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Movements, Habitat Utilization, and Post-Release Survival of Cobia (Rachycentron Canadum) That Summer in Virginia Waters Determined Using Pop-Up Satellite Archival Tags (Psats)

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Movements, Habitat Utilization, and Post-Release Survival of Cobia (*Rachycentron canadum*) that Summer in Virginia Waters Determined Using Pop-Up Satellite Archival Tags (PSATs)

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For knowledge and its best application.

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ABSTRACT

Cobia (*Rachycentron canadum*) is a cosmopolitan marine fish inhabiting tropical, sub-tropical, and temperate marine and estuarine waters. Recent changes in U.S. cobia management have sparked controversy and highlighted limitations in our understanding of seasonal movement patterns and problems with estimating recreational harvests. Consecutive years (2015 and 2016) of estimated overharvests from the Atlantic Migratory Group stock triggered accountability measures to prevent overfishing by recreational anglers. My project employed pop-up satellite archival tags (PSATs) to study cobia movements, habitat utilization, and post-release survival. It was, therefore, designed to enhance knowledge of cobia biology and aid sustainable management. We deployed 36 PSATs on cobia caught in Virginia state waters using standard recreational techniques in August 2016 and August – September 2017. All fish larger than 37-inches total length were tagged, and several of these were deep-hooked. No mortalities were inferred from the 24 cobia whose PSATs reported. Only five PSATs remained attached until the 180-day programmed release date. This made it difficult to accurately describe cobia seasonal movement patterns, although it appears that areas near North Carolina's continental shelf break may be important overwintering habitat. Other overwintering areas may exist, however, as some fish made longer migrations, and one PSAT reported in Florida waters (beyond the current stock demarcation boundary). Cobia have a strong affinity for waters ≥20°C, even in the coldest months. They also display distinct seasonal differences in vertical movement patterns which make them more susceptible to capture in the summer when Virginia recreational anglers often employ sight-fishing techniques.

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<u>Introduction</u>

Cobia (*Rachycentron canadum*) is a marine fish of economic importance to Virginia and throughout much of its nearly circumglobal range, primarily because it is a highly sought after species by recreational anglers. Fishery closures were implemented along the U.S. eastern seaboard in 2016 and 2017 due to estimated harvests greatly exceeding the allowable catch limit. These restrictions, combined with uncertainty of stock structure and amended stock definitions, have turned cobia management into a topic of ever-growing controversy (Cochran, 2016). My project is intended to improve management decisions by increasing our understanding of movements, habitat utilization, and post-release survival of cobia that summer in Virginia coastal waters.

Cobia Biology & Life History

Cobia reach 2 meters in total length and weigh up to 60 kilograms. They are a fast-growing species with lifespans of 10 – 15 years (Shaffer & Nakamura, 1989). They have elongate, fusiform bodies with a long, broad, and depressed head and an extended lower jaw. They are dark brown dorsally with a lighter, whitish-yellow-brown underbelly and a distinctive dark band extending the full length of the body which often fades as a fish ages (Smith, 1995). Their villiform teeth indicate a carnivorous diet.

Cobia were originally described by Linnaeus in 1766 but have a host of regional common names, including crabeater and lemonfish (United States), runner (South Africa and Tanzania), bonito negro (Uruguay and Argentina) and black kingfish (Australia, India, and Pakistan) (Shaffer & Nakamura, 1989). The diversity of common names can be attributed to the nearly circumglobal distribution of the species in tropical, subtropical, and temperate coastal waters. Cobia are not native to the eastern Pacific Ocean but may have become established in the area following the escape of thousands of aquaculture-raised large juveniles from their Ecuadorian holding pens in 2015; sightings of cobia in the eastern Pacific have now been reported as far north as Panama (Castellanos-Galindo et al., 2016).

Cobia exhibit rapid growth and typically reach sexual maturity at ages two and three for males and females, respectively. Spawning occurs May – October along the U.S. Atlantic coast with annual fecundity estimated to exceed five million eggs for large females (Richards, 1967). Younger specimens have annual fecundities of approximately two million eggs (Richards, 1967). Multiple batch spawning appears to occur throughout the warm months each year (Smith, 1995). Given their ample fecundity and the relatively low number of juvenile fish observed each year (Joseph et al., 1964), cobia eggs and larvae experience extremely high rates of natural mortality like most marine fishes. Cobia eggs are easily recognizable because of their size (greater than 1.0 mm diameter) and distinctive single, large oil globule (approx. 0.38 mm diameter) (Joseph et al., 1964). Eggs have been found in estuaries and across coastal waters, but the spawning habits of cobia have not been thoroughly studied.

In their native ranges, cobia follow annual migration patterns, moving from tropical and subtropical waters into more temperate zones in the summer months. Migratory patterns, however, remain inadequately described for management purposes (SEDAR 28, 2013).

Biologically meaningful stock boundaries, likewise, have not been well-defined. Although there appear to be several geographically disjunct populations, there has not been a genetic study of cobia stock structure on a global scale. Genetic studies have examined cobia stock regional stock structures including those within the Persian Gulf and Gulf of Oman (Salari et al., 2009), the Andaman Sea and Gulf of Thailand (Phinchongsakuldit et al., 2013), Australian waters (Fry et al., 2010), the Gulf of Mexico (Hrincevich, 1993; Gold et al., 2013), and the western North Atlantic (Darden et al., 2012; Gold et al., 2013; Darden et al., 2018; McDowell et al., 2018). Only Gold et al. (2013) compared broadly separated fishes near Taiwan and the western Atlantic Ocean. Not surprisingly, these populations were genetically distinct. On a smaller spatial scale, Hrincevich (1993) found no significant genetic heterogeneity among cobia collected within the Gulf of Mexico. Gold et al. (2013) likewise found no significant genetic differences between cobia from the Gulf of Mexico and coastal Atlantic waters. Darden et al. (2012, 2018) reported the presence of genetically distinct populations based on fish captured in coastal areas of South Carolina and Virginia but homogeneity in fishes captured near Florida and the Carolinas. Based on the available genetic and conventional tagging data, management has formally recognized two cobia stocks, the Atlantic Migratory Group and the Gulf Migratory Group, separated at the Georgia – Florida state boundary (Perkinson & Denson, 2012; SEDAR 28, 2013).

Cobia Ecology and Behavior

Fisher (1891) described cobia as being aggressive and voracious feeders, similar to freshwater pike. The trophic level of cobia is estimated to be 4.0 (Froese & Pauly, 2017), which classifies them as higher order predators. As extensively described by Smith (1995), cobia are opportunistic, visual feeders (Horodysky et al., 2010) consuming a wide variety of prey with diet shifts coincidental to ontogenetic progression. Cobia larvae and young juveniles feed on zooplankton, whereas large juveniles and adults consume a plethora of crustaceans in addition to an assortment of forage fish species including smooth dogfish pups, Dasyatid sting rays, and other elasmobranchs (Smith, 1995). Dolphinfish (*Coryphaena hippurus*) are known to prey upon juveniles, and shortfin mako sharks (*Isurus oxyrinchus*) have been reported to consume adult cobia (Smith, 1995).

Cobia associate with large marine fauna and static objects. They are commonly sighted following rays, sharks, turtles, and other large ocean occupants (Shaffer & Nakamura, 1989). It is speculated that cobia capitalize on food scraps not consumed in this commensal relationship.

Cobia Fisheries

Cobia have been targeted by recreational and commercial fisheries along U.S. Atlantic and Gulf coasts since before the turn of the 20th century, but commercial landing data were not recorded until the mid-20th century, and landings data from the recreational fishery were not recorded until 1981. Landings data for commercial cobia harvests only go back to 1950, and little is known about the extent of the cobia fishery before that time. Prior to the first recreational landings estimates in 1981, the commercial fishery was thought to be the largest source of fisheries mortality, but it is now known that recreational fishery landings dominate cobia harvest (SEDAR 28, 2013). The recreational fishery has accounted for 80-95% of U.S. annual cobia harvest in recent decades. The current commercial quota is set at 8% of the total allowable catch limit (SEDAR 28, 2013). Recreational and commercial cobia harvests have been routinely estimated for several decades now, but this basic information has recently faced intense scrutiny.

The U.S. recreational cobia fishery is primarily conducted with hook and line, although other gears are used as allowed by state laws. The traditional method of capturing cobia has been to use chum and fish with live or cut baits near the bottom of known travel corridors

(Burnley, 2017). In recent decades, sight fishing for cobia has gained in popularity, whereby anglers cruise in boats looking for cobia swimming near the surface and then cast jigs or live bait in front of the fish. Modern trolling motor and sonar technology have also allowed anglers to successfully vertical jig for cobia above warm water reefs and ship wrecks (McNally, 2016). The recreational fishery is estimated to have harvested more than 1.7 million pounds of cobia in 2016 along the U.S. eastern seaboard alone (MRIP, 2017). This harvest is closely monitored because it exceeded the 1.46 million pound catch limits for both 2015 and 2016 (MRIP, 2017). There is considerable uncertainty regarding commercial and recreational cobia harvests in other areas of the world.

There is no directed U.S. commercial cobia fishery, because cobia do not aggregate into large schools, making large-scale harvests difficult (although cobia have anecdotally been reported to seasonally form pods of several dozen fish). Cobia are most frequently caught as bycatch in commercial shrimp trawls, long lines and trolling gear, and occasionally tuna purse seines. Commercial fishermen will also target cobia with hook and line if the fish are spotted during routine operations. The commercial cobia harvest in the United States has been approximately 50,000 pounds annually since 1950 (SEDAR 28, 2013).

Aquaculture production of cobia is beginning to rival production from recreational and commercial fisheries. As previously noted, cobia are rapid-growing fish with desirable meat, qualities conducive to profitable aquaculture operations. Companies in China and Taiwan, in particular, are capitalizing on international demand for cobia fillets, and global culture production exceeded 50,000 metric tons in 2012 (FAO, N.D.).

Assessment and Management

Stock Assessment

The most recent comprehensive stock assessment for cobia in U.S. Atlantic waters was conducted in 2012 (SEDAR 28, 2013), and a new cobia stock assessment is underway. This 2012 stock assessment considered both fisheries dependent and independent catch data through 2011, as well as all pertinent biological information available at the time. It included data from conventional tagging and genetic studies. The 2012 assessment concluded that cobia stocks were not overfished nor was overfishing occurring. The stock was deemed healthy with spawning stock biomass at 1.75 times that required for maximum sustainable yield (MSY), and fishing mortality (F) was below the threshold for maintaining biomass at or above MSY (F_{MSY}), with $F/F_{MSY} = 0.42$ in 2011 (SEDAR 28, 2013). Estimated overharvests in recent years, however, may have a significant but yet undetermined impact on the status of the stocks.

Recommendations from the 2012 stock assessment included the use of conventional, genetic, and satellite tags to study cobia stock structure and movements and that post-release mortality rates be investigated. The rate of post-release mortality from the recreational and commercial fisheries is currently assumed to be five percent (SEDAR 28, 2013); however, there have been no studies supporting the assumption.

Cobia Movements and Stock Boundaries

Cobia are migratory, crossing state boundaries and residing in both state and federal jurisdictional waters (defined as within and beyond three nautical miles of shore, respectively). Conventional tagging studies have been conducted over the past 60 years (SEDAR 28, 2013), but have not had sufficient recaptures to delineate cobia stocks within U.S. waters. From the available tagging data, it appears that Florida's east coast waters may be a mixing zone. Only one percent of recaptured cobia tagged north of Florida were in the Gulf of Mexico and vice versa, suggesting very limited exchange of the two presumed populations (Perkinson & Denson, 2012).

Although conventional tag recapture numbers were relatively low, they were the best available data to delineate stock boundaries at the time of the 2012 stock assessment. Present stock boundaries are based on tag – recapture data analyses conducted by the South Carolina Department of Natural Resources (SC DNR). SC DNR examined recaptures of cobia tagged in Brevard County, Florida to evaluate the theory that Cape Canaveral (in Brevard County) may represent a latitudinal barrier. Of the 36 recaptured cobia tagged in Brevard County, 39% were recaptured within waters adjacent to Brevard County, while 25% were recaptured in areas to the north and 36% to the south of the county (SEDAR 28, 2013). Based on these data, SC DNR concluded that the best delineation of the two stocks, now named the Atlantic Migratory Group and the Gulf Migratory Group, is Brevard County, Florida, or slightly north thereof. An advisory panel working group subsequently recommended that the Georgia – Florida state line be used as the management boundary for ease of communication and regulation enforcement (GoMFMC, 2014). This is the current stock boundary, implemented in 2015. Prior to 2015, cobia were still managed as two stocks, but the demarcation line between stocks was set at the Florida Keys. The 2015 re-designation of the stock boundary at the Georgia – Florida state line is one aspect of cobia management that remains controversial.

Management Controversy

The implementation of new cobia management (stock) boundaries would not have been controversial if it were not for the reallocation of catch limits and estimates of significant overharvests from one of the stocks, which recreational fisheries contended was inequitable. When fish on the east coast of Florida were considered to be within the Atlantic Migratory Group, the annual allowable catch limit (ACL) was set at 1.44 million pounds (NMFS, 2017). When the new management boundaries were put in place in 2015, the recreational ACL was split, with 620,000 pounds allocated to the states from Georgia northward and 840,000 pounds allocated to the east coast of Florida (NMFS, 2017). 2015 was designated as a transition year with ACLs of 630,000 pounds and 830,000 pounds for the respective management zones (GoMFMC, 2014). This ACL, however, noticeably differed from the average harvests from the two areas for the prior decade (2005-2014). Over the 10-year period, the average recreational landings from Georgia northward were estimated to be 706,000 pounds while the recreational landings from the east coast of Florida averaged only 413,000 pounds (NMFS, 2017; ASMFC, 2016). Only in 2011 and 2014 did the east coast of Florida have higher estimated recreational harvests than the states from Georgia northward (NMFS, 2017). Furthermore, 2011 was an anomalous year with the lowest decadal landings estimates for Georgia northward and the highest decadal landings estimates for the east coast of Florida (NMFS, 2017).

The primary source for estimating cobia recreational harvests is the Marine Recreational Information Program (MRIP), a collection of fishery survey data compiled by the National Marine Fisheries Service of the National Oceanic and Atmospheric Administration that is used for species assessment, monitoring, and management. The survey program began in 1981 and provides time series data on annual cobia landings using catch intercepts, cobia landings witnessed and recorded by designated dockside observers. Intercept data are extrapolated using effort data from mail or telephone surveys of fishing licensees to estimate total annual harvest.

Recent MRIP harvest estimates are also focal points of the cobia management controversy. Estimated landings of fish from the Atlantic Migratory Group in 2015 and 2016 were 1.57 and 1.34 million pounds, respectively. Virginia was the single greatest contributor to these totals with back-to-back record catches of 882,000 and 915,000 pounds, both far in excess of the entire regional ACL. The 2015 and 2016 Virginia landings estimates were based on only 38 and 37 cobia catch intercepts, respectively, extrapolated with effort data. Harvest estimates from the east coast of Florida for the same years were 425,000 and 447,000 pounds (NMFS, 2017). The MRIP estimates for 2017 are much lower, below historical norms, with Georgia northward harvesting 457,000 pounds and the east coast of Florida taking 295,000 pounds (MRIP, 2018).

Because of the estimated overharvest, the recreational cobia season in federal waters was closed for the first time in June 2016, following the 2015 harvest estimate of 248% of the ACL (Daniel, 2016). Southeast Atlantic states with cobia fisheries (Virginia, North Carolina, South Carolina, and Georgia) reacted by tightening regulations (size and bag limits) and seasons in their state waters to prevent a complete fishery closure. Despite area closures and tighter state-by-state restrictions, the 2016 estimated recreational harvest exceeded 1.3 million pounds, 217% of the ACL (NOAA Southeast Regional Office, 2017). As a result, the 2017 season was completely closed in federal waters (Federal Register, 2017). This is perhaps the aspect of cobia management that has received the most attention as recreational anglers have been very vocal about new restrictions. Cobia angling in federal waters (waters greater than three nautical miles from shore) re-opened for the 2018 season following 2017 landings estimates that were below the ACL.

Federal recreational angling regulations historically set a minimum cobia harvest size of 33 inches fork length and a limit of 2 fish per angler, up to 6 fish per vessel, without seasonal restrictions (Federal Register, 2016). Within states' jurisdictional waters, the same size and possession limits set by federal regulators were enforced until the first season closure in federal waters. Since that time, disputes over the accuracy of harvest estimates and desires to protect state interests have led to a diverse set of state restrictions. Management of cobia was transferred from the South Atlantic Fisheries Management Council (a body impaneled by the federal government to set fisheries regulations) to the Atlantic States Fishery Management Commission (a body impaneled by the state governments) in 2018 because most cobia harvests occur in state waters.

Objectives

Many of the controversies associated with cobia management are a direct result of the lack of thorough understanding of cobia stock structure and how the stocks are impacted by recreational angling. The 2012 stock assessment made several recommendations that could provide better insights into cobia population dynamics; these included studies of stock structure (employing genetic and conventional/telemetry tagging methodologies), movements, and post-release survival. This thesis addresses some of these research needs by using pop-up satellite archival tags (PSATs) to investigate seasonal movements, habitat utilization, and post-release survival of cobia that summer in Virginia coastal waters. PSATs can provide timely assessments of movement patterns that should enable estimates of more realistic stock boundaries. The habitat utilization data collected by PSATs also give insights on the vulnerability of cobia to various fishing gears, allowing a better translation of catch-per-unit-effort data to abundance.

Finally, post-release mortality of cobia caught in the recreational fishery can be directly inferred from PSAT data, providing information needed to better estimate recreational fishing mortality -- an estimate which has heightened importance given new regulations that are likely to increase regulatory discards.

Materials & Methods

All angling and tagging procedures were approved by the William & Mary Institutional Animal Care and Use Committee (IACUC-2016-07-25-11296-jegrav) and complied with all relevant state and federal regulations. Fish were captured within the Chesapeake Bay and surrounding coastal Virginia waters, and tagged fish were representative of the size classes targeted by recreational fishermen (greater than 37 inches total length).

PSATs

PSATs attached to fish collect environmental data such as water temperature, pressure (depth), and light levels for programmed durations ranging from days up to two years. These data can be studied to infer habitat utilization, movements, and post-release survival of fishes. Following automatic release from a fish after the specified data-gathering period, a PSAT floats to the surface and transmits archived data to the ARGOS (Advanced Research Global Observation Satellite) network (Wildlife Computers, 2017). In addition to receiving and retransmitting data, ARGOS satellites determine the location of PSAT transmitters with 1.5-kilometer accuracy using the Doppler frequency shift of received transmissions.

A total of 41 PSATs were available for deployment: 30 mrPAT units from Wildlife Computers (Redmond, WA), 4 model PTT-100 units from Microwave Telemetry, Inc. (MTI) (Columbia, MD), and 7 model X-Tags also from Microwave Telemetry, Inc. The three different PSAT models used in this study are shown in Figure 1. The mrPAT tags were selected because their relatively low cost ($1,500 each) allowed the greatest possible sample size with the available resources. The mrPAT tags are primarily designed for movement studies to transmit the location of fish after a predetermined period. They also record (and subsequently transmit following release from the fish) daily maximum and minimum environmental temperatures and the average of the daily maximum and minimum tag inclination, data useful for limited environmental and survival analyses. The two tag models from Microwave Telemetry, Inc. were used opportunistically as leftover or recovered tags from previous studies. These tags have additional capabilities in that they record light, pressure (depth), and temperature data which are summarized into 15 – 30 minute intervals. These units, therefore, provide data on habitat utilization as well as post-release survival and movements.

Tag Deployment

All cobia were caught and tagged in the Chesapeake Bay or within 3 miles of the Virginia shoreline. PSATs were attached to cobia (regardless of condition) exceeding a minimum length threshold set for each tag model: 37 inches total length for Wildlife Computers mrPATs and Microwave Telemetry, Inc. X-Tags; 45 inches total length for Microwave Telemetry, Inc. PTT-100s. These criteria were set in an effort to ensure that fish survival would be negligibly impacted by the presence of a towed PSAT (Note that the PTT-100 is larger than the other two models, Figure 1). The chosen minimum size also corresponded with the federal minimum size of 33-inch fork length, deemed equivalent to 37-inch total length. Although the effects of PSATs on teleost fish physiology have not been studied, PSATs should have negligible impact on cobia swimming kinematics and metabolism. This inference is drawn from a study on juvenile sandbar sharks (*Carcharhinus plumbeus*) smaller than the cobia tagged, in which researchers noted less than a 5% change in metabolic rate and negligible impacts on swimming kinematics when sharks were fitted with a Microwave Telemetry X-Tag (Lynch et al., 2016).

Cobia were caught by recreational anglers (both private and charter) using methods representative of typical recreational fishing practices in Virginia. The most common methods of fishing for cobia were chumming or sight-casting using live or artificial baits rigged with J-hooks or circle hooks, or lures rigged with J-hooks. Fish were hooked, landed, netted, and brought into the boat for measurement and tag attachment. Data recorded for each fish included total length, estimated weight, fight time, air exposure time, bait, hook type, hooking location, release coordinates, and any observational notes. Hooking location was defined as superficial (jaw or other hook location easily removed) or deep (in the mouth, esophagus, or gut).

Tags were attached to fish using standard methods developed by Graves et al. (2002). Each PSAT was tethered to an intramuscular anchor that was inserted into the fish musculature below the posterior dorsal fin and well above the coelomic cavity, with the dart presumably interlocking with the pterygiophores. Fish were subsequently released as quickly as possible. The tether linking the intramuscular anchor to the PSAT was 80-pound test monofilament line secured with stainless steel crimps; total tether length was approximately 16 centimeters.

All PSATs were programmed for six-month attachment but had conditional release functions. X-Tags would initiate the release/transmit sequence if the tag remained at a constant depth (±3 meters) for four consecutive days in the event that a fish died and sank to the bottom or the PSAT separated from the fish prior to the programmed release date (and was thus floating at the surface). The mrPAT tags had a wet/dry conductivity sensor that could determine if the unit released from the fish prematurely when a tag was "dry" for a total of six minutes in any rolling two-hour window (with sampling interval of three seconds) to initiate the release/transmit sequence. The PTT-100 "constant depth" feature was not activated as it would initiate the release/transmit sequence when a tag remained at constant depth (±10 meters) for four consecutive days. Chesapeake Bay is shallow enough that premature releases would be almost guaranteed with constant depth ±10 meters as the threshold for initiating release.

Data Analysis

The transmitted data were used to determine net travel distance, habitat utilization, and rates of post-release survival. Net travel distance was defined as the minimum straight-line distance between the location of fish release and the first location report. Only ARGOS location codes 1, 2, or 3 were used, ensuring that transmitting locations were determined with 1.5 km precision. Average daily displacement was calculated as the net travel distance divided by the time the PSAT remained attached to the fish (deployment duration).

Depth and temperature data were used to describe individual habitat utilization and to assess possible changes in habitat utilization associated with diurnal cycles, lunar cycles, and seasons. Data were summarized to show percentage of time spent at different water temperatures and depths by month and by fish. Aggregate data from multiple tags may bias results towards those fish whose tags transmitted more data. If data are received unevenly spaced throughout the deployment period, results may be biased if the transmitted data are not representative of overall behavior. Aggregating all data received assumes these risks but became necessary with the limited amount of data available. Contributions were weighted by tag to assess and minimize these biases. Summaries of depth and temperature frequencies were weighted such that each tag contributed an equal proportion for each assessment if tags reported unequal data. Pearson's chi-square tests were used to evaluate differences between raw and weighted data distributions with alpha = 0.05. Raw data distributions were used if there were no meaningful differences with weighted distributions.

Diurnal analyses compared observations grouped by day and night. Since precise sunrise and sunset times were not known and varied over the course of the study, day observations were defined as the periods of 0342 to 1222 GMT each day, a time window corresponding with the 30 minutes after and before sunrise and sunset times, respectively, for the winter solstice in Virginia Beach, Virginia. Similarly, night observations were defined as the periods 1639 to 0141 GMT, corresponding with 30 minutes after and before sunset and sunrise times, respectively, for Virginia Beach, Virginia on August 1st, the longest day length in this study. Defining these windows for day and night enabled data sorting with certainty that a given observation was a true day or night observation, respectively. Any observation not falling within these two time slots was considered crepuscular data and not included in diurnal data distributions.

