tags did not transmit until the programmed dates (February 7, 2002 and February 3, 2003), that were selected because they were estimated to precede normal spring migration to coastal rivers.

PAT tag pop-up location was determined by the Service ARGOS satellite system from PAT tag transmissions (by measuring Doppler effect on transmitted frequency) and was communicated by e-mail. However, periods from a few hours to several days after programmed pop-up time, depending on conditions, were required before ARGOS could acquire accurate location information. Because the PAT tag may have drifted significant distances during these periods, the initial locations do not precisely correspond to the location at time of PAT tag–release. Transmissions of data summaries were received for about 2 weeks before battery power was exhausted. Data summaries were analyzed using proprietary software (PAT Decoder, Wildlife Computers) and included maximum and minimum depth and temperature, as well as light level data collected for the purpose of estimating geolocation.

Fish tagged with PAT tags were also tagged with acoustic tags. Other fish were tagged with acoustic tags alone. Coded acoustic telemetry tags (CT-82–3 or CHP-87-L, Sonotronics) (67 × 18 mm diameter, 10 g in water, 48-month battery life; 90 × 18 mm diameter, 15 g in water, 18-month battery life) were attached using monel wire passed through the two holes in the transmitter tag and through two matching holes made at the base of the dorsal fin. In one case, the acoustic tag was surgically implanted (Craft et al. 2001).

Acoustic relocation surveys were conducted from small boats using hand-held hydrophone and receiver systems (DH-4 and USR-5W, Sonotronics). The boat was moved from point to point on a grid of stations or along a river or shoreline, and the directional hydrophone was scanned through 360 degrees to detect any acoustic signals present and identify the fish from the transmitted code. In 2002, weekly (weather-contingent) searches of the Gulf of Mexico were made from February 8 through April 15. A total of twelve 4-h (typical) searches were made in the Gulf at approximately 1.6 km offshore and stopping every 1.6–2.4 km to scan for acoustic signals. Random distribution of searching effort was not attempted, but instead, much of the effort was focused on areas near a reported PAT tag pop-up location in the Gulf east of Choctawhatchee Bay. Choctawhatchee Bay was searched in 2002 in four 6-h trips between February 8 and April 17 and also searched on December 12 and 16. The Apalachicola River was searched in summer 2002 in 10 searches (stopping at each river bend) between May 30 and December 23. Weekly searches of the nearshore Gulf were restarted on December 12 and continued through March 24, 2003 in 16 searches (4–8 h each) in the nearshore Gulf covering the area from Pensacola to Apalachee Bay, as well as the Intercoastal Waterway from Pensacola to Apalachicola. Choctawhatchee Bay was searched 14 times in 2003 between January 10 and May 2. The Apalachicola River was searched four times between April and October.

Range of detection for CHP-87-L acoustic tags was estimated to be up to 3 km in the bays and about 1.5–2.5 km in the open Gulf, depending on conditions. In shallow (2–4 m) Gulf areas south of the Suwannee River, detection range of CT-82–3 acoustic tags (less power than CHP-87-L) was as low as 0.3 km, as determined by deploying a transmitter attached to a float and moving the boat away until the signal was no longer detected. A remote acoustic detection/recording station (USR-90 receiver, DH-4 directional hydrophone, DL-95 data logging system Sonotronics; and HP 1000CX 1-MB palmtop PC, powered by a 12-V battery), located just inside Choctawhatchee Bay at the inlet between the bay and the Gulf of Mexico at Destin Pass, also provided relocation information.

Results

2001–2002

Twenty fish were tagged with PAT tags, and 15 with acoustic tags alone, in the fall of 2001 (Table 1). Twelve of the PAT-tagged fish were from the Suwannee River, four from the Choctawhatchee River, two from the Apalachicola River, and two from the Yellow River. PAT tag transmissions and pop-up locations were received, starting on February 7, 2002, by ARGOS from eight Suwannee River PAT tags, one Choctawhatchee River PAT tag, and one Yellow River PAT tag. The eight tags from the Suwannee reported locations in the Gulf of Mexico 58–250 km south of the Suwannee River and about 45–100 km west of the Florida coast. Depth data (all recorded depths were 0–2 m) transmitted by these eight reporting PAT tags indicated that the tags had been drifting at the surface for weeks prior to the programmed pop-up date and that they had not released at the deep, offshore locations reported by ARGOS. Of the remaining four Suwannee tags, two transmitted signals, but position could not be determined by ARGOS (presumably because of insufficient signal strength or quality); and two

TABLE 1. Number, total length range, and weight range for Gulf sturgeon captured and released with PAT or acoustic tags for each river system in 2001 and 2002.

