Migration Patterns of Adult Summer Flounder from Chesapeake Bay: Implications for Stock Structure

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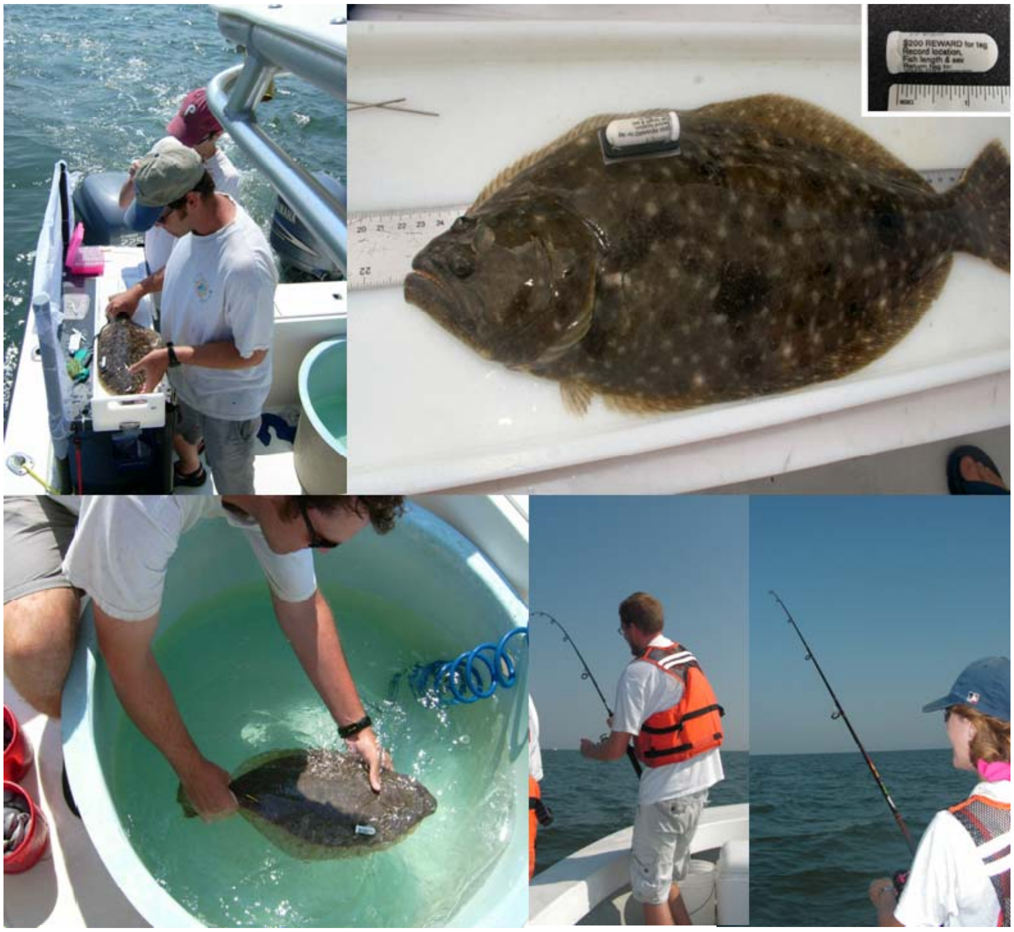

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Executive Summary

Summer flounder *Paralichthys dentatus* are one of the most highly targeted and valuable commercial and recreational fish species of the US Atlantic coast. Mature summer flounder migrate from coastal bays and estuaries during the fall to spawn along the edge of the continental shelf. After spawning is complete, individuals return to coastal bays and estuaries, where they reside during the spring and summer. Summer flounder are managed as a single stock from Maine to North Carolina, but some fisheries scientists have suggested that multiple stocks exist within this range. To investigate the stock structure of this species, we proposed to reconstruct probable spawning migration routes and identify spawning locations of individual summer flounder as revealed by archival tags. The archival tags used in this study recorded depth and temperature experienced by the fish. We tagged and released 262 mature summer flounder with archival tags during August and September 2009 in and around Chesapeake Bay; of these, 14 were recovered (5% recapture rate) from flounder that were at large from 1 to 86 days. *Unfortunately, no tags were recovered from any fish that were at large throughout the spawning season, thus we were unable to make inferences about potential spawning migration patterns of summer flounder (our original objective).* However, the depth and temperature histories revealed by the recovered tags provided insight into the fine-scale movement patterns of these fish. While at large, most fish tended to remain relatively sedentary for 2 or more consecutive weeks; during this time, observed depth changes were primarily associated with tidal fluxes, although brief intervals of "off-bottom" movement were observed. Fish tended to be more active 1) during night, 2) when temperatures were between 21 and 26°C, and 3) close to the time of the new moon and when the moon was in the 3rd quarter phase. Fish length and tidal state did not appear to have any influence on movement. Lower-than-expected recovery rates of archival tags may have been due to various factors including: 1) tags were shed, 2) fish experienced increased mortality due to the tagging process or due to post-release entanglement, or 3) commercial fishery reporting rates are lower for the summer flounder fishery than for other flatfish fisheries. We suggest that future investigations using archival tags include a pilot study using "dummy" tags to estimate expected recovery rates. If these studies are conducted in structured locations, then we also recommend that the tags be surgically implanted in the fish's peritoneal cavity. In our study, surgical implantation of archival tags would have resulted in decreased entanglement risks and could have led to increased recovery rates.

Introduction

Summer flounder *Paralichthys dentatus* are one of the most highly targeted and valuable commercial and recreational fish species of the US Atlantic coast (Terceiro 2001). This population is currently managed under a rebuilding plan due to large declines in abundance observed in the early 1990s. The 2010 target date for rebuilding the stock was recently extended to 2013 in response to lower-than-expected population growth. The success of the rebuilding plan depends on the efficacy of regulations, which rely on our understanding of the ecology and stock structure of the summer flounder population (Hilborn and Walters 1992, Ocean Studies Board 2000). Summer flounder are managed as a single stock from Maine to North Carolina, but some fisheries scientists have suggested that multiple stocks exist within this range. If multiple stocks are present, then management of the summer flounder population as a single stock could hinder rebuilding efforts because individual stocks have unique rates of recruitment, growth, and mortality (Cushing 1981, Hilborn and Walters 1992). In this study, we attached archival tags to summer flounder captured within Chesapeake Bay to observe spawning migration patterns and to investigate the stock structure of this species.

In recent decades, the stock structure of summer flounder has been a topic of debate: some fisheries scientists suggest the existence of a single stock, and others believe the evidence supports a multiple-stock hypothesis (Desfosse 1995; Burke et al. 2000; Kraus and Musick 2001). The single-stock hypothesis is consistent with results from a study indicating a lack of genetic diversity in mitochondrial DNA haplotypes for summer flounder along the Atlantic coast (Jones and Quattro 1999), and with an earlier study based on morphometric analysis (Wilk et al. 1980). However, migration patterns inferred from mark-recapture studies suggest multiple stocks of summer flounder may exist along the US Atlantic coast (Desfosse 1995; Burke et al. 2000; Kraus and Musick 2001). The apparent conflict between conclusions drawn from genetic studies and inferences made from mark-recapture studies is not unusual, and can be reconciled. Waples (1998) suggested that genetic differences between putative stocks could be diluted when even a small number of individuals stray between stocks. The genetic dilution explanation was cited by Thorrold et al. (2001) who used otolith microchemistry to demonstrate stock structure within a population of weakfish *Cynoscion regalis* that was previously thought to consist of a single stock based on genetic analyses (Crawford et al. 1989, Graves et al. 1992). The weakfish example illustrates that genetic analyses are not always sufficient to identify stock structure and suggests that the use of novel techniques may be necessary to reveal structure within some fish populations.

One approach that has been used to investigate stock structure is the study of spawning migration patterns as revealed by archival tags. Different migration patterns within a population could be used to spatially and/or temporally separate conspecifics that form reproductively isolated stocks (Secor 1999, Bain 2005). Archival tags are useful in reconstructing migration patterns from environmental conditions (e.g. temperature, light, depth, etc.) recorded at regular time-intervals. These continuous measurements provide more information than can be obtained with conventional tags, where data are limited to the date and location of release and recapture (Bolle et al. 2005). Archival tags have been used to monitor migration behavior of a number of commercially important species, including bluefin tuna *Thunnus* spp. (Block et al. 2001; 2005), yellowtail flounder *Limanda ferruginea* (Walsh and Morgan 2004), Pacific salmon *Onchorhyncus* spp. (Friedland et al. 2001), and North Sea plaice *Pleuronectes platessa* (Hunter et al. 2003; 2004). Such studies often produce novel and unexpected results. For example, Atlantic bluefin tuna *Thunnus thynnus* were found to undertake cross-oceanic migrations, presumably to spawn in the Mediterranean Sea (Block et al. 2001). The observed mixing between the eastern and western Atlantic bluefin stocks provided a critical piece of information for managers, who had previously assumed no mixing between stocks (Block et al. 2005). Incorporating stock mixing scenarios into the assessment of this overfished species could aid in the recovery of both Atlantic stocks. Similarly, understanding the migration patterns of summer flounder could aid in the development of appropriate management strategies to ensure the sustainability of this population.

We designed this study to investigate migration patterns of summer flounder using bathymetric and temperature data recorded by archival tags attached to mature fish. Mature summer flounder migrate from coastal bays and estuaries during the fall to spawn along the edge of the continental shelf (Morse 1981, Kraus and Musick 2001). Spawning occurs for a protracted time period from September through March, with peak spawning occurring in October in the mid-Atlantic region (Morse 1981). After spawning is complete, individuals return to coastal bays and estuaries, where they reside during the spring and summer (Kraus and Musick 2001). Although this general migration pattern is well known, uncertainties remain about the existence of distinct migration routes and the potential for mature summer flounder to use discrete spawning areas along the shelf. Studies with flatfish have shown that migration routes and spawning areas can be identified using temperature and depth data recorded by archival tags (Hunter 2003, Cadrin and Westwood 2004). For this study, we tagged mature summer flounder with archival tags prior to the fall spawning migration. Using temperature and depth data recorded during the spawning migration, along with temperature and depth profiles of coastal waters measured by deployed data loggers, we proposed to reconstruct the probable migration routes and spawning locations of individual fish. Migration patterns can then be used to investigate the single- and multiple-stock hypotheses based on similarities and differences among individuals.

Methods

Archival tags

During August and September 2009, summer flounder (n=262) were captured, tagged with archival tags, and released in the lower Chesapeake Bay (Figure 1). These fish ranged from 295 mm (11.6”) to 714 mm (28.1”) in length, with an average length of 413 mm (16.3”). The majority of fish (98.5%) were captured by hook-and-line. The remaining fish were captured during a trawl-based survey (Chesapeake Bay Multispecies Monitoring and Assessment Program).

Lengths were recorded for each fish prior to the attachment of Star-Oddi DST milli-L archival tags, which measured 12.5 mm in diameter by 38.4 mm in length and weighed 5 g in water. Tags were configured to record temperature from -1 to +40 °C with ± 0.1 °C accuracy every 60 minutes and depth from 1 to 250 m with ± 2 m accuracy every 20 minutes. To maximize survival of fish after tag attachment, and avoid abnormal behaviors associated with application of a tag that is too heavy, only fish that exceeded 290 mm (11.5”) total length were tagged.

