Climate change in the Mission-Aransas Reserve: Evaluating vulnerability of coastal ecosystem and communities using long-term data sets and development of relevant adaptation strategies

Phase I Technical Report

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Mission-Aransas National Estuarine Research Reserve, 750 Channel View Dr., Port Aransas, TX 78373

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Executive Summary

This report assesses the long-term impacts of climate changes, such as temperature and precipitation, on the Mission-Aransas National Estuarine Research Reserve fisheries and bird species, in the past several decades. Increasing annual water temperatures and declining annual precipitation were observed in the Reserve since 1978. More than 30 years of fisheries-independent data from the Texas Parks and Wildlife Department were analyzed, along with bird count data that has been collected since 1949 as part of the National Audubon Society 'Christmas Bird Count'. Six out of the 61 fish species, and nineteen out of more than 180 bird species were identified as being more impacted by either winter freezes (fish = average minimum temperature of coldest week; bird = coldest temperature Dec 14 – Jan 5) or precipitation (fish = summer drought; birds = second half of the year precipitation for birds) on their abundances (both fish and bird) or average length (only fish) than other species in this region. This report strengthens our understanding of climate variables and their potential impact on the ecology the Mission-Aransas Estuary, and it also helps to identify climate change vulnerability assessment targets for adaptation planning.

1. Introduction

Climate changes present major threats to the nation's estuaries. Alternations in air and water temperature, precipitation, freshwater runoff, salinity and pH, sea level, and water exchange with coastal ocean, all could potentially impact the health and resilience of estuarine ecosystems (i.e., Najjar et al., 2000; Scavia et al., 2002). For example, the increase of air and water temperature may lead to more water evaporation, which would increase estuarine salinity and modify stratification and mixing. This could in turn influence distributions and life histories of biota, including commercial and recreational fisheries.

The Mission-Aransas National Estuarine Research Reserve (Reserve) is located in the coastal zone of southeast Texas, in the western Gulf of Mexico (Fig. 1). The climate of the Reserve is subtropical weather with hot and humid summers along with mild to cool winters. Temperatures of the Reserve vary from an average summer maximum of 33.8 °C to an average winter minimum of 9.2 °C, average precipitation is about 79cm yr^{-1} with peak usually in summer months (92 cm yr^{-1} from June to August), according to data collected by National Climatic Data Center (NCDC) in the past three decades. The Reserve is a complex of wetland, terrestrial, and marine environments, supporting many different species including fish and birds. It has been noted that the subtropical Mission-Aransas Estuary appears to be undergoing a series of transitions that are being accelerated by the changing climate. For example, in recent years the establishment of biota more characteristic of tropical habits has been observed, with range expansions of red and black mangrove, mangrove snapper, snook, and other species (i.e., Montagna, 2011). In addition, more droughts and hypersaline conditions within Mission-Aransas Estuary have been observed recently, indicating that the Reserve is experiencing more intense rainfall events with longer, dry periods in between due to climate changes (Evans et al, 2012). Therefore, the Reserve presents an ideal location to assess climate variability and changes for the western Gulf of Mexico.

Despite strong indications that the Mission-Aransas Estuary is undergoing a series of climate-related alternations, little work has been done to evaluate the impacts of climate change on estuarine habitats and associated species. However, the Reserve does have access to a number of high quality, long-term datasets including fisheries and birds that are useful for examining the sensitivity of the Reserve habitats and species to climate change. In this report, we will synthesize and analyze these datasets in an effort to identify those species that have been most strongly affected by the climate change in the past. This report provides useful information for conducting vulnerability assessments and creating adaptation plans that can help resource managers better protect and conserve coastal resources in the face of a rapidly changing climate.

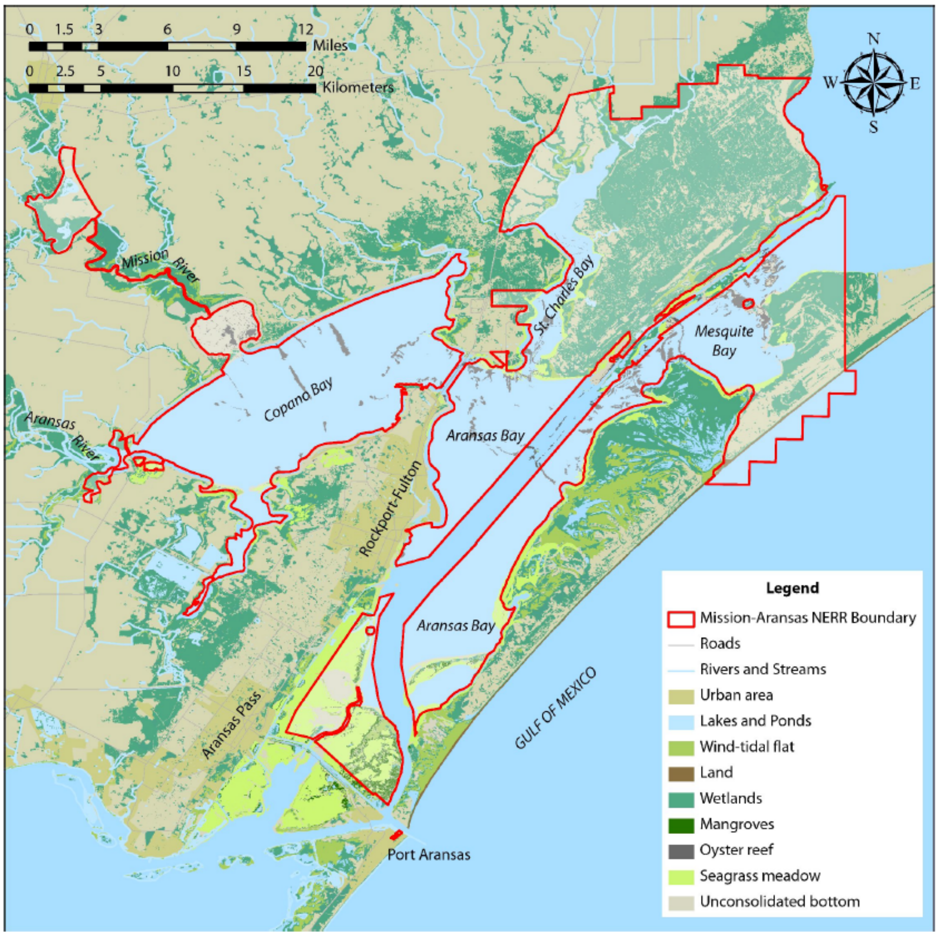

Fig. 1 Map of the Mission-Aransas National Estuarine Research Reserve.

2. Methods

2.1 Data collection

2.1.1. Water quality and climate-related data

The Texas Coastal Ocean Observation Network (TCOON) (http://lighthouse.tamucc.edu/pq), operated by the Division of Nearshore Research

(DNR) at Texas A&M University Corpus Christi, has continuously measured water temperature, and various other water quality and meteorological parameters within the Reserve at Rockport and Copano Bay stations (Fig. 2) since 1996. Additional climate data, such as daily air temperature and precipitation, were collected via National Climatic Data Center (NCDC) (http://www.ncdc.noaa.gov/cdo-web/search?datasetid=GHCND) since 1949 from the National Oceanic and Atmospheric Administration (NOAA) weather station at Corpus Christi International Airport (CCIA), which is about 50 km to the west of the Reserve.

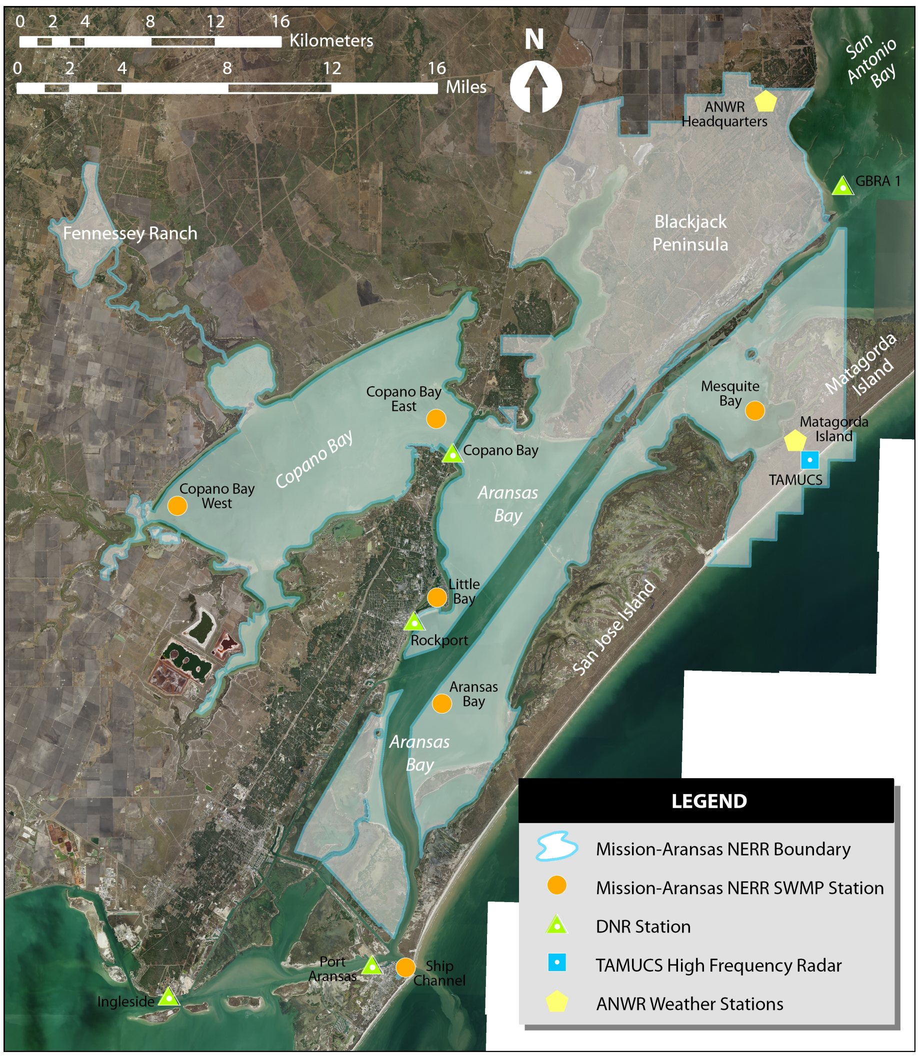

Fig. 2 Map showing the location of Rockport and Copano Bay DNR stations (along with Mission-Aransas NERR System Wide Monitoring Program stations).

2.1.2. Fisheries data

The Texas Parks and Wildlife Department (TPWD) utilizes several sampling gears for its monthly fisheries-independent monitoring of finfish and shellfish communities along the Texas bays. Each gear has greater efficiency for certain species in various habitats. These gears include: (1) bag seines for collecting smaller organisms in near shore environments; (2) bay trawl for collecting organisms near the open bay bottom; (3) gill net for catching larger fish near shore. The data include the number of each species captured (i.e., catch abundance or catch per unit effort (CPUE)), the average total length of each species in every sample, and the hydrological data, such as water temperature and salinity while sampling. Mission-Aransas esturary, is one of the sampling locations along the coast (http://gulfcoast.harc.edu/CoastalResources/CoastalFisheries/TexasCoatalFisheries/tabid/2236/Default.aspx). Figure 3 shows sampling locations for each gear type within Aransas and Copano bays. A total of 61 different fish species were collected since the late 1970's.