Year	Tag	River	*N*	TL range (cm)	Weight range (kg)
2001	PAT	Suwannee	12	162–199	23.0–53.0
		Choctawhatchee	4	189–229	46.7–73.5
		Apalachicola	2	184–218	45.4–68.0
		Yellow	2	203–228	58.5–71.2
2001	Acoustic[a]	Suwannee	4	156–173	22.8–32.2
		Choctawhatchee	7	184–210	40.1–51.5
		Apalachicola	2	165–173	25.4–28.6
		Yellow	0	–	–
2002	PAT	Suwannee	2	196–201	44.0–52.6
		Choctawhatchee	0	–	–
		Apalachicola	2	183–208	36.5–50.8
		Yellow	1	197	43.0–43.0
2002	Acoustic[a]	Suwannee	3	162–181	24.0–36.0
		Choctawhatchee	5	176–208	26.5–52.2
		Apalachicola	3	175–197	28.1–38.1
		Yellow	2	188–190	39.9–58.5

[a] Not including those on PAT-tagged fish.

did not transmit (signals not received by ARGOS).

Pop-up locations were reported for two PAT tags from the Panhandle area, one from the Choctawhatchee River (C1) and one from the Yellow River (Y1) (Figure 2). The former was located at 30.396°N, 86.274°W, within Choctawhatchee Bay. That location was visited on February 8, and the fish's presence was confirmed by acoustic relocation. C1 was again relocated within the bay on February 22 and March 15 (Table 2), indicating that it had remained in the bay during the entire winter, as had been reported by Fox et al. (2002) for some other adult Gulf sturgeon from the Choctawhatchee system. The second Choctawhatchee tag failed to transmit, as did the second Yellow River tag and both of the Apalachicola tags.

The first reported location for Y1 was 29.920°N, 85.386°W (determined 8 h after scheduled pop-up), which is very close to the coastline near Mexico Beach, Florida (Figure 2). The area was searched on February 9, the first day of suitable weather, but Y1 was not relocated until February 13, on which date it was acoustically relocated at 29.943°N, 85.457W, about 7.3 km from the first ARGOS location, 1.5 km offshore, and in water 4 m deep over sandy sediments. The relocation confirmed that the PAT tag had popped up from the fish and therefore the fish had migrated at least 180 km from the Yellow River. Fish Y1 was again relocated on March 18, 2002 at 30.074°N, 85.659°W, about 25 km west of the February 13 first relocation point, 0.9 km offshore (Figure 2), and in water 6 m deep over sandy sediments. Also, recorded data from the Destin Pass remote station indicated that Y1 had been detected just inside Choctawhatchee Bay prior to PAT pop-up on December 12, 21, and 23 and later on March 24. Subsequently, Y1 was relocated acoustically on May 21, 2002 in a known summer resting area in the Choctawhatchee River at 30.471°N, 85.867°W.

Three other acoustic-tagged Gulf sturgeon were relocated in early 2002 in the area between Y1's first two relocation points (Figure 2). While searching for Y1 on February 9 near the reported pop-up location, we detected a Gulf sturgeon (A1) that had been tagged in the Apalachicola River with a PAT tag that had failed to report. Fish A1 was relocated in the