Archival tags were attached externally following the methods of Cadrin and Moser (2006). Briefly, tags were attached to the pigmented side of the fish with 2 nickel pins that pierced the dorsal musculature (Figure 2a). On the non-pigmented side of the fish, earring backings were used to secure each pin. We allowed about 4 mm of space between the earring backings and the skin of the fish to permit growth. Each pin was clipped and crimped around the earring backing to ensure the tag would not be shed (Figure 2b). A t-bar anchor tag was also inserted into the dorsal musculature as a secondary identification tool and as a means to ascertain shedding rates of archival tags. After tagging, we removed small sections of the dorsal fin and collected a muscle-tissue biopsy sample for future genetic analyses.

Because it is necessary to retrieve the archival tags to obtain data recorded on the tag, we offered a $200 reward for returned tags and broadly disseminated information about the project. The availability of this reward was prominently displayed on all archival tags (Figure 2a). Based on recapture rates estimated from previous tagging studies with summer flounder (Lucy and Bain 2007, Fabrizio et al. 2007), and the increased reporting rates expected with high rewards (Pollock et al. 2001), we anticipated a recapture rate of 10 to 15% (approximately 30-40 tags). To further advertise the archival tagging program, we (1) disseminated information through presentations at six angler clubs throughout southeastern Virginia, (2) made a guest appearance on a local radio show (Don Lancaster’s “Fishing Tidewater”), (3) posted information on fishing websites such as www.tidalfish.com, and (4) distributed posters at approximately 50 docks and fish processing houses from New Jersey to North Carolina.

Data from recovered archival tags were downloaded with Star-Oddi SeaStar software and examined for quality assurance prior to conducting analyses. Quality assurance protocols identified and removed all temperature and depth measurements recorded prior to the deployment date and after the tag was recovered. Negative depth measurements (i.e., measurements indicating the fish was above the sea surface) were reassigned to a depth of 1 meter. These negative depth measurements are most likely the result of inaccurately resolved pressure signals that occurred when fish resided in waters less then 1 meter deep (recall that accuracy of depth measurements is ± 2 m). Preliminary analyses included calculating mean, minimum, and maximum conditions (temperature and depth) in which the fish resided. These data were examined graphically to evaluate movement based on changes in depth.

To determine the effect of fish length, time of day, tidal state, temperature and lunar phase on summer flounder movement, we plotted depth changes and movement probabilities against these factors for each recaptured fish. We examined these factors because they have been included in previous studies of summer flounder movement behavior (Szedlmayer and Able 1993, Fabrizio et al. 2007, Sackett et al. 2008). Only depth changes observed after a fish was at large for 24 hours or more were included in the analysis to exclude aberrant behaviors in response to the tagging process. In addition, data from one fish were eliminated from analysis because the tag was recovered on a beach and it was unknown if the fish had died, shed the tag, or was consumed by a predator. For analysis purposes, temperatures recorded by archival tags were rounded to the nearest degree Celsius. Tidal stage and lunar phase were estimated with the Tides and Currents software program. Movement behaviors were examined graphically based on two response variables: (1) mean depth change per hour, and (2) mean movement probability. Because a single, highly mobile fish may unduly influence the estimate of mean depth change, and because individual differences are obscured in the calculation of a mean, we also examined movement probability of individual fish. For each fish, mean movement probability is defined as the number of observed movements within a given time period (e.g., low tide, new moon) or environmental condition (e.g., 17˚C) divided by the total number of hours the fish was observed in that time period or condition. Movements were characterized by rapid changes in depth totaling more than 2 meters per hour. This arbitrary rate of depth change was selected because it comprised the top 5% of all depth changes exhibited by recaptured fish. As a result, we were able to distinguish behaviorally-induced depth changes from depth changes associated with daily tidal fluxes and smaller movements within localized areas. Using this response, we were able to determine when an individual fish was more likely to move with respect to environmental factors and partially adjust for the large variability in movement behaviors observed among fish.

Temperature loggers

During fall and winter 2009-2010, eight temperature loggers were deployed in coastal waters from North Carolina to Delaware (Figure 3). Data from these loggers provided spatially explicit information on bottom-water temperature. Six temperature loggers were deployed in September 2009 at shallow (25 m) and deep (100 m) sites on the continental shelf off the coasts of Delaware, Virginia, and North Carolina. Two temperature loggers were deployed in January 2010 at the mouth of the Chesapeake Bay at a depth of 10 m. The loggers in Chesapeake Bay were deployed later then those deployed offshore due to a delay in obtaining the necessary permits. At each location, an Onset® TidBit v2 temperature logger was attached to a 150 lb anchor by an ORE Offshore Shallow Water Release to allow for future retrieval. Temperature loggers have an accuracy of ± 0.2°C from 0°C to 50°C. Loggers were retrieved during summer 2010; temperature data were downloaded, examined for quality assurance, and plotted as a time series for each deployment site.

Results

Archival tags

To date, we recovered 14 archival tags (5% recapture rate) from flounder that were at large from 1 to 86 days (Table 1). Although fish were released on 16 days over an interval of 37 days, a large percentage (50%) of the recovered fish was released on 25 August 2009. It is unclear why fish released on this date experienced an increased recapture rate. Twelve of the tags were recovered within three months of release. One tag (Tag 98) was recovered on a beach in North Carolina unattached to a fish. Examination of the depth data recorded by this tag suggests two possible scenarios, both of which involve mortality of the summer flounder. A predator may have consumed the fish that carried this tag in early September 2009; after this time, we observed extreme depth changes that were not apparent among other summer flounder. Another possibility is that the summer flounder shed the archival tag, or died, in October 2009. After this time, depth changes recorded by the tag appear to be due to tidal fluctuations only. The tag recovered most recently (Tag 157) was returned to the program in November 2010; the angler reported that the fish was recaptured in October 2010. Careful examination of the depth and temperature data recorded by this tag revealed that the fish was most likely recovered one year earlier – in October 2009. *Because we lack recaptures of archival-tagged fish that were at large throughout the spawning season, we are unable to make inferences about potential spawning migration patterns of summer flounder (our original objective).* However, the depth and temperature histories revealed by the recovered tags (Figure 4) provides insight into the fine-scale movement patterns of these fish.

Temperature histories downloaded from recovered tags indicate that summer flounder tolerate a wide range of thermal conditions during their occupancy of Chesapeake Bay. In general, temperatures within Chesapeake Bay were similar among locations regardless of the depth the fish occupied (Figure 5a,b). However, during late August, water temperatures varied by as much as 11°C between sites in the lower Chesapeake Bay occupied by summer flounder. The largest observed temperature differences occurred between shallow sites, such as Lynnhaven Inlet, and deeper sites near the Chesapeake Bay Bridge Tunnel (CBBT) (Figure 5 c,d). Also during this period, fish believed to be in the southern portion of the lower bay (e.g., First Island) experienced temperatures that were consistently 6°C greater than those experienced by fish assumed to be in the northern portion of the lower bay (e.g., the High Rise). These large temperature differences between nearby habitats were preceded by a span of 5 days (20 August 2009 – 25 August 2009) during which temperatures recorded by a single tag fluctuated by as much as 6°C over a 6-hour tidal cycle (Figure 5c, Figure 6a). The observed rapid temperature changes are believed to be the result of changes in offshore circulation patterns associated with Hurricane Bill, which was approximately 450 miles off the coast of Virginia on 22 August 2009. Observed cyclical temperature changes during this time were not related to changes in occupied depth, as the only observed depth changes were due to tidal fluxes (Figure 5d, Figure 6b). During this 5-day period, the temperature cycle experienced by fish released in the northern portion of the lower bay was offset from the temperature cycle experienced by fish released in the southern portion of the lower bay by 2-4 hours (Figure 6a). In both the northern and southern sections of the lower bay, temperature cycles were offset from tidal height predictions, which may have been related to shifting tidal currents.

Recapture locations and depth histories indicated that most archival-tagged fish moved away from the tagging location. After release, fish tended to move farther into Chesapeake Bay (i.e., away from the Bay mouth; Figure 7); the average straight-line distance between release and recapture locations was 12.8 km. While at large, most fish tended to remain relatively sedentary for 2 or more consecutive weeks; during this time, observed depth changes were primarily associated with tidal fluxes, although brief intervals of "off-bottom" movement were observed (Figure 4, Figure 6b). These sedentary intervals were interspersed with rapid changes in depth associated with movements within the water column and movements to locations with different bathymetric characteristics. These two "off-bottom" movement patterns can be differentiated on the basis of two features: (1) the magnitude and duration of the depth changes, and (2) differences in depth before and after the off-bottom behavior. Movements within the water column were generally of a higher magnitude (2-10 m) and lasted about 20-40 minutes. Movements to new locations of different depths were identified by rapid depth changes that occurred over several hours and 2-5 m differences in depth before and after movement.

The magnitude of depth changes and the movement probabilities were influenced by the time of day, temperature, and lunar phase. Fish length did not appear to have an effect on mean depth change or on a fish's movement probability (Figure 8). Depth changes and movement probabilities were influenced by the time of day such that the greatest mean depth changes occurred during the early morning (0300 – 0600 hrs) and early evening (1900 – 2100 hrs; Figure 9). The greatest depth changes and movement probabilities occurred close to the time of the new moon and when the moon was in the 3rd quarter phase (Figure 10). Tidal state did not affect the magnitude of depth changes or the movement probabilities of summer flounder (Figure 11). Interpretation of the influence of temperature on depth change and movement probability was confounded by large differences in sample sizes for the temperatures recorded during the study. Over 70% of our observations were from fish occupying waters between 21 and 24°C. Even with these limitations, mean depth changes appeared to increase with increasing temperature from 20 to 26°C; as temperatures exceeded 26°C, mean depth changes decreased (Figure 12). Likewise, mean movement probabilities were consistently greater at temperatures exceeding 21°C. The greatest mean depth changes were observed at temperatures below 18°C, but this was primarily due to movements recorded for a single fish (Tag 199) that constituted 81-90% of all depth data recorded at these temperatures. This was the only fish that was recovered outside of Chesapeake Bay, and the time series of mean daily depth changes for this fish indicates that the magnitude of depth changes increased after water temperatures dropped below 20°C in mid-October (Figure 13). These increases in depth changes at colder temperatures most likely occurred while the fish was moving out of Chesapeake Bay and encountering deeper waters.

Temperature loggers

Seven of the eight deployed temperature loggers were retrieved between June and September 2010. The temperature logger (and acoustic release) deployed at 100 meters off the Virginia coast could not be retrieved. We believe this logger (and its acoustic release) was lost either due to strong currents associated with a nearby canyon or due to trawling activity in the area. As expected for the mid-Atlantic Bight, mean temperatures were more consistent in deep waters than in the shallow waters off the coast of Delaware (Figure 14a, Table 2). On average, shallow and deep locations off Delaware differed by 2.89 ± 4.33 ˚C. From January through mid-March, temperatures observed at the mouth of the Chesapeake Bay (10 m) were comparable to those observed off Virginia at a depth of 25 m. After mid-March, temperatures recorded at the mouth of the bay were more variable, and increased at a faster rate, than those at 25 m deep (Figure 14b). Compared with the measurements off Delaware, the shallow and deep locations off North Carolina had a greater temperature range (Figure 14c, Table 2). At the two North Carolina sites, we observed mean temperature difference of only 1.23 ± 4.66 ˚C (Table 2). Water temperatures at the shallow water site off Chesapeake Bay were consistently lower than those observed at the shallow water site off North Carolina (mean difference = 2.93 ± 3.51 ˚C) and consistently higher than those at the shallow water site off Delaware (mean difference = 1.00 ± 0.63 ˚C) (Figure 15a). Temperatures at the deep sites off Delaware and North Carolina were similar, especially between November and March (Figure 15b). Due to the sporadic high temperatures recorded throughout the year off North Carolina, mean temperature difference between the two deep-water locations was 2.50 ± 3.56 ˚C.