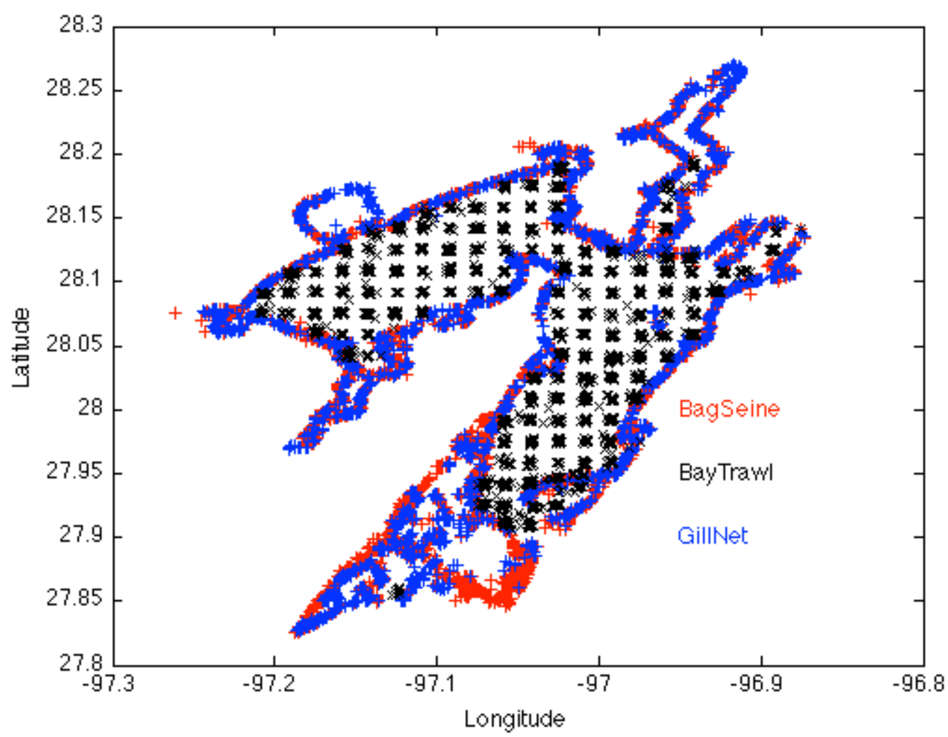

Fig. 3 The sampling locations of three different gear types used by the TPWD fisheries-independent monitoring within the Reserve.

2.1.3. Bird data

During the National Audubon Society's 'Christmas Bird Count (CBC)', volunteers from all over the United States take part from Dec. 14 – Jan. 5 each year in the collection of bird count data for the CBC database. The CBC monitoring program has been in place for over one hundred years in some locations. There are three annual CBC sites located within the Mission-Aransas Reserve, with their observation years listed as: Aransas National Wildlife Refuge (ANWR) (1949-2012), Rockport (1950-1956 & 1994-2012), and Port Aransas (1978-2012) (Fig. 4). Over 180 bird species were identified within or in close proximity to the Reserve.

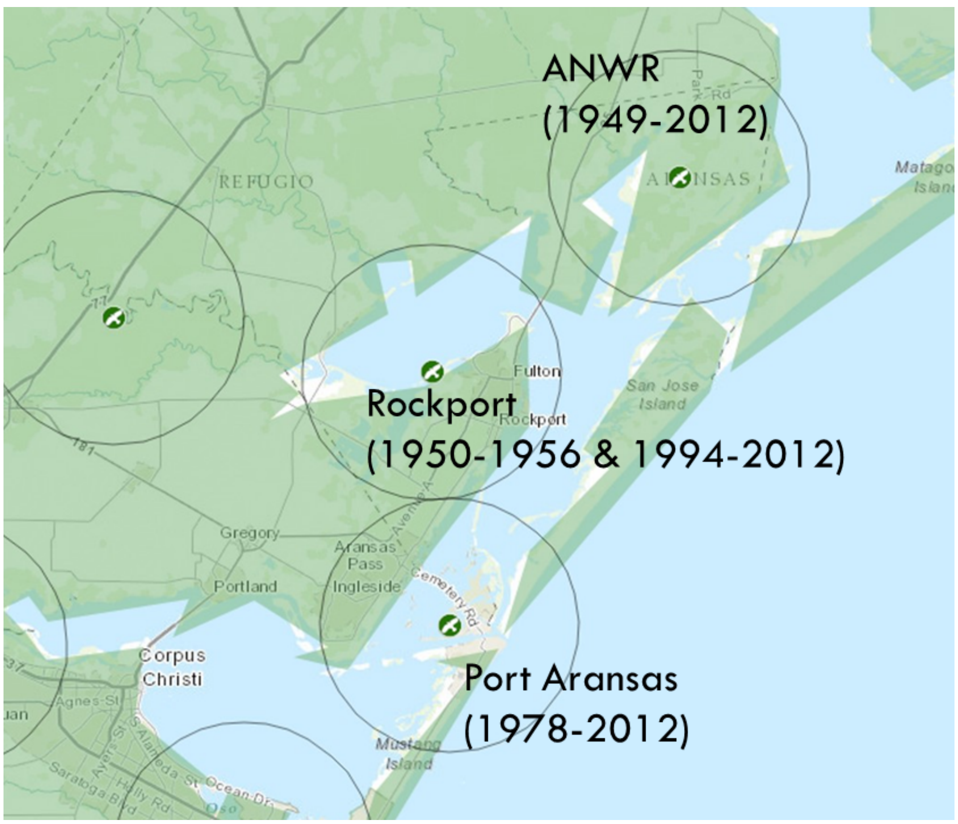

Fig. 4 The location of the three bird CBC observation sites located within or in close proximity to the Reserve.

2.2 Statistical methods

First order linear regression was used to identify the connection between climate variables and the long-term datasets of Reserve fish and bird species.

3. Results

3.1. Long-term climate changes

3.1.1 Air temperature

The average air temperature near the Reserve, according to the NOAA weather station at CCIA, is about 22.3±0.6 °C (minimum: 17.1±0.6 °C; maximum: 27.5±0.8 °C) for the past 66 years (1948-2013). Large temperature variations have been found prior to the early 1980's. The affects of global warming, however, has resulted in a steady increase of the air temperature by 0.04°C yr^{-1} (1.3°C overall) since late 1970's (Fig. 5).

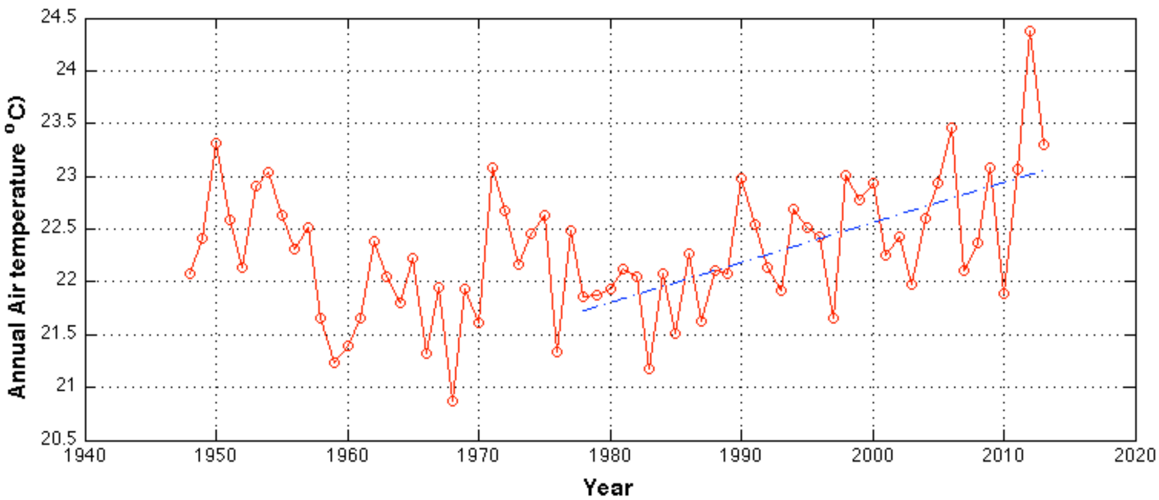

Fig. 5 The average annual air temperature at CCIA NOAA weather station near the Mission-Aransas Reserve between 1948-2013.

3.1.2 Water temperature

Water temperature has been continuously detected within the Reserve since 1996 at the TCOON Rockport and Copano Bay stations. The average annual water temperature is 24.5±0.6 °C in Rockport with a 1.4 °C overall temperature increase in the past 17 years (Fig. 6). Similarly, Copano Bay has average water temperature 24.2±0.9 °C and 0.3 °C overall temperature increase in the past 17 years.

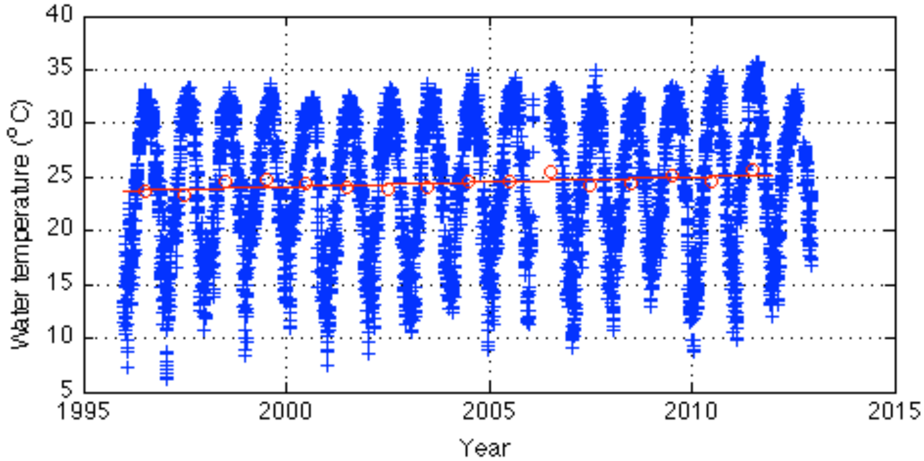

Fig. 6 The daily (+) and annual (o) water temperature at Rockport station monitored by TCOON between 1996-2012.

The daily water temperature at the TCOON station in Rockport (located inside the Mission-Aransas Reserve) has a high first order correlation ($r=0.86$, $n=5940$, $p<0.0001$) with the daily air temperature at the CCIA weather station (located near the Reserve) for the time period of 1996-2012 (Fig. 7). This high correlation implies that the water and air temperatures have consistent changing patterns in the past within or in close proximity to the Reserve. Therefore, the trend of the air temperature since 1948 can be used to approximate the changing trend of water temperature inside of the Reserve, which has been monitored for a much shorter time period than air temperature.

