DO HURRICANES AND OTHER SEVERE WEATHER EVENTS AFFECT FISHING EFFORT AND CATCH PER UNIT EFFORT OF REEF-FISH IN THE FLORIDA KEYS?

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ABSTRACT

Severe weather events frequently affect important marine fish stocks and fisheries along the United States Atlantic and Gulf of Mexico coasts. However, the effects of these events on fish and fisheries are not well understood. The availability of self-reported data from two fisheries in a region frequently affected by tropical cyclones provided a unique opportunity to investigate short-term responses to past events. This study involved selecting severe weather events, calculating changes in effort and catch-per-unit- effort (CPUE), and analyzing those changes across various temporal, spatial, and species-specific scenarios. Responses in each variable were analyzed within and across scenario factors and explored for correlations and linear multivariate relationships with hypothesized explanatory variables. A negative overall directional change was identified for logbook fishing effort. Based on both correlations and linear models, changes in logbook fishing effort were inversely related to changes in average maximum wind speed. Severe weather events are more likely to affect fishing effort than catch rates of reef-fish species. However, lack of responses in CPUE may also relate to the ability of this study to detect changes. The temporal and spatial scales analyzed in this study may not have been adequate for identifying changes in effort for the headboat fishery, or in CPUE for either fishery. Although there was no region-wide response in CPUE associated with severe weather events, further research on this topic is necessary to determine if storm-induced changes in fishery data are likely strong, long-lasting, or widespread enough to influence the outcome of stock-wide assessments.

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CHAPTER 1 – LITERATURE REVIEW OF TROPICAL CYCLONES AND SOUTH FLORIDA FISHERIES

Introduction

Tropical cyclones are organized low-pressure storm systems that form over tropical and subtropical waters across the globe. In the North Atlantic, tropical cyclones are categorized by their wind intensity as tropical depressions, tropical storms or hurricanes (McAdie et al. 2009). Severe tropical cyclones, namely, hurricanes and tropical storms, can cause considerable damage to coastal communities and marine ecosystems (NWS 2011; Harmelin-Vivien 1994).

The highest potential for annual tropical cyclone strikes in the nation occurs in the southeastern United States, which includes states along the Gulf of Mexico and the Atlantic coasts, from Texas to North Carolina. (NMFS 2009; Keim 2007). Fishing-related industry, infrastructure and livelihoods, as well as fish and their habitats in the southeastern United States are all vulnerable to the influence of tropical cyclones. Additionally, the ability to effectively manage the region's fisheries may also be influenced explicitly when tropical cyclone-related effects are not properly accounted for in assessment models used to evaluate stock status and project changes in response to management approaches, a process called stock assessment.

Traditionally, the occurrences of events, such as tropical cyclones, are not incorporated into stock assessments. Because of this, the influence of these storms evidenced in the fisheries data might often be attributed to incorrect factors. For example, what may in fact be a change in fish distribution may be incorrectly attributed to being a change in abundance. If not accounted for appropriately, storm-induced changes can potentially increase variability and uncertainty in assessments or lead to mistaken interpretations of stock status, or other important indices used to manage fisheries.

Fisheries and Fisheries Management

Marine resources support diverse and regionally different fisheries and fishing-related industries. In the United States, fisheries are generally managed at the stock level, where stocks are defined by both management and biological concerns (Cooper 2009; Begg et al. 2001). Generally stocks are subpopulations of a species that are further categorized to incorporate management jurisdictions. For example, pink shrimp (*Farfantepenaeus duorarum)* in the southeastern United States are managed as two stocks, the Gulf of Mexico pink shrimp stock and the South Atlantic pink shrimp stock; however, these stocks have been identified to be genetically homogeneous (McMillen-Jackson and Bert 2004).

Fisheries in the United States are managed at both state and federal levels. Between the coast and three nautical miles from shore, nine nautical miles in the case of Florida's west coast and Texas, fisheries are managed by state agencies. Beyond the state boundary to 200 nm, except where boundaries meet with Bermudian, Bahamian and Cuban waters, is a region that is called the exclusive economic zone (EEZ). Fisheries in this region are federally managed by the National Marine Fisheries Service (NMFS), which is part of the United States Department of Commerce's National Oceanic and Atmospheric Administration (NOAA).

The Magnuson-Stevens Act (MSA) is the primary law governing how federal marine fisheries are managed in the United States. When this act was originally enacted in 1976, it established the EEZ and also created regional fisheries management councils (FMC) to meet regionally specific management needs (NMFS 2012). Each FMC is responsible for creating fishery management plans in a transparent and public process, incorporating scientific advice. Additional FMC responsibilities and obligations are further specified by the 1976 and 2006 amendments to the MSA, and include eliminating overfishing to ensure sustainable harvest and mandating the recovery of overfished stocks (NMFS 2012).

Federally managed fisheries along the southeastern coast of the United States are divided into two FMC regions, the South Atlantic and Gulf of Mexico. The states included in the Gulf of Mexico region are Alabama, Louisiana, Mississippi, Texas and the west coast of Florida. The states included in the South Atlantic region are North Carolina, South Carolina, Georgia, and the east coast of Florida.

Diverse marine resource in the southeastern US support highly valued commercial and recreational fisheries. In 2009, an estimated 5.2 million recreational anglers participated in 41 million fishing trips in the South Atlantic and Gulf of Mexico regions combined, spending $15 billion on fishing trips and related equipment (NMFS 2010). Important recreational species or species groups in the south Atlantic include black seas bass (*Centropristis striata*), bluefish

(*Pomatomus saltatrix*), dolphinfish (*Coryphaena hippurus*), spot (*Leiostomus xanthurus*), Atlantic croaker (*Micropogonias undulatus*), spotted seatrout (*Cynoscion nebulosus*), king and Spanish mackerels (*Scomberomorus cavalla*, and *S. maculatus*), sheepshead (*Archosargus probatocephalus*), red drum (*Sciaenops ocellatus*), and sharks. For Gulf of Mexico recreational fisheries, important species include Atlantic croaker (*Micropogonias undulatus*), gulf and southern kingfish (*Menticirrhus littoralis* and *M. americanus*), sand, silver, and spotted seatrouts (*Cynoscion arenarius, C. nothus,* and *C. nebulosus*), sheepshead (*Archosargus probatocephalus*), red drum (*Sciaenops ocellatus*), red snapper (*Lutjanus campechanus*), southern flounder (*Paralichthys lethostigma*), Spanish mackerel (*Scomberomorus maculatus*), and striped mullet (*Mugil cephalus*) (NMFS 2010).

As for commercial fisheries, in 2009 fishermen in the South Atlantic and Gulf of Mexico regions landed 1.5 billion pounds, almost 20 percent of the year's total landings in the entire United States (NMFS 2010). Total landings revenue in 2009 for the two regions combined was $773 million. Shellfish contributed the majority of revenue in each region, at about 46 percent and 78 percent, in the South Atlantic and Gulf of Mexico respectively (NMFS 2010). Important commercial species or species groups in the South Atlantic include blue crab (*Callinectes sapidus*), king mackerel (*Scomberomorus cavalla*), swordfish (*Xiphias gladius*), and various species of groupers (*Epinephelus spp.*), snappers (*Lutjanus spp.*), tunas (*Thunnus spp.*), clams, flounders, oysters, and shrimps. Species or species groups of commercial importance in the Gulf of Mexico region include blue crab (*Callinectes sapidus*), red snapper (*Lutjanus campechanus*), stone crab (*Menippe mercenaria*), and various species of groupers (*Epinephelus spp.*), menhaden (*Brevoortia spp.*), tunas (*Thunnus spp.*), crawfish, mullets, oysters, and shrimps (NMFS 2010).

Florida Fisheries

Occurring along both its Atlantic and Gulf of Mexico coasts, Florida's fisheries are important at both regional and national scales. In 2009, fisheries in only two other states, California and Massachusetts, supported more jobs than Florida's fisheries supported, and total sales generated by Florida's seafood industry where only exceed by sales in California (NMFS 2010). Also in 2009, commercial fishing landings revenue on the state's east coast was 28 percent of the landings in the entire south Atlantic region, while landings on the Florida's west coast were 18 percent of the total landings revenue in the entire Gulf of Mexico region (NMFS

2010). Furthermore, 53 percent and 70 percent of all 2009 recreational trips in the south Atlantic and Gulf of Mexico regions, respectively, occurred in Florida (NMFS 2010).

Important species and species groups for Florida's east coast commercial fisheries include blue crab (*Callinectes sapidus*), king and Spanish mackerels (*Scomberomorus cavalla*, and *S. maculatus*), swordfish (*Xiphias gladius*), groupers (*Epinephelus spp.*), snappers (*Lutjanus spp.*), as well as various species of clams, lobsters, sharks, and shrimps. Key recreational species for Florida's east coast are bluefish (*Pomatomus saltatrix*), dolphinfish (*Coryphaena hippurus*), kingfish (*Menticirrhus spp.*), spotted seatrout (*Cynoscion nebulosus*), gray snapper (*Lutjanus griseus*), Florida pompano (*Trachinotus carolinus*), king and Spanish mackerels (*Scomberomorus cavalla*, and *S. maculatus*), sheepshead (*Archosargus probatocephalus*), and red drum (*Sciaenops ocellatus*) (NMFS 2010).

Key species or species groups for Florida's west coast commercial fisheries include blue crab (*Callinectes sapidus*), gag (*Mycteroperca microlepis*), quahog clam (*Mercenaria mercenaria*), red grouper (*Epinephelus morio*), red snapper (*Lutjanus campechanus*), stone crab (*Menippe mercenaria*), and various species of lobsters, mullets, oysters, and shrimps. Important recreational species or species groups for the west coast of Florida include common snook (*Centropomus undecimalis*), sand and silver seatrouts (*Cynoscion arenarius*, and *C. nothus)*, gag (*Mycteroperca microlepis*), gray snapper (*Lutjanus griseus*), king and Spanish mackerels (*Scomberomorus cavalla*, and *S. maculatus*), sheepshead (*Archosargus probatocephalus*), red drum (*Sciaenops ocellatus*), and various species of mullets (NMFS 2010).

Frequency and Effects of Tropical Cyclones

Tropical cyclones are synoptic-scale systems that develop over tropical or subtropical waters and have closed surface wind circulation about a warm and well-defined core (OCFM 2007). Hurricanes, tropical storms and tropical depressions are all terms used to describe tropical cyclones and classification depends on whether one minute maximum sustained winds are <18 meters per second (m/s) (39 mph), 18 m/s to < 33 m/s (39 to <74mph), or >33 m/s (74mph), respectively (McAdie et al. 2009). The Saffir-Simpson Hurricane Wind Scale is used to further classify hurricanes from 1-5, with categories 3-5 referred to as major hurricanes (NWS 2012a). The National Hurricane Center (NHC), which is part of NOAA's National Weather

Service (NWS), is responsible for forecasting, tracking, and maintaining data records of tropical cyclone activity in the North Atlantic (McAdie et al. 2009).

Although tropical cyclones are both spatially and temporally variable, they are considered part of the climate regime of the eastern United States. From 1851-2006 a total of 521 north Atlantic tropical cyclones (an average of 3.3 per year) were recorded that crossed or passed immediately adjacent to the United States coastline (McAdie et al. 2009). Furthermore, sediment records in northwest Florida have revealed records of hurricanes over millennia (Liu and Fern 2000).

Along the coast from Texas to Maine, there are certain locations that have had higher numbers of tropical cyclone strikes. These include southeastern Texas, south Florida, the Outer Banks of North Carolina, and the north-central Gulf Coast (Table 1.1). Figure 1.1 shows the frequency of tropical storms, hurricanes, and major hurricanes that have passed near selected coastal points between 1851-2006 (McAdie et al. 2009). In addition to investigating spatial and temporal trends of tropical cyclones, observations recorded during past events can also be explored for general disturbances and effects on coastal communities and marine ecosystems.

Hurricanes and tropical storms are associated with extreme weather conditions that can bring about extensive changes in both terrestrial and marine environments. Destructiveness of tropical cyclones is not only related to the magnitude and temporal exposure of physical processes such as strong wind or heavy rain; additional factors include the mechanisms (e.g. direct or indirect, immediate or delayed) and spatial scales of disturbing forces, as well as the types of organisms, structures, and habitats exposed to them (Harmelin-Vivien 1994). Physical forces associated with tropical cyclones that affect shallow marine ecosystems include waves, changes in sea level, and heavy rains (Harmelin-Vivien 1994). Meanwhile, physical forces associated with tropical cyclones that affect coastal communities include storm surge, winds, floods, and tornadoes (NWS 2012b). Table 1.2 summarizes storm related agents of disturbance.

The effects of tropical cyclones in the marine environment are difficult to quantify, as sampling can be limited during, immediately after and occasionally for sometime following a tropical cyclone event. Both safety concerns and low visibility can be factors inhibiting research, especially for visual surveys in near shore areas where low visibility can persist for months (Bell and Hall 1994). Another difficulty is limited predictability of when and where a cyclone will strike. Thus, sampling methods of habitat monitoring, biological surveys or tagging studies are often designed with objectives unrelated to researching tropical cyclone effects.

Types of data available to analyze cyclone effects on marine ecosystems include pre-and post-event survey comparisons, tagging and mark-recapture studies, meteorological and water quality monitoring, personal communication and incidental observations. Fisheries data, such as catch rates, catch at age, length frequency, and spatial distributions of catch and effort may also contribute to understanding tropical cyclone effects.

Table 1.3 summarizes storm-related changes in marine ecosystems. Examples of disturbances on marine systems recorded during or following tropical cyclone events include turbulent water-motion (Stoddart 1963; Tabb and Jones 1962), sediment movement (Timant et al. 1994), changes in atmospheric pressure (Heupel et al. 2003), and changes in water quality variables, such as turbidity (Bell and Hall 1994; Tabb and Jones 1962; Timant et al. 1994), nutrient availability (Timant et al. 1994), oxygen availability (Tabb and Jones 1962; Timant et al. 1994), and salinity (Goreau 1964; Tabb and Jones 1962). Examples of tropical cyclone-related effects on habitat include physical changes to habitat structure, such as alterations to seagrass or mangrove abundance (Tabb and Jones 1962), algal blooms and changes in primary production (Walsh 1983; Conner et al. 1989) and alterations to natural or artificial reefs (Walsh 1983; Woodley et al. 1981; Goreau 1964). Effects to biota include changes in mortality and changes in fish behavior. Fish mortality can be associated with fish that are stranded when storm surges or floods recede, or fish that suffocate in areas where suspended sediments can clog gills or in areas where oxygen availability is low (Tabb and Jones 1962). Changes in the behavior and distribution of fishes can result from responses to changing atmospheric pressure (Heupel et al. 2003), or to changes in water quality or habitat availability following tropical cyclones (Walsh 1983;, Kaufman 1983; Turpin and Bortone 2002; Patterson et al. 2001; Watterson et al. 1998).

Although major hurricanes, category 3 and above, only make up 20% of total landfalls, they account for over 85% of tropical cyclone related damage in the United States (McAdie et al. 2009). Direct damages to fisheries include damage to boats, offloading facilities, docks and marinas, boat yard, ice houses and bait and tackle shops (NMFS 2007).

Stock Assessments

Scientists perform stock assessments to estimate current stock status and predict how stocks will likely change in response to alternative management approaches. This information provides managers with critical information needed to evaluate and choose between management strategies. Various types of data go into models used in stock assessments, including data related to catch, abundance, and population demographic rate statistics. Additionally, there are multiple types of models used for stock assessments that vary in complexity and require different data input (Cooper 2009). The type, quality, and quantity of data available often determine the type of model that can be used (Cadima 2003).

Data used in stock assessments can be classified as either fishery-dependent or fishery-independent. Fishery-dependent data are derived from the fishing process itself and can be obtained through biological sampling at landing ports, observing and sampling onboard fishing vessels, telephone surveys, self-reporting programs, or vessel monitoring systems. Fishery-independent data are derived from activities that do not involve the commercial or recreational harvest of fish. Examples of fishery-independent data include biological sampling on board research vessels, including trawl, acoustic, video, and research surveys and some tagging experiments (Cooper 2009; Cadima 2003).

Self-reported fishery-dependent data often include counts and measurements related to catch, landings, fishing effort, and gear characteristics. Catch rates, also called catch per unit effort (CPUE), are frequently derived from self-reported data. Estimates of CPUE are often standardized and interpreted as indices of abundance. Standardized measurements of CPUE are assumed to change proportionally in relation to changes in actual abundance:

$$CPUE_t = qN_t$$

where N_t is the population abundance at time t, and q is the catchability coefficient. The term catchability relates to the proportion of a stock that is susceptible to a single unit of effort. Limitations of standardized CPUE based on constant catchability are reviewed by Mauner et al. (2006).

Fisheries scientists are increasingly incorporating methods to evaluate uncertainty associated with stock assessment output (Caddy 1995). Doing so provides managers with probability distributions for critical management reference points, allowing managers to make more informed decisions based on risk assessments.

Different types of error contribute to uncertainty in the stock assessment process. The types of errors can be categorized as process, observation, model, estimation, implementation and institution errors (Francis and Shotton 1997). Environmental variability, including the occurrence of severe weather events, likely contributes to both process and observation errors. Process error describes the stochasticity in population dynamics such as variation in demographic rates and processes, while observation error describes measurement and sampling errors that occur in the process of collecting data (Francis and Shotton 1997). Tropical cyclones can be considered as a source of process error by increasing variation in natural phenomena as well as a source of observation error by influencing the ability of researchers to take unbiased samples.

In the southeastern United States, the NMFS and South Atlantic, Gulf, and Caribbean Fisheries Management Councils work together in the Southeast Data, Assessment, and Review stock assessment process (SEDAR). Within SEDAR there is no established protocol for incorporating tropical cyclone events into stock assessments. In some years, a large component of the process and measurement errors that contribute to uncertainty in the assessments process may be due to extreme weather events that go unaccounted for in the assessments.

Incorporating Disturbance Events into Stock Assessments

In a situation where the effects of a disturbance event are not specifically attributed to the event, they may be wrongly attributed to other factors. This can potentially lead to misinterpretations of stock status, or incorrect population projections. In contrast, appropriately including responses in assessments can lead to improved stock status determinations and a better understanding of how stocks may respond to future disturbances. This point is illustrated in the 2009 Gulf of Mexico assessments for both red and gag grouper where statistical age-structured models were adjusted to account for additional mortality associated with a red tide event (SEDAR 2009a; SEDAR 2009b).

Red tides in the Gulf of Mexico are caused by algae blooms of a toxic marine dinoflagellate called *Karenia brevis*. *K. brevis* naturally occurs in low numbers throughout the Gulf of Mexico and produces a suite of neurotoxins that, in high concentrations, are responsible for fish-kills and die-offs of other marine organisms (Heil and Steidinger 2009).

In 2005 an unusually large red tide that lasted the entire year occurred on the west Florida shelf. Direct reports of fish-kills, and declines observed across indices of abundance in each species, both in 2005 and 2006 (Figures 2.2a and 2.2b), suggested that a large number of fish deaths were likely associated with the red tide (SEDAR 2009a; SEDAR 2009b).

Traditional models, referred to as central models, which did not explicitly incorporate the 2005 red-tide related mortality, could only account for the large declines in abundance in 2005 and 2006 by increasing natural mortality over a number of years. Because of this, the models were found to poorly recreate historical data (Figures 2.3a and 2.3b). This result led assessments scientists to develop an ad hoc method to account for the unusually high mortality observed during the severe 2005 red tide. The method involved incorporating an additional mortality parameter for 2005, referred to as an episodic mortality rate. The episodic mortality was applied equally to all ages and was considered additive to the baseline natural mortality (SEDAR 2009a; SEDAR 2009b).

Models that included the episodic mortality rate were better able to fit strong declines in 2005 and 2006, and also better able to recreate historical trends (Figures 2.3a and 2.3b) than models that were not adjusted to account for the red tide. For both gag and red groupers, the model that incorporated the episodic mortality was selected by the Gulf of Mexico Science and Statistical Division as the basis for management advice. Using these models scientists were able to estimate that 21 and 18 percent of the 2005 populations of red and gag groupers, respectively, were likely killed by the red tide (SEDAR 2009a; SEDAR 2009b).

Since red tides occur often, they will likely be incorporated into future assessments of red and gag groupers, and other affected species. Now that scientists are aware of the importance of including these events in the assessment process, steps are being taken to identify relationships that can be used to develop an index of red tide severity, and to develop methods to incorporate such an index (Walter et al. 2009).

Like red tides, we can expect severe weather events to continue to affect marine resources and fisheries in the southeastern United States. However, little is known about the extent to which responses following severe weather events may influence marine stock assessments.

Because severe weather events can potentially influence the data input into stock assessments, they may also influence our ability to manage for sustainable and healthy fisheries. As an example, a storm-induced change in the distribution of fish that results in a change in catch rates may be mistakenly attributed to a change in abundance. This change in abundance could be further attributed to a change in recruitment or mortality parameter estimates. Failure to account for other hypothetical storm-induced changes, such as changes in fish distributions, behavior or catchability, would have similar implications. Scientists could incorporate ways to correct for the effects of severe weather in stock assessments, as has been done in cases involving red tide where an episodic mortality rate was incorporated (SEDAR 2009a; SEDAR 2009b), but need more information about specific responses to these events.

In this study, I investigated specific stock and fishery responses to severe weather events in the Florida Keys for four reef species in two fisheries. I analyzed responses in fishing effort and CPUE to identify if, and describe when, responses to severe weather events are reflected in self-reported fishery data.

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Table 1.1: Number of hurricane events by category for specified coastal states, 1851-2006. State totals represent only the highest category experienced for each hurricane (McAdie et al. 2009).

	Hurricane Category						
	1	**2**	**3**	**4**	**5**	**All**	**(3, 4, 5)**
Texas (TX)	24	18	12	7	0	61	19
(North)	13	7	3	4	0	27	7
(Central)	8	5	3	2	0	18	5
(South)	7	7	7	1	0	22	8
Louisiana (LA)	19	15	16	3	1	54	20
Mississippi (MS)	2	6	8	0	1	17	9
Mississippi (MS) (inland)	1	0	0	0	0	1	0
Alabama (AL)	11	5	5	0	0	21	5
Alabama (AL) (inland)	6	0	0	0	0	6	0
Florida (FL)	43	34	29	6	2	114	37
(Northwest)	26	18	14	0	0	58	14
(Northeast)	13	8	1	0	0	22	1
(Southwest)	17	10	8	4	1	38	13
(Southeast)	13	14	11	3	1	42	15
Georgia (GA)	6	5	2	1	0	14	3
Georgia (GA) (inland)	8	0	0	0	0	8	0
South Carolina (SC)	17	7	4	2	0	30	6
North Carolina (NC)	21	14	11	1	0	47	12
North Carolina (NC) (inland)	3	0	0	0	0	3	0
Virginia (VA)	5	2	0	0	0	8	1
Virginia (VA) (inland)	2	0	0	0	0	2	0
Maryland (MD)	1	1	0	0	0	2	0
Delaware (DE)	2	0	0	0	0	2	0
Pennsylvania (PA) (inland)	1	0	0	0	0	1	0
New Jersey (NJ)	2	0	0	0	0	2	0
New York (NY)	6	1	0	0	0	12	5
Connecticut (CT)	5	3	0	0	0	11	3
Rhode Island (RI)	3	2	0	0	0	9	4
Massachusetts (MA)	5	2	0	0	0	10	3
New Hampshire (NH)	1	1	0	0	0	2	0
Maine (ME)	5	1	0	0	0	6	0
Total in U.S. (Texas to Maine)	108	74	75	18	3	278	96

Table 1.2: Summary of potential storm related agents of disturbance in marine ecosystems.