Moon phase analyses similarly grouped data distributions by the four primary lunar phases: new moon, first quarter moon, full moon, and third quarter moon. Data were assigned to each of these four primary phases if an observation was made within ± 2 days of the phase peak as defined by the U.S. Naval Observatory. Any data falling outside these 5-day windows were not considered in lunar cycle analyses. Monthly analyses grouped data by calendar month.

Individuals were considered to have survived capture if the tag remained attached and indicated movements for at least ten days after release. The ten-day duration was selected as a time period short enough to minimize observations of natural mortality but long enough to detect mortality resulting from capture events. This was primarily intended to detect short-term post-release mortality (<72 hours) but also included the possibility of detecting long-term mortality (>72 hours) as defined by Pollock & Pine (2007). It is usually impossible to distinguish natural mortalities from catch-related mortalities that occur several days after release, so it was assumed that any mortality within 10 days of release is fishing mortality (resulting from the processes of capture, tagging, and release). Tags that released prematurely before 10 days and had data consistent with survival were not included in the analysis of post-release mortality. A mortality could be inferred from mrPAT inclinometer readings if an individual died and sank to the ocean floor resulting in a nearly vertical (0 degree) mean inclinometer reading. Mortality could be inferred from MTI X-Tags and PTT-100s if a specimen died and sank to the ocean floor resulting in data showing a nearly constant relatively low temperature combined with an extended constant pressure followed by eventual tag release. Mortality confidence intervals were obtained using estimation methods developed by Goodyear (2002) with 10,000 trial simulations, a natural mortality rate of 0.2, and survival expression period of 10 days.

Results

A total of 36 cobia were tagged during August 2016 and August – September 2017 in Virginia waters: 7 with MTI X-Tags, 3 with MTI PTT-100s, and 26 with WC mrPATs. Five tags (one PTT-100 and four mrPATs) were not deployed due to limited specimen availability.

The size of fish tagged ranged from 38 to 59 inches total length with estimated weights of 15 to 60 pounds (Table 1). The most prevalent size class was those 38 to 40 inches total length (Figure 2). Not only was this size class the most frequently encountered, but several tags were deployed by a cooperating charter captain whose clients wished to retain legal-sized fish (>40-inch minimum total length) but who were willing to tag and release fish below the minimum size or larger fish once they reached their bag limit. Fight time ranged from 0:45 to 15:00 minutes and fish experienced air exposure times (landing, hook removal, and tagging) approximately 1.5 to 4.5 minutes (Table 1). Eight of the tagged cobia were deep-hooked (inside the mouth, esophagus, or gut) with the line being cut as close to the hook as possible and the hook left embedded within the fish.

Tag Reporting and Performance

Received percentages of transmissible data are shown in Table 2. Twenty-four PSATs transmitted data, 11 did not report, and 1 reported but provided no useable data. Of the 24 tags that reported useable data, 19 released prematurely (1 X-Tag, 1 PTT-100, and 17 mrPATs), remaining attached to the fish for periods ranging from 1 to 99 days. Five tags (3 X-Tags, 1 PTT-100, and 1 mrPAT) remained attached to fish for the entire 6-month programmed deployment duration and successfully reported data. The 11 non-reporting tags consisted of 3 X-

Tags and 8 mrPATs. One PTT-100 reported after six months but very few transmissions were received, and those provided no useable data or location information. The 24 reporting tags provided a total of 1,686 data days.

These 1,686 cobia data days are a fantastic wealth of information for an understudied species, but are only one-quarter of the data expected had this study gone perfectly. The three primary reasons for less than perfect data recovery are early-, late-, and non-reporting tags. The 11 non-reporting tags (8 of 26 mrPATS and 3 of 7 X-Tags) are a mystery.

Analysis of the data from the 19 early-reporting tags did not provide many insights as to why the tags released prematurely. One of the X-Tags reported prematurely when it separated from the fish after 81 days, and floated on the surface for 4-days at which time the constant depth release was activated and the tag began to transmit its archived data. One of the PTT-100s also separated from its specimen prematurely after 86 days; however, its constant depth release was not activated because of the depth-sensitivity conflict previously mentioned, so it did not begin transmitting data until the scheduled 6-month release time. During the time between the premature release and the programmed release, this tag drifted to the middle of the North Atlantic. Transmissions from all 17 early-reporting mrPATs indicated that each tag was classified as a “floater” based on air exposure, and the release-transmit sequence was initiated.

An additional tag performance observation was late reporting of three X-Tags and 1 PTT-100. The three full duration X-Tags all reported 5-9 days late. Data received indicate each tag’s release mechanism was triggered on schedule after 6 months, but rather than rising to the surface after release, the data indicated that the tags remained attached to the fish. When each of these tags eventually separated from the fish, they quickly floated to the surface allowing reception of transmitted data. Data from the late-reporting PTT-100 tag indicated that it separated from the fish after 6 months as scheduled, but floated at or near the surface for 13 days before the first transmitted data were received. The delayed reporting of these four tags resulted in lower data recoveries, as the tags were transmitting in vain underwater for several days after the initiation of the release process, consuming limited battery power. Less than 50% of the transmissible data were received from each of these late-reporting tags, compared to an expected 70% or more for tags that effectively send data for the full 20-30 days of transmitting battery life. Received percentages of transmissible data are shown in Table 2.

Post-Release Survival

I could infer no post-release mortalities from the transmitted data. Of the 24 tags that reported useable data, all had temperature/depth (X-Tags and PTT-100s) or inclinometer (mrPATs) values that were consistent with survival. Twenty PSATs met the minimum 10-day duration for survivorship after release. All temperature/depth data evidenced active vertical movement prior to tag release (Figure 3). Similarly, all mean inclinometer readings were greater than 50º from vertical for the day prior to tag release (Appendix 1) suggesting that the fish was moving at that time; a non-moving fish would be evidenced with inclination near 0º from vertical (Lynch et al., 2017). Figure 4 shows the daily inclinometer readings of the cobia that carried its mrPAT for the full 180-day term. Our 95% confidence interval for post-release cobia mortality is 0% to 5%, using the Goodyear (2002) method and the 20 tags attached to fish for at least 10 days. No survival or mortality conclusions can be drawn from the 11 tags that did not report or the one tag which reported but provided no useable data.

Movement

Twenty-four PSATs reported quality location data (ARGOS location codes 1, 2, & 3), and 22 were deemed to accurately reflect fish locations at the time of the first transmission (Figure 5). Locations obtained from two PSATs were excluded because too much time had elapsed between tag separation and first location report. (One PTT-100 separated from the fish after 86 days and floated 98 days until the 6-month point when ARGOS located the tag in the middle of the North Atlantic. Another PTT-100 separated from its cobia on-time but floated near the surface for 13 days before reporting an accurate location; it is likely this tag was southwest of its first reported location when it released from the fish, but how far is hard to say.) Additionally, one premature X-Tag (81-day attachment duration) floated at the surface for four days before reporting its location, but we can safely assume this tag was near the continental shelf south of Hatteras, North Carolina at the time of separation from its cobia because another PSAT had a similar drift trajectory. The other 21 PSAT locations are assumed to represent accurate locations of the fish within hours of release with 1.5 kilometer accuracy. Figure 5 presents the first reporting locations of all PSATs (except the one that reported from the middle of the North Atlantic Ocean).

Only 5 PSATs remained attached for the full six-month programmed duration, but the locations and dates of first transmissions of the PSATs that released prematurely provide insights into the migratory behavior of cobia caught in Virginia waters. The six PSATs that reported in August, within a few weeks of deployment, were in the Chesapeake Bay or offshore of Virginia. Of the three PSATs that detached and reported in September, two were in Virginia waters, and the third was offshore of North Carolina. Four PSATs detached and reported in October: two showed that cobia had moved to areas south of Hatteras, North Carolina; one had remained in Virginia waters; and the fourth had moved north into the Maryland portion of the Chesapeake

Bay. The four PSATs that detached and reported in November were more geographically scattered; one was offshore of Savannah Georgia, and three were off North Carolina. No tags reported in December or January. The five PSATs that remained attached for the full programmed duration reported cobia were in waters offshore of Florida, South Carolina, and North Carolina in February and early March. With the exception of the one tag reporting from the Maryland portion of Chesapeake Bay (not far from where the fish was originally tagged), all tags attached to cobia for at least 30 days indicated net southern movements for the period of September to early March. The reporting tags also show that cobia tend to move offshore starting in November. All reported locations prior to 15 November (offshore of Maryland, Virginia, and North Carolina) were within 15 kilometers of shore (mean 7.7 km), while all locations after 15 November (offshore of North Carolina, South Carolina, Georgia, and Florida) were at least 15 kilometers from the nearest shoreline (mean 61.7 km), with the furthest tag being 77 kilometers from the nearest shoreline.

Net displacements and tag attachment periods for all reporting tags are shown in Table 2. The daily mean displacement of all specimens was 4.0 kilometers (±0.7 km SE) per day. The northernmost location-reporting tag had the smallest mean daily displacement, (0.6 km) over the course of its 55-day tag attachment (Figure 6). Cobia can travel more than 10 kilometers per day, shown by two specimens, one that traveled a net of 43 kilometers over 4 days and another fish with 260 kilometers displacement over 22 days.

Habitat Utilization

Habitat utilization data were derived from the four X-Tags and two PTT-100 PSATs that transmitted temperature and depth data recorded in 15- or 30-minute intervals. Data recoveries for these tags ranged from 21% to 72% of the transmissible data. Daily minimum and maximum temperature data were also received from 18 WC mrPATs, but the following habitat utilization analyses are based on the 6 MTI tags unless otherwise noted.

Temperature Habitat Utilization

The maximum and minimum recorded temperatures of water occupied by cobia were 30°C and 12°C, respectively. Raw and weighted distributions of all temperature observations are shown in Figure 7. The raw distribution (Figure 7, upper panel) includes all temperature observations for times when PSATs remained attached to cobia. The weighted distribution (Figure 7, lower panel) shows temperature observations when data from each tag were given equal weight over the entire deployment period. These temperature distributions are limited, as they only include data collected from August through March, and are skewed by a greater number of tags reporting data for the months of September and October (Figure 8). These raw and weighted distributions look virtually identical, but a chi-square test comparing the distributions shows that they are significantly different ($p < 0.05$). A more useful figure is the boxplot depicting mean temperatures by month and the temperature range boxes representing the middle 50% of all observations (Figure 9). Data show decreasing monthly mean temperature of occupied water from 27°C in August to 19°C in February. Breakdowns of monthly temperature distributions are presented in Figures 10 & 11. Temperature observations were also grouped into distributions by month to assess diurnal differences and lunar effects on habitat temperature (Appendices 2 & 3). Diurnal and moon phase groupings did not show any meaningful difference between temperatures occupied during the day or at night, or when comparing observations grouped by lunar phase.

Temperature data collected from the mrPATs are shown in Figure 12, depicting the daily minimum and maximum temperatures occupied each day for all 18 tags, with values ranging from 16°C to 30°C. These data show a strong likelihood for cobia to occupy waters at least 20°C.

Depth Habitat Utilization

The maximum and minimum recorded depths occupied by cobia are 118 meters and 0 meters, respectively. Raw and weighted distributions of all depth observations from the X-Tags and PTT-100 PSATs are shown in Figure 13. The raw distribution (Figure 13, upper panel) includes all depth observations for times when PSATs remained attached to their specimens. The weighted distribution (Figure 13, lower panel) are the depth observations when data from each tag were given equal weight over the full deployment period. These depth distributions were limited in that they only include data collected during the months of August through March and were skewed by a greater number of observations for the for the earlier months of the study. The raw and weighted distributions appear virtually identical, but a chi-square comparison indicated the distributions are significantly different from one another ($p < 0.05$). Comparisons of raw and weighted observations by month are shown in Appendix 4. A more useful figure is the boxplot depicting mean depth by month and the depth range box representing the middle 50% of all observations (Figure 14). The boxplot shows decreasing monthly mean depth of 3.8 meters in August to 32.1 meters in February. Depth observations were also grouped into distributions by month to assess diurnal and lunar differences (Appendix 5). These distributions do not show any meaningful difference between depths occupied during the day or at night, or when comparing depths grouped by lunar phase each month. Minor differences in the depth distributions by monthly lunar phase are more likely attributable to seasonal progression and weather changes than to behavioral changes associated with lunar cycles. To assess differences between individual cobia, box plots of depths occupied by each fish are broken down by month (Figures 15 and 16).

There was a strong seasonal association with the surface (Figures 17 and 18) in that 38% of depth observations from the month of August were in the top one meter of the water column. This value drops to 25% in September, 6% in October, and less than 2% for the months November through February.

Discussion

This study sought to aid management by providing critical information on cobia migration, post-release survival, and habitat utilization, and it was successful in achieving those objectives.

Tag Deployment

There are a handful of PSAT manufacturers offering a variety of tag models with prices ranging from as low as $600 to more than $4,000. The non-trivial expense of these tags necessarily limits sample sizes of studies conducted with them. My study attempted to optimize grant funding and existing resources to maximize the potential sample size.

Of the 41 available PSATs, 36 were deployed to study cobia movement, survival, and habitat utilization. A number of factors (weather, vessel availability, fish catchability) prevented all PSATs from being deployed. Although cobia are known to be present in Virginia waters as early as late May each year, tagging efforts were not initiated until August (during the last weeks of the Virginia recreational cobia fishing season) to minimize the likelihood of tagged fish being recaptured. Even so, we received reports that 2 of our tagged fish were recaptured in Virginia waters within two weeks of tagging. One fish was released with its X-Tag intact, but that PSAT did not report. The second recaptured fish was harvested, and the angler was kind enough to return the mrPAT tag to ensure full data recovery.

Tag Reporting and Performance

PSATs are extremely useful tools for studying large, migratory marine species, but there are challenges with the technology. Data recovery from our PSATs was less than ideal, largely resulting from non-reporting and early reporting tags, although transmission delays also played a role. All three PSAT models used had some technical or mechanical challenges. Of the 26 mrPATs, 1 reported after a full-term deployment, 1 fish was harvested, 16 reported early, and 8 did not report. Of the seven X-Tags, one reported early, three reported five to nine days late after full-term deployments, and three did not report. Of the three PTT-100s, two separated early and one was delayed 13 days in reporting after a full-term deployment. Analysis of the data from the 19 PSATs that released from the fish prior to their programmed release date did not provide many insights as to why the tags released prematurely.

Relative to previous PSAT studies in our laboratory (Graves et al., 2002; Graves et al., 2009; Graves & Horodysky, 2008; Graves & Horodysky, 2010; Horodysky et al., 2004), we were surprised by the high number of non-reporting tags and low data recoveries in this study. Our results, however, are not out of character with other studies using PSAT technology. Musyl et al.'s (2011) meta-analysis of 731 deployed PSATs on 19 species showed an average tag reporting rate of 79%, and only 18% of reporting tags remained attached to their specimens for the programmed duration. Our study had 69% reporting rate (25/36) with 20% of reporting tags attached for the full duration (5/25).

The premature reporting of 16 mrPATs was particularly surprising. Transmissions indicated that all 16 of these tags were identified as "floaters" by the tag's programming, and the release-transmit sequence was initiated. It is probable that some of these tags separated from the fish before the conditional release feature was activated, similar to what occurred for one X-Tag and one PTT-100. Several mechanical issues could be responsible for early separation, including possible failures with the anchor, tether, nose cone, or release wire. Another likely possibility for early reporting mrPATs stems from a limited understanding of the mrPAT conditional release feature and cobia vertical movement patterns. Depth data showed that cobia spend 38% and 25% of their time in the top meter of the water column during the months of August and September, respectively. Of the 16 premature premature releases, 9 occurred during these months; another 4 premature releases occurred in October, and 3 in November. It is plausible that a cobia basking very near the water's surface would allow the top of the tag to float above the surface for an extended period. As the default conditional release setting for mrPAT tags is activated when the conductivity sensor reads "dry" for a total of only 6 minutes in any rolling 2-hour window, it is possible that the conditional release may have been activated as fish basked near the surface. This would begin the release and data transmission sequence. It is not possible to determine if any of these 16 tags were attached to the fish at the time the release sequence was initiated. Three of the prematurely-released tags washed up on North Carolina beaches and were found by beachcombers. All three tags lacked the tether, anchor, and nosecone, which would have been jettisoned as part of the release sequence. None of the recovered tags exhibited any physical damage suggestive of tag predation.

The mrPAT model is one of the more cost-effective PSATs to analyze fish movements, and I recommend changes to deployment methods for future cobia studies. The default release settings should be changed to require a greater dry (15-30 minutes in a 2-hour window). A shorter tether should also be used to keep the PSAT closer to the fish, minimizing the possibility of air exposure; 8-10 centimeters should be sufficient tether length to set the anchor deep enough into pterygiophores without resulting in the PSAT being too close to the fish and inhibiting device movement as the fish swims. The mrPAT tag is very new in general, with only two published studies. One study reported 100% success with 18 tags attached to Greenland sharks (*Somniosus microcephalus*) with programmed deployment durations of up to 45 days (Hussey et al., 2018). The second study deployed 10 mrPATs on Japanese eels (*Anguilla japonica*) with varied programmed durations up to 121 days and had 4 premature reports and 6 “lost” tags (Chen et al., 2018). Our 31% non-reporting rate is much worse than the 0% non-reporting in the Hussey et al. (2018) study, but better than Chen et al.’s (2018) 60% of tags lost.

Three of seven X-Tags remained attached for the full programmed six-month deployment period, but all three of these were delayed in reporting even though release was initiated after 6 months as programmed. The depth data suggest that the PSATs remained attached to the fish for five to nine days after activation of the release sequence, followed by a rapid rise to the surface and immediate successful transmissions. This leads to the conclusion that the release wire was not fully corroded for several days after initiation of the release mechanism. No satisfactory explanation for this delay will be found unless the tags are recovered. The delay in separation from the specimen after release initiation resulted in tags transmitting underwater to no avail, consuming battery power. Once the tags surfaced and were able to successfully transmit, the limited battery life resulted in reduced data recovery. Other researchers have had similar problems with tag reporting, and tagged bluefin tuna (*Thunnus thynnus*) and striped bass (*Morone saxatilis*) have been recaptured with an undamaged, non-reporting X-Tag still attached (Lutcavage et. al, 2015; Graves and Horodysky, unpublished data). This reporting malfunction was noticed in the first year of this study, and combined with cost (to maximize sample size), was a major factor in the decision to purchase mrPATs rather than more expensive PSATs, such as the X-Tag.

All three of the PTT-100s reported after six months as programmed, but there were substantial data recovery challenges for two of the tags. Because the PTT-100 constant depth release has a pressure sensitivity ±10 m, it was almost certain to result in premature releases while cobia were in the shallow Chesapeake Bay and coastal Virginia waters. To avoid this problem, we chose to not activate the constant depth release on these tags, but by doing so, we would only get a report from the tag at the end of its 6-month deployment, regardless of whether it was still attached to a fish or not. Of the two PTT-100s with reporting issues, one tag reported at the programmed time, but its transmissions were so few and without reliable location that no useable data were recovered. This tag likely separated from the fish prematurely, was beached, and/or was at least partially covered by debris, hampering effective transmissions at the end of six months. The other tag did not report until 13 days after its programmed release date. The most probable explanation for the reporting delay is that the tag released from the fish on time but encountered debris that interfered with the antenna as it rose to the surface. When the tag successfully transmitted, the remaining battery life was limited and only 44% of the transmissible data were received.

Although this study encountered many challenges with PSAT data recovery, the devices remain one of the most effective methods for obtaining fishery-independent data on mortality, location, and habitat utilization. PSATs were the best tool available for this study, and remain one of the best options for future studies (Thorstad et. al, 2013).

Post-Release Survival

This is the first study of post-release survival of cobia caught in the recreational fishery, and the results validate angler anecdotes that cobia is an extremely hardy species. Zero mortalities were detected from 24 data reporting tags. NOAA's SEDAR 28 (the 2012 federal cobia stock assessment) estimate of 5% mortality for cobia management purposes (SEDAR 28, 2013) falls on the upper end of our 0% to 5% confidence interval obtained using the 20 tags that were attached for at least 10 days.

There are no previous estimates of cobia post-release mortality with which to compare our results. Bartholomew & Bohnsack's (2005) meta-analysis of post-release mortality included 20 saltwater species, 6 of which had mean post-release mortalities of less than 10%, but post-release mortalities exceeding 50% were observed for some species. Another application of PSATs on red drum (*Sciaenops ocellatus*) caught in the Chesapeake Bay detected 0 mortalities from 17 reporting tags (Graves & Horodysky, unpublished data). Our 0 detected cobia mortalities from 24 specimens is clearly a low-end mortality observation, but it is within the reasonable set of expected outcomes given mortality estimates from other teleost studies.

One limitation of using PSATs to assess post-release mortality is the ambiguity in differentiating a prematurely released tag from a floating deceased specimen. It is not possible to detect a difference between a cobia basking near the surface (an activity suggested by depth observations) causing premature mrPAT detachment and a deceased specimen that floated. The proportion of moribund cobia that sink is unknown. One study of teleost fishes discarded from prawn trawls, 0 – 55 meters deep, reported approximately half of the deceased fish floated and the other half sank (Hill & Wassenberg, 1990). Our study assumes a deceased specimen would sink as most cobia in the Virginia recreational fishery are caught near the surface or from depths less than 10 meters, minimizing the likelihood of swim bladder over-inflation and subsequent floating.

Another important assumption for post-release mortality estimates is that specimen handling is representative of typical recreational practices. Angling for this study was done solely by research volunteers using methods of their choosing, not directed by the researchers. One aspect of potential bias, however, is that volunteer anglers are likely self-selective among sportsmen for practicing better-than-average care for their target specimens. Several fish were deep-hooked, but all cobia were treated with care; the line was cut and the hook was left in the fish's esophagus or gut. Not all anglers treat their released fish with such care, or are willing to "lose" a hook in a released cobia. Even though all cobia were treated with respect by anglers, all specimens in this study experienced the additional trauma of tag anchor insertion followed by the increased energetic demand of towing a PSAT. We contend that our overall handling procedures can be assumed reflective of cobia handling by the Virginia population of recreational anglers.

Non-reporting tags complicate estimates of post-release survival. Most studies have not included them in estimates of post-release survival, although a few of these have also reported "conservative" estimates of post-release mortality, considering non-reporting tags as mortalities (Musyl et al., 2011). We excluded all non-reporting tags from our mortality estimates for consistency.

This first study of cobia post-release mortality confirms that cobia is a hardy fish with low rates of post-release mortality when handled quickly and respectfully. Management's estimate of 5% cobia post-release mortality is corroborated as reasonable given our 0% to 5% confidence interval.

Movements

The high rate of non-reporting PSATs and large number of premature releases prevented a robust delineation of cobia overwintering grounds. The received data, however, provide considerable insights into the timing and movements of Virginia cobia as they undertake their fall migration south and offshore. Previous analyses of conventional tagging data have highlighted movements of cobia north and south along the Atlantic coast, but because tagged cobia are generally recovered by recreational fishermen and most recreational trips are close to the coast, these analyses have provided limited information on inshore/offshore movements.

My results show consistent fall offshore movement with simultaneous occupation of greater depths. All 8 tags that reported locations after 15 November were greater than 15 km from shore (mean 61.7 km), while all 14 tags that reported prior to 15 November were less than 15 km (mean 7.7 km) from the nearest coastline. The seasonal offshore movement of cobia is consistent with the results of recent acoustic studies that note a conspicuous absence of cobia reports from inshore receivers during the months of December through March (SEDAR 58, 2018). Young et al. (2018) tagged 146 cobia with acoustic transmitters and received reports in spring, summer, and fall months on multiple receivers, the majority of which were within 15 km of shore. The absence of acoustic reports in December through March indicate that cobia are in areas void of acoustic receivers, consistent with offshore movement.