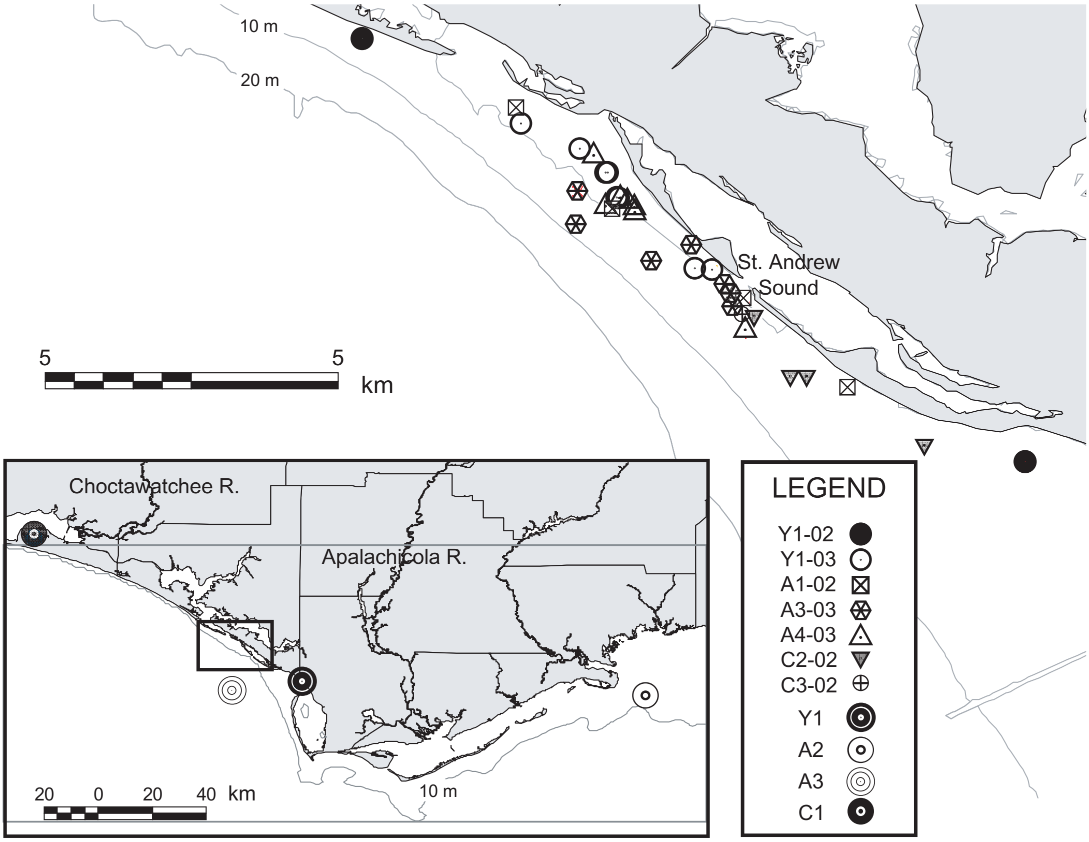

FIGURE 2. Below, Florida Panhandle area (inset a in Figure 1) with pop-up locations Y1, A2, A3, and C1 (located within a small embayment along the southern shore of Choctawhatchee Bay). Above, detail of area of concentrated relocations (inset shown below). Relocations are designated by fish and year of relocation (e.g., Y1–02 shows relocations of fish Y1 *in* 2002).

same general area on six dates between February 9 and April 15, 2002. The last relocation position was not plotted because it was within 100 m of the penultimate relocation on February 26 and may be that of a shed tag. Two Gulf sturgeon that had been tagged in the Choctawatchee River with acoustic tags only were relocated in the same general area. C2 was relocated on 5 d between February 13 and March 18 and again on March 25 by the remote station at the entrance to Choctawhatchee Bay. C3, a fish that had been previously internally tagged on March 28, 1997 by Fox et al. (2000) was relocated in the area on February 11.

2002–2003

Five Gulf sturgeon were tagged with PAT tags and 14 with acoustic tags in fall 2002 (Table 1). Two of the PAT-tagged fish were from the Suwannee, two from the Apalachicola, and one from the Yellow River. ARGOS received transmissions from three PAT tags. The Yellow River tag and one Suwannee tag failed to transmit. The other Suwannee PAT tag (S1) transmitted data and location starting on the programmed pop-up date (February 3, 2003). The first reported location was 29.051°N, 82.979°W or about 22 km W of the coastline and 11 km SSW of Cedar Key, Florida (Figure 1). This general

TABLE 2. Relocated Gulf sturgeon, type of tag, date tagged, total length, relocation period, and number of relocations (excluding PAT tag pop-up).

Fish	Tags[a]	Date tagged	TL (cm)	Relocation dates (*N*)
A1	PAT+A	Oct 30, 2001	184	Feb 9–Apr 15, 2002 (6)
A2	PAT+A	Sep 17, 2002	208	None
A3	PAT+A	Oct 21, 2002	183	Jan 13–Feb 26, 2003 (7)
A4	A	Oct 21, 2002	180	Jan 14–Feb 12, 2003 (7)
A5	PAT+A	Nov 11, 2001	218	None[b]
C1	PAT+A	Jan 27, 2001	229	Feb 8–Mar 15, 2002 (4)
C2	A	Oct 28, 2001	206	Feb 13–Mar 25, 2002 (6)
C3	A	Mar 27, 1997	168	Feb 11, 2002 (1)
S1	PAT+A	Oct 14, 2002	192	None
S2	A	Sep 24, 2003	157	Jan 29 and Feb 10, 2004 (2)
Y1	PAT+A	Oct 21, 2001	203	Feb 13 2002–May 13, 2003 (13)[b]

[a] PAT = pop-up archival transmitting, A = acoustic.
[b] PAT tag found and data downloaded.

area was searched on February 7 (the first day permitted by weather) in an attempt to detect the signal from the acoustic tag and thus verify that the PAT tag had in fact popped up from the fish near that location. The acoustic tag was not detected in the search area, in which water depth was 3–4 m.

One of the two PAT tags (A2) attached to Gulf sturgeon tagged in the Apalachicola River immediately transmitted data on February 3, and its location was reported by ARGOS as 29.878°N, 84.245°W on the western side of Apalachee Bay (Figure 2) in an area with depths of 2–6 m. The area was searched on February 4 and 6, but signals from the acoustic tag were not detected. Transmitted depth data for the latest date, January 29, was 2–6 m and was consistent with the depths in the area near the reported pop-up location.