Potential Storm Related Disturbance	Supporting Literature
Water-motion	
Waves, storm surge, tides	Stoddart 1963; Tabb and Jones 1962
Sediment movement	Timant et al. 1994
Barometric/ hydrostatic pressure changes	Heupel et al. 2003
Water quality	
Sediment suspension/turbidity	Bell and Hall 1994; Tabb and Jones 1962, and Timant et al. 1994
Nutrient Influx	Timant et al. 1994
Oxygen depletion	Tabb and Jones 1962; Timant et al. 1994
Salinity change	Goreau 1964; Tabb and Jones 1962
Salinity change	Goreau 1964; Tabb and Jones 1962

Table 1.3: Summary of literature regarding general physical, biological, and social alterations caused by tropical cyclones

Effects	Supporting Literature
Habitat-Related	
Mangrove abundance	Tabb and Jones 1962
Natural/artificial coral structure and or health	Walsh 1983; Woodley et al. 1981; Goreau 1964
Sea grass abundance	Tabb and Jones 1962
Algal blooms/Primary Production	Walsh 1983; Conner et al. 1989
Fish-Related	
Mortality	
Mangled, Stranded, Buried, or Suffocated	Tabb and Jones 1962
Behavior	Kaufman 1983,
Distributions/Relocation	Walsh 1983; Kaufman 1983; Turpin and Bortone 2002; Patterson et al. 2001; and Watterson et al. 1998
Fishery-Related	
Infrastructure Damage	NMFS 2007
Commercial Catch	Tabb and Jones 1962
Recreational Catch	Tabb and Jones 1962; and Personal Communication in Timant et al. 1994

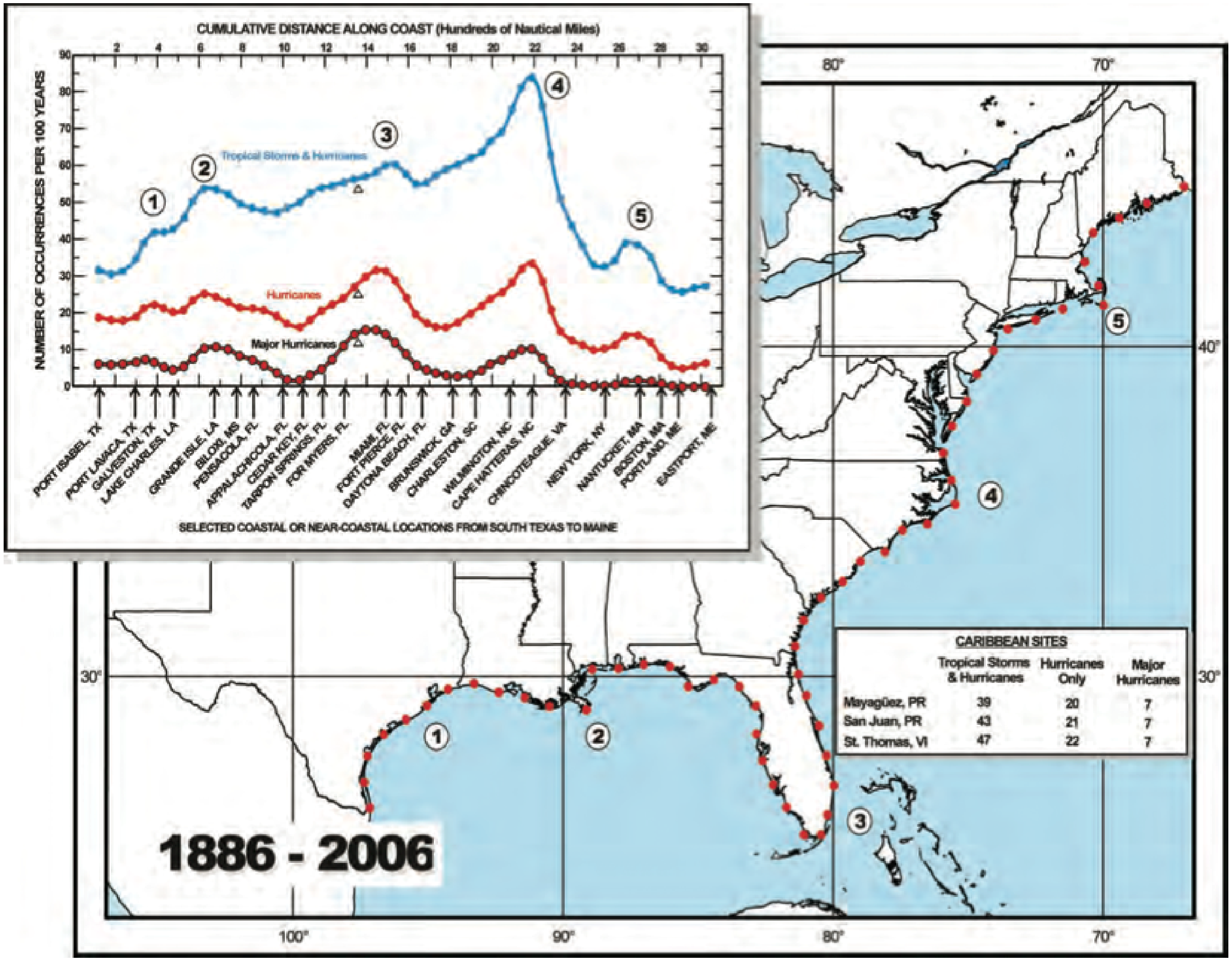
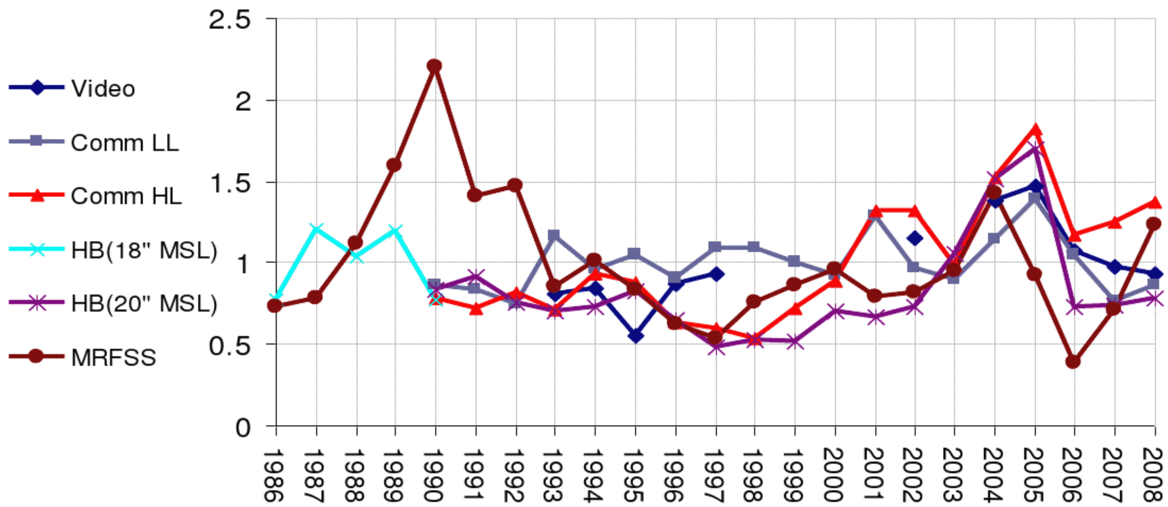


Figure 1.1: Tropical cyclone frequency and intensity along the United States coastline, south Texas to Maine. Inset chart gives frequency of tropical cyclones for three different intensity categories, passing near selected coastal (a white triangle designates Key West, FL). Comparable data for a few Caribbean sites are given in the lower right corner of map (McAdie et al. 2009; [public domain]).

a. Red Grouper Indices



b. Gag Grouper Indices

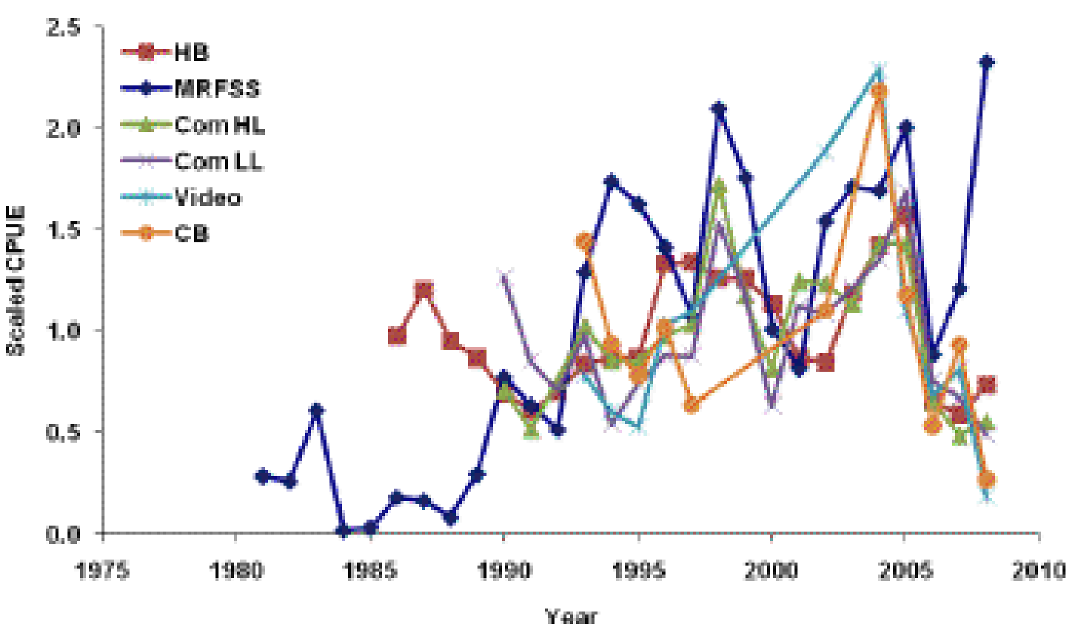
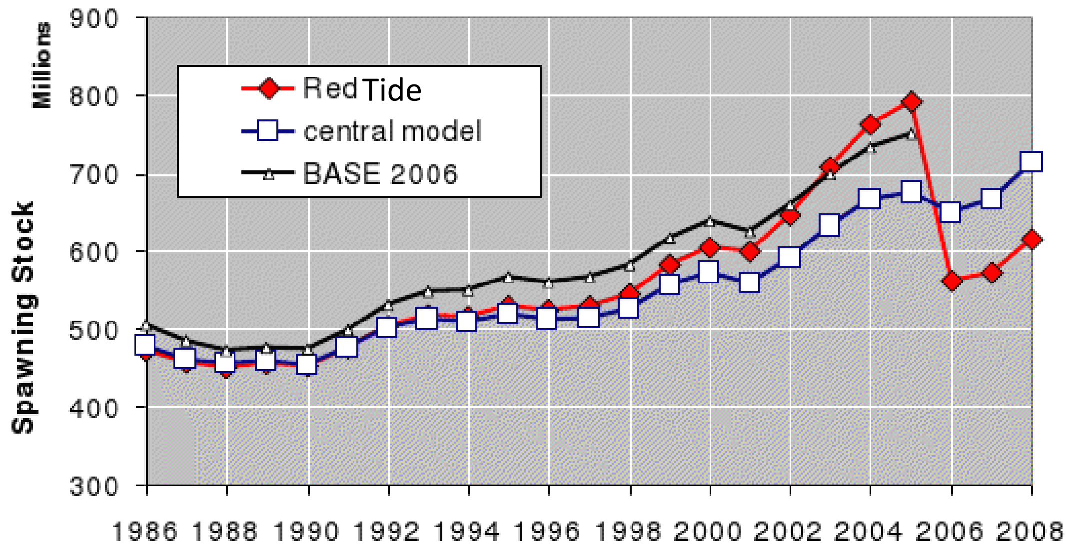


Figure 1.2: Catch per unit effort indices used in 2009 red (a) and gag (b) grouper Gulf of Mexico Stock assessments (SEDAR 2009a, SEDAR 2009b; [public domain]).

a. Red Grouper Spawning Stock Biomass Trajectory



b. Gag Grouper Spawning Stock Biomass Trajectory

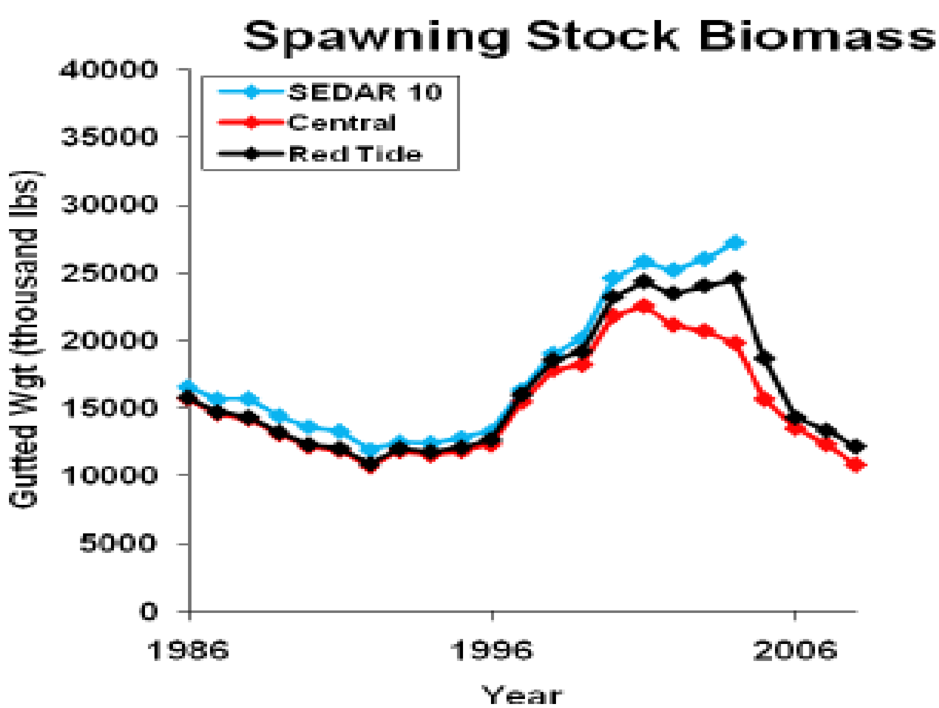


Figure 1.3: Biomass trajectories for three forward-computing statistical catch-at-age model runs for red (a) and gag (b) groupers. Base 2006 and SEDAR 20 biomass trajectories reflect models that were previously run in 2006; central biomass trajectories reflect models run in 2009 without additional red tide mortality; and red tide biomass trajectories reflect models run in 2009 that incorporate episodic mortality in 2005 (SEDAR 2009a, SEDAR 2009b; [public domain]).

CHAPTER 2 – EFFECTS OF HURRICANES AND OTHER SEVERE WEATHER EVENTS ON FISHING EFFORT AND CATCH PER UNIT EFFORT OF REEF-FISH IN THE FLORIDA KEYS

Introduction

Severe weather events, such as tropical cyclones frequently affect fish and fisheries in the southeastern United States (NWS 2011; Harmelin-Vivien 1994). In response to these disturbances, fish may move from their usual habitat while fishing fleets may change in size and behavior. However, environmental disturbances such as these are not traditionally incorporated into stock assessments.

If not accounted for appropriately, disturbance-induced changes can potentially increase variability and uncertainty in assessments, lead to mistaken interpretations of stock status, or propagate inaccuracies in indices or projections used to manage fisheries. Scientists could incorporate ways to correct for the effects of severe weather events in stock assessment, as has been done in cases involving episodic mortality associated with toxic algal blooms (SEDAR 2009a; SEDAR 2009b), but need more information about specific responses to severe weather.

Directly observing the effects of severe weather events on fish stocks is difficult, as sampling can be limited during, immediately after and occasionally for sometime following events (Bell and Hall 1994). An additional difficulty is the limited predictability of when and where severe weather will occur (Keim et al. 2006). Due to these complications, there is a lack of empirical research related to how extreme weather events affect fisheries and fish stocks.

The availability of self-reported fishing data from a region frequently affected by tropical cyclones provided a unique opportunity to investigate short-term responses to past events. Self-reported data are routinely reported in many United States fisheries, and these data are also frequently incorporated in stock assessment. However, they have yet to be comprehensively investigated for potential fishery or stock-wide responses to severe weather disturbances.

This study explored whether variability observed in fishery-dependent data gathered for use in stock assessments may be related to severe weather events. To do this, I investigated specific stock and fishery responses to multiple severe weather events for two fisheries in the Florida Keys. To interpret when and how severe weather events may affect fish and fisheries in this region I selected severe weather events, calculated changes in effort and catch per unit effort (CPUE), and analyzed those changes across various temporal, spatial, and species-specific scenarios.

Methods

Study Site

The primary study site was defined as the Florida Keys region in south Florida (Figure 2.1). The Florida Keys are a chain of islands that extend about 350 km to the southwest from southeast Florida to the Dry Tortugas. The area's coastal marine ecosystem includes estuary, lagoon, mangrove, seagrass, and coral reef habitats. The third largest barrier reef in the world runs parallel to the island chain along its Atlantic coast. Diverse marine resources in the region support multiple industries including highly valued commercial and recreational fisheries.

While areas across the coast from Texas to Maine are all vulnerable to tropical cyclone strikes, the Florida Keys are particularly susceptible. South Florida saw the highest frequency of hurricane strikes in the United States between 1901 and 2005 (Keim et al. 2006). Thirteen tropical cyclones came within 100 nautical miles of the center of the study site (82W, 25N) between 1995 and 2010 (Figure 2.2). This included five tropical storms, seven hurricanes and one extra-tropical storm (Table 2.1). I selected this site based on both the frequency of hurricane and tropical storm strikes in the past two decades, and on the availability of spatially and temporally overlapping fishery and meteorological data collection programs.

Species Analyzed

The 4 reef-fish stocks analyzed in this study were yellowtail snapper (*Ocyurus chrysurus*), mangrove snapper (*Lutjanus griseus*), mutton snapper (*Lutjanus analis*), and white grunt (*Haemulon plumier*). Species were primarily chosen based on the frequency with which they were reported in south Florida fisheries (see data sources section below). Selecting heavily targeted species allowed me to both identify important species and ensure high numbers of reported trips for analysis. To ultimately a select diverse group of frequently targeted species, and to analyze data for each selected species similarly over multiple years, I also considered factors such as life history strategies and species-specific fishing regulations. What follows is a brief review of the life history of each species (summarized in table 2.2).

Yellowtail Snapper

The yellowtail snapper is a coastal reef fish in the western Atlantic that is distributed between Massachusetts and Brazil. The species is particularly abundant in the Bahamas, off south Florida and in the Caribbean. Yellowtail snapper occur mostly in waters up to 70 m deep and frequently are found in large schools over hard substrate and coral reefs (Allen 1985). Yellowtail snapper have been observed to live up to 17 years, but most aged fish of the species have been under the age of 5 (Muller et al. 2003). Yellowtail snapper are commonly about 40 cm long (total length), and in the Florida Keys, yellowtail snapper spawn in offshore aggregations between February and November, with peak spawning activity between April and June (Allen 1985; Muller et al. 2003).

Mutton Snapper

The mutton snapper is a coastal reef fish in the western Atlantic that is distributed from Massachusetts to Brazil. Mutton snapper are most abundant along the Bahamas, off south Florida and in the Caribbean. Juvenile and sub-adults inhabit estuaries and mangrove coastal areas, while adults are associated with reef and hard bottom areas in depths between 25 and 95m deep (Burton 2002; Allen 1985). With a common length of 50 cm (Allen 1985), mutton snapper is the largest of the four species analyzed in the present study. In Florida's Atlantic waters and in the Florida Keys, Burton (2002) recorded a maximum age of 29 years, and maximum length of 88 cm. While mutton snapper along the west coast of Florida have been aged as old as 40, most sampled fish have been younger than 8 (Faunce et al. 2007). In Florida waters, spawning takes place in aggregations from March to July, with a peak between April and June (Faunce et al. 2007).

Mangrove Snapper

The mangrove snapper, also known as gray snapper, is a coastal and offshore reef fish in the western Atlantic that is distributed from Massachusetts to Brazil, and Bermuda. It is especially abundant off of south Florida. Mangrove snapper juveniles and sub-adults can be found in estuaries, mangroves, and lower reaches of rivers, while adults inhabit coral reefs and hard bottom areas (Allen 1985). Occurring from shallow inshore waters to depths of 180 m, mangrove snapper has the largest depth range of the species analyzed in this study (Carpenter 2002). Burton (2001) recorded a maximum age of 24 years along the east coast of Florida. Mangrove snapper are commonly about 40 cm long (total length) (Burton 2001). Near Key West FL, mangrove snapper spawn in offshore aggregations in the summer with peak spawning between June and July (Starck 1971; Domeier et al. 1993).

White Grunt

The white grunt is a coastal reef fish in the western Atlantic that is found from the Chesapeake Bay to Brazil. With a common length of 30 cm and inhabiting depths of up to 40 m (Carpenter 2002), white grunt has both the smallest common length and the shallowest habitat of the four species analyzed in this study. White grunt are found commonly along mangrove coasts and in reef habitats (Carpenter 2002). In south Florida white grunt have been observed to live up to 15 years (Potts and Manooch 2001). White grunt in south Florida form spawning aggregations between April and September, with peak spawning in April and May (Murie and Parkyn 1999).

Relevant Fishing Regulations

Species-specific federal fishing regulations are in place for the species analyzed in this study. They include minimum size limits, and bag limits. Minimum size limits apply to both commercial and recreational fishing. Over the entire period being analyzed in this study (1995 - 2010) the minimum total length was 12 inches for both yellowtail snapper and mangrove snapper and 16 inches for mutton snapper (56 FR 56016; 59 FR 66270). There was no minimum size for white grunt.

Bag limits differ between areas of the study site that are considered part of the Gulf of Mexico (Areas 1 and 2) and areas considered part of the South Atlantic (Areas 2580, 2482, 2481, and 2480). Bag limits are also specific to either commercial or recreational fisheries. For recreational fisheries in both the South Atlantic and Gulf of Mexico there is a limit of 10 snappers per person per day (56 FR 56016). In the South Atlantic, recreational fishing is also limited to 20 fish per person per day among a list of species that includes white grunt (64 FR 3624). For commercial fishing in the South Atlantic there is a seasonal bag limit from May to June for mutton snapper. During these months only 10 mutton snapper can be landed per commercial fishing trip and no more than 10 can be retained per person per day (56 FR 56016). Relevant bag limits, both recreational and commercial, were implemented prior to the respective years over which data from commercial and recreational fisheries were analyzed in this study (1995-2010 and 2006-2010, respectively).

In addition to the species-specific federal fishing regulations just described, there are also designated management zones within the Florida Keys study region (Figure 2.3). These include national marine sanctuaries, national parks, state parks, preservation areas, refuges, and reserves (Brandt et al. 2009). The extent to which fishing and other activities are restricted varies among the different areas. Individual management areas in the Florida Keys, and their respective regulations, were established both before and during the period analyzed in this study. Notable additions after 1995 include a network of no take marine reserves established in 1997 as part of the Florida Keys National Marine Sanctuary management plan, an expansion to that network in 2001, and the designation of a research area within the Dry Tortugas National Park in 2007 (Brandt et al. 2009).

Data Collection Programs

Fisheries in the Florida Keys are managed at both state and federal levels and monitored by various state, federal, and academic research programs. This study explored relationships between extreme weather and changes in fisheries using data from three long-term data collection programs. They included one commercial fishery-dependent program, one recreational fishery-dependent program, and one meteorological data collection program. I selected these programs based on each program's spatial and temporal resolutions and coverage in the Florida Keys region between 1995 and 2010. The data programs were the Coastal Fisheries Logbook program, the Southeast Headboat Logbook Survey, and the Coastal-Marine Automated Network program.