The one fish in this study known to have traveled to Florida illustrates that some cobia found in Virginia waters in the summer do make extensive seasonal migrations. This individual has garnered extra attention because the Georgia – Florida state boundary has been the management stock demarcation since 2015. If one only considers the PSATs that remained attached for the full six-month duration, one in five fish traveled across the current management boundary. While this sample size is insufficient to make any quantitative inferences, it is noteworthy. Given recent management changes, uncertainty about cobia stocks, and active angler participation in management, this single occurrence is enough to fuel a debate about how many cobia from the northern portion of west Atlantic cobia stocks migrate such distances. Conventional tagging since the 1980s demonstrates that only about 3% of cobia tagged in Virginia waters travel as far south as Florida (Perkinson et al., 2018). These conventional tagging statistics, however, are dependent on the timing and location of angling pressure, and the cooperation of anglers to report tag recaptures. A recent study in which 13 cobia, caught in Virginia waters, were implanted with acoustic transmitters reported the presence of one of the tagged fish in waters offshore of Florida. This fish was offshore of the fixed array receivers, but was detected by a Bureau of Ocean Energy Management autonomous wave glider (Weng et al., 2018). Taken together, this observation and the one long distance movement I observed may suggest that cobia cross the current management boundary more often than indicated by historical tagging data. Further study is needed to determine the porosity of the current management boundary.

The PSAT data in this study show that cobia can move quickly. Across all individuals, the average daily displacement was 4.0 km per day, with some cobia exceeding 10 km per day. No comparable horizontal movement studies have been reported on cobia, but one study of a cobia relative, the dolphinfish (*Coryphaena hippurus*), showed a daily mean horizontal movement ranging from 2.4 to 29.1 kilometers per day over PSAT attachment periods up to 120 days (Merten et al., 2016). These numbers are slightly higher but comparable to the figures reported in our study of mean net daily cobia horizontal movements ranging from 0.6 to 11.8 kilometers (dolphinfish are pelagic and movements are likely aided by travel with ocean currents such as the Gulf Stream). Precisely how far cobia swim in a given period remains unknown, however, as these are minimum straight-line averages. It is plausible that cobia may swim a total of tens of kilometers per day, or more.

The light data provided by MTI tags have been used in other studies to describe in greater detail the likely travel paths of fish undertaking large-scale movements (Sippel et. al, 2015; Lutcavage et. al, 2015). Light-based geolocation analyses were not included in my study, as it is believed that the effort would not provide any useful insights into cobia movements. This is primarily due to the large geolocation error associated with light-based estimates and the relatively small displacements noted by tag reporting locations. Even the best available methods for filtering light and environmental data to determine location has typical errors greater than 100 km (Braun et al., 2017). Errors this large make it impossible to determine when cobia are crossing state boundaries, or to assess whether cobia are associating with shorelines or the continental shelf break. Furthermore, cobia occupy nearshore waters with high turbidity and may not approach the surface for extended periods during the colder months, making sunrise and sunset determinations needed for location estimates less accurate than observations from pelagic species in clearer surface waters. With no net displacements exceeding 1,000 kilometers, and only 2 fish whose net displacement exceeded 500 kilometers, the margin for error in geolocating travel paths would not have provided meaningful insights.

More information is needed to understand cobia movements and continued studies should be encouraged (including conventional, acoustic, and other electronic tagging methods). Each method has its advantages and limitations. Conventional tag/recapture methods have the advantages of potentially large numbers of tags deployed for minimal cost and a strong likelihood to identify cobia movements relative to fishing pressure. The downside of these conventional tags, though, is that movement patterns not coincidental to fishing pressure will go unrecognized (Bolle et. al, 2005). Low recreational fishing pressure during winter months is part of the reason why we do not know more about cobia habits during this season. Acoustic tags are lower cost than PSATs and have the potential to generate numerous location reference points over multiple years, but they are limited to detection distances a few hundred meters from receiver arrays (Heupel et. al, 2006). These acoustic receivers are largely located in estuaries or within 15 km of shore (although a few arrays extend further), providing limited information when specimens are farther from shore. As such, acoustic tags cannot be expected to reveal cobia winter activity without greatly extending existing receiver arrays. PSATs are not hampered by spatial limitations of fishing pressure or acoustic receiver arrays, but they are very expensive and plagued with questions of reliability in reporting and data recovery (Musyl et. al, 2011; Lutcavage et. al, 2015). No perfect solution exists for studying cobia movements and migrations, but a combination of techniques will continue to improve collective knowledge of cobia populations.

Cobia found in Virginia waters in the summer migrate south and offshore for the fall and winter periods, but the full extent of their migrations cannot be fully understood with the available information. Cobia found in Virginia waters in the summer transition out of the area in late August to early October. Movement offshore is at least as important as southerly migration with specimens being found in February and early March near the continental shelf break offshore of North and South Carolina, and as far south as Florida. Of the 8 PSATs that reported after 15 November, 5 (including 3 of the 5 full-duration tags) were in waters offshore of North Carolina, near the continental shelf break, suggesting that these waters may be important overwintering habitat for cobia. It is likely that Virginia's summer cobia have additional winter ranges, and a combination of movement study methods are needed to further elucidate cobia seasonal migratory patterns.

Habitat Utilization

Prior to this study, very little information existed on cobia habitat utilization. The application of PSATs showed marked seasonal differences in habitat utilization for cobia found in Virginia waters in the summer. The observed increase in depth and declining water temperatures as the fall/winter season progresses corroborates the PSAT location data indicating that cobia move offshore. Cobia primarily occupy shallow waters in August and September and begin transitioning to deeper waters (offshore) in October with mean depths near 20 meters or greater being the norm for months November through February. Even though these observations are based on only six individuals, the behavior appears sufficiently consistent across fish to make generalizations. These results combined with anecdotes of winter cobia pods forming in deeper waters offshore of North Carolina may lead to increased angling pressure on a species infrequently targeted outside of the summer months. Very few studies have examined fish habitat utilization across seasons, but juvenile bluefin tuna (*Thunnus thynnus*) exhibit seasonal changes similar to cobia, occupying shallower waters in summer months and deeper waters in the cooler months (Galuardi and Lutcavage, 2012). When looking at the depths occupied by individual cobia across the study timeline, there are no stark differences between the fish that traveled to Florida (Figures 15 & 16, Fish C) and the other subjects.

The depth data also show that cobia spend a preponderance of time in the top meter of the water column in warm months (Figure 18). This is particularly of interest with the increased popularity of sight-fishing for cobia in the past decade (Burnley, 2011; Wittman, 2018). These data make it clear why sight-fishing is such a productive tactic when the target fish may be spending 40% of its time in the top meter of the water column where it is most susceptible to visually searching anglers. Why cobia spend so much time near the surface during the summer months is still unknown. Plausible hypotheses include aiding the digestive process in warmer surface waters, occupying waters with higher oxygen concentrations, visual silhouette cueing for spawning readiness, and enhanced feeding opportunities. It is certainly beyond the scope of this study to explain the cause, but the data clearly show a strong surface affinity in the summer, with October being a clear transition month.

The PSAT temperature data confirm that cobia are a warm water fish but able to tolerate cooler temperatures for short durations. The temperatures of waters occupied by cobia in this study ranged from 12°C to 30°C, similar to the temperature range of dolphinfish (*Coryphaena hippura*), which has been recorded at temperatures ranging from 16.2°C to 30.9°C (Merten et. al, 2014). Cobia show a clear partiality for waters near 20°C or warmer. Even in January and February, only 12% and 10% of received data, respectively, show cobia in waters 18°C or colder.

Anglers have known the importance of water temperature to cobia for quite some time. Most anglers don't even bother looking for cobia until the water temperature is at least 20°C (Burnley, 2011). The importance of water temperature also suggests that cobia range may expand and contract based on interannual temperature variability, expected to become more prominent based on the majority of future climate models (Parmesan & Yohe, 2003). Informal angler networks are now routinely reporting cobia in New York and New Jersey, where cobia appearances were formerly rare. Perhaps cobia fisheries may develop further north. Fishery managers should anticipate this possibility and be proactively involved to promote sustainability.

Future Research Recommendations

This first medium-term study of cobia with PSATs has revealed new insights but revealed even more unknowns of cobia behavior. Future cobia studies should focus on long-term, large-scale cobia movement patterns to identify stock definitions, spawning habits, and seasonal susceptibility to angling pressure. PSATs are useful tools to accomplish this research, but they are very expensive and have some reliability issues. They may, however, be the best tools available unless large scale investments are made in acoustic receiver networks. Without PSATs, this study could not have made any meaningful statements about cobia post-release survival or habitat utilization. Acoustic receivers could be the best available tool for a multitude of marine species movement studies but are lacking the spatial distribution necessary to truly understand the nature of cobia movements, especially since this and other recent studies show there is a clear offshore component of cobia migratory behavior in the winter months. PSATs are imperfect tools, but they may be the best technology available to study cobia's migratory nature. Using PSATs for longer (1- or 2-year) deployments may further elucidate population-scale migrations and possible spawning and wintering residencies.

Conclusions

Fishery managers have had the unenviable task of managing a species using extremely limited information. Prior to my study, there was no formal estimate of post-release mortality and an extremely limited description of cobia habitat utilization. Likewise, movement data were restricted to those provided by conventional tag returns. My results provide several new and useful insights into cobia behavior. Cobia are indeed a hardy species that can survive catch-and-release even with hooks lodged deep in their throats and the additional trauma of satellite tag anchor insertion. The observation of no post-release mortality (0% to 5% estimated confidence interval) in this study is undoubtedly below the actual value, but it suggests the 5% estimate assumed by fishery managers is reasonable. Knowledge of cobia movements and migrations is limited, but we are beginning to get a sense for when and where these fish travel. PSAT location reports combined with archived temperature and depth data show that cobia found in Virginia waters in the summer have largely left by October and occupy waters at least 15 kilometers offshore of North Carolina, South Carolina, and Florida during the winter months. A very small number of tags successfully reporting data after a full deployment prevent us from describing population-level overwintering grounds, but the evidence suggests that North Carolina waters near the continental shelf break may be one area of importance for wintering cobia. There may be other critical winter habitats, evidenced by cobia known to have traveled farther south, but more information is needed to say this with any certainty. It is clear, though, that offshore movements in winter are at least as important as north – south cobia movements. These movements are almost certainly temperature-driven, as cobia have a clear affinity for waters 20°C or warmer. They also display marked seasonal differences in water column depth utilization. The incredibly high proportion of time spent in the top one meter of the water column during the warmest months may make cobia too susceptible to exploitation given the growing prevalence of sight-fishing. It is abundantly obvious that more information about population-level cobia behavior is needed, especially given recent controversy surrounding the species' management. No perfect method for studying cobia exists, so a combination of techniques is needed to learn how to best manage this endearing sportfish.

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Table 1. Deployment data for all 36 PSATs deployed on cobia for this study. Unknown information marked with "UNK."

#	Tag Model	Deployment Date	Fish TL (inches)	Est. Weight (lbs)	Fight Time (minutes)	Air Exposure (minutes)	Hooking Location
1	X-Tag	8/12/2016	43	25	3:31	3:50	Superficial
2/C	X-Tag	8/14/2016	46	30	5:53	2:35	Superficial
3/D	X-Tag	8/17/2016	51	45	2:48	1:23	Superficial
4	X-Tag	8/17/2016	50	40	4:20	1:40	Superficial
5	X-Tag	8/17/2016	55	55	UNK	UNK	Superficial
6/B	X-Tag	8/20/2016	38	18	1:40	2:50	Superficial
7/A	X-Tag	8/30/2016	49	40	4:32	1:43	Superficial
8/E	PTT-100	8/25/2017	48	40	1:45	2:35	Deep
9/F	PTT-100	9/04/2017	50	40	0:45	2:00	Superficial
10	PTT-100	9/04/2017	51	45	15:00	2:00	Deep
11	mrPAT	8/03/2017	42	22	3:27	3:13	Superficial
12	mrPAT	8/03/2017	38	19	3:03	2:49	Superficial
13	mrPAT	8/03/2017	38	18	1:49	2:05	Superficial
14	mrPAT	8/05/2017	49	UNK	10:00	2:00	Superficial
15	mrPAT	8/06/2017	38	15	7:00	2:00	Superficial
16	mrPAT	8/09/2017	59	60	10:00	3:00	Superficial
17	mrPAT	8/09/2017	43	24	6:48	2:41	Superficial
18	mrPAT	8/10/2017	42.5	26	3:09	3:08	Superficial
19	mrPAT	8/10/2017	45	28	2:32	3:44	Deep
20	mrPAT	8/13/2017	38	18	2:10	2:02	Superficial
21	mrPAT	8/17/2017	40	21	UNK	2:00	Superficial
22	mrPAT	8/17/2017	42	22	3:13	2:41	Deep
23	mrPAT	8/19/2017	40	21	3:40	2:04	Superficial
24	mrPAT	8/20/2017	38	20	2:00	2:30	Superficial
25	mrPAT	8/25/2017	42	24	UNK	3:12	Superficial
26	mrPAT	8/26/2017	40	20	5:10	3:02	Superficial
27	mrPAT	8/26/2017	39.5	20	3:30	2:20	Superficial
28	mrPAT	8/27/2017	44	23	8:00	4:00	Superficial
29	mrPAT	8/27/2017	43	22	4:00	2:00	Deep
30	mrPAT	8/27/2017	42	21	2:00	3:00	Deep
31	mrPAT	9/03/2017	38.5	UNK	3:26	2:12	Deep
32	mrPAT	9/04/2017	42	UNK	5:00	2:00	Superficial
33	mrPAT	9/08/2017	39	19	2:38	2:59	Superficial
34	mrPAT	9/09/2017	39	15	3:10	2:07	Superficial
35	mrPAT	9/09/2017	38	18	2:10	4:22	Superficial
36	mrPAT	9/17/2017	39	18	4:37	2:05	Deep

Table 2. A summary of tag reports, including tag type, deployment date, fish size (total length in inches), deployment duration (days), net displacement (kilometers), and percentage of transmissible data received. * Indicates estimated displacement using approximate pop-up location. A dash represents no usable data.

#	Tag Model	Deployment Date	Fish TL (inches)	Deployment duration (# days)	Net displacement (kilometers)	Data %
2/C	X-Tag	8/14/2016	46	192	982	21
3/D	X-Tag	8/17/2016	51	188	203	45
6/B	X-Tag	8/20/2016	38	189	312	38
7/A	X-Tag	8/30/2016	49	81	250*	70
8/E	PTT-100	8/25/2017	48	86	-	72
9/F	PTT-100	9/04/2017	50	194	444	44
12	mrPAT	8/03/2017	38	40	59	100
16	mrPAT	8/09/2017	59	13	24	100
17	mrPAT	8/09/2017	43	55	34	100
19	mrPAT	8/10/2017	45	9	20	100
21	mrPAT	8/17/2017	40	99	721	100
22	mrPAT	8/17/2017	42	96	418	100
23	mrPAT	8/19/2017	40	11	48	100
24	mrPAT	8/20/2017	38	6	23	100
25	mrPAT	8/25/2017	42	180	459	56
26	mrPAT	8/26/2017	40	30	21	100
28	mrPAT	8/27/2017	44	5	25	100
29	mrPAT	8/27/2017	43	1	3	100
30	mrPAT	8/27/2017	42	4	43	100
31	mrPAT	9/03/2017	38.5	66	232	100
32	mrPAT	9/04/2017	42	32	175	100
34	mrPAT	9/09/2017	39	57	-	18
35	mrPAT	9/09/2017	38	33	-	100
36	mrPAT	9/17/2017	39	22	260	100

Figure 1. Pop-Up Satellite Archival Tags used in this study. Left to right: Microwave Telemetry Inc. PTT-100, Microwave Telemetry Inc. X-Tag, and Wildlife Computers mrPAT. Not to scale.

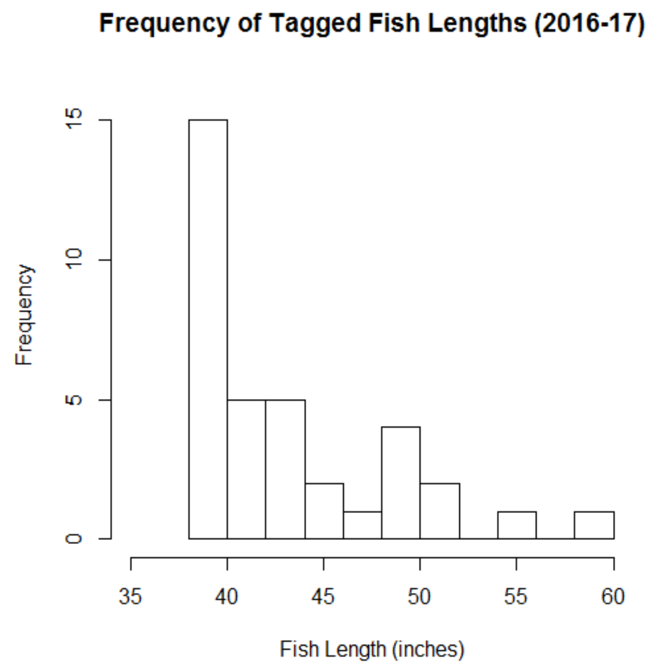


Figure 2. Total length distribution of cobia tagged with pop-up satellite archival tags. The preponderance of cobia tagged in this study fall in the 38 – 40 inch size class, although specimens up to 59 inches total length were included.

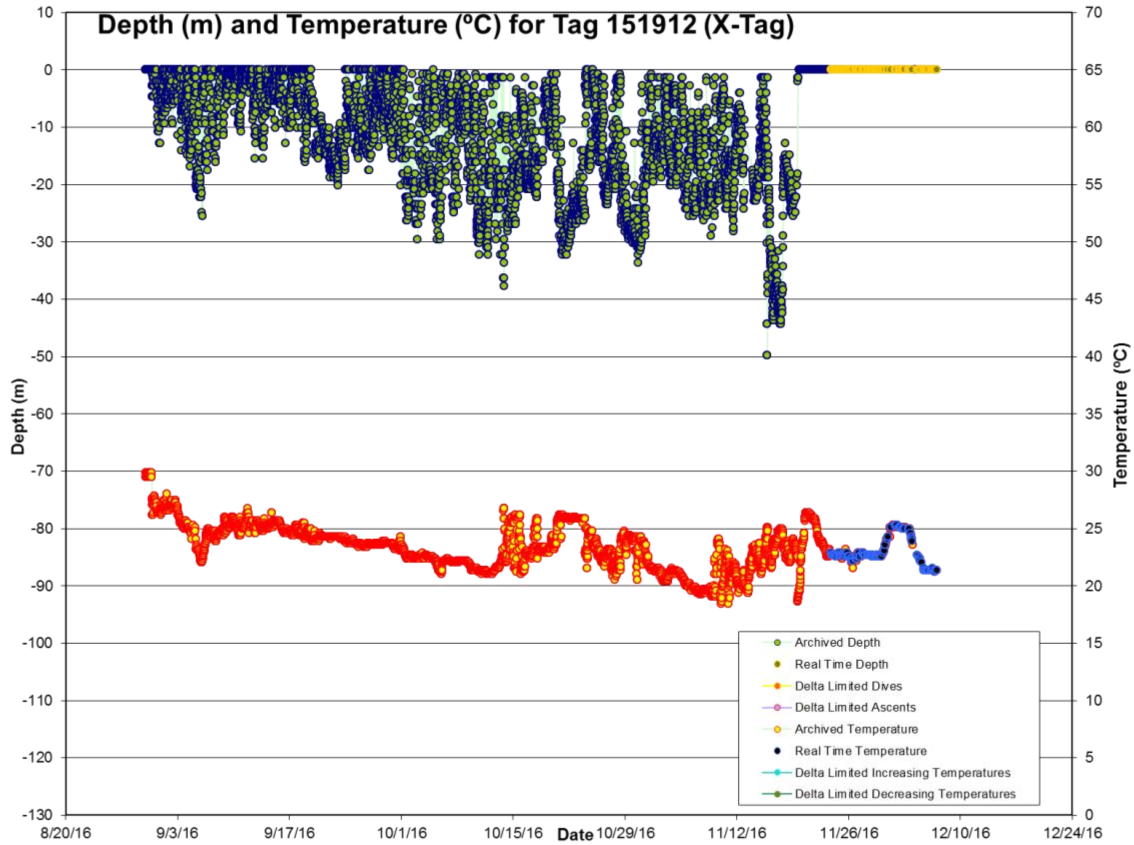


Figure 3. Example depth and temperature chart from a reporting MTI tag attached to a cobia. This chart is for X-Tag # 7/A, which reported 4 days after prematurely separating from its specimen on 19 November 2016. All reporting MTI tags evidenced a living fish, moving up and down in the water column, immediately prior to tag release.

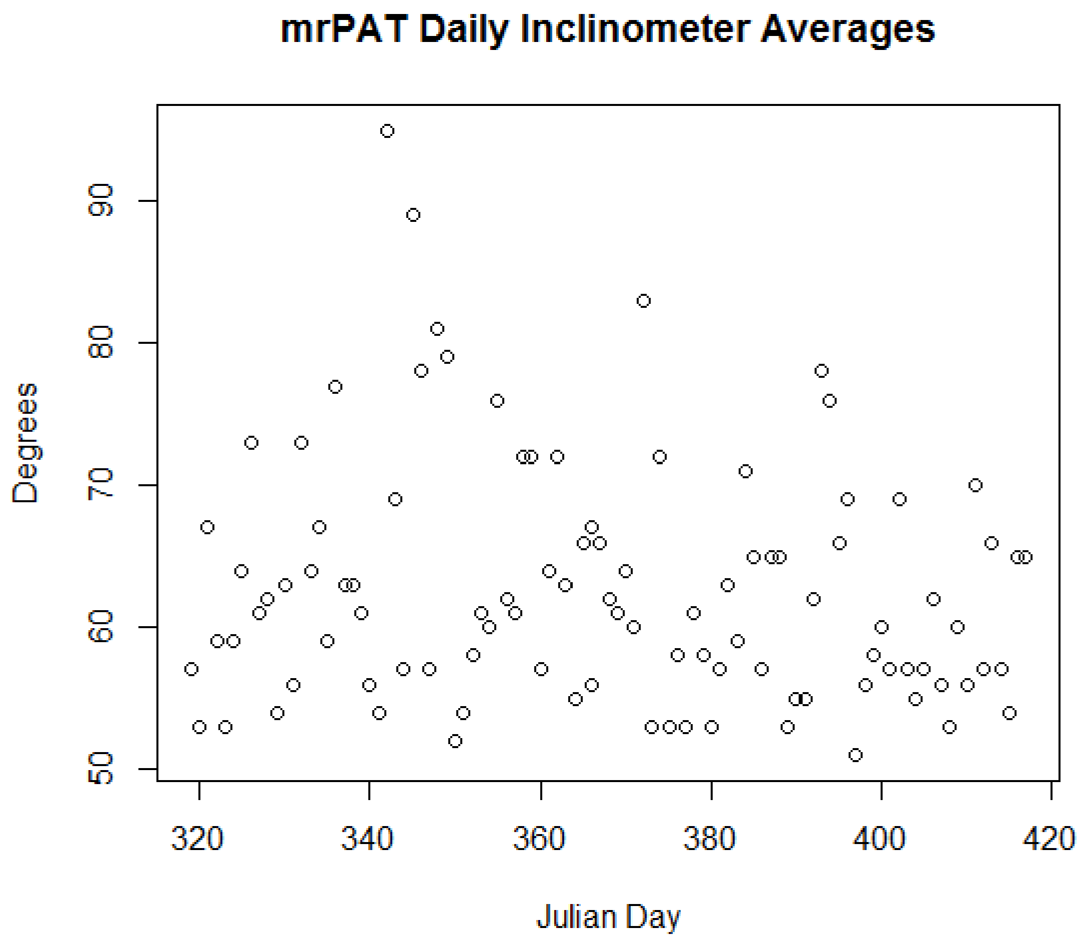


Figure 4. Scatter plot of inclinometer values for the only mrPAT that remained attached to a cobia for the full 6-month duration. This tag only reported the last 100 days of data. mrPATs report the average of the maximum and minimum inclination values each day. The range of values is 51° to 95° degrees from vertical (0°), with a median value of 61°. A tag attached to a moribund cobia is expected to report a near vertical value (0°) for the last day(s) of data collection. The lowest reported value among all tags for the day prior to tag release was 52° (Appendix 1), and the lowest reported value from all tags during the deployment period while attached to a specimen was 40°. This data can be used to infer that all cobia were alive at the time of mrPAT separation.