Transmissions from a second Apalachicola River PAT tag (A3) were received on February 5 and were first located at 29.898°N, 85.615°W or about 12 km offshore (SW) from the area of numerous 2002 relocations (Figure 2). Depth data transmitted from this PAT tag indicated depths of 6–12 m as late as January 24 (the latest reported date), indicating that the tag had not detached prematurely. Strong winds (20–35 km/h) from the N to NNW were reported (NOAA/NOS/CO-OPS Station 8728690-Apalachicola) in the area for 30 h prior to the first location report; thus, the tag would have drifted offshore during the more than 2 d between scheduled pop-up and first location. Rough seas and resultant antenna movement and submersion may have accounted for the failure to successfully transmit for 2 d after pop-up.

More importantly, this fish (A3) was relocated by acoustic telemetry before (January 13 and 29), on (February 3), and after (February 5, 12, 20, and 26, 2003) the pop-up date, verifying that the PAT tag had detached as programmed. All of its relocations were within an about 4-km stretch along the coast directly inshore of the first location reported by its PAT tag (Figure 2).

Acoustic searches in the Florida Panhandle area before and after the scheduled pop-up date resulted in relocation and identification of two other fish in this same area of Gulf sturgeon relocation concentration. Most significantly, fish Y1 was again relocated in 2003 on 8 d from January 13 to March 10 (Figure 2) in the same area as in 2002. This same fish was then relocated within Choctawhatchee Bay on April 2 and, finally, for a second year, in a known summer resting area in the Choctawhatchee River on May 13, 2003. A fish (A4) that had been tagged with an acoustic tag only (no PAT tag) in the Apalachicola River in fall 2002 was also relocated in the concentration area on 7 d between January 14 and February 12, 2003 (Figure 2).

PAT Tag Transmitted or Recovered Data

Only two PAT tags (S1 and A3) transmitted meaningful data summaries. Much of the data contained transmission error (as determined by checksum procedures of the PAT Decoder software) and therefore was not used. Reported depths were typically in the range of 4–6 m (max = 9 m for S1 and 12 m for A3), indicating that the fish had remained in coastal areas and had not migrated far offshore. Maximum depths of 4 m were reported by S1 for the 8 d, through January 29 (the last reported date, 4 d before pop-up). These depths are consistent with those in the area of the pop-up location. S1's latest depth summaries showed depths varying from 0–2 m to 4–6 m on each day, indicating that the PAT tag was not drifting at the surface. Because PAT tags were developed for deep diving animals, depths recorded over long periods can be inaccurate for animals in shallow waters (see discussion).

Daily maximum temperature for S1 and A2 ranged from 9.8°C to 26.0°C, and 12.2°C to 28.4°C, respectively. Minimum temperature reported for S1 and A3 was 9.8°C and occurred on January 25 and 26, 2003, respectively. Daily temperature range (maximum–minimum) was 0.0–3.4°C (mean = 0.9°C). S1 temperatures (Figure 3) were also very similar to those reported at NOAA/NOS Station No. 0232359 at Cedar Key, except that Cedar Key temperatures typically were more variable. A1 temperatures