Meteorological Data

I obtained meteorological data from the Coastal-Marine Automated Network (C-MAN) program operated by the National Weather Service's National Data Buoy Center (NDBC 2009). The C-MAN program was established in the early 1980's and is made up of about 60 stations located on lighthouses, beaches, near shore islands, and offshore platforms along the United States' coasts. Each station collects and transmits hourly data for wind direction, wind speed, barometric pressure, and air temperature. Some stations are also equipped to measure sea surface water temperature, water level, waves, relative humidity, precipitation and visibility. There are six C-MAN Stations in the study site, but data from only one C-MAN station, station SMRK1 located at Sombrero Key, was used in this study (Figure 2.1). I selected station SMRK1 based on higher temporal coverage of wind speed and barometric pressure measurements between 1995 and 2010 compared to the other stations within the study site.

I calculated daily maximum wind speed and minimum barometric pressure for station SMRK1 from the hourly measurements provided by the National Data Buoy Center. Because tropical cyclones differed in both intensity and proximity to the study site, I used daily maximum wind-speed from the C-MAN station on Sombrero Key to describe locally observed weather severity. Mean daily maximum wind speed was 9.56 m/s (21.31 mph), while the highest daily maximum wind speed was 42 m/s (93.95 mph) and was associated with Hurricane Georges on August 25, 1998. The relationship between local daily maximum wind speed and minimum barometric pressure for all dates, 1995 to 2010, is shown in figure 2.4. Dates associated with tropical cyclone events are highlighted in red, and illustrate the high wind speeds and low barometric pressures associated with these events.

Coastal Fisheries Logbook Program

The Coastal Fisheries Logbook Program is a self-reporting fishery-dependent program for multiple coastal fisheries in the south Atlantic United States. The Coastal Fisheries Logbook Program, from here on referred to as the "logbook" program, is part of the Fisheries Logbook System managed by the National Marine Fisheries Service (NMFS) Southeast Fisheries Science Center (Poffenberger 2005). The logbook program was initially implemented in 1990 for vessels in the Gulf of Mexico reef fishery and was expanded to include the South Atlantic snapper-grouper fishery in 1992, coastal shark fisheries in 1993, and king and Spanish mackerel fisheries in 1999. Vessels with permits in these fisheries are required to submit a logbook form for each individual trip that lands fish. Information on each logbook form includes total pounds for each species landed, the type and quantity of gear, the date of departure and return, the county and state where the catch is landed, an estimate of fishing time, the number of crew, and fished area code.

I narrowed the logbook data down to only single day trips between 1995 and 2010 that reported vertical line gears and fishing areas within the study site (Figure 2.5). I also filtered the logbook data to remove trips with unreliable, missing, or impossible data following methods used by McCarthy (2011). This included removing trips that submitted logbook forms more than 45 days after a vessel had unloaded its catch, and also removing trips with missing effort data, fractions of gear fished, multiple reported areas, or a daily fishing time greater than 24 hours.

Based on McCarthy's (2011) methods, which included removing effort outliers, I removed trips with number of crew, lines fished, or hooks-per-line outside of respective gear specific 99.9th percentiles. Handline gear trips that I removed in this step included those that reported more than 8 crew members, having fished more than 8 lines at a time, or having fished more than 14 hooks per line. Outliers for the electric reel gear included trips that reported more than 4 crew members, having fished more than 4 lines at a time, or having fished more than 12 hooks per line.

Total hook hours represented the total effort measure for each logbook trip. I calculated total hook hours as the product of the number of lines fished, number of hooks per line, and number of hours fished (McCarthy 2011). I calculated species-specific CPUE as total pounds of a given species landed on a trip divided by the total hook hours of that trip (McCarthy 2011). To exclude unreliably high and potentially mistaken values of CPUE, I also removed trips with species-specific CPUE values outside of respective 99.9th percentiles for each of the four species analyzed (McCarthy 2011). This included trips that reported CPUE greater than 159, 47, 110, and 67 total pounds per hook hour for yellowtail snapper, mutton snapper, mangrove snapper, and white grunt, respectively. In addition to McCarthy's filtering methods, I also removed unreliable trip records that reported identical fishing activity but inconsistent landings for a given species. Over the time period between1995 to 2010 the filtered logbook dataset included 102,397 individual trips made by 1,509 unique vessels. Over the years 1995 to 2010 yellowtail snapper was the most frequently caught species (Table 2.3), and area 2481 was the most frequently fished area (Table 2.4).

Southeast Headboat Logbook Survey

Headboats, also known as party-boats, are for-hire fishing vessels that accommodate 6-60 recreational anglers (Conn 2009). Passengers pay per-person admission fees and typically fish using handlines. The headboat fishery frequently targets species associated with reefs and hard bottom habitats, such as snappers, groupers, and grunts.

The Southeast Region Headboat Survey is a two-part recreational fishery survey administered by the NMFS (Brennan 2010). The SRHS began in North and South Carolina in 1972 and grew to include northeast Florida in 1976, southeast Florida and the Florida Keys in 1978 and the Gulf of Mexico coast from southwest Florida to Texas in 1986. The first component of the survey is a dockside intercept-sampling program and the second is a self-reported logbook program, the latter was used in this study and will here on be referred to as the "headboat program". Licensed headboat charter vessels are required to submit a logbook form for every trip. The form details the numbers and weights of individual species caught, number of passengers, number of anglers, location fished, area docked, trip date, trip duration, and the disposition and numbers of released fish. Location fished is specified to an approximately 10 mile by 10 mile grid and trip duration is specified as either half day, three-quarters of a day, full day, or by the number of days in a multi-day trip. Headboat trips included in this study were subset to only include single day trips (½ day, ¾ day and full day), and trips whose fishing location was specified to be within the study region. To achieve a comparative spatial resolution between the logbook and headboat programs, headboat fishing locations were redefined to a resolution of 1^{o} latitude by 1^{o} longitude (Figure 2.6).

The measure of effort for each headboat trip was total angler hours. I calculated total angler hours as the product of hours fished and the number of anglers (Conn 2009). I assumed hours fished to be 5 hours for half day trips, 7 hours for three quarters day trips, and 9 hours for full day trips (Conn 2009). I calculated species-specific CPUE for any caught species as the sum of numbers kept, numbers released alive, and number released dead, divided by the total angler hours (Brown 2006). Headboat trips in the study site prior to 2006 were excluded due to low fisher compliance and low numbers of trips being reported in the early and mid 2000s (Figure 2.7). The resulting dataset included 8,469 individual trips made by 11 unique vessels. Over the years 2006 to 2010 the most frequently caught species in those trips was yellowtail snapper (Table 2.3), and the most frequently fished area was area 2480 (Table 2.4). Not all headboat areas had sufficient trips to meet data confidentiality requirements; when this occurred analysis results and summary information for such areas remained confidential.

Date Selection

In order to analyze fish and fishery changes in response to multiple severe weather events ranging in severity, I first identified the specific events over which to analyze changes in effort and CPUE. Since high daily maximum wind speeds and low barometric pressure were not exclusively associated with tropical cyclone events (Figure 2.6), I used a subjective process to select events based on locally observed weather severity, with severity defined as maximum wind speed. When two events with high daily maximum wind speeds occurred close in time, only the more severe event was selected.

To avoid analyzing overlapping data for any two events, I used buffers such that selected events were set a minimum number of days apart. This allowed me to associate the periods analyzed before and after each event with only a single selected severe weather event. To avoid introducing missing meteorological data, I also applied buffers around dates without measurements for maximum daily wind speed. I used buffer lengths of 11, 15, and 29 days, that corresponded with 5-, 7-, and 14-day periods over which data was analyzed before and after each event.

To select events, I indexed all dates between 1995 and 2010 by daily maximum wind speed. I then designated the date with the highest daily maximum wind speed as the first selected event. I subsequently removed both the date of the selected event and the appropriate number of days before and after from the selection pool of potential events. I repeatedly identified events and removed dates from the selection pool until no more events could be selected. I did this separately for each buffer length and only included dates selected for all three buffers in a final list, thus ensuring that events were local maxima.

Between 1995 and 2010, the period over which responses in the logbook data were to be analyzed, I identified 112 events to analyze. The mean and maximum wind speeds of those 112 events were 17.51 m/s and 42.00 m/s, respectively. Eight of the events were associated with tropical cyclones. They were Georges, Mitch, Irene, Dennis, Rita, Wilma, Ernesto, and Fay (Table 2.1). Between 2006 and 2010, the period over which responses for the headboat data were to be analyzed, I identified 36 events (a subset of the 112 selected events over the longer timeframe). The mean and maximum wind speeds of those 36 events were 16.25 m/s and 26.80 m/s, respectively. Two of the 36 events were associated with tropical cyclones. They were tropical storm Ernesto and tropical storm Fay.

Calculating Response Variables

To calculate changes in effort and CPUE following dates associated with severe weather, I designated before and after periods for each selected event. These periods were the 5, 7 or 14 days immediately before or after an event. As values for change in CPUE are only available when fishing effort is non-zero both before and after an event, I set the shortest period length as 5 days to minimize scenarios with insufficient data. While responses may exist at shorter or longer intervals than 5, 7 or 14 days, I selected these three period lengths for the present exercise of exploring short-term changes in effort and CPUE and investigating if they persist across relevant, but arbitrarily selected time intervals.

For each fishery, I calculated changes in effort and CPUE for different combinations of event, species, area, and period length. I defined change in effort as the difference between average total daily effort between periods directly before and after an event. Total daily effort for a given date was the sum of effort for all trips associated with that day.

I defined change in CPUE as the difference between average CPUE per trip between periods directly before and after an event. Days without effort did not contribute information to the averages used to calculate changes in CPUE. At least one reported trip in the period directly before, and one in the period directly after an event were necessary to obtain a value for change in CPUE.

While I calculated differences in effort and CPUE for specific event, species, area, and period length scenarios, I did not consider all scenarios informative and applicable for analysis. I excluded scenarios in which fishing effort was zero both before and after from analyses on change in effort. Similarly, I excluded scenarios in which CPUE was unavailable either before or after an event from analyses on change in CPUE.

Statistical Analyses

For each fishery, changes in effort and catch-per-unit-effort following severe weather events were analyzed to identify and describe fishery and fish stock responses to past weather events. Responses in each variable were analyzed within and across scenario factors and explored for correlations and linear multivariate relationships with hypothesized explanatory variables. Results were interpreted generally as well as with specific regard to fishery, period lengths, species, and fishing areas. All analyses were performed in the R language and environment for statistical computing (R Development Core Team 2010).

Identifying and Describing Changes in Fisheries and Fish Stocks to Past Weather Events

The first objective was to identify and describe fishery specific changes to past weather events. This was to be achieved using paired t-tests to identify if overall responses were significantly different from zero, and ANOVAs to identify differences across scenario factors. However, in order to determine if these analyses (as well as subsequent analysis for correlations) would be conducted using parametric or non-parametric methods, assumptions of normally distributed responses were tested.

I performed the Shapiro-Wilks test of normality for each response variable using the Shapiro.test function from the stat library available on the Comprehensive R Archive Network (Venables and Ripley 2002). For each response variable within each fishery, I performed the test separately for scenarios associated with different period lengths; first for all species and areas, then by species for all areas, and lastly by area for all species. I used an alpha, or probability of falsely accepting a null hypothesis (type I error), of 0.05 as a cut off to determine when to reject the assumption of normality. If the majority of distributions were not approximately normal, and no obvious transformations were available, I subsequently analyzed changes using non-parametric methods.

When assumption of normally distributed responses in either effort or CPUE were not met, I used a non-parametric version of a paired t-test called the Wilcoxon signed rank test to test if, and identify when, responses were frequently different from zero (Wilcoxon 1945). I did this using the "wilcox.test" function from the stat library on the Comprehensive R Archive Network (Venables and Ripley 2002). For each response variable within each fishery, I performed the test separately for scenarios associated with different period lengths; first for all species and areas, then by species for all areas, and lastly by area for all species. I used an alpha of 0.05 to define medians that were significantly non-zero, and thereby interpret if overall directional changes were present.

Next, I used the non-parametric Kruskal-Wallis one-way analysis of variance was used to determine if differences in responses for each variable were observed across period lengths, species, or areas (Kruskal and Wallis 1952). To do this I used the "kruskal.test" function from the stat library on the Comprehensive R Archive Network (Venables and Ripley 2002). For each response variable within each fishery, I ran the analyses across different period lengths; first for all species and areas, by species for all areas, and by area for all species. This test was also performed across species and across areas for individual period lengths. I used an alpha of 0.05 to identify distributions that were significantly different, and determine if differences existed across scenario factors.

Identifying Variables Related to Changes in Fisheries and Fish Stocks

The second objective was to identify changes in the environment that are potentially indicative of changes in fishing effort or CPUE. To do this, I first explored changes in each variable for correlations with hypothesized explanatory variables, such as variables related to weather severity. I calculated correlations using the "cor" function from the stat library on the Comprehensive R Archive Network (Venables and Ripley 2002). When assumption of normally distributed responses in either effort or CPUE were not met, I used spearman's rank order correlation coefficient, denoted as ρ (Spearman 1904). A value of ρ equal to 1 describes a perfectly monotonic relationship between two variables. I interpreted values of ρ greater than 0.70 as strong, 0.50 - 0.07 as moderate, and ρ between 0.40-0.50 as weak relationships.

Variables that I tested for correlations with change in effort included maximum wind speed on the date being analyzed, minimum barometric pressure on the date being analyzed, change in average daily maximum wind speed between the before and periods, and change in average daily minimum barometric pressure between the before and after periods (Table 2.5). Variables that I tested for correlations with change in CPUE for each fishery included the four variables described for change in effort, and additional variables related to changes in fishing behavior. They were change in effort between the before and after periods, and the number of consecutive days without fishing starting on the date associated with a severe weather event. I also included change in the percent of trips that reported a given species between the before and after period to address potential relationships between CPUE and any changes in targeted effort (Table 2.5).

Finally, I generated multivariate linear regression models using stepwise methods to identify a subset of variables that together best describe the variability associated with changes in effort and in CPUE following severe weather events. I included all of the previously described hypothesized explanatory variables as well as additional factors such as area, species, year, and season (Appendices A and B). I then ran stepwise model selection in both backward and forward directions by exact AIC using the "stepAIC" function from the MASS library available on the Comprehensive Archive Network (Venables and Ripley 2002).

Results

Identifying and Describing Changes in Fisheries and Fish Stocks to Past Weather Events

Changes in effort following severe weather events were both positive and negative (Example histograms in figures 2.8 and 2.9). The same was true for changes in CPUE (Example histograms in figure 2.10 and 2.11). For each variable and in each fishery, I rejected assumptions of normal distributions (based on $\alpha = 0.05$) more often than not (Tables 2.6 and 2.7). Thus, to identify any significant directional responses, I subsequently used non-parametric hypotheses test.

Overall, logbook fishing effort was reduced by extreme events (Table 2.8). Area 2481 at the 5-day period had the largest decline in effort, as indicated by the largest significantly negative median (p value ≤ 0.05). In contrast to the overall decline in logbook fishing effort, headboat fishing effort did not change (Table 2. 8). Although area 2481 showed increases in headboat fishing effort in response to the severe weather analyzed at both the 5 and 7-day period lengths, the analyses for changes in headboat effort did not reveal an overall consistent direction of change in the study site.

CPUE did not change in response to severe weather events in either fishery (Table 2.9). Although analyses with significantly non-zero median values for change in CPUE occurred for each fishery, the medians were still very close to zero (absolute values of median changes in CPUE were less than 0.30 pounds per hook hour, and those for headboat CPUE were less than 0.07 fish per angler hour). While change in CPUE did not have an overall directional response following severe weather events of varying intensities in either fishery, direction and magnitude of changes in CPUE may still relate to the conditions associated with individual events, or scenario factors, such as period length, specie, or area.

Responses in logbook fishing effort differed across all three of the scenario factors analyzed (Tables 2.10 and 2.11). Significant differences noted across time periods for logbook effort (Table 2.10, p-value ≤ 0.05) all showed stronger negative median responses at the shorter time periods analyzed (Table 2.8). Across species and within each period length, logbook effort declined the most for yellowtail snapper (Table 2.8). Meanwhile, across areas and within each period length, area 2481 had the largest negative median responses in logbook fishing effort, followed by area 2480 (Table 2.8). In contrast to the logbook fishery, responses in headboat fishing effort only differed across areas and only for the 5-day period length (Tables 2.10 and 2.11), where area 2481 had the largest positive responses in headboat fishing effort (9.5 angler hrs, Table 2.8).

Responses in logbook CPUE only differed across areas and only for the 7-day period length (Tables 2.10 and 2.11), where area 2481 had the largest negative median responses in CPUE (-0.29 pounds per hook hour) and area 2480 had the largest positive median response in CPUE (0.17 pounds per hook hour, Table 2.9). Responses in headboat CPUE only differed across species and only for the 5 and 7-day period lengths (Tables 2.10 and 2.11), where white grunt had the largest negative median response in CPUE (-0.05 fish per angler hour, Table 2.9). Although differences in CPUE across species and were identified using the Kruskal-Wallis analysis of variance, it is important to highlight that recall that overall, median changes in CPUE were small (on the scale of less than half a pound of fish per hour the logbook fishery and, and tenths of a fish per hour for the headboat fishery).

The results so far only describe overall patterns and difference across multiple events without regard to event severity. Even when there are no overall directional changes, responses in each variable still warrant further investigation, as there is still potential for relationships between changes in each of the response variables and additional information associated with individual events. Correlations between the direction and degree of observed changes in each effort and CPUE with potential explanatory variables are discussed next.

Identifying Variables Related to Changes in Fisheries and Fish Stocks

Based on spearman correlation coefficients (ρ), changes in logbook fishing effort were only weakly (defined here as $0.40 < |\rho| < 0.50$), or not at all ($|\rho| < 0.40$), associated with the variables I used to describe weather severity (Table 2.12). Only one relationship was suggested based on the correlations between fishing effort and each of the variables related weather severity. This was a weak negative relationship ($-0.40 < \rho < -0.50$) between change in effort and change in wind speed that was only observed in particular scenarios associated with the logbook fishery (Table 2.12).

Example scatter plots of change in effort versus change in average daily maximum wind speed are shown in figures 2.12 and 2.13. While weak ($0.40 < |\rho| < 0.50$), these correlations suggest that increases and decreases in logbook fishing effort may relate more to changes in the conditions over the entire period analyzed than to extremes occurring on a single day.

Changes in headboat fishing effort were not related to any of the variables I used to describe weather severity ($|\rho| < 0.40$, Table 2.13). This suggests that either the headboat fishing effort may be relatively unaffected by extreme weather events or that any responses that relate to meteorological conditions are not reflected at the temporal or spatial scales analyzed in this study.

Changes in CPUE to any of the variables I used to describe weather severity or to describe changes in fishing behavior (Table 2.14 to 2.17). Thus, none of the hypothesized explanatory variables were considered indicative of change in CPUE. However, this can only be said for the fisheries and species analyzed and at the spatial and temporal scales explored.

While the goal of analyzing correlations was to identify potential indicators of change in each CPUE and fishing effort, the exercise also revealed an unexpected relationship associated with each response variable. In each fishery, there was a negative relationship between change in effort and the effort observed in period analyzed prior to each event (Table 2.18 and example plotted in figure 2.14). A similar relationship was observed in each fishery between change in CPUE and the CPUE in the period analyzed prior to each event (Table 2.19 and figure 2.15), such that the larger the effort or CPUE in the period prior to an event, the greater the negative response following the event, but not necessarily as the result of it. Difference observed in the periods prior to events may relate to factors such as year, season, area or species.

In the majority of scenarios, multivariate linear regression models did not explain large proportions of variance in either response variable (Adjusted R-squared values < 0.20). I arbitrarily selected an adjusted R-square value of 0.20 to identify the best performing models. Only seven models, all of which were associated with modeling responses in fishing effort, had proportions of variance explained that were greater than or equal to 0.20 (Tables 2.20 and 2.21). Six of were for change in logbook fishing effort, and one was for change in headboat fishing effort.

The models that performed best at describing changes in logbook fishing effort (Adjusted R-square values between 0.20 and 0.26) included those for the 5 and 7-day period lengths associated with yellow tail snapper over all areas, area 2481 over all species, and area 2480 over all species (Table 2.20).

Each of the best performing models for logbook effort were associated with scenarios in which both a negative overall change, and a negative relationship with change in wind speed were previously identified (Tables 2.8 and 2.12). All of these logbook models also reflected a negative relationship between fishing effort and change in wind speed (Appendix C, models 1 - 6), again suggesting that changes in logbook fishing effort relate to weather conditions over the entire period being analyzed. As lower variability in weather conditions would be expected over shorter periods of time, models associated with the shorter period lengths may have better summarized weather conditions over the periods being analyzed.

The only model that performed well for headboat fishing effort was associated with the 14-day period in area 2481 over all species (R-square value = 0.31; Table 2.21). In contrast to the models for logbook effort, this model was not associated with a previously identified overall response or with any relationships to weather conditions based on the correlation analyses (Tables 2.8 and 2.13). However, like the six best models associated with logbook effort, this model for headboat effort also reflected a negative relationship between change in effort and change in wind speed (Appendix C, model 7). While this suggested that headboat fishing effort may relate to overall weather conditions, little can be said about the spatial and temporal scales at which this may be true for the entire fishery.

Among the multivariate models for logbook fishing effort that performed best, certain variables were repeatedly selected (Table 2.22 and Appendix C). They included change in wind speed, change in pressure, and factors such as season, species (when analyzing across areas), and area (when analyzing across species) (Table 2.22). Additional hypothesized explanatory variables specifically describing the severity of the selected events, such as maximum wind speed or minimum barometric pressure, were not consistently included in models.

Results from the correlations analyses and multiple linear regression models suggested similar conclusions. At the spatial and temporal scales analyzed, changes in fishing effort and in CPUE for either fishery were not related to event severity. However, for certain area-specific and species-specific scenarios, short-term changes in logbook fishing effort were related to changes in overall weather conditions.

Discussion

Severe weather events are likely to affect vertical line fishing effort (Tables 2.8) than they are to affect catch rates of reef-fish species (Tables 2.9). In this study I analyzed responses across multiple events, species and areas. Differences across areas suggest that responses to severe weather events may occur at smaller spatial scales than the entire Florida Keys region (Table 2.11). Meanwhile, differences across species suggest that responses in CPUE may be species specific (Table 2.11). For example, at the 5-day period length, CPUE for white grunt declined while CPUE for each of the three snapper species did not change. As the species with both the shallowest habitat and smallest maximum size, white grunt may potentially be more affected by severe weather events than other species (Table 2.2). Under regular circumstances, the headboat anglers frequently catch white grunt (Table 2.3), however changes in effort, such as fishing in deeper water that might make white grunt less of a targeted species, could also result in reduced CPUE for this species.

In addition to specifically exploring changes in fishing effort and CPUE in two fisheries following extreme weather events, this study also served as an exercise in identifying limitations associated with analyzing short-term responses to multiple disturbance events. Although self-reported fishery-dependent data collection programs take place year-round with relatively high spatial coverage, reporting errors, incomplete information, and unbalanced sampling can complicate the use of this data. Furthermore, analyzing responses to specific events requires making subjective decisions related to identifying events, selecting the spatial and temporal scales for which to analyze responses, and defining how to calculate changes. Such topics are further addressed in the context of this study.

Self-reported Fishery Data

Reporting errors associated with self-reported data reduce the quantity of data available to analyze. I encountered various types of reporting errors were encountered in the logbook dataset. Identifying and filtering out incomplete and unreliable records was not a trivial process. In the process of removing errors, I also investigated different types of errors to ensure that correct information was not available, and that removal was necessary.

In addition to addressing reporting errors, I also excluded multi-day trips in each fishery as I could not accurately attribute effort and catch information with individual dates. As longer trip lengths are associated with fishing farther from shore, removing multi-day trips reduced the number of trips in certain areas more often than others (Table 2.22).