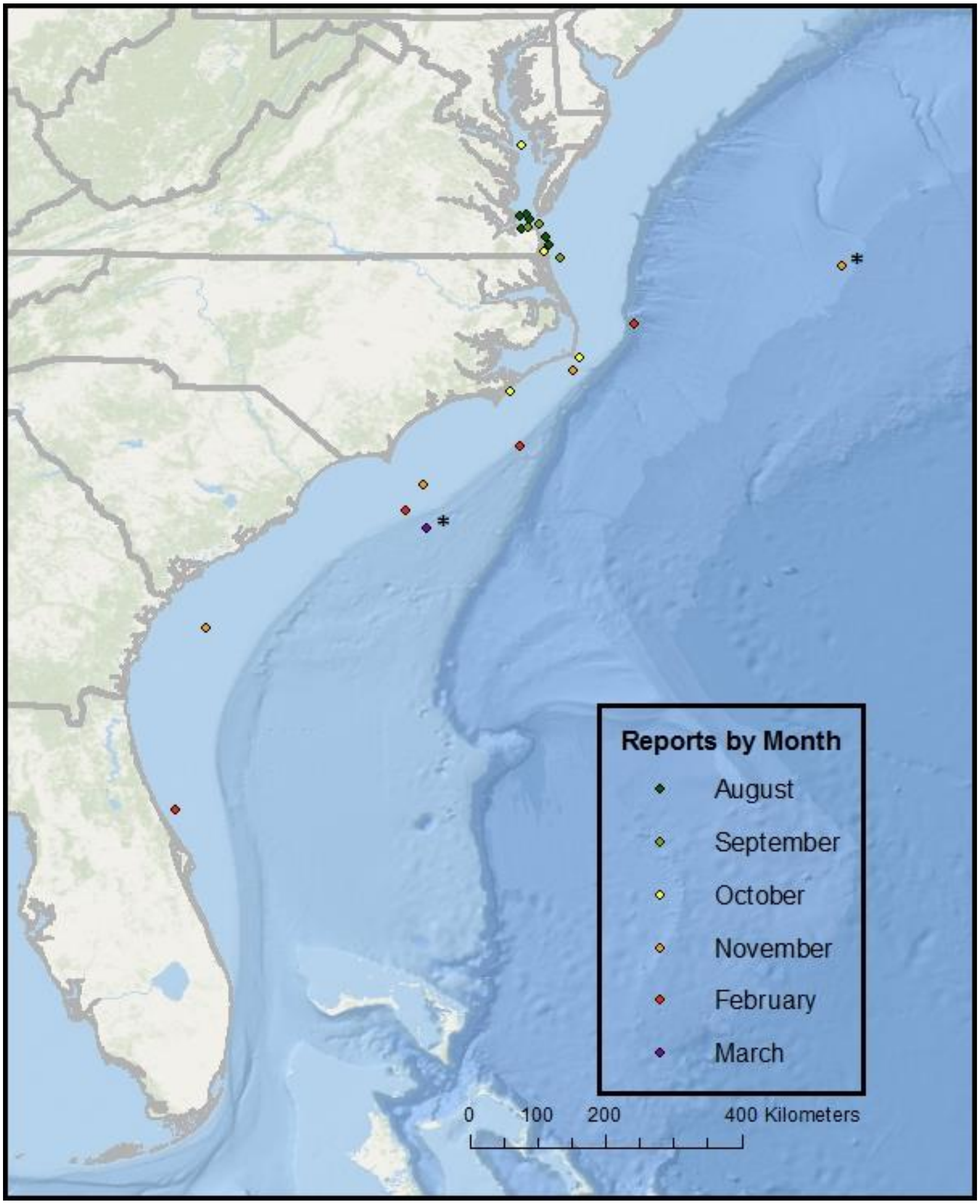


Figure 5. A map showing the first location reported by each tag. Each point represents one cobia tagged in Virginia waters, color-coded by its month of tag report. The orange (November) location marked with an asterisk (*) is the location marked by the X-Tag that floated on the surface for 4-days prior to giving this first location. The purple (March) location marked with an asterisk (*) is the first location given by the PTT-100 that floated for 13 days before being located; it is difficult to approximate the drift trajectory, although it is reasonable to infer that the fish was southwest of this point prior to tag release.

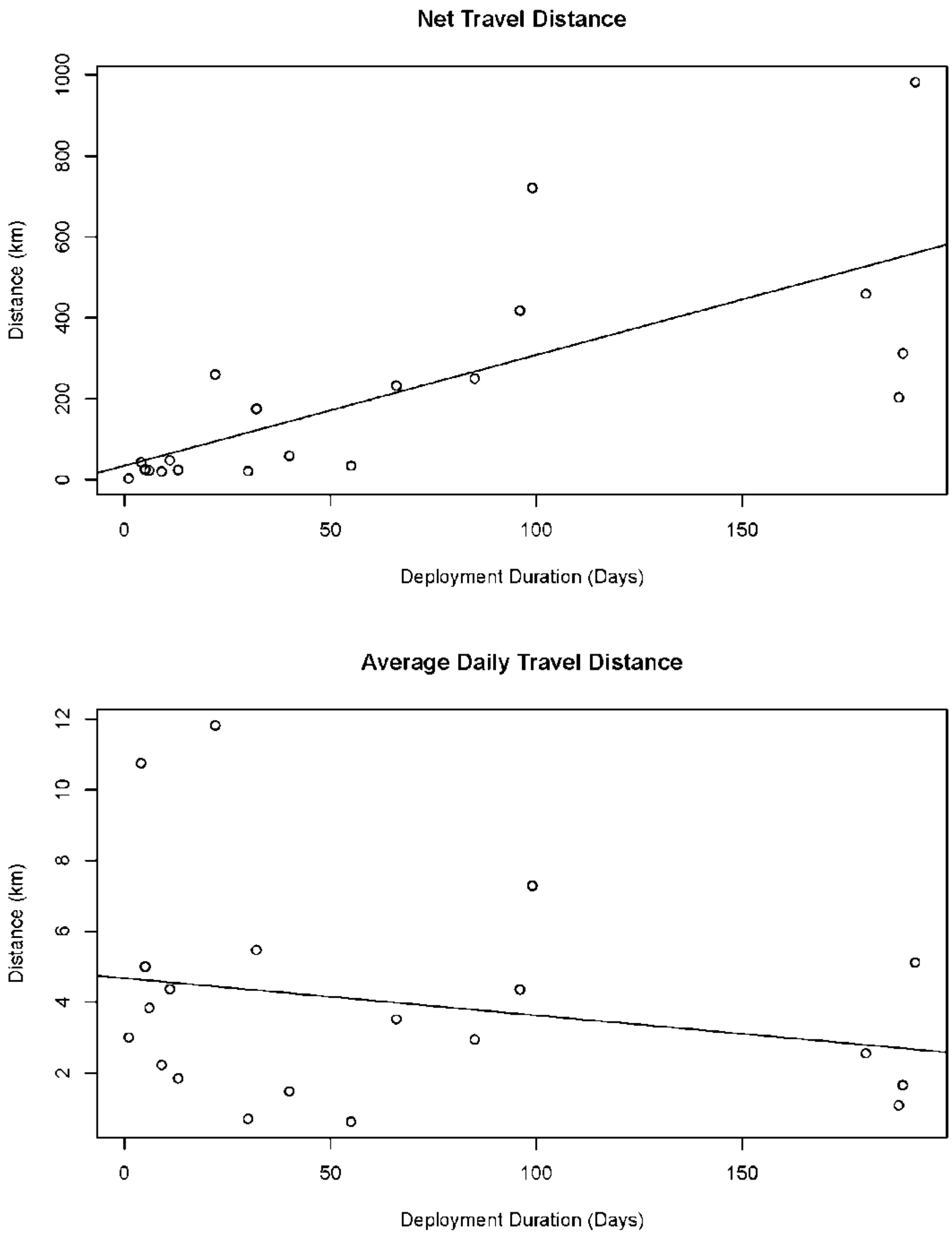


Figure 6. Net displacement of each tagged cobia plotted against the duration the tag was attached to the fish (upper panel) and the average daily net displacement of each fish (lower panel).

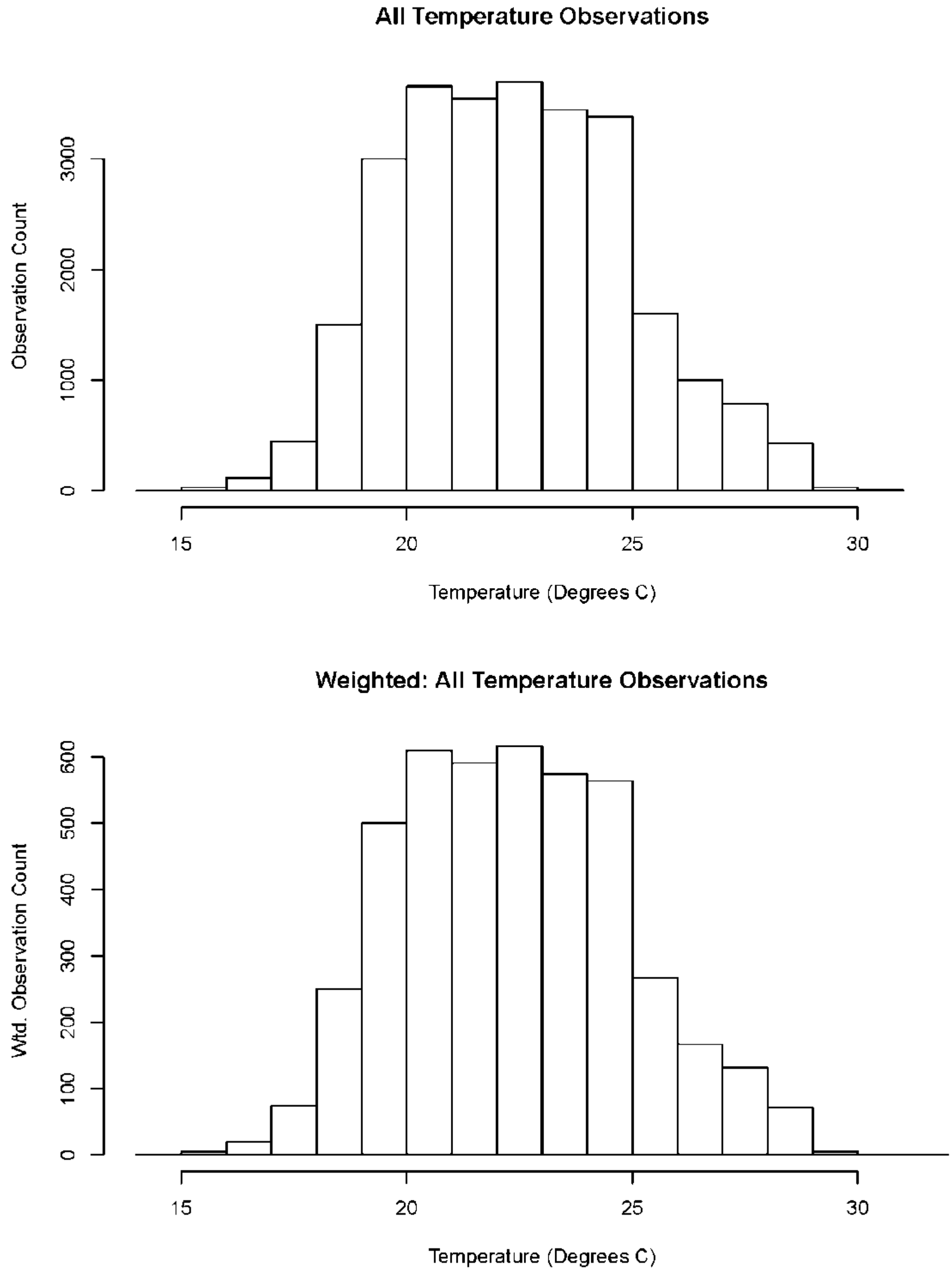


Figure 7. Raw (upper panel) and weighted (lower panel) distributions of temperature observations from all 6 MTI tags attached to a cobia. Data were weighted to minimize bias of tags reporting more/less data.

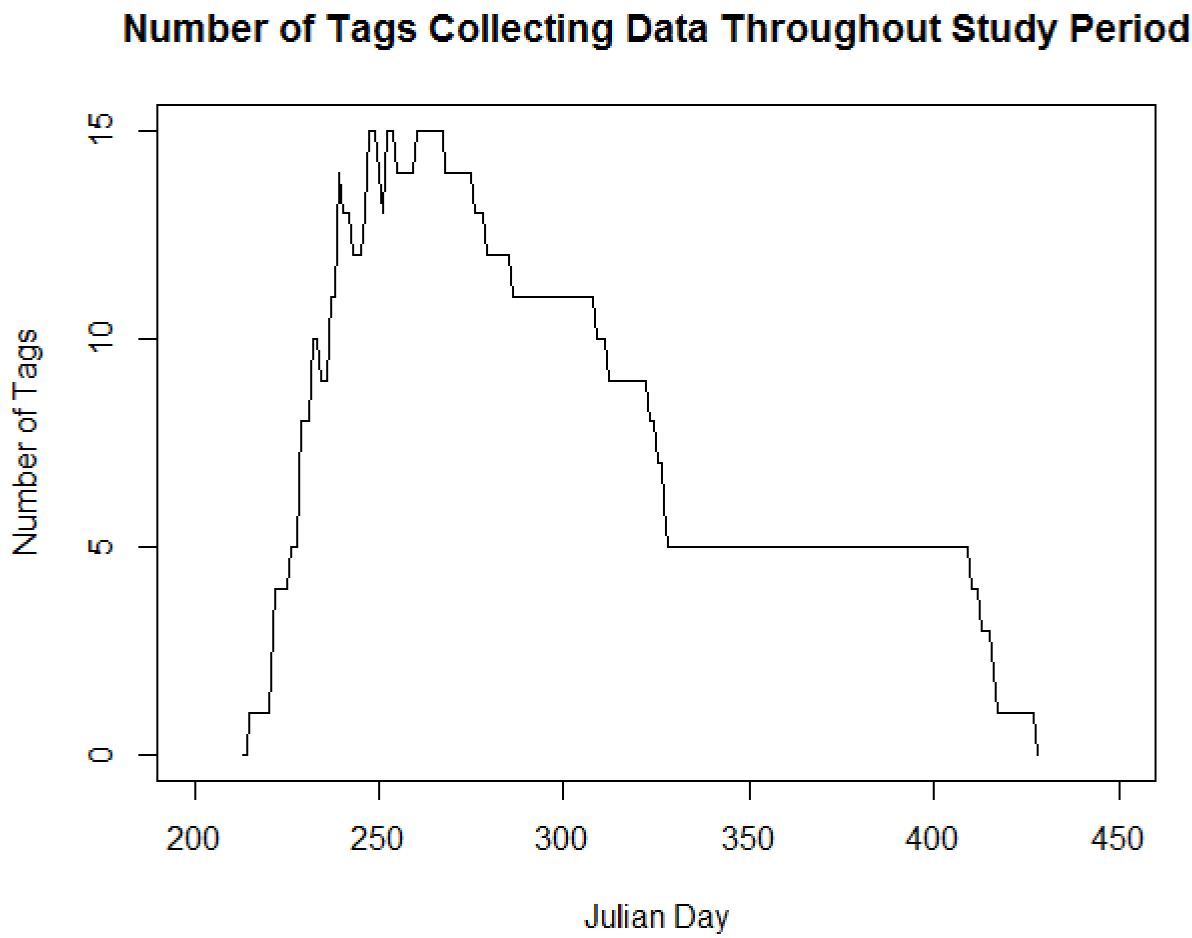


Figure 8. Plot of how many reporting tags gathered data over the study period. Many tags released prematurely, so there is much less environmental data for the later months than for September and October. A total of 24 tags reported, but due to the high number of premature reports, there were never more than 15 tags gathering data on the same calendar day.

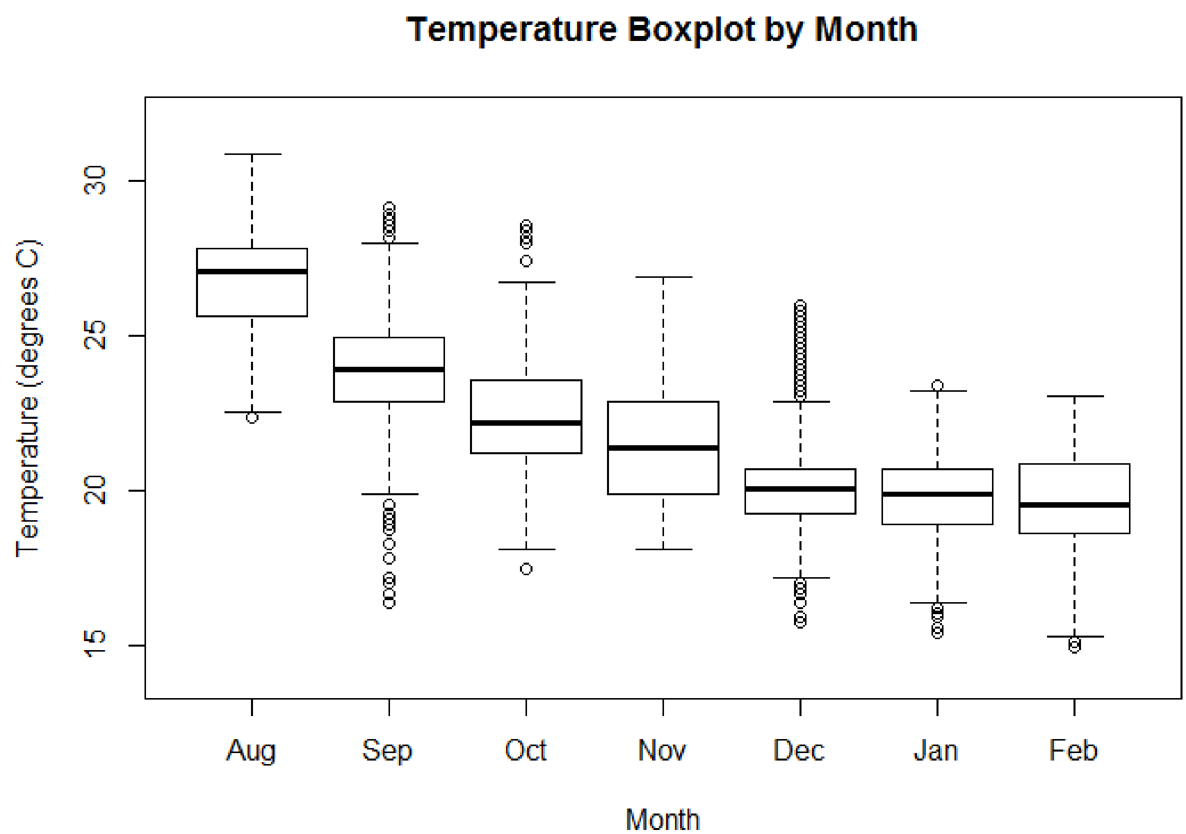


Figure 9. Boxplot of cobia temperature observations by month. The dark bar in each box is the mean of that month's temperature observations. The boxes encompass the 25th to 75th percentile of observations. The "whisker" lengths are determined by the lesser of the most extreme observation for the month or 1.5 times the inter-quartile range (IQR). The points outside the whiskers are all observations more extreme than 1.5 times IQR.

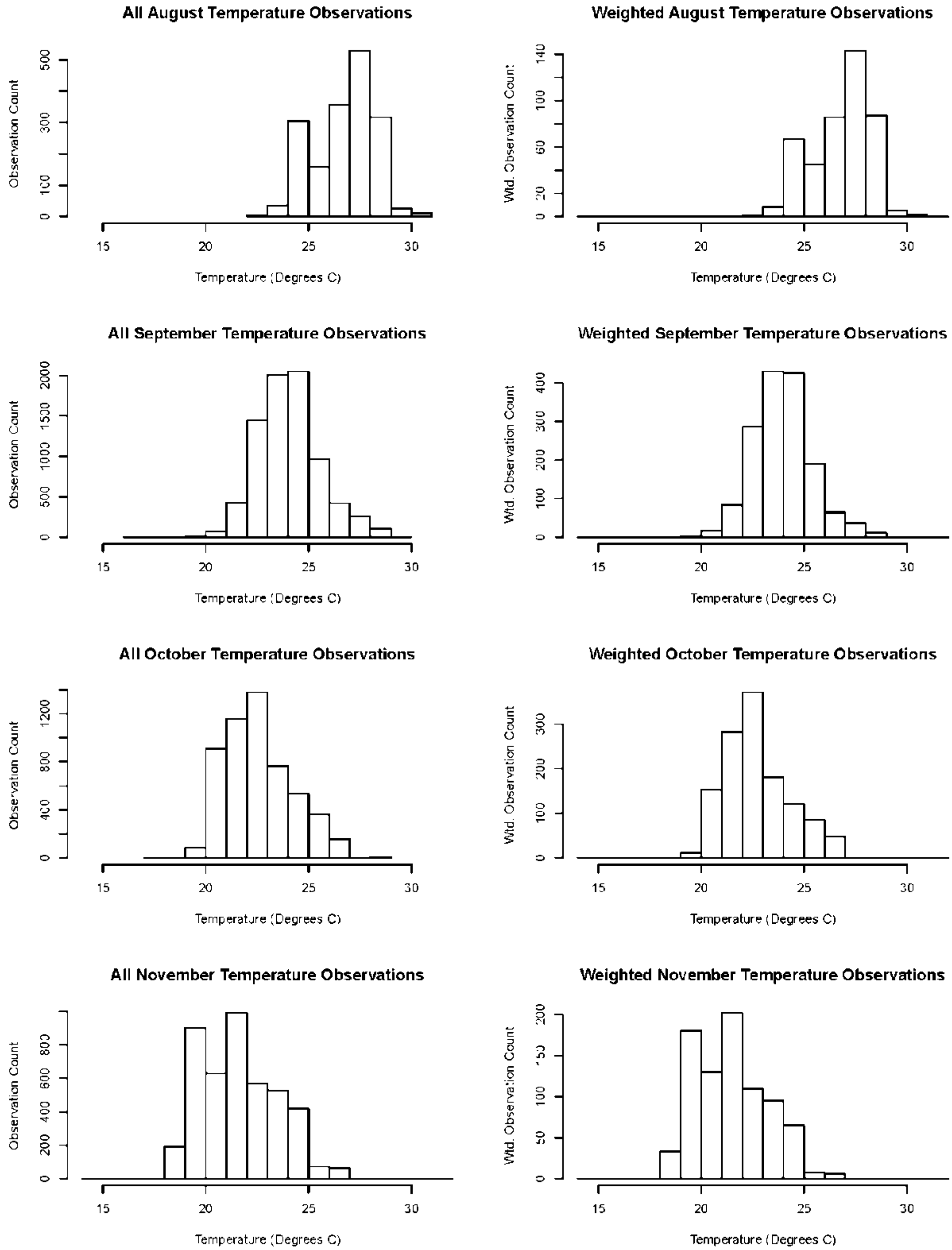


Figure 10. Raw and weighted cobia temperature distributions by month, August through November. Data were weighted to minimize bias of tags reporting more/less data.