Discussion

Information from archival tags revealed time-dependent movements of summer flounder associated with the diurnal cycle, lunar cycle, and water temperatures; however, such data must be interpreted with caution until a more rigorous analysis can be conducted. One of the most striking patterns observed was the difference between day and night movements of individual fish. During night, fish tended to be more active within the water column. Temperature and lunar phase also appeared to affect the magnitude of depth changes experienced by fish. These results are similar to those from a previous acoustic telemetry study with this species in Chesapeake Bay wherein we found that time-of-day and lunar phase were important determinants of fish movement (Henderson et al. *in prep.*). To appropriately account for individual variability in movement behaviors, we plan to analyze the archival tagging data with a repeated measures model. Furthermore, we will explore potential interactions among factors that may influence summer flounder movement. For example, fish may be particularly active during nights with a new moon and less active on nights nearest the full moon. Such analyses will provide us with a better understanding of the effect of environmental factors on localized movement patterns of summer flounder.

It is unclear why the recovery rate of archival tags was lower than expected. Experiments with similar tags and attachment procedures have been conducted on other flatfish with recovery rates of 10-39% (Hunter et al. 2003, Cadrin and Moser 2006). Potential explanations for our lower recovery rates include: 1) tags were shed, 2) fish experienced increased mortality due to the tagging process or due to post-release entanglement, and 3) commercial fishery reporting rates are lower for the summer flounder fishery than for other flatfish fisheries. The hypothesis of tag shedding is supported by the recovery of one tag that was unattached to a fish and the recovery of another fish without an archival tag (t-bar anchor tag was retained). The fish recovered without an archival tag exhibited scarring patterns that indicated the attachment needles had moved through the dorsal musculature. In this fish, the tag may have become snagged, and the fish may have struggled to free itself thereby pulling the pins and attached archival tags through the musculature. Other evidence of snagging of the archival tags includes the recapture of three fish whose tags were entangled in gillnets, and the recapture of one fish in entangled fishing line. All archival-tagged fish were released in structured habitats subject to high recreational fishing pressure and that presented a number of potential snags (e.g., fishing line entanglements). Externally attached archival tags may lead to entanglement and higher mortality of tagged fish, thereby decreasing the number of fish effectively available for recovery. Finally, some tagged fish released by the Virginia Game Fish Tagging Program have been reported by fish markets and fish processing houses instead of by the commercial fishers that recovered the fish (L. Gillingham, pers. comm.). The failure of the commercial fishers to report recoveries may be due to overlooked tags in large catches, as well as to low desire to cooperate with fisheries scientists. We intended to enhance reporting rates from the commercial fishery sector by offering a large reward and by instituting a widespread advertising campaign at docks and fish-processing houses. To identify potential causes of the low recovery rate of archival-tagged fish we plan to initiate a laboratory study during summer 2011 to examine shedding rates and tag-induced mortality. Results from the planned study should help to design future summer flounder archival tagging projects.

Several lessons were learned from the archival tagging study. First, a pilot study using “dummy” tags should be conducted to estimate expected recovery rates (Cosgrove et al. 2010). This approach was not feasible for this project due to the one-year nature of the funding award. We recommended that any future study using expensive tagging technology include a pilot study to determine if the results will be cost effective. Another lesson from this study is that archival tags should be implanted surgically in fish released in structured locations. Nearly one third of the recovered fish were snagged by their archival tags in gillnets or fishing lines. We elected to use an external attachment because this technique has been used successfully with flatfish, with no apparent increases in mortality associated with fish entanglement (Hunter et al. 2003, Cadrin and Moser 2006). However, fish in those studies were released in offshore locations that, presumably, are characterized by homogeneous bottom types (i.e., less structure). Surgical implantation of acoustic tags is possible with summer flounder, and has a minimal tag-related mortality rate (Fabrizio and Pessutti 2007). Surgically implanting archival tags in the peritoneal cavity of our fish would have resulted in decreased snagging risks and may have increased the recovery rate of fish in this study. Finally, temperature measurements downloaded from the offshore temperature loggers appear to be useful in designing future tagging studies. Temperature data from the loggers suggest that it should be possible to distinguish between fish that migrate north or south of Chesapeake Bay, and to distinguish between inshore and offshore locations for fish that travel north. However, ambient temperature measurements alone would be insufficient to distinguish between inshore and offshore locations for fish that migrate south of Chesapeake Bay. Incorporating the lessons learned from this study into the design of future archival tagging projects would improve the probability of successfully recovering a sufficient number of tags to determine migration routes for this species.

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Table 1. Tagging and recapture information for 14 summer flounder released in Chesapeake Bay with archival tags.

Tag #	Length when tagged (mm)	Release Date	Tagging Location	Recapture Date	Recapture Location	Days at large	Average Temp (˚C)	Average Depth (m)
11a	321	8/12/2009	CBBT - High Rise	8/23/2009	Cape Charles	11	24.7	12.15
11b	440	9/15/2009	Buoy 18a	10/8/2009	Plantation Creek	23	22.4	3.58
37	398	8/14/2009	Cape Henry Wreck	10/19/2009	Harrison Fishing Pier	66	22.0	8.74
98*	322	8/20/2009	CBBT – High Rise	10/23/2009*	Unknown	64	22.2	24.3
123	324	8/20/2009	CBBT – High Rise	9/13/2009	Rigby Island	24	23.7	20.42
154	331	8/25/2009	Lynnhaven Inlet	9/20/2009	Lynnhaven Inlet	26	24.7	5.58
155	473	8/25/2009	Lynnhaven Inlet	9/30/2009	CBBT – 1st Island	36	24.3	4.07
157	397	8/25/2009	Lynnhaven Inlet	10/6/2009	CBBT – 4th Island	42	23.6	7.03
162	398	8/25/2009	Lynnhaven Inlet	9/9/2009	Lynnhaven Inlet	15	25.5	3.65
191	443	8/21/2009	CBBT – 1st Island	10/23/2009	Little Creek	63	21.5	10.34
199	541	8/25/2009	CBBT – 1st Island	11/19/2009	Offshore VA Beach	86	20.0	15.94
207	437	8/25/2009	CBBT – 1st Island	10/16/2009	Little Creek	52	21.9	13.29
209	414	8/25/2009	CBBT – 1st Island	8/26/2009	CBBT – 1st Island	1	21.8	13.39
299	501	9/15/2009	Buoy 18a	10/1/2009	Plantation Creek	16	22.7	6.54

*This tag was recovered on a beach in North Carolina and it is unknown whether the fish shed the tag or was consumed by a predator. The recapture date is the day prior to the day the tag recorded tidal fluxes as the only depth change

Table 2. Summary statistics of temperature measurements (˚C) recorded by loggers deployed at five locations on the Atlantic continental shelf; the data logger at the Chesapeake Bay offshore site was not recovered.

	Delaware		Chesapeake Bay		North Carolina	
	Inshore	Offshore	Inshore	Offshore	Inshore	Offshore
Deployment date (2009)	Sept 21	Sept 13	Sept 20	Sept 15	Sept 17	Sept 18
Retrieval date (2010)	May 31	May 31	June 22	NA	June 08	June 08
Count	6047	6227	6607	NA	6333	6300
Minimum	3.06	6.38	3.80	NA	4.40	6.31
Maximum	21.03	17.77	22.11	NA	27.58	27.43
Range	17.97	11.39	18.31	NA	23.18	21.13
Mean	9.57	12.49	10.67	NA	13.71	14.88
Standard Error	0.07	0.03	0.07	NA	0.08	0.05

Figure 1. Locations of summer flounder released with archival tags during August-September 2009.

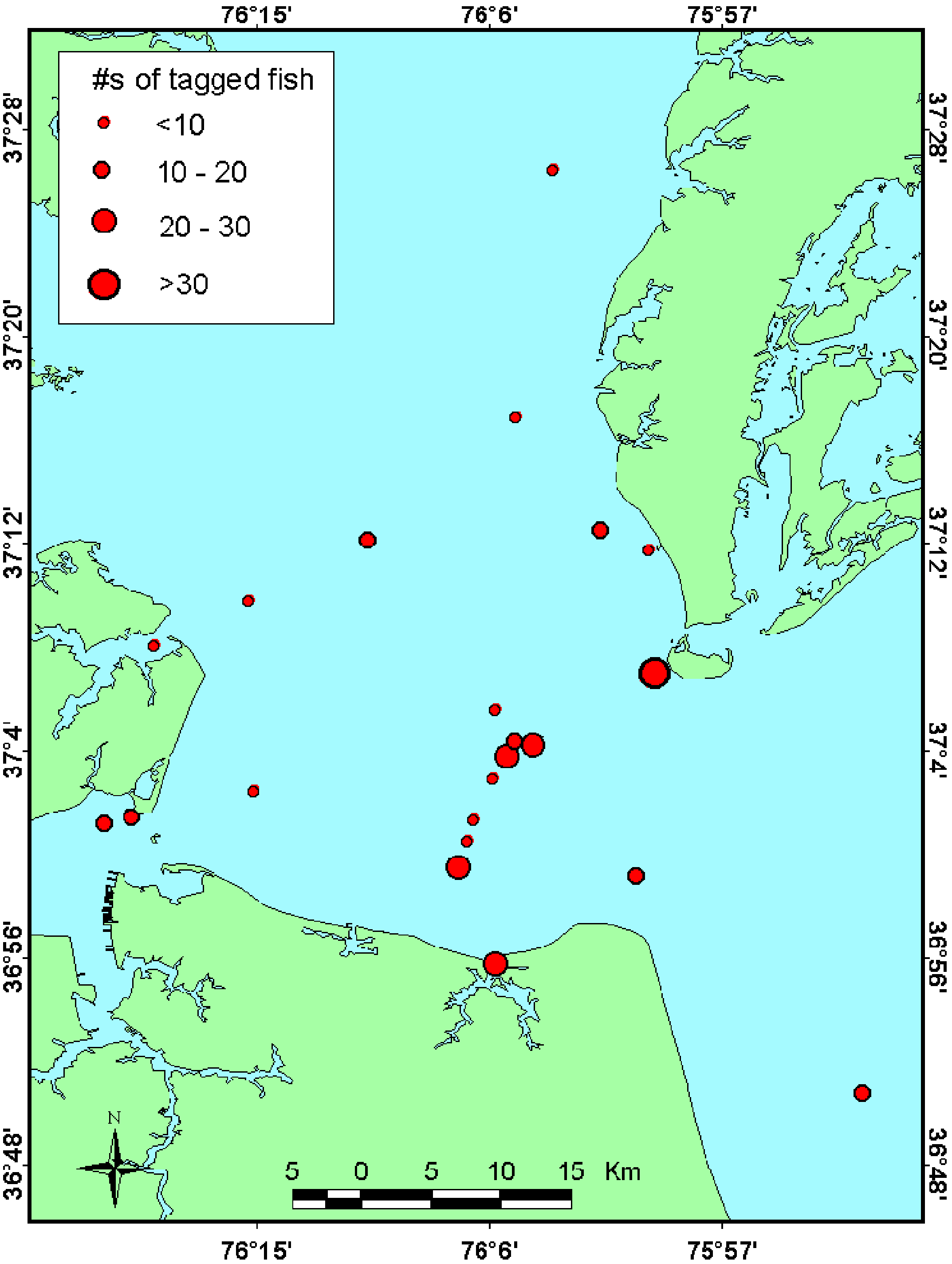


Figure 2. Archival tag location (a) and attachment technique (b) for summer flounder