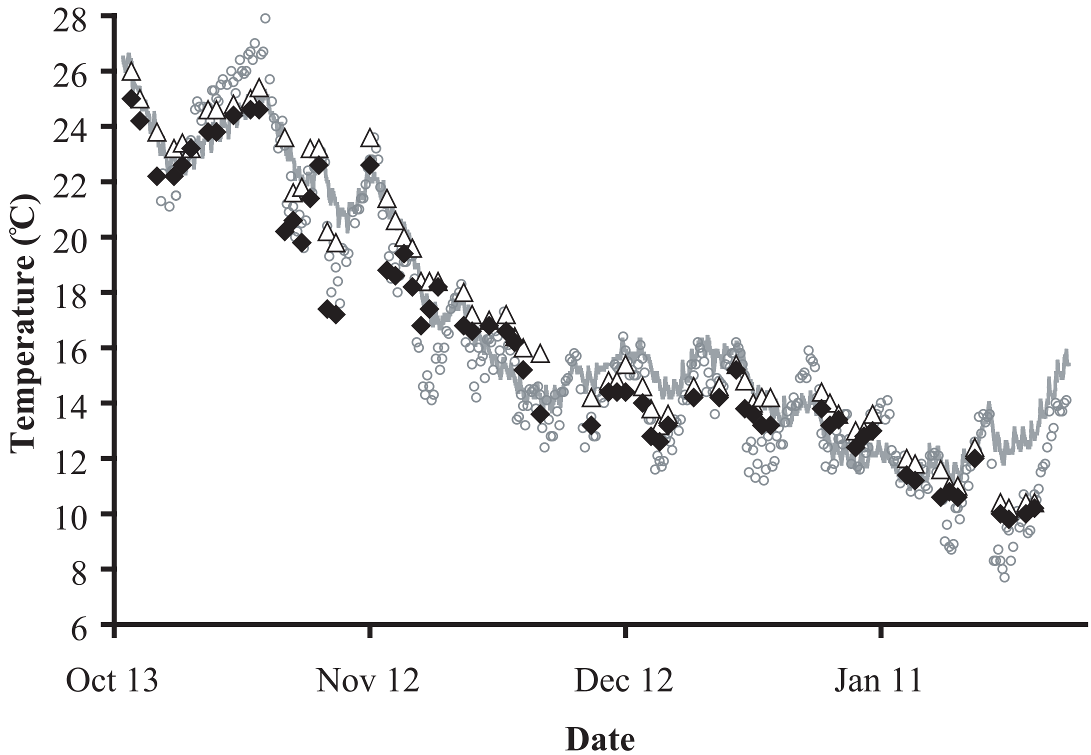

FIGURE 3. Temperature daily maxima (triangles) and minima (diamonds) transmitted by PAT tag S1. Water temperatures in the lower Suwannee River (USGS Station 02323592 AB Gopher River near Suwannee, Florida) (solid gray line) and at Cedar Key (NOAA National Data Buoy Station CDRF1) (circles) are also plotted.

are not plotted but showed comparable patterns, in that they were not greatly different from, but diurnally less variable than, those recorded by coastal monitoring stations in the region.

Two PAT tags (Y1 and A5) were found after washing ashore, and their complete data archives were recovered. Depth readings (1-min intervals) for Y1 ranged from 1.5 to 24.0 m, with typical depths being 2–4 m in the first month of deployment trending downward to about 10–12 m in the last month. Deepest depth readings occurred during "dives" in which depth increased by up to 10–16 m in less than 30 min. Depths for A5 ranged from 2 to 20 m, with typical values in the 3–4 m range during the second week after deployment and 7–10 m during in the last week. A5 depth data also exhibited numerous "dives" of up to 10 m or more. No obvious diurnal pattern of depth could be discerned for Y1 or A5. Due to apparent indications of depth sensors drifting out of calibration, this depth data should be viewed with reservation (see discussion) and, for that reason, are not plotted.

Y1 temperatures (Figure 4) ranged from as high as 25.1°C in the first week after deployment and stayed above or near 20°C until the last week in December, at which time temperature fell rapidly to 11.4°C on January 3. It then gradually rose to as high as 18.7°C on February 1, and fell back to 15–16°C in the last 2 d prior to pop-up. Daily range was typically 1.0–1.5°C until early December, less than 2°C in December until December 21 (3°C). On the date of lowest recorded temperature, January 3, the range was 3°C and on January 5 had in-