While the number of single day trips over the periods analyzed was high for the entire region (102,397 for logbook 1995-2010 and 8,469 for headboat 2006-2010), not all areas and species combinations had sufficient trips to analyze each selected weather event across all scenarios. That some scenarios had more selected events to analyze than others reflected differences in the number of trips reported by species and by areas (Tables 2.2 and 2.3). As a result, scenarios that were more likely to have higher trip numbers likely drive the results of this study.

A major difference between the data available for each fishery was the extent to which fishers reported fish that were discarded, in addition to fish that were kept or landed. Since 2004, participants in the headboat fishery have been required to include numbers of fish discarded in addition to number of fish landed, together referred to as total catch. In contrast, discard information for the vertical line logbook fishery, while available since 2001, were only collected for only a sample of vessels operating in the fishery. Each year, only 20 percent of vessels with Gulf of Mexico, South Atlantic snapper-grouper, king mackerel, Spanish mackerel or shark permits were selected to report total catch (Poffenberger 2004).

Due to the lack of reported discards for all vertical line logbook trips, effort and CPUE data were interpreted differently between the two fisheries. The interpretation for changes in logbook fishing effort or CPUE was only in regard to trips that landed a given species, also referred to as positive trips. In contrast, the interpretations for changes in headboat fishing effort or CPUE were related to the total fishing effort that a given species was exposed to and thus to all of the fisheries encounters with a given species.

Both catch and landings of reef-fish fisheries are frequently associated with multiple species. However, reported landings in a given trip may not always reflect the species and quantities that are actually caught, as fishers can selectively choose to land only certain species. This is referred to as targeting and can affect estimates of both fishing effort and CPUE.

There is no clear way clear way to objectively differentiate between trips that likely kept all or most legal size fish that were caught, versus those that did not. By having analyzed species-specific changes for only positive trips associated with individual species, the extent to which changes in the logbook data are related to changes in targeting are unknown. Thus, the analyses for changes in effort and in CPUE that were conducted in this study assumed that all legally sized commercial valuable fish that were caught were also landed.

In addition to differences in the data available for each fishery, differences between how the logbook and headboat fisheries operate may relate to how fishing effort in each fishery changes in response to severe weather events. Commercial fisheries generate income by selling landings and are capable of gear switching. Changes in targeted logbook commercial fishing effort may reflect changes in the demand and prices of certain species. Targeted fishing effort may also reflect expected fishing success based on both current marine conditions and on prior experiences of fishers.

In contrast to commercial fisheries, headboat fisheries generate income based on the number of passengers and anglers they take fishing. The numbers of anglers willing to go fishing at any time may reflect factors such as local weather and marine conditions, headboat vessel reputation, and additional statistics related to tourism. Although, angler experience is generally improved when the quantities of fish caught are high, high CPUE during normal conditions is not as essential for the headboat fishery as it is for the commercial fishery in order to generate income. Regardless of if there are any changes in CPUE following severe weather events, headboat vessels are able to operate and generate income as long as vessel and weather conditions permit and anglers are willing to go out fishing.

Differences in how the fisheries operate were apparent in the number of vessels and frequency of trips in each fishery that reported single-day fishing trips in the study site (Table 2.23). For each of the years analyzed for both fisheries, the number of vessels fishing in the study site was higher for the logbook fishery (Table 2.24). However, the average number of trips per vessel was higher for the headboat fishery (Table 2.25).

Negative responses in fishing effort for the logbook fishery may relate to an increased ability to change gear or fishing strategy. While logbook trips included in this study were those reporting vertical line gears, which included both handlines and electric reels, vessels in the coastal logbook fishery can operate using various other fishing methods, including trolling, diving, or using nets, longlines, or traps. Low average trips per vessel imply that part-time vessels are operating in the vertical line fleet, potentially due to an ease of switching gears. By having analyzed only a subset of all gears, the extent to which changes in logbook fishing effort may relate to reductions in effort versus shifts to different gears is unknown.

Identifying and Analyzing Individual Events

A main assumption in this study was that the periods analyzed before and after each event were associated with only a single severe weather event. Although each selected event represented the highest daily maximum wind speed observed over a window of time, weather is constantly changing and can have lingering effects. The influence of events or conditions occurring before the period analyzed for each event were not addressed.

Selecting events that ranged in severity was done purposely to potentially observe differences across event severity. However, among the selected events, truly extreme events, such as hurricanes, were a minority (Table 2.26). In addition to analyzing few extreme events overall, the number of extreme events analyzed also differed between the two fisheries (Table 2.26). Because of this, the results of this study may also reflect differences in the range of years, and thus severity of the events that were analyzed for each respective fishery.

Due to using only one central meteorological station for the entire site, uncertainties remained related to the extent that weather conditions were spatially localized. Meteorological data was most relevant for analyzing changes in areas closest to the station from data were obtained. This was observed in that relationships between change in logbook effort and weather conditions were only observed among area-specific analyses in areas closest to the meteorological station on Sombrero Key.

Metrological data from Sombrero Key was used to both characterize weather across the study site, and to identify dates associated with severe weather that were then analyzed. Thus, both the overall meteorological data, and the dates associated with the events analyzed were less appropriate for regions that were increasingly distant from Sombrero Key. Identifying area-specific severe weather events and more accurately describing local weather by incorporating multiple metrological stations could lead to more meaningful results both across the Florida Keys study site, as well as across future research locations.

Fishery-Dependent Data Versus Fishery-Independent Data

Obtaining adequate data for analyzing responses to tropical cyclones is complicated by the limited spatial and temporal predictability associated with severe weather events. As a result, both fishery-dependent data, such as the self-reported data used in this analysis, and other fishery-independent data, such as biological surveys or tagging studies, are often designed with objectives unrelated to researching tropical cyclone effects.

Studies on short-term effects of past severe weather events on reef-associated fish primarily focus on analyzing individual extreme events, such as hurricanes, and doing so using a combination of data from biological surveys, interviews, and broad observations (Kaufman 1983; Tilmant et al. 1994; Robbins 1957; Woodley et al. 1981; Tabb and Jones 1962; Walsh 1983; Halford et al. 2004; Fenner 1991). Among these studies, there is little empirical information regarding the effects of tropical cyclones on catch rates.

Long-term survey programs, both in the Florida Keys and elsewhere, are often associated with limited temporal resolutions that intend to monitor long-term changes in community structure as well as species abundances or distributions. One such program in the Florida Keys is the Reef Visual Census (RVC). The RVC is a fishery-independent visual monitoring program conducted once a year in the Florida Keys, and every even year in the Dry Tortugas (NPS, 2009). Though this program, annual abundances and size distributions of reef populations are estimated using a habitat-based stratified random survey design and stationary visual survey method. However, the annual temporal resolutions and lack of repeated site-specific surveying within a year, RVC data could not provide insight towards understanding short-term responses to severe but short-lived disturbance events.

Future Research

Based on past research, responses of reef fish to severe weather events may include short-term spatial redistributions of fish. However, both the spatial scales of any such movements, and the length of time they may persist, remain obscure. Future research using both fishery-independent and fishery-dependent methods can further contribute to identifying the most appropriate scales in which fisheries and fish stocks may be most affected.

Due to practical restrictions associated with sampling, limited fishery-independent research techniques are available for studying the short-term effects of storms on fisheries. Comprehensive large-scale tagging programs, potentially even using acoustic telemetry, could provide further information as to the correct spatial scales over which to expect changes in distributions of reef fish, if any, without regard to sampling biases associated with fishers. Examples of such programs in the Gulf of Mexico that were ongoing during tropical cyclones include red snapper tagging studies and acoustic telemetry tags on juvenile black tip sharks (Watterson 1998 et al. 2001; Heupel et al. 2003).

Future work with fishery-dependent data could address some of the limitations in the present study. For example, to further understand responses in logbook fishing effort it would be wise to account for shifts between fishing gears. Also, a certain threshold of event severity could be imposed to exclusively analyze fish and fisher responses to only extreme events.

Further exploring potential storm-induced changes in any fishery would also benefit from investigating additional spatial and temporal scales and from conducting analyses using area-specific meteorological data. As Sombrero Key provided interesting results in the fishing areas close by, additional meteorological stations both in the South Florida and elsewhere could be incorporated to both to better describe weather and potentially to identify area-specific extreme events.

Furthermore, instead of reporting effort and catch for individual multi-day trips, reporting catch and effort could be adapted to reflect individual fishing days. Such a change in how trip-specific information is routinely collected could improve the accuracy CPUE estimates, and increase the amount of data available for short-term analyses, especially in areas farther from shore.

In addition to improving the research in the Florida Keys, this work could also be replicated in other regions that are frequently associated with tropical cyclones such as the central Gulf of Mexico or the Outer Banks of North Carolina.

Management Implications

Severe weather events, such as hurricanes, are only one of many types of disturbances in the marine environment for which effects on important marine resources are not well understood. Additional disturbances such as extreme red tide events and oil spills are also increasingly being researched to understand when and how they should be accounted for in stock assessments.

In the case of an unusually strong and long-lasting red tide that occurred in 2005 on the west Florida shelf, declines observed across multiple fishery indices led scientist to adapt assessment models of gag and red grouper to account for additional mortality associated with this disturbance (SEDAR 2009a; SEDAR 2009b). Including an additional mortality parameter in the 2009 assessments for each grouper species was found to improve the assessment models.

Red tides are relatively common in the Gulf of Mexico, and their effects on the fish are fairly well understood (Heil and Steidinger 2009). While the 2005 red tide stood out in both size and duration, lasting an entire year, it was the declines in indices that prompted scientists to explicitly account for the event. In comparison to red tides, the effects of severe weather events on fish and fisheries are not as well understood. Furthermore, in comparison to the 2005 west Florida red tide, responses associated with severe weather events, like tropical cyclones, are likely to occur over shorter time periods and smaller areas.

At the spatial and temporal scales analyzed in this study, the lack of overall changes observed in CPUE suggested that catch rates are not affected by severe weather events. Had changes in CPUE following severe weather events been identified, they would need to be interpreted in the context of any changes in effort, as spatial changes in total fishing effort in either fishery, or changes in targeted effort specifically in the logbook fishery, can potentially lead to changes in CPUE.

Where and when fishery-dependent data are available are determined by where and when fishing occurs. As abundance indices for entire regions are often extrapolated from non-random fishery-dependent data, understanding spatial changes in fishing effort, and thus sampling, is important for interpreting indices (Walters 2003). However, it is unclear whether the spatial changes in fishing effort and short-term declines following severe weather events are significant enough to affect how indices are spatially interpreted. Further research analyzing standardized indices of CPUE from storm-affected areas is also necessary to determine if storm-induced changes that may or may not be reflected in fishery data are likely to influence the outcome of stock assessments.

Conclusions

Different disturbances affect ecosystems at different spatial and temporal scales. In order to understand how severe weather events affect both fish stocks and fisheries it is important to analyze them at correspondingly adequate scales. This study explored responses at three temporal resolutions for four species in two fisheries. Based on the limited data and analyses in this study, I would not argue for adjusting stock assessments to include severe weather events. Future fishery-independent data programs could help to describe the nature of reef-fish responses to severe weather, as well as to identify the spatial and temporal scales at which fish are most affected. Scientists could then use this information to investigate if severe events may influence the outcome of stock assessments, regardless of whether responses are reflected in fishery-dependent data.

Events, such as hurricanes and tropical storms, will continue to adversely affect coastal habitats and fishing communities in the southeastern United States. Whether future tropical cyclones might also adversely, or even positively, affect fish or fishery catch rates could not be determined with the available data. Considering the limitations of data that are currently available, changes could be made to current fishery-dependent data collection programs in order to more accurately measure responses in fishing effort and in CPUE following future disturbances, and allow for analyses of those responses at finer spatial and temporal resolutions.

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Table 1: Names, category and dates of tropical cyclones that came within 100 nautical miles of the center of the study site (82W, 25N) since 1995 (NOAA 2012). Tropical cyclones selected as severe weather events in this study are highlighted in gray.

Tropical Cyclone Name	Date (Closest to Site)	TC Category (Closest to Site)	Sombrero Key Max. Wind Speed (m/s)	Figure 1 Path ID
Georges	Sep. 25, 1998	Category 2 Hurricane	42	1
Mitch	Nov. 5, 1998	Tropical Storm	20.8	2
Harvey	Sep. 21, 1999	Tropical Storm	18.6	3
Irene	Oct. 15, 1999	Category 1 Hurricane	28.4	4
Charley	Aug. 13, 2004	Category 2 Hurricane	18.6	5
Ivan	Sep. 21, 2004	Extra-Tropical Cyclone	NA	6
Dennis	July 9, 2005	Category 1 Hurricane	33.0	7
Katrina	Aug. 26, 2005	Category 1 Hurricane	29.9	8
Rita	Sep 20, 2005	Category 2 Hurricane	31.5	9
Wilma	Oct. 24, 2005	Category 3 Hurricane	38.7	10
Ernesto	Aug 30, 2006	Tropical Storm	17.1	11
Fay	Aug. 18, 2008	Tropical Storm	26.8	12
Bonnie	July 23, 2010	Tropical Storm	11.6	13

Table 2.2: Summary of life history characteristics, including maximum age, size and habitat depth as well as spawning months of the four species analyzed.

Species	Max. Age	Max. Size	Max. Depth	Spawning Months	References
Yellowtail Snapper	17 years	40 cm	70 m	April - June	Allen 1985; Muller et al. 2003
Mutton Snapper	29 years	50 cm	95 m	April - June	Allen 1985; Burton 2002; Faunce et al. 2007
Mangrove Snapper	24 years	40 cm	180 m	June - July	Allen 1985; Burton 2001; Domeier et al. 1993 Stark 1971;
White Grunt	15 years	30 cm	40 m	April - May	Carpenter 2002; Murie and Parkyn 1999; Potts and Manooch 2001

Table 2.3 Percentages of trips that reported each species analyzed by fishery.

	Percentage of logbook trips (1995 -2010)	**Percentage of headboat trips (2006 – 2010)**
Yellowtail Snapper	66.8%	87.2%
Mutton Snapper	22.0%	44.9%
Mangrove Snapper	12.1%	54.5%
White Grunt	3.7%	79.5%

Table 2.4 Percentages of trips that reported individual areas by fishery.

	Percentage of logbook trips (1995 -2010)	**Percentage of headboat trips (2006 – 2010)**
Area 2	3.63%	
Area1	13.75%	
Area 2580	12.52%	[X]
Area 2482	3.08%	[X]
Area 2481	41.04%	[X]
Area 2480	25.99%	[X]

[X] Confidential (Area 2580 did not have sufficient vessels reporting over the years analyzed to meet data confidentiality requirements.)

Table 2.5 Variables tested for correlations with changes in effort and in CPUE. Shaded variables were only tested for correlations with change in CPUE.

Variable	**Description**
Wind Speed	Maximum wind speed on date being analyzed
Pressure	Minimum barometric pressure on date being analyzed
Change in wind speed	Change in average daily maximum wind speed
Change in pressure	Change in average daily minimum sea level pressure
Days without fishing	Number of consecutive days with zero fishing starting on the day of the event
Change in Percent Positive	Change in the percent of trips that reported a given species
Change in effort	Change in average total daily effort

Table 2.6: Summary of Shapiro-Wilks normality test significance for changes in fishing effort and number of scenarios (unique combinations of event, species, area and period length) over which responses were analyzed. Analyses with significant p-values (α = 0.05) are highlighted in gray. Significance is represented by "***", "**", and "*", for p-values of ≤ 0.001, ≤ 0.01, and ≤ 0.05, respectively.

	Logbook 1995-2010			**Headboat** 2006-2010		
Period Lengths	**5-day**	**7-day**	**14-day**	**5-day**	**7-day**	**14-day**
All Species, All Areas	*** 1889†	*** 2044†	*** 2263†	*** 501†	*** 520†	*** 550†
Yellowtail Snapper, All Areas	*** 626	*** 646	*** 663	** 135	137	139
Mutton Snapper, All Areas	*** 516	*** 565	*** 615	** 120	* 132	*** 136
Mangrove Snapper, All Areas	*** 503	*** 551	*** 617	* 116	** 120	* 134
White Grunt, All Areas	*** 244	*** 282	*** 368	** 130	131	** 141
All Species, Area 2	*** 218	*** 269	*** 337			
All Species, Area 1	*** 364	*** 384	*** 417			
All Species, Area 2580	*** 309	*** 334	*** 364	x	x	x
All Species, Area 2482	*** 225	*** 263	*** 319	* 140	141	144
All Species, Area 2481	*** 417	*** 426	*** 437	*** 128	* 129	132
All Species, Area 2480	*** 356	*** 368	*** 389	** 126	136	** 143

† Plotted in Figures 2.8 and 2.9
X Confidential

Table 2.7: Summary of Shapiro-Wilks normality test significance for changes in CPUE and number of scenarios (unique combinations of event, species, area and period length) over which responses were analyzed. Analyses with significant p-values ($\alpha = 0.05$) are highlighted in gray. Significance is represented by "***", "**", and "*", for p-values of ≤ 0.001, ≤ 0.01, and ≤ 0.05, respectively.

	Logbook 1995-2010			**Headboat** 2006-2010		
Period Lengths	**5-day**	**7-day**	**14-day**	**5-day**	**7-day**	**14-day**
All Species, All Areas	*** 1233[†]	*** 1455[†]	*** 1859[†]	*** 388[†]	** 429 [†]	*** 488[†]
Yellowtail Snapper, All Areas	*** 517	*** 565	*** 638	109	120	129
Mutton Snapper, All Areas	*** 290	*** 364	*** 496	* 85	99	*** 121
Mangrove Snapper, All Areas	*** 322	*** 382	*** 503	87	* 97	111
White Grunt, All Areas	*** 104	*** 144	*** 222	** 107	113	* 127
All Species, Area 2	*** 88	*** 112	*** 212			
All Species, Area 1	*** 244	*** 289	*** 364			
All Species, Area 2580	*** 206	*** 249	*** 301	x	x	x
All Species, Area 2482	*** 72	*** 116	*** 211	* 127	131	142
All Species, Area 2481	*** 342	*** 378	*** 416	*** 119	* 121	122
All Species, Area 2480	*** 281	*** 311	*** 355	* 95	109	* 130

[†] Plotted in Figures 2.10 and 2.11
[X] Confidential

Table 2.8: Summary of wilcoxon signed rank test significance and median change in fishing effort associated with weather events identified by maximum wind speed. Analyses with significant p-values (α = 0.05) are highlighted in gray. Significance is represented by “***”, “**”, and “*”, for p-values of ≤ 0.001, ≤ 0.01, and ≤ 0.05, respectively.

	Logbook 1995-2010			**Headboat** 2006-2010		
Period Lengths	**5-day**	**7-day**	**14-day**	**5-day**	**7-day**	**14-day**
All Species, All Areas	*** -1.60[†]	*** -1.14[†]	*** -0.29[†]	2.00[†]	0.36[†]	2.14[†]
Yellowtail Snapper, All Areas	*** -3.20	*** -2.29	*** -1.07	-4.00	-2.14	-1.71
Mutton Snapper, All Areas	-0.80	-0.71	-0.14	9.50	3.43	3.82
Mangrove Snapper, All Areas	*** -1.80	*** -1.43	* -0.57	6.00	-1.14	-1.46
White Grunt, All Areas	*** -1.30	-0.64	0.21	-4.5	-2.14	2.86
All Species, Area 2	-0.40	-0.29	0.43			
All Species, Area 1	** -1.20	*** -1.14	*** -0.57			
All Species, Area 2580	-1.20	* -1.14	-0.39	x	x	x
All Species, Area 2482	* -1.60	-0.57	0.00	-9.20	-1.71	-3.25
All Species, Area 2481	*** -4.20	*** -2.86	* -0.71	* 9.50	** 9.29	9.11
All Species, Area 2480	*** -1.70	*** -1.71	* -0.79	6.20	-3.14	-4.64

[†] Plotted in Figures 2.8 and 2.9
[X] Confidential

Table 2.9: Summary of wilcoxon signed rank test significance and median change in CPUE associated with weather events identified by maximum wind speed. Analyses with significant p-values (α = 0.05) are highlighted in gray. Significance is represented by "***", "**", and "*", for p-values of ≤ 0.001, ≤ 0.01, and ≤ 0.05, respectively.

	Logbook 1995-2010			Headboat 2006-2010		
Period Lengths	**5-day**	**7-day**	**14-day**	**5-day**	**7-day**	**14-day**
All Species, All Areas	-0.02†	-0.08†	-0.01†	0.00†	0.00†	0.00†
Yellowtail Snapper, All Areas	-0.17	-0.27	-0.14	0.03	0.00	0.01
Mutton Snapper, All Areas	-0.07	-0.03	* 0.07	0.00	0.00	0.00
Mangrove Snapper, All Areas	0.04	-0.10	-0.02	0.00	0.00	0.01
White Grunt, All Areas	0.03	-0.03	-0.08	* -0.06	* -0.05	0.00
All Species, Area 2	0.13	0.24	-0.10			
All Species, Area 1	-0.21	-0.14	-0.03			
All Species, Area 2580	-0.32	-0.23	-0.14	x	x	x
All Species, Area 2482	-0.12	-0.02	-0.11	0.00	0.00	0.00
All Species, Area 2481	-0.01	* -0.29	-0.04	0.01	0.00	0.00
All Species, Area 2480	** 0.15	** 0.17	* 0.14	0.00	0.00	0.00

† Plotted in Figures 2.10 and 2.11
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Table 2.10: Summary results from the Kruskal-Wallis one-way analysis of variance across period lengths for each fishery. Significant chi-squared values (α = 0.05) are highlighted in gray. Significance is represented by "***", "**", and "*", associated with p-values of ≤ 0.001, ≤ 0.01, and ≤ 0.05, respectively.

	Effort		CPUE	
	Logbook 1995-2010	**Headboat** 2006-2010	**Logbook** 1995-2010	**Headboat** 2006-2010
	Differences Across Period Lengths (df = 3)			
All Species, All Areas	** $\chi^2 = 27.74$	$\chi^2 = 0.07$	$\chi^2 = 0.10$	$\chi^2 = 1.52$
Yellowtail Snapper, All Areas	* $\chi^2 = 9.09$	$\chi^2 = 0.04$	$\chi^2 = 0.04$	$\chi^2 = 1.01$
Mutton Snapper, All Areas	$\chi^2 = 0.91$	$\chi^2 = 0.39$	$\chi^2 = 1.88$	$\chi^2 =1.03$
Mangrove Snapper, All Areas	*** $\chi^2 = 14.72$	$\chi^2 = 0.37$	$\chi^2 = 0.26$	$\chi^2 = 0.70$
White Grunt, All Areas	*** $\chi^2 = 9.56$	$\chi^2 = 0.32$	$\chi^2 = 1.34$	$\chi^2 = 3.64$
Area 2, All Species	$\chi^2 = 2.90$		$\chi^2 = 0.81$	
Area 1, All Species	$\chi^2 = 0.39$		$\chi^2 = 1.05$	
Area 2580, All Species	$\chi^2 = 1.34$	X	$\chi^2 = 0.92$	X
Area 2482, All Species	$\chi^2 = 5.24$	$\chi^2 = 2.36$	$\chi^2 = 0.62$	$\chi^2 = 1.86$
Area 2481, All Species	*** $\chi^2 = 18.35$	$\chi^2 = 0.54$	$\chi^2 = 1.62$	$\chi^2 = 1.37$
Area 2480, All Species	$\chi^2 = 3.38$	$\chi^2 = 2.37$	$\chi^2 = 0.89$	$\chi^2 = 1.02$

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Table 2.11: Summary results from the Kruskal-Wallis one-way analysis of variance across species and areas for each fishery. Significant chi-squared values (α = 0.05) are highlighted in gray. Significance is represented by "***", "**", and "*", associated with p-values of ≤ 0.001, ≤ 0.01, and ≤ 0.05, respectively.