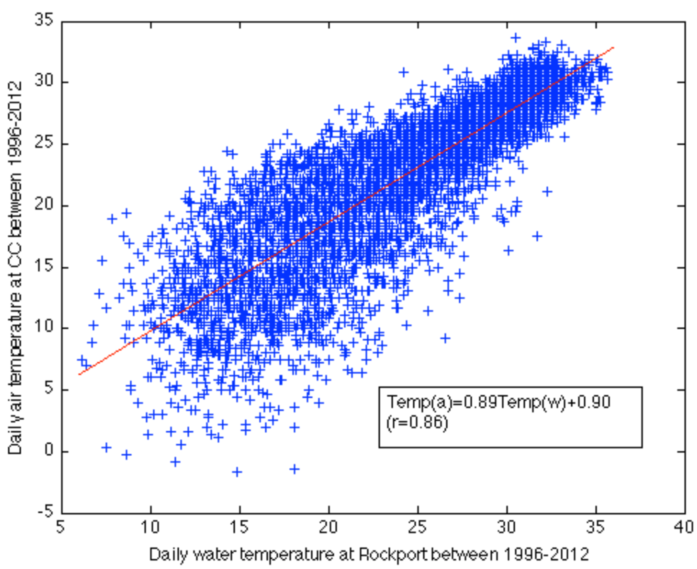

Fig. 7 The plot of daily water temperature in Rockport and daily air temperature at CCIA station between 1996-2012.

3.1.3 Precipitation

The average annual precipitation at the CCIA weather station is 76.2±23.0 cm yr^{-1} for the past 66 years. There were large variations, with the highest record shown in 1991 (122 cm yr^{-1}), and the lowest record in 2011 (48 cm yr^{-1}) (Fig. 8). The overall trend for annual precipitation is decreasing with 0.5 cm yr^{-1} (17 cm overall) since the late 1970's.

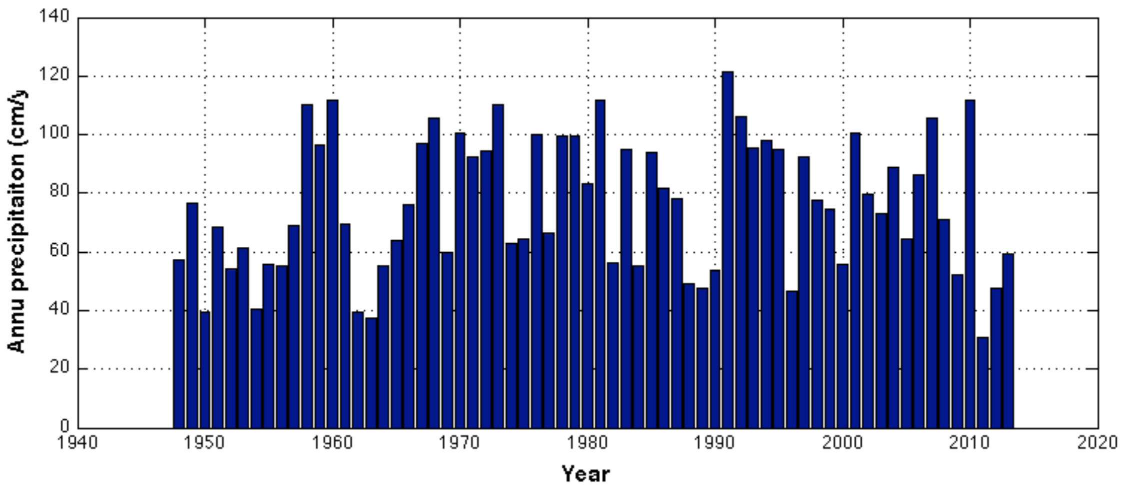

Fig. 8 The average annual precipitation at CCIA weather station near the Mission-Aransas Reserve between 1948-2013.

Since most of the birds migrate seasonally and the data analyzed was collected during winter, we restricted the analysis of precipitation impacts on bird populations to the second half of the year precipitation. Fig. 9 shows the average precipitation of the second half year at CCIA weather station near the Reserve. The average precipitation of the second half year is about 44 ±18 cm yr^{-1}, with large variations among the data. The highest precipitation of the second half year occurred in 1967 (78 cm), while the lowest value occurred in 2011 (12 cm). A high correlation ($r=0.76$, $p<0.0001$) is found between annual and the second half-year precipitations.

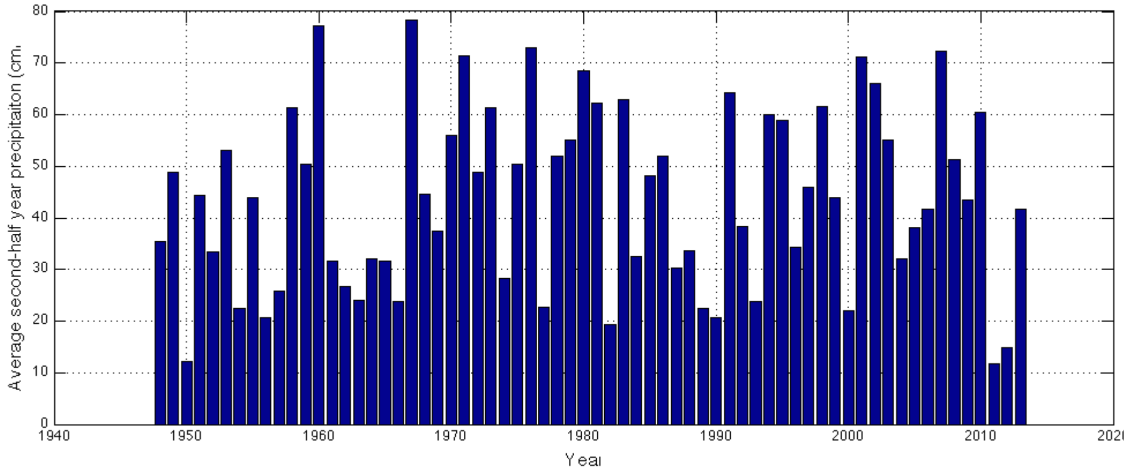

Fig. 9 The average precipitation from the second half year at CCIA weather station near Mission-Aransas Reserve between 1948-2013.

3.1.4 Winter freezes

Although the average temperature shows an increase over the last approximately 66 years, the major temperature impacts within the Mission-Aransas Reserve are often attributed to winter freeze events and intense temperature drops with passing cold fronts, which significantly bring down temperatures for a certain time period (Evans et al., 2012). Holt and Holt (1983) reported the mortality of six major fish species (i.e., sand seatrout, pigfish, Atlantic spadefish, sheepshead, black drum, and bearded brotula) in Port Aransas due to a cold front that rapidly dropped the water temperature to near freezing in January 1982. They also suggested that these fish species were even more vulnerable to sudden cold spells after a warmer than usual summer and fall, due to the fact that more tropical marine species may migrate to and remain inshore in winter than they would be in normal years. Thus, low temperature stress has previously been identified as the major cause for the episodic mass fish mortalities in coastal oceans (Hurst, 2007) and has previously been observed within the Reserve (Holt and Holt, 1983). Severe winter freeze events usually occur between December and February, with most events happening in January. To track changes in winter freeze events over time, we calculated the average minimum temperature of the coldest week for each year (Fig. 10). At least eight years have been reported to have winter air temperatures significantly colder than usual (the average is 3.2 °C) in the coldest week since late 1970's.

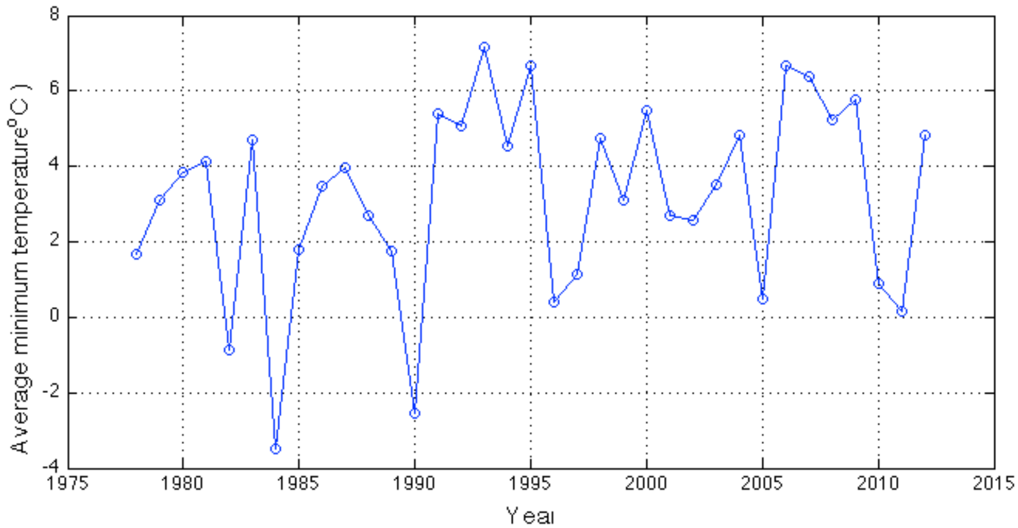

Fig. 10 The average minimum temperature of the coldest week each year between 1978-2012.

Since the birds were counted only during Dec. 14 – Jan. 5 each year, the most related severe winter freeze needs to be calculated within these three weeks, in order to find the most direct impact on bird abundance. Fig. 11 shows the trend of annual coldest air temperature within Dec. 14 – Jan. 5 since 1949. The coldest air temperature decreased 4 °C overall in the first 40 years (before 1990), then increased 0.8 °C in the past 22 years.

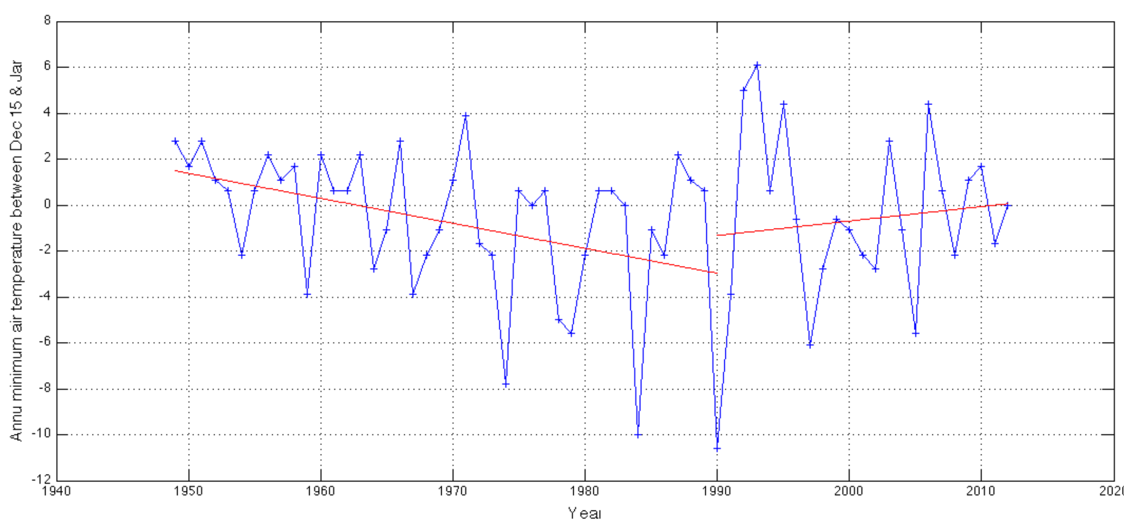

Fig. 11 The coldest air temperature within Dec. 14 and Jan. 5 at CCIA since 1949.