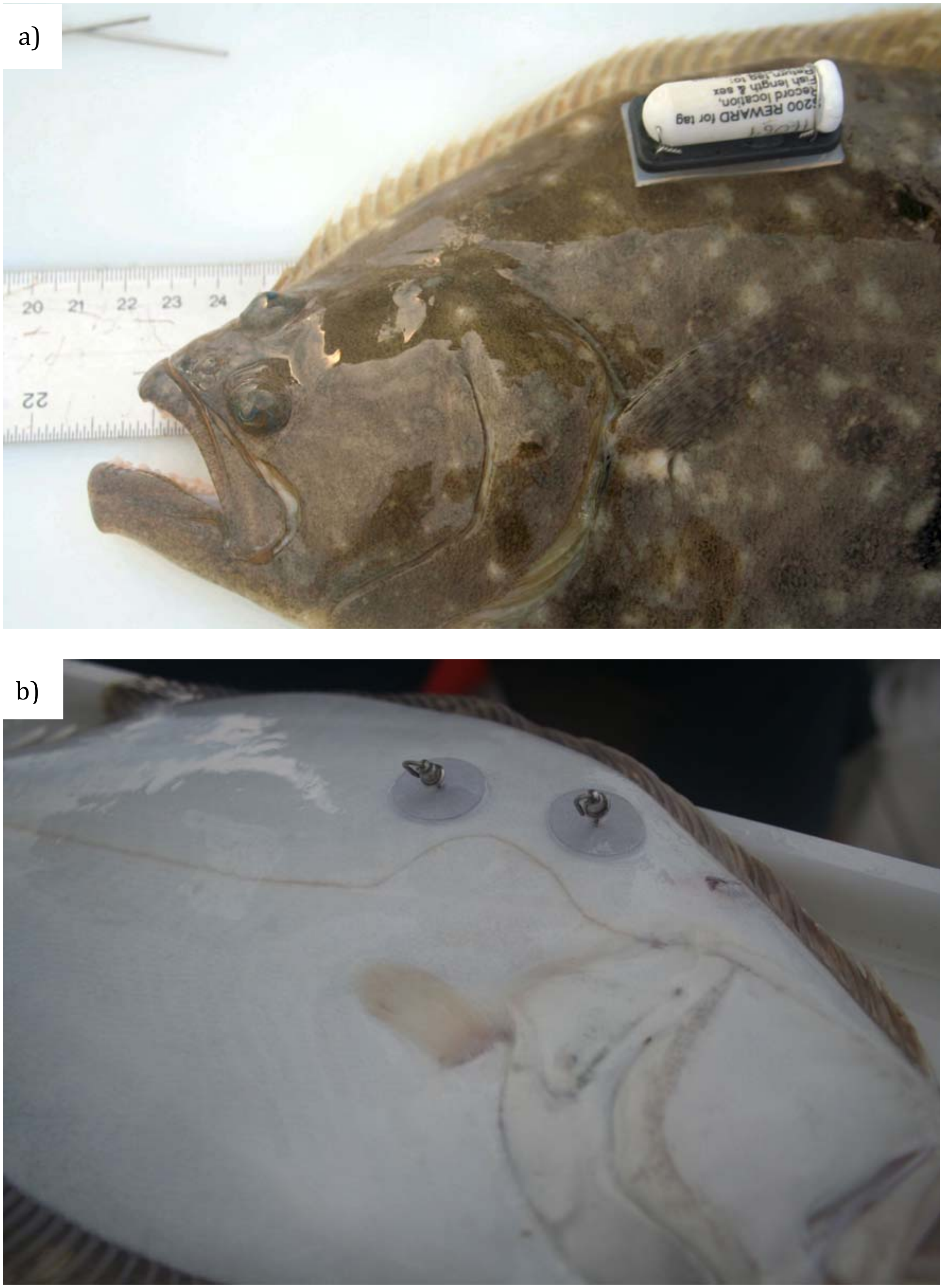


Figure 3. Location of temperature loggers (red circles) deployed at the mouth of the Chesapeake Bay and along the continental shelf. Sites at the mouth of the Chesapeake Bay were 10 m deep, other inshore sites were 25 m deep, and offshore sites were 100 m deep.

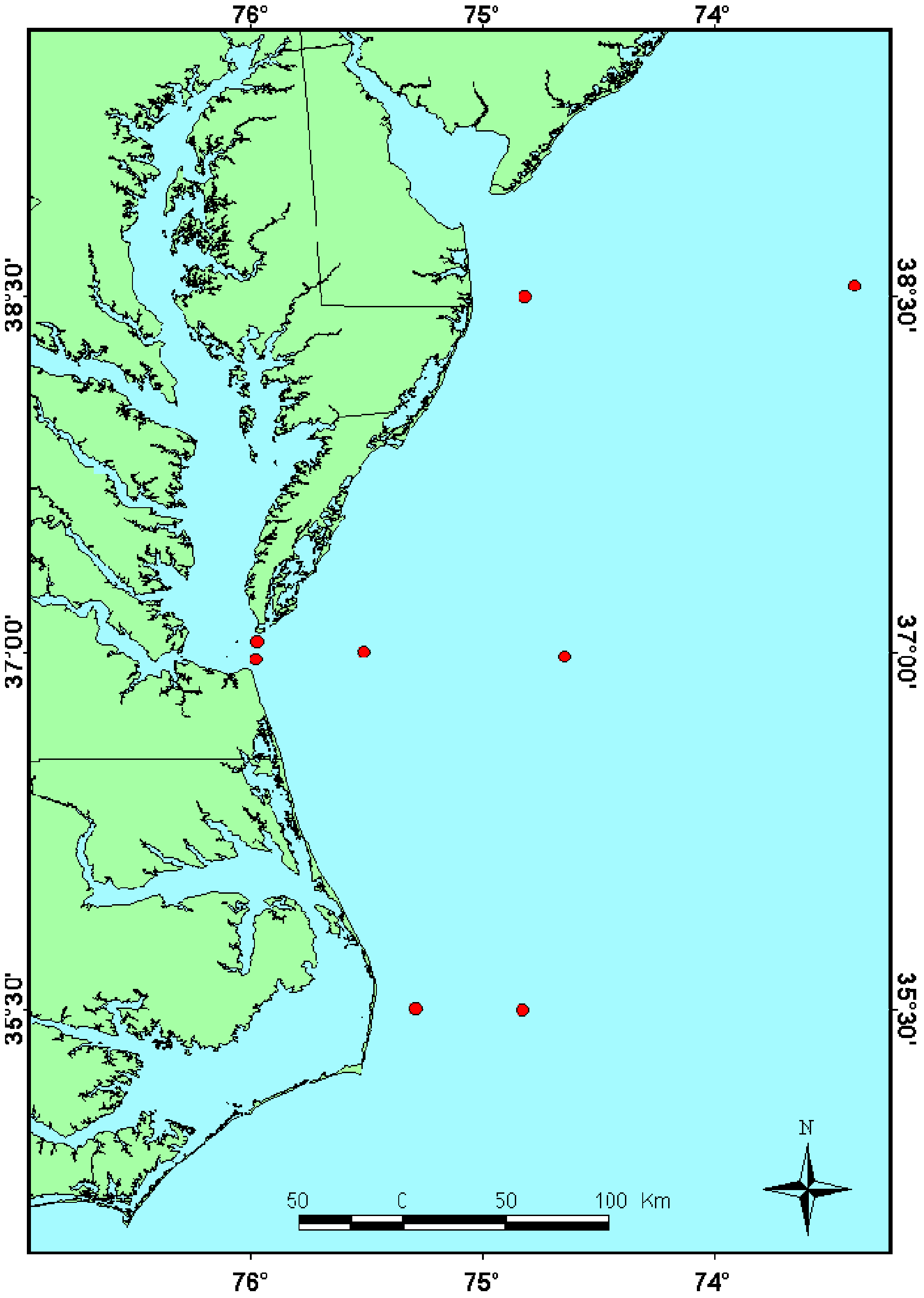


Figure 4. Individual temperature and depth histories from 14 archival-tagged summer flounder (see Table 1 for tagging and recapture information).

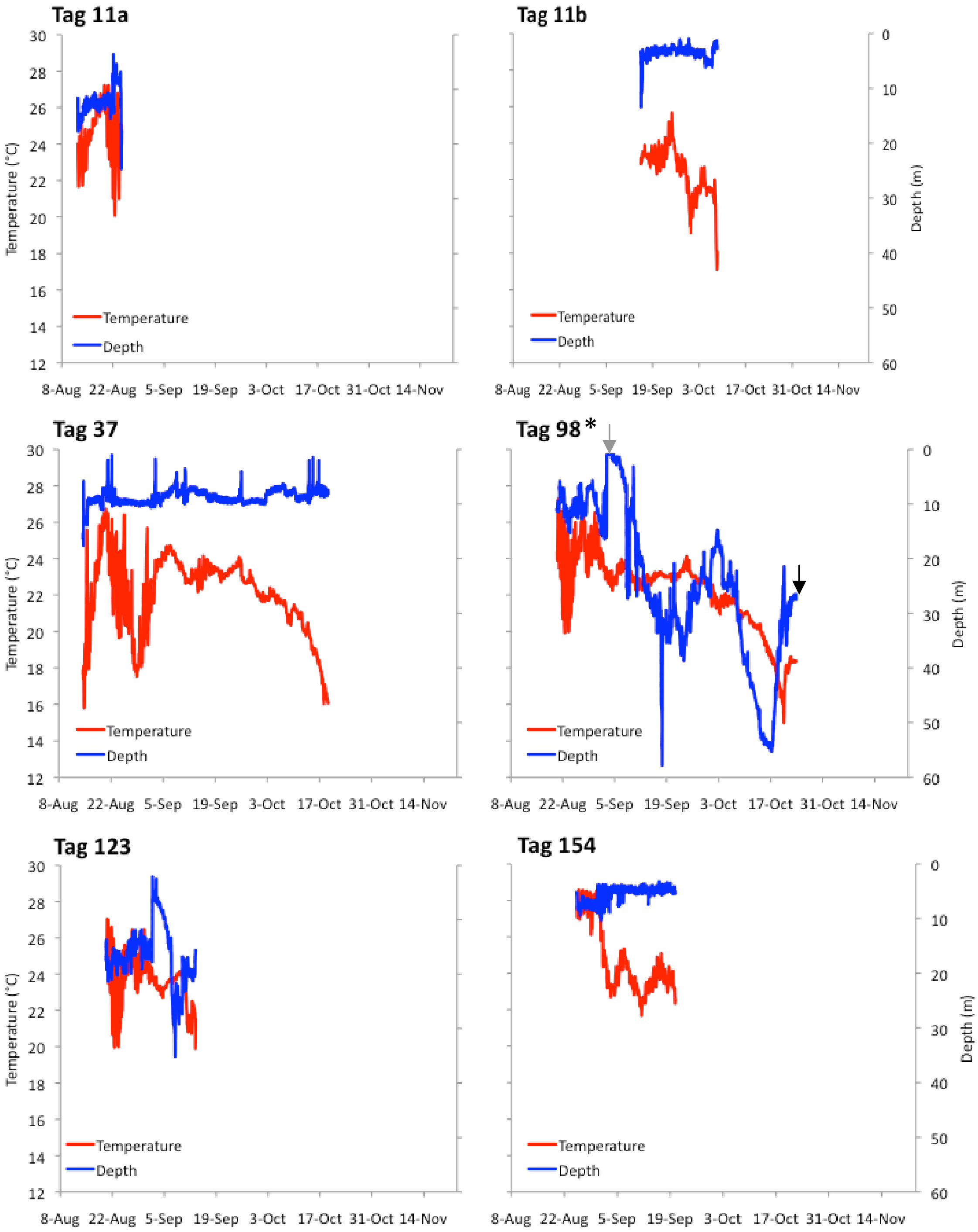


Figure 4 cont.