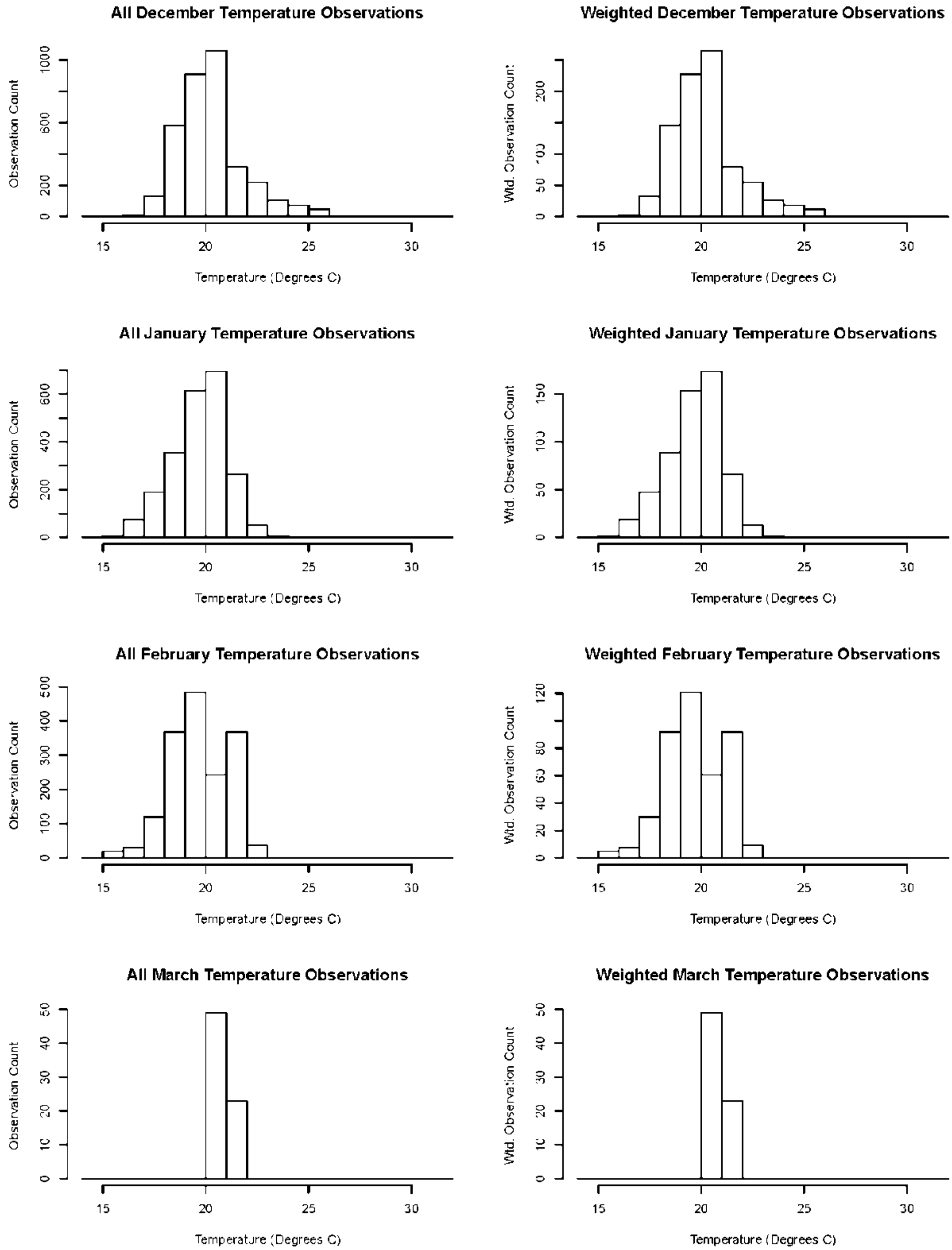


Figure 11. Raw and weighted cobia temperature distributions by month, December through March. Data were weighted to minimize bias of tags reporting more/less data.

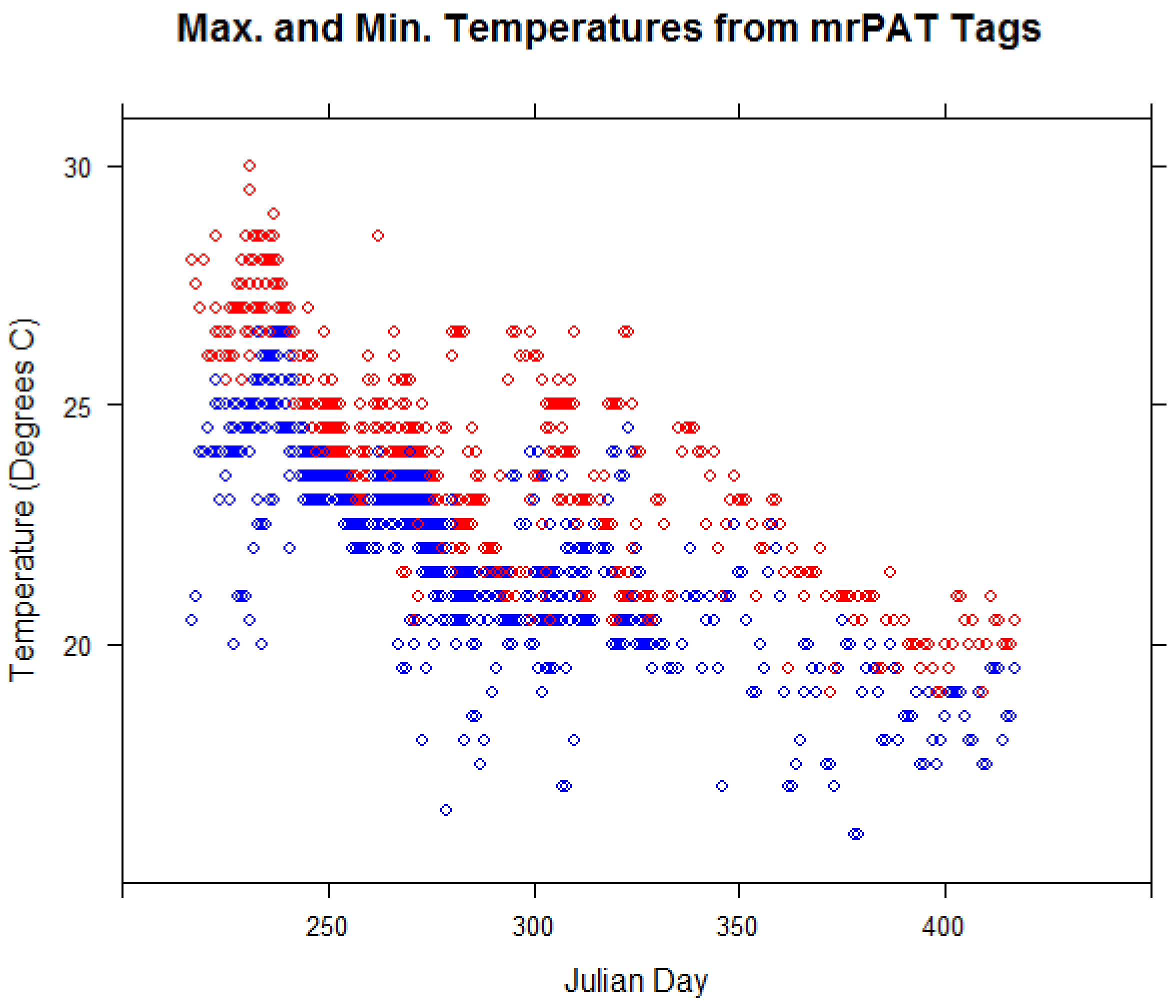


Figure 12. Daily maximum (red) and minimum (blue) temperatures recorded by 18 mrPATs attached to cobia. This figure uses only mrPAT temperature data. Daily maximum and minimum temperature observations are shown for each tag, so most days have multiple extreme observations. This is useful in showing the range of temperatures occupied by cobia throughout the study period.

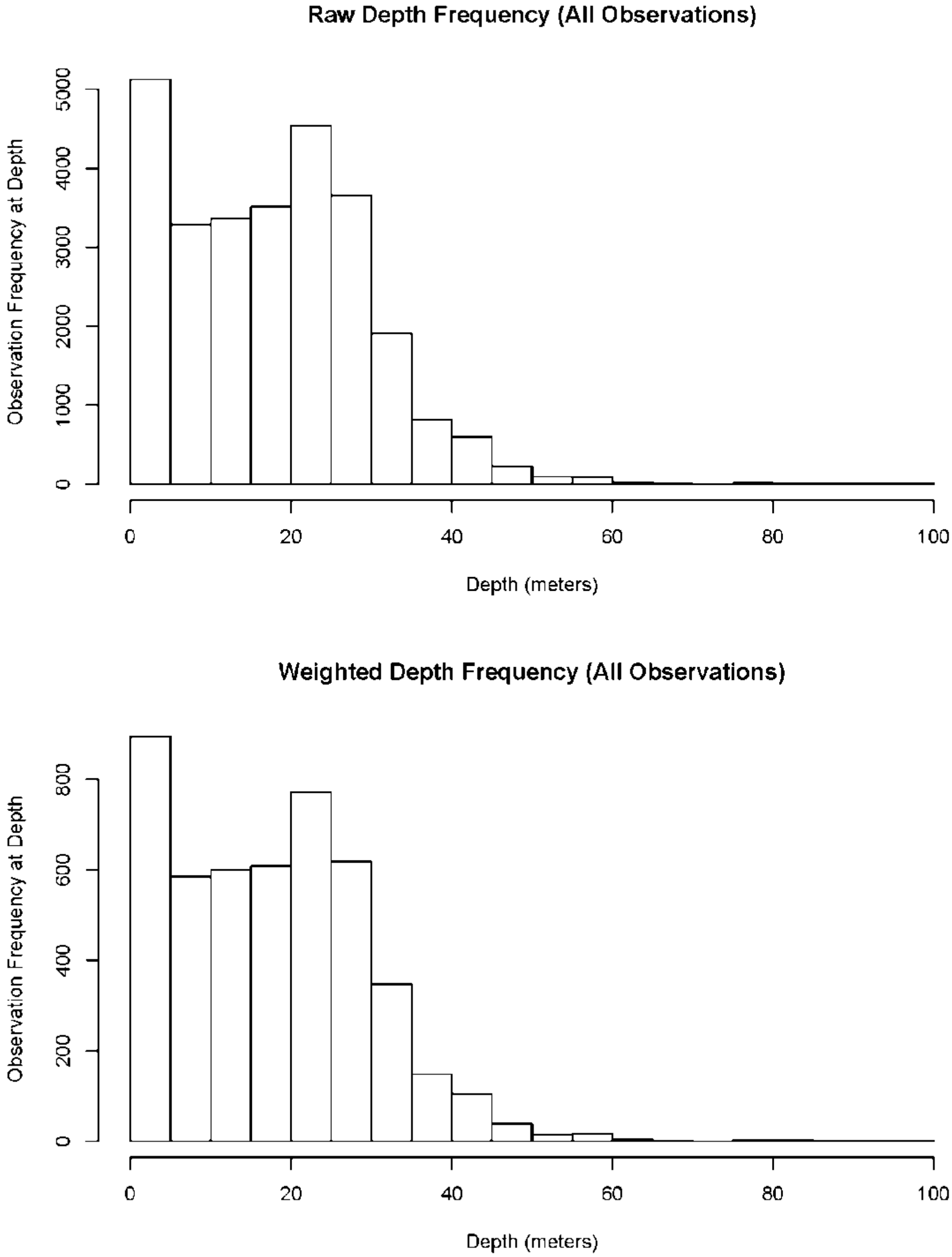


Figure 13. Raw (upper panel) and weighted (lower panel) distributions of cobia depth observations from all 6 MTI tags. Data were weighted to minimize bias of tags reporting more/less data. All 27,383 depth observations from the 6 reporting MTI tags were included. Four of the six tags reported 6-months of data, while two of the tags prematurely released in November.

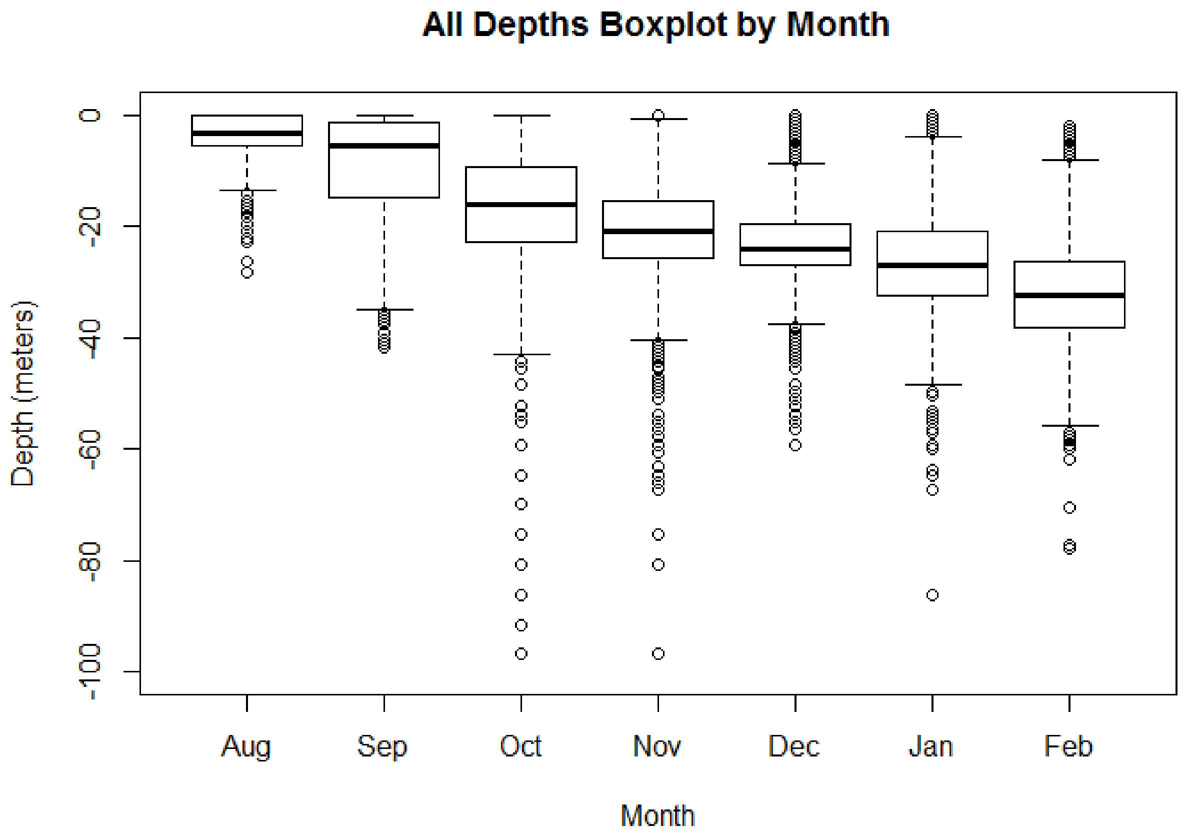


Figure 14. Boxplot of cobia depth observations by month. The dark bar in each box is the mean of that month's depth observations. The boxes encompass the 25th to 75th percentile of observations. The "whisker" lengths are determined by the lesser of the most extreme observation for the month or 1.5 times the inter-quartile range (IQR). The points outside the whiskers are all observations more extreme than 1.5 times IQR. Mean depth decreases each month from a mean of 3.8 meters in August to 32.1 meters in February.

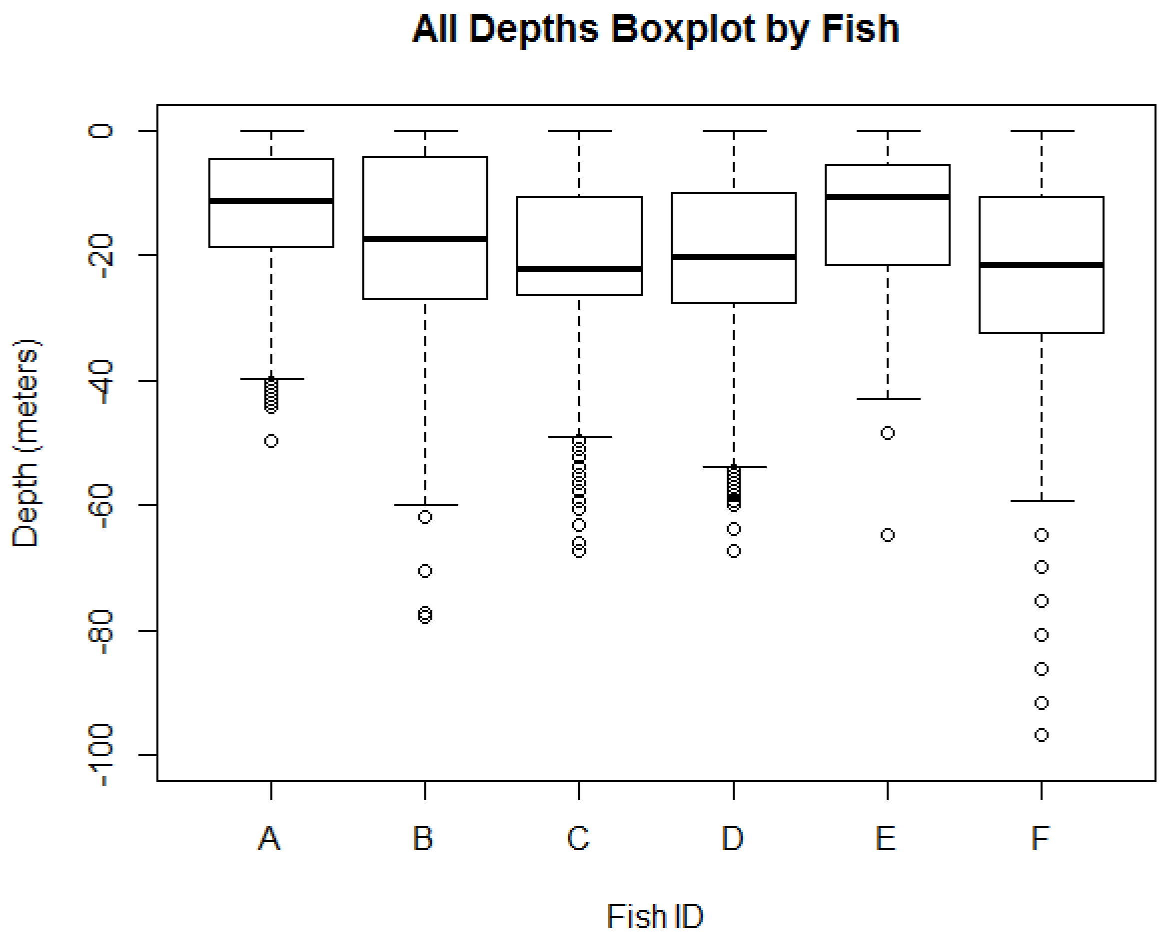


Figure 15. Boxplots of depth observations are shown for each cobia across all months that the tag was attached to the fish. Small differences in depth utilization appear stochastic without any clear pattern. Fish C is the specimen known to have traveled to Florida.

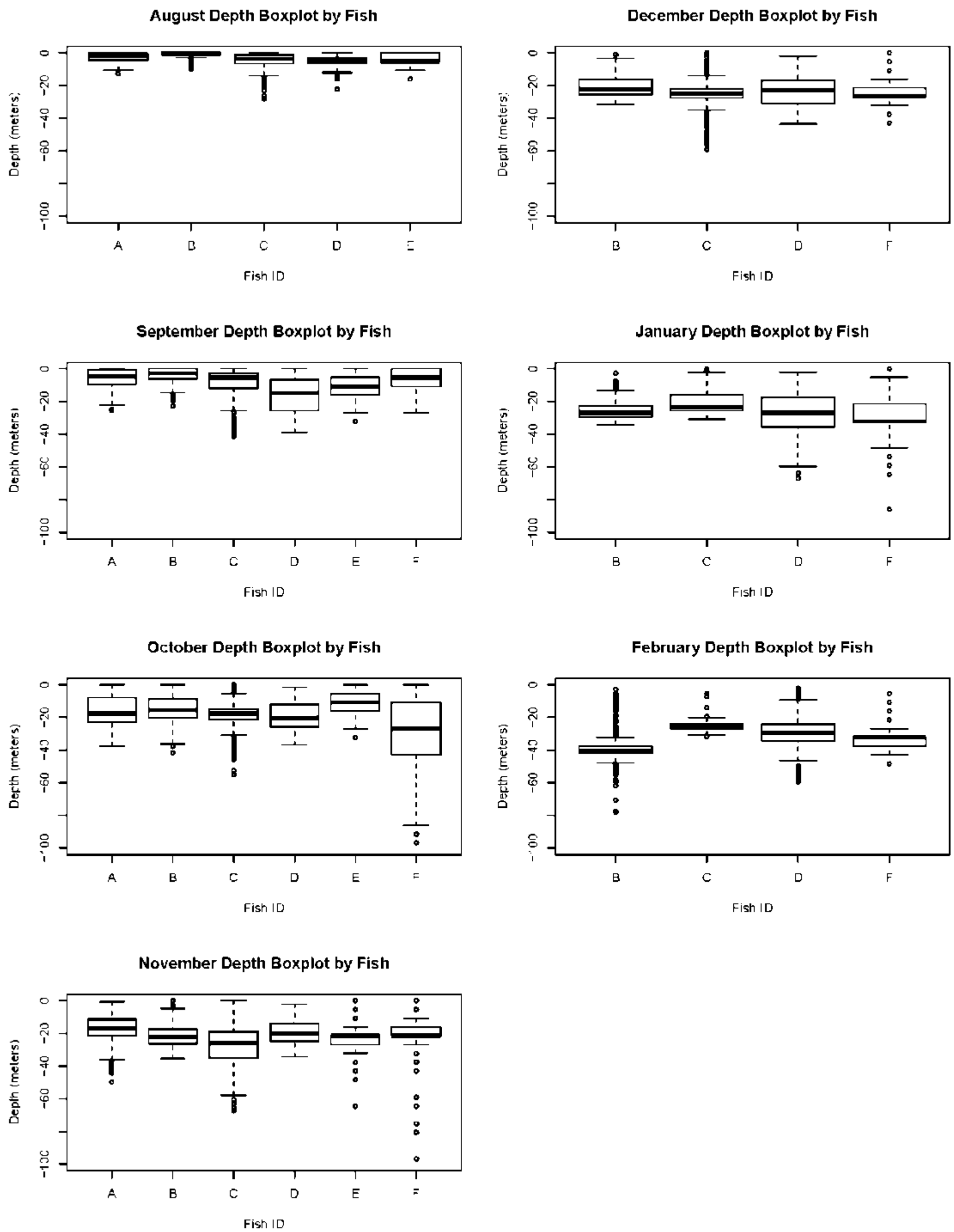


Figure 16. Boxplots of depth observations are shown for each cobia by month that the tag was attached to the fish. Only four tags were attached to specimens for the months December – February. Differences in depth utilization appear stochastic without any clear pattern. Fish C is the specimen known to have traveled to Florida.