3.1.5 Summer drought

Severe drought is a frequent occurrence during summer time due to the fact that high temperatures lead to high evaporation rates, which often greatly exceed precipitation during the summer months. During droughts, the estuaries intermittently become hypersaline, which has been reported to significantly affect fish or bird breeding, growth, or distribution in coastal waters (Gaines et al., 2000; Dolbeth et al., 2010). Recent observations of increased droughts and hypersaline conditions within the Reserve indicate changing climatic conditions (Evans, 2012). When severe drought happens in summer, high water salinity tends to be observed especially at the end of the summer months. Here we report the average water salinity of August and September each year to represent the water salinity level in summer time (Fig. 12). Salinity consistency is found between water salinity along the shoreline and inside of the Aransas Bay. Water salinity showed an increasing trend between 1978 and 1989, then slightly decreased between 1990-1993, increased to the highest level in 1996, and appeared decreasing again till 2007.

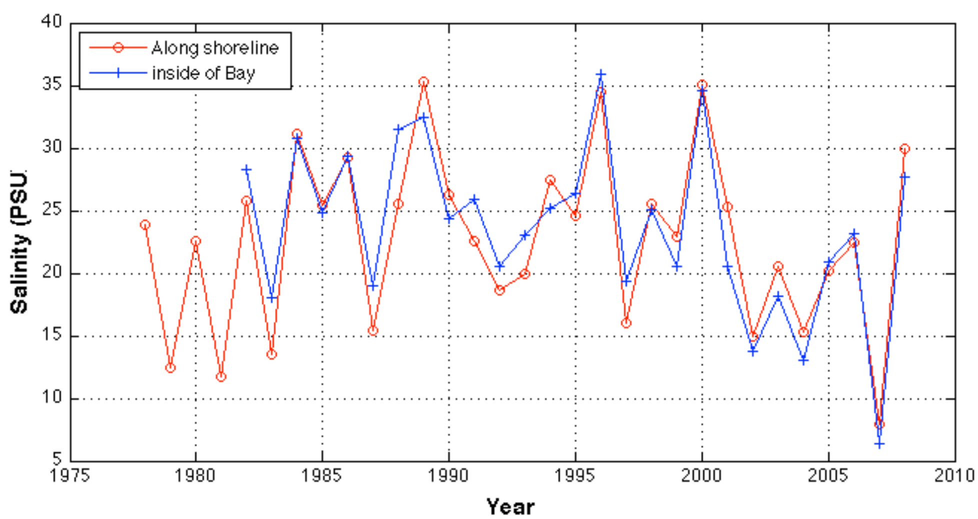

Fig. 12 The average water salinity of August and September between 1978-2008 inside and along the Aransas Bay shoreline.

3.2 Long-term changes of species within the Reserve

The Reserve has access to a variety of long-term ecological datasets, mainly including fish and bird species, which allowed us to examine the changing patterns of fish and birds within the Reserve.

3.2.1 Fisheries

Long-term fisheries datasets in Aransas Bay have been collected by TPWD since 1978. Twenty-one relatively dominant species (i.e., alligator gar, Atlantic croaker, bay anchovy, black drum, blue crab, brown shrimp, gafftopsail catfish, gizzard shad, gulf menhaden, hardhead catfish, ladyfish, pinfish, pink shrimp, red drum, sand seatrout, sheepshead minnow, southern flounder, spot, spotted seatrout, stripped mullet, white shrimp), which have average relative catch abundance greater than 1% (i.e., more than one such species was found in a sample which had 100 animal catches) in at least one of the gear types, were selected for the examination of long-term changes in catch abundance, total length, and trend.

3.2.1.1 Average length distribution for different gear type

Significant length differences were found among these three gear types, as shown in Fig. 13 by Atlantic croaker as an example. In general, bag seines were more likely to collect juvenile species, while bay trawl and gill net tended to collect sub-adult and adult, respectively.

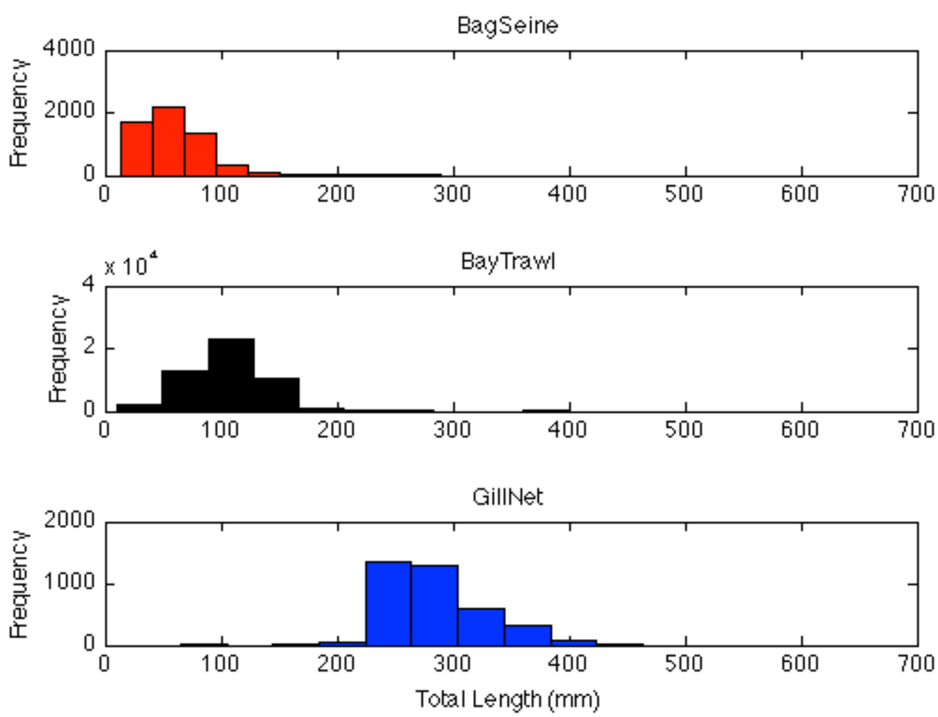

Fig. 13 The total length distribution of Atlantic croaker collected in the three different gear types since late 1970's.

3.2.1.2 Seasonal characteristics of catch abundance

All fish species show seasonality in their catch abundances. For example, Atlantic croaker showed peak catch abundance in early spring (February and March) for bag seine (Fig.14a), in spring and early summer for bay trawl (Fig.14b), and in fall for gill net sampling (Fig.14c). The seasonal catch abundance distributions of the dominant species in each gear type are shown in Appendix 1 for reference (Appendix 1).

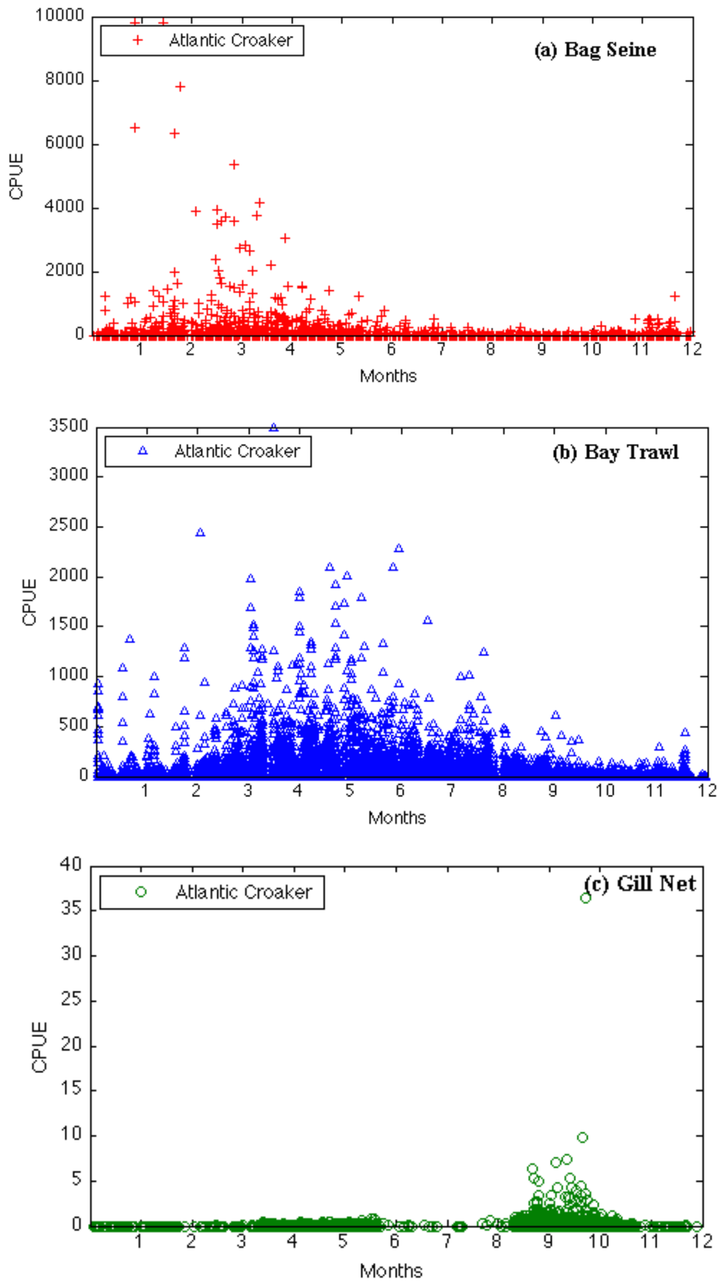

Fig. 13 The monthly distribution of catch abundance for Atlantic Croaker in Aransas Bay by (a) bag seine; (b) bay trawl; and (c) gill net.

3.2.1.3 Trend of annual catch abundance

Considering that different species show distinct seasonality, we used the yearly average catch abundance to represent the annual abundance of each species and to analyze the long-term trend (1978-2008) of annual catch abundance for each species in the Reserve. The slope of the first order linear regression between annual catch abundance and individual year was calculated and listed in Table 1 as annual trends (%), which represent the percentage changes in population per year. The changing trend might be significantly different for the same species but with different gear types. **Species that consistently increased in all gear types were: black drum, sand seatrout, spotted seatrout, pinfish, and spot (shown in blue). Species that consistently decreased were: blue crab and southern flounder (shown in red).**

Table. 1 The annual trend of catch abundance for the dominant fish species in Aransas Bay between 1978-2008 for three different gear types. The annual trends (%) represent the percentage changes in population per year.