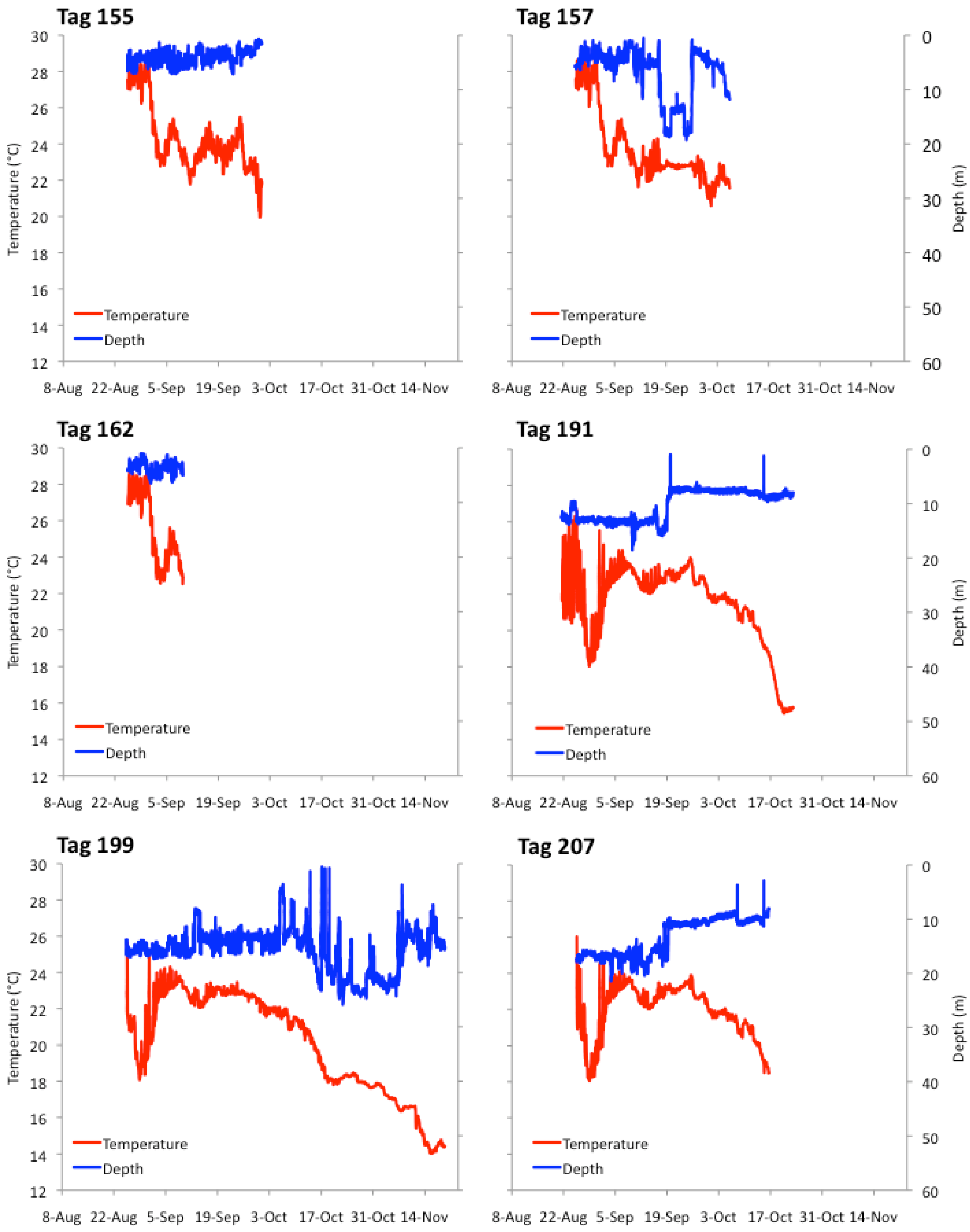
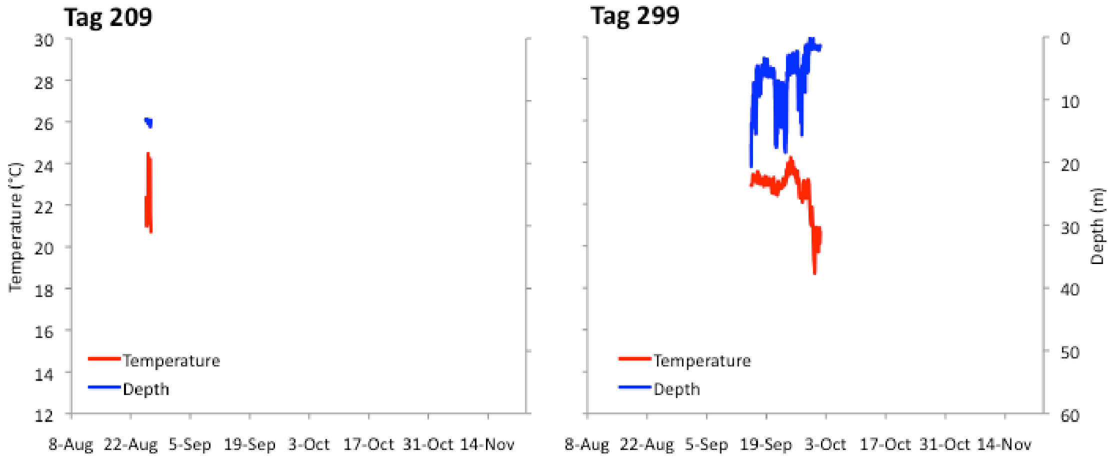


Figure 4 cont.



*Note: Tag 98 was recovered on a beach and it is unknown if this fish was consumed by a predator in early September (gray arrow) or died/shed the tag in late October (black arrow).

Figure 5. Temperature and depth recordings from 14 recovered archival tags for (a,b) the entire period at large, and (c,d) a period of rapid temperature fluctuations (20 August 2009 – 3 September 2009). The black box in (a,b) indicates the period of rapid temperature fluctuation. (See Table 1 for tagging and recapture information).

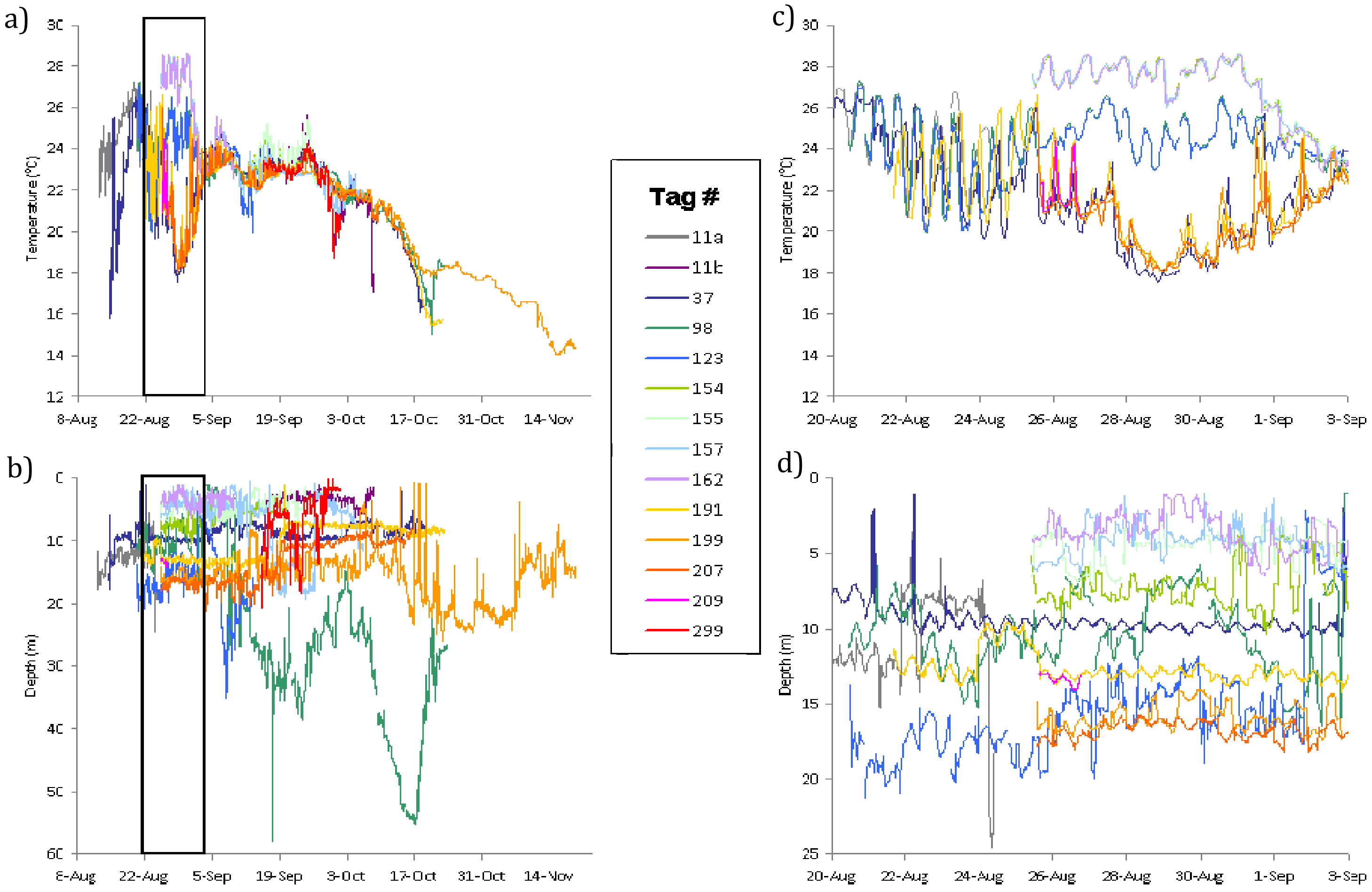


Figure 6. (a) Temperature and (b) depth measurements from two archival-tagged summer flounder at large during the period of rapid temperature fluctuation in late August 2009. Based on release and recapture locations, fish 37 (dark red, dark blue) was presumed to be near the first island of the Chesapeake Bay Bridge Tunnel and tag 123 (light red, light blue) was presumed to be near the high rise of the Chesapeake Bay Bridge Tunnel. Also shown is the predicted tidal height at the mouth of the Chesapeake Bay (grey line).