	Effort		CPUE	
	Logbook 1995-2010	**Headboat** 2006-2010	**Logbook** 1995-2010	**Headboat** 2006-2010
Differences Across Species (df = 3)				
5-Day, All Areas	*** $\chi^2 = 23.91$	$\chi^2 = 2.25$	$\chi^2 = 1.68$	*** $\chi^2 = 13.27$
7-Day, All Areas	*** $\chi^2 = 19.77$	$\chi^2 = 0.83$	$\chi^2 = 1.81$	* $\chi^2 = 8.19$
14-Day, All Areas	* $\chi^2 = 7.99$	$\chi^2 = 1.09$	$\chi^2 = 3.99$	$\chi^2 = 3.24$
Differences Across Areas (df = 5 logbook; 3 headboat)				
5-Day, All Species	*** $\chi^2 = 37.19$	* $\chi^2 = 9.88$	$\chi^2 = 10.22$	$\chi^2 = 1.42$
7-Day, All Species	*** $\chi^2 = 25.88$	$\chi^2 = 6.79$	*** $\chi^2 = 14.86$	$\chi^2 = 0.58$
14-Day, All Species	*** $\chi^2 = 16.35$	$\chi^2 = 2.23$	$\chi^2 = 5.19$	$\chi^2 = 1.79$

Table 2.12: Spearman correlation coefficients between change in logbook fishing effort and variables related to weather severity. Correlations greater than |0.4| are highlighted in gray for illustrative purposes.

	Change in wind speed			**Wind speed on day of event**			**Change in barometric pressure**			**Barometric pressure on day of event**		
Period Length	**5**	**7**	**14**	**5**	**7**	**14**	**5**	**7**	**14**	**5**	**7**	**14**
All Species, All Areas	-0.37	-0.36	-0.34	0.01	0.01	0.00	-0.10	-0.11	-0.03	-0.07	-0.08	-0.06
Individual Species, All Areas												
Yellowtail Snapper	-0.48†	-0.46	-0.48	-0.01	-0.03	-0.04	-0.14	-0.15	-0.05	-0.08	-0.08	-0.08
Mutton Snapper	-0.26	-0.28	-0.25	0.02	0.04	0.03	-0.06	-0.10	-0.05	-0.12	-0.11	-0.06
Mangrove Snapper	-0.39	-0.38	-0.35	-0.02	0.01	0.00	-0.09	-0.08	0.00	-0.04	-0.08	-0.06
White Grunt	-0.33	-0.23	-0.17	0.11	0.15	0.08	-0.14	-0.17	0.03	-0.02	-0.04	0.00
Individual Areas, All Species												
Area 2	-0.20	-0.30	-0.31	-0.02	0.00	0.00	0.04	-0.11	-0.04	-0.08	0.00	-0.04
Area 1	-0.38	-0.31	-0.30	0.11	0.07	-0.01	-0.18	-0.20	0.02	-0.10	-0.13	-0.07
Area 2580	-0.33	-0.36	-0.35	0.04	0.04	0.00	-0.12	-0.10	-0.04	-0.01	-0.03	0.00
Area 2482	-0.28	-0.20	-0.19	-0.07	-0.04	-0.01	0.00	0.03	-0.09	-0.02	-0.07	-0.05
Area 2481	-0.42	-0.42	-0.38	-0.08	-0.04	-0.05	-0.10	-0.13	-0.01	-0.12	-0.13	-0.07
Area 2480	-0.49†	-0.47	-0.47	0.03	0.02	0.08	-0.15	-0.14	-0.04	-0.07	-0.09	-0.13

†Plotted in Figures 2.12 and 2.13

Table 2.13: Spearman correlation coefficients between change in headboat fishing effort and variables related to weather severity.

	Change in wind speed			Wind speed on day of event			Change in barometric pressure			Barometric pressure on day of event		
Period Length	**5**	**7**	**14**	**5**	**7**	**14**	**5**	**7**	**14**	**5**	**7**	**14**
All Species, All Areas	-0.11	-0.20	-0.17	-0.02	-0.08	-0.02	-0.06	0.13	0.06	0.01	0.01	-0.03
Individual Species, All Areas												
Yellowtail Snapper	-0.21	-0.27	-0.22	0.01	-0.05	0.04	-0.12	0.09	0.01	0.00	-0.01	-0.09
Mutton Snapper	0.07	-0.02	-0.10	-0.08	-0.07	-0.05	-0.17	-0.04	-0.06	-0.09	-0.10	-0.10
Mangrove Snapper	-0.14	-0.26	-0.14	-0.10	-0.19	-0.04	0.09	0.27	0.17	0.08	0.14	0.06
White Grunt	-0.15	-0.24	-0.20	0.03	-0.07	-0.03	-0.04	0.21	0.10	0.05	0.02	-0.02
Individual Areas, All Species												
Area 2580	X	X	X	X	X	X	X	X	X	X	X	X
Area 2482	-0.30	-0.37	-0.22	-0.24	-0.31	-0.08	0.05	0.25	-0.04	0.17	0.19	0.02
Area 2481	-0.07	-0.28	-0.23	0.08	0.05	0.05	0.02	0.25	0.26	0.11	0.05	0.01
Area 2480	-0.04	-0.08	-0.05	0.13	0.02	0.01	-0.19	0.01	0.01	-0.19	-0.14	-0.15

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Table 2.14: Spearman correlation coefficients between change in logbook CPUE and variables related to weather severity.

	Change in wind speed			Wind speed on day of event			Change in barometric pressure			Barometric pressure on day of event		
Period Length	**5**	**7**	**14**	**5**	**7**	**14**	**5**	**7**	**14**	**5**	**7**	**14**
All Species, All Areas	-0.04	-0.05	-0.04	0.00	0.00	0.00	0.01	-0.01	-0.04	-0.08	-0.04	-0.05
Individual Species, All Areas												
Yellowtail Snapper	-0.02	-0.06	-0.08	0.00	0.00	-0.02	0.04	0.02	-0.09	-0.07	-0.04	-0.07
Mutton Snapper	-0.02	0.06	0.00	0.09	0.01	-0.04	-0.02	-0.06	-0.09	-0.11	-0.11	-0.02
Mangrove Snapper	-0.08	-0.15	-0.08	-0.04	-0.01	0.02	-0.05	-0.01	0.07	-0.02	0.02	-0.04
White Grunt	0.01	0.04	0.14	0.08	0.05	0.14	0.10	0.00	0.02	-0.21	-0.06	-0.02
Individual Areas, All Species												
Area 2	0.08	0.03	-0.19	0.04	0.02	-0.05	0.11	-0.01	-0.16	-0.21	-0.15	-0.11
Area 1	0.01	-0.04	-0.07	0.02	0.00	0.03	-0.06	-0.05	0.00	-0.18	-0.11	-0.07
Area 2580	-0.06	-0.04	-0.03	-0.02	-0.04	0.00	0.07	0.04	0.00	0.07	0.00	-0.01
Area 2482	0.03	-0.02	-0.03	0.05	0.05	0.06	-0.01	0.03	-0.03	0.05	0.15	0.04
Area 2481	-0.11	-0.08	0.00	0.05	0.03	0.01	0.04	0.04	-0.03	-0.08	-0.05	-0.05
Area 2480	-0.07	-0.10	0.08	-0.04	-0.03	-0.05	-0.04	-0.06	-0.03	-0.12	-0.07	-0.07

Table 2.15: Spearman correlation coefficients between change in logbook CPUE and variables related to fishing effort.

	Δ in effort			**days w/o fishing**			**Δ in % positive**		
Period Length	**5**	**7**	**14**	**5**	**7**	**14**	**5**	**7**	**14**
All Species, All Areas	-0.02	0.02	0.03	0.01	0.00	-0.03	0.11	0.10	0.14
Individual Species, All Areas									
Yellowtail Snapper	-0.05	-0.02	-0.01	-0.01	0.00	-0.06	0.10	0.11	0.12
Mutton Snapper	-0.03	0.04	0.05	0.01	-0.03	0.02	0.18	0.11	0.11
Mangrove Snapper	0.01	0.10	0.14	0.00	0.00	-0.04	0.05	0.11	0.26
White Grunt	-0.03	-0.07	-0.22	0.00	-0.04	-0.01	0.24	0.10	0.01
Individual Areas, All Species									
Area 2	-0.17	0.00	0.06	-0.02	-0.02	-0.06	0.05	0.23	0.12
Area 1	0.06	0.10	0.11	0.06	0.13	0.06	0.15	0.12	0.12
Area 2580	-0.06	-0.04	-0.10	-0.06	-0.14	-0.06	0.21	0.14	0.07
Area 2482	-0.31	-0.15	0.13	0.06	-0.07	-0.09	-0.01	-0.02	0.21
Area 2481	0.06	0.07	0.01	0.10	0.06	0.02	0.11	0.12	0.12
Area 2480	-0.03	-0.01	0.01	-0.01	0.01	-0.03	0.07	0.06	0.24

Table 2.16: Spearman correlation coefficients between change in headboat CPUE and variables related to weather severity.

	Change in wind speed			Wind speed on day of event			Change in barometric pressure			Barometric pressure on day of event		
Period Length	**5**	**7**	**14**	**5**	**7**	**14**	**5**	**7**	**14**	**5**	**7**	**14**
All Species	0.11	0.02	0.05	0.02	0.07	0.03	-0.06	-0.08	-0.11	-0.07	-0.04	0.03
Individual Species, All Areas												
Yellowtail Snapper	0.19	-0.04	-0.07	0.09	0.08	0.05	-0.06	-0.18	-0.32	-0.24	-0.13	-0.08
Mutton Snapper	0.06	0.03	0.28	0.08	0.03	0.05	-0.02	0.01	0.04	-0.01	-0.03	0.01
Mangrove Snapper	0.11	0.08	0.05	0.01	0.00	-0.10	0.21	0.18	0.20	0.08	0.10	0.16
White Grunt	0.06	0.03	0.08	0.02	0.12	0.07	-0.22	-0.16	-0.23	-0.04	-0.05	0.01
Individual Areas, All Species												
Area 2580	X	X	X	X	X	X	X	X	X	X	X	X
Area 2482	0.05	-0.07	0.05	-0.03	-0.03	-0.09	0.15	0.03	0.03	-0.02	-0.02	0.13
Area 2481	0.17	0.03	-0.01	0.06	0.09	0.00	-0.08	-0.02	-0.19	-0.06	0.05	0.10
Area 2480	0.21	0.09	0.00	0.02	0.13	0.14	-0.22	-0.17	-0.15	-0.23	-0.16	-0.12

[X] Confidential

Table 2.17: Spearman correlation coefficients between change in headboat CPUE and variables related to fishing effort.

	Δ in effort			days w/o fishing			Δ in % positive		
Period Length	**5**	**7**	**14**	**5**	**7**	**14**	**5**	**7**	**14**
All Species, All Areas	0.01	0.02	-0.06	-0.04	-0.02	-0.03	0.16	0.14	0.14
Individual Species, Across All Areas									
Yellowtail Snapper	0.03	-0.01	-0.15	-0.06	-0.03	-0.01	0.18	0.15	0.09
Mutton Snapper	-0.03	0.15	0.00	-0.08	-0.05	0.01	0.31	0.33	0.26
Mangrove Snapper	-0.05	0.03	0.15	0.05	0.02	-0.08	0.20	0.15	0.20
White Grunt	-0.01	0.01	-0.10	-0.02	-0.03	0.02	0.09	0.10	0.13
Individual Areas, Across All Species									
Area 2580	[x]	[x]	[x]	[x]	[x]	[x]	[x]	[x]	[x]
Area 2482	-0.07	0.02	-0.06	-0.08	-0.04	-0.14	0.16	0.20	0.13
Area 2481	-0.02	-0.02	-0.04	-0.10	-0.04	-0.04	0.10	0.08	0.12
Area 2480	0.12	0.11	-0.06	0.00	-0.04	0.03	0.21	0.20	0.23

[x] Confidential

Table 2.18: Spearman correlation coefficients between change in effort and the effort in the period before events for each fishery. Correlations greater than |0.4| are highlighted in gray for illustrative purposes.

Nonparametric correlations between change in effort and effort in the period analyzed prior to each event						
	Logbook 1995-2010			**Headboat** 2006-2010		
Period Length	**5**	**7**	**14**	**5**	**7**	**14**
All Species, All Areas	-0.56	-0.54	-0.36	-0.44	-0.38	-0.34
Individual Species, Across All Areas						
Yellowtail Snapper	-0.55	-0.52	-0.36	-0.42	-0.37	-0.38
Mutton Snapper	-0.55	-0.57	-0.42	-0.55	-0.43	-0.34
Mangrove Snapper	-0.63	-0.60	-0.38	-0.38	-0.39	-0.42
White Grunt	-0.73	-0.63	-0.46	-0.41	-0.35	-0.29
Individual Species, Across All Areas						
Area 2	-0.64	-0.67	-0.53			
Area 1	-0.55	-0.58	-0.41			
Area 2580	-0.54	-0.54	-0.39	X	X	X
Area 2482	-0.77[†]	-0.70	-0.44	-0.57	-0.49	-0.47
Area 2481	-0.58	-0.53	-0.31	-0.49	-0.41	-0.46
Area 2480	-0.54	-0.52	-0.41	-0.45	-0.49	-0.49

[†] Plotted in Figure 2.14
[X] Confidential

Table 2.19: Spearman correlation coefficients between change in CPUE, and CPUE in the periods before events for each fishery. Correlations greater than |0.4| are highlighted in gray for illustrative purposes.

Nonparametric correlations between change in CPUE and CPUE in the period analyzed prior to each event						
	Logbook 1995-2010			**Headboat** 2006-2010		
Period Length	**5**	**7**	**14**	**5**	**7**	**14**
All Species, All Areas	-0.37	-0.36	-0.36	-0.25	-0.28	-0.22
Individual Species, All Areas						
Yellowtail Snapper	-0.47	-0.45	-0.45	-0.27	-0.31	-0.33
Mutton Snapper	-0.58	-0.53	-0.47	-0.48	-0.41	-0.42
Mangrove Snapper	-0.43	-0.46	-0.51	-0.28	-0.28	-0.32
White Grunt	-0.56[†]	-0.56	-0.59	-0.49	-0.48	-0.42
Individual Areas, All Species						
Area 2	-0.47	-0.34	-0.47			
Area 1	-0.46	-0.46	-0.37			
Area 2580	-0.48	-0.47	-0.37	X	X	X
Area 2482	-0.45	-0.36	-0.48	-0.3	-0.27	-0.1
Area 2481	-0.41	-0.44	-0.4	-0.13	-0.25	-0.21
Area 2480	-0.14	-0.14	-0.16	-0.37	-0.38	-0.27

[†] Plotted in Figure 2.15
[X] Confidential

Table 2.20: R-squared values for models generated using stepwise linear regression by exact AIC for change in fishing effort. R-square values >0.2 are highlighted in gray for illustrative purposes.

	Logbook Effort			Logbook CPUE		
	5 - Day	7 - Day	14 - Day	5 - Day	7 - Day	14 - Day
All Species, All Areas	0.16	0.14	0.10	0.02	0.01	0.03
Yellowtail Snapper, All Areas	0.24	0.22	0.17	0.03	0.03	0.03
Mutton Snapper, All Areas	0.07	0.09	0.05	0.05	0.03	0.03
Mangrove Snapper, All Areas	0.16	0.15	0.10	0.00	0.01	0.05
White Grunt, All Areas	0.07	0.07	0.03	0.15	0.04	0.07
Area 2, All Species	0.07	0.06	0.10	0.12	0.09	0.04
Area 1, All Species	0.19	0.17	0.08	0.06	0.01	0.01
Area 2580, All Species	0.09	0.12	0.12	0.06	0.05	0.04
Area 2482, All Species	0.10	0.07	0.05	0.09	0.01	0.04
Area 2481, All Species	0.23	0.20	0.16	0.03	0.02	0.05
Area 2480, All Species	0.26	0.23	0.17	0.06	0.02	0.07

Table 2.21: R-squared values for models generated using stepwise linear regression by exact AIC for change in CPUE. R-square values >0.2 are highlighted in gray for illustrative purposes.

	Headboat Effort			Headboat CPUE		
	5 - Day	7 - Day	14 - Day	5 - Day	7 - Day	14 - Day
All Species, All Areas	0.05	0.08	0.14	0.04	0.02	0.02
Yellowtail Snapper, All Areas	0.09	0.12	0.16	0.05	0.04	0.13
Mutton Snapper, All Areas	0.00	0.00	0.07	0.18	0.09	0.13
Mangrove Snapper, All Areas	0.02	0.10	0.13	0.08	0.12	0.09
White Grunt, All Areas	0.03	0.06	0.13	0.08	0.07	0.05
Area 2580, All Species	X	X	X	X	X	X
Area 2482, All Species	0.16	0.16	0.18	0.04	0.06	0.05
Area 2481, All Species	0.19	0.16	0.31	0.04	0.00	0.02
Area 2480, All Species	0.07	0.05	0.13	0.13	0.11	0.05

[X] Confidential

Table 2.22: Regression formulas for R^2 results highlighted in table 2.20 and 2.21. Significant regression variables (Pr(> F) < 0.05) in are highlighted in bold. Additional details about each model are included in Appendix C.

Change in Logbook Effort	Adj. R^2	Regression Formula
5 – Day Yellowtail Snapper, All Areas	0.24	**~ Season** + **Area** + **Change in Wind Speed** + **Change in Pressure**
7 – Day Yellowtail Snapper, All Areas	0.22	**~ Season** + **Area** + **Change in Wind Speed** + **Change in Pressure**
5 – Day Area 2481, All Species	0.23	**~ Season** + **Species** + **Change in Wind Speed** + **Maximum Wind Speed**
7 – Day Area 2481, All Species	0.20	~ **Species** + **Change in Wind Speed** + Change in Pressure + Maximum Wind Speed + Minimum Pressure
5 – Day Area 2480, All Species	0.26	**~ Season** + **Species** + **Change in Wind Speed** + **Change in Pressure**
7 – Day Area 2480, All Species	0.23	**~ Season** + Species + **Change in Wind Speed** + **Change in Pressure**

Change in Headboat Effort	Adj. R^2	Regression Formula
14 – Day Area 2481, All Species	0.31	**~ Season** + **Change in Wind Speed** + **Change in Pressure**

Table 2.23: Numbers and percentages of multiday trips by area for each fishery. Percentages are based on total number of trips (both single and multiday) prior to removal of single day trip outliers.

	Areas					
	1	**2**	**2480**	**2481**	**2482**	**2580**
Logbook Multiday Trips	8,625 19.41 %	15,984 63.33 %	6,382 8.44 %	8,846 8.97 %	9,338 55.64 %	2,246 6.92 %
Headboat Multiday Trips			16 0.16 %	0 0.00 %	4,421 15.32 %	x

[X] Confidential

Table 2.24: Number of vessels operating in the logbook and headboat fisheries by area and year.

		YEAR															
Area		**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Logbook	**1**	147	100	109	97	96	104	105	98	89	81	86	61	52	48	46	43
	2	16	25	42	33	53	49	50	50	43	38	45	40	38	29	27	24
	2480	158	132	152	121	130	96	87	99	89	85	81	86	86	74	67	75
	2481	63	173	251	239	236	213	201	182	175	162	153	131	120	110	104	94
	2482	13	15	29	26	29	37	34	31	40	39	33	37	32	33	32	31
	2580	56	51	83	98	76	79	64	78	78	77	71	67	74	59	58	60
Headboat	**2480**												5	X	6	3	4
	2481												X	X	X	X	X
	2482												4	3	4	3	4
	2580												X	X	X	X	X

*1995-2010 for the logbook fishery and 1996-2010 for the headboat fishery

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Table 2.25: Average number of fishing trips per vessel operating in the logbook and headboat fisheries by area and year.

	Area	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Logbook	1	13.04	10.27	10.15	8.97	9.93	10.28	10.06	9.66	11.02	9.54	8.65
Logbook	2	10.13	6.68	6.86	5.06	4.79	3.65	4.66	6.40	6.63	8.05	6.29
Logbook	2480	17.09	16.09	15.76	17.17	15.49	16.86	20.98	16.63	16.83	18.06	16.05
Logbook	2481	17.10	12.49	13.71	13.47	15.19	15.17	16.54	17.17	18.07	18.16	17.24
Logbook	2482	13.15	9.20	9.41	13.35	4.66	4.78	5.53	7.65	7.48	5.69	5.36
Logbook	2580	10.57	11.94	11.92	10.60	12.16	10.18	12.88	13.19	12.62	11.32	11.69
Headboat	2480											
Headboat	2481											
Headboat	2482											
Headboat	2580											

	Area	2006	2007	2008	2009	2010
Logbook	1	9.98	8.83	11.25	12.43	10.63
Logbook	2	7.53	6.45	5.52	8.52	5.58
Logbook	2480	14.53	15.58	17.54	15.19	12.93
Logbook	2481	16.85	17.67	19.17	20.25	16.77
Logbook	2482	4.70	4.50	5.21	4.38	5.13
Logbook	2580	11.00	10.16	11.46	10.07	9.50
Headboat	2480	41.80	X	55.17	150.00	160.50
Headboat	2481	X	X	X	X	X
Headboat	2482	113.25	204.33	180.00	246.67	168.75
Headboat	2580	X	X	X	X	X

X Confidential

Table 2.26: Numbers of severe weather events with tropical cyclone and hurricane force daily maximum wind speeds that were analyzed for each fishery

	Logbook Data 1995-2010	Headboat Data 2006-2010
Total number of selected events	112	76
Tropical storm force (Max wind speed > 17 m/s or 39 mph < 33 m/s or 74mph)	48	13
Hurricane force (Max wind speed > 33 m/s or 74mph)	2*	0

* Georges on Sep. 25, 1998, and Wilma Oct. 24, 2005

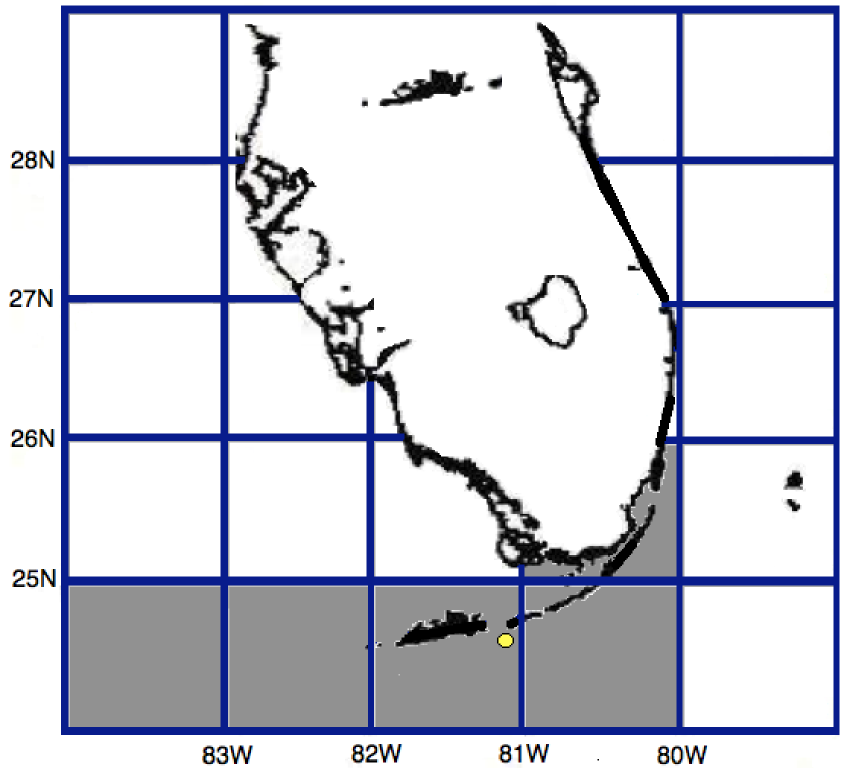


Figure 2.1: Location of study site in south Florida shaded in gray. The yellow circle designates the location of the Coastal-Marine Automated Network meteorological station on Sombrero Key.