Annual trends (%)	BagSeine	BayTrawl	GillNet
Brown shrimp	0.4	-3	-
Pink shrimp	1.4	-3	-
white shrimp	-1.9	9	-
Atlantic croaker	-0.2	2	-0.7
Bay anchovy	-2	1.5	-
Blue crab	-1	-6	-0.9
Gulf menhaden	-9	0.5	-2
Pinfish	2	3	-
Spot	0.4	5	-
Striped mullet	-3	9	-
Black drum	0.2	6	3
Red Drum	2.9	-3	2.5
Sheepshead	-0.5	3	-1.9
Sand seatrout	6.4	7	-
Spotted seatrout	0.9	0.9	3
Southern flounder	-2	-6	-1.9
Alligator	-	-	1
Gafftopsail	-	-	1
Gizzard	-	-	3
Hardhead catfish	-	-	4
Ladyfish	-	-	9

3.2.1.4 Trend of annual average total length

In addition to fish catch abundance, we studied average total length (i.e., size) of each species and examined the annual trend in total length since the late 1970's. The average total length is an indication of the growth rate of each species by different gear type. The trends of annual average total length, which represent the percentage change in average total length per year for each species, were calculated by the slope of the first order linear regression between annual average total length and individual years (Table 2). All of the length changes are in the range of -2 to 4% with an average of 0.3% between 1978-2008. **Species that consistently increased their length in all gear types were: bay anchovy, striped mullet, and sheepshead (shown in blue). The only species that consistently decreased in length was brown shrimp (shown in red).**

Table. 2 The annual trend of average total length between 1978-2008 for fishes by different gear types. The annual trends (%) represent the percentage changes in average total length per year.

Annual trends (%)	BagSeine	BayTrawl	GillNet
Brown shrimp	-0.3	-0.6	-
Pink shrimp	0.2	-0.6	-
white shrimp	0.6	-0.03	-
Atlantic croaker	-1	0.9	-0.4
Bay anchovy	0.01	0.9	-
Blue crab	-2	0.4	0.2
Gulf menhaden	0.2	2	-0.01
Pinfish	-0.6	0.3	-0.4
Spot	0.03	0.7	-0.2
Striped mullet	0.05	0.7	0.2
Black drum	-1	2	0.6
Red Drum	-0.2	4	0.4
Sheepshead	0.4	2	0.5
Sand seatrout	0.4	0.8	-0.3
Spotted seatrout	0.5	0.1	-0.02
Southern flounder	-1	1	0.4
Alligator	-	-	-0.04
Gafftopsail	-	-	-0.2
Gizzard	-	-	0.2
Hardhead catfish	-	-	0.02
Ladyfish	-	-	0.6

To summarize, we identified 11 fish species that have either consistent increasing or decreasing trend on catch abundance or average total length between 1978-2008 (Table 3). Abundances of **both blue crab and southern flounder consistently declined in the past 3 decades, while those of pinfish, spot, black drum, sand seatrout and spotted seatrout consistently increased. The size of brown shrimp declined, but the total length of the other three fishes, bay anchovy, striped mullet and sheepshead, have increased since 1978.**

Table. 3 Annual trend of fish abundances and average total length in Aransas Bay in 1978-2008. '+' represents a consistent increase trend, '-' represents a consistent decrease trend.

Species	Catch abundance	Average total length
Brown shrimp		-
Pink shrimp		
white shrimp		
Atlantic croaker		
Bay anchovy		+
Blue crab	-	
Gulf menhaden		
Pinfish	+	
Spot	+	
Striped mullet		+
Black drum	+	
Red Drum		
Sheepshead		+
Sand seatrout	+	
Spotted seatrout	+	
Southern flounder	-	
Alligator		
Gafftopsail		
Gizzard		
Hardhead catfish		
Ladyfish		

3.2.2 Birds

Long-term bird data have been collected, with over 180 bird species identified inside of the Reserve in the past half century. In this report we focused on the 28 species that either have been identified by Foster et al. (2009) as having significant impacts from human activity, were the dominant species (>1%) in all three observational sites inside of the Reserve, or were species of special interest (i.e., Whooping Crane).

3.2.2.1 Abundance trend of 28 birds between 1949-2012

At the ANWR site, birds were observed annually since 1949. At the Rockport site, this observation was interrupted into two periods: 1950-1956 & 1994-2012 (i.e., there was no bird observations between these time intervals). In both sites, the trends of bird abundance over the past 64 years were calculated by the first order linear relationship between bird abundance and individual years (Table 4). **Five species (Brown Pelican, Laughing Gull, Double-crested Cormorant, Forster's Tern, and Western Sandpiper) consistently increased, and the other four species (Gull-billed Tern, Piping Plovers, Eared Grebe, and American Wigeon) consistently decreased, with more than 1% changes at both sites in the past 64 years.** Whooping Crane increased by 3% at ANWR since 1949.

Table. 4 Annual trend of 28 bird species at ANWR and Rockport CBC sites since 1949.

bird name	Slope (%) ANWR	Slope (%) Rockport
	1949-2012	
Gull-billed tern	-4	-5
Piping plovers	-3	-2
Eared grebe	-1	-4
Herring gull	-0.8	-4
Brown pelican	5	2
Black-bellied plover	4	0.1
Laughing gull	4	1
Doubled-crested cormorant	3	2
Forster's tern	3	1
American oystercatcher	3	0.4
Great blue heron	2	0.2
Sanderling	2	-0.5
Royal tern	1	-2
Caspian tern	1	0.3
Black skimmer	0.1	0.5
Red knot	-	-
American Robin	2	-0.7
American White Pelican	4	-1
American Wigeon	-3	-3
dowitcher sp.	1	-1
duck sp.	0.3	-11
Great-tailed Grackle	-10	2
Northern Pintail	-0.5	0.9
Red-winged Blackbird	-0.9	2
Redhead	3	0.4
Western Sandpiper	4	1
Whooping crane	3	-0.9

3.2.2 Abundance trend of 28 birds 1994-2012

Birds have been monitored at all three CBC sites in or near the Reserve since 1994. Table 5 lists the annual trend of bird abundance in the past 19 years at each of the three locations. Most of the birds showed different changing trends at the three CBC sites. **Only Brown Pelicans, American Oystercatchers, and Great-tailed Grackles consistently increased in all three locations since 1994. Whooping Cranes increased in both the ANWR and Rockport since 1994, but was not reported in Port Aransas. Six species including Eared Grebe, Black-bellied Plover, Sanderling, American Wigeon, Dowitcher sp., and Duck sp. consistently decreased inside of the Reserve.** It is worth noting that most (23 out of 28) species showed decreasing trends at the Rockport site in the past 19 years.

Table. 5 The annual trends of 28 bird species between 1994-2012 at all three CBC locations inside of the Reserve. The annual trends (%) represent percentage change in bird counts per year.

bird name	ANWR	Slope (%) Rockport 1994-2012	Port Aransas
Gull-billed tern	9	-5	2
Piping plovers	-7	-5	3
Eared grebe	-10	-13	-0.3
Herring gull	2	-4	2
Brown pelican	5	3	7
Black-bellied plover	-6	-1	-6
Laughing gull	5	-4	-2
Doubled-crested cormorant	5	-4	-9
Forster's tern	0.5	-3	0.3
American oystercatcher	7	0.1	3
Great blue heron	1	-1	1
Sanderling	-4	-9	-3
Royal tern	0.3	-0.3	7
Caspian tern	-2	-4	0.2
Black skimmer	2	-1	-3
Red knot	-	-	4
American Robin	-4	7	-4
American White Pelican	2	-1	0.9
American Wigeon	-9	-15	-9
dowitcher sp.	-2	-4	-3
duck sp.	-14	-11	-21
Great-tailed Grackle	7	2	3
Northern Pintail	-6	0.9	-4
Red-winged Blackbird	9	7	-2
Redhead	19	-7	3
Western Sandpiper	6	-3	-8
Whooping crane	2	5	-

To summarize, **Brown Pelican showed increasing trend in both long term (1949-2012) and short term (1994-2012) datasets, and was identified as the consistent increasing species within the Reserve in the past**. **Both Eared Grebe and American Wigeon were identified as the consistent decreasing species (Table. 6).**

Table. 6 The positive (+) or negative (-) changing trend for bird abundance in both long-term and short-term datasets.

bird name	1949-2012 2 locations	1994-2012 3 locations
Doubled-crested cormorant	+	
Eared grebe	-	-
Herring gull		
Forster's tern	+	
Royal tern		
Gull-billed tern	-	
Caspian tern		
Black skimmer		
Great blue heron		
Black-bellied plover		-
Piping plovers	-	
Brown pelican	+	+
American oystercatcher		+
Laughing gull	+	
Sanderling		-
Red knot		
American Robin		
American White Pelican		
American Wigeon	-	-
dowitcher sp.		-
duck sp.		-
Great-tailed Grackle		+
Northern Pintail		
Red-winged Blackbird		
Redhead		
Western Sandpiper	+	
Whooping crane		

3.3 Long-term impact of severe winter freeze on species

3.3.1 Impact on fish catch abundance

As mentioned, winter freeze is one of the major temperature impacts on fish populations inside of the Reserve. Here we used winter temperature from the coldest week in winter to represent winter freezes for all fish cases, though we didn't get freeze every year. To understand the relationship between winter freezes and fish abundance, we calculated the first linear correlation between the long-term annual winter temperature for the coldest week and the annual catch abundance of each species for different gear types. The species that had significant correlation ($r>0.3$, $n=31$, $p<0.05$) or were affected by winter freezes but not significantly ($0.13<r<0.3$, $n=31$, $0.05<p<0.25$) are listed in Table 7. **Species that show negative affects due to winter freezes in at least two gear types are highlighted in bold: red drum, sheepshead, spotted seatrout, sand seatrout, Atlantic croaker, and black drum.**

Table. 7 Species that had catch abundance negatively affected by winter freezes.

catch abundance affected by **winter freeze**	**BagSeine**	**BayTrawl**	**GillNet**
significantly afftected r>0.3 (n=31,p<0.05)		**Spotted seatrout (0.49)** **Sand seatrout (0.39)** **Atlantic croaker (0.38)** Bay Anchovy (0.34) striped mullet (0.33) **Sheepshead (0.32))**	Gizzard (0.38) **Black drum (0.31)**
affected but not significantly 0.13<r<0.3 (0.05<p<0.25)	**Red drum (0.20)** Pink shrimp (0.19) spotted seatrout (0.17) **Sheepshead (0.16)**	white shrimp (0.27) **Black drum (0.14)**	**Spotted seatrout (0.27)** Hardhead catfish (0.26) **Red Drum (0.23)** Ladyfish (0.23) **Atlantic croaker (0.18)** Pinfish (0.13)

3.3.2 Impact on the average total fish length

The first order linear correlations between the long-term winter temperature for the coldest week and the average total length of each species for different gear types were calculated, and the most affected species are listed in Table 8. **The total length of the species highlighted in bold were shown to be affected by winter freezes in at least two gear types. The species highlighted in red were affected by winter freezes for both catch abundance and average total length. These species include: spotted seatrout, Atlantic croaker, bay anchovy, sand seatrout, sheepshead, striped mullet, hardhead catfish, and black drum.**

Table. 8 Species that had average total length negatively affected by winter freezes.