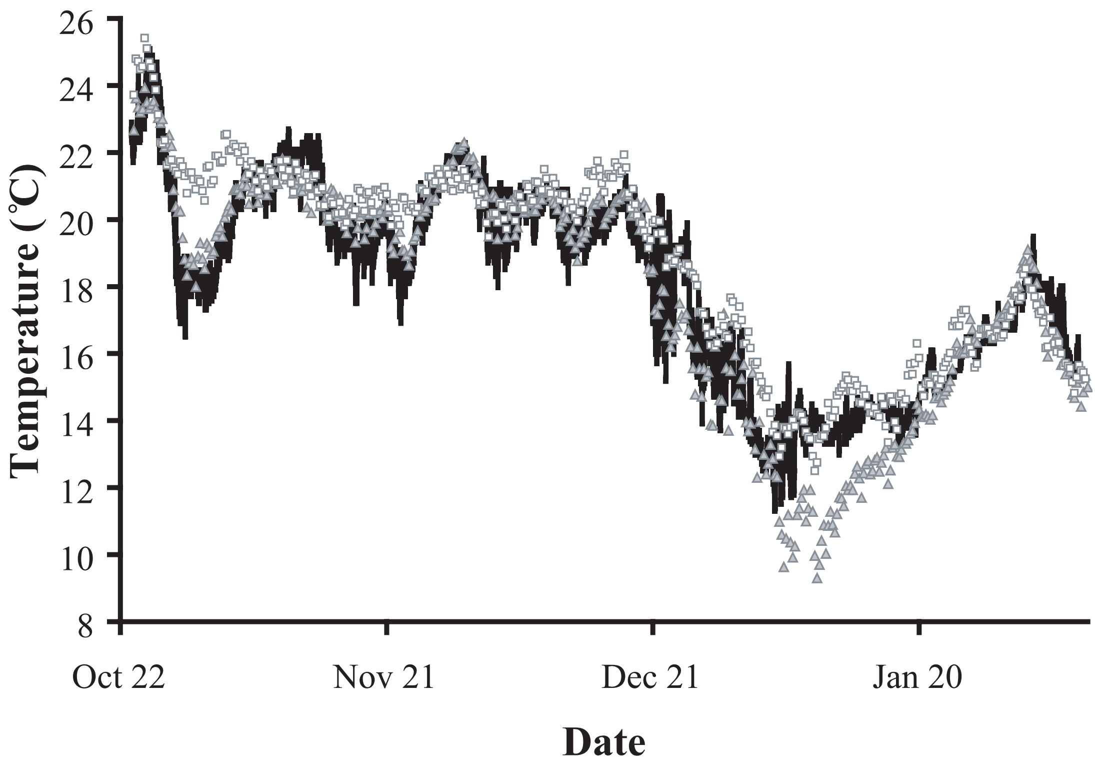

FIGURE 4. Temperature (solid line) downloaded from PAT tag Y1. Water temperatures at Pensacola (NOAA NOS Station 8729840-Pensacola, Florida) (triangles) and at Panama City Beach (NOAA NOS Station 8729210-Panama City Beach, Florida) (squares) are also plotted.

creased to 4°C. Daily range was near 2°C in the last week before pop-up. Y1 temperatures followed general patterns and trends of those at coastal monitoring stations (Figure 4). A5 temperatures (not plotted) fell to 18.5°C on November 2, increased to more than 20°C by November 4, and remained above 19.5°C until December 21, at which time it fell rapidly to 15.1°C on December 31. By January 4, it had fallen to it its minimum, 11.9°C. On February 6, temperatures were 15.5–17.1°C. Daily range was less than 2°C until becoming 3.2°C on January 3. Three days later it returned to a range of 1.5–2.0°C, for the duration of the deployment. A5 temperature patterns and trends were similar to those at coastal monitoring stations.

Transmitted and downloaded light level data failed to provide consistent and meaningful geolocation estimates, perhaps due to variable turbidity and color of coastal waters. Because light data provided little or no insight into migrations or habitats, they are not discussed further.

Discussion

PAT Data

The similarity of transmitted and recovered temperature data to those recorded by coastal monitoring stations in the general areas during the period indicates that the fish remained in coastal waters (Figures 3 and 4). S1 temperatures (Figure 3) suggested that the fish had entered shallow Gulf waters at least by November 3, at which time the PAT temperatures were very similar to nearshore Gulf water temperatures that had fallen rapidly below 20°C and were substantially lower than those in the Suwannee River. This is consistent with previous acoustic tracking that indicated that Gulf sturgeon emigrate from the Suwannee when temperature falls below about 20°C (Edwards et al. 2003). Overall, the temperature data show no evidence that Gulf sturgeon seek thermal refuge during the winter, but instead show that they utilize habitats with temperature regimes not unlike those of typical coastal marine environments.

Although depth data indicated that the PAT-tagged Gulf sturgeon did not migrate to into very deep water, the actual depths cannot be precisely estimated for two reasons. Depth transducers inherently drift out of calibration. When PAT tags are used on animals that regularly make deep dives from the surface, transducer drift is overcome by the data being automatically corrected by a programmed algorithm that incrementally adjusts depth estimates toward zero (surface) when temperature remains constant (indicating that the animal is not diving and hence is at or near the surface). Transmitted data include only the corrected depths; data directly downloaded from recovered PATs include both corrected and uncorrected depths. However, for animals that do not make dives from the surface, PAT tag corrected depths may include spurious corrections and do not properly adjust for transducer drift.

Analysis of uncorrected depth data downloaded from Y1 and A5 showed indications of positive transducer drift (indicating depth deeper than actual depth). For example, Y1 uncorrected depths were as great as 15 m on December 21, a day on which its presence was recorded by the remote station just inside Choctawhatchee Bay where maximum charted depths in the area are 12 m. This suggests that the transducer had drifted at least + 3 m over the 3 months after deployment. Similarly, depth data during the last week of deployment of Y1 included several dives in which depth increased about 8 m (e.g., from 11 to 19 m) in 10–15 min. A fish would have to swim at least 10 km offshore to experience depth changes of that magnitude from natural bathymetry in the area, but such changes could occur if the fish swam to the bottom of the Port St. Joe navigation channel that is less than 5 km southeast of the pop-up location. However, the depth of the navigation channel is only 12–13 m. Also, depths surrounding the channel are at least 7 m, except very near the terminus of the channel (within a few hundred meters of shore). Only there could a fish change depth by 8 m in a few minutes, and it would occur by its swimming from about 4 m to the bottom of the 12-m-deep channel.

Uncorrected depth data indicated that the fish was 10 m deep before beginning the dive to 18 m and therefore suggest that the depth sensor had an accumulated drift of about + 6 m by the last week of the PAT tag deployment. Downloaded depth data for A5 showed similar evidence of transducer drift. Depths during the last few days of deployment were typically around 9–10 m, with maximum depths of 16–17 m, whereas depths at the reported pop-up location were only around 3–8 m, and the nearest location where depth was 16 m was 22 km offshore of the pop-up location. Therefore, it can be roughly estimated that A5's depth transducer had drifted at least + 6 m.