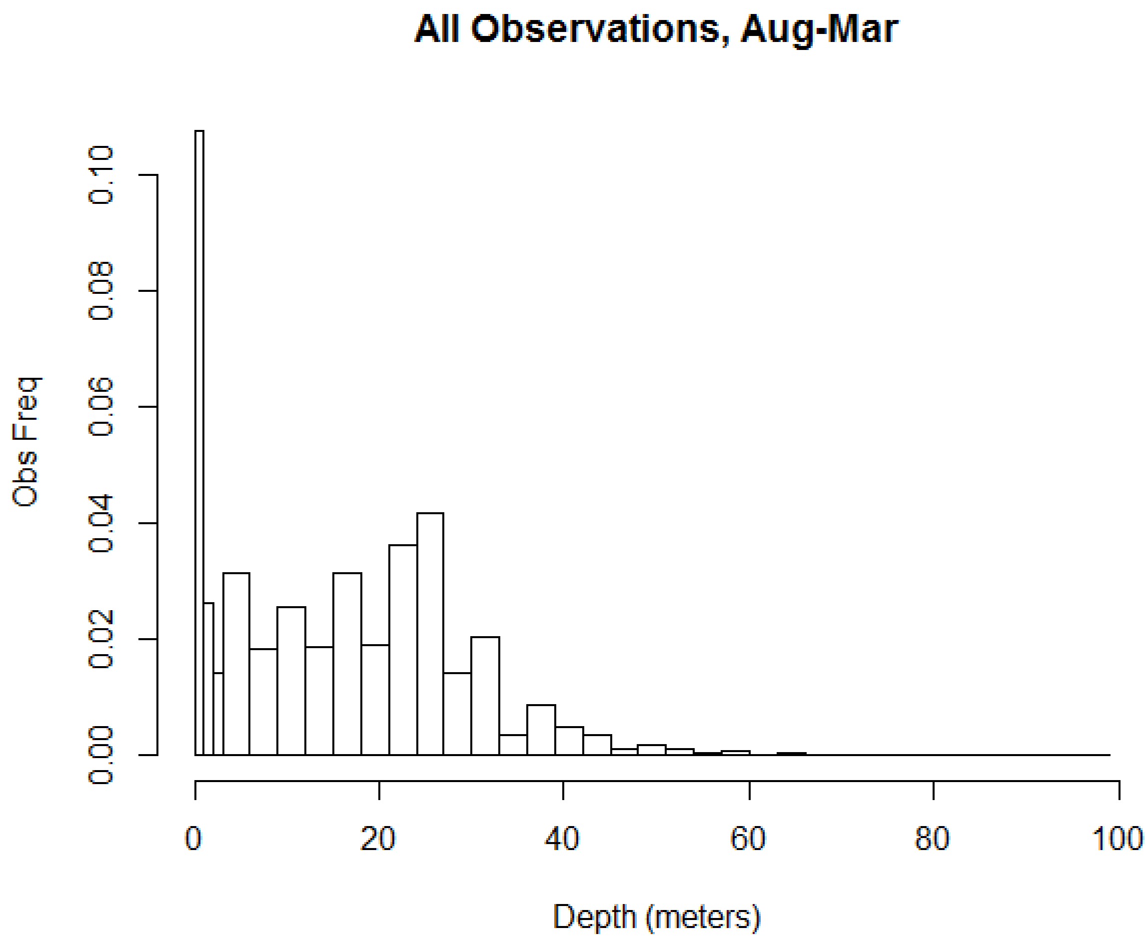


Figure 17. Histogram comparing the relative frequency of cobia depth observations in the top 1 meter of the water column for the months of this study.

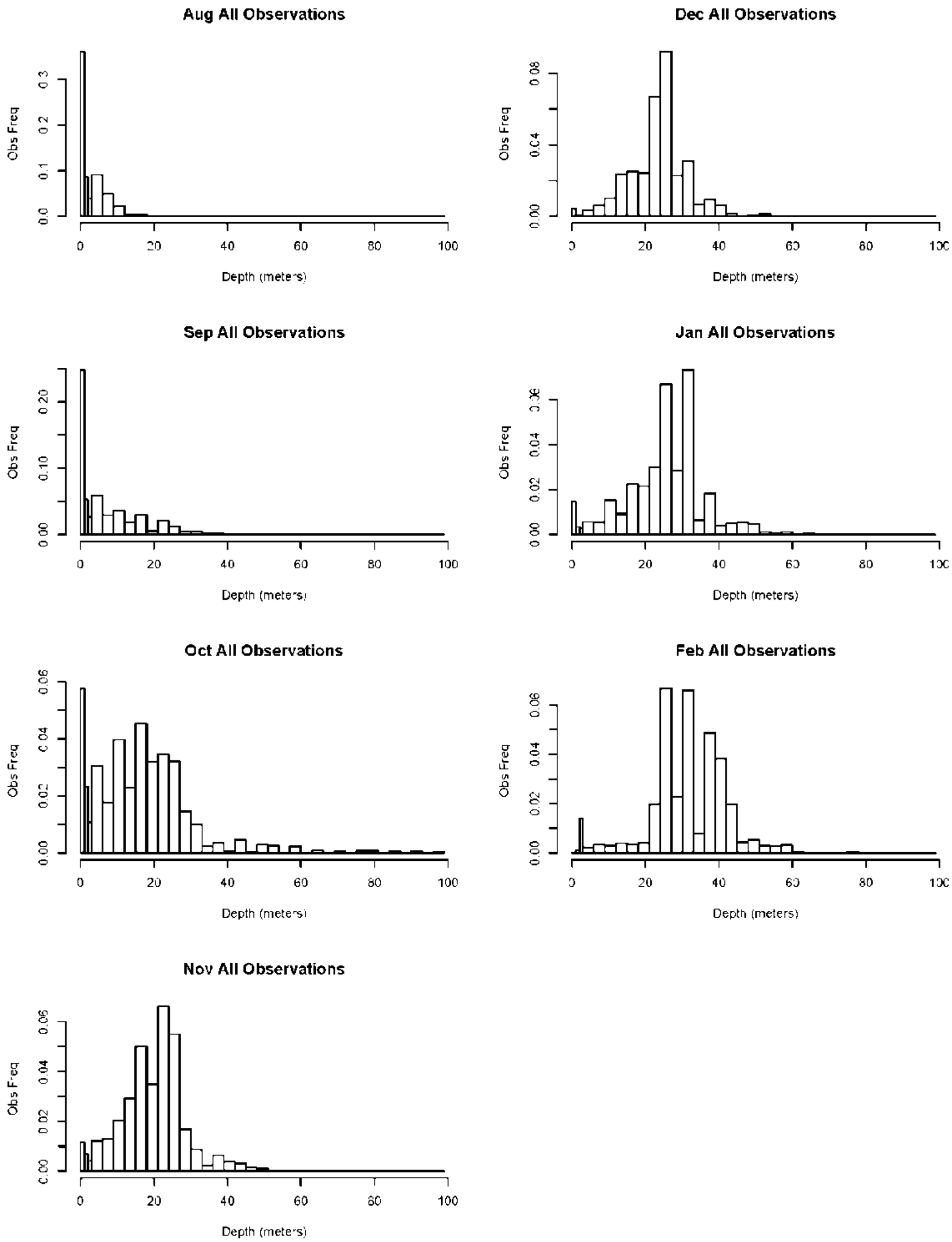
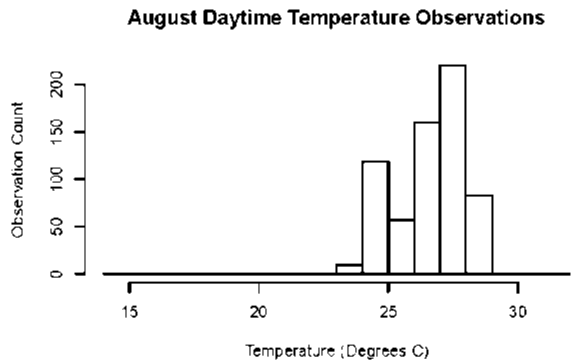


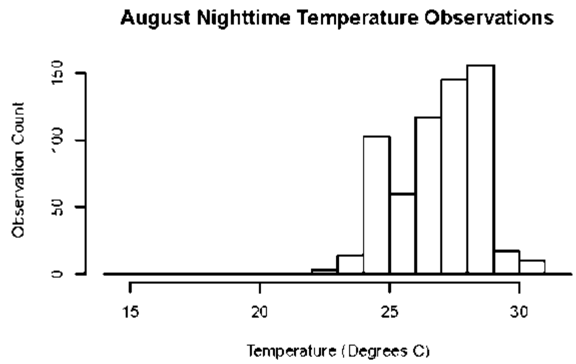
Figure 18. Histograms comparing the relative frequency of cobia depth observations in the top 1 meter of the water column for the months of this study. 38% of the depth observations from the month of August were in the top 1 meter of the water column. This drops to 25% in September, 6% in October, and less than 2% for the months November through February.

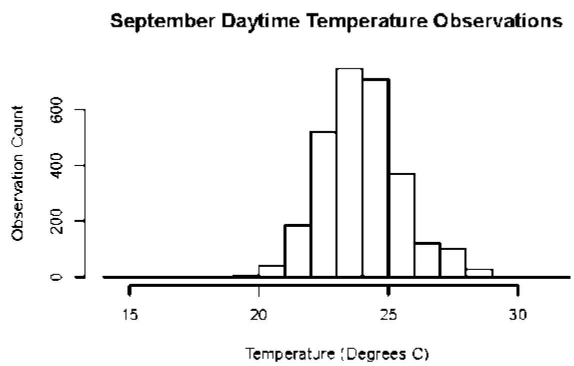
Appendix 1 – Last day average inclinometer readings for mrPATs attached to cobia

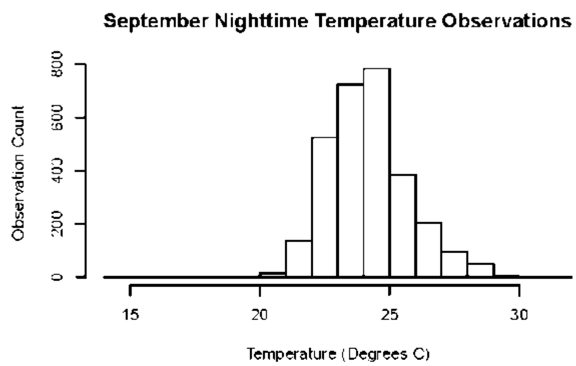
#	Tag Model	Deployment Date	Fish TL (inches)	Inclinometer Reading (degrees from vertical)
12	mrPAT	8/03/2017	38	56
16	mrPAT	8/09/2017	59	75
17	mrPAT	8/09/2017	43	57
19	mrPAT	8/10/2017	45	61
21	mrPAT	8/17/2017	40	52
22	mrPAT	8/17/2017	42	67
23	mrPAT	8/19/2017	40	69
24	mrPAT	8/20/2017	38	71
25	mrPAT	8/25/2017	42	65
26	mrPAT	8/26/2017	40	82
28	mrPAT	8/27/2017	44	64
29	mrPAT	8/27/2017	43	59
30	mrPAT	8/27/2017	42	70
31	mrPAT	9/03/2017	38.5	56
32	mrPAT	9/04/2017	42	77
34	mrPAT	9/09/2017	39	94
35	mrPAT	9/09/2017	38	72
36	mrPAT	9/17/2017	39	58

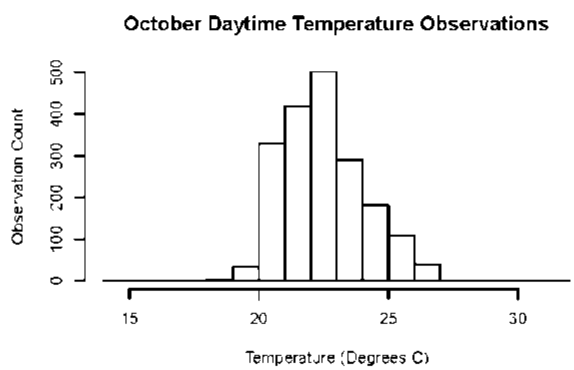
Appendix 2 – Diurnal temperature observations of cobia

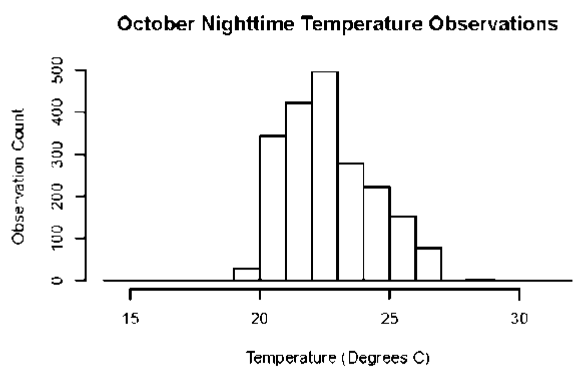


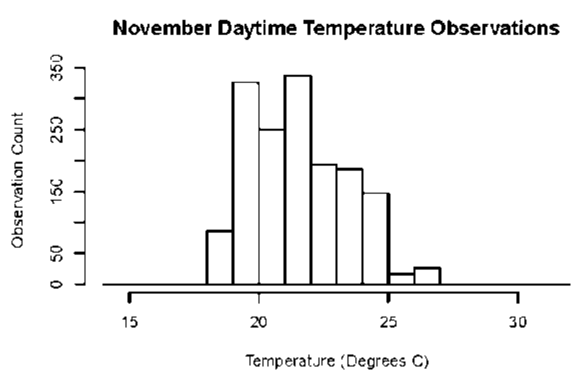


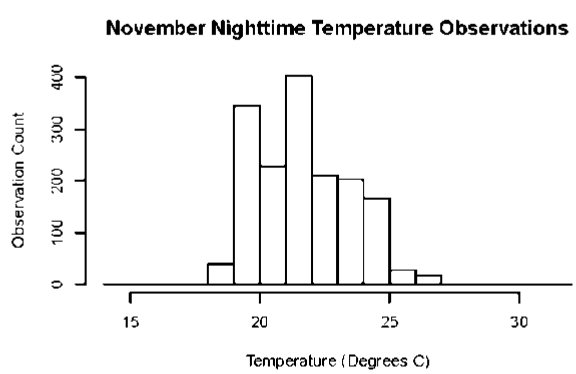




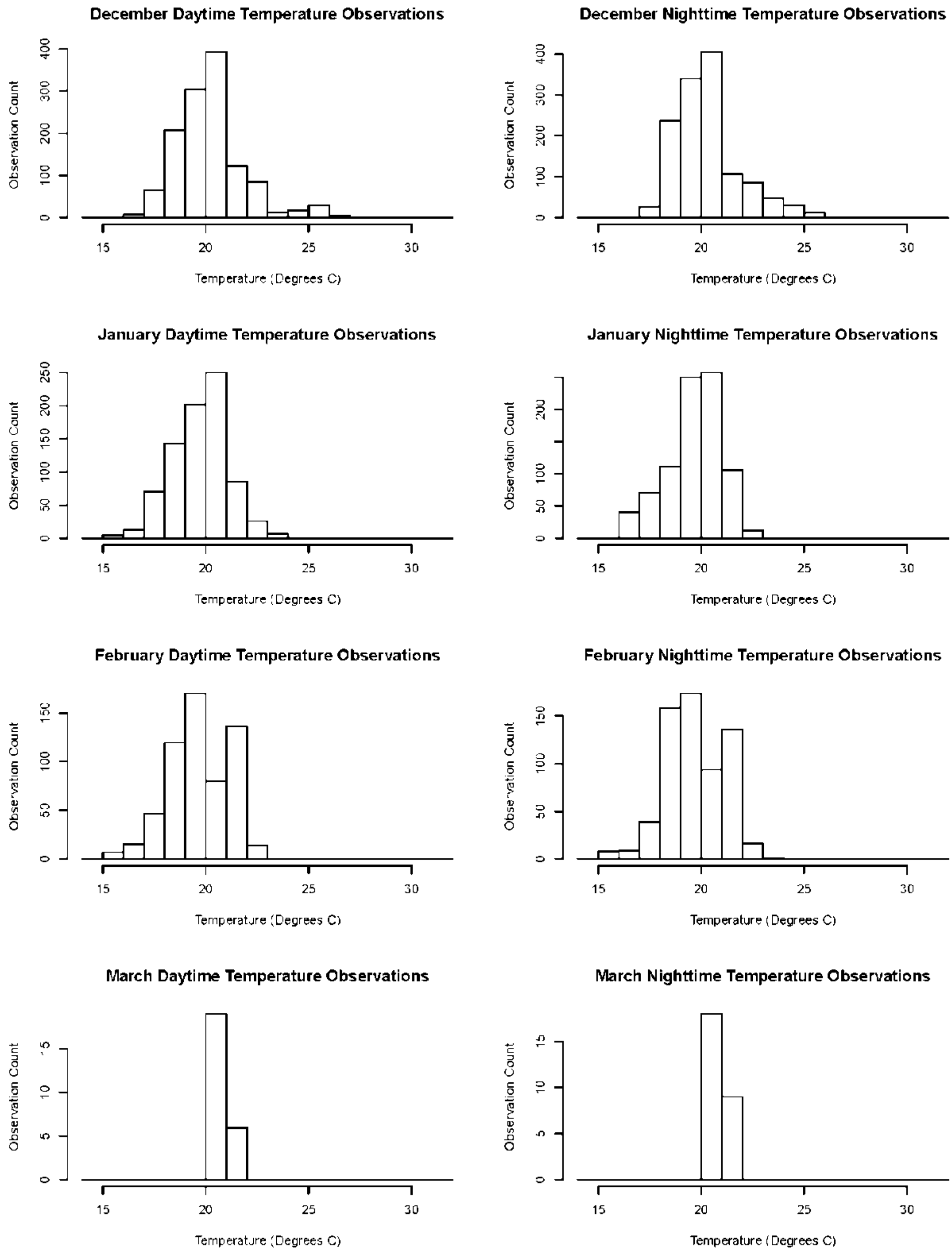




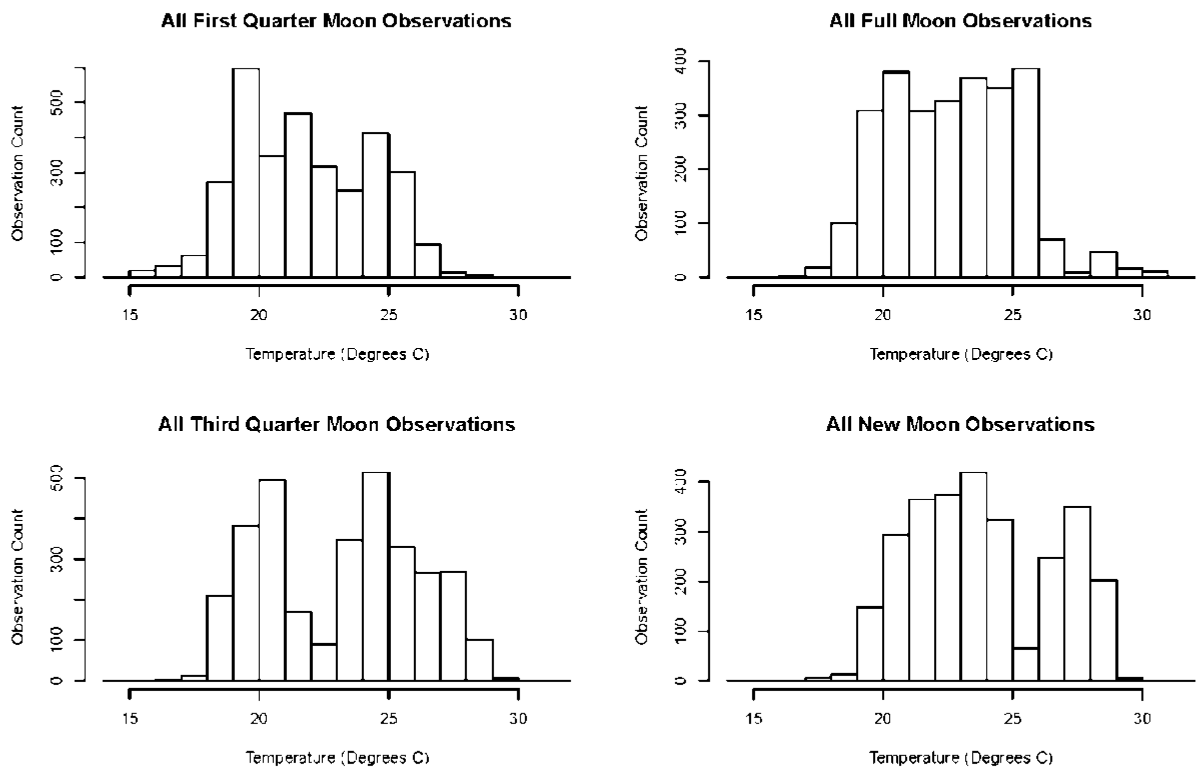




Appendix 2 – Diurnal temperature observations of cobia



Appendix 3 – Cobia temperature observations by lunar phase



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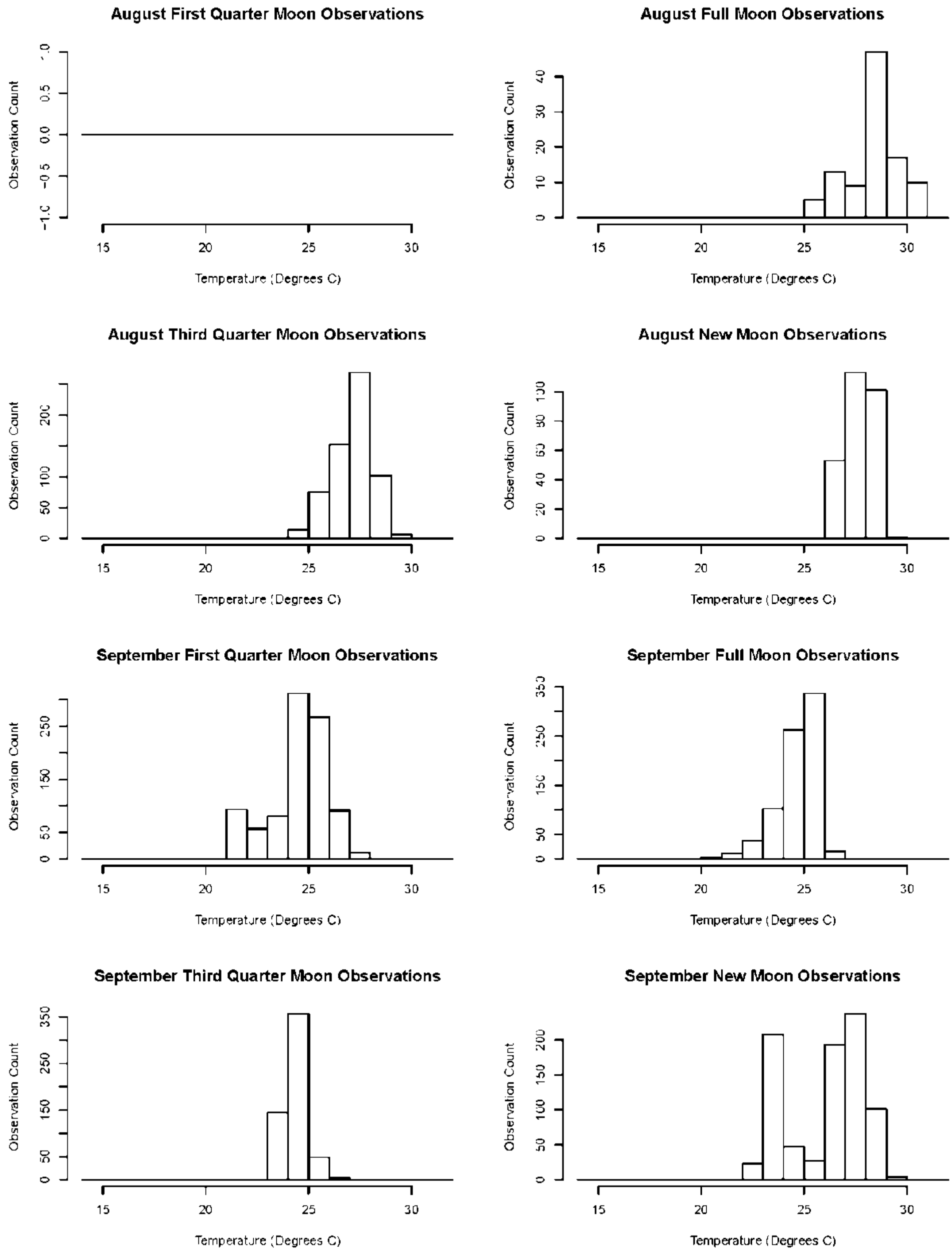