average length affected by winter freeze	BagSeine	BayTrawl	GillNet
significantly afftected r>0.3 (n=31,p<0.05)	White shrimp (0.44) **Sand seatrout (0.34)**	Atlantic croaker (0.58) Pinfish (0.58) Spot (0.55) Bay anchovy (0.52) **Gulf menhaden (0.40)** **southern flounder (0.33)**	**Southern flounder (0.64)** Blue crab (0.32)
affected but not significantly 0.13<r<0.3 (0.05<p<0.25)	**Southern flounder (0.24)** **spotted seatrout (0.20)**	Red drum (0.30) **Sand seatrout (0.29)** Sheepshead (0.21) Striped mullet (0.14)	Hardhead (0.28) **Spotted seatrout (0.25)** **Gulf menhaden (0.15)** Black Drum (0.15)

3.3.3 Impact on bird abundance

Since birds were counted only during Dec. 14 – Jan. 5 each year, the correlations were calculated between bird abundance and the annual coldest air temperatures during these three specific weeks (to represent winter freezes in bird cases) (Fig. 11) and are listed in Table 9. Different from fish species, birds were affected by winter freezes in two ways: (1) limited affect when a positive correlation exists between abundance and the coldest winter temperature, and (2) enhanced abundance when correlation was negative. The correlations that were significant (p<0.05) or not that significant but still correlated (0.05<p<0.25) are highlighted with yellow or light green, respectively. **Three species (Doubled-crested cormorant, Forster's tern, & Piping Plovers, all highlighted in red) were identified as more likely to be limited by the cold freeze, while ten other species (i.e, Caspian tern, Great Blue Heron, Black-bellied plover, Brown pelican, Laughing Gull, American Robin, American Wigeon, dowitcher sp., Great-tailed Grackle, and Northern Pintail, highlighted in blue) actually showed higher abundances during colder winters, especially in Copano Bay. These ten species were more likely limited by the increases on minimum winter temperature instead. Western Sandpiper showed a complicated relation with winter freezes, as abundance was significantly limited at ANWR but enhanced at the Rockport site during coldest winter temperature.** Whooping Cranes were among the group that showed a slight increased abundance by cold temperature, but not significant at all.

Table. 9 The correlations between abundance of each bird species and coldest air temperature inside of the Reserve.

Bird name	correlation coefficient with coldest air temp ANWR 1949-2012	Rockport 1950-1956 & 1994-2012	Port Aransas 1978-2012
Doubled-crested cormorant	0.24	0.21	-0.08
Eared grebe	0.14	-0.08	-0.09
Herring gull	-0.06	-0.02	0.09
Forster's tern	0.14	-0.23	0.37
Royal tern	0.16	-0.01	0.04
Gull-billed tern	-0.08	0.21	-0.16
Caspian tern	-0.17	-0.15	0.11
Black skimmer	0.07	-0.2	0.06
Great blue heron	-0.07	-0.27	-0.16
Black-bellied plover	0.16	-0.3	-0.1
Piping plovers	0.2	0.4	0
Brown pelican	0.02	-0.27	0.17
American oystercatcher	0.06	-0.11	-0.01
Laughing gull	-0.14	-0.4	-0.09
Sanderling	0.09	-0.16	-0.17
Red knot	-	-	0.14
American Robin	-0.08	-0.36	0.04
American White Pelican	0.1	-0.26	0.17
American Wigeon	-0.16	-0.05	-0.27
dowitcher sp.	-0.23	-0.38	0.08
duck sp.	0.1	-0.02	0.1
Great-tailed Grackle	-0.04	-0.47	0.15
Northern Pintail	-0.1	-0.29	-0.1
Red-winged Blackbird	-0.06	-0.05	0.02
Redhead	0.06	-0.12	-0.02
Western Sandpiper	0.29	-0.36	-0.03
Whooping crane	-0.03	-0.11	-

*'red' limited by winter freeze

(yellow) represents $p<0.05$

(green) represents $0.05<p<0.25$

3.4. Long-term impact of summer drought on fish species

3.4.1 Impact on fish catch abundance

The average salinity between August and September was used to represent the summer drought status each year. Linear correlations between the long-term summer drought status and catch abundance of each species for different gear types were calculated. Table 10 lists the species most affected by summer drought according to the correlation coefficients. **The species that were negatively affected by summer drought in at least two gear types are indicated in bold and include: striped mullet, sheepshead, sand seatrout, red drum, spot, and Atlantic croaker.**

Table. 10 Species that had catch abundance affected by summer drought.

catch abundance affected by Summer drought	BagSeine	BayTrawl	GillNet
significantly afftected r<-0.3 (n=31,p<0.05)	**striped mullet (-0.37)** **sheepshead (-0.33)** **sand seatrout (-0.33)** Blue crab (-0.31)	**Sand seatrout (-0.64)** **Spot (-0.50)** **Atlantic croaker (-0.45)** White shrimp (-0.44) **Striped mullet (-0.33)** Red drum (-0.32)	**Atlantic croaker (-0.37)**
affected but not significantly r[-0.3 -0.13] (0.05<p<0.25)	**Red drum (-0.25)** Pinfish (-0.16) Brown shrimp (-0.14)		**sheepshead (-0.26)** ladyfish (-0.15)

3.4.2 Impact on average total fish length

Similarly, Table 11 lists the species for which average total length was negatively affected by summer drought. **Bold text indicate species that were negatively affected in at least two gear types and includes: sheepshead, blue crab, bay anchovy, Gulf menhaden, pinfish, Atlantic croaker, southern flounder, and spotted seatrout. Species highlighted in red indicate those that were affected by summer drought for both average total length and catch abundance and include: sheepshead, blue crab, pinfish, striped mullet, red drum, Atlantic drum, and sand seatrout.**

Table. 11 Species that has average total length affected by summer drought.

average length affected by Summer drought	BagSeine	BayTrawl	GillNet
significantly afftected r<-0.3 (n=31,p<0.05)	Pink shrimp (-0.40) **sheepshead (-0.37)** **Blue crab (-0.34)** White shrimp (-0.32)	**Sheepshead (-0.47)** **Bay anchovy (-0.43)** **Gulf menhaden (-0.39)** **Blue crab (-0.35)**	**Blue crab (-0.41)**
affected but not significantly r[-0.3 -0.13] (0.05<p<0.25)	**Pinfish (-0.27)** **Bay anchovy (-0.23)** Brown shrimp (-0.22) Striped mullet (-0.20) **Southern flounder (-0.19)** **Gulf menhaden (-0.16)** **Spotted seatrout (-0.15)**	Red drum (-0.19) **Atlantic Croaker (-0.18)** Sand seatrout (-0.16) **Pinfish (-0.14)**	Hardhead (-0.29) **Atlantic Croaker (-0.27)** **Spotted seatrout (-0.26)** **Southern flounder (-0.19)**

3.5 Long-term impact of precipitation on bird species

Since many of the birds included in the study migrate seasonally, we focused on the second half of the year precipitation and analyzed the impact on the bird abundance during the winter season (Dec 14 – Jan 5). The correlations between abundance of each bird species and corresponding second half of the year precipitation are listed in Table 12. The correlations that are significant ($p<0.05$) or not that significant but still correlated ($0.05<p<0.25$) are highlighted with yellow or light green, respectively. Eight bird species (highlighted in red), including **Doubled-crested Cormorant, Eared grebe, Forster's Tern, Black skimmer, Black-bellied plover, Sanderling, dowitcher sp., and Western Sandpiper increased with more precipitation in at least one of the Reserve sampling sites, indicating they were likely limited by second half year drought, while three birds (highlighted in blue), Piping plover, Red-winged Blackbird, and Redhead showed decreases in abundance with increasing precipitation.** Whooping Crane tended to decrease with more precipitation in both ANWR and Rockport, but not significantly at all.

Table. 12 Correlation between abundance of each bird species and precipitation during the second half of the year.

Bird name	Correlation coefficient with second half year precipitation ANWR 1949-2012	Rockport 1950-1956 & 1994-2012	Port Aransas 1978-2012
Doubled-crested cormorant	**0.08**	**0.25**	**0.07**
Eared grebe	-0.15	0.05	0.45
Herring gull	**-0.06**	**-0.04**	**-0.03**
Forster's tern	0.08	0.44	0.18
Royal tern	-0.07	0.05	-0.1
Gull-billed tern	0.2	-0.05	0.1
Caspian tern	**-0.02**	**-0.03**	**-0.04**
Black skimmer	0.04	0.51	-0.1
Great blue heron	0.03	0.07	-0.1
Black-bellied plover	-0.06	-0.05	0.25
Piping plovers	0.17	-0.33	-0.05
Brown pelican	**0.12**	**0.13**	**0.17**
American oystercatcher	0.05	0.27	-0.05
Laughing gull	0.02	0.22	-0.11
Sanderling	**0.09**	**0.01**	**0.21**
Red knot	-	-	0.11
American Robin	-0.1	-0.27	0.18
American White Pelican	0.01	-0.18	0.19
American Wigeon	**0.08**	**0.07**	**0.06**
dowitcher sp.	**0.15**	**0.27**	**0.34**
duck sp.	-0.18	0.13	0.06
Great-tailed Grackle	0.08	-0.12	-0.14
Northern Pintail	**-0.22**	**-0.02**	**-0.01**
Red-winged Blackbird	0.09	-0.1	-0.29
Redhead	**-0.34**	**-0.01**	**-0.05**
Western Sandpiper	0.02	0.26	-0.08
Whooping crane	-0.05	-0.55	-

*'red' limited by second half year drought

(yellow) represents $p<0.05$

(light green) represents $0.05<p<0.25$

3.6. Long-term combined impact of winter freeze & summer drought on fish species

3.6.1 Combined impact on fish catch abundance and average total length

Winter freezes and summer drought sometimes occurred in the same year, with combined impacts on the fish catch abundance and average total length. Tables 13 and 14 list all of the species affected by the combined winter freeze and summer drought conditions. **The bolded species were found to be affected based on data collected using at least two gear types for either catch abundance or average length. The species highlighted in red were affected for both catch abundance and total length under the combined effect of winter freeze and summer drought. Considering both catch abundance and total length, three species were identified as impacted by combined winter freeze and summer drought in at least two gear types: sand seatrout, Atlantic croaker and spotted seatrout.**

Table. 13 Fish species that had catch abundance affected by combined winter freeze and summer drought.

catch abundance affected by

Winter freeze & Summer drought	**BagSeine**	**BayTrawl**	**GillNet**
significantly afftected r>0.3 (n=31,p<0.05)	**Sand seatrout (0.34)** **Sheepshead (0.33)** Blue crab (0.32)	**Sand seatrout (0.57)** **Atlantic croaker (0.56)** **Spotted seatrout (0.49)** White shrimp (0.37) Bay anchovy (0.35)	**Atlantic croaker (0.38)**
affected but not significantly 0.13<r<0.3 (0.05<p<0.25)	**Red drum (0.28)** Pink shrimp (0.19) Pinfish (0.16)	Striped mullet (0.25)	**Spotted seatrout (0.27)** **Sheepshead (0.26)** Ladyfish (0.25) **Red drum (0.23)** Alligator (0.16)

Table. 14 Fish species that had average total length affected by combined winter freeze and summer drought.

average length affected by

Winter freeze & Summer drought	**BagSeine**	**BayTrawl**	**GillNet**
significantly afftected r>0.3 (n=31,p<0.05)	White shrimp (0.48) Pink shrimp (0.41)	Bay anchovy (0.61) **Atlantic croaker (0.58)** Gulf menhaden (0.50) Sheepshead (0.48) **Blue crab (0.35)**	**southern flounder (0.64)** **Blue crab (0.46)** Hardhead (0.36) **Spotted seatrout (0.31)**
affected but not significantly 0.13<r<0.3 (0.05<p<0.25)	**Southern flounder (0.27)** **Spotted seatrout (0.22)**	Sand seatrout (0.30)	**Atlantic croaker (0.27)**

4. Discussion

4.1 Climate

An increase in annual water temperature, along with a decline in annual precipitation, was observed in the Reserve since 1978. A long-term trend of increasing water temperature was also found along the entire Texas coast, with an overall average increase rate of 0.0428 $^{o}C\ yr^{-1}$ since 1978 (Fig. 4.5 in Montagna, 2011). Associated with the increase of water temperature, long-term trends of reduced rainfall and dissolved oxygen were also observed along the Texas coast in the Gulf of Mexico (Montagna, 2011), indicating that climate changes are not limited to the Reserve, but are occurring along the entire Texas coast.