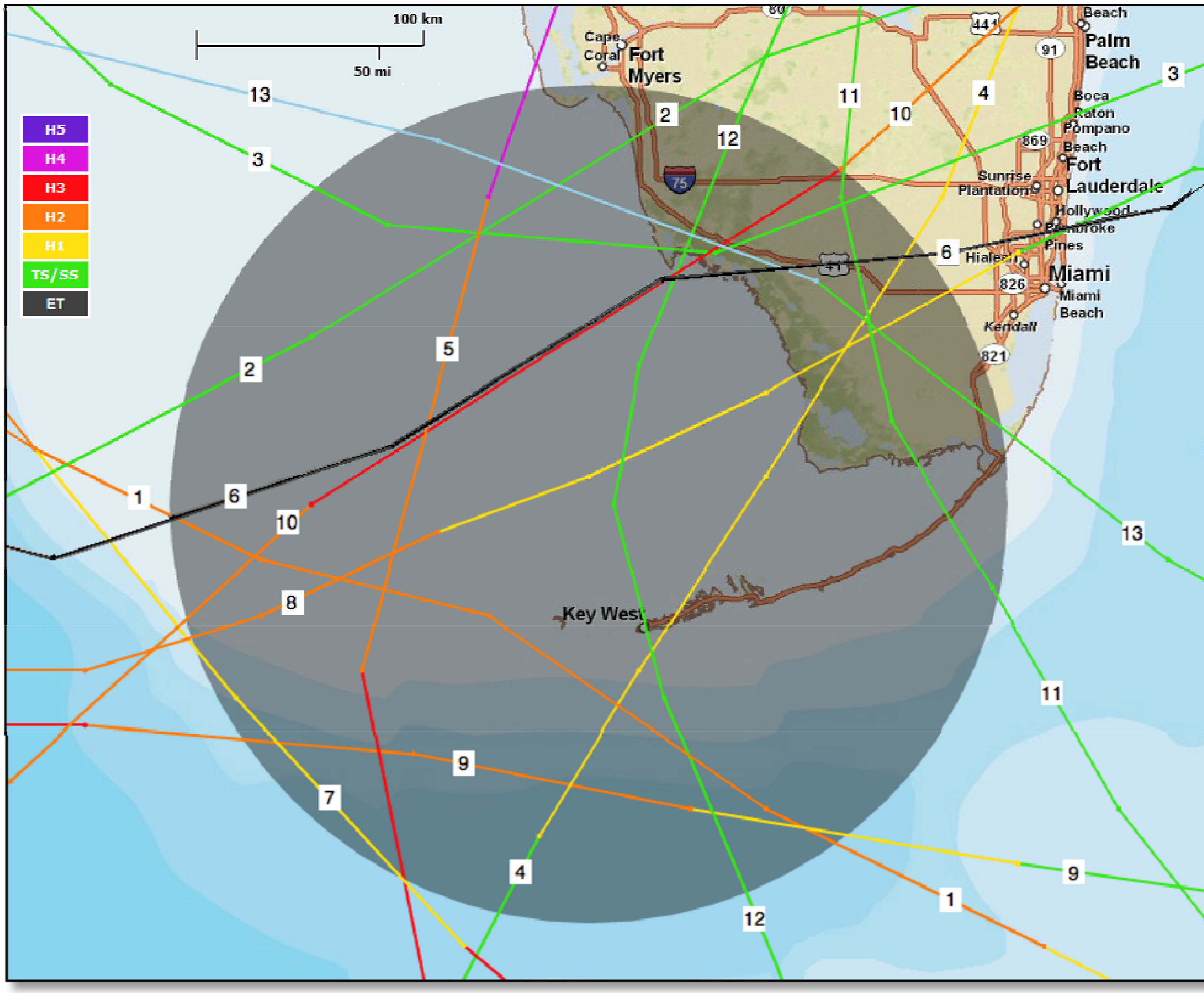


Figure 2.2: Paths of tropical storms and hurricanes that came within 100 nautical miles of the center of the study site (82°W, 25°N). Path numbers area associated with specific tropical cyclones listed in table 2.1.

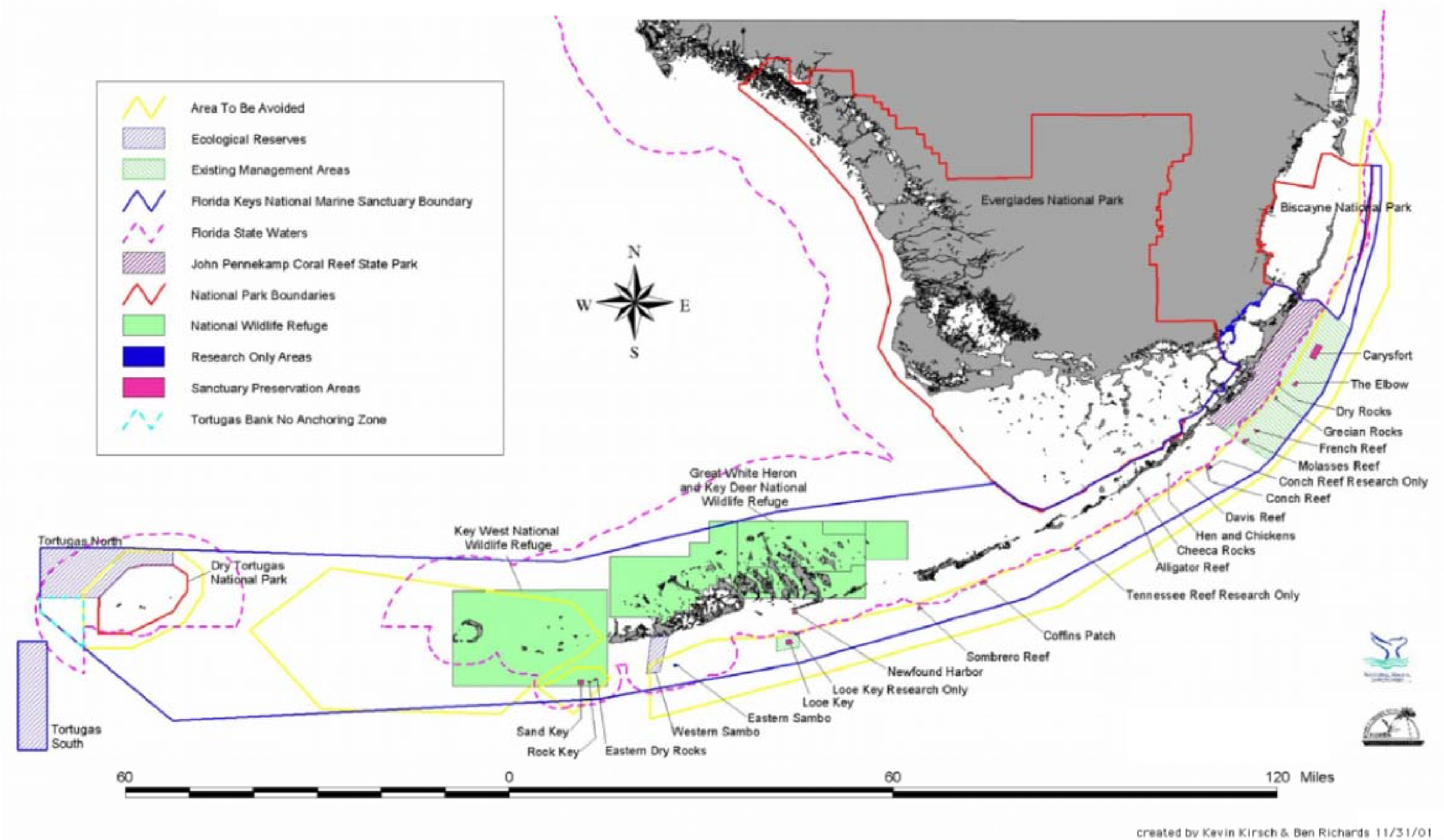


Figure 2.3 Location and type of management areas within in the Florida Keys (Brandt et al. 2009; [public domain]).

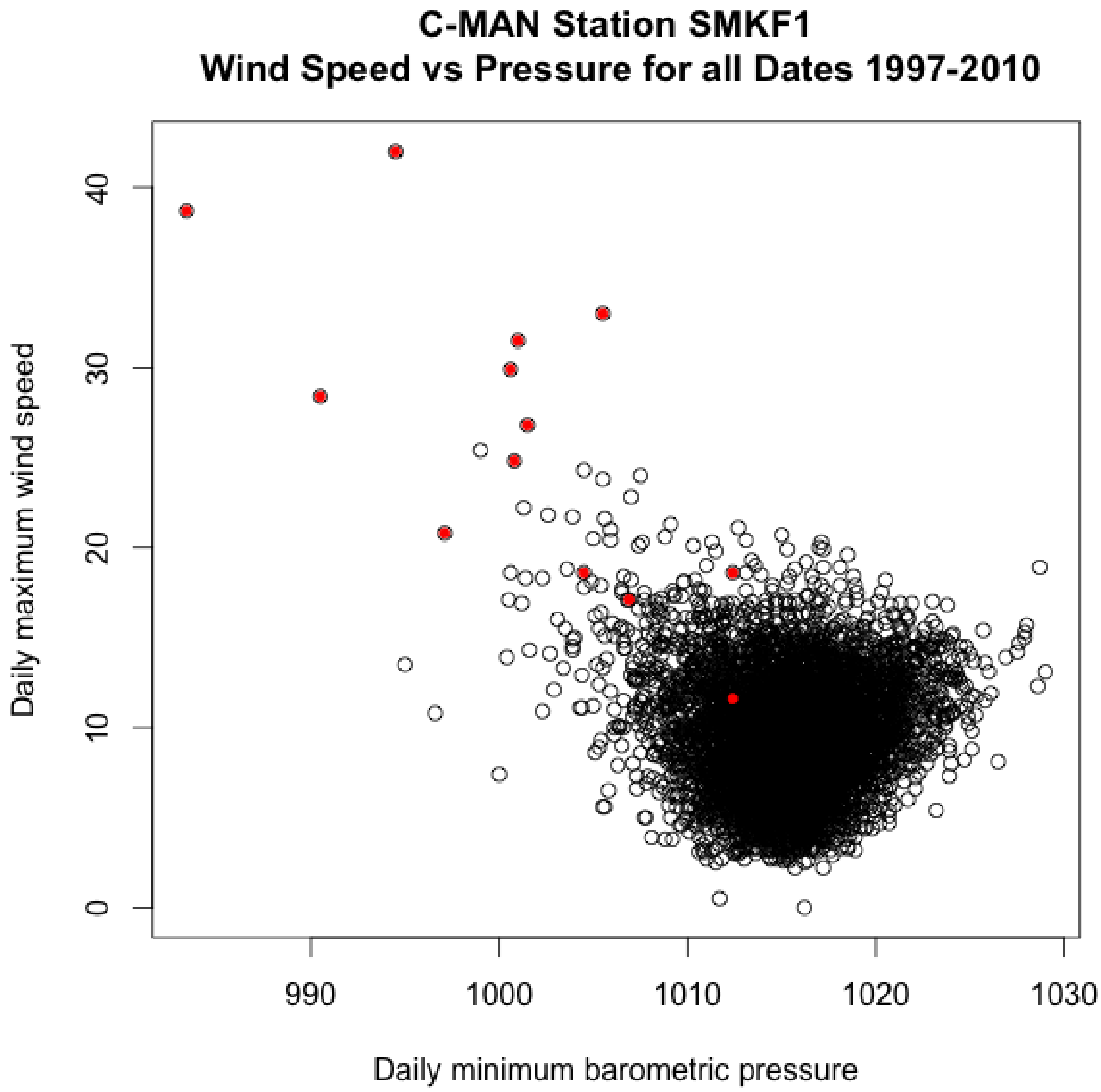


Figure 2.4: Daily maximum wind speed versus daily minimum barometric pressure for all dates (1995 to 2010). Red points (●)are associated with tropical cyclone events that came within 100 of the center of the study site (82W, 25N).

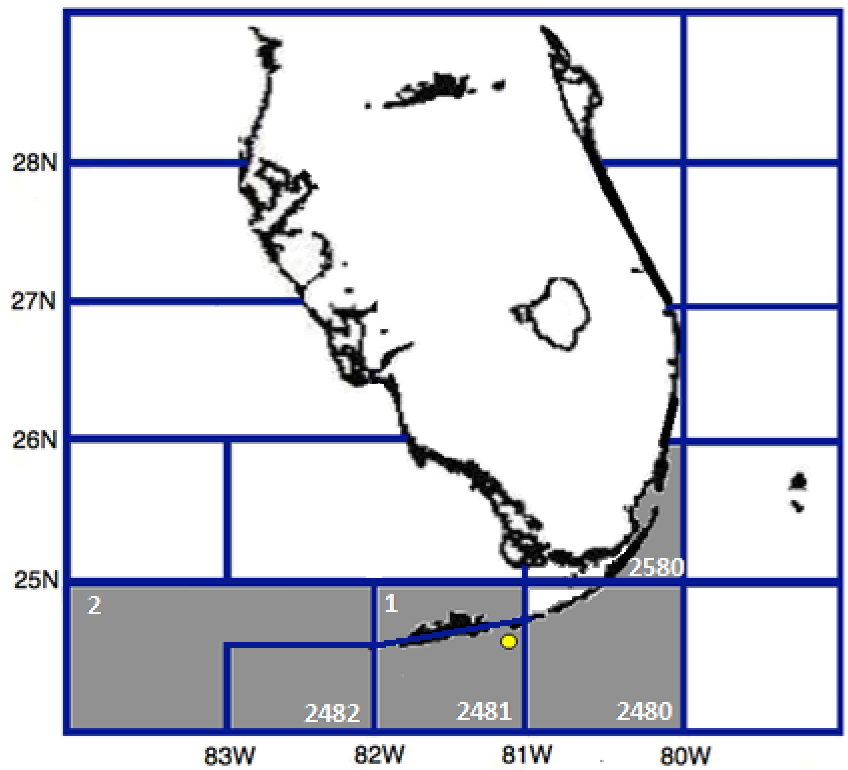


Figure 2.5: Logbook areas analyzed within the study site. The yellow circle designates the location of the Coastal-Marine Automated Network meteorological station on Sombrero Key.

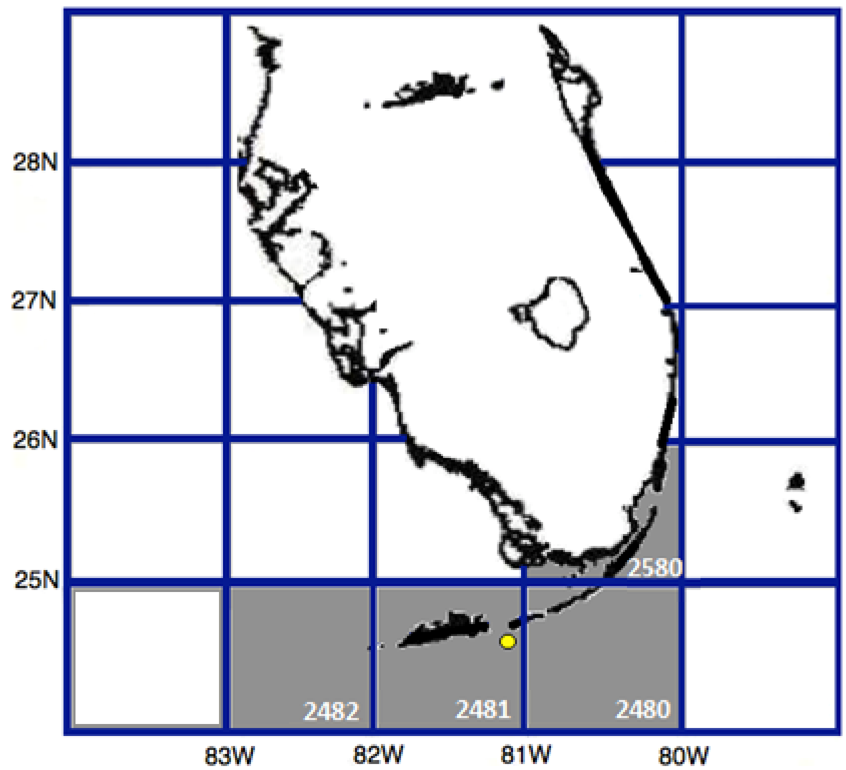


Figure 2.6: Headboat areas analyzed within the study site. The yellow circle designates the location of the Coastal-Marine Automated Network meteorological station on Sombrero Key.

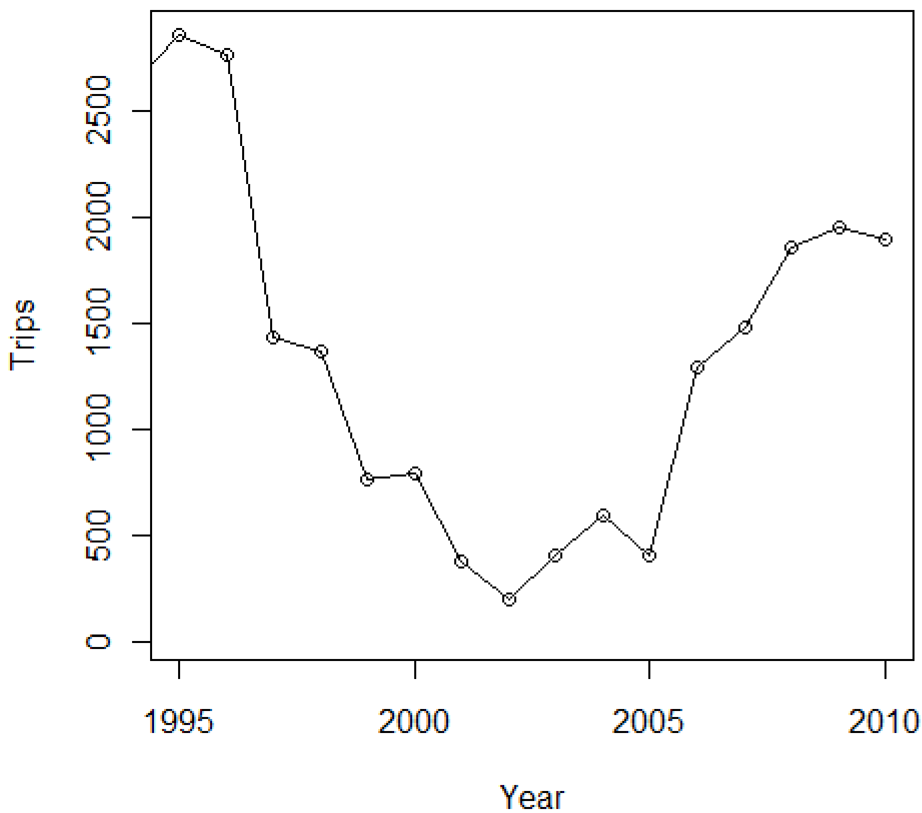
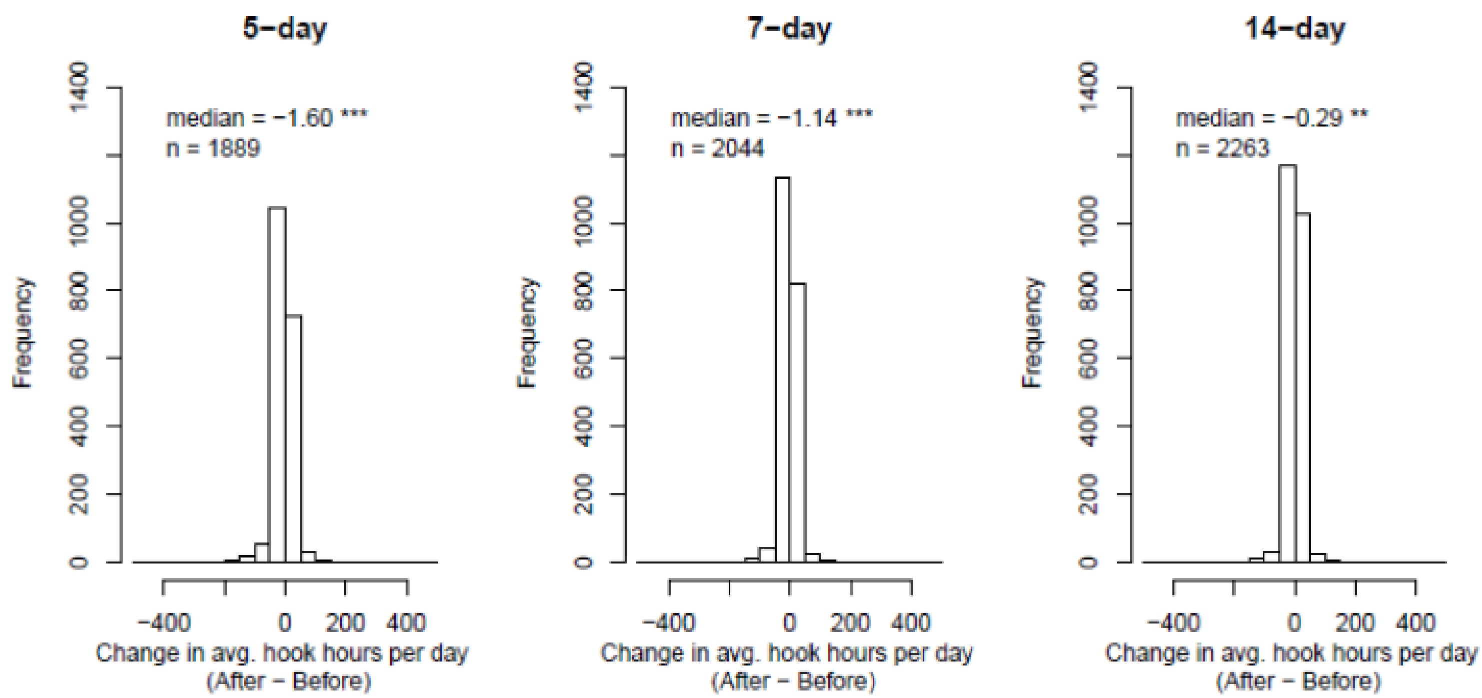
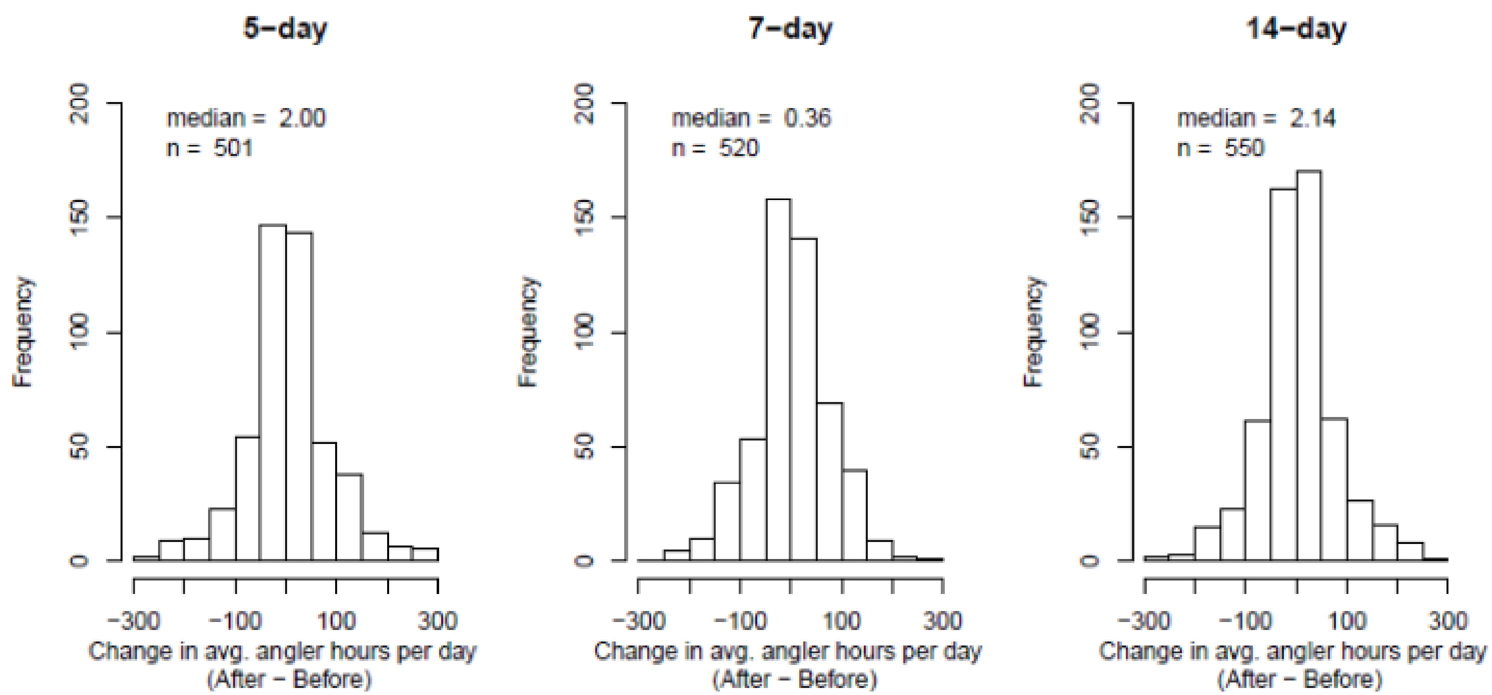


Figure 2.7: Number of single-day headboat trips reported in areas 2580, 2482, 2481, or 2480 by year (1995 – 2010).