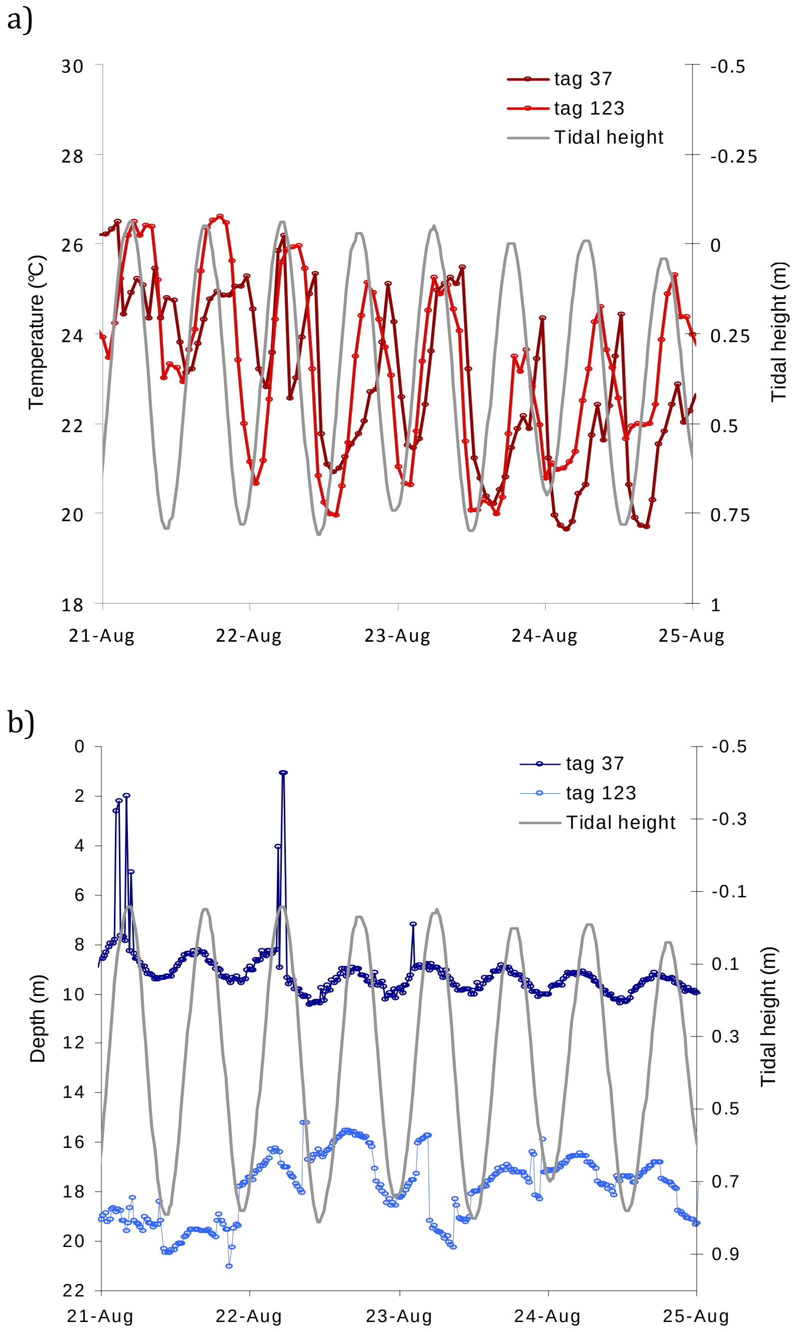


Figure 7. Release (black stars) and recapture (red circles) locations for all recovered summer flounder tagged with archival tags and with known recapture locations. The dashed arrows are the straight lines connecting the release and recapture locations; small arrow heads represent a single fish; large arrow heads represent two fish.

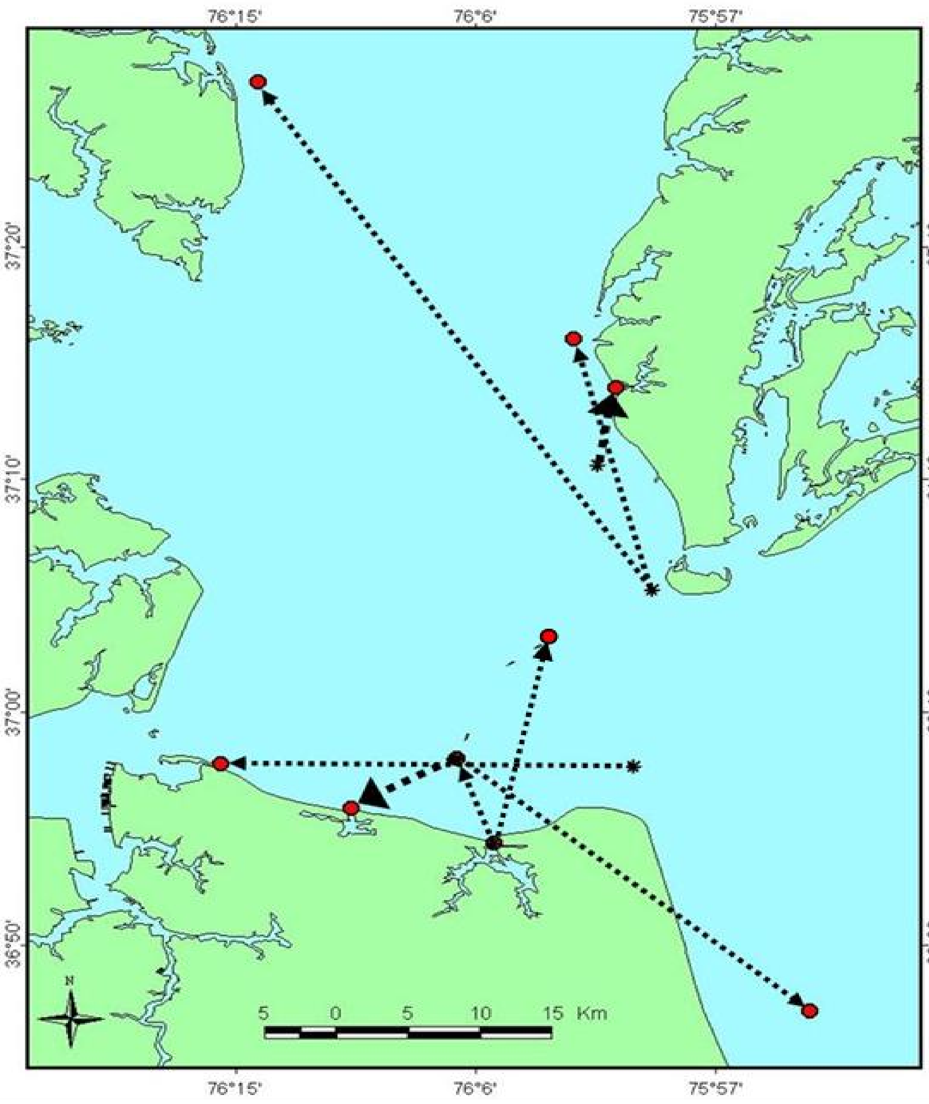


Figure 8. Relationship between individual fish length (mm) and (a) mean depth change per hour, and (b) movement probability [the probability a fish will carry out vertical movements totaling more than 2 m per hour]. Numbers on the plots are the tag numbers from Table 1. Error bars indicate ±1 standard error.

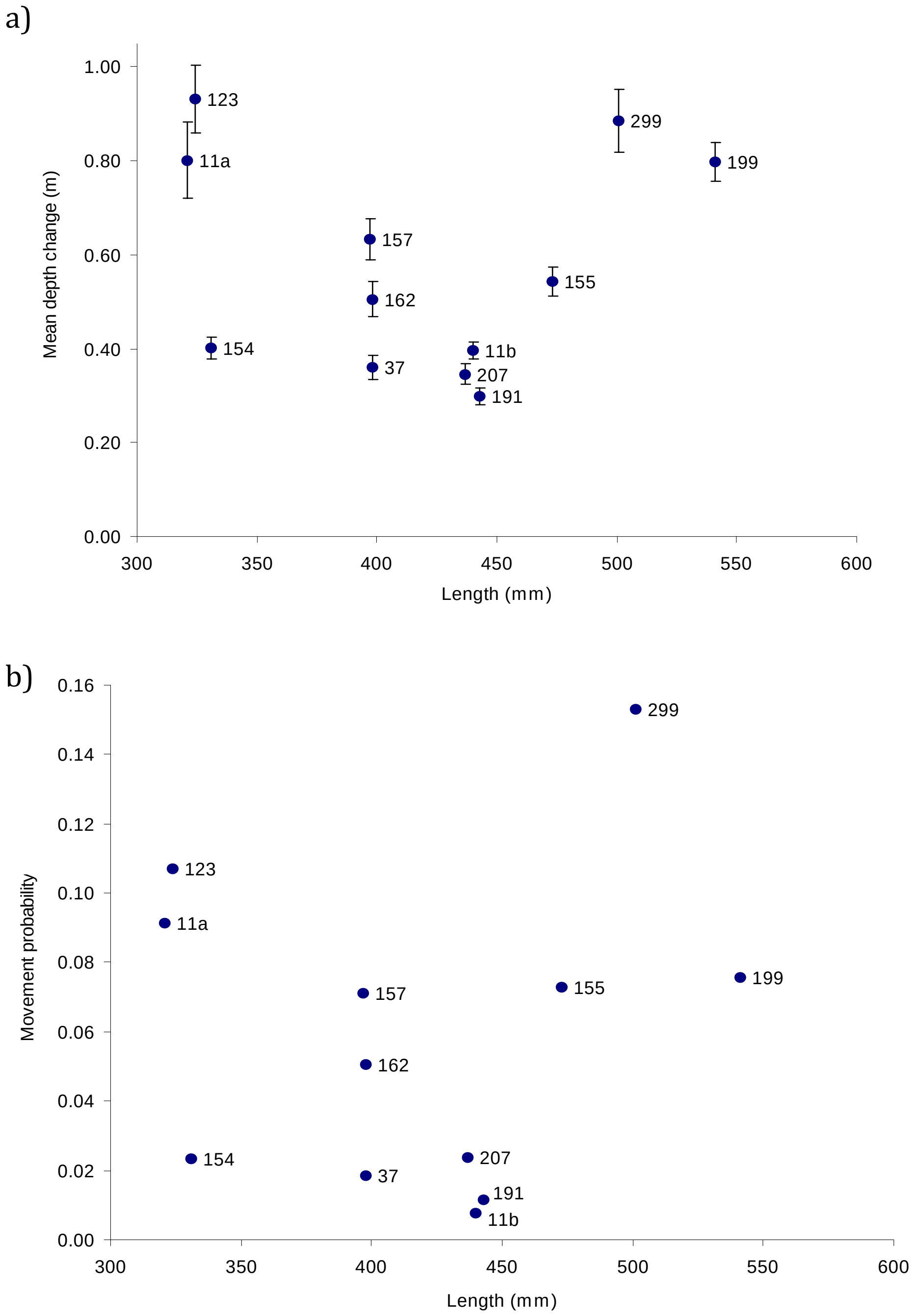


Figure 9. (a) Temporal fluctuations in mean depth change (m) per hour for summer flounder. Numbers on the plots are the number of fish/total hours of data recorded. (b) Temporal fluctuations in mean movement probability per fish plotted against time. Numbers on the plots are the number of fish that moved/total observed movement hours. Error bars indicate ±1 standard error.