Local precipitation levels have a strong influence on the drought severity in the area of the Reserve. Increasing annual temperatures, together with decreasing precipitation, have been observed in the past 3 decades, and may have led to more drought stress in Texas bays. Since the impact of precipitation on drought is cumulative by days, average daily rainfall over 0.35 inch in a month is defined as a heavy rainfall month, and daily rainfall less than 0.01 inch as light rain month (Hansen, 2013). According to this definition, Table 15 shows the number of light and heavy rainfall months at the CCIA weather station for each of the past five decades. In 2002-2013, the number of heavy rain months was high, while the number of light rain months was doubled compared with the previous two decades. This result indicates that the Mission-Aransas Reserve area is having more frequent intense rainfalls with longer drought periods in between, consistent with other recent climate change studies in the southeastern United States (Thomas et al., 2009).

Table. 15 Number of light or heavy rain months in the Reserve for the last five decades.

Year	No. of light rainfall months (Precipitation<0.76 cm mo^{-1})	No. of heavy rainfall months (Precipitation>26.7 cm mo^{-1})
1954-1965	23	3
1966-1977	22	4
1978-1989	15	4
1990-2001	15	2
2002-2013	30	4

4.2 Abundance and/or length changes for fish species

In total, 11 out of the 16 fish species examine in this study were identified as having consistent increasing or decreasing changes in the trend of either catch abundance or average total length in the Reserve since the late 1970's (Table 3). Some of the declining species have already drawn researcher's attention. Southern flounders (both juvenile and adult) along the Texas coast were reported to have declined by 1-3% in abundance since 1975 (Froeschke et al., 2011). In addition, Ward (2012) reported that a declining trend has been observed for blue crab, in both abundance and size, in the Texas bays since the mid-1980s. Though not coast-wide, the annual average length of brown shrimp, has also significantly decreased in Sabine Lake, Galveston Bay, East Matagorda Bay, West Matagorda Bay, San Antonio Bay and Lower Laguna Madre between 1977-2000 (TPWD, 2002).

There are species, however, that have been dramatically enhanced by changed fishing regulation and stocking programs, such as red drum (Vega et al., 2011; Carson et al., 2014), which declined in the 1970s and 1980s in the Northern Gulf of Mexico, but have increased about 3% since 1978 for both bag seine and gill net catches in the Reserve. Moreover, recent management focus on controlling size and number of fishing vessels allowed to capture small species, such as shrimp, and allowing them to grow larger and to more valuable sizes before harvesting (Caillouet Jr. et al., 2008). In these cases, the changing of the fish abundance was not only affected by climate factors, but also by species management and potential harvesting.

4.3 Fish species impacted by climate variables

Long-term changes, particularly the declines of fishery abundances and/or lengths in Texas bays, indicates the need to better understand the environmental factors impacting these species. Several studies have reported effects of either temperature or salinity on fish species in Texas bays. Sand seatrout abundance was found to be inversely related to salinity, and abundance was shown to decrease in summer when temperature was the highest (McDonald et al., 2009). Juvenile spotted seatrout distribution was also reported to be closely linked to salinity and temperature (Froeschke & Froeschke, 2011).

In this report, we identified several fish species that likely have been affected by winter freezes, summer drought, or the combined effect of freeze-drought in at least two TPWD sampling gear types (Table 16). In particular, decreases in the catch abundance and total length of **Atlantic croaker and spotted seatrout** were impacted by both winter freezes and summer droughts (red checkmarks). Whereas, only the catch abundance of **red drum, sheepshead, and sand seatrout** were affected by winter freeze and summer drought (blue checkmarks). Finally, the total length of **Southern flounder** was affected by winter freeze and summer drought (green checkmarks).

Table. 16 The list of species that had been affected by winter freeze, summer drought or both of them in catch abundance and total length, in at least two gear types.

	winter freeze		summer drought		winter freeze & summer drought	
Species	**catch abundance**	**length**	**catch abundance**	**length**	**catch abundance**	**length**
Brown shrimp						
Pink shrimp						
white shrimp						
Atlantic croaker	✔		✔	✔	✔	✔
Bay anchovy				✔		
Blue crab				✔		✔
Gulf menhaden	✔			✔		
Pinfish				✔		
Spot						
Striped mullet			✔			
Black drum	✔					
Red Drum	✔		✔		✔	
Sheepshead	✔		✔	✔	✔	
Sand seatrout	✔	✔	✔		✔	
Spotted seatrout	✔	✔		✔	✔	✔
Southern flounder		✔		✔		✔
Alligator						
Gafftopsail						
Gizzard						
Hardhead catfish						
Ladyfish						

Impacts on the abundance and size of each fishery are not the only potential impacts of a changing climate on fisheries. Changes in the structure or community of the fish species (Gelwick et al., 2001), may also occur, but that is outside of the scope of this report. The other important climate variable in Texas bays that we did not discuss, but is also important, is dissolved oxygen, which can significantly influence fish community and abundances (i.e., Gelwick et al., 2001; Froeschke & Stunz, 2012). Moreover, factors other than climate change, such as population dynamics, predator/prey relationship, genetic composition, etc., must also be considered when examining species abundance (Carey, 2009). Therefore, it is a difficult task to establish a simple cause and effect relation between a single climate change variable with a species change. Clearly, more research is needed to more fully understand the impact of multiple climate variables on the fisheries of the Reserve.

4.4 Bird species identified to have been impacted by climate variables

Climate changes can cause variations in food supply, habitat structure, and other factors that may severely impact bird reproduction, migration, and other activities (Carey, 2009). A significant northward shift of many bird species has been globally observed, and was proposed to be caused by global warming and increases in minimum winter temperature (i.e., Thomas & Lennon, 1999; Valiela & Bowen, 2003; Audubon, 2009). Evidence also showed that both distribution and abundance of some songbirds were limited by temperature in winter (Butler et al., 2007). Moreover, precipitation has been found to mostly affect the long-term survival of many bird species, because changes in precipitation can affect plant growth, soil moisture, water storage and insect abundance and distributions (Michelson, 2014).

Table. 17 lists the bird species that have been affected by different climate variables within the Reserve. Nineteen out of the 28 bird species have been identified affected by one aspect of climate change, mostly the increases on minimum winter temperature or drought during the second half of the year, during the past several decades. In particular, **ten species** (marked in column 2, including **Caspian tern, Great blue heron, Black-bellied plover, Brown pelican, Laughing gull, American Robin, American Wigeon, dowitcher sp., Great-tailed Grackle, and Northern Pintail**) were identified as being affected by the **increases on minimum winter temperature, while** only **four species** (marked in column 1, including **Doubled-crested cormorant, Forster's tern, Piping plovers, and Western Sandpiper**) were limited by **winter freezes**. In addition, **eight species** (marked in column 3, including **Double-crested cormorant, Eared grebe, Forster's tern, Black skimmer, Black-bellied plover, Sanderling, dowitcher sp., and Western Sandpiper**) were limited by the **drought**

during the second half of the year. Three species, Doubled-crested cormorant, Forster's tern, and Wester Sandpiper, were identified to be limited by both winter freezes and second half year drought, while two other species (Black-bellied plover and dowitcher sp.) were found limited by both increases on minimum winter temperature and second half year drought.

Table. 17 The list of bird species that were impacted by either winter freezes (minimum temperature during Dec. 14 –Jan. 5) or drought during the second half of the year inside of the Reserve.

bird name	winter freeze		second half year drought	
	limit	promote	limit	promote
Doubled-crested cormorant	✔		✔	
Eared grebe			✔	
Herring gull				
Forster's tern	✔		✔	
Royal tern				
Gull-billed tern				
Caspian tern		✔		
Black skimmer			✔	
Great blue heron		✔		
Black-bellied plover		✔	✔	
Piping plovers	✔			✔
Brown pelican		✔		
American oystercatcher				
Laughing gull		✔		
Sanderling			✔	
Red knot				
American Robin		✔		
American White Pelican				
American Wigeon		✔		
dowitcher sp.		✔	✔	
duck sp.				
Great-tailed Grackle		✔		
Northern Pintail		✔		
Red-winged Blackbird				✔
Redhead				✔
Western Sandpiper	✔		✔	
Whooping Crane				

It is worth noting that only 28 birds species, either most dominant ones or most likely to be affected by human impacts, were chosen for the analysis in this report, and the remaining over 150 species were not included due to their minor contributions. However, they were also likely affected by the climate change, and some of them may have been threatened by abundance. Additional research on these less abundant species could be beneficial.

5. Conclusion

To help us better understand the long term climate change impacts on the Mission-Aransas Reserve, long-term climate and biological datasets (NCDC, TCOON, TPWD, and Audubon) have been analyzed, and the species most impacted by major climate variables have been identified in this report. Six out of the 61 fish species, and nineteen out of more than 180 bird species were identified as having been more impacted by climate variables than the other species in this area.

This report will help the Reserve and its partners strengthen their understanding of the impact that climate variables have on local estuarine species. As winter air temperatures continue to increase and more frequent intense rainfall events are separated by longer periods of drought, this information will be become increasingly more important. The results will also help establish priorities for future research efforts that assess vulnerability and lead to the development of adaptation strategies that address the major climate change threats.