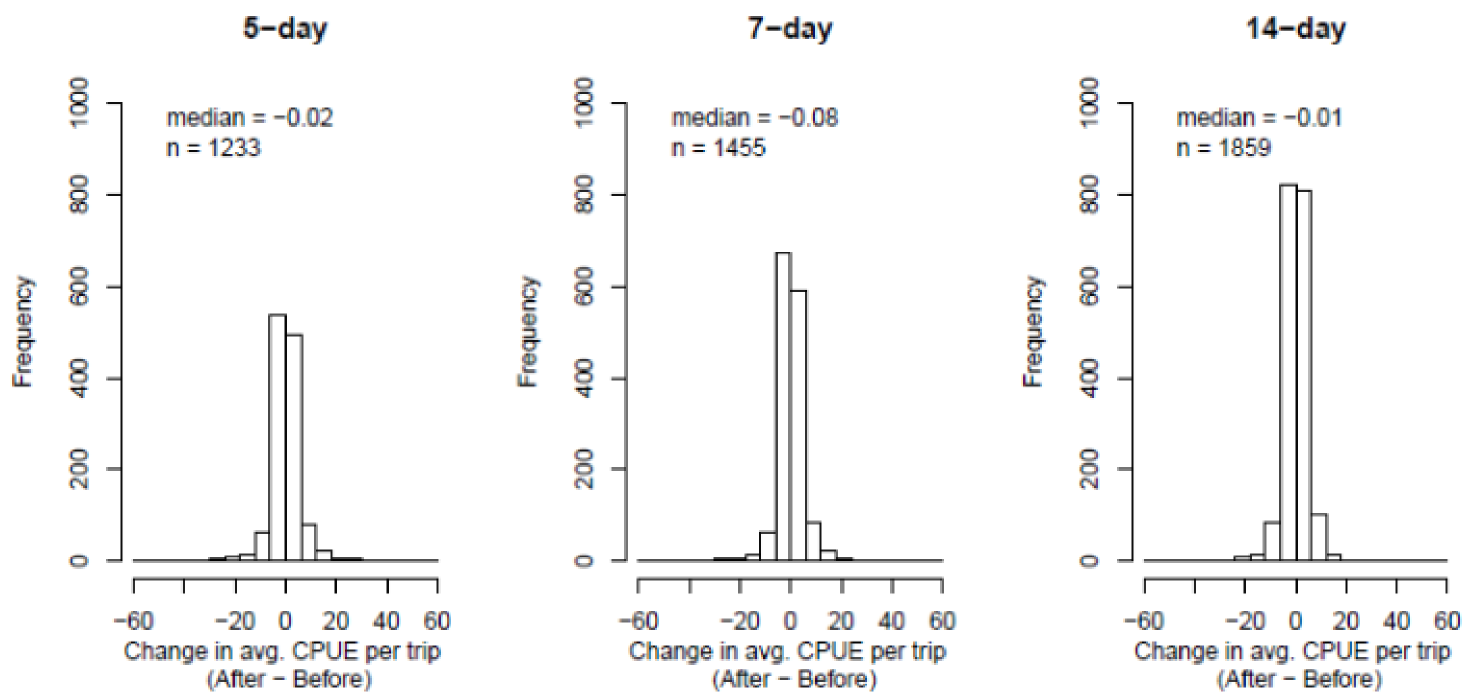
Figures 2.8 - 2.11: Examples of histograms summarizing changes in logbook fishing effort, logbook CPUE, headboat fishing effort or headboat CPUE. Each histogram summarizes changes over all applicable event, species, and area combinations over one of three before and after period lengths (5, 7, and 14-day). Applicable combinations for change in effort include those in which at least one trip was observed either in the period being analyzed before, or in the period being analyzed after an event. Applicable combinations for CPUE include those in which at least one trip was observed each in the period being analyzed before, and in the period being analyzed after an event. Medians and numbers of combinations (n) for the data summarized in each histogram are specified. Significance of wilcoxon signed rank test is represented by "***", "**", and "*", for p-values of ≤ 0.001, ≤ 0.01, and ≤ 0.05, respectively.



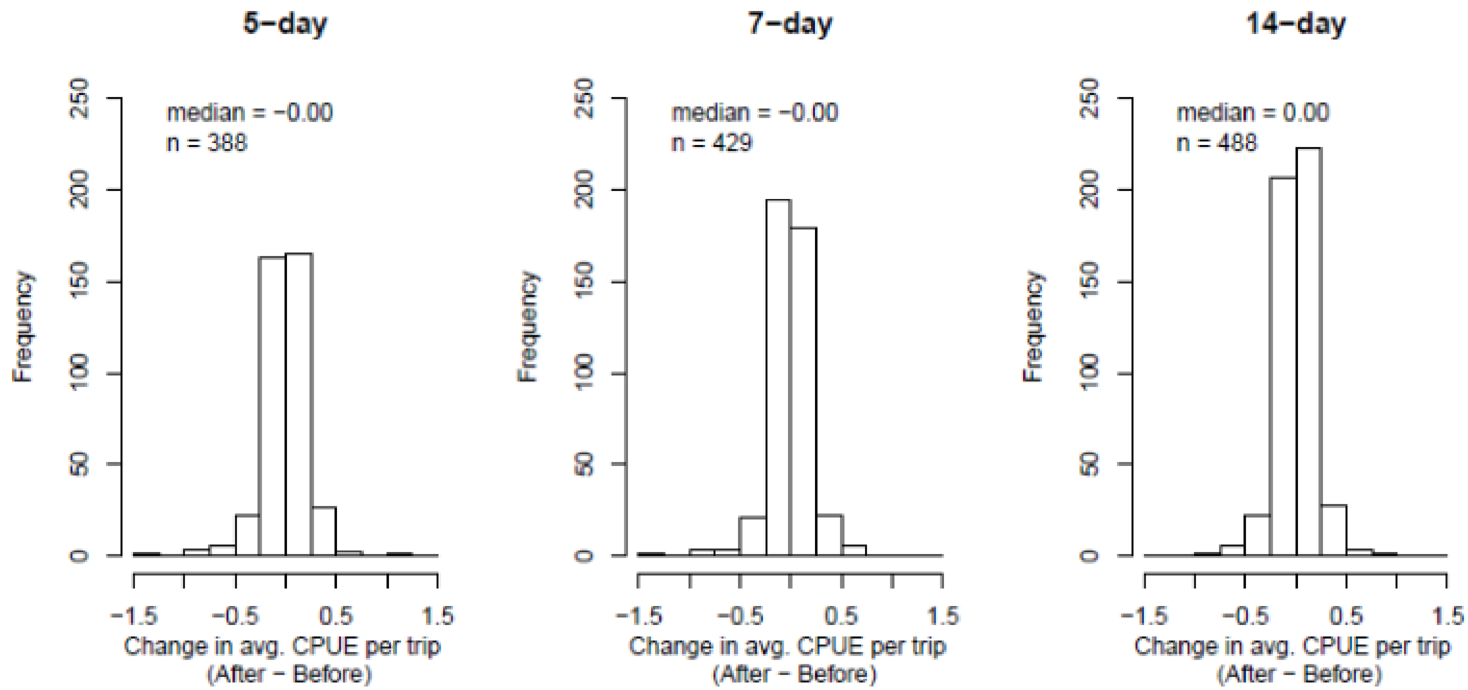
Figures 2.8: Histograms of change in logbook fishing effort over all applicable event, species, and area combinations by period length.



Figures 2.9: Histograms of change in headboat fishing effort over all applicable event, species, and area combinations by period length.



Figures 2.10: Histograms of change in logbook CPUE over all applicable event, species, and area combinations by period length.



Figures 2.11: Histograms of change in headboat CPUE over all applicable event, species, and area combinations by period length.

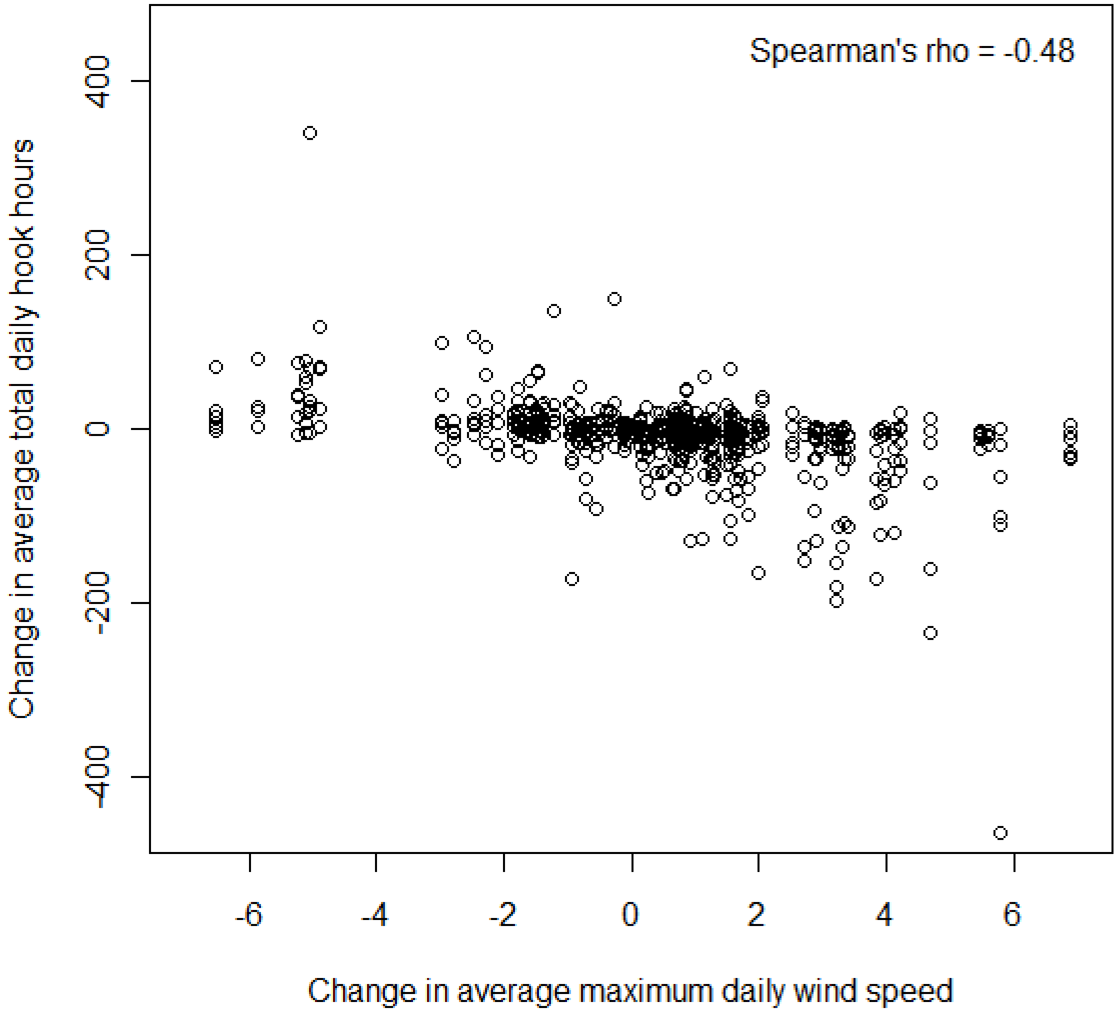


Figure 2.12: Scatter plot of change in wind speed and change in fishing effort for logbook fishing associated with yellowtail snapper and the 5-day period length (over all areas).

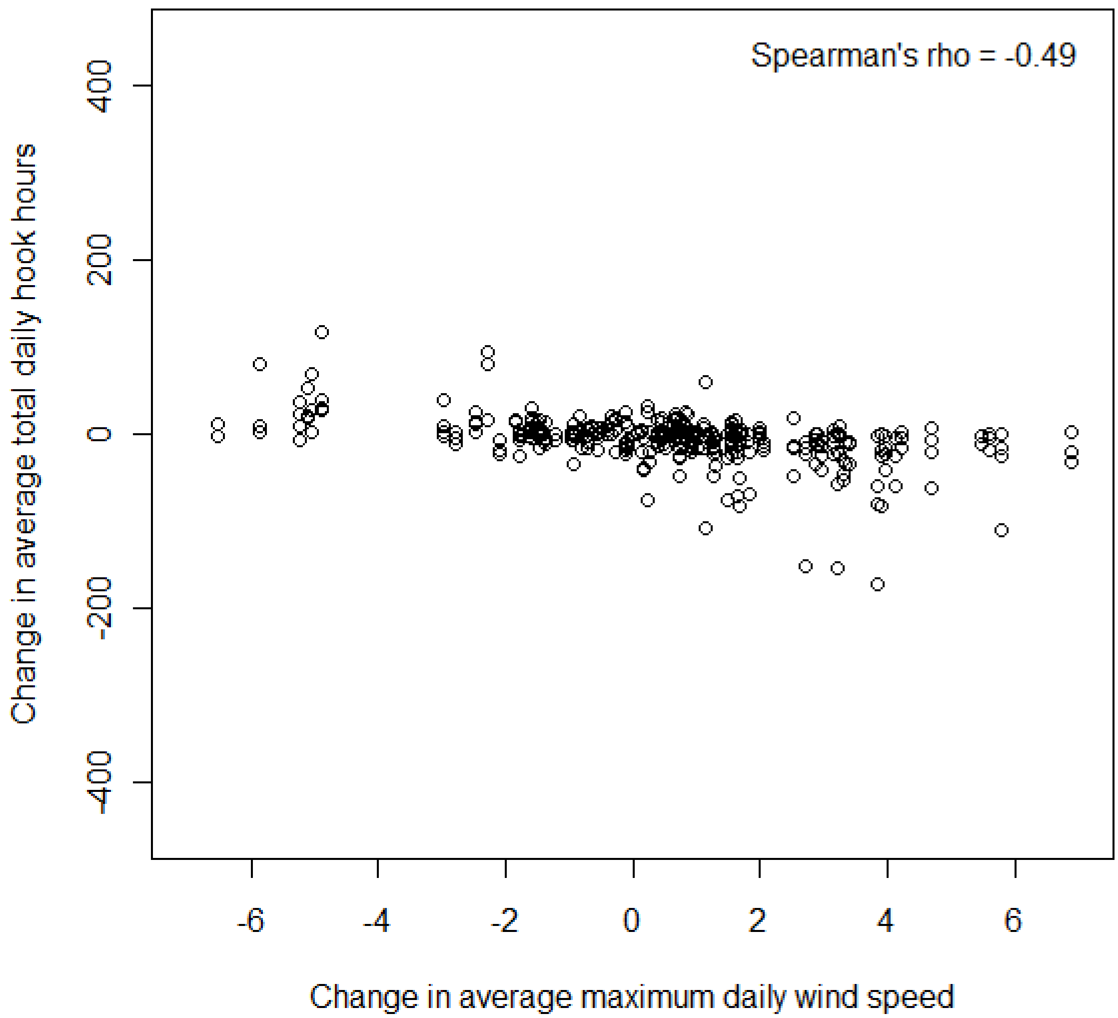


Figure 2.13: Scatter plot of change in wind speed and change in fishing effort for logbook fishing in area 2481 and the 5-day period length (over all species).

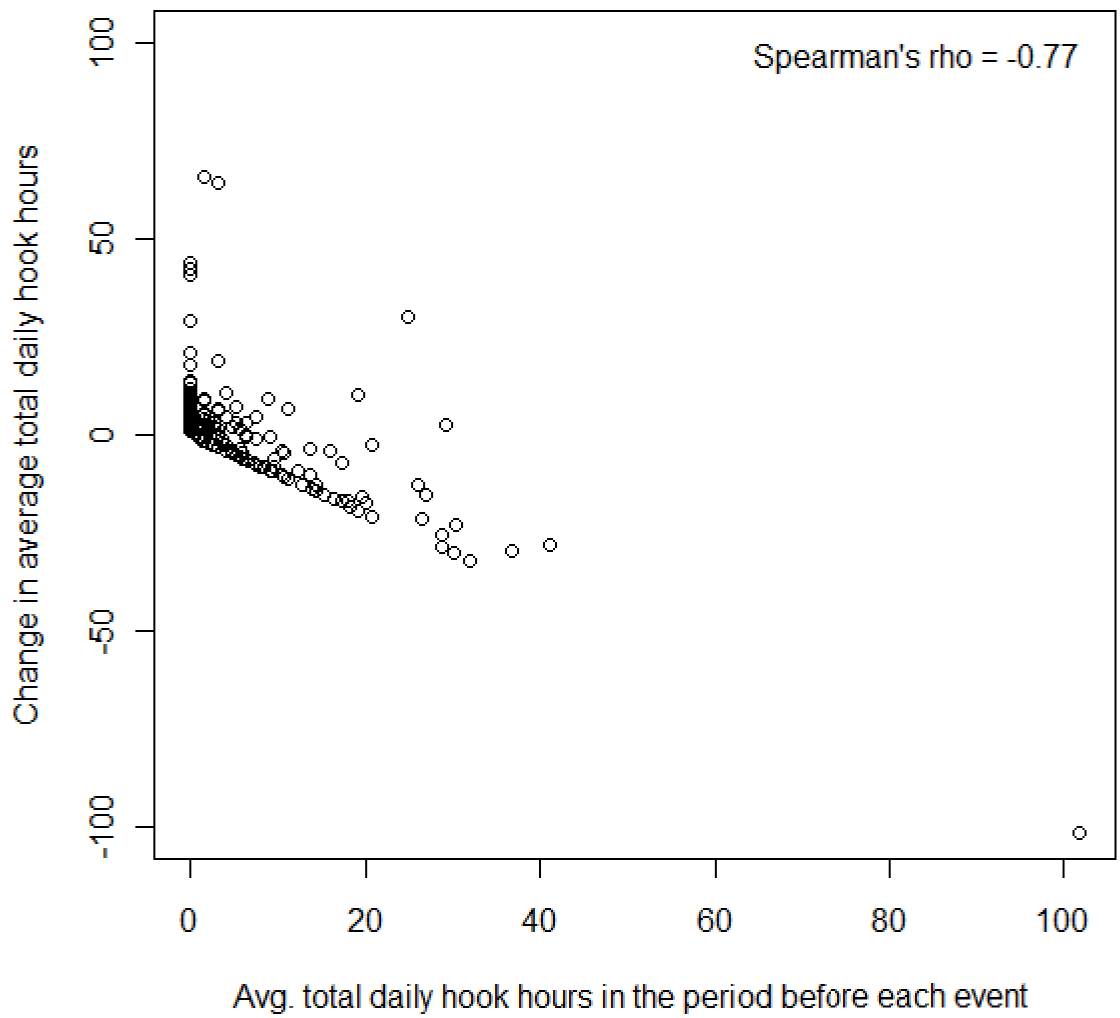


Figure 2.14: Scatter plot of fishing effort prior to each event versus change in fishing effort for logbook fishing in area 2482 and the 5-day period length (over all species).

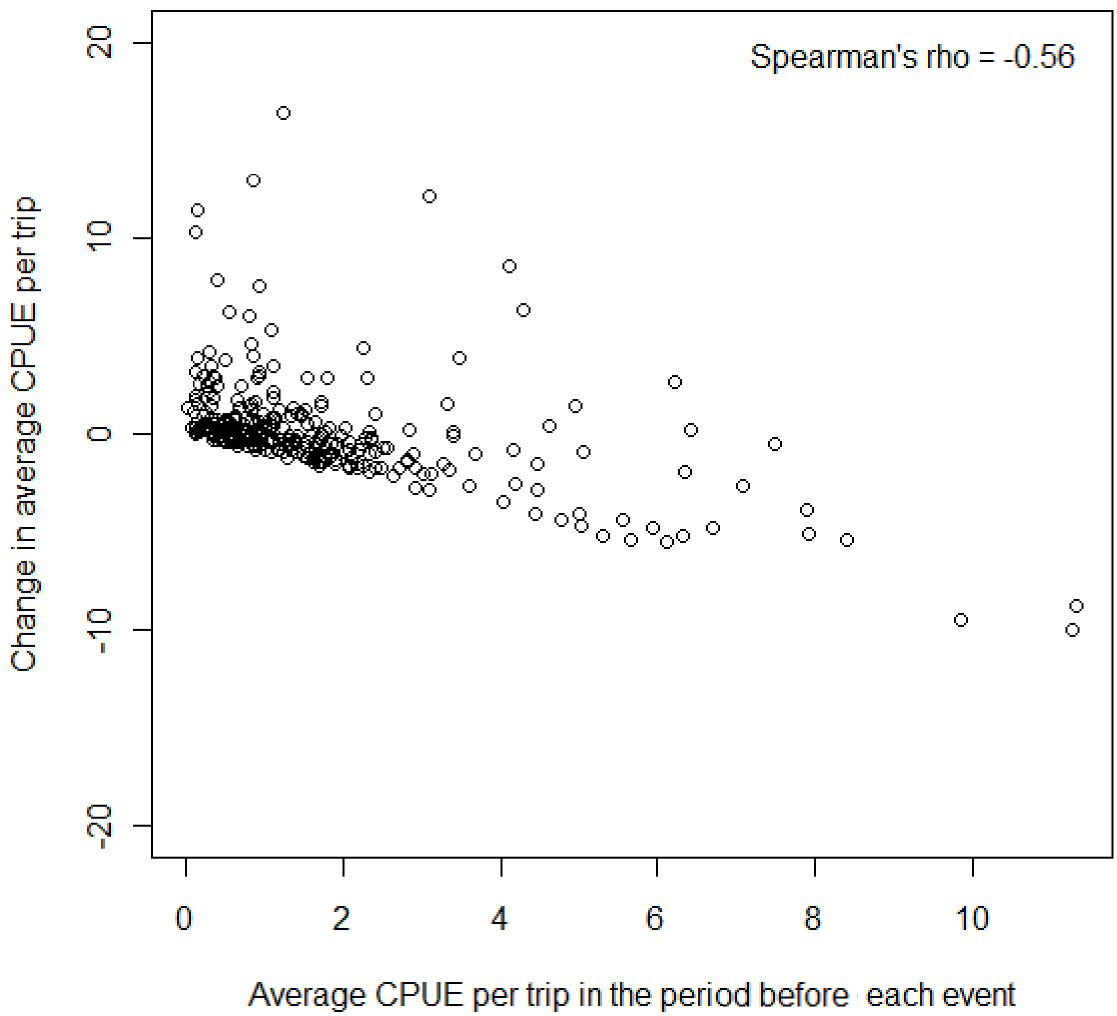


Figure 2.15: Scatter plot of CPUE in the period before each event versus change in CPUE for logbook fishing associated with mutton snapper and the 5-day period length (over all areas).