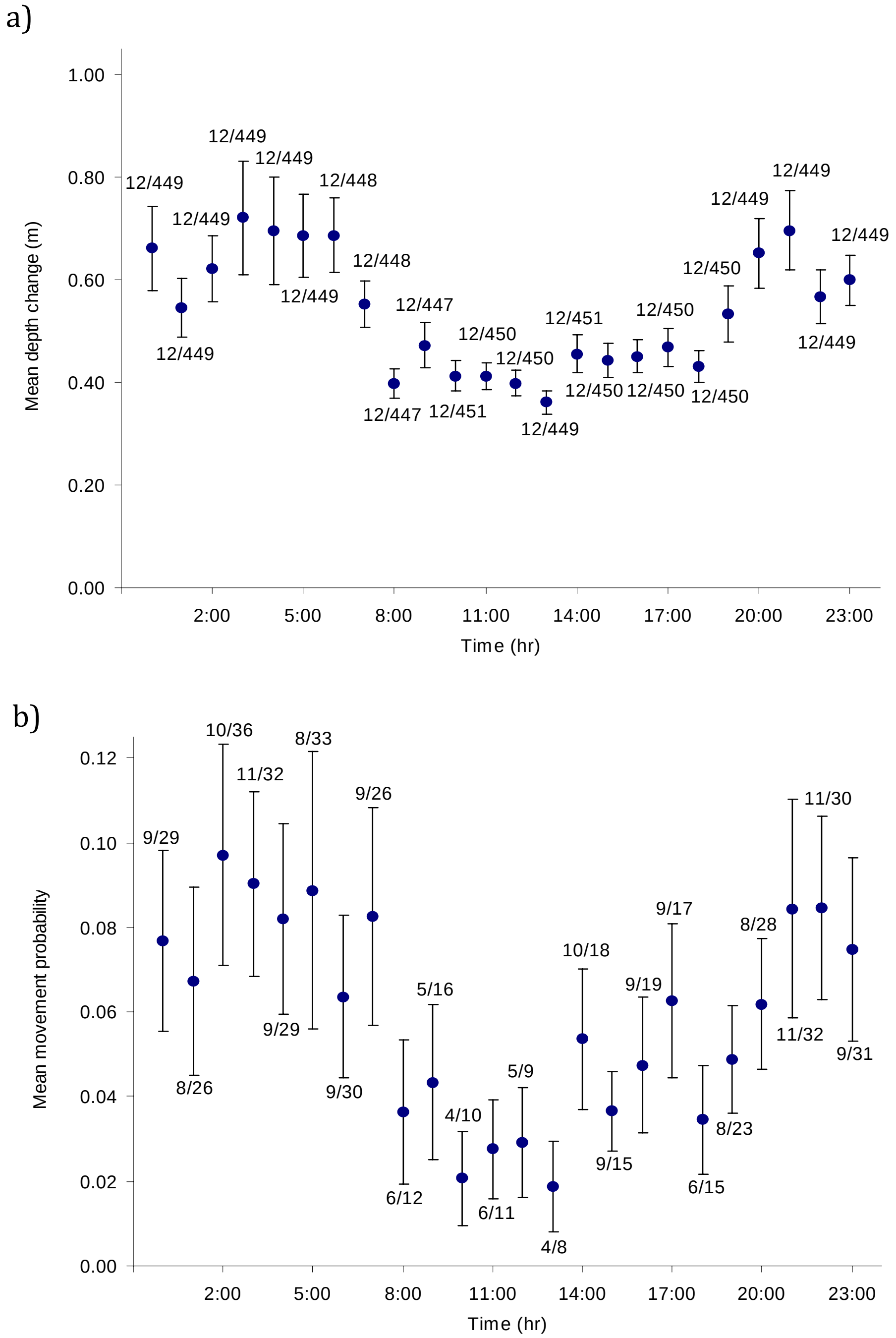


Figure 10. (a) Fluctuations in mean depth change per hour during different lunar phases. Numbers on the plots are the number of fish/total hours of data recorded. (b) Fluctuations in mean movement probability per fish during different lunar phases. Numbers on the plots are the number of fish that moved/total observed movement hours. Error bars indicate ±1 standard error.

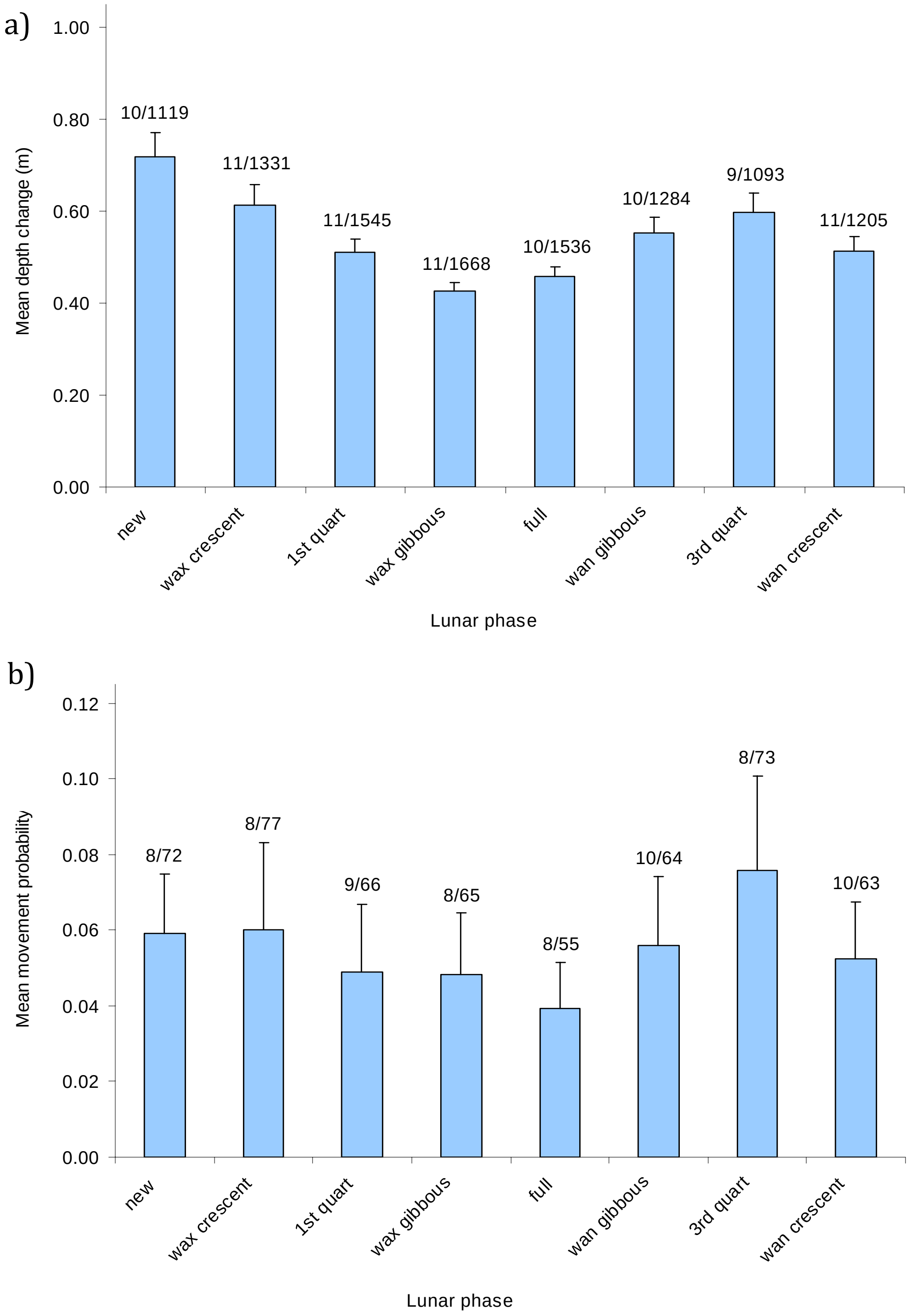


Figure 11. (a) Fluctuations in mean depth change per hour during different tidal stages. Numbers on the plots are the number of fish/total hours of data recorded. (b) Fluctuations in mean movement probability per fish during different tidal stages. Numbers on the plots are the number of fish that moved/ total observed movement hours. Error bars indicate ±1 standard error.

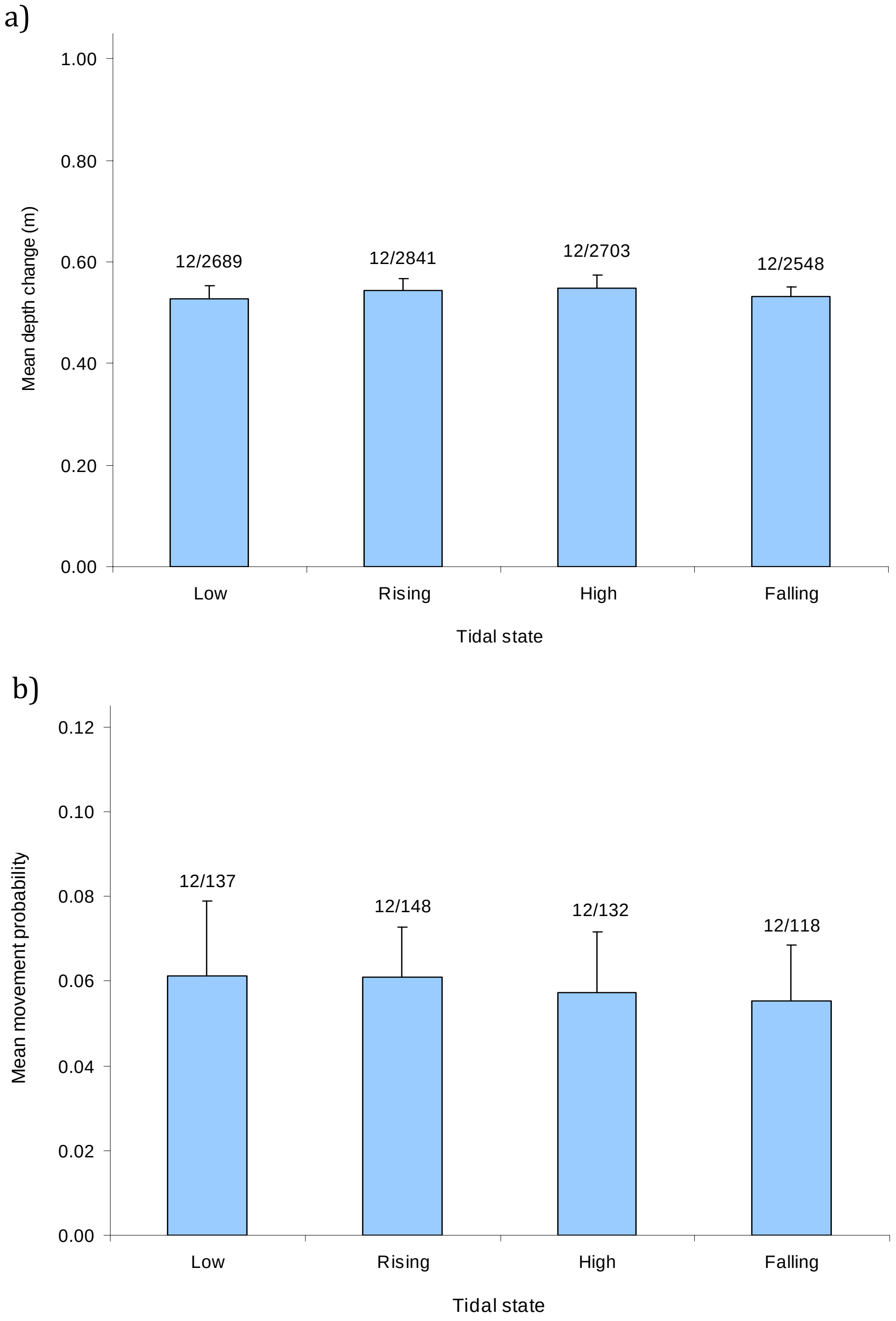


Figure 12. (a) Fluctuations in mean depth change per hour at different temperatures. Numbers on the plots are the number of fish/total hours of data recorded. (b) Fluctuations in mean movement probability per fish at different temperatures. Numbers on the plots are the number of fish that moved/ total observed movement hours. In both plots, open circles with dashed error bars represent the temperatures where a single fish accounted for most of the observed depth changes and movements. Error bars indicate ±1 standard error.