Overall Findings

We initially viewed satellite pop-up archival tagging as a promising new technique that could provide valuable information about location of heretofore unknown winter, marine habitats of Gulf sturgeon. However, the 2001–2002 results, in which only 3 of 20 PAT tags functioned as planned, were very discouraging, especially in view of the cost ($3,500/PAT tag in 2001). The 2002–2003 results, in which three of five PAT tags provided meaningful information, were improved, but the small sample size prevents us from being sure if the modified attachment technique (lanyard attached at the base of the dorsal fin, instead of through a dorsal scute) resulted in significantly enhanced effectiveness. However, Erickson and Hightower (2007) had six of seven PAT tags attached in this manner function as planned, albeit on a different sturgeon species, green sturgeon, that may have different behavioral responses to tags.

Most nonreporting PAT tags probably were shed by the Gulf sturgeon very soon after they were attached. The February 2002 Suwannee PAT tags all reported depths only in the 0–2 m range for dates as early as October 21 (two tags), suggesting that they had been drifting for many weeks prior to the pop-up date. Dates of detachment cannot be determined with certainty because Gulf sturgeon may utilize habitats less than 2 m deep in nearshore marine areas (Edwards et al. 2003), because depths were reported for only a few days, and because earliest reported dates for some PAT tags were as late as December.

PAT tag shedding was probably due to two factors. Gulf sturgeon may have behavioral responses, such as rubbing against the bottom or objects, that results in tags being detached. Comparable rubbing and shedding of external transmitters has been observed for shortnose sturgeon *A. brevirostrum* (Collins et al. 2002). PAT tags have a thin, stainless-steel tubular-pin attachment point. At release time, a voltage is applied to this pin so that it electrolytically corrodes away and allows the PAT tag to detach from the tether and float to the surface. Due to overall size limitations, battery power available for this corrosion is low; thus, the pin must be relatively thin, resulting in a literal weak link in the overall concept and design of these PAT tags. Other researchers have had similarly low success rates, presumably caused by premature detachment due to weakness of the release pin, even on pelagic species that would have little or no opportunity to detach them by rubbing against objects or the bottom (M. Dormier, PIER Foundation, personal communication).

Despite the overall low success rate, the few successful PAT tags led us to important relocations of acoustic-tagged Gulf sturgeon in the area near where Y1's PAT tag popped up in 2002 and where Y1 was relocated again numerous times in 2003. Three fish tagged in the Apalachicola River (A1, A3, and A4) and two fish tagged in the Choctawatchee River (C2 and C3) were relocated in the area. Thus fish tagged in three different rivers were found in the same general area. Similarly, although searches in February 2003 for S1 near its pop-up location were unsuccessful, searching near the S1 pop-up position in early 2004 led to relocation of one acoustic-tagged Gulf sturgeon (S2) and observation of another Gulf sturgeon that jumped near the acoustic relocation position (8.5 km west-southwest of S1) on January 29, and relocation of S2 again in the same area on February 10, 2004.

Thus, the combination of satellite pop-up archival tagging and acoustic tagging has provided new information about locations of late-winter, marine habitat of Gulf sturgeon at locations distant from known Gulf sturgeon habitats in rivers and bays. Previously, Edwards et al. (2003) relocated one Gulf sturgeon (Fish 284, Figure 1) about 60 km northwest of the Suwannee River (Figure 1) on 2 d in mid-January. Prior to that, information was limited to relocation of three Gulf sturgeon in the Gulf of Mexico very near or rapidly moving toward and into Choctawhatchee Bay in March (Fox et al. 2002). Therefore, those relocations shed little light on winter marine feeding habitats, and Fox et al. (2002) concluded, "The location of Gulf sturgeon foraging grounds in the Gulf of Mexico remains unknown."

Interestingly, in both cases in which Suwannee River Gulf sturgeon were relocated in the open Gulf of Mexico (S2 and 284), other Gulf sturgeon were observed jumping in the immediate areas. Thus, Gulf sturgeon jump not only while in the rivers (Sulak et al. 2002) and in adjacent estuarine areas, they also jump while in winter marine habitats. Erickson and Hightower (2007) describe PAT tag depth data that show that green sturgeon make rapid ascents that suggest that they also jump while in marine environments.

In addition to locating winter marine habitats, these results provide new insights into Gulf sturgeon migration and habitat utilization. Gulf sturgeon were found to migrate considerable distances from the river in which they were tagged. Distances ranged from more than 180 km (Y1) to only about 30 km (S1 and S2). Gulf sturgeon do not migrate in one direction along the coast; one fish (A2) from the Apalachicola River migrated about 70 km eastward, while three others (A1, A3 and A4) moved about 80 km westward along the coast after leaving the river. Fish S1 and S2 migrated about 30 km southward, whereas the previously relocated Suwannee River fish (Edwards et al. 2003) had moved about 60 km northward. Choctawhatchee fish (C2 and C3) moved about 90–110 km (depending on whether they emigrated from Choctawhatchee Bay through Destin Pass into the open Gulf or if they traveled through the Intercoastal Waterway to St. Andrew Bay before entering the Gulf).