Appendix A: Initial Models for Change in Effort for Each Fishery Prior to Stepwise Variable Selection

All Areas, All Species:

$\hat{E}_{ijklm} = \beta_0 + \beta_1\ MWS_i + \beta_2\ CWS_i + \beta_3\ MBP_i + \beta_4\ CBP_i + \beta_{5j}\ Y_{ij} + \beta_{6k}\ SE_{ik} + \beta_{7l}\ A_{il} + \beta_{8m}\ SP_{im} + \varepsilon_{ijklm}$

Individual Species, All Areas:

$\hat{E}_{ijkl} = \beta_0 + \beta_1\ MWS_i + \beta_2\ CWS_i + \beta_3\ MBP_i + \beta_4\ CBP_i + \beta_{5j}\ Y_{ij} + \beta_{6k}\ SE_{ik} + \beta_{7l}\ A_{il} + \varepsilon_{ijkl}$

Individual Areas, All Species:

$\hat{E}_{ijkm} = \beta_0 + \beta_1\ MWS_i + \beta_2\ CWS_i + \beta_3\ MBP_i + \beta_4\ CBP_i + \beta_{5j}\ Y_{ij} + \beta_{6k}\ SE_{ik} + \beta_{7m}\ SP_{im} + \varepsilon_{ijkm}$

Where:

$\hat{E}$ = Estimate for Change in Effort — i = 1, …, n (sample sizes, n, listed in table 2.6)

MWS = Maximum Wind Speed on Day of Event

CWS = Change in Wind Speed

MBP = Minimum Barometric Pressure on Day of Event

CPB = Change in Barometric Pressure

Y = Year as Factor — j = 1, …, 15 (logbook) j = 1, 2, 3, 4, 5 (headboat)

SE = Season as Factor — k = 1, 2, 3, 4

(Winter: December-February; Spring: March-May; Summer: June-August; Fall: September-November)

A = Area as Factor — l = 1, 2, 3, 4, 5, 6 (logbook) l = 1, 2, 3, 4 (headboat)

SP = Species as Factor — m = 1, 2, 3, 4

ε = Normally Distributed Random Error with Mean = 0, and Variance = σ^2

Appendix B: Initial Models for Change in CPUE for Each Fishery Prior to Stepwise Variable Selection

All Areas, All Species:

$$\hat{C}_{ijklm} = \beta_0 + \beta_1\, MWS_i + \beta_2\, CWS_i + \beta_3\, MBP_i + \beta_4\, CBP_i + \beta_5\, CE_i + \beta_6\, FF_i + \beta_7\, CP_i + \beta_{8j}\, Y_{ij} + \beta_{9k}\, SE_{ik} + \beta_{10l}\, A_{il} + \beta_{11m}\, SP_{im} + \varepsilon_{ijklm}$$

Individual Species, All Areas:

$$\hat{C}_{ijklm} = \beta_0 + \beta_1\, MWS_i + \beta_2\, CWS_i + \beta_3\, MBP_i + \beta_4\, CBP_i + \beta_5\, CE_i + \beta_6\, FF_i + \beta_7\, CP_i + \beta_{8j}\, Y_{ij} + \beta_{9k}\, SE_{ik} + \beta_{10l}\, A_{il} + \varepsilon_{ijkl}$$

Individual Areas, All Species:

$$\hat{C}_{ijklm} = \beta_0 + \beta_1\, MWS_i + \beta_2\, CWS_i + \beta_3\, MBP_i + \beta_4\, CBP_i + \beta_5\, CE_i + \beta_6\, FF_i + \beta_7\, CP_i + \beta_{8j}\, Y_{ij} + \beta_{9k}\, SE_{ik} + \beta_{10m}\, SP_{im} + \varepsilon_{ijkm}$$

Where:

$\hat{C}$ = Estimate for Change in CPUE — $i = 1, \ldots, n$ (sample sizes, n, listed in table 2.7)

MWS = Maximum Wind Speed on Day of Event

CWS = Change in Wind Speed

MBP = Minimum Barometric Pressure on Day of Event

CPB = Change in Barometric Pressure

CE = Change in Fishing Effort

FF = Number of Days of Forgone Fishing

CP = Change in Percent Positive

Y = Year as Factor — $j = 1, \ldots, 15$ (logbook) — $j = 1, 2, 3, 4, 5$ (headboat)

SE = Season as Factor — $k = 1, 2, 3, 4$

(Winter: December-February; Spring: March-May; Summer: June-August; Fall: September-November)

A = Area as Factor — $l = 1, 2, 3, 4, 5, 6$ (logbook) — $l = 1, 2, 3, 4$ (headboat)

SP = Species as Factor — $m = 1, 2, 3, 4$

ε = Normally Distributed Random Error with Mean = 0, and Variance = σ^2

Appendix C: Regression Output for Models Highlighted in Tables 2.20 and 2.21

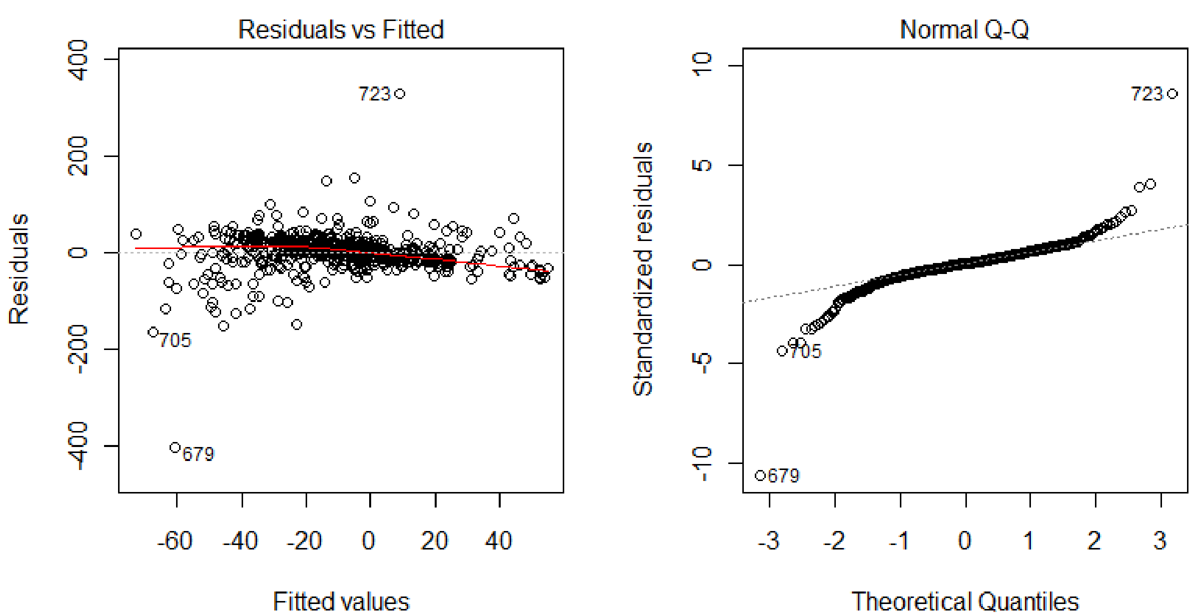
Model 1

Logbook Effort: 5 - Day, Yellowtail Snapper, All Areas

Regression Model Coefficients		
	Estimate	Pr (>|t|)
Intercept	9.66	
Area 2481	-24.33	***
Area 2480	-9.74	
Area 2580	0.46	
Area 2	-0.28	
Area 1	-6.28	
Spring	-4.45	
Summer	-6.15	
Winter	-13.19	**
Change in Wind Speed	-7.84	***
Change in Pressure	-1.28	*

Adjusted R-squared	F - statistic	P - value
0.24	20.84 on 10 and 615 DF	< 0.001

Residuals				
Minimum	1st Quantile	Median	3rd Quantile	Maximum
-403.62	-12.58	2.20	16.91	329.68



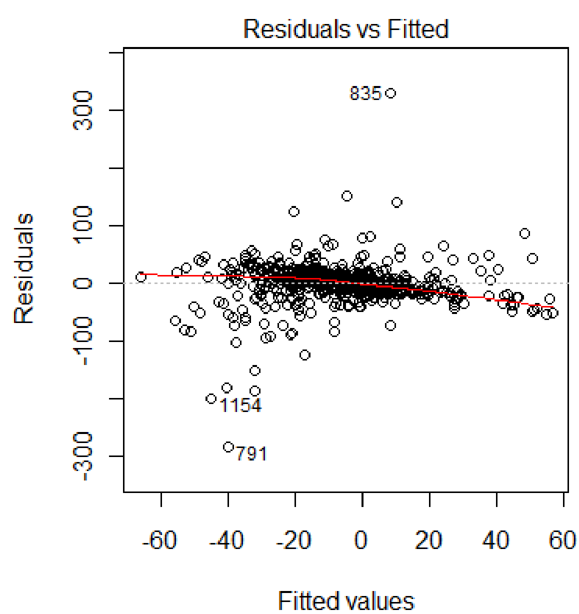
Model 2

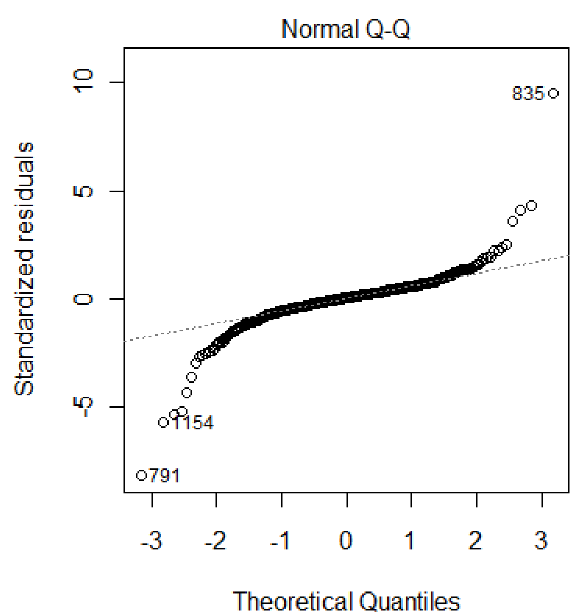
Logbook Effort: 7 - Day, Yellowtail Snapper, All Areas

Regression Model Coefficients		
	Estimate	Pr (>|t|)
Intercept	8.42	
Area 2481	-17.39	***
Area 2480	-6.43	
Area 2580	0.68	
Area 2	1.63	
Area 1	-4.02	
Spring	-6.78	
Summer	-6.38	
Winter	-11.85	**
Change in Wind Speed	-7.60	***
Change in Pressure	-1.44	**

Adjusted R-squared	F - statistic	P - value
0.21	18.38 on 10 and 635 DF	< 0.001

Residuals				
Minimum	1st Quantile	Median	3rd Quantile	Maximum
-283.74	-12.37	2.18	14.77	331.85





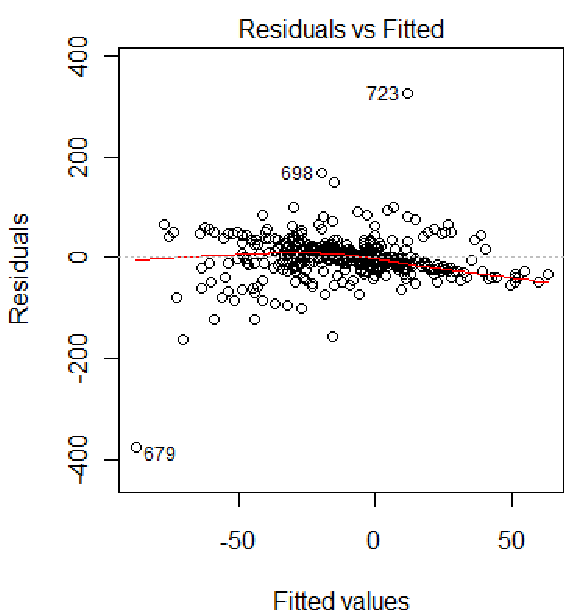
Model 3

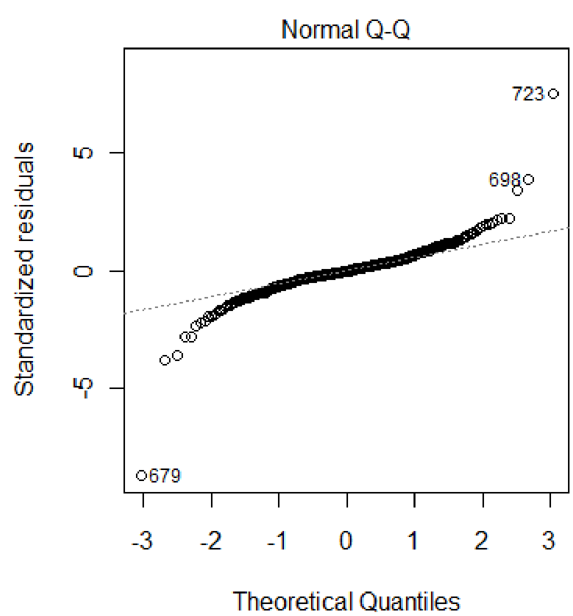
Logbook Effort: 5 - Day, Area 2481, All Species

Regression Model Coefficients		
	Estimate	Pr (>|t|)
Intercept	5.43	
Spring	-7.60	
Summer	-7.39	
Winter	-17.52	**
Mutton Snapper	26.77	***
Mangrove Snapper	14.87	*
White Grunt	23.52	***
Change in Wind Speed	-8.3452	***
Maximum Wind Speed	-1.069	*

Adjusted R-squared	F - statistic	P - value
0.23	16.21 on 8 and 408 DF	<0.001

Residuals				
Minimum	1st Quantile	Median	3rd Quantile	Maximum
-376.66	-15.87	-0.35	17.12	326.90





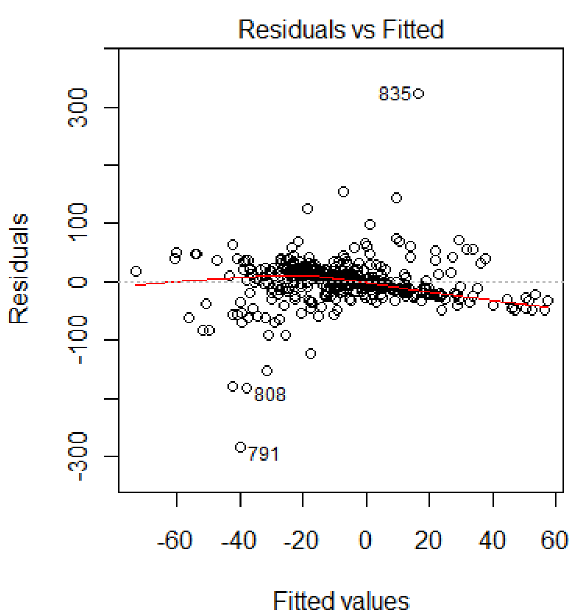
Model 4

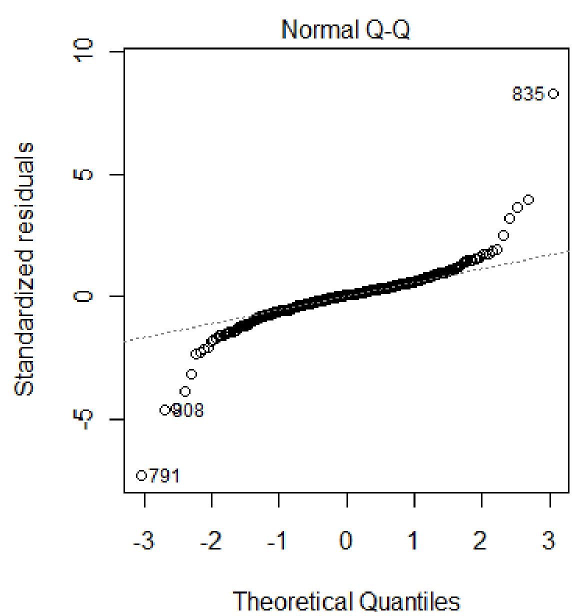
Logbook Effort: 7 - Day, Area 2481, All Species

Regression Model Coefficients		
	Estimate	Pr (>|t|)
Intercept	554.84	
Mutton Snapper	19.32	***
Mangrove Snapper	12.61	*
White Grunt	18.60	***
Change in Wind Speed	-8.75	***
Change in Pressure	-1.14	
Minimum Pressure	-0.55	
Maximum Wind Speed	-0.92	

Adjusted R-squared	F - statistic	P - value
0.20	16.38 on 7 and 418 DF	< 0.001

Residuals				
Minimum	1st Quantile	Median	3rd Quantile	Maximum
-283.65	-14.43	1.69	15.47	323.72





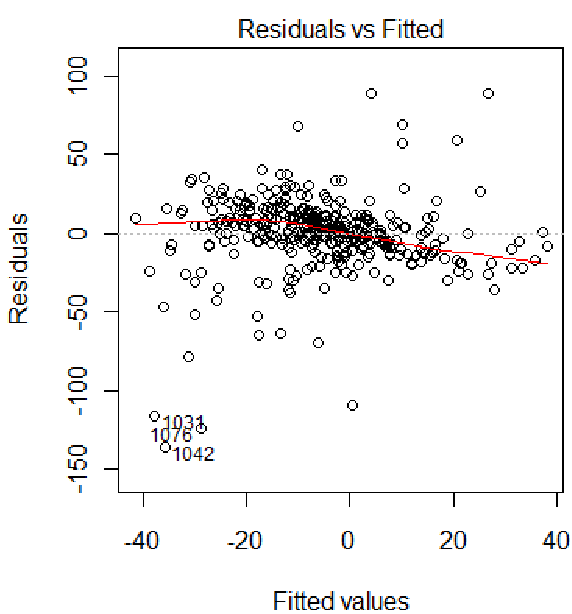
Model 5

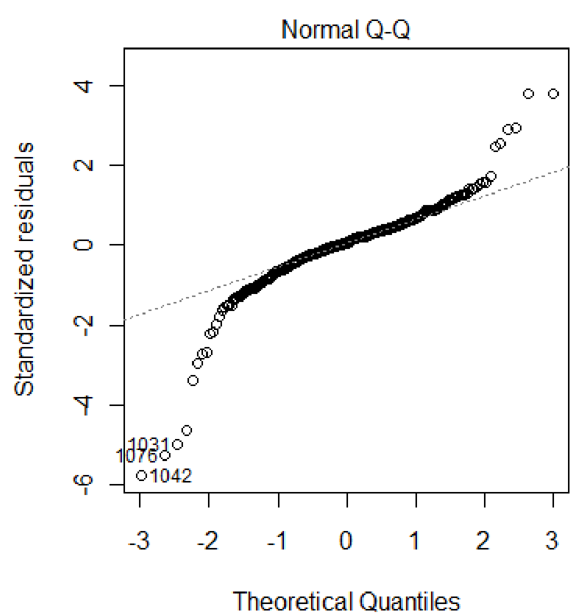
Logbook Effort: 5 - Day, Area 2480, All Species

Regression Model Coefficients		
	Estimate	Pr (>|t|)
Intercept	-2.80	
Spring	-3.92	
Summer	-5.96	
Winter	-9.96	**
Mutton Snapper	10.51	**
Mangrove Snapper	6.01	
White Grunt	11.17	*
Change in Wind Speed	-5.00	***
Change in Pressure	-1.08	**

Adjusted R-squared	F - statistic	P - value
0.26	16.28 on 8 and 347 DF	< 0.001

Residuals				
Minimum	1st Quantile	Median	3rd Quantile	Maximum
-136.01	-8.08	1.52	10.81	89.33





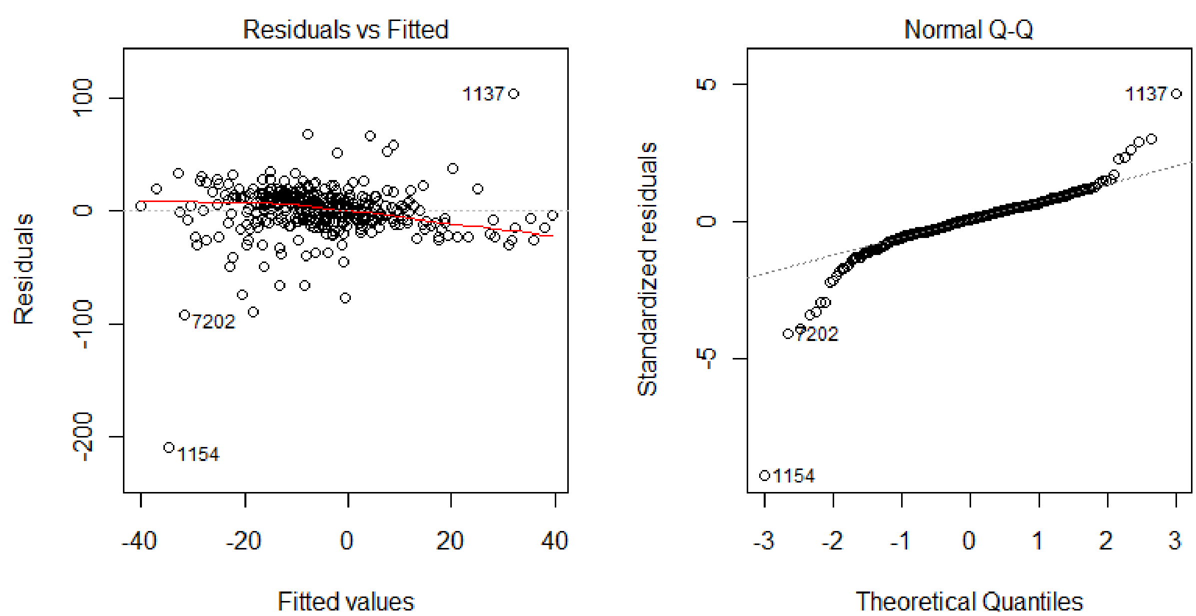
Model 6

Logbook Effort: 7 - Day, Area 2480, All Species

Regression Model Coefficients		
	Estimate	Pr (>|t|)
Intercept	0.55	
Spring	-6.24	
Summer	-6.96	*
Winter	-11.37	**
Mutton Snapper	7.32	*
Mangrove Snapper	3.10	
White Grunt	6.06	
Change in Wind Speed	-5.09	***
Change in Pressure	-1.06	*

Adjusted R-squared	F - statistic	P - value
0.23	14.64 on 8 and 359 DF	< 0.001

Residuals				
Minimum	1st Quantile	Median	3rd Quantile	Maximum
-210.02	-8.67	1.91	11.35	104.84



Model 7

Headboat Effort: 14 - Day, Area 2481, All Species

Regression Model Coefficients		
	Estimate	Pr (>|t|)
Intercept	37.52	*
Spring	-74.96	***
Summer	-42.46	*
Winter	14.68	
Change in Wind Speed	-13.11	***
Change in Pressure	16.54	***

Adjusted R-squared	F - statistic	P - value
0.31	12.67 on 5 and 126 DF	< 0.001

Residuals				
Minimum	1st Quantile	Median	3rd Quantile	Maximum
-174.37	-43.46	-6.99	42.37	170.83