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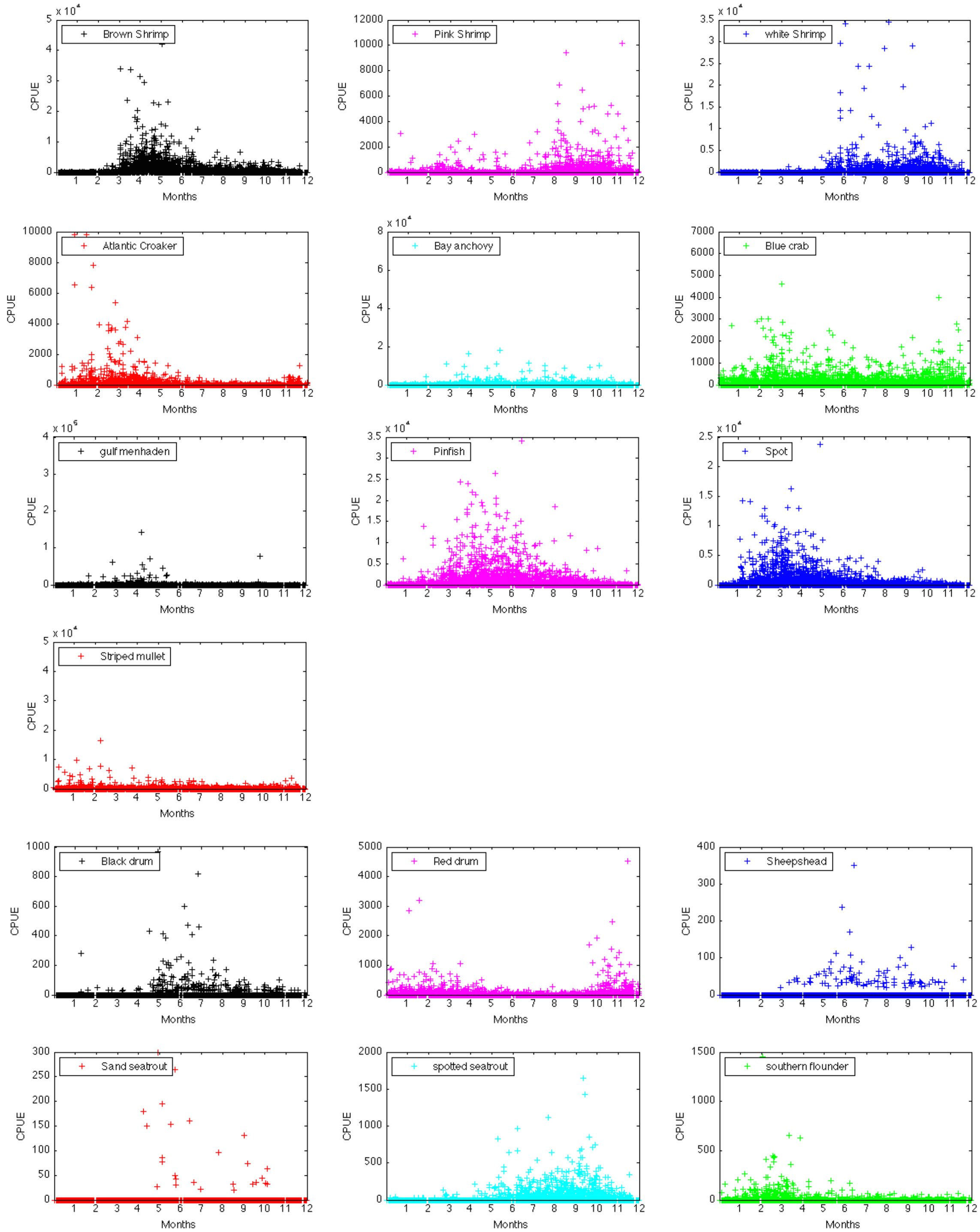
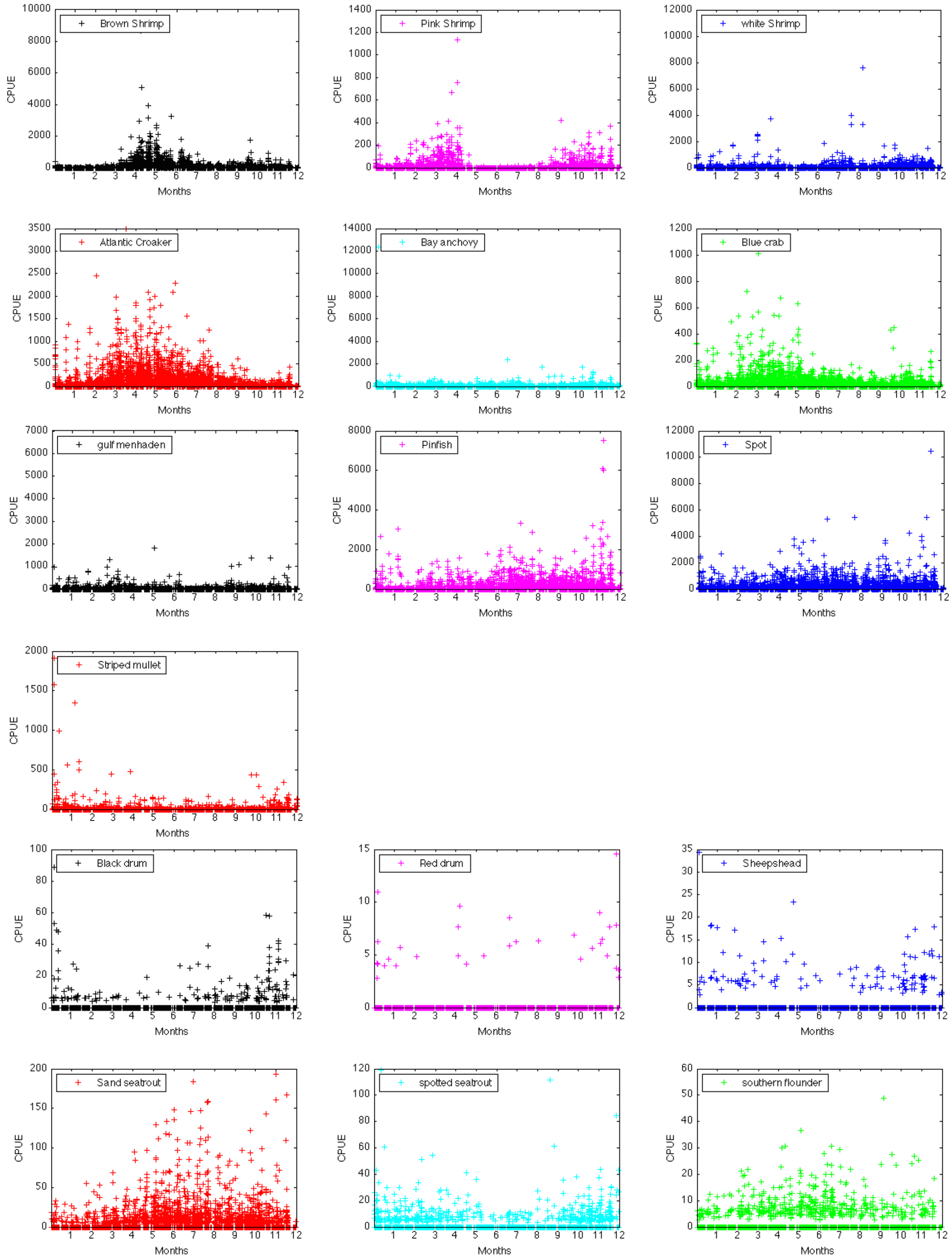
Appendix 1

The monthly catch abundance distribution for all dominant fishes by (a) bag seine, (b) say trawl, and (c) gill net, respectively.

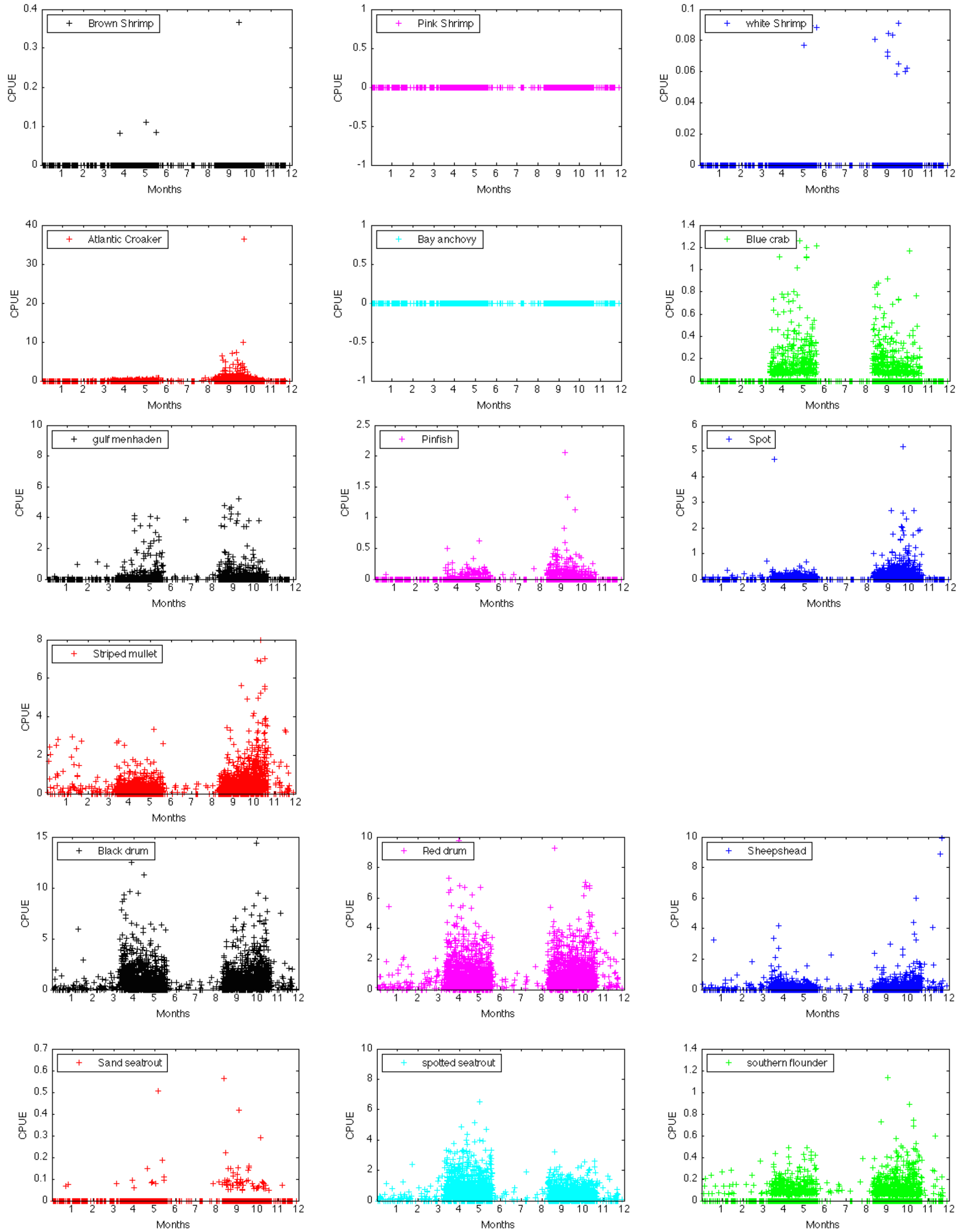
(a) bag seine:



(b) bay trawl


Brown Shrimp
Pink Shrimp
white Shrimp
Atlantic Croaker
Bay anchovy
Blue crab
gulf menhaden
Pinfish
Spot
Striped mullet
Black drum
Red drum
Sheepshead
Sand seatrout
spotted seatrout
southern flounder
CPUE
Months

(c) gill net


Brown Shrimp
Pink Shrimp
white Shrimp
Atlantic Croaker
Bay anchovy
Blue crab
gulf menhaden
Pinfish
Spot
Striped mullet
Black drum
Red drum
Sheepshead
Sand seatrout
spotted seatrout
southern flounder
CPUE
Months