Although Gulf sturgeon populations from different rivers are genetically distinct (Stabile et al. 1996), our results indicate considerable mixing of individuals from different populations and overlap of winter habitat utilization. Fish from the Yellow, Choctawhatchee, and Apalachicola rivers were found along the same 25-km stretch of coastline. Movements of Y1 were particularly notable with regard to populations, in that it had been tagged in the Yellow River yet was relocated the following two summers in the Choctawatchee River. However, it is possible that the Choctawatchee River was Y1's natal river and that its capture in the Yellow River reflected temporary straying. Fox et al. (2002) also documented movement of one Gulf sturgeon between the Choctawhatchee and Escambia rivers. Similarly, Carr et al. (1996) documented movements between the Apalachicola and Suwannee rivers. Atlantic sturgeon do not spawn every year (Smith 1985), so for Gulf sturgeon, that presumably do not spawn annually either, straying and summer presence in nonnatal rivers would not have genetic ramifications as long as the fish return to natal rivers in spawning years.

All of the relocations are consistent with alongshore migrations and utilization of relatively shallow habitats; depths at relocation positions were 2–6 m, and relocations were close to shore (within about 2 km along the Florida Panhandle and within 12 km from shore along the more gradually sloping West Florida shelf [see 10-m isobath in Figure 1]). Although none of the PAT tags popped up at locations in deeper water, the results do not preclude the possibility of some Gulf sturgeon utilizing deeper, offshore areas that are much more extensive and difficult to search for acoustic-tagged Gulf sturgeon. Extrapolating from Atlantic sturgeon, it is likely that at least some Gulf sturgeon migrate to deeper habitats. For example, Timoshkin (1968) captured a 225 cm total length Atlantic sturgeon in a bottom trawl off New York northwest of the Hudson Canyon at 39.858°N, 72.00°W at a depth of 110 m and caught a second Atlantic sturgeon (size and exact locality not given) about 130 km southeast of Atlantic City, New Jersey, in the area of the Wilmington submarine canyon. Stein et al. (2004) reported records of some Atlantic sturgeon being captured by northeastern U.S. commercial fisheries at locations far offshore.

The pattern of Gulf sturgeon migrations, being more alongshore than offshore–inshore, and of concentration in nearshore habitat, parallels that found in recent studies of Atlantic sturgeon and Pacific green sturgeon. Laney et al. (2007) analyzed SEAMAP winter trawl data and found that Atlantic sturgeon were caught close to shore, inside the 20-m isobath, with many inside the 10-m contour. Because almost all trawling was in areas deeper than about 9 m, it is possible that Atlantic sturgeon are even more abundant in shallower areas. The Atlantic sturgeon were concentrated (based on catch versus trawl densities) in an about 80-km area along the Outer Banks coastline, centered about 100 km north of Cape Hatteras, North Carolina. Information from recaptures of two fish tagged in this area indicates mixing of populations occurs in the area; one fish was later recaptured in the Hudson River and another in the Potomac River (Laney et al. 2007). This also shows that Atlantic sturgeon migrate long distances to this area of winter habitat. Recently, Stein et al. (2004) showed that Atlantic sturgeon bycatch in trawl, sink gill net, and drift gill net fisheries along the northeast Atlantic coast were concentrated in, but not limited to, inshore areas, many of which were relatively distant from rivers known to support large populations of Atlantic sturgeon. Although definitive conclusions are not possible without detailed analysis of the effort of these fisheries relative to depth and distance offshore, the findings of Stein et al. (2004) indicate that Atlantic sturgeon migrations are more alongshore than offshore–inshore in nature. Similarly, Erickson and Hightower (2007) found that green sturgeon generally occupied depths of 40–70 m, despite proximity of deeper habitats along the steeply sloping shelf, and migrated long distances (221–968 km) along nearshore waters to areas in which green sturgeon from different systems concentrate and mix.

Together, these studies and ours provide an emerging concept of anadromous sturgeon marine migration and habitat utilization in which adult sturgeon, to degrees varying by species and by individuals, undertake substantially long coastal migrations to relatively shallow, nearshore habitats, in which they temporarily mix with individuals from other populations. Conversely, they provide no evidence of mass migration to population-specific habitats or to deep habitats on the continental shelf, although the possibility of some sturgeon migration to deeper habitats, as shown for Atlantic sturgeon by Timoshkin (1968) and Stein et al. (2004), is not precluded. Additionally, these studies all point to the importance, with regard to management and conservation of these species, of obtaining additional scientific information about locations, distribution, and characteristics of these critically important winter marine habitats.

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