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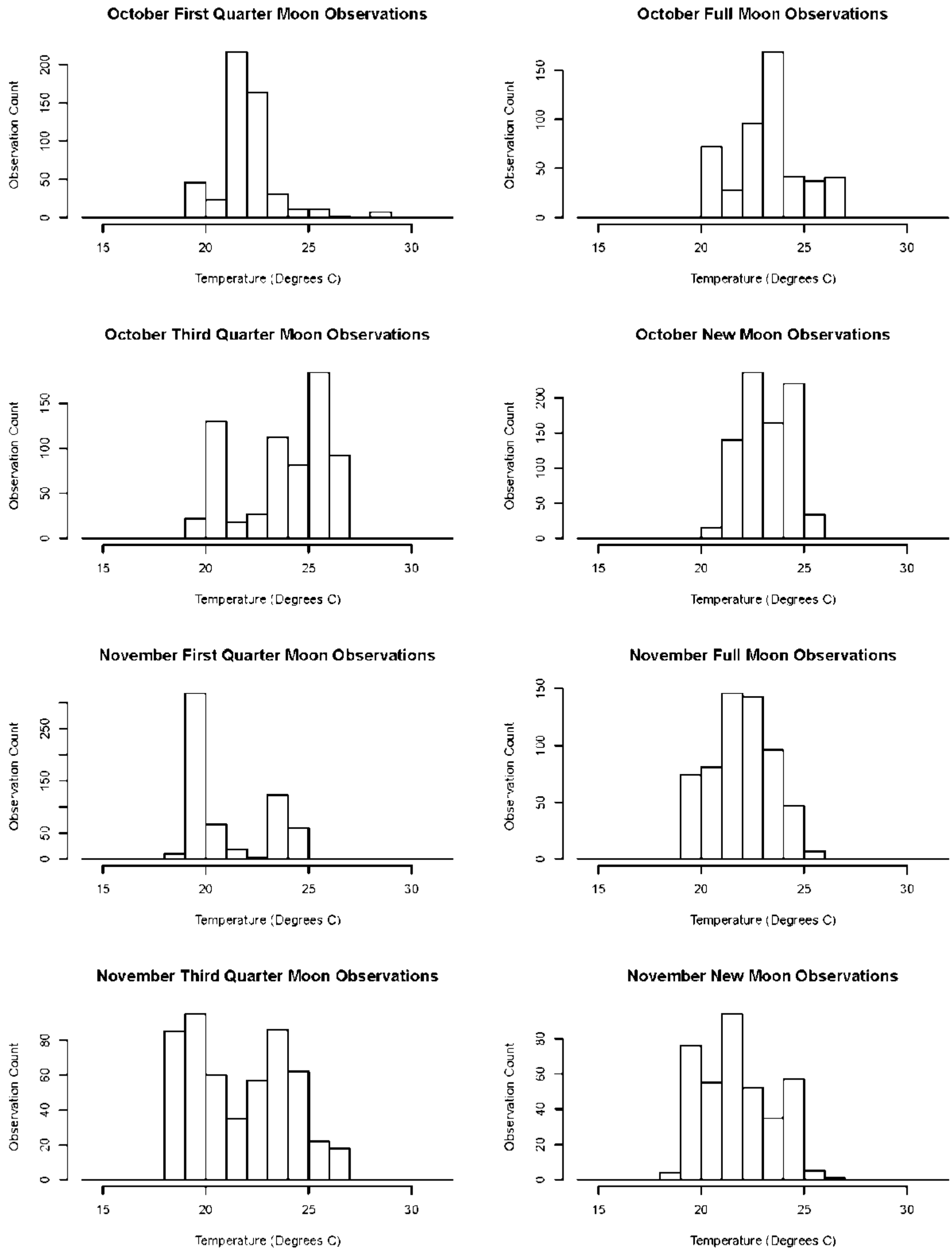

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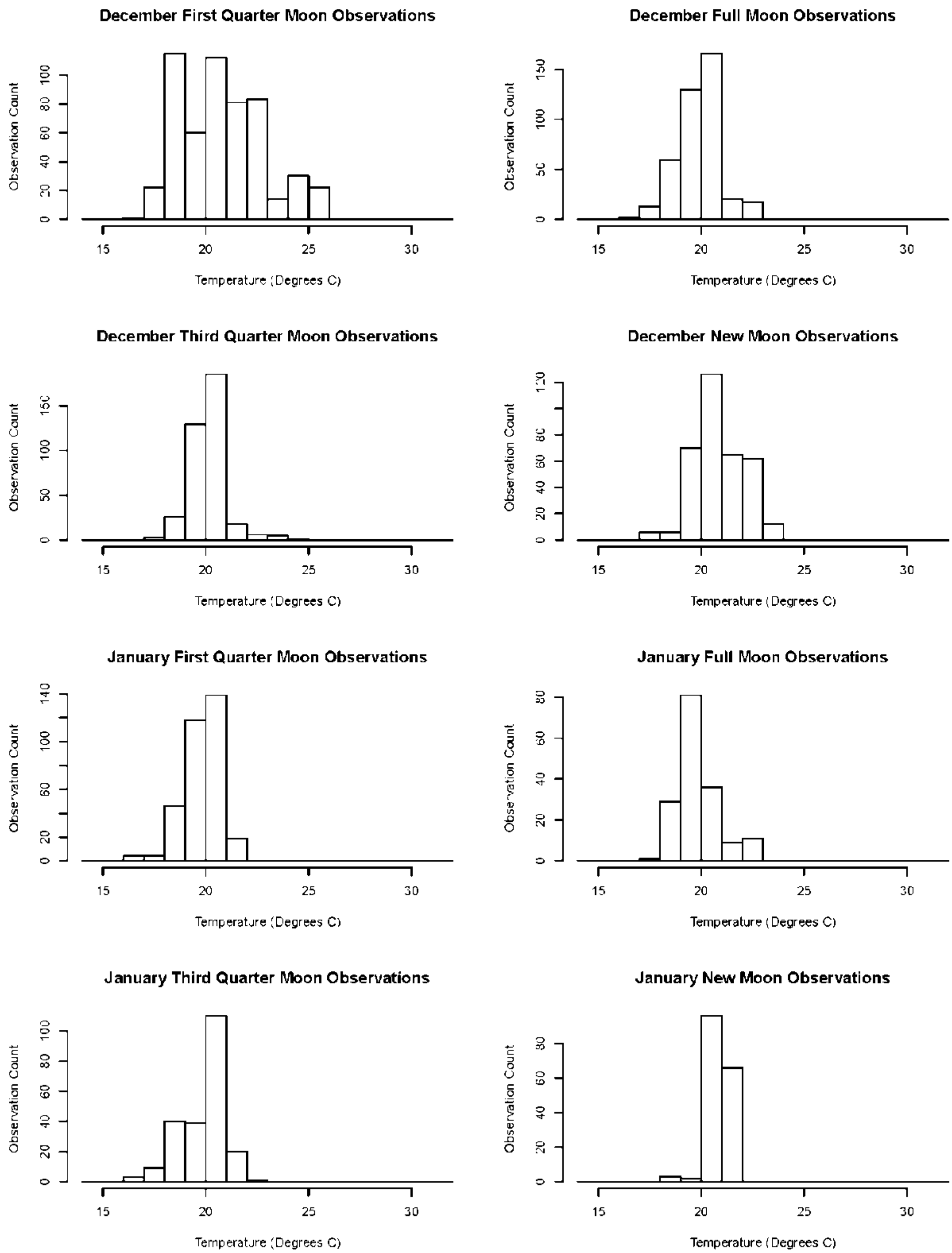

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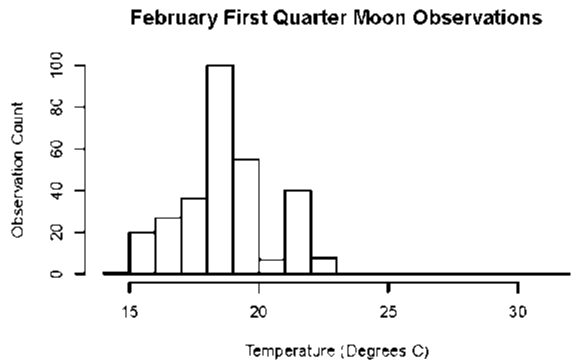
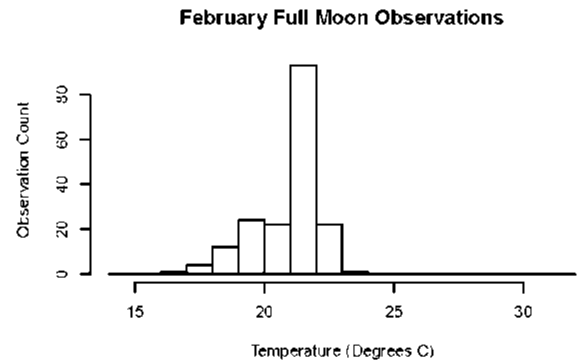
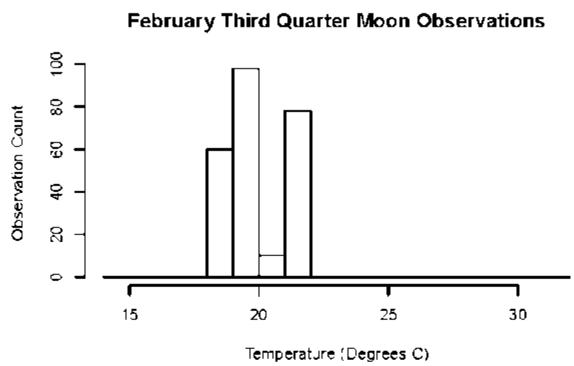
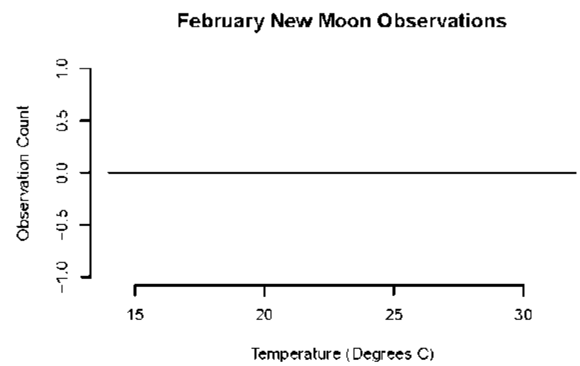
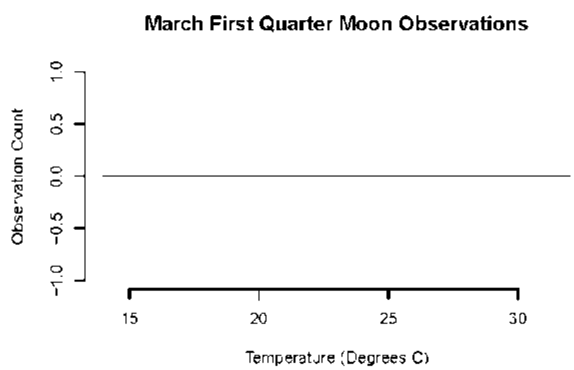
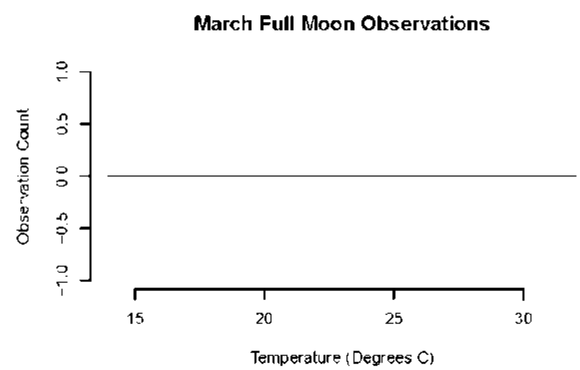


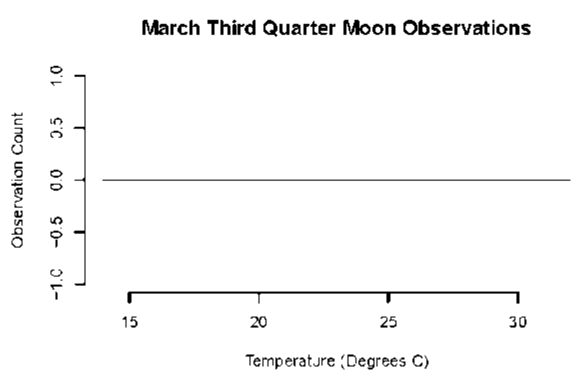


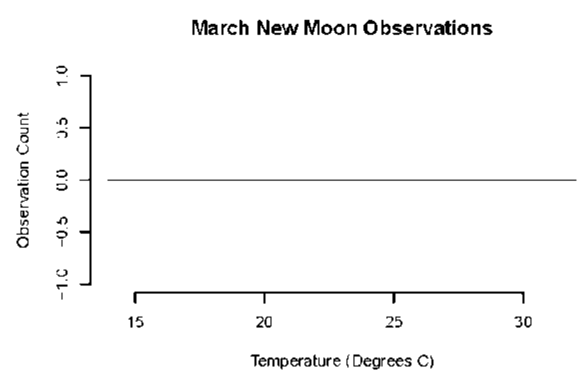




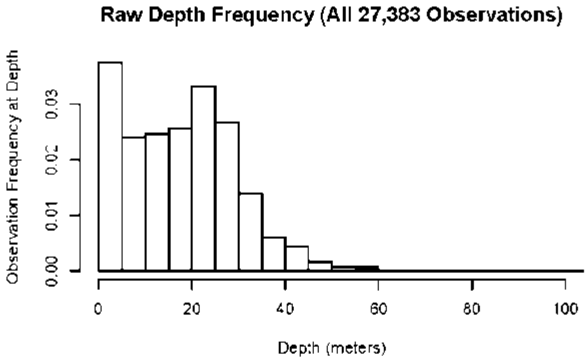


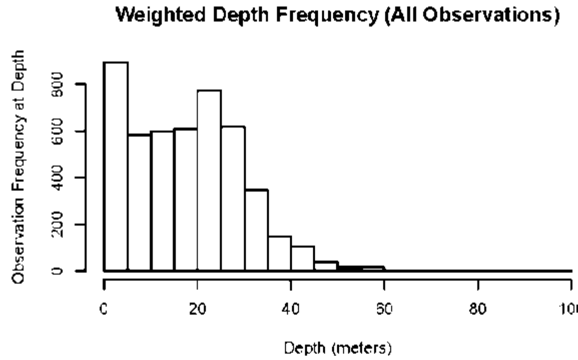


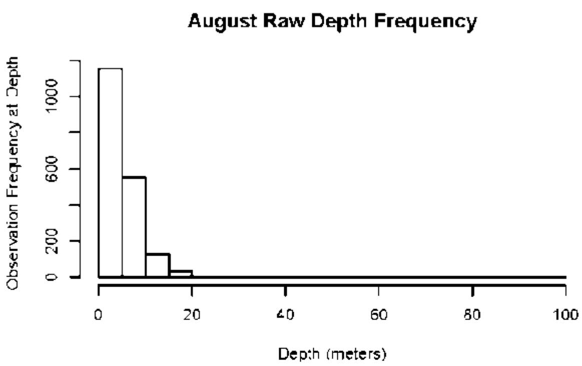


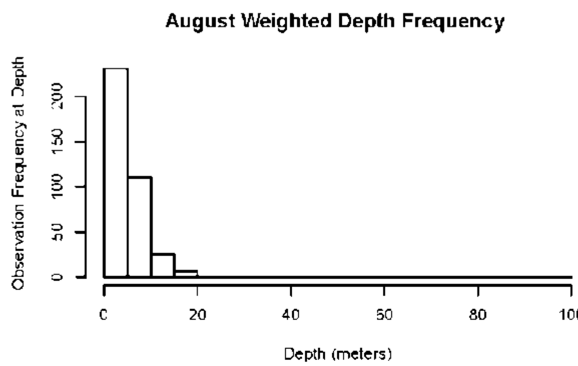


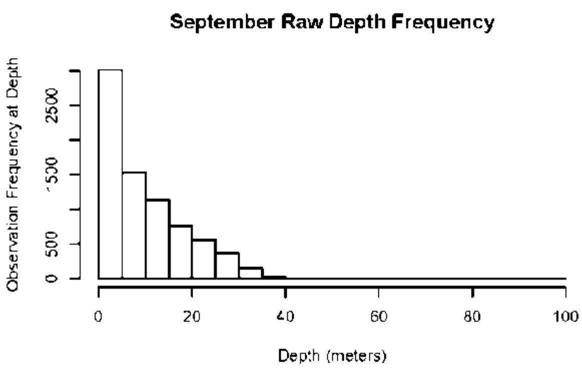
Appendix 4 – Raw and weighted cobia depth distributions by month

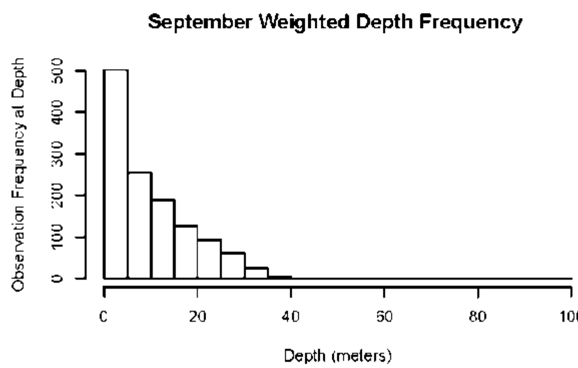


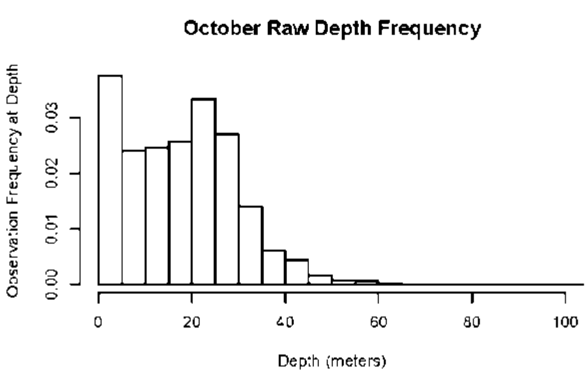


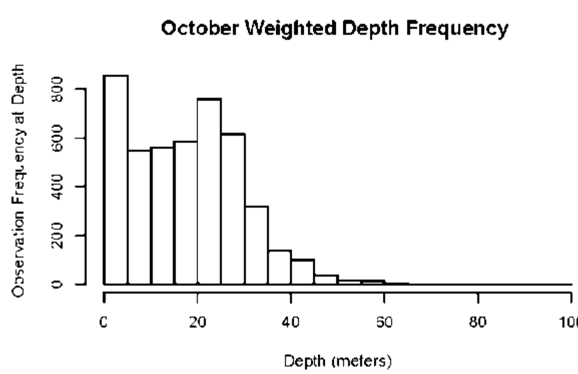












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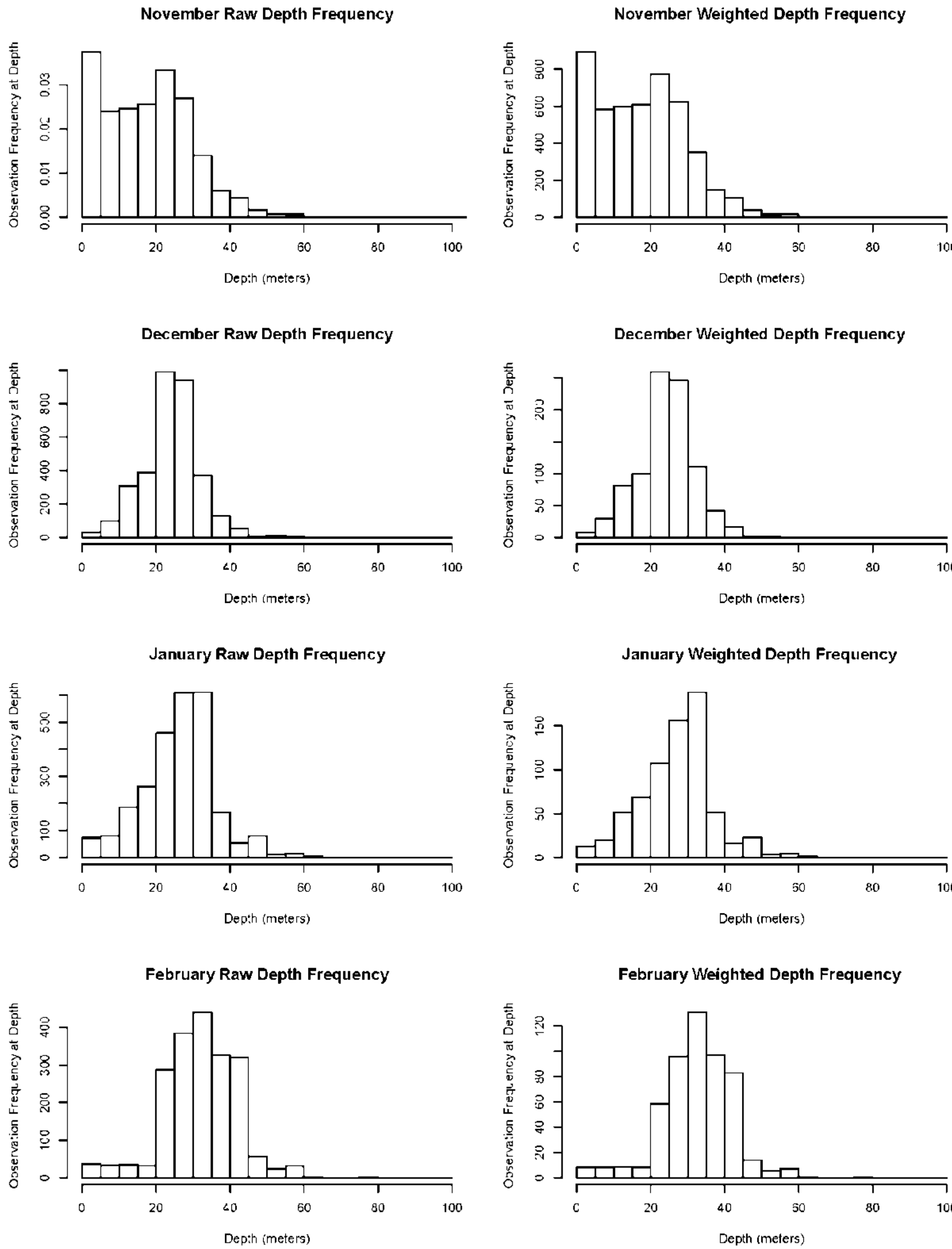
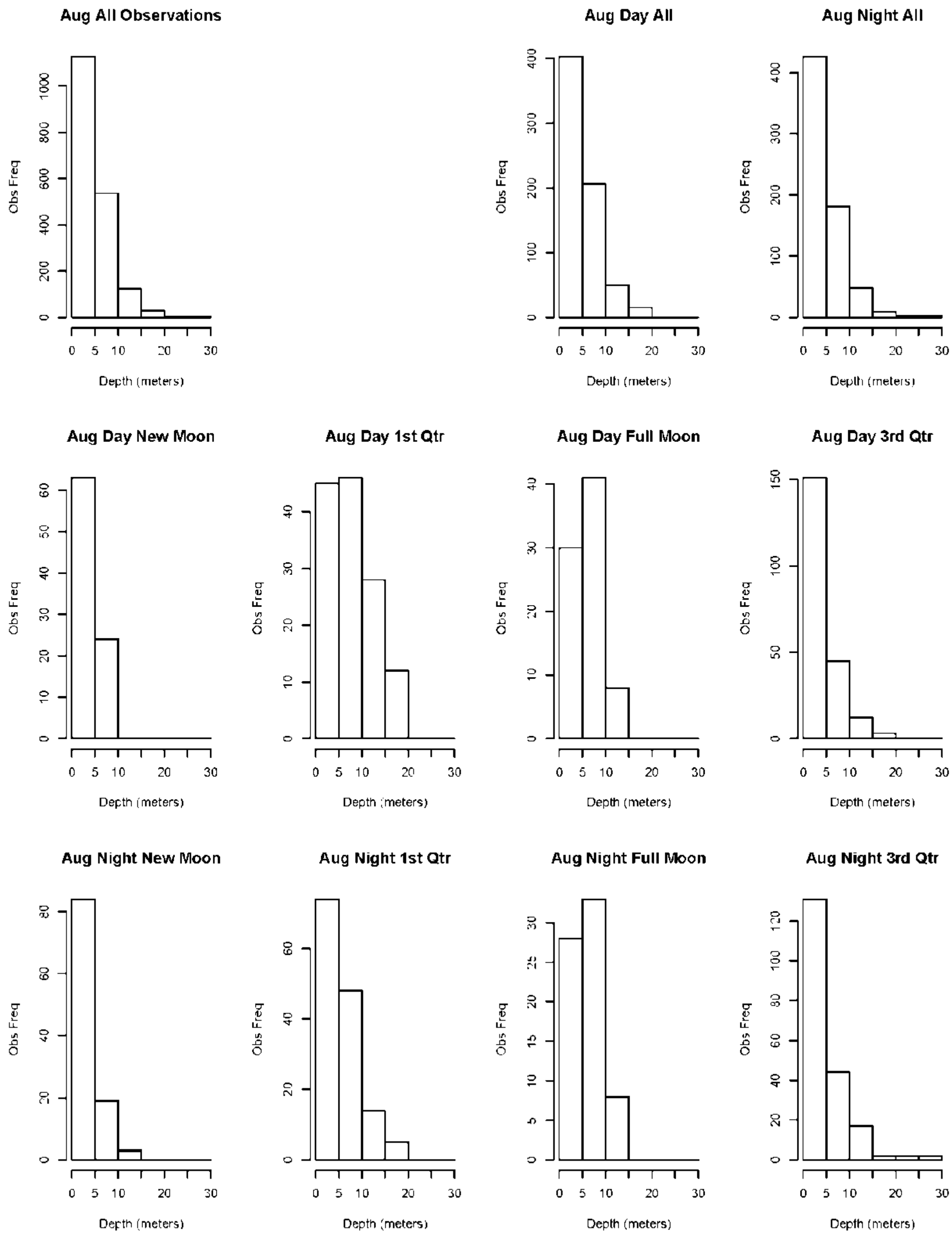