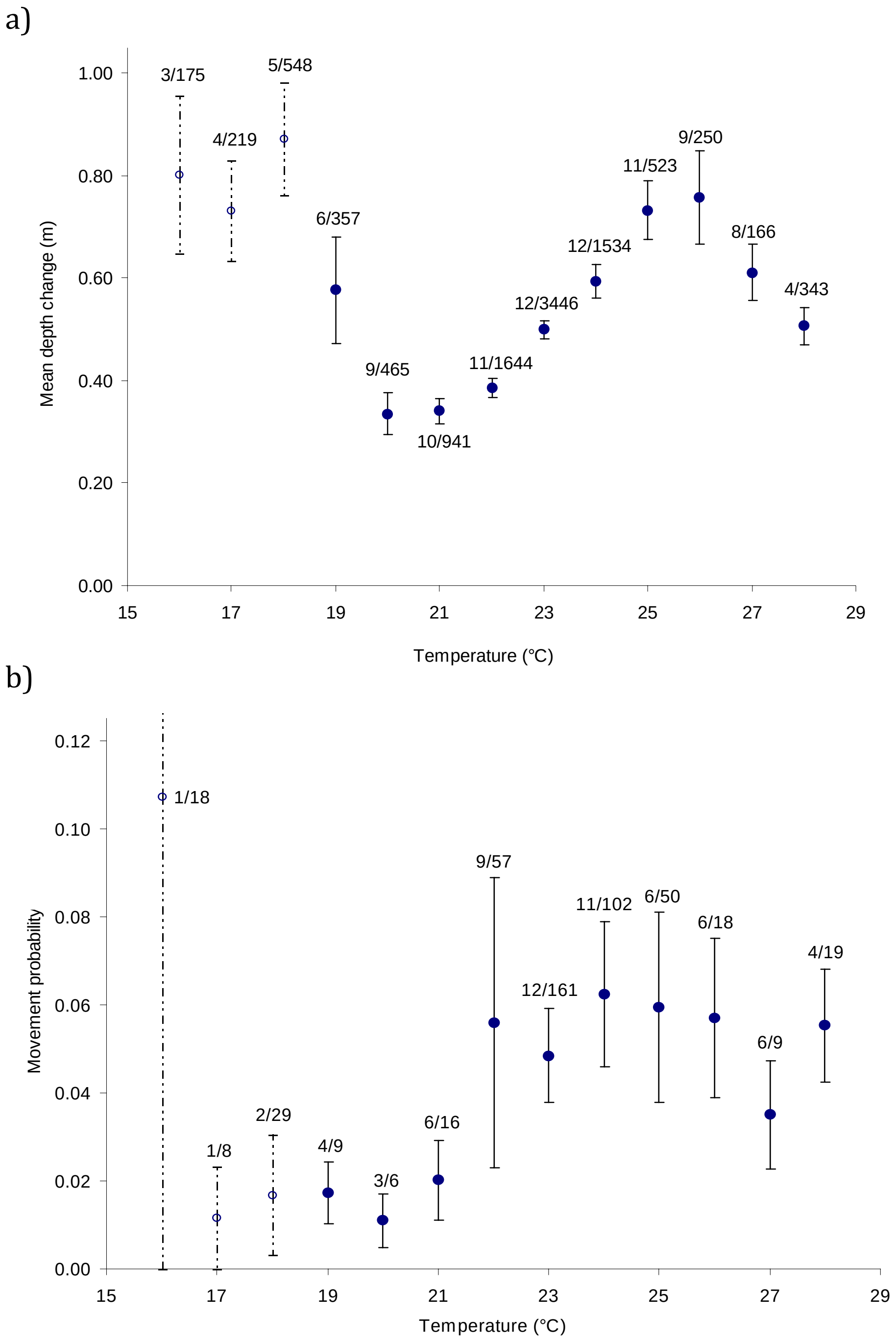


Figure 13. Mean daily depth changes (black line, open circles), temperature (red line), and depth (blue line) experienced by a single fish recovered outside of Chesapeake Bay (Tag 199, see Table 1).

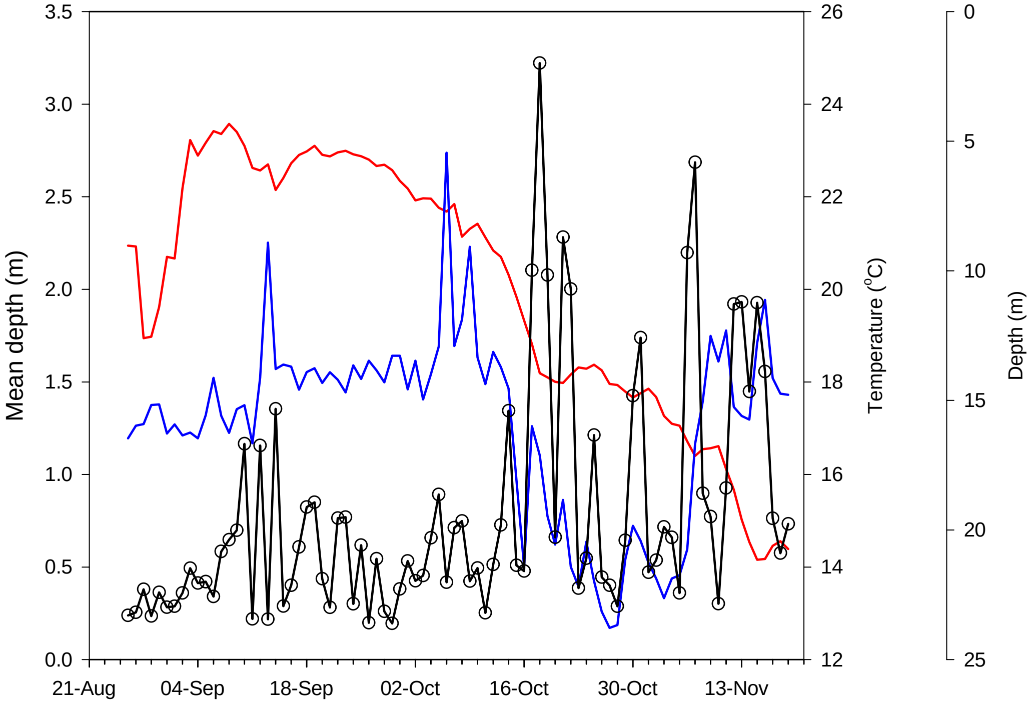


Figure 14. Bottom water temperatures recorded by loggers deployed off the coast of (a) Delaware, (b) Virginia, and (c) North Carolina between August 2009 and June 2010.

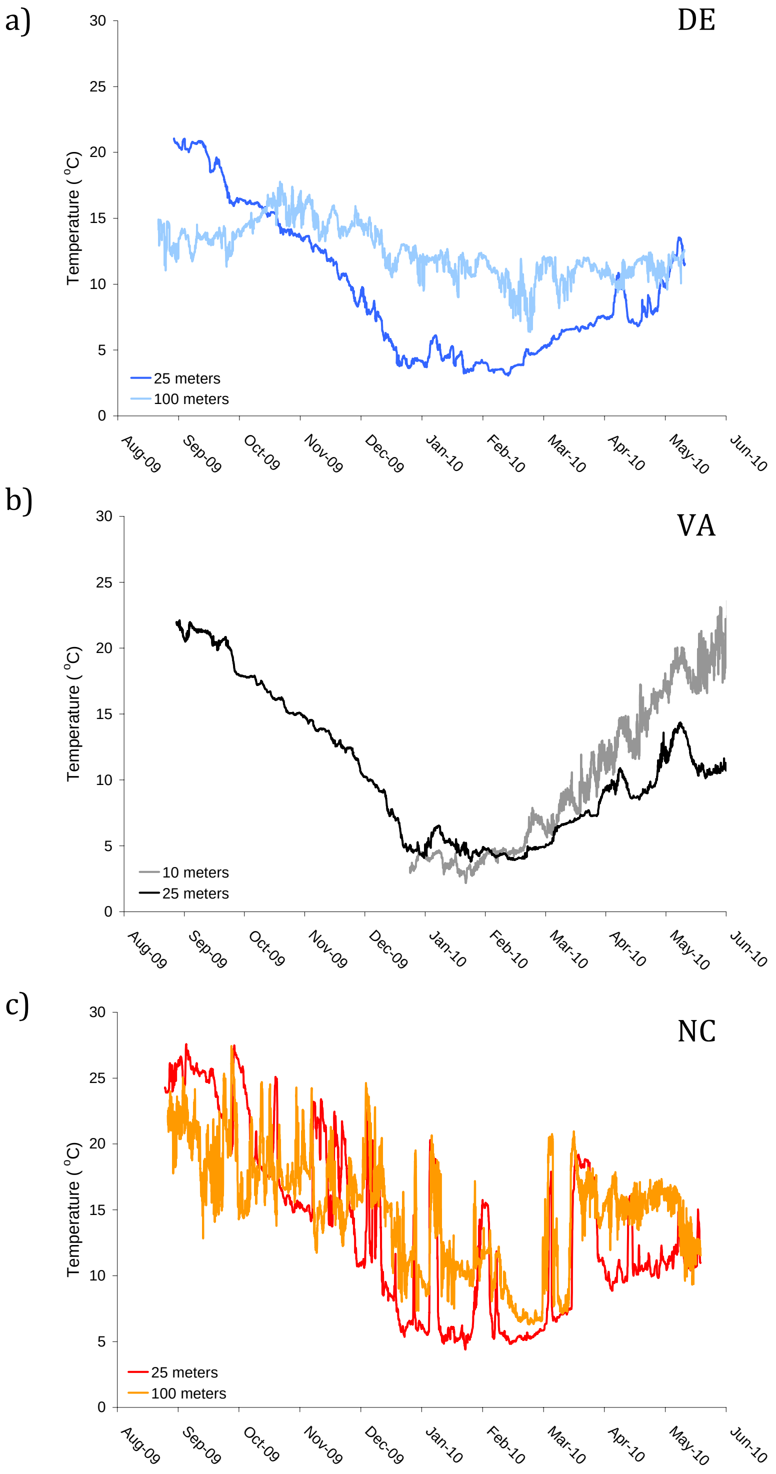


Figure 15. Bottom water temperatures recorded by loggers deployed on the continental shelf at (a) 25 m, and (b) 100 m off the Delaware, Virginia, and North Carolina coasts from August 2009 to June 2010.