Appendix 5 – Cobia depth utilization results by month assessing night/day & lunar cycles



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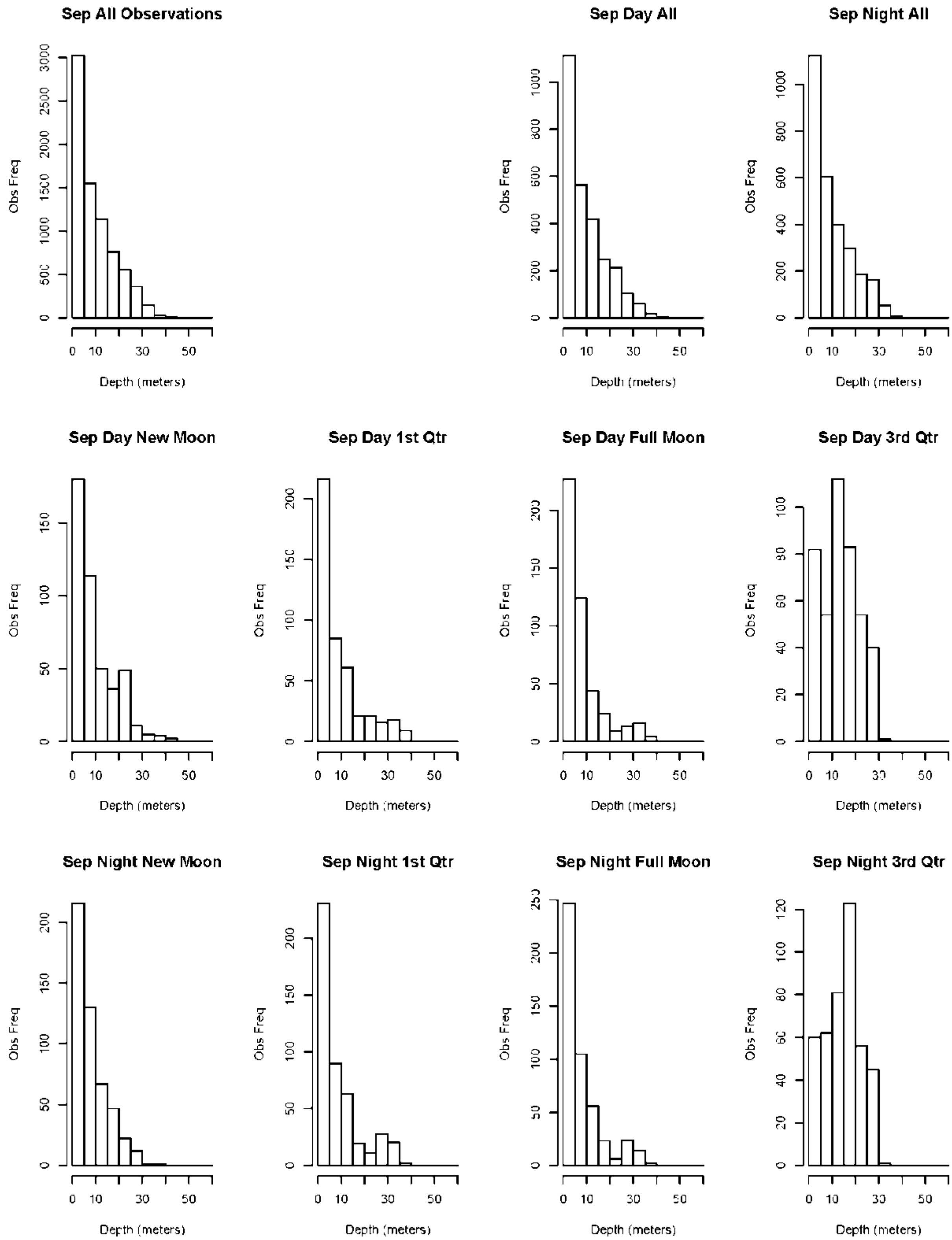

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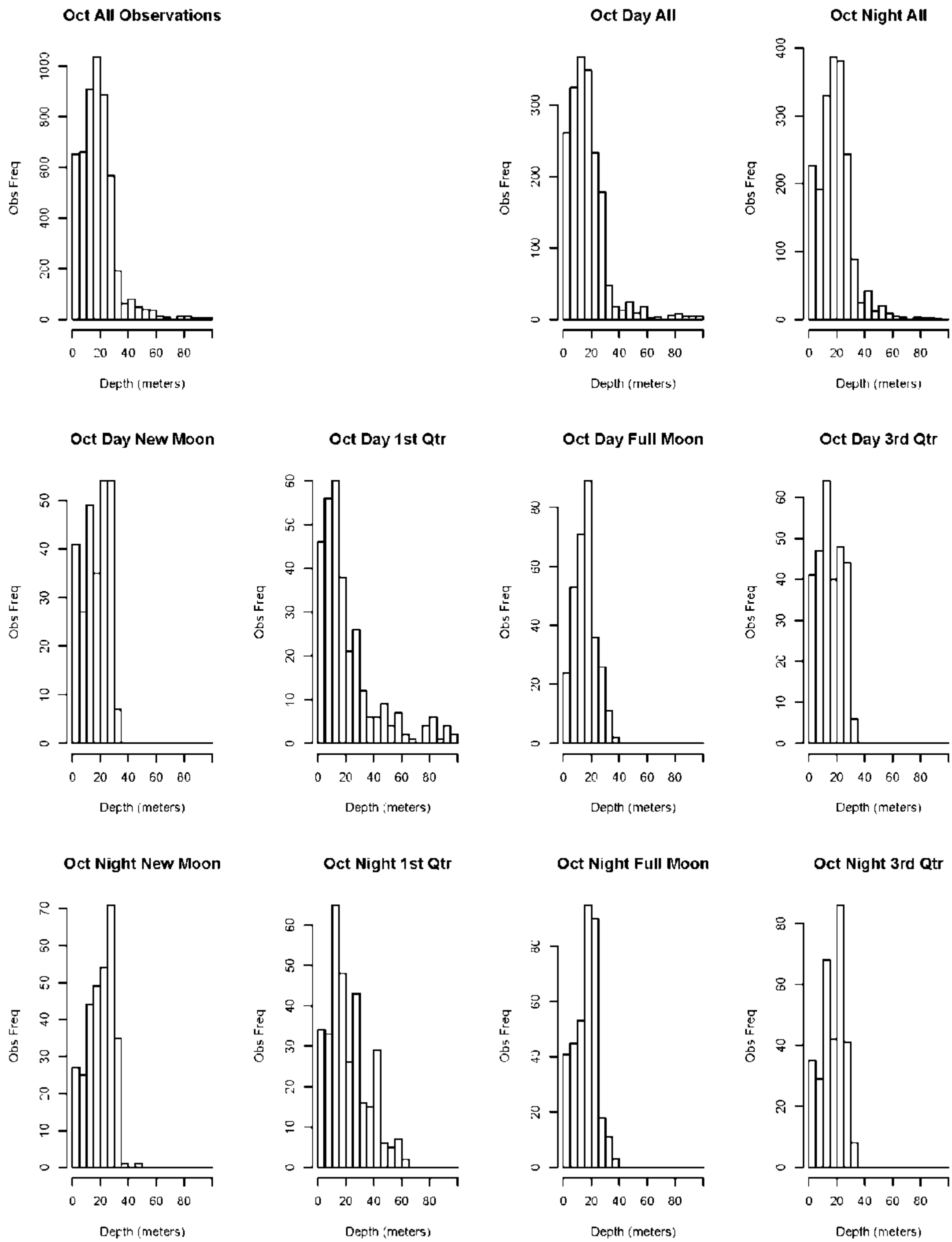

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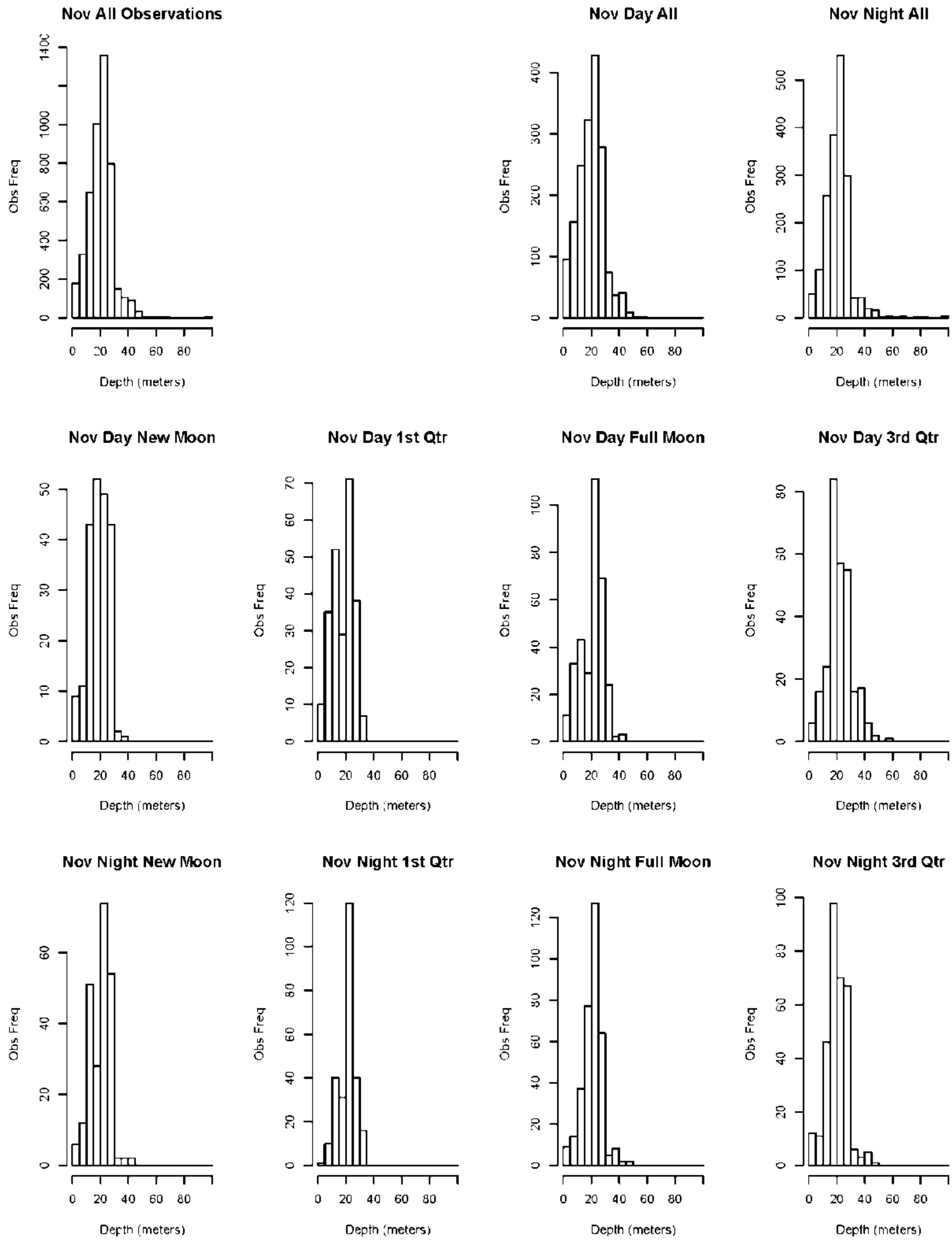

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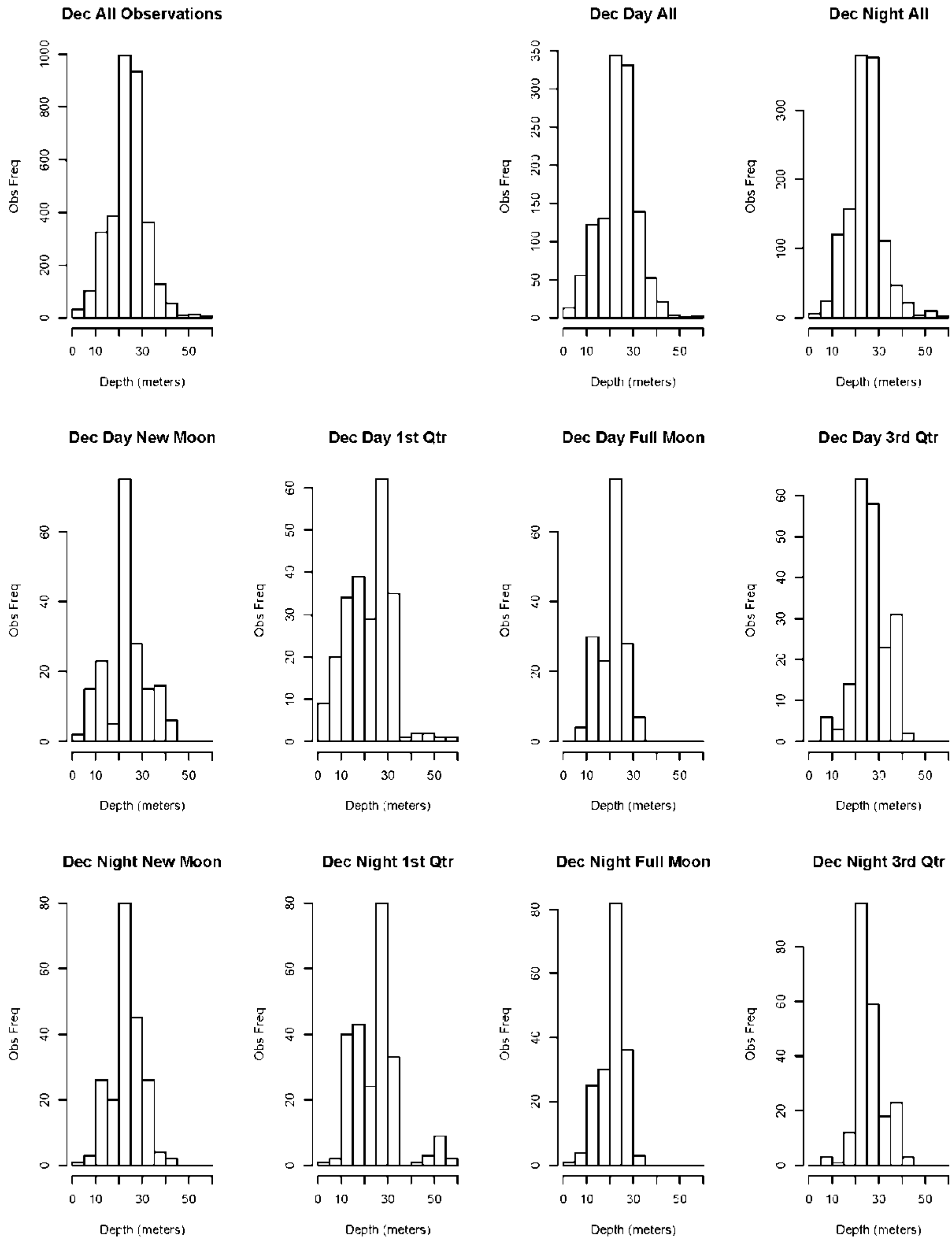

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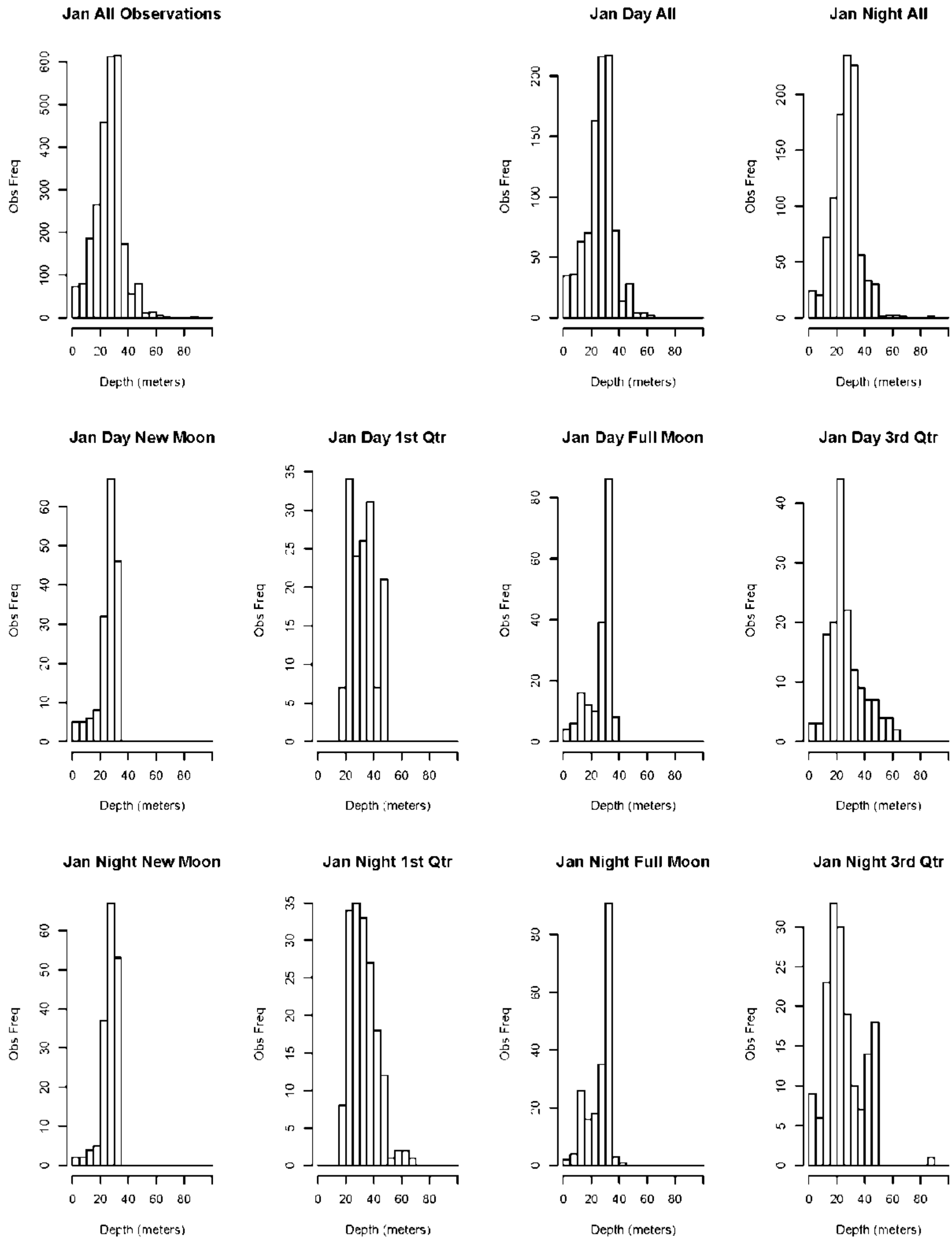

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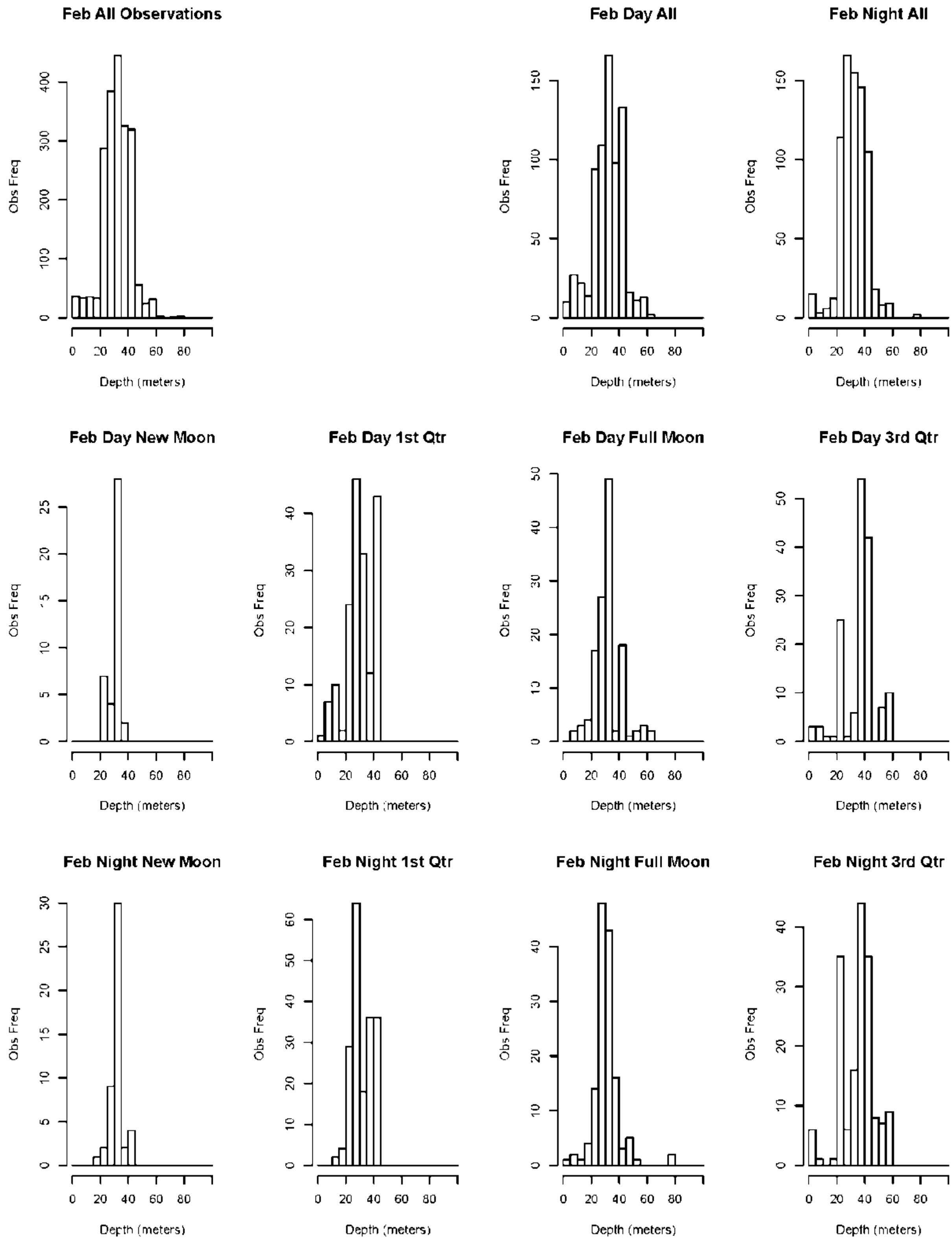

VITA

Douglas R. Jensen

Douglas was born in Anderson, Indiana on 1 August 1985. He graduated from Neillsville High School in Neillsville, Wisconsin in 2004. He earned a B.S. in Engineering Mechanics and Astronautics from the University of Wisconsin – Madison in 2008. Douglas spent the next seven years serving in the United States Air Force. He completed a M.B.A. from Trident University International in 2011. Douglas entered the master's program in Fisheries Science at the Virginia Institute of Marine Science, College of William & Mary in 2016, advised by Dr. John